

# The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2021)

Monday 23 August 2021 - Saturday 28 August 2021



## Book of Abstracts



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## Axion Physics and Experiments / 374

**Breaking Peccei-Quinn Symmetry at Low Scales**Author: Peihong Gu<sup>None</sup>

We propose an efficient mechanism to realize an invisible axion from a low scale Peccei-Quinn symmetry breaking. Our basic model only contains a gauge boson, an up-type vector-like quark, two Higgs doublets and two Higgs singlets besides the standard model fermions and gauge bosons. The physical Peccei-Quinn global symmetry is a result of two independent global symmetries connected by the new gauge symmetry. Any one of these two global symmetries only acts on either the right-handed top quark or the left-handed new quark so that it can avoid the domain wall problem. Thanks to the electroweak and new gauge interactions, the Higgs doublet for the top quark mass generation and the Higgs singlet for the new quark mass generation can only contribute a tiny fraction in the axion. The axion decay constant can be largely enhanced by a factor composed of the vacuum expectation values of the four Higgs scalars. Our mechanism provides a new opportunity to fully test the Peccei-Quinn symmetry at colliders.

## Axion Physics and Experiments / 458

**Searching for solar axions with SNO**Author: Nick Houston<sup>1</sup>Co-authors: Aagaman Bhusal<sup>2</sup>; Tianjun Li<sup>2</sup><sup>1</sup> BJUT<sup>2</sup> ITP-CAS

Corresponding Author: nhouston@bjut.edu.cn

We explore a novel detection possibility for solar axions, which relies only on their couplings to nucleons, via the axion-induced dissociation of deuterons into their constituent neutrons and protons. An opportune target for this process is the now-concluded Sudbury Neutrino Observatory (SNO) experiment, which relied upon large quantities of heavy water to resolve the solar neutrino problem. From the full SNO dataset we exclude in a model-independent fashion isovector axion-nucleon couplings  $|g_{aN}^3| \equiv \frac{1}{2}|g_{an} - g_{ap}| > 2 \times 10^{-5} \text{GeV}^{-1}$  at 95% C.L. for sub-MeV axion masses, covering previously unexplored regions of the axion parameter space. In the absence of a precise cancellation between  $g_{an}$  and  $g_{ap}$  this result also exceeds comparable constraints from other laboratory experiments, and excludes regions of the parameter space for which astrophysical constraints from SN1987A and neutron star cooling are inapplicable due to axion trapping.

Based on Phys.Rev.Lett. 126 (2021) no.9, 091601, arXiv:2004.02733

## Axion Physics and Experiments / 43

**Axion Quality from Superconformal Dynamics**Authors: Yuichiro Nakai<sup>1</sup>; Motoo Suzuki<sup>1</sup><sup>1</sup> T. D. Lee Institute, Shanghai

Corresponding Author: ynakai0930@gmail.com

We discuss a possibility that a superconformal dynamics induces the emergence of a global U(1)PQ symmetry to solve the strong CP problem through the axion. Fields spontaneously breaking the

U(1)PQ symmetry couple to new quarks charged under the ordinary color SU(3)<sub>C</sub> and a new SU(N) gauge group. The theory flows into an IR fixed point where the U(1)PQ breaking fields hold a large anomalous dimension leading to the suppression of U(1)PQ-violating higher dimensional operators. The spontaneous breaking of the U(1)PQ makes the new quarks massive. The U(1)PQ symmetry is anomalous under the SU(3)<sub>C</sub> but not under the SU(N) so that the axion couples to only the color SU(3)<sub>C</sub> and the usual axion potential is generated. We also comment on a model that the U(1)PQ breaking fields are realized as meson superfields in a new supersymmetric QCD.

**Axion Physics and Experiments / 176**

## Detecting an Axion-like particle with machine learning and jet substructure variables at the LHC

**Authors:** Daohan Wang<sup>1</sup>; Jie Ren<sup>2</sup>; Jinmin Yang<sup>3</sup>; Lei Wu<sup>4</sup>; mengchao zhang<sup>5</sup>

<sup>1</sup> *Institute of theoretical physics, CAS*

<sup>2</sup> *Institute of Theoretical Physics, Chinese Academy of Sciences*

<sup>3</sup> *Institute of Theoretical Physics (ITP)*

<sup>4</sup> *Nanjing Normal University*

<sup>5</sup> *IBS-CTPU*

**Corresponding Author:** wdh9508@gmail.com

Axion-like particles (ALPs) appear in various new physics models with spontaneous global symmetry breaking. When the ALP mass is in the range of MeV to GeV, the cosmology and astrophysics bounds are so far quite weak. In this work, we investigate such light ALPs through the ALP-strahlung production process  $pp \rightarrow Va(\rightarrow \gamma\gamma)$  at the 14 TeV LHC with an integrated luminosity of  $3000 \text{ fb}^{-1}$  (HL-LHC). Building on the concept of jet image which uses calorimeter towers as the pixels of the image and measures a jet as an image and several jet substructure variables, we propose two methods to identify the highly boosted ALPs which decay to a pair of highly collimated photons. With the photon-jet algorithm and the CNN tagging algorithm, we demonstrate that our approaches can extend current LHC sensitivity and probe the ALP mass range from  $0.3 \text{ GeV}$  to  $10 \text{ GeV}$ . The obtained bounds are stronger than the existing limits on the ALP-photon coupling.

**Axion Physics and Experiments / 356**

## Probe Dark Matter Axions with Broadband and Narrowband methods

**Authors:** Gao Yu<sup>None</sup>; Qiaoli Yang<sup>1</sup>

<sup>1</sup> *Jinan University*

**Corresponding Author:** qiaoliyang@jnu.edu.cn

The cosmological axions/axion-like particles can compose a significant part of dark matter, however the uncertainty of their mass is large. Here we propose to search the axions broadbandly using a cylindrical capacitor, in which the static electric field converts dark matter axions into an oscillating magnetic field. A superconductor ring-coil pickup system can further boost the sensitivity. This proposed setup is capable of wide mass range searches. On the other hand, The hyperfine splitting between the spin 0 singlet ground state and the spin 1 triplet state of hydrogen is  $0.59 \times 10^{-5} \text{ eV}$ , which is close to the mass of the QCD dark matter axions. With some additional adjustment by the Zeeman effect, quantum transitions could be induced between these hydrogen states. We believe this method will be efficient for a narrowband search of the QCD axions.



**Axion Physics and Experiments / 350**

## **Axion haloscope array With PT symmetry beyond the quantum limit**

**Corresponding Author:** yifan.chen@lpthe.jussieu.fr

We generalize the recently proposed PT-symmetric axion haloscope to a larger array with more PT-symmetric structures. The optimized signal-to-noise ratio (SNR) has a greater enhancement, as well as the signal power. Furthermore, we show that the robustness of the detector towards the variations of the array coupling is the strongest when a binary tree structure is introduced which contains a largely enhanced PT symmetry. The multiple allowed probing sensors can further increase the SNR by a factor of sensors' number due to the correlation of the signals. This type of array can strongly boost the search for axion compared to single mode resonant detection. The enhancement to the SNR becomes the most manifest when applied to the newly proposed detection using superconducting radiofrequency cavity with AC magnetic field where most of the parameter space of the QCD axion above kHz can be probed.

**Axion Physics and Experiments / 266**

## **The echo method for axion dark matter detection**

**Author:** Ariel Arza<sup>1</sup>

<sup>1</sup> *ITMP, Lomonosov Moscow State University*

**Corresponding Author:** ariel.arza@gmail.com

In this talk I will present a new idea to search for axion dark matter. It is based on the backscattering of a powerful electromagnetic wave that is produced due to the stimulated decay of ambient axions. This backscattering, the echo, is a negligible (but detectable) signal with frequency spectrum centered at one half the axion mass. In the mass range where the axion is motivated to be the dark matter, one would expect the echo signal in the microwave, radio, or even infrared ranges of the electromagnetic spectrum. I will show the main properties of the echo signal, possible detection schemes and future prospects.

**Axion Physics and Experiments / 301**

## **Axion Telescopes: detecting stellar axions.**

**Author:** Maurizio Giannotti<sup>1</sup>

<sup>1</sup> *Barry University*

**Corresponding Author:** mgiannotti@barry.edu

Axions and other light, weakly interacting particles might be copiously produced in stars. Can we detect them? Here I will discuss the strategies, challenges and possibilities to detect stellar axions and axion-like particles with existent and next-generation instruments.

**Axion Physics and Experiments / 192**

## Photophilic hadronic axion from heavy magnetic monopoles

**Author:** Anton Sokolov<sup>None</sup>

**Co-author:** Andreas Ringwald<sup>1</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron DESY*

**Corresponding Author:** anton.sokolov@desy.de

We propose a model for the QCD axion which is realized through a coupling of the Peccei-Quinn scalar field to magnetically charged fermions at high energies. We show that the axion of this model solves the strong CP problem and then integrate out heavy magnetic monopoles using the Schwinger proper time method. We find that the model discussed yields axion couplings to the Standard Model which are drastically different from the ones calculated within the KSVZ/DFSZ-type models, so that large part of the corresponding parameter space can be probed by various projected experiments. Moreover, the axion we introduce is consistent with the astrophysical hints suggested both by anomalous TeV-transparency of the Universe and by excessive cooling of horizontal branch stars in globular clusters. We argue that the leading term for the cosmic axion abundance is not changed compared to the conventional pre-inflationary QCD axion case for axion decay constant  $f_a > 10^{12}$  GeV.

**Axion Physics and Experiments / 104**

## Hunting Axions Using Astrophysical Observation and Quantum Metrology

**Author:** Yifan Chen<sup>1</sup>

<sup>1</sup> *LPTHE, Paris*

**Corresponding Author:** yifan.chen@lpthe.jussieu.fr

Ultralight bosons behave like coherent waves when the occupation number is large enough. If they are coupled to the Standard Model sector of the particle physics, such an oscillating background can induce a tiny signal. Near a fast rotating black hole, axion within one order of the mass window can accumulate through superradiance, with a large density saturating the non-linear self-interaction. If linearly polarized radiation is emitted near the black hole, axion can contribute to birefringence effect that shifts the position angle periodically, making the polarimetric measurements of the Event Horizon Telescope a powerful way to look for ultra-light axions. On the other hand, quantum metrology can play huge roles in the measurements of fundamental physics. Among these, resonant detection of axion dark matter based on electromagnetic coupling is a popular direction attracting many ongoing experiments and proposals such as microwave cavity, LC circuit and superconducting radio-frequency cavity. A quantum network of resonators can strongly enhance the signal power and boost the search.

**Axion Physics and Experiments / 466**

## Thermal QCD axions across thresholds

**Author:** Seokhoon Yun<sup>1</sup>

<sup>1</sup> *Padua University*

**Corresponding Author:** seokhoon.yun@pd.infn.it

Thermal axion production in the early universe goes through several mass thresholds, and the resulting rate may change dramatically across them. Focusing on the KSVZ and DFSZ frameworks for the invisible QCD axion, we perform a systematic analysis of thermal production across thresholds and provide smooth results for the rate. The QCD phase transition is an obstacle for both classes of models. For the hadronic KSVZ axion, we also deal with production at temperatures around the mass of the heavy-colored fermion charged under the Peccei-Quinn (PQ) symmetry. Standard model fermions are PQ-charged within the DFSZ framework, and additional thresholds are the heavy Higgs bosons masses and the electroweak phase transition. We investigate the cosmological implications with a specific focus on axion dark radiation quantified by an effective number of neutrino species and explore the discovery reach of future CMB-S4 surveys.

**Axion Physics and Experiments / 465**

## Thermal axion production across the QCD phase transition

**Author:** Fazlollah Hajkarim<sup>1</sup>

<sup>1</sup> *Padua University*

**Corresponding Author:** fazlollah.hajkarim@pd.infn.it

We study thermal axion production around the confinement scale. At higher temperatures, we extend current calculations to account for the masses of heavy quarks, whereas we quantify production via hadron scattering at lower temperatures. Matching our results between the two opposite regimes provides us with a continuous axion production rate across the QCD phase transition. We employ such a rate to quantify the axion contribution to the effective number of neutrino species.

**Axion Physics and Experiments / 180**

## Non-thermally trapped inflation due to the tachyonic instability

**Authors:** Shota Nakagawa<sup>1</sup>; Fuminobu Takahashi<sup>None</sup>; Naoya Kitajima<sup>None</sup>; Prateek Agrawal<sup>2</sup>; Matthew Reece<sup>3</sup>

<sup>1</sup> *Tohoku University*

<sup>2</sup> *University of Oxford*

<sup>3</sup> *Harvard University*

**Corresponding Author:** shota.nakagawa.r7@dc.tohoku.ac.jp

The motion of the axion field explosively produces hidden photons due to the tachyonic instability. We consider the Abelian Higgs model coupled to the hidden photon which leads to the effective mass of the Higgs. When the axion starts to oscillate and the hidden photon are produced, the Higgs is trapped by the effective mass. If the vacuum energy of the Higgs dominates the universe, then the inflation non-thermally occurs in the late-time universe. In this talk, we will present our results and its implication for cosmology.

**Axion Physics and Experiments / 179**

## Cosmic Birefringence Triggered by Dark Matter Domination

**Authors:** Shota Nakagawa<sup>1</sup>; Fuminobu Takahashi<sup>1</sup>; Masaki Yamada<sup>1</sup>

<sup>1</sup> *Tohoku University*

**Corresponding Author:** m.yamada@tohoku.ac.jp

Cosmic birefringence is predicted if an axion-like particle (ALP) moves after the recombination. We show that this naturally happens if the ALP is coupled to the dark matter density because it then acquires a large effective mass after the matter-radiation equality. We give a simple model to realize this scenario, where dark matter is made of hidden monopoles, which give the ALP such a large effective mass through the Witten effect. The mechanism works if the ALP decay constant is of order the GUT-scale without a fine-tuning of the initial misalignment angle.

**Axion Physics and Experiments / 240**

## Heavy QCD axion inflation and strong CP problem

**Author:** Wen Yin<sup>None</sup>

**Corresponding Author:** yinwen@hep-th.phys.s.u-tokyo.ac.jp

The QCD axion mass may receive contributions from small-size instantons or other Peccei-Quinn breaking effects. I show that it is possible for such a heavy QCD axion to induce slow-roll inflation if the potential is sufficiently flat near its maximum by balancing the small instanton contribution with another Peccei-Quinn symmetry breaking term. In addition, requiring the axion hilltop inflation may result in the strong CP phase that is close to zero.

**Axion Physics and Experiments / 404**

## Resurrecting Low-Mass Axion Dark Matter Via a Dynamical QCD Scale

**Author:** Fei Huang<sup>1</sup>

<sup>1</sup> *ITP CAS and UC Irvine*

**Corresponding Author:** huangf4@uci.edu

In the framework where the strong coupling is dynamical, the QCD sector may confine at a much higher temperature than it would in the Standard Model, and the temperature-dependent mass of the QCD axion evolves in a non-trivial way. We find that, depending on the evolution of  $\Lambda_{QCD}$ , the axion field may undergo multiple distinct phases of damping and oscillation leading generically to a suppression of its relic abundance. Such a suppression could therefore open up a wide range of parameter space, resurrecting in particular axion dark-matter models with a large Peccei-Quinn scale  $f_a \gg 10^{12}$  GeV, i.e., with a lighter mass than the standard QCD axion.

**Axion Physics and Experiments / 83**

## High-quality axions in solutions to the $\mu$ problem

**Author:** Prudhvi Bhattiprolu<sup>1</sup>

**Co-author:** Stephen Martin<sup>1</sup>

<sup>1</sup> Northern Illinois University**Corresponding Author:** pbhattiprolu@niu.edu

Solutions to the  $\mu$  problem in supersymmetry based on the Kim-Nilles mechanism naturally feature a Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) axion with decay constant of order the geometric mean of the Planck and TeV scales, consistent with astrophysical limits. We investigate minimal models of this type with two gauge singlet fields that break a Peccei-Quinn symmetry, and extensions with extra vectorlike quark and lepton supermultiplets consistent with gauge coupling unification. We show that there are many anomaly-free discrete symmetries, depending on the vectorlike matter content, that protect the Peccei-Quinn symmetry to sufficiently high order to solve the strong CP problem. We study the axion couplings in this class of models. Models of this type that are automatically free of the domain wall problem require at least one pair of strongly interacting vectorlike multiplets with mass at the intermediate scale, and predict axion couplings that are greatly enhanced compared to the minimal supersymmetric DFSZ models, putting them within reach of proposed axion searches.

Axion Physics and Experiments / 12

## The Earth as a transducer for dark-photon dark-matter detection

**Author:** Saarik Kalia<sup>1</sup>**Co-authors:** Derek Jackson Kimball<sup>2</sup>; Michael Fedderke<sup>3</sup>; Peter Graham<sup>1</sup><sup>1</sup> Stanford University<sup>2</sup> California State University, East Bay<sup>3</sup> The Johns Hopkins University**Corresponding Author:** saarik@stanford.edu

In this talk, I will propose the use of the Earth as a transducer for ultralight dark-matter detection. In particular I will point out a novel signal of kinetically mixed dark-photon dark matter: a monochromatic oscillating magnetic field generated at the surface of the Earth. Similar to the signal in a laboratory experiment in a shielded box (or cavity), this signal arises because the lower atmosphere is a low-conductivity air gap sandwiched between the highly conductive interior of the Earth below and ionosphere or interplanetary medium above. At low masses (frequencies) the signal in a laboratory detector is usually suppressed by the size of the detector multiplied by the dark-matter mass. Crucially, in our case the suppression is by the radius of the Earth, and not by the (much smaller) height of the atmosphere. The magnetic field signal exhibits a global vectorial pattern that is spatially coherent across the Earth, which enables sensitive searches for this signal using unshielded magnetometers dispersed over the surface of the Earth. I will summarize the results of such a search using a publicly available dataset from the SuperMAG collaboration. The constraints from this search are complementary to existing astrophysical bounds. Future searches for this signal may improve the sensitivity over a wide range of ultralight dark-matter candidates and masses.

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## Search for Dark Sector at Belle

**Corresponding Author:** giacomo.depietro@roma3.infn.it

The Belle experiment at the KEKB asymmetric-energy  $e^+e^-$  collider has accumulated close to  $1 \text{ ab}^{-1}$  of data in electron-positron collisions at center-of-mass energies around various  $\Upsilon(nS)$  resonances. These data can be used to perform a number of new physics searches in the context of dark sector with an unprecedented precision.

We present the results of a search of the dark photon in  $B$ -meson decays, the search for dark matter in bottomonium decays, as well as the latest results in the search for dark forces, via direct production, or in the decay of mesons.

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## Cancellation in Dark Matter-Nucleon Interactions: the Role of Non-Standard-Model-like Yukawa Couplings

**Authors:** Bibhabasu De<sup>1</sup>; Debottam Das<sup>1</sup>; Subhadip Mitra<sup>2</sup>

<sup>1</sup> *IOP Bhubaneswar*

<sup>2</sup> *IIT Hyderabad*

**Corresponding Author:** bibhabasude@gmail.com

Extensive searches to probe the particle nature of dark matter (DM) have been going on for some decades now but, so far, no conclusive evidence has been found. Among various options, the Weakly Interacting Massive Particles (WIMP) remains one of the prime possibilities as candidates for DM near the TeV scale. Taking a phenomenological view, such null results may be explained for a generic WIMP in a Higgs-portal scenario if we allow the light-quark Yukawa couplings to assume non-Standard Model (non-SM)-like values. This follows from a cancellation among different terms in the DM-nucleon scattering which can, in turn, lead to a vanishingly small direct-detection cross section. It might also lead to isospin violation in the DM-nucleon scattering. Such non-SM values of light-quark Yukawa couplings may be probed in the high luminosity run of the LHC.

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## A probe into leptophilic scalar dark matter

**Authors:** Sreemanti Chakraborti<sup>1</sup>; Rashidul Islam<sup>2</sup>

<sup>1</sup> *Indian Institute of Technology, Guwahati, India*

<sup>2</sup> *Mathabhanga College*

**Corresponding Author:** sreemanti.c@gmail.com

We revisit the scalar singlet dark matter (DM) accompanied by vectorlike dark leptons in two scenarios: in case I, the dark sector consists of a Dirac fermionic doublet; while in case II, a doublet fermion and a singlet. In both cases, the dark leptons couple with other dark sector particles and the Standard Model (SM) via gauge and Yukawa interactions. As a result, (i) new DM annihilation processes, including pair annihilation and coannihilation channels emerge, and (ii) new production channels for leptonic final states giving much enhancement in cross sections open up for DM searches in the LHC. In the former case, the mass splitting between the dark leptons is loop induced at best makes the distinction of the dark sector particles of different isospins a challenging task.

In the latter case, we alleviate the said limitation by introducing an extra singlet leptonic dark sector field. The “singlet-doublet mixing” produces an arbitrary mass splitting between the two components of the doublet in a gauge-invariant way, as well as provides a useful handle to distinguish between the dark sector particles of different isospins. As the dark leptons coannihilate non-trivially, the mixing effectively enhances the viable parameter space for the relic density constraint. In a low DM mass regime, with a non-zero mixing, it is possible to relax the existing indirect search bounds on the upper limit of the DM-SM coupling. From the analysis of the  $3\tau + E_T^{\text{miss}}$  and  $\ell\tau + E_T^{\text{miss}}$  channels for LHC at  $\sqrt{s} = 13$  TeV, one ensures the presence of the mixing parameter between the dark sector particles of the theory by looking at the distinct peak and tail positions of the kinematic

distributions, which remains a constant feature of the model. While both the channels present us the opportunity to detect the mixing signature at the LHC/HL-LHC, the former gives better results in terms of a larger region of mixing parameter. From the fiducial cross section, the projected statistical significance for the integrated luminosity,  $\mathcal{L} = 3ab^{-1}$ , are shown for a combined parameter region obeying all the existing constraints, where there is the best possibility to detect such a signature.

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### Searches for dark matter with the ATLAS detector

**Author:** Jay Chan<sup>1</sup>

<sup>1</sup> *University of Wisconsin Madison (US)*

**Corresponding Author:** jay.chan@cern.ch

The presence of a non-baryonic Dark Matter (DM) component in the Universe is inferred from the observation of its gravitational interaction. If Dark Matter interacts weakly with the Standard Model (SM) it could be produced at the LHC. The ATLAS experiment has developed a broad search program for DM candidates, including resonance searches for the mediator which would couple DM to the SM, searches with large missing transverse momentum produced in association with other particles (light and heavy quarks, photons, Z and H bosons) called mono-X searches and searches where the Higgs boson provides a portal to Dark Matter, leading to invisible Higgs decays. The results of recent searches on 13 TeV pp data, their interplay and interpretation will be presented. Prospects for HL-LHC will also be discussed.

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### A dark matter WIMP that can be detected and definitively identified with currently planned experiments

**Authors:** Bailey Tallman<sup>1</sup>; Caden LaFontaine<sup>1</sup>; Roland Allen<sup>2</sup>; Brandon Torres<sup>1</sup>; Diego Cristancho Guerrero<sup>1</sup>; Drue Lubanski<sup>1</sup>; Jessica Jaksik<sup>1</sup>; Sabrina Hernandez<sup>1</sup>; Spencer Ellis<sup>1</sup>; Trevor Croteau,<sup>1</sup>

<sup>1</sup> *Texas A&M University*

<sup>2</sup> *Texas A&M University*

**Corresponding Author:** allen@tamu.edu

A recently proposed dark matter WIMP [1] has only second-order couplings to gauge bosons and itself. As a result, it has small annihilation, scattering, and creation cross-sections, and is consequently consistent with all current experiments and the observed abundance of dark matter. These cross-sections are, however, still sufficiently large to enable detection in experiments that are planned for the near future, and definitive identification in experiments proposed on a longer time scale. The (multi-channel) cross-section for annihilation is consistent with thermal production and freeze-out in the early universe, and with current evidence for dark matter annihilation in analyses of the observations of gamma rays by Fermi-LAT and antiprotons by AMS-02, as well as the constraints from Planck and Fermi-LAT. The cross-section for direct detection via collision with xenon nuclei is estimated to be slightly below  $10^{-47}$  cm<sup>2</sup>, which should be attainable by LZ and Xenon nT and well within the reach of Darwin. The cross-section for collider detection via vector boson fusion is estimated to be  $\sim 1$  fb, and may be ultimately attainable by the high-luminosity LHC; definitive collider identification will probably require the more powerful facilities now being proposed. This dark matter particle is compatible with a supersymmetric candidate in a multicomponent scenario.

[1] Reagan Thornberry, Maxwell Throm, John Killough, Dylan Blend, Michael Erickson, Brian Sun, Brett Bays, Gabe Frohaug, and Roland E. Allen, “Experimental signatures of a new dark matter WIMP”, EPL (European Physics Letters), in press, arXiv:2104.11715 [hep-ph].

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## Dark matter flux from Accreting Black Holes and Direct Detections

**Author:** Sichun Sun<sup>None</sup>

**Corresponding Author:** sichunssun@gmail.com

We discuss the possibility that accreting black hole systems could be sources for dark matter flux through several different mechanisms. We firstly discuss two types of systems: coronal thermal plasmas around supermassive black holes in active galactic nuclei (AGNs), and accretion disks of stellar-mass X-ray black hole binaries (BHBs). We explore how these black hole systems may produce keV light dark matter fluxes and find that the dark fluxes from those sources might be too weak to account for the current XENON1T excess. On the other hand, black holes can be good accelerators to accrete and boost heavy dark matter particles. If considering collisions or dark electromagnetism, those particles could then escape and reach the benchmark speed of  $0.1c$  at the detector. We also extend the black hole mass region to primordial black holes (PBHs) and discuss the possibility of contributing to keV light dark flux via superradiance of PBHs.

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## Dark Sector searches in CMS

**Author:** Sushil Chauhan<sup>1</sup>

<sup>1</sup> *Panjab Univ., India*

**Corresponding Author:** sushil.chauhan@cern.ch

New physics may have gone unseen so far due to it being hidden in a dark sector. This may result in a rich phenomenology which we can access through portal interactions. In this talk, we present recent results from dark-sector searches in CMS using the full Run-II data-set of the LHC.

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## Flavor anomalies, Dark matter with vector-like fermions and scalar leptoquark

**Authors:** Rukmani Mohanta<sup>1</sup>; Shivaramakrishna Singirala<sup>2</sup>; Suchismita Sahoo<sup>3</sup>

<sup>1</sup> *University of Hyderabad*

<sup>2</sup> *School of physics, University of Hyderabad, Hyderabad 500046*

<sup>3</sup> *Central University of Karnataka*

**Corresponding Author:** krishnas542@gmail.com

We make a comprehensive study of vector-like fermionic dark matter and flavor anomalies in a simple extension of standard model. The model is added with doublet vector-like fermions of quark



and lepton type, and also a  $S_1(\bar{3}, 1, 1/3)$  scalar leptoquark. An additional lepton type singlet fermion is included, whose admixture with vector-like lepton doublet plays the role of dark matter and is examined in relic density and direct detection perspective. Electroweak precision observables are computed to put constraint on model parameter space. We constrain the new couplings from the branching ratio and angular observables associated with  $b \rightarrow sll(\nu_l\bar{\nu}_l)$ ,  $b \rightarrow s\gamma$  decays. We then estimate the branching ratios of the rare lepton flavor violating  $\tau$  decays such as  $\tau \rightarrow \mu(\gamma, \phi, \eta, \eta')$ . We also investigate the muon anomalous magnetic moment.

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### A search for dark matter using sub- PeV gamma-rays observed by Tibet AS $\gamma$

**Author:** Tarak Nath Maity<sup>1</sup>

**Co-authors:** Ranjan Laha<sup>1</sup>; Abhishek Dubey<sup>1</sup>; Akash Kumar Saha<sup>2</sup>

<sup>1</sup> *Indian Institute of Science*

<sup>2</sup> *Indian Institute of Science*

**Corresponding Author:** tarak.maity.physics@gmail.com

The discovery of diffuse sub-PeV gamma-rays by the Tibet AS $\gamma$  collaboration promises to revolutionize our understanding of the high-energy astrophysical universe. It has been shown that this data broadly agrees with prior theoretical expectations. We study the impact of this discovery on a well-motivated new physics scenario: PeV-scale decaying dark matter (DM). Considering a wide range of final states in DM decay, a number of DM density profiles, and numerous astrophysical background models, we find that this data provides the most stringent limit on DM lifetime for various Standard Model final states. In particular, we find that the strongest constraints are derived for DM masses in between a few PeV to few tens of PeV. Near future data of these high-energy gamma-rays can be used to discover PeV-scale decaying DM.

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### Gravitational SIMPs

**Authors:** Basabendu Barman<sup>None</sup>; Nicolás Bernal<sup>1</sup>

<sup>1</sup> *Universidad Antonio Nariño*

**Corresponding Author:** basabendu88barman@gmail.com

We study the impact of thermalization and number-changing processes in the dark sector on the yield of gravitationally produced dark matter (DM). We take into account the DM production through the  $s$ -channel exchange of a massless graviton both from the scattering of inflatons during the reheating era, and from the Standard Model bath via the UV freeze-in mechanism. By considering the DM to be a scalar, a fermion, and a vector boson we show, in a model-independent way, that DM self-interaction gives rise to a larger viable parameter space by allowing lower reheating temperature to be compatible with Planck observed relic abundance. As an example, we also discuss our findings in the context of the  $\mathbb{Z}_2$ -symmetric scalar singlet DM model.

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### Light singlino DM of the natural NMSSM

**Authors:** Arindam Chatterjee<sup>1</sup>; Waleed Abdallah<sup>2</sup>; Asesh Krishna Datta<sup>3</sup>

<sup>1</sup> *Department of Physics, Shiv Nadar University, Gautam Buddha Nagar 201314, India*

<sup>2</sup> *Faculty of Science, Cairo University, Giza 12613, Egypt*

<sup>3</sup> *Harish-Chandra Research Institute, HBNI, Allahabad 211019, India*

**Corresponding Author:** awaleed@sci.cu.edu.eg

Inspired by the fact that relatively small values of the effective higgsino mass parameter of the Z3-symmetric Next-to-Minimal Supersymmetric Standard Model (NMSSM) could render the scenario ‘natural’, we explore the plausibility of having relatively light neutralinos and charginos (the electroweakinos or the ewinos) in such a scenario with a rather light singlino-like Lightest Supersymmetric Particle (LSP), which is a Dark Matter (DM) candidate, and singlet-dominated scalar excitations. By first confirming the indications in the existing literature that finding simultaneous compliance with results from the Large Hadron Collider (LHC) and those from various DM experiments with such light states is, in general, a difficult ask, we proceed to demonstrate, with the help of a few representative benchmark points, how exactly and to what extent could such a highly motivated ‘natural’ setup with a singlino-like DM candidate still remains plausible.

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## Freezing In with Lepton Flavored Fermions

**Author:** Shiuli Chatterjee<sup>1</sup>

**Co-authors:** Giancarlo D’Ambrosio ; Ranjan Laha<sup>1</sup>; Sudhir Kumar Vempati<sup>2</sup>

<sup>1</sup> *Indian Institute of Science*

<sup>2</sup> *Centre for High Energy Physics, Indian Institute of Science*

**Corresponding Author:** shiulic@iisc.ac.in

Dark, chiral fermions carrying lepton flavor quantum numbers are natural candidates for freeze-in. Small couplings with the Standard Model fermions of the order of lepton Yukawas are ‘automatic’ in the limit of Minimal Flavor Violation. In the absence of total lepton number violating interactions, particles with certain representations under the flavor group remain absolutely stable. For masses in the GeV-TeV range, the simplest model with three flavors, leads to signals at future direct detection experiments like DARWIN. Interestingly, freeze-in with a smaller flavor group such as SU (2) is already being probed by XENON1T.

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## Radio-frequency Dark Photon Dark Matter across the Sun

**Author:** Jia Liu<sup>1</sup>

<sup>1</sup> *Peking University*

**Corresponding Author:** liujia02@gmail.com

Dark photon as an ultralight dark matter candidate can interact with the Standard Model particles via kinetic mixing. We propose to search for the ultralight dark photon dark matter using radio telescopes with solar observations. The dark photon dark matter can efficiently convert into photons in the outermost region of the solar atmosphere, the solar corona, where the plasma mass of photons is close to the dark photon rest mass. Due to the strong resonant conversion and benefiting from the short distance between the Sun and the Earth, the radio telescopes can lead the dark photon

search sensitivity in the mass range of  $4 \times 10^{-8} - 4 \times 10^{-6}$  eV, corresponding to the frequency 10 – 1000 MHz. As a promising example, the operating radio telescope LOFAR can reach the kinetic mixing  $\epsilon \sim 10^{-13}$  ( $10^{-14}$ ) within 1 (100) hour solar observations. The future experiment SKA phase 1 can reach  $\epsilon \sim 10^{-16} - 10^{-14}$  with 1 hour solar observations.

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## A dark clue to seesaw and leptogenesis in a pseudo-Dirac singlet doublet scenario with (non)standard cosmology

**Author:** SUDIPTA SHOW<sup>1</sup>

<sup>1</sup> *Physical Research Laboratory*

**Corresponding Author:** sudipta29show@gmail.com

We propose an appealing alternative scenario of leptogenesis assisted by dark sector which leads to the baryon asymmetry of the Universe satisfying all theoretical and experimental constraints. The dark sector carries a non minimal set up of singlet doublet fermionic dark matter extended with copies of a real singlet scalar field. A small Majorana mass term for the singlet dark fermion, in addition to the typical Dirac term, provides the more favourable dark matter of pseudo-Dirac type, capable of escaping the direct search. Such a construction also offers a formidable scope to radiative generation of active neutrino masses. In the presence of a (non)standard thermal history of the Universe, we perform the detailed dark matter phenomenology adopting the suitable benchmark scenarios, consistent with direct detection and neutrino oscillations data. Besides, we have demonstrated that the singlet scalars can go through CP-violating out of equilibrium decay, producing an ample amount of lepton asymmetry. Such an asymmetry then gets converted into the observed baryon asymmetry of the Universe through the non-perturbative sphaleron processes owing to the presence of the alternative cosmological background considered here. Unconventional thermal history of the Universe can thus aspire to lend a critical role both in the context of dark matter as well as in realizing baryogenesis.

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## Low-mass primordial black holes as the dark matter candidate

**Author:** Ranjan Laha<sup>1</sup>

<sup>1</sup> *Indian Institute of science (IN)*

**Corresponding Author:** ranjan.laha@cern.ch

Primordial black holes (PBHs), possibly formed via gravitational collapse of large density perturbations in the very early universe, are one of the earliest proposed and viable dark matter (DM) candidates. Recent studies indicate that PBHs can make up a large or even entire fraction of the present day DM density for a wide range of masses. Ultralight PBHs in the mass range of  $10^{15} - 10^{17}$  g, emit particles through Hawking radiation, and can be probed via observations of those emitted particles in various detectors. In this talk, I will discuss how the observations of the 511 keV gamma ray line and continuum gamma-rays set some of the most stringent exclusion limits on the DM fraction of ultralight PBHs. I will also demonstrate how measurements of low-energy photons from the Galactic Center by the imminent telescopes such as AMEGO can probe the DM fraction of PBHs into a completely unexplored mass window.

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## **Neutrino and Axion Astronomy with Dark Matter Experiments**

**Author:** Volodymyr Takhistov<sup>None</sup>

**Corresponding Author:** vtakhist@physics.ucla.edu

Beyond their unprecedented sensitivity to dark matter (DM), as I will demonstrate, large direct detection experiments constitute impressive neutrino telescopes. This opens a new window into astronomy, leading to possible insights into major problems such as the origin of supermassive black holes. Furthermore, DM experiments can be exploited as novel tools in multi-messenger astronomy for exploration of new physics. I will discuss detection of relativistic axions from transient astrophysical sources (e.g. axion star explosions), which can lead to new insights into the fundamental axion potential.

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## **Prospects for Low Mass Dark Matter Searches at DUNE**

**Author:** Wooyoung Jang<sup>1</sup>

<sup>1</sup> *Texas U, Arlington*

**Corresponding Author:** wooyoung.jang@uta.edu

Design goals for future neutrino experiments, including high-intensity proton beams and precise detectors, provide an opportunity to explore physics beyond the standard model. Dark matter accounts for 27% of our universe, but its particle nature remains to be uncovered, and many efforts have been made to elucidate the properties of dark matter.

The DUNE experiment uses high-intensity 120 GeV proton beams and a target system made out of graphite. The high-intensity proton beam interactions in the target will produce copious amounts of photons. Through vector portal processes, these photons may couple to dark photons that subsequently decay to dark matter at the sub-GeV mass scale and its footprints can be detected by a precision Near Detector complex located at 574m downstream of the target facility.

In this presentation, I will discuss the concept and method of the analysis searching for low mass dark matter in DUNE, and present estimated sensitivities for this search, along with prospects for further improvements in this type of probes.

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## **(In)elastic Boosted Dark Matter Search Prospects at DUNE**

**Author:** Doojin Kim<sup>1</sup>

<sup>1</sup> *Texas A&M University*

**Corresponding Author:** doojin.kim@tamu.edu

The far detector of the Deep Underground Neutrino Experiment (DUNE) comprising four liquid argon time projection chambers (LArTPCs) totaling 70-kton mass will be installed at a depth of 1,500 m at the Sanford Underground Research Facility. Thanks to its large volume and the LArTPC-based precision imaging capability, the DUNE far detector can probe signals of cosmic origin. Of these, boosted dark matter has been receiving a lot of attention as a plausible thermal dark matter scenario beyond the weakly interacting massive particle. We discuss the signal detection prospects of boosted dark matter at the DUNE far detector, taking solar-captured boosted dark matter and galactic

inelastic boosted dark matter as concrete examples. In addition to the drastic cosmic background reduction due to the underground detector location, we argue that kinematic features arising in the unique boosted dark matter signatures can be readily captured by the far detector, strongly reducing contamination from neutrino-sourced backgrounds in these searches.

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## **Lepton Number Violating Electron Recoils at XENON1T and PandaX by the U(1)B-L Model with Non-Standard Interactions**

**Author:** Yugen Lin<sup>1</sup>

**Co-authors:** Yu Gao<sup>1</sup>; Tianjun Li<sup>2</sup>

<sup>1</sup> *Institute of High Energy Physics of the Chinese Academy of Sciences*

<sup>2</sup> *Institute of Theoretical Physics of Chinese Academy of Sciences*

**Corresponding Author:** linyugen@ihep.ac.cn

I will introduce an  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$  model, in which the neutrino masses and mixing can be generated via Type-I seesaw mechanism after U(1)B-L breaking. A light mediator emerges and enables non-standard interaction that violates the lepton number. It shows that the non-standard interaction leads to low energy recoil events that is consistent with the observed KeV range electron recoil excess at the XENON1T and PandaX experiment. Observational bounds on the nonstandard couplings will be discussed.

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## **Asymmetric Dark Matter and Baryons from Dark Phase Transitions**

**Author:** Robert McGehee<sup>1</sup>

<sup>1</sup> *University of Michigan*

**Corresponding Author:** rmcgehee@umich.edu

We present several models of asymmetric dark matter (ADM) and baryons coming from dark phase transitions and unique complementary signals. One achieves both baryogenesis and ADM in a minimal “mirror” sector, while another adds (heavy) ADM to any standard baryogenesis scenario. Yet another uses the most minimal dark sector to achieve baryogenesis alone. Thanks to the necessity of the vector and neutrino portals, discoverable signals include nuclear/electron recoils in direct detection experiments, visibly decaying dark photons, exotic Higgs and Z decays, extra relativistic degrees of freedom, and gravitational waves from the dark phase transition.

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## **White Dwarfs as Axion Probes**

**Author:** Christopher Dessert<sup>1</sup>

<sup>1</sup> *University of Michigan*

**Corresponding Author:** dessert@umich.edu

Axions, if they exist, can be produced efficiently in white dwarfs, free-stream out of the star due to their weak interactions with matter, and then be converted to a photon in the stellar magnetosphere. X-ray telescope observations of these stars can provide strong constraints on the coupling to electromagnetism and matter. I discuss the results of the first dedicated observation of a magnetic white dwarf in hard X-rays, and what it tells us about axions.

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## **Roads for Right-handed Neutrino Dark Matter: Relentless, Standard Freeze-out, and Early Matter Domination**

**Authors:** Giorgio Arcadi<sup>None</sup>; Jacinto Paulo Neto<sup>1</sup>; Farinaldo Queiroz<sup>2</sup>; Clarissa Siqueira<sup>3</sup>

<sup>1</sup> *Federal University of Rio Grande do Norte*

<sup>2</sup> *International Institute of Physics -Natal*

<sup>3</sup> *Instituto de Física de São Carlos - Universidade de São Paulo (IFSC/USP)*

**Corresponding Author:** jacinto.neto.100@ufrn.edu.br

Right-handed neutrinos appear in several extensions beyond the Standard Model, specially in connection to neutrino masses. Weak scale right-handed neutrino dark matter constructions are typically rather constrained by data. In this work, we carry out the dark matter phenomenology of a weak scale right-handed neutrino dark matter, within a type I seesaw model, in the presence of a fast early expansion of the universe (relentless production), and early matter-domination before or during dark matter freeze-out. We compute the dark matter relic density, the non-conventional direct detection rate featuring a spin-independent but velocity suppressed operator, and the existing collider bounds.

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## **Gravitational Microlensing by Dark Matter Subhalos and Boson Stars**

**Author:** Zihui Wang<sup>1</sup>

<sup>1</sup> *NYU*

**Corresponding Author:** zihui.wang@nyu.edu

Multiple microlensing surveys have been conducted to place limits on primordial black holes in nearby dark matter halos. We show that these existing limits on PBHs can be recast to constrain dark matter lenses that are more spatially extended than PBHs. As two representative cases, we examine NFW subhalos and boson stars, which are predicted in many models such as axion miniclusters and axion stars. For the Subaru-HSC survey, the finite size of the source stars must also be considered. we find that the survey can probe NFW subhalos up to  $O(100)$  solar radii and boson stars up to  $O(1000)$  solar radii.

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## **Multi-component multiscatter capture of Dark Matter**

**Authors:** Caleb Levy<sup>1</sup>; Cosmin Ilie<sup>2</sup>

<sup>1</sup> *Colgate*

<sup>2</sup> *Colgate University*

**Corresponding Author:** cmlevy@colgate.edu

In recent years, the usefulness of astrophysical objects as Dark Matter (DM) probes has become more and more evident, especially in view of null results from direct detection and particle production experiments. The potentially observable signatures of DM gravitationally trapped inside a star, or another compact astrophysical object, have been used to forecast stringent constraints on the nucleon-Dark Matter interaction cross section. Currently, the probes of interest are: at high redshifts, Population III stars that form in isolation, or in small numbers, in very dense DM minihalos at  $z \sim 15 - 40$ , and, in our own Milky Way, neutron stars, white dwarfs, brown dwarfs, exoplanets, etc. Of those, only neutron stars are single-component objects, and, as such, they are the only objects for which the common assumption made in the literature of single-component capture, i.e. capture of DM by multiple scatterings with one single type of nucleus inside the object, is valid. In this paper, we present an extension of this formalism to multi-component objects and apply it to Pop III stars, thereby investigating the role of He on the capture rates of Pop III stars. As expected, we find that the inclusion of the heavier He nuclei leads to an enhancement of the overall capture rates, further improving the potential of Pop III stars as Dark Matter probes.

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## Asteroid g-2 experiments: new fifth force and ultralight dark sector tests

**Author:** Yu-Dai Tsai<sup>1</sup>

<sup>1</sup> *Fermilab*

**Corresponding Author:** ytsai@fnal.gov

We study for the first time the possibility of probing long-range fifth forces utilizing asteroid astrometric data, via the fifth force-induced orbital precession. We examine nine Near-Earth Object (NEO) asteroids whose orbital trajectories are accurately determined via optical and radar astrometry. Focusing on a Yukawa-type potential mediated by a new gauge field (dark photon) or a baryon-coupled scalar, we estimate the sensitivity reach for the fifth-force coupling strength and mediator mass in the mass range  $m \simeq 10^{-21} - 10^{-15}$  eV. Our estimated sensitivity is comparable to leading limits from torsion balance experiments, potentially exceeding these in a specific mass range. The fifth force-induced precession increases with the orbital semi-major axis in the small  $m$  limit, motivating the study of objects further away from the Sun. We discuss future exciting prospects for extending our study to more than a million asteroids (including NEOs, main-belt asteroids, Hildas, and Jupiter Trojans), as well as trans-Neptunian objects and exoplanets.

This talk is based on <https://arxiv.org/abs/2107.04038>.

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## Higgs-portal dark matter in brane world cosmology

**Author:** Taoli Liu<sup>1</sup>

**Co-authors:** Nobuchika Okada<sup>2</sup>; Digesh Raut<sup>3</sup>

<sup>1</sup> *The University of Alabama*

<sup>2</sup> *University of Alabama*

<sup>3</sup> *University of Delaware*

**Corresponding Author:** tliu20@crimson.ua.edu

I will discuss the Higgs-portal dark matter scenario in the 5-dimensional brane world cosmology, such as Randall-Sundrum cosmology and Gauss-Bonnet cosmology.

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## **Status of DEAP-3600**

**Author:** Pushparaj Adhikari<sup>1</sup>

<sup>1</sup> *Carleton University*

**Corresponding Author:** pushpaparticle@gmail.com

DEAP-3600 is a dark matter direct detection experiment running at the SNOLAB in Sudbury, Canada. The spherical detector is situated 2 km below the earth's surface with a low cosmic muon background environment consisting of 3.3 tonnes of liquid argon target surrounded by an array of 255 photomultiplier tubes. The major backgrounds for DEAP-3600 come from alpha particles induced by dust particles present inside the detector and detector components, from external neutrons, and from Argon-39 beta decays. In this talk, the latest results from DEAP-3600 and effort for the detailed background model, pulse-shape discrimination, and sensitivity of the dark matter will be presented. In addition, I will review ongoing R&D projects for hardware upgrades.

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## **Neutrino as the Dark Force**

**Authors:** Nicholas Orlofsky<sup>1</sup>; Yue Zhang<sup>1</sup>

<sup>1</sup> *Carleton University*

**Corresponding Author:** norlofsky@physics.carleton.ca

We point out a novel role for the Standard Model neutrino in dark matter phenomenology where the exchange of neutrinos generates a long-range potential between dark matter particles. The resulting dark matter self interaction could be sufficiently strong to impact small-scale structure formation, without the need of any dark force carrier. This is a generic feature of theories where dark matter couples to the visible sector through the neutrino portal. It is highly testable with improved decay rate measurements at future Z, Higgs, and  $\tau$  factories, as well as precision cosmology.

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## **Dark Matter searches in CMS**

**Author:** Reham Aly<sup>1</sup>

<sup>1</sup> *Bari University - Italy*



**Corresponding Author:** reham.aly@cern.ch

Searches in CMS for dark matter particles, mediators, and dark sector extensions will be presented. Various final states, topologies, and kinematic variables are explored utilizing the full Run-II data-set collected at the LHC.

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## The CYGNO experiment for Dark Matter direct detection

**Author:** Andrea Messina<sup>1</sup>

<sup>1</sup> *Sapienza Universita e INFN, Roma I (IT)*

**Corresponding Author:** andrea.messina@cern.ch

Innovative experimental techniques are needed to further search for dark matter weakly interacting massive particles. The ultimate limit is represented by the ability to efficiently reconstruct and identify nuclear and electron recoil events at the experimental energy threshold. Gaseous Time Projection Chambers (TPC) with optical readout are very promising candidates thanks to the 3D event reconstruction capability of the TPC technique and the high sensitivity and granularity of last generation scientific light sensors. The Cygno experiment is pursuing this technique by developing a TPC operated with He(Ar)-CF<sub>4</sub> gas mixture at atmospheric pressure equipped with a Gas Electron Multipliers (GEM) amplification stage that produces visible light collected by scientific CMOS camera. A fast photodetector is used to measure the drift time of the primary ionisation electrons and thus reconstruct the third coordinate of the ionisation track. Events are then reconstructed with an innovative multi-stage pattern recognition algorithm based on advanced clustering techniques. In this contribution, we present the performances of prototype detectors assessed by exposing them to radioactive sources. We show that good energy and spatial resolution as well as discriminating power between nuclear and electron recoils is achieved in the KeV energy range. Finally, we discuss the plan to build a 1m<sup>3</sup> demonstrator expected to be installed and operated at LNGS in 2021/22. This experimental campaign aims at proving the scalability of such a detector concept to a bigger apparatus able to significantly extend our knowledge about DM and neutrinos.

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## Dark matter and Leptogenesis in Type Ib seesaw model

**Authors:** Bowen Fu<sup>1</sup>; Marco Chianese<sup>2</sup>; Stephen F King<sup>1</sup>

<sup>1</sup> *University of Southampton*

<sup>2</sup> *University of Naples "Federico II"*

**Corresponding Author:** b.fu@soton.ac.uk

We study the connection between neutrino mass and two unsolved cosmological problems: the existence of dark matter (DM) and matter-antimatter asymmetry. To have a testable connection, we consider the low energy type Ib seesaw mechanism instead of the traditional type I seesaw mechanism. In the minimal type Ib seesaw mechanism, the effective neutrino mass operator involves two different Higgs doublets, and two right-handed neutrinos form a (pseudo-) Dirac pair. The DM candidate can be included by adding a neutrino portal with a dark fermion and a dark scalar, while the baryon asymmetry can be approached through resonant leptogenesis in an extended model where the type Ib seesaw mechanism is realised effectively. We explore the parameter space of the models consistent with both oscillation data and observations. Within this framework, we show how DM and leptogenesis can be directly related to laboratory experiments for a heavy Dirac neutrino mass around 1–100 GeV.

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**Sensitivity of future  $e^+e^-$  colliders to processes of dark matter production with light mediator exchange**

**Authors:** Aleksander Filip Zarnecki<sup>1</sup>; Jan Henryk Kalinowski<sup>2</sup>; Krzysztof Mekala<sup>1</sup>; Pawel Sopicki<sup>2</sup>; Wojciech Kotlarski<sup>3</sup>

<sup>1</sup> *University of Warsaw*

<sup>2</sup> *University of Warsaw (PL)*

<sup>3</sup> *TU - Dresden*

**Corresponding Author:** jan.kalinowski@cern.ch

High energy  $e^+e^-$  colliders offer unique possibility for the most general search for dark matter (DM) based on the mono-photon signature. As any  $e^+e^-$  collision process may include hard initial-state photon radiation, analysis of the energy spectrum and angular distributions of observed photons can be used to search for hard processes with an invisible final state.

We consider production of DM particles at the International Linear Collider (ILC) and Compact Linear Collider (CLIC) experiments via a mediator exchange. Dedicated procedure of merging the matrix element calculations with the lepton ISR structure function was developed to model the Standard Model background processes contributing to mono-photon signature with WHIZARD.

Detector effects are taken into account within the DELPHES fast simulation framework. Limits on the light DM production cross section in a simplified model are set as a function of the mediator mass and width based on the expected two-dimensional distributions of the reconstructed mono-photon events.

Limits on the mediator couplings are then presented for a wide range of mediator masses and widths. For light mediators, for masses up to the centre-of-mass energy of the collider, coupling limits derived from the mono-photon analysis are more stringent than those expected from direct resonance searches in decay channels to SM particles.

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**Dark Matter in non-standard cosmologies**

**Authors:** Dimitrios Karamitros<sup>1</sup>; Paola Arias<sup>None</sup>; Nicolas Bernal<sup>None</sup>; Leszek Roszkowski<sup>None</sup>; Carlos Maldonado<sup>None</sup>; Moira Venegas<sup>None</sup>

<sup>1</sup> *NCBJ*

**Corresponding Author:** dkaramit@yahoo.com

We examine the implications of non-standard cosmologies (NSCs) on Dark Matter. We present a detailed analysis of the impact of NSCs on frozen-in relics and examine their lower allowed mass limit. Moreover, we discuss how the “natural” axion window can be extended, which can potentially help us to exclude NSCs once the axion is discovered.

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**Phenomenological Implications of Non-Perturbative Effects for Colored Dark Sectors**

**Authors:** Dipan Sengupta<sup>1</sup>; Emanuele Copello<sup>2</sup>; Julia Harz<sup>3</sup>; Mathias Becker<sup>2</sup>; KIRTIMAAN MOHAN<sup>4</sup>

<sup>1</sup> *UC San Diego*

<sup>2</sup> *Technical University of Munich*

<sup>3</sup> *Technical University of Munich (TUM)*

<sup>4</sup> *MSU*

**Corresponding Author:** mathias.becker@tu-dortmund.de

We demonstrate the impact of non-perturbative effects on the annihilation cross section of DM in a model of simplified t-channel DM. Specifically, we study the case of Majorana fermion DM coupling to the standard model (SM) quarks via a colored scalar.

For DM masses in the GeV-TeV range, direct detection experiments strongly constrain the DM coupling to the SM quarks. From a cosmological point of view however, a large coupling to the SM is not mandatory if the mass splitting between the colored scalar and the DM candidate is sufficiently small. This region of the parameter space is subject to non-perturbative effects, namely the Sommerfeld effect and bound state formation, which can significantly enhance the effective DM annihilation cross section.

We present the impact of this effect on current and upcoming collider searches as well as direct detection experiments.

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## Constraining Dark Matter interactions with nucleons and electrons using White Dwarfs

**Author:** Sandra Robles<sup>1</sup>

<sup>1</sup> *The University of Melbourne*

**Corresponding Author:** robles.sandra@gmail.com

White dwarfs are the most abundant stellar remnants. They provide a promising means of probing dark matter (DM) interactions complementary to direct searches. The scattering of DM off stellar constituents, ions or degenerate electrons, leads to gravitational capture, with important observational consequences. In particular, white dwarf heating due to the energy transfer in the DM capture and subsequent annihilation can occur in white dwarfs located in DM-rich environments. In this case, the DM-nucleon/electron scattering cross sections can be constrained by comparing the heating rate due to captured DM with observations of cold white dwarfs. We apply this technique to observations of old white dwarfs in the globular cluster Messier 4, which we assume to be formed in a DM subhalo. We consider the capture of DM by scattering off either ions or degenerate electrons. For ions, we account for the stellar structure, the star opacity, realistic nuclear form factors and finite temperature effects relevant to sub-GeV DM. Electrons are treated as relativistic, degenerate targets, with Pauli blocking, finite temperature and multiple scattering effects all taken into account. We also estimate the DM evaporation rate for both targets. For DM-nucleon scattering, we find that white dwarfs can probe the sub-GeV mass range inaccessible to direct detection experiments, with the low mass reach limited only by evaporation, and can be competitive with direct detection in the 1GeV–10TeV range. White dwarf limits on DM-electron scattering are found to outperform current electron recoil experiments over the full mass range considered, and extend well beyond the  $\sim 10$  GeV mass regime where the sensitivity of electron recoil experiments is reduced.

**Dark Matter and Astroparticle Physics / 392**

## Searching for Dark Matter in the Sun and in the Galactic Centre using Hyper-Kamiokande

**Author:** Sandra Robles<sup>1</sup>

<sup>1</sup> *The University of Melbourne*

**Corresponding Author:** robles.sandra@gmail.com

We study the prospects for indirect detection of dark matter (DM) in the Sun and in the Galactic halo using the Hyper-Kamiokande (HyperK) neutrino experiment, currently under construction. We undertook a dedicated simulation of the HyperK detector, which we benchmarked against results from the Super-Kamiokande (SuperK) experiment and HyperK physics projections. For DM annihilation to neutrino final states in the Galactic halo, we find that HyperK will be sensitive to thermal annihilation cross-sections for DM with mass around 20-40 MeV, assuming an NFW halo profile. For neutrino signals produced via the annihilation of DM captured in the Sun, we determined the HyperK sensitivity to the DM spin-dependent scattering cross-section for various standard model final states. We find that HyperK will improve upon current SuperK limits by a factor of 2-3, with a further improvement in sensitivity possible if systematic errors can be decreased relative to SuperK.

**Dark Matter and Astroparticle Physics / 9**

## Lorentz Violation of Cosmic Photons from a Phenomenological Viewpoint

**Author:** Bo-Qiang Ma<sup>1</sup>

<sup>1</sup> *Peking University*

**Corresponding Author:** mabq@pku.edu.cn

Cosmic photons from astrophysical sources are ideal for investigating the Lorentz symmetry violation (LV). A series of studies on high energy gamma-ray burst (GRB) photons suggest a light speed variation with linear energy dependence at the Lorentz violation scale of  $3.6 * 10^{17}$  GeV, with subluminal propagation of high energy photons in cosmological space. Constraints on Lorentz violation from recent observation of PeV scale photons from LHAASO collaboration are also discussed.

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## On-shell mediator dark matter models and the Xenon1T excess

**Authors:** Jinhan Liang<sup>1</sup>; Mingxuan Du<sup>1</sup>; VQ Tran<sup>1</sup>; Yilun Xue<sup>1</sup>

<sup>1</sup> *nanjing university*

**Corresponding Author:** mg1722018@smail.nju.edu.cn

We present a dark matter model to explain the excess events in the electron recoil data recently reported by the Xenon1T experiment. In our model, dark matter annihilates into a pair of on-shell particles, which subsequently decay into the final state; interacts with electrons to generate the observed excess events. Because of the mass hierarchy, the velocity of can be rather large and can have an extended distribution, providing a good fit to the electron recoil energy spectrum. We estimate the flux of from dark matter annihilations in the galaxy and further determine the interaction cross section, which is sizable but sufficiently small to allow to penetrate the rocks to reach the underground labs.

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## Probing dark matter and primordial black holes with CMB and 21cm observations

**Authors:** Junsong Cang<sup>1</sup>; Yin-Zhe Ma<sup>2</sup>; Yu Gao<sup>3</sup>

<sup>1</sup> *Chinese Academy of Sciences*

<sup>2</sup> *University of KwaZulu-Natal*

<sup>3</sup> *IHEP*

**Corresponding Author:** cangjs@ihep.ac.cn

Radiation produced by decaying/annihilating dark matter (DM) and evaporating primordial black holes (PBH) can ionize and heat up intergalactic medium (IGM) before reionization. Such effects can be efficiently probed using observations of cosmic microwave background (CMB) and 21cm signal of neutral hydrogen. In this talk I will show that CMB data from Planck and 21cm data from EDGES can set some of the most stringent and robust bounds on decay/annihilation rates of DM and abundance of PBH, future CMB missions can improve current Planck limits by up to two orders of magnitudes. This talk is partially based on our work in ArXiv 2002.03380 and 2011.12244.

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## Dark Matter and Radiative Neutrino Mass with dark $SU(2)$ gauge symmetry

**Authors:** Hiroshi Okada<sup>1</sup>; Takaaki Nomura<sup>2</sup>

<sup>1</sup> *Asia Pacific Center for Theoretical Physics*

<sup>2</sup> *Sichuan University*

**Corresponding Author:** nomura@scu.edu.cn

We discuss a model with dark sector described by non-Abelian  $SU(2)_D$  gauge symmetry where we introduce  $SU(2)_L \times SU(2)_D$  bi-doublet vector-like leptons to generate active neutrino masses and kinetic mixing between  $SU(2)_D$  and  $U(1)_Y$  gauge fields at one-loop level. After spontaneous symmetry breaking of  $SU(2)_D$ , we have remnant  $Z_4$  symmetry guaranteeing stability of dark matter candidates. We formulate neutrino mass matrix and related lepton flavor violating processes and discuss dark matter physics estimating relic density. It is found that our model realize multicomponent dark matter scenario due to the  $Z_4$  symmetry and relic density can be explained by gauge interactions with kinetic mixing effect.

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## Pseudo-Nambu-Goldstone Dark Matter Model Inspired by Grand Unification

**Authors:** Koji Tsumura<sup>1</sup>; Naoki Yamatsu<sup>1</sup>; Takashi Toma<sup>2</sup>; Yoshihiko Abe<sup>3</sup>

<sup>1</sup> *Kyushu University*

<sup>2</sup> *Kanazawa University*

<sup>3</sup> *Kyoto University*

**Corresponding Author:** toma@staff.kanazawa-u.ac.jp

A pseudo-Nambu-Goldstone boson (pNGB) is an attractive candidate for dark matter due to the simple evasion of the current severe limits of dark matter direct detection experiments. One of the

pNGB dark matter models has been proposed based on a gauged U(1) B–L symmetry. The pNGB has long enough lifetime to be a dark matter and thermal relic abundance can be fit with the observed value against the constraints on the dark matter decays from the cosmic-ray observations. The pNGB dark matter model can be embedded into an SO(10) grand unified theory, whose SO(10) is broken to the Pati-Salam gauge group at the unified scale, and further to the Standard Model gauge group at the intermediate scale. Unlike the previous pNGB dark matter model, the parameters such as the gauge coupling constants and the gauge kinetic mixing are determined by solving the renormalization group equations for gauge coupling constants with appropriate matching conditions. From the constraints of the dark matter lifetime and gamma-ray observations, the pNGB dark matter mass must be less than O(100) GeV. We find that the thermal relic abundance can be consistent with all the constraints when the dark matter mass is close to half of the CP even Higg masses.

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## BSM physics explanations of $a_\mu$ in light of the FNAL muon $g - 2$ measurement

**Authors:** Douglas Jacob<sup>1</sup>; Peter Athron<sup>None</sup>; Csaba Balazs<sup>1</sup>; Wojciech Kotlarski<sup>2</sup>; Dominik Stoeckinger<sup>3</sup>; Hyejung Stoeckinger-Kim<sup>3</sup>

<sup>1</sup> Monash University

<sup>2</sup> TU - Dresden

<sup>3</sup> TU Dresden

**Corresponding Author:** douglas.jacob@monash.edu

The first results of the Fermilab Muon  $g-2$  experiment are in full agreement with the previous BNL measurement and push the world average deviation in  $\Delta a_\mu$  from the Standard Model to  $4.2 \sigma$ . In this talk I will present an extensive survey of its impact on beyond the Standard Model physics, focusing on simple extensions of the standard model, based on arXiv:2104.03691. In this work we used state-of-the-art calculations and a sophisticated set of tools to make predictions for  $a_\mu$ , dark matter and LHC searches. We examined a wide range of simple models with up to three new fields which represent some of the few ways that large  $\Delta a_\mu$  can be explained. The results show that the new measurement excludes a large number of models and provides crucial constraints on others. Generally, these models provide viable explanations of the  $a_\mu$  result only by using rather small masses and/or large couplings with chirality flip enhancements, which can lead to conflicts with limits from LHC and dark matter experiments. I will present results for a range of models extending the standard model by one, two and three new fields including scalar leptoquarks and simple models constructed to explain dark matter and  $g - 2$  simultaneously.

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## WimPyDD: a modular and customizable Python code for the calculation of WIMP-nucleon scattering direct detection signals in virtually any scenario

**Authors:** Gaurav Tomar<sup>None</sup>; Injun Jeong<sup>None</sup>; Stefano Scopel<sup>1</sup>; Sunghyun Kang<sup>1</sup>

<sup>1</sup> Sogang University

**Corresponding Author:** shkang901013@gmail.com

We introduce WimPyDD, a modular, object-oriented and customizable Python code that calculates accurate predictions for the expected rates in WIMP direct-detection experiments within the framework of Galilean-invariant non-relativistic effective theory in virtually any scenario, including inelastic scattering, an arbitrary WIMP spin and a generic WIMP velocity distribution in the Galactic

halo. WimPyDD exploits the factorization of the three main components that enter in the calculation of direct detection signals: i) the Wilson coefficients of the effective theory, that encode the dependence of the signals on the ultraviolet completion of the effective theory; ii) a response function that depends on the nuclear physics and on the features of the experimental detector (acceptance, energy resolution, response to nuclear recoils); iii) a halo function that depends on the WIMP velocity distribution and that encodes the astrophysical inputs. In WimPyDD these three components are calculated and stored separately for later interpolation and combined together only as the last step of the signal evaluation procedure. This makes the phenomenological study of the direct detection scattering rate with WimPyDD transparent and fast also when the parameter space of the WIMP model has a large dimensionality.

We briefly summarize some of several published results obtained with WimPyDD so far as illustrative examples of its power and flexibility.

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### Re-analysis of 3.5 keV line

**Authors:** Benjamin Safdi<sup>None</sup>; Christopher Dessert<sup>1</sup>; Joshua Foster<sup>1</sup>; Yujin Park<sup>2</sup>

<sup>1</sup> *University of Michigan*

<sup>2</sup> *University of California, Berkeley*

**Corresponding Author:** yjpark99@berkeley.edu

I describe a reanalysis of data sets that have previously been found to harbor evidence for an unidentified X-ray line at 3.5 keV in order to quantify the robustness of earlier results that found significant evidence for a new X-ray line at this energy. The 3.5 keV line is intriguing in part because of possible connections to dark matter. We analyze observations from the XMM-Newton and Chandra telescopes. We investigate the robustness of the evidence for the 3.5 keV line to variations in the analysis framework and also to numerical error in the chi-square minimization process. For example, we consider narrowing the energy band for the analysis in order to minimize mismodeling effects. The results of our analyses indicate that many of the original 3.5 keV studies (i) did not have fully converged statistical analyses, and (ii) were subject to large systematic uncertainties from background mismodeling. Accounting for these issues we find no statistically significant evidence for a 3.5 keV line in any X-ray data set.

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### Self-interacting dark matter, a dark force, and galaxy anomalies

**Authors:** Amin Abou Ibrahim<sup>1</sup>; Zhu-Yao Wang<sup>2</sup>; Pran Nath<sup>2</sup>; Wan-Zhe Feng<sup>3</sup>

<sup>1</sup> *Institute for theoretical physics, Münster University*

<sup>2</sup> *Northeastern University*

<sup>3</sup> *Center for Joint Quantum Studies and Department of Physics, Tianjin University*

**Corresponding Author:** wang.zhu@northeastern.edu

**Abstract:** A large amount of data from dwarf galaxies to galaxy clusters appears to indicate that dark matter (DM) acts like a collisional fluid at galaxy scales to a collisionless fluid at the scale of galaxy clusters. We will discuss a particle physics model with the standard model extended with a gauged abelian hidden sector to explain this phenomenon. In this model dark matter consists of fermions of the hidden sector and they have self interactions via exchange of dark photons which constitute a new dark force in the model. The analysis involves solutions to Boltzmann equations coupling the visible sector and the hidden sectors at different temperatures, one for each sector. The model

produces a velocity - dependent DM cross section where the DM acts like a collisional fluid at small galaxy scales and acts collisionless at large galaxy scales, and we fit the data including those from THINGS, LSB and the Bullet Cluster. The talk is based on the paper Phys. Rev. D 103, 075014 (2021), arXiv: 2008.00529 [hep-ph], by Amin Aboubrahim, Wan-Zhe Feng, Pran Nath, and Zhu-Yao Wang.

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### Improving the sensitivity to light dark matter with the Migdal effect

**Authors:** Andrea Messina<sup>1</sup>; Giovanni Grilli di Cortona<sup>2</sup>; Stefano Piacentini<sup>1</sup>

<sup>1</sup> *Università di Roma Sapienza and INFN*

<sup>2</sup> *University of Sao Paulo*

**Corresponding Author:** ggrillidc@gmail.com

The search for dark matter (DM) weakly interacting massive particles with noble elements has probed masses down and below a  $\text{GeV}/c^2$ . The ultimate limit is represented by the experimental threshold on the energy transfer to the nuclear recoil. Currently, the experimental sensitivity has reached a threshold equivalent to a few ionization electrons. In these conditions, the contribution of a Bremsstrahlung photon or a so-called Migdal electron due to the sudden acceleration of a nucleus after a collision might be sizeable. We present a recent work where, using a Bayesian approach, we studied how these effects can be exploited in experiments based on liquid argon detectors. In particular we develop a simulated experiment to show how the Migdal electron and the Bremsstrahlung photon allow to push the experimental sensitivity down to masses of  $0.1 \text{ GeV}/c^2$ , extending the search region for dark matter particles of previous results. For these masses we estimate the effect of the Earth shielding that, for strongly interacting dark matter, makes any detector blind. Finally, given the relevance of the Migdal electrons to the search for low mass DM, we discuss some new ideas on how to possibly measure such an effect with detectors based on a Time Projection Chamber exposed to an high neutron flux.

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### Direct detection of non-galactic light dark matter

**Authors:** Alejandro Ibarra<sup>None</sup>; Gonzalo Herrera<sup>1</sup>

<sup>1</sup> *Technical University of Munich, Max Planck Institute for Physics*

**Corresponding Author:** gonzalo.herrera@tum.de

A fraction of the dark matter in the solar neighborhood might be composed of non-galactic particles with speeds larger than the escape velocity of the Milky Way. The non-galactic dark matter flux would enhance the sensitivity of direct detection experiments, due to the larger momentum transfer to the target. In this note, we calculate the impact of the dark matter flux from the Local Group and the Virgo Supercluster diffuse components in nuclear and electron recoil experiments. The enhancement in the signal rate can be very significant, especially for experiments searching for dark matter induced electron recoils.

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## Dark-sector physics at Belle II

**Author:** Sascha Simon Dreyer<sup>1</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron DESY*

**Corresponding Author:** sascha.dreyer@desy.de

The Belle II experiment at the asymmetric  $e^+e^-$  collider, SuperKEKB, is a substantial upgrade of the Belle/KEKB experiment. Belle II aims to record  $50 \text{ ab}^{-1}$  of data over the course of the project. During the first physics runs in 2018-2020, around  $100 \text{ fb}^{-1}$  of data were collected. These early data include specifically-designed low-multiplicity triggers which allow a variety of searches for light dark matter and dark-sector mediators in the GeV mass range.

This talk will present the very first world-leading physics results from Belle II: searches for the invisible decays of a new vector  $Z'$ , and visible decays of an axion-like particle; as well as the near-term prospects for other dark-sector searches. Many of these searches are competitive with the data already collected or the data expected in the next few years of operation.

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## Thermal WIMPs and the scale of new physics

**Author:** Tomas Gonzalo<sup>1</sup>

<sup>1</sup> *RWTH Aachen*

**Corresponding Author:** gonzalo@physik.rwth-aachen.de

The non-observation of conclusive WIMP signals raises the question whether WIMPs can still account for the dark matter of the universe. In this talk I will present results from a global analysis of effective field theory operators describing the interactions between WIMPs and Standard Model particles. In this bottom-up approach, the global fitting framework GAMBIT is used to simultaneously vary the coefficients of 14 such operators, along with the WIMP mass, the scale of new physics and several nuisance parameters. The likelihood functions include the latest data from Planck, direct and indirect detection experiments, and the LHC. Although the observed relic density can be reproduced in large regions of parameter space, there cannot be a large hierarchy between the WIMP mass and the scale of new physics, which raises concerns about the validity of the effective field theory. I will discuss possible ways to address this issue in order to consistently interpret the latest results from WIMP searches at the LHC.

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## Lower Mass Bounds on Freeze-in Dark Matter

**Authors:** Alessandro Lenoci<sup>1</sup>; Francesco D'Eramo<sup>2</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron DESY*

<sup>2</sup> *University of Padua*

**Corresponding Author:** alessandro.lenoci@desy.de

Feebly Interacting Massive Particles (FIMPs) are dark matter candidates that never thermalize in the early universe and whose production takes place via decays and/or scatterings of thermal bath particles. If FIMPs interactions with the thermal bath are renormalizable, a scenario which is known as freeze-in, production is most efficient at temperatures around the mass of the bath particles and

insensitive to unknown physics at high temperatures. Working in a model-independent fashion, we consider three different production mechanisms: two-body decays, three-body decays, and binary collisions. We compute the FIMP phase space distribution and matter power spectrum, and we investigate the suppression of cosmological structures at small scales. Our results are lower bounds on the FIMP mass. Finally, we study how to relax these constraints in scenarios where FIMPs provide a sub-dominant dark matter component.

**Dark Matter and Astroparticle Physics / 165**

## Dark matter phenomenology in two higgs doublet model with complex scalar singlet

**Author:** Juhi Dutta<sup>1</sup>

**Co-authors:** Gudrid Moortgat-Pick<sup>2</sup>; Merle Schreiber<sup>1</sup>

<sup>1</sup> *University of Hamburg*

<sup>2</sup> *DESY and University of Hamburg*

**Corresponding Author:** juhi.dutta@desy.de

Extensions of the two higgs doublet models with a singlet scalar can easily accommodate all current experimental constraints and are highly motivated candidates for Beyond Standard Model Physics. It can successfully provide a dark matter candidate, explain baryogenesis and provide gravitational wave signals. In this work, we focus on the dark matter phenomenology of the two higgs doublet model extended with a complex scalar singlet which serves as the dark matter candidate. We study the variations of the dark matter observables, i.e relic density and direct detection cross-section, with respect to the model parameters. We obtain a few benchmark points in the light and heavy dark matter mass region. We are also currently studying possible signatures of this model at current and future colliders and the possibility to distinguish this model from other new physics scenarios.

**Dark Matter and Astroparticle Physics / 4**

## Interplay Between Dark Matter Freeze Out/In and Primordial Black Hole Evaporation

**Authors:** Lucien Heurtier<sup>1</sup>; Andrew Cheek<sup>2</sup>; Jessica Turner<sup>3</sup>; Yuber F. Perez-Gonzalez<sup>None</sup>

<sup>1</sup> *IPPP, Durham, England*

<sup>2</sup> *CP3, UCL*

<sup>3</sup> *Durham University*

**Corresponding Author:** lucien.heurtier@durham.ac.uk

In this talk, I will present the phenomenology of dark-matter production in the case where it is both produced by a freeze-out or freeze-in mechanism and by the evaporation of primordial black holes. I will show that the presence of a vector mediator between the hidden and the visible sector affects the production of dark-matter particles as well as its phase space distribution. I will also show that the

population of DM particles produced by evaporation may be warm enough to re-thermalize with the pre-existing DM relic abundance, leading to non-trivial imprints on the value of the relic abundance at later time.

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## Searching for Solar KDAR with DUNE

**Author:** Olexiy Dvornikov<sup>1</sup>

<sup>1</sup> *University of Hawai'i at Manoa (US)*

**Corresponding Author:** olexiy@hawaii.edu

The observation of 236 MeV muon neutrinos from kaon-decay-at-rest (KDAR) originating in the core of the Sun would provide a unique signature of dark matter annihilation. Since excellent angle and energy reconstruction are necessary to detect this monoenergetic, directional neutrino flux, DUNE with its vast volume and reconstruction capabilities, is a promising candidate for a KDAR neutrino search. In this talk, we evaluate the proposed KDAR neutrino search strategies by realistically modeling both neutrino-nucleus interactions and the response of DUNE. We find that, although reconstruction of the neutrino energy and direction is difficult with current techniques in the relevant energy range, the superb energy resolution, angular resolution, and particle identification offered by DUNE can still permit great signal/background discrimination. Moreover, there are non-standard scenarios in which searches at DUNE for KDAR in the Sun can probe dark matter interactions.

**Dark Matter and Astroparticle Physics / 316**

## Gamma-ray signatures of velocity-dependent dark matter annihilation

**Authors:** Andrew Pace<sup>None</sup>; Jack Runburg<sup>None</sup>; Jason Kumar<sup>None</sup>; Eric Baxter<sup>None</sup>

**Corresponding Author:** jkumar@hawaii.edu

If the dark matter annihilation cross-section is velocity-dependent, then gamma-ray signals from astrophysical targets depend non-trivially on the dark matter velocity distribution. Since different targets can have different characteristic velocity scales, analyses of ensembles of targets can potentially find evidence for particular scenarios of dark matter microphysics. We discuss recent work on the prospects for future observations of dwarf spheroidal galaxies and galactic subhalos to not only detect evidence of dark matter annihilation, but also to determine the velocity dependence.

**Dark Matter and Astroparticle Physics / 241**

## Early kinetic decoupling and Higgs invisible decay in simple dark matter models

**Author:** Tomohiro Abe<sup>1</sup>

<sup>1</sup> *Tokyo University of Science*

**Corresponding Author:** abe.tomohiro@rs.tus.ac.jp

We revisit the Higgs-invisible decay branching ratio in Higgs-portal dark matter models. If the mass of the dark matter is slightly below the half of the mass of the Higgs boson, then pairs of the DM particles annihilate into the SM particles efficiently thanks to the Higgs resonance. The DM-Higgs coupling is required to be small to obtain the right amount of the dark matter relic abundance. As a result, the DM-nucleon scattering is highly suppressed and can explain the current null result of the dark matter signal at the direct detection experiments such as the XENON1T experiment. Another consequence of the tiny coupling is that the kinetic decoupling of dark matter from the thermal plasma in the early Universe may happen earlier. This implies that the standard calculation of the relic abundance may not be justified. We reevaluate the DM relic abundance with the evolution of the DM temperature. We show that the DM-Higgs coupling was underestimated in the literatures. Therefore, the Higgs invisible decay branching ratio is larger than previously expected, and the future collider experiments, such as the ILC experiment, can probe larger parameter space.

**Dark Matter and Astroparticle Physics / 32**

## Wino dark matter searches with dwarf spheroidal galaxies

**Authors:** Koji Ishiwata<sup>1</sup>; Shin'ichiro Ando<sup>2</sup>

<sup>1</sup> *Kanazawa University*

<sup>2</sup> *University of Amsterdam*

**Corresponding Author:** koji.ishiwata.r@gmail.com

We study observable signals from dark matter that self-annihilates via Sommerfeld effect in dwarf spheroidal galaxies (dSphs). Since the effect of the Sommerfeld enhancement depends on the velocity of dark matter, it is crucial to determine the profile of dSphs to compute the J-factor, i.e., the line-of-sight integral of density squared. In our study we use the prior distributions of the parameters for satellite density profiles in order to determine the J-factor, making most out of the recent developments in the N-body simulations and semi-analytical modeling for the structure formation. As concrete model, we analyze fermionic dark matter that annihilates via a light scalar and Wino dark matter in supersymmetric models. We find that, with the more realistic prior distributions that we adopt in this study, the J-factor of the most promising dwarf galaxies is decreased by a factor of a few, compared with earlier estimates based on non-informative priors. Nevertheless, the Cherenkov Telescope Array should be able to detect thermal Wino dark matter by pointing it toward best classical or ultrafaint dwarf galaxies for 500 hours.

**Dark Matter and Astroparticle Physics / 339**

## Primordial black holes as a natural dark matter candidate in supersymmetry

**Author:** Marcos Flores<sup>1</sup>

**Co-author:** Alexander Kusenko<sup>2</sup>

<sup>1</sup> *UCLA*

<sup>2</sup> *UCLA Department of Physics & Astronomy*

**Corresponding Author:** mmflores@physics.ucla.edu

Primordial black holes (PBH) are a natural and generic dark matter candidate in supersymmetry. In the early universe, the flat directions of supersymmetry form scalar condensates with large expectation values. These condensates can subsequently fragment into non-topological solitons, SUSY Q-balls, which become the building blocks of PBHs. The PBH masses resulting from supersymmetry naturally fall into the sublunar mass window, where the PBHs can account for all dark matter. We

will discuss two scenarios which result in the formation of PBHs. First, if the SUSY Q-balls dominate the energy density of the universe then statistical fluctuations and gravitational forces allow for the formation of PBHs in this intermediate matter-dominated era. Second, SUSY Q-balls may interact via a light scalar mediator. This attractive force allows for the formation of structure even in the radiation dominated era, while simultaneously removing energy and angular momentum from the systems of solitons by means of scalar radiation. These mechanisms are able to explain the present-day dark matter abundance in addition to potential candidate events observed with lensing experiments.

**Dark Matter and Astroparticle Physics / 335**

## **Cogeneration of Baryons and Twin Quark Dark Matter**

**Author:** Christopher Verhaaren<sup>1</sup>

<sup>1</sup> *Brigham Young University*

**Corresponding Author:** chrisverhaaren@gmail.com

The dark sector may be as rich and varied as the standard model. Twin Higgs models, which explain the little hierarchy problem, provide a compelling and predictive realization of such a dark sector, where the standard model field content is copied in a hidden sector. I show how spontaneously breaking the twin color can naturally lead to asymmetric dark matter and baryogenesis in addition to solving the hierarchy problem. I outline how this scenario can be tested at the LHC and future colliders.

**Dark Matter and Astroparticle Physics / 131**

## **The SBC Liquid Argon Bubble Chamber for Dark Matter and CEvNS from reactors**

**Author:** Marie-Cécile Piro<sup>1</sup>

<sup>1</sup> *University of Alberta*

**Corresponding Author:** mariecci@ualberta.ca

The SBC Collaboration is constructing a 10-kg liquid argon bubble chamber with scintillation readouts. The goal is to achieve 100 eV nuclear recoils detection with near-complete discrimination against electron recoil events. In addition to a dark matter search, SBC targets a CEvNS measurement of MeV-scale neutrinos from nuclear reactors. A high-statistics, high signal-to-background detection would enable precision searches for physics beyond the standard model. In this talk, I will present the physics reach of the SBC detectors and the advantages of using such technology. I will also discuss the progress towards the construction at Fermilab to test the sub-keV threshold performance and at SNOLAB for the search of dark matter.

**Early Universe Cosmology / 235**

## **Matter Genesis in the Coupled-Higgs-Tachyon Bounce Universe**

**Authors:** Baiyang Sun<sup>1</sup>; Lei Ming<sup>1</sup>; Yeuk-Kwan E Cheung<sup>1</sup>

<sup>1</sup> *Nanjing University***Corresponding Author:** jifen0423@163.com

In this talk we will present a mechanism for matter generation in a string-inspired bounce universe. Utilizing the coupling between a higgs-like scalar field and the tachyon emerged from the D-brane and anti-D-brane co-annihilation, we study the conversion between tachyon and standard model fields. During the matter-dominated contraction phase the SM particles that are produced by tachyon can be effectively converted back to tachyons. However during the expansion phase the SM fields lose energy and thus remain in the spectrum. We show that for a generic set of parameter values all tachyon quanta are successfully converted into SM particles, as represented by the Higgs-like scalar. This process is greatly aided by the phase space enhancement effects, called parametric resonance, due to the Bose condensation of the Higgs produced. We close with a few open questions and future directions of exploration.

**Early Universe Cosmology / 467**

## Affleck-Dine Leptogenesis from Higgs Inflation

**Author:** Chengcheng Han<sup>1</sup><sup>1</sup> *SYSU***Corresponding Author:** hanchengcheng800@gmail.com

We investigate the possibility of simultaneously explaining inflation, the neutrino masses and the baryon asymmetry through extending the Standard Model by a triplet Higgs. The neutrino masses are generated by the vacuum expectation value of the triplet Higgs, while a combination of the triplet and doublet Higgs' plays the role of the inflaton. Additionally, the dynamics of the triplet, and its inherent lepton number violating interactions, lead to the generation of a lepton asymmetry during inflation. The resultant baryon asymmetry, inflationary predictions and neutrino masses are consistent with current observational and experimental results.

**Early Universe Cosmology / 279**

## Warm Inflation and TCC

**Author:** Vahid Kamali<sup>None</sup>**Corresponding Author:** vkamali1362@gmail.com

warm axion inflation has been introduced as an alternative to standard (cold) inflation. Coupling between inflaton (axion) field and gauge fields changes the evolution of scalar field even at the background level. It was discussed that the system with this coupling can be thermalized inherently and is protected against tachyonic instability. I will discuss that this scenario is compatible with observation and is in the landscape of quantum gravity conjectures.

**Early Universe Cosmology / 256**

## Massless Preheating and Electroweak Vacuum Metastability

**Author:** Jeff Kost<sup>1</sup>**Co-authors:** Chang Sub Shin <sup>2</sup>; Takahiro Terada <sup>2</sup>

<sup>1</sup> *University of Sussex*<sup>2</sup> *Institute for Basic Science***Corresponding Author:** j.d.kost@sussex.ac.uk

Current measurements of Standard-Model parameters suggest that the electroweak vacuum is metastable. This metastability has important cosmological implications because large fluctuations in the Higgs field could trigger vacuum decay in the early universe. For the false vacuum to survive, interactions which stabilize the Higgs during inflation—e.g., inflaton-Higgs interactions or non-minimal couplings to gravity—are typically necessary. However, the post-inflationary preheating dynamics of these same interactions could also trigger vacuum decay, thereby recreating the problem we sought to avoid. This dynamics is often assumed catastrophic for models exhibiting scale invariance since these generically allow for unimpeded growth of fluctuations. In this talk, we examine the dynamics of such “massless preheating” scenarios and show that the competing threats to metastability can nonetheless be balanced to ensure viability. We find that fully accounting for both the backreaction from particle production and the effects of perturbative decays reveals a large number of disjoint “islands of (meta)stability” over the parameter space of couplings. Ultimately, the interplay among Higgs-stabilizing interactions plays a significant role, leading to a sequence of dynamical phases that effectively extend the metastable regions to large Higgs-curvature couplings.

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## Constraining inflaton coupling from CMB in different inflation models

**Author:** Lei Ming<sup>1</sup>**Co-author:** Marco Drewes<sup>2</sup><sup>1</sup> *Department of Physics, Nanjing University*<sup>2</sup> *CP3, UCLouvain***Corresponding Author:** mingleips@outlook.com

This talk focusses on constraining the inflaton couplings and reheating temperature by the CMB data in different inflation models. It has been pointed out that within a given inflation model, it is possible to “measure” the inflaton coupling from CMB. The model parameters can be related to the observable CMB data by the reheating parameters. Using the Planck 2018 data, we give constraints to the inflaton couplings and the reheating temperature in three inflation models. In these models there exist regions where it is possible to give analytic relations between the inflaton couplings and the spectral index. Besides, we find that in a specific model one can impose a lower (or upper) bound on the couplings only using the spectral index, even if the tensor-to-scalar ratio is never measured.

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## Mapping the viable parameter space for testable leptogenesis

**Authors:** Yannis Georis<sup>1</sup>; Marco Drewes<sup>1</sup>; Juraj Klarić<sup>2</sup><sup>1</sup> *Catholic University of Louvain*<sup>2</sup> *École polytechnique fédérale de Lausanne***Corresponding Author:** yannis.georis@student.uclouvain.be

We for the first time map the range of active-sterile neutrino mixing angles in which leptogenesis is possible in the type I seesaw model with three heavy neutrinos with Majorana masses between 50

MeV and 70 TeV, covering the entire experimentally accessible mass range. Our study includes both, the asymmetry generation during freeze-in (ARS mechanism) and freeze-out (resonant leptogenesis) of the heavy neutrinos. The range of mixings for which leptogenesis is feasible is considerably larger than in the minimal model with only two heavy neutrinos and extends all the way up to the current experimental bounds. For such large mixing angles the HL-LHC could potentially observe a number of events that is large enough to compare different decay channels, a first step towards testing the hypothesis that these particles may be responsible for the origin of matter and neutrino masses.

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## Gravitational Leptogenesis in Bounce Cosmology

**Author:** Neil Barrie<sup>None</sup>

**Corresponding Author:** nlbarrie@gmail.com

We investigate whether successful Gravitational Leptogenesis can take place during an Ekpyrotic contraction phase. Two possible paths by which this can occur are coupling the Ekpyrotic scalar to a gravitational Chern-Simons term, or to a U(1) gauge field Chern-Simons term. These couplings lead to the production of chiral gravitational waves, which generate a lepton number asymmetry through the gravitational-lepton number anomaly. This lepton asymmetry is subsequently reprocessed by equilibrium sphaleron processes to produce a baryon asymmetry. We find successful Gravitational Leptogenesis to be possible in Ekpyrotic bounce cosmologies through both of these mechanisms.

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## Fate of electroweak symmetry in the early Universe: Non-restoration and trapped vacua in the N2HDM

**Authors:** Georg Ralf Weiglein<sup>1</sup>; Maria Olalla Olea Romacho<sup>2</sup>; Jose Miguel No<sup>3</sup>; Sven Heinemeyer<sup>4</sup>; Thomas Biekötter<sup>5</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron (DE)*

<sup>2</sup> *DESY*

<sup>3</sup> *IFT-UAM/CSIC*

<sup>4</sup> *CSIC (Madrid, ES)*

<sup>5</sup> *Deutsches Elektronen-Synchrotron DESY*

**Corresponding Author:** maria.olalla.olea.romacho@desy.de

Extensions of the Standard Model (SM) Higgs sector allow for a rich cosmological history around the electroweak (EW) scale. In the context of the next-to 2HDM (N2HDM) we analyse the phenomena of EW symmetry non-restoration as well as vacuum trapping. We show that these phenomena can occur in relevant parts of the parameter space. Focusing on the type II N2HDM and taking into account various theoretical and experimental constraints, we demonstrate how these novel finite-temperature effects are related and how they can be used to further constrain the parameter space of the model. In particular, we show that the presence of a global EW minimum at zero temperature might not be a sufficient requirement for the validity of the vacuum configuration.

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## Gravitino Cosmology and No-Scale Higgs Inflation

**Author:** Waqas Ahmed<sup>1</sup>

<sup>1</sup> *Hubei Polytechnic University*

**Corresponding Author:** waqasmit@hbpu.edu.cn

In this talk I will discuss about Higgs inflation in the framework of a minimal extension of the Standard Model gauge symmetry by a  $U(1)_{B-L}$  factor. Furthermore I will talk about physics related to the nature of gravitino, considering possible scenarios, including that it is the lightest supersymmetric particle (LSP) where it can be considered as a DM candidate. The other possibility including the gravitino is not the LSP, then we have a short lived gravitino and a long-lived depending upon the mass range of gravitino.

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## Hybrid Inflation in no-scale supergravity

**Author:** Ahmad Moursy<sup>1</sup>

<sup>1</sup> *Cairo University*

**Corresponding Author:** a.moursy@cu.edu.eg

We consider Hybrid inflation and Tribrid Inflation models in no-scale supergravity framework. We show that a Starobinsky like inflation can be realized with asymptotically flat potentials.  $U(1)_R$  symmetry can be broken on the renormalizable level or by Planck suppressed non-renormalizable operators. A connection to the low energy physics as well as the neutrino masses is addressed.

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## On anomalous production of slow gravitinos in minimal supergravity inflation and its resolution

**Author:** Takahiro Terada<sup>1</sup>

<sup>1</sup> *Institute for Basic Science*

**Corresponding Author:** momentum.musical@gmail.com

In the “Minimal Supergravity Inflation”, whose only degrees of freedom are the (real) inflaton, gravitino, and graviton, an issue of the catastrophic production of slow gravitinos after inflation has been reported. We will briefly comment on the origin of such catastrophic production and propose an alternative model with the same physical degrees of freedom that is free from the issue. We utilize a cubic nilpotent superfield to realize it and demonstrate that inflation is possible in this framework. However, even though there is no issue of gravitino production related to the sound-speed change, the standard gravitino problem turns out to be severe.

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## Supergravity Inflation in braneworld

**Author:** Mudassar Sabir<sup>1</sup>

**Co-authors:** Waqas Ahmed<sup>2</sup>; Yungui Gong<sup>3</sup>; Shan Hu<sup>4</sup>; Tianjun Li<sup>5</sup>; Lina Wu<sup>6</sup>

<sup>1</sup> *China University of Geosciences, Wuhan*

<sup>2</sup> *Hubei Polytechnic University*

<sup>3</sup> *Huazhong University of Science and Technology*

<sup>4</sup> *Hubei University, Wuhan, Hubei 430062, China*

<sup>5</sup> *Chinese Academy of Sciences*

<sup>6</sup> *School of Science, Xi'an Technological University*

**Corresponding Author:** mudassar.sabir@live.com

We discuss supergravity inflation in braneworld cosmology for the class of potentials  $V(\phi) = \alpha\phi^n \exp(-\beta^m \phi^m)$  with  $m = 1, 2$ . These minimal SUGRA models evade the  $\eta$  problem due to a broken shift symmetry and can easily accommodate the observational constraints. In the high energy regime  $V/\lambda \gg 1$ , the numerical predictions and approximate analytic formulas are given for the scalar spectral index  $n_s$  and tensor-to-scalar ratio  $r$ . The models with smaller  $n$  are preferred while the models with larger  $n$  are out of the  $2\sigma$  region. Remarkably, the  $\rho^2/\lambda$  correction to the energy density in Friedmann equation results in sub-Planckian inflaton excursions  $\Delta\phi < 1$ .

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## The primordial black holes and secondary gravitational waves from string inspired general no-scale supergravity

**Authors:** Lina Wu<sup>1</sup>; Tianjun Li<sup>2</sup>; Yungui Gong<sup>3</sup>

<sup>1</sup> *Xi'an Technological University*

<sup>2</sup> *Chinese Academy of Sciences*

<sup>3</sup> *Huazhong University of Science and Technology*

**Corresponding Author:** wulina@xatu.edu.cn

The formation of primordial black hole (PBH) dark matter and the generation of scalar induced secondary gravitational waves (SIGWs) have been studied in the generic no-scale supergravity inflationary models. By adding an exponential term to the Kahler potential, the inflaton experiences a period of ultra-slow-roll and the amplitude of primordial power spectrum is enhanced to  $\mathcal{O}(10^{-2})$ . The enhanced power spectra of primordial curvature perturbations can have both sharp and broad peaks. A wide mass range of PBH is realized in our model, and the frequencies of the scalar induced gravitational waves are ranged from nHz to Hz. We show three benchmark points where the PBH mass generated during inflation is around  $\mathcal{O}(10^{-16} M_\odot)$ ,  $\mathcal{O}(10^{-12} M_\odot)$  and  $\mathcal{O}(M_\odot)$ . The PBHs with masses around  $\mathcal{O}(10^{-16} M_\odot)$  and  $\mathcal{O}(10^{-12} M_\odot)$  can make up almost all the dark matter, and the associated SIGWs can be probed by the upcoming space-based gravitational wave (GW) observatory. Also, the wide SIGWs associated with the formation of solar mass PBH can be used to interpret the stochastic GW background in the nHz band, detected by the North American Nanohertz Observatory for Gravitational Waves, and can be tested by future interferometer-type GW observations.

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## Simplified smooth hybrid inflation in supersymmetric SU(5)

**Author:** Umer Zubair<sup>1</sup>

**Co-author:** Mansoor Rehman<sup>2</sup>

<sup>1</sup> *University of Delaware*<sup>2</sup> *Quaid-i-Azam University Islamabad***Corresponding Author:** umer@udel.edu

A scheme of simplified smooth hybrid inflation is realized in the framework of supersymmetric  $SU(5)$ . The smooth model of hybrid inflation provides a natural solution to the monopole problem that appears in the breaking of  $SU(5)$  gauge symmetry. The supergravity corrections with non-minimal Kahler potential are shown to play important role in realizing inflation with a red-tilted scalar spectral index  $n_s < 1$ , within Planck's latest bounds. As compared to shifted model of hybrid inflation, relatively large values of the tensor-to-scalar ratio  $r \leq 0.01$  are achieved here, with non-minimal couplings  $-0.05 \leq \kappa_S \leq 0.01$  and  $-1 \leq \kappa_{SS} \leq 1$  and the gauge symmetry-breaking scale  $M \simeq (2.0 - 16.7) \times 10^{16}$  GeV.

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## Supersymmetric flat directions and formation of primordial black holes

**Author:** Marcos Flores<sup>1</sup>**Co-author:** Alexander Kusenko<sup>2</sup><sup>1</sup> *UCLA*<sup>2</sup> *UCLA Department of Physics & Astronomy***Corresponding Author:** mmflores@physics.ucla.edu

Supersymmetric flat directions develop large expectation values in the early universe, leading to formation of SUSY Q-balls and ultimately primordial black holes (PBH). This makes PBHs a natural and generic dark matter candidate in supersymmetry. The PBH masses resulting from supersymmetry naturally fall into the sublunar mass window, where the PBHs can account for all dark matter. We will discuss two scenarios which result in the formation of PBHs. First, if the SUSY Q-balls dominate the energy density of the universe then statistical fluctuations and gravitational forces allow for the formation of PBHs in this intermediate matter-dominated era. Second, SUSY Q-balls may interact via a light scalar mediator. This attractive force allows for the formation of structure even in the radiation dominated era, while simultaneously removing energy and angular momentum from the systems of solitons by means of scalar radiation. These mechanisms are able to explain the present-day dark matter abundance in addition to potential candidate events observed with lensing experiments.

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## Warming Up Cold Inflation

**Author:** Saarik Kalia<sup>1</sup>**Co-authors:** Peter Graham<sup>1</sup>; William DeRocco<sup>1</sup><sup>1</sup> *Stanford University***Corresponding Author:** saarik@stanford.edu

The axion is a well-motivated candidate for the inflaton, as the radiative corrections that spoil many single-field models are avoided by virtue of its shift symmetry. However, axions generically couple to gauge sectors. As the axion rolls through its potential, this coupling can result in the production of a co-evolving thermal bath, a situation known as “warm inflation.” Inflationary dynamics in this

warm regime can be dramatically altered and result in significantly different observable predictions. In this talk, I will show that for large regions of parameter space, axion models once assumed to be safely “cold” are in fact warm, and must be reevaluated in this context.

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## Superheavy Dark Matter from String Theory

Author: Rouzbeh Allahverdi<sup>1</sup>

<sup>1</sup> *University of New Mexico*

Corresponding Author: rouzbeh@unm.edu

I argue that generic features of string compactifications, namely a high scale of supersymmetry breaking and one or more epochs of modulus domination, can accommodate superheavy neutralino dark matter with a mass around  $10^{10}$ – $10^{11}$  GeV. Interestingly, this mass range may also explain the recent detection of ultra-high-energy neutrinos by IceCube and ANITA via dark matter decay.

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## Yangian bootstrap in three-body effective potential in general relativity

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## A new approach to $t$ -channel singularities in cosmology

Author: Michał Iglicki<sup>1</sup>

<sup>1</sup> *University of Warsaw*

Corresponding Author: michal.iglicki@fuw.edu.pl

A  $t$ -channel singularity of a cross section occurs in a  $2 \rightarrow 2$  process when the mediator is allowed to be on-shell, i.e. when the process can be treated as a sequence of a  $1 \rightarrow 2$  decay and a  $2 \rightarrow 1$  inverse decay. If, moreover, the mediator is stable, this singularity cannot be regularized within the common Breit-Wigner approach.

In this talk I will discuss the conditions for the singularity to occur and briefly summarize attempts (proposed in literature) to regularize it in case of collider physics and cosmological considerations of a thermal medium of particles. After showing that none of previously proposed ways to solve the problem is satisfactory in the cosmological case, I will present a natural solution developed within the Keldysh-Schwinger formalism: a non-zero imaginary part of the mediator’s self-energy that appears as a consequence of interactions between the mediator and the thermal medium. Consequently, the mediator acquires a non-zero effective decay width and the cross section becomes finite.

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## Initial conditions of pre-inflation in LQC

**Authors:** Mohammad Sami<sup>1</sup>; Mohd Shahalam<sup>2</sup>; Wang Anzhong<sup>3</sup>

<sup>1</sup> *Jamia Millia Islamia New Delhi*

<sup>2</sup> *Zhejiang University of Technology*

<sup>3</sup> *Baylor University*

**Corresponding Author:** mohdshahamu@gmail.com

We discuss the preinflationary dynamics of the spatially flat FLRW universe filled with a single scalar field that has the generic potentials, in the framework of loop quantum cosmology. The evolution can be divided into two different classes, one is dominated initially (at the quantum bounce) by the kinetic energy of the scalar field, and one is not. In both cases, we identify numerically the physically viable initial conditions that lead to not only a slow-roll inflationary phase, but also enough e-folds to be consistent with observations, and find that the output of such a viable slow-roll inflationary phase is generic. In addition, we also show that in the case when the evolution of the universe is dominated initially by the kinetic energy of the scalar field, the evolution before reheating is always divided into three different phases: bouncing, transition and slow-roll inflation.

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## Classical gravitational scattering from a gauge-invariant double copy

**Author:** Gang Chen<sup>1</sup>

**Co-authors:** Andreas Brandhuber<sup>1</sup>; Gabriele Travaglini<sup>1</sup>; Congkao Wen<sup>1</sup>

<sup>1</sup> *Queen Mary University of London*

**Corresponding Author:** jinyun.chern@gmail.com

The Gravity effects play an important role both in the black hole scattering and early universe inflation. On the other hand, extremely heavy dynamic systems, e.x. The black hole and early universe, provide a natural environment for detecting classical and quantum gravitational effects. In this talk, we majorly focus on the theoretical part of the gravity effects. We propose a systematic framework to obtain the classical and quantum gravity effect on the two-body scattering bending angle. The framework is based on the heavy-mass effective field theory approach to general relativity. The amplitudes in this effective field theory are constructed using a recently proposed novel color-kinematic/double copy duality, where the duality numerators are gauge invariant and local concerning the massless gravitons. We provide the explicit result on two body bending angles to the third post-Minkowskian order for the classical part and the one-loop order for the quantum part.

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## Messenger inflation in gauge mediation and superWIMP dark matter

**Authors:** Nobuchika Okada<sup>1</sup>; Shinsuke Kawai<sup>2</sup>

<sup>1</sup> *University of Alabama*

<sup>2</sup> *Sungkyunkwan University*

**Corresponding Author:** shinsuke.kawai@gmail.com

We discuss phenomenological viability of a novel inflationary model in the minimal gauge mediated supersymmetry breaking scenario. In this model, cosmic inflation is realized in the flat direction along the messenger supermultiplets and a natural dark matter candidate is the gravitino from the out-of-equilibrium decay of the bino-like neutralino at late times, which is called the superWIMP scenario. The produced gravitino is warmish and can have a large free-streaming length; thus the cusp anomaly in the small scale structure formation may be mitigated. We show that the requirement of the Standard Model Higgs boson mass to be  $m_{h^0} = 125.1$  GeV gives a relation between the spectrum of the cosmic microwave background and the messenger mass  $M$ . We find, for the e-folding number  $N_e = 60$ , the Planck 2018 constraints (TT, TE, EE+lowE+lensing+BK15+BAO, 68% confidence level) give  $M > 3.64 \times 10^7$  GeV. The gravitino dark matter mass is  $m_{3/2} < 5.8$  GeV and the supersymmetry breaking scale  $\Lambda$  is found to be in the range  $(1.28 - 1.33) \times 10^6$  GeV. Future CMB observation is expected to give tighter constraints on these parameters.

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## Primordial Black Holes in the Excursion Set Theory

**Author:** Encieh Erfani<sup>1</sup>

**Co-authors:** Shant Baghran<sup>2</sup>; Hamed Kameli<sup>3</sup>

<sup>1</sup> IASBS, Zanjan, Iran

<sup>2</sup> Sharif Uni

<sup>3</sup> Sharif Uni.

**Corresponding Author:** encieherfani@gmail.com

We study primordial black holes (PBHs) formation in the excursion set theory (EST) in a vast range of PBHs masses with and without confirmed constraints on their abundance. In this work, a new concept of the first touch in the EST is introduced for PBHs formation which takes into account the earlier horizon reentry of smaller masses. Our study shows that in the EST, it is possible to produce PBHs in different mass ranges which could make up all dark matter. We also show that in a broad blue-tilted power spectrum, the production of PBHs is dominated by a smaller mass. Our analysis put an upper limit  $\sim 0.1$  on the amplitude of the curvature power spectrum at length scales relevant for PBHs formation.

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## Maximally misaligned axions

**Author:** Mario Reig<sup>1</sup>

<sup>1</sup> Instituto de Física Corpuscular (IFIC)

**Corresponding Author:** mario.reig@ific.uv.es

In this talk I will discuss a simple model of maximal axion misalignment. Maximally-misaligned axions with masses larger than  $10^{\sim 22}$  eV constitute an attractive DM candidate with interesting phenomenology. On the other hand, maximally-misaligned axions with masses  $m = \mathcal{O}(1-100)H_0$  generically behave as dark energy with a decay constant that can take values well below the Planck scale, avoiding problems associated to super-Planckian scales.

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## From Neutrino Masses to the Full Size of the Universe - Some Intriguing Aspects of the Tetron Model

**Author:** Bodo Lampe<sup>None</sup>

**Corresponding Author:** lampe.bodo@web.de

The universe according to the tetron model consists of invisible tiny constituents, elastically bound with bond length about the Planck length and binding energy the Planck energy.

A tetron transforms as the fundamental fermion(=octonion) representation 8 of SO(6,1). With respect to the decomposition SO(6,1)→SO(3,1)×SO(3) a tetron possesses spin 1/2 and isospin 1/2, i.e. it represents an isospin doublet of Dirac spinors.

The 24 known quarks and leptons arise as eigenmode excitations of a tetrahedral fiber structure, which is made up from 4 tetrons and extends into 3 additional 'internal' dimensions.

While the laws of gravity are due to the elastic properties of the tetron bonds, particle physics interactions take place within the internal fibers.

I will concentrate on two of the most intriguing features of the model:

-understanding small neutrino masses from the conservation of isospin, and, more in general, calculating the spectrum of quark and lepton masses. This is obtained from the tetron model's interpretation of the Higgs mechanism.

-the possibility to determine the full size of the universe from future dark energy measurements. This is obtained from the tetron model's interpretation of the dark energy phenomenon.

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## Analysis of Dark Radiation Abundance in Axion-Gauge Fields Models

**Authors:** Masahito OGATA<sup>1</sup>; Mitsuru Kakizaki<sup>2</sup>; Osamu Seto<sup>None</sup>

<sup>1</sup> *U. of Toyama*

<sup>2</sup> *University of Toyama*

**Corresponding Author:** kakizaki@sci.u-toyama.ac.jp

In the axion-gauge fields model, the nontrivial configuration and dynamics of the axion and hidden gauge fields during inflation induce gravitational wave background. In particular, the energy density of the axion needs to be sufficiently large to generate observable gravitational waves. After inflation ends, the axion decays into gauge fields, and they behave as dark radiation, which modifies the neutrino effective degrees of freedom  $N_{\text{eff}}$ . Therefore, the model can be constrained from precise measurements of  $N_{\text{eff}}$ . In this study, we investigate the testability of this model from future observations of  $\Delta N_{\text{eff}}$ , in the parameter region where the ratio of tensor fluctuations from the vacuum to those from the gauge fields is  $\mathcal{O}(10^{-1})$ .

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## Cosmological parameter shifts and AdS-EDE

**Authors:** Gen Ye<sup>1</sup>; Yun-Song Piao<sup>1</sup>

<sup>1</sup> *University of Chinese Academy of Sciences*

**Corresponding Author:** yegen14@mailsucas.ac.cn

The well-known Hubble tension is widely thought to be an indication of new physics beyond  $\Lambda$ CDM. Theoretical modification happening before recombination (early) seems to be more viable than post-recombination (late) ones since they are less constrained by observations. We propose the AdS-EDE model which solves the tension at  $1\sigma$  level for the first time while remaining compatible with data. Predictions of important cosmological parameters are shifted in correlation with  $H_0$  in the early solutions, including EDE, from their  $\Lambda$ CDM values. The AdS-EDE model proves to be an ideal candidate for studying parameter shifts due to its large  $H_0$  value. EDE models show a positive correlation between the scalar primordial spectrum index  $n_s$  and  $H_0$ , and become fully compatible with a Zeldovich-Harrison ( $n_s = 1$ ) spectrum given the locally measured  $H_0$  value. I will talk about the physical origin of this correlation and its profound implication on our understanding of the early Universe and inflation. The other parameter shift I will discuss is the positive  $\omega_{cdm} - H_0$  correlation. The enhancement in  $\omega_{cdm}$  induces a larger  $S_8$ , exacerbating the so called  $S_8$  problem which is sometimes employed to criticize EDE. I will explain this correlation is mainly a requirement of background CMB+BAO compatibility and seems inevitable in the simplest EDE models. However, clear knowledge of the physical origin of this correlation actually tells us how to possibly restore concordance with  $S_8$  and LSS in the EDE models.

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## Exotic Higgs Decays at CMS

**Author:** Fengwangdong Zhang<sup>1</sup>

<sup>1</sup> *University of California Davis (US)*

**Corresponding Author:** fengwangdong.zhang@cern.ch

A review of the recent searches for Exotic Decays of the Higgs boson performed by the CMS experiment will be presented. Whilst it is an overview talk, the speaker can choose a couple of subjects to develop in more detail.

**Electroweak, Top quark, and Higgs Physics / 302**

## BSM Higgs searches at CMS

**Author:** Paul Asmuss<sup>1</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron (DE)*

**Corresponding Author:** paul.asmuss@cern.ch

Since the first idea by Brout, Englert and Higgs in 1964, the Higgs boson had been searched for intensively. Finally, it was discovered at a mass of about 125 GeV in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN. While currently all measurements of e.g. cross sections and branching ratios show a good agreement with the Standard Model predictions, there are strong reasons to expect physics beyond the Standard Model, which could manifest itself in an extended Higgs sector. This could result in additional observable Higgs bosons, or in subtle deviations of the 125 GeV Higgs boson properties from the SM. This presentation summarizes recent results on searches for an extended Higgs sector in the CMS experiment.

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## Vacuum stability and asymptotic behaviour in Extended Higgs and Leptoquarks



**Author:** SHILPA JANGID<sup>1</sup>

**Co-authors:** Priyotosh Bandyopadhyay<sup>2</sup>; P.S. Bhupal Dev P.S. Bhupal Dev ; Manimala Mitra Manimala Mitra<sup>3</sup>; Arjun Kumar Arjun Kumar<sup>4</sup>

<sup>1</sup> IIT HYDERABAD

<sup>2</sup> IIT Hyderabad

<sup>3</sup> IOPB

<sup>4</sup> IIT Delhi

**Corresponding Author:** ph19resch02006@iith.ac.in

The status of Standard Model vacuum stability with generic problems beyond Standard Models (BSM) will be scrutinised.

We will see how addition of scalar from different SU(2) representations, i.e.

Inert Higgs Doublet model (IDM) and Inert Higgs triplet model (ITM) enhance the stability of electroweak vacuum[1]. Addition of fermions can decrease the stability and need additional scalar to get to the stability which would be clear while discussing the extension with Type-I Seesaw and IDM[2]. We also see for Type-III seesaw +IDM due to SU(2) triplet fermions, the impact on  $g_2$  is visible and it increases with energy unlike SM or Type-I Seesaw and IDM losing the asymptotic freedom[3]. This constraints the fermion generation to only two for Planck scale stability. Finally, Vacuum stability and perturbativity for scalar Doublet and Triplet Leptoquarks is also studied. In this scenario, the behaviour of all gauge couplings will be modified. We have also studied the perturbativity of the scalar quartic couplings. Dark matter and collider phenomenologies will also be discussed briefly in IDM and ITM.

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**Electroweak, Top quark, and Higgs Physics / 236**

## Charged Higgs from different representations at the LHC

**Author:** Priyotosh Bandyopadhyay<sup>1</sup>

**Co-authors:** SHILPA JANGID<sup>2</sup>; Antonio Costantini<sup>3</sup>

<sup>1</sup> Indian Institute of Technology Hyderabad

<sup>2</sup> IIT HYDERABAD

<sup>3</sup> INFN

**Corresponding Author:** bpriyo@phy.iith.ac.in

Charged Higgs from Higgs doublets generally couples to fermions thus mainly decay to fermionic modes. However, the inert doublets cannot have such two-body decays and mainly decays via three-body. Even then the coupling of charged Higgs with Z and W bosons are absent at the tree-level due to custodial symmetry. SU(2) triplet Higgs boson with Y=0 hyper charge breaks the custodial symmetry leading to a tree-level vertex with Z and W boson. This prompts the decays into ZW as compared to tb in a doublet charged Higgs case. However, additional  $Z_2$  symmetry can make this triplet as inert leading to displaced mono/di-leptonic signatures. In case of complex triplet, the

model produces a pure triplet dark matter along with a pure and mixed triplet charged Higgs bosons. The last scenario this gives rise to both the displaced and the prompt charged leptons in the final states. We try to distinguish such scenarios at the LHC.

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## Probing the B+L violation process with the observation of cosmic magnetic field

**Author:** Ligong Bian<sup>1</sup>

<sup>1</sup> *Chongqing University*

**Corresponding Author:** lgbycl@cqu.edu.cn

We numerically investigate the B+L violation process by performing three-dimensional lattice simulations of a unified scenario of first-order phase transitions and the sphaleron generation. The simulation results indicate that the Chern-Simons number changes along with the helical magnetic field production when the sphaleron decay occurs. Based on these numerical results, we then propose a novel method to probe the baryon asymmetry generation of the Universe, which is a general consequence of the electroweak sphaleron process, through the astronomical observation of corresponding helical magnetic fields.

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## The Road Not Taken: more dimension-4's before EFT

**Author:** George W.S. Hou<sup>1</sup>

<sup>1</sup> *National Taiwan University*

**Corresponding Author:** wshou@phys.ntu.edu.tw

The LHC has not discovered any New Physics beyond the anticipated  $h(125)$  boson, pushing the SUSY scale to multi-TeV, and new ideas abound for out-of-the-box searches, or Effective Field Theory with high cutoff scale. But, have we exhausted dimension-4 operators involving sub-TeV particles that are not exotic (non-XLP)? We advocate the existence of an extra Higgs doublet that possesses extra Yukawa couplings, where emergent mass-mixing hierarchies and alignment have well-hidden their effects so far.  $\mathcal{O}(1)$  extra Higgs quartics can induce first order electroweak phase transition and imply sub-TeV spectrum. The extra Yukawa couplings, led by  $\rho_{tt}$  and  $\rho_{tc}$  that can be  $\mathcal{O}(1)$ , can drive electroweak baryogenesis, while  $\rho_{ee}/\rho_{tt} \propto \lambda_e/\lambda_t$ , the ratio of standard electron and top Yukawa couplings, can tame electron EDM. Finding these extra Higgs bosons via  $cg \rightarrow tH/A \rightarrow tt\bar{c}$ ,  $tt\bar{t}$  and  $cg \rightarrow bH^+ \rightarrow bt\bar{b}$  processes (plus processes allowed by Higgs boson splittings) at the LHC, and pushing the flavor frontier to break the flavor code, would usher in a new Higgs/flavor era. SUSY may still be realized at a higher scale, possibly related to the Landau pole of the scalar sector.

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## Impact of quark flavor violating SUSY on $h(125)$ decays

**Authors:** Helmut Eberl<sup>1</sup>; Elena Ginina<sup>1</sup>; Keisho Hidaka<sup>2</sup>

<sup>1</sup> *HEPHY, Vienna*

<sup>2</sup> *Tokyo Gakugei University*

**Corresponding Author:** hidaka@u-gakugei.ac.jp

We study the Higgs boson decays  $h \rightarrow c \bar{c}, b \bar{b}, b \bar{s}, \text{photon photon}$  and  $h \rightarrow \text{gluon gluon}$  in the Minimal Supersymmetric Standard Model (MSSM) with general quark flavor violation (QFV), identifying the  $h$  with the Higgs boson with a mass of 125 GeV. We compute the widths of the  $h$  decays to  $c \bar{c}, b \bar{b}, b \bar{s}$  ( $s \bar{b}$ ) at full one-loop level in the MSSM with QFV. For the  $h$  decays to  $\text{photon photon}$  and  $h \rightarrow \text{gluon gluon}$  we compute the widths at NLO QCD level. We perform a systematic MSSM parameter scan respecting all the relevant constraints, i.e. theoretical constraints from vacuum stability conditions and experimental constraints, such as those from K- and B-meson data and electroweak precision data, as well as recent limits on Supersymmetric (SUSY) particle masses and the 125 GeV Higgs boson data from LHC experiments. From the parameter scan, we find the followings:

- (1)  $\text{DEV}(h \rightarrow c \bar{c})$  and  $\text{DEV}(h \rightarrow b \bar{b})$  can be very large simultaneously:  $\text{DEV}(h \rightarrow c \bar{c})$  can be as large as about  $\pm 60\%$  and  $\text{DEV}(h \rightarrow b \bar{b})$  can be as large as about  $\pm 20\%$ . Here  $\text{DEV}(h \rightarrow X Y)$  is the deviation of the decay width  $\Gamma(h \rightarrow X Y)$  in the MSSM from the SM prediction:  $\text{DEV}(h \rightarrow X Y) = \Gamma(h \rightarrow X Y)_{\text{MSSM}} / \Gamma(h \rightarrow X Y)_{\text{SM}} - 1$ .
- (2) The QFV decay branching ratio  $\text{BR}(h \rightarrow b \bar{s} / \bar{b} s)$  can be as large as about 0.17% in the MSSM. It is almost zero in the SM. The sensitivity of ILC(250 + 500 + 1000) to this decay BR could be about 0.1% at 4 sigma signal significance.
- (3)  $\text{DEV}(h \rightarrow \text{photon photon})$  and  $\text{DEV}(h \rightarrow \text{gluon gluon})$  can be large simultaneously:  $\text{DEV}(h \rightarrow \text{photon photon})$  can be as large as about + 4% and  $\text{DEV}(h \rightarrow \text{gluon gluon})$  can be as large as about -15%.
- (4) There is a very strong correlation between  $\text{DEV}(h \rightarrow \text{photon photon})$  and  $\text{DEV}(h \rightarrow \text{gluon gluon})$ . This correlation is due to the fact that the stop-loop (stop-scharm mixture loop) contributions dominate the two DEVs.
- (5) The deviation of the width ratio  $\Gamma(h \rightarrow \text{photon photon}) / \Gamma(h \rightarrow \text{gluon gluon})$  in the MSSM from the SM value can be as large as about +20%.
- (6) All of these large deviations in the  $h$  decays are due to large scharm-stop mixing and large stop/scharm involved trilinear couplings  $T_{U23}, T_{U32}, T_{U33}$  and large sstrange-sbottom mixing and large sstrange/sbottom involved trilinear couplings  $T_{D23}, T_{D32}, T_{D33}$ .
- (7) ILC can observe such large deviations from SM at high signal significance.
- (8) In case the deviation pattern shown here is really observed at ILC, then this would strongly suggest the discovery of QFV SUSY (MSSM with QFV).

Note: This work is based on collaboration with H. Eberl and E. Ginina (HEPHY, Vienna).

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**Electroweak, Top quark, and Higgs Physics / 234**

## Electroweak Restoration at the LHC and Beyond: The $Vh$ Channel

**Authors:** Ian Lewis<sup>1</sup>; Li Huang<sup>2</sup>; Samuel Lane<sup>2</sup>; Zhen Liu<sup>3</sup>

<sup>1</sup> *The University of Kansas*

<sup>2</sup> *University of Kansas*

<sup>3</sup> *University of Minnesota*

**Corresponding Author:** samuel.lane@ku.edu

The LHC is exploring electroweak (EW) physics at the scale EW symmetry is broken. As the LHC and new high energy colliders push our understanding of the Standard Model to ever-higher energies, it will be possible to probe not only the breaking of but also the restoration of EW symmetry. We propose to observe EW restoration in double EW boson production via the convergence of the Goldstone boson equivalence theorem. This convergence is most easily measured in the vector boson plus Higgs production,  $Vh$ , which is dominated by the longitudinal polarizations. We define EW restoration by carefully taking the limit of zero Higgs vacuum expectation value (vev). EW restoration is then measured through the ratio of the  $p_T^h$  distributions between  $Vh$  production in the Standard Model and Goldstone boson plus Higgs production in the zero vev theory, where  $p_T^h$  is the Higgs transverse momentum. As EW symmetry is restored, this ratio converges to one at high energy. We present a method to extract this ratio from collider data. With a full signal and background analysis, we demonstrate that the 14 TeV HL-LHC can confirm that this ratio converges to one to 40% precision while at the 27 TeV HE-LHC the precision will be 6%. We also investigate statistical tests to quantify the convergence at high energies. Our analysis provides a roadmap for how to stress test the Goldstone boson equivalence theorem and our understanding of spontaneously broken symmetries, in addition to confirming the restoration of EW symmetry.

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## Higgs boson measurements in its decays into bosons with the ATLAS experiment

**Author:** Rafael Coelho Lopes De Sa<sup>1</sup>

<sup>1</sup> *University of Massachusetts (US)*

**Corresponding Author:** rafael.lopesdesa@cern.ch

With the full LHC Run 2 pp collision dataset collected at 13 TeV, very detailed measurements of Higgs boson properties can be performed using its decays into bosons. This talk presents measurements of Higgs boson properties using decays into bosons and their combination with fermionic decays, including production mode cross sections and simplified template cross sections, as well as their interpretations.

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## Searches for low- and high-mass Higgs-like resonances with the ATLAS detector

**Author:** Shuo Han<sup>1</sup>

<sup>1</sup> *Lawrence Berkeley National Lab. (US)*

**Corresponding Author:** shuo.han@cern.ch

Several theories beyond the Standard Model predict the existence of new particles decaying into pairs of gauge bosons. These states generally have masses larger than that of the Higgs boson, while some theories predict resonances with masses smaller than it. The latest ATLAS results on searches for such resonances in final states with leptons and photons based on pp collision data collected at 13 TeV will be presented.

**Electroweak, Top quark, and Higgs Physics / 424**

## Resonant and non-resonant HH production at CMS

**Corresponding Author:** siddhesh.gopichand.sawant@cern.ch

A review of the recent searches for production of Higgs boson pairs (both resonant and non-resonant) performed by the CMS experiment will be presented. Whilst it is an overview talk, the speaker can choose a couple of subjects to develop in more detail.

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## Rare top quark production at ATLAS and CMS: ttZ, ttW, ttgamma, tZ, tgamma, and tttt production

**Author:** Emanuele Usai<sup>1</sup>

<sup>1</sup> *Brown University (US)*

**Corresponding Author:** emanuele.usai@cern.ch

A comprehensive set of measurements of top quark pair and single top quark production in association with EWK bosons (W, Z or  $\gamma$ ) using data collected by ATLAS and CMS detectors presented. The results are compared to theory predictions and re-interpreted as searches for new physics inducing deviations from the standard model predictions. The status of the search for four top quark production, to which the LHC experiments are starting to be sensitive, and that has important BSM re-interpretations, is also reported.

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## The anomalous Zbb couplings at the LHC and lepton-hadron colliders

**Author:** Bin Yan<sup>1</sup>

**Co-authors:** Zhite Yu<sup>2</sup>; C.-P. Yuan<sup>2</sup>

<sup>1</sup> *Los Alamos National Laboratory*

<sup>2</sup> *MSU*

**Corresponding Author:** binyan@lanl.gov

To resolve the long-standing discrepancy between the precision measurement of bottom quark forward-backward asymmetry at LEP/SLC and the Standard Model prediction, we propose several novel methods to probe the  $Zbb$  coupling at the LHC and lepton-hadron colliders (HERA and EIC).

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## The Higgs-top CP phase with tth at the 14 TeV LHC and 100 TeV FCC

**Authors:** Dorival Gonçalves<sup>1</sup>; Jeong Han Kim<sup>2</sup>; K.C. Kong<sup>3</sup>; Yongcheng Wu<sup>1</sup>

<sup>1</sup> *Oklahoma State University*<sup>2</sup> *Chungbuk National University*<sup>3</sup> *University of Kansas***Corresponding Author:** ycwu0830@gmail.com

Precision measurement of the Higgs boson properties is an important topic at the LHC and future collider experiments. We studied the potential to directly probe the magnitude and CP phase of the top quark Yukawa coupling in  $t\bar{t}h$  production with  $h \rightarrow b\bar{b}$ . The BDRS algorithm is used to tag the boosted Higgs, while the  $t\bar{t}$  rest frame is constructed using  $M_2$  assisted reconstruction. Further, sideband events of the major background  $t\bar{t}b\bar{b}$  are used to reduce the corresponding systematics, and the  $t\bar{t}Z$  process is used to reduce the systematics of the signal. With these excellent handles on the uncertainties, we can achieve high precision on measuring both the magnitude and CP phase of the top Yukawa couplings.

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## Higgs boson measurements at CMS

**Author:** Soumya Mukherjee<sup>1</sup><sup>1</sup> *Tata Inst. of Fundamental Research (IN)***Corresponding Author:** soumya.mukherjee@cern.ch

A review of the recent measurements of the SM Higgs couplings and properties performed by the CMS experiments will be presented. Whilst it is an overview talk, the speaker can choose a couple of subjects to develop in more detail.

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## $Z$ polarization as a probe of anomalous gauge-Higgs coupling

**Authors:** Kumar Rao<sup>1</sup>; Priyanka Sarmah<sup>2</sup>; Saurabh D. Rindani<sup>3</sup><sup>1</sup> *IIT Bombay*<sup>2</sup> *phd student*<sup>3</sup> *Physical Research Laboratory, India***Corresponding Author:** sarmahpriyanka07@gmail.com

$Z$  boson being a spin-one particle provides eight polarization parameters. We show how the  $Z$  boson polarization can be used to study the  $ZH$  production at future  $e^+e^-$  colliders and at the LHC. Using the spin density matrix of the  $Z$ -boson we calculate the 8 independent polarization parameters which are sensitive to anomalous gauge-Higgs couplings. We then estimate bounds on the anomalous  $ZZH$  couplings by constructing angular asymmetries from the  $Z$  boson decay leptons, which are related to the polarization observables. Taking into account possible longitudinal beam polarizations at two different center of mass energies, we find that oppositely polarized beams at 500 GeV c.m. energy provides tighter bounds on the couplings than the same sign polarized and unpolarized beams. We find that most of the  $1\sigma$  limits are of the order of a few times  $10^{-3}$  for 14 TeV LHC with integrated luminosity of  $1000 \text{ fb}^{-1}$  and for 500 GeV  $e^+e^-$  colliders with oppositely polarized beams.

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## **Applying $A_4$ to three-Higgs doublet model implies alignment**

**Author:** Soumita Pramanick<sup>1</sup>

**Co-author:** Amitava Raychaudhuri<sup>2</sup>

<sup>1</sup> *National Centre for Nuclear Research (NCBJ), Warsaw, Poland*

<sup>2</sup> *Department of Physics, University of Calcutta, India*

**Corresponding Author:** soumita509@gmail.com

[This talk will be on JHEP 1801 (2018) 011 by Soumita Pramanick and Amitava Raychaudhuri]

Three-higgs doublet model in  $A_4$  symmetric framework will be discussed. It was observed that if we consider three  $SU(2)_L$  doublet scalars forming a triplet under  $A_4$  symmetry, alignment follows for four global minima configurations of the vacuum expectation values (vevs) naturally owing to the  $A_4$  symmetry. No fine-tuning was needed. Positivity and unitarity conditions were satisfied.

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## **Boosted semi leptonic top tagging with tau**

**Authors:** Amandip De<sup>1</sup>; Amit Chakraborty<sup>2</sup>; Monoranjan Guchait<sup>3</sup>; Rohini Godbole<sup>4</sup>

<sup>1</sup> *Indian Institute of Science*

<sup>2</sup> *High Energy Accelerator Research Organization (KEK)*

<sup>3</sup> *Tata Institute of Fundamental Research (TIFR)*

<sup>4</sup> *Centre for High Energy Physics, Indian Institute of Science, Bengaluru, India*

**Corresponding Author:** deamandip93@gmail.com

Boosted top quark tagging is one of the challenging tasks in high energy physics experiments, in particular in exploring new physics signals at the LHC. Several techniques are already developed to tag boosted top quark in its hadronic decay channel, and recently tagging in the semi leptonic channel also has been receiving a lot of attention. In this current study we try to develop boosted ( $p_T > 300$  GeV) semi leptonic top quark tagging methodology in tau channel considering its hadronic mode. In this method two sub jets inside the top like fat jets are constructed employing standard jet substructure techniques, and then cleaning those using soft drop methods. Eventually, two sub jets are identified as b and  $\tau$  like jets, naively applying techniques used in the LHC experiments. Investigating several kinematic variables of these sub jets, such as sub jets energy fractions, invariant mass etc, we show that the main QCD background can be rejected achieving higher signal tagging efficiency. It is observed that the signal efficiency  $\sim 82\%$  against background rejection efficiency of  $\sim 98\%$  can be achievable. We try to improve further by employing multivariate analysis techniques applying boosted decision tree inputting several kinematic variables constructed out of these two subjects. Tagging boosted top quark in its tau decay channel is very useful in improving signal efficiencies, for instance, in searching very energetic Leptoquark, top squarks in R-parity breaking SUSY model etc.

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## **Probing anomalous HVV couplings using Higgs production in electron-proton collisions**

**Authors:** Ambresh Shivaji<sup>1</sup>; Mukesh Kumar<sup>2</sup>; PRAMOD SHARMA<sup>3</sup>

<sup>1</sup> IISER Mohali, Punjab, India

<sup>2</sup> University of the Witwatersrand, Johannesburg, Wits 2050, South Africa

<sup>3</sup> IISER Mohali

**Corresponding Author:** pramodsharma221995@gmail.com

**Abstract:** We probe anomalous HZZ coupling through single Higgs boson production at the Large Hadron-electron collider with 60 GeV (7 TeV) of electron (proton) energy. The sensitivity of CP-even and CP-odd anomalous couplings are assessed through azimuthal angle difference between scattered electron and forward jets along with cross-section as a function of luminosity. Comparative studies for HWW anomalous couplings are also performed.

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## Measuring Higgs Boson Self-couplings with 2→3 VBS Processes

**Authors:** Chih-Ting Lu<sup>1</sup>; Junmou Chen<sup>2</sup>; Yongcheng Wu<sup>3</sup>

<sup>1</sup> National Tsing Hua University

<sup>2</sup> Jinan University

<sup>3</sup> Oklahoma State University

**Corresponding Author:** chenjm@jnu.edu.cn

We study the measurement of Higgs boson self-couplings through 2→3 vector boson scattering (VBS) processes in the framework of Standard Model effective field theory (SMEFT) at both proton and lepton colliders. The SMEFT contribution to the amplitude of the 2→3 VBS processes, taking  $WLWL \rightarrow WLWLh$  and  $WLWL \rightarrow hhh$  as examples, exhibits enhancement with the energy  $\propto \Lambda^2$ , which indicates the sensitivity of these processes to the related dimension-six operators in SMEFT. Simulation of the full processes at both hadron and lepton colliders with a variety of collision energies are performed to estimate the allowed region on  $c_6$  and  $c_{\Phi^1}$ . Especially we find that, with the help of exclusively choosing longitudinal polarizations in the final states and suitable  $p_T$  cuts,  $WW_h$  process is as important as the more widely studied triple Higgs production ( $hhh$ ) in the measurement of Higgs self-couplings. Our analysis indicates that these processes can play important roles in the measurement of Higgs self-couplings at future 100 TeV pp colliders and muon colliders. However, their cross sections are generally tiny at low energy machines, which makes them much more challenging to explore.

**Electroweak, Top quark, and Higgs Physics / 449**

## Higgs boson measurements in couplings to quarks and leptons with the ATLAS experiment

**Author:** Guy Koren<sup>1</sup>

<sup>1</sup> Tel Aviv University (IL)

**Corresponding Author:** guy.koren@cern.ch

Testing the Yukawa couplings of the Higgs boson to quarks and leptons is important to understand the origin of fermion masses. The talk presents several new measurements in Higgs boson decays to two bottom quarks or two tau leptons, searches for Higgs boson decays to two charm quarks or



two muons, as well as indirect constraints of the charm-Yukawa coupling. The production of Higgs bosons in association with top quarks will also be discussed. These analyses are based on pp collision data collected at 13 TeV.

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## **Combined Higgs boson measurements and their interpretations in Effective Field Theories and new physics models with the ATLAS experiment**

**Author:** Lei Zhang<sup>1</sup>

<sup>1</sup> *Nanjing University (CN)*

**Corresponding Author:** lei.zhang@cern.ch

Combining measurements of many production and decay channels of the observed Higgs boson allows for the highest possible measurement precision for the properties of the Higgs boson and its interactions. These combined measurements are interpreted in various ways; specific scenarios of physics beyond the Standard Model are tested, as well as a generic extension in the framework of the Standard Model Effective Field Theory. The latest highlight results of these measurements and their interpretations performed by the ATLAS Collaboration will be discussed.

**Electroweak, Top quark, and Higgs Physics / 452**

## **Searches for additional Higgs bosons in ATLAS**

**Author:** Adam Bailey<sup>1</sup>

<sup>1</sup> *Univ. of Valencia and CSIC (ES)*

**Corresponding Author:** adam.bailey@cern.ch

The discovery of the Higgs boson with the mass of about 125 GeV completed the particle content predicted by the Standard Model. Even though this model is well established and consistent with many measurements, it is not capable to solely explain some observations. Many Supersymmetric extensions addressing such shortcomings introduce additional Higgs-like bosons which can be either neutral, singly-charged or even doubly-charged. The current status of searches based on the full LHC Run 2 dataset of the ATLAS experiment at 13 TeV are presented.

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## **Searches for resonances decaying to boson pairs in ATLAS**

**Author:** William Balunas<sup>1</sup>

<sup>1</sup> *University of Oxford (GB)*

**Corresponding Author:** bill.balunas@cern.ch

Many new physics models, including supersymmetric extensions to the Standard Model such as two Higgs doublet models (2HDMs), predict the existence of new particles decaying into two bosons

(W, Z, photon, or Higgs bosons) making these important signatures in the search for new physics. Searches for such diboson resonances have been performed in final states with different numbers of leptons, photons, as well as jets and b-jets where new jet substructure techniques are used to disentangle the hadronic decay products in highly boosted configuration. This talk summarises recent ATLAS searches with Run 2 data collected at the LHC and explains the experimental methods used, including vector- and Higgs-boson-tagging techniques.

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## Correlating the anomalous moment of the muon and the W mass in the MSSM

**Author:** Emanuele Angelo Bagnaschi<sup>1</sup>

**Co-authors:** Sven Heinemeyer<sup>2</sup>; Georg Ralf Weiglein<sup>3</sup>

<sup>1</sup> *Paul Scherrer Institute (CH)*

<sup>2</sup> *CSIC (Madrid, ES)*

<sup>3</sup> *Deutsches Elektronen-Synchrotron (DE)*

**Corresponding Author:** emanuele.angelo.bagnaschi@cern.ch

The electroweak (EW) sector of the Minimal Supersymmetric Standard Model (MSSM) naturally provides a cold dark matter candidate, the neutralino, and it is also able to explain current experimental observations and evade existing constraints.

In particular the EW sector of the MSSM can explain the discrepancy between the experimental result for the anomalous magnetic moment of the muon and its Standard Model prediction.

Using the recent results from the FNAL  $g-2$  experiment, and focusing on the phenomenology of the EW sector of the MSSM only (i.e. assuming that the colored sector is heavy, in agreement with the current experimental limits) we study the correlation between the  $g-2$  and MW predictions in the MSSM, while keeping into account collider and DM constraints.

We also study the impact that future MW measurements, e.g. at the ILC, could have in shaping the bounds of the allowed parameter space of the MSSM.

**Electroweak, Top quark, and Higgs Physics / 211**

## Techniques for the SUSY-QCD corrections to pseudoscalar Higgs production via gluon fusion

**Authors:** Thanh Tien Dat Nguyen<sup>1</sup>; Jens Spira Michael<sup>2</sup>; Liebler Stefan Rainer<sup>3</sup>; Lukas Fritz<sup>4</sup>; Milada Margarete Mühlleitner<sup>3</sup>

<sup>1</sup> *Karlsruhe Institute of Technology*

<sup>2</sup> *Paul Scherrer Institute*

<sup>3</sup> *KIT - Karlsruhe Institute of Technology (DE)*

<sup>4</sup> *Paul Scherrer Institut*

**Corresponding Author:** faregas2007@gmail.com

We present the technical methods for the NLO SUSY-QCD corrections to the production of the pseudoscalar MSSM Higgs boson in the gluon

fusion channel. While the genuine SUSY-QCD corrections have been calculated in the limit of large SUSY particle masses some while ago, the finite mass effects are unknown. In this talk, I will present the technical details of our calculation of the NLO SUSY-QCD corrections including the full mass dependence of the loop particle masses. Since analytic formulae for the massive two-loop integrals of the virtual corrections are unknown the calculation is performed numerically. The details of the computation will be presented including the treatment of the threshold regions for numerical stability by IBP methods. Our consistent renormalization scheme worked out for the quark/squark sector and applied in the calculation will be explained in detail.

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## NLO SUSY-QCD Corrections to Pseudoscalar Production via Gluon Fusion

**Authors:** Emanuele Angelo Bagnaschi<sup>1</sup>; Lukas Fritz<sup>2</sup>; Michael Spira<sup>1</sup>; Milada Margarete Mühlleitner<sup>None</sup>; Stefan Rainer Liebler<sup>3</sup>; Thanh Tien Dat Nguyen<sup>4</sup>

<sup>1</sup> *Paul Scherrer Institute (CH)*

<sup>2</sup> *Paul Scherrer Institut*

<sup>3</sup> *KIT - Karlsruhe Institute of Technology (DE)*

<sup>4</sup> *ICISE*

**Corresponding Author:** lukas.fritz@psi.ch

In this talk I will present the genuine SUSY-QCD corrections to the production of the pseudoscalar Higgs boson in the Minimal Supersymmetric Standardmodel (MSSM). These corrections have been numerically calculated with no expansion in the mass ratios. A comparison to existing approximations is done in order to see how significant the effects beyond these approximations are. The (consistent) treatment of  $\gamma_5$  is discussed. The genuine SUSY-QCD corrections can be large in several MSSM benchmark scenarios and are supplemented by sizeable contributions beyond the previously known approximations.

**Electroweak, Top quark, and Higgs Physics / 164**

## Electroweak physics and Z/W boson measurements at LHCb

**Authors:** LHCb Collaboration<sup>None</sup>; Miguel Ramos Pernas<sup>1</sup>

<sup>1</sup> *University of Warwick (GB)*

**Corresponding Author:** miguel.ramos.pernas@cern.ch

The LHCb experiment covers the forward region of proton-proton collisions, and it can improve the current electroweak landscape by studying the production of W and Z boson in this phase space complementary to ATLAS and CMS. In this talk an overview of the wide LHCb electroweak measurement program will be presented. Several preliminary studies have shown the potential of the LHCb experiment to measure the W boson mass with a muon pT based technique, which could yield a statistical precision of 10 MeV if using the full Run 2 dataset.

A proof-of-concept measurement of the W boson mass, using only the 2016 dataset, will be presented, together with a measurement of the angular coefficients of Z boson decays.

**Electroweak, Top quark, and Higgs Physics / 429**

## **SM precision measurements in top production at LHC**

**Author:** Lorenzo Massa<sup>1</sup>

<sup>1</sup> *Universita e INFN, Bologna (IT)*

**Corresponding Author:** lorenzo.massa@cern.ch

Measurements of top quark cross sections and properties using data collected by the ATLAS and CMS experiment at 13 TeV are presented. Among them, latest precision results on production cross sections, top mass, angular correlations and charge asymmetries will be discussed.

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## **Vector boson scattering in CMS**

**Author:** Miao Hu<sup>1</sup>

<sup>1</sup> *Massachusetts Inst. of Technology (US)*

**Corresponding Author:** miao.hu@cern.ch

In this talk, vector boson scattering measurements performed by the CMS experiment will be presented. In addition to standard model measurements, some explanation of its application to search for new physics will also be shown.

**Electroweak, Top quark, and Higgs Physics / 260**

## **Search for a Higgs portal scalar decaying in MicroBooNE**

**Author:** Pawel Guzowski<sup>1</sup>

<sup>1</sup> *University of Manchester*

**Corresponding Author:** pawel.guzowski@manchester.ac.uk

The MicroBooNE detector is an 85-ton liquid argon time projection chamber that has been operating in Fermilab's neutrino beamlines since 2015. Although primarily designed to measure neutrino interactions, the high intensity meson beamlines coupled with the high resolution detector and excellent high-multiplicity electron, muon or pion identification, allows for searches for New Physics in rare meson decays. In the Higgs portal model a new scalar boson mixes with the Higgs boson. The scalar boson can be produced in kaon decays, and decay to lepton or pion pairs. This model attracted some interest due to its ability to explain an excess of neutral kaon decays reported by the KOTO experiment in 2019. In this talk I will present recent MicroBooNE competitive limits on the Higgs portal scalar model.

**Electroweak, Top quark, and Higgs Physics / 454**

## **Performance and calibration for the identification of boosted Higgs bosons decaying into beauty quark pairs in ATLAS**

**Author:** Changqiao Li<sup>1</sup>

<sup>1</sup> *Shanghai Jiao Tong University (CN)*

**Corresponding Author:** changqiao.li@cern.ch

The physics programme at ATLAS involves a variety of Standard Model and Beyond Standard Model resonances decaying to two b quarks, including the Higgs Boson. In order to identify these resonances at high momentum, ATLAS has developed the boosted  $X \rightarrow b\bar{b}$  tagger, a new NN-based tagging algorithm which combines the flavour information of up to three sub-jets associated to the large-R jet capturing the decays of these particles. This talk presents the Monte Carlo performance for the boosted  $X \rightarrow b\bar{b}$  tagger and the corresponding calibration strategy using the full Run-2 dataset gathered by ATLAS and comparing to simulation. Foreseen results include the signal tagging efficiencies derived using  $Z \rightarrow b\bar{b} + \text{jets}$  and  $Z \rightarrow b\bar{b} + \text{gamma}$  events, and background mistag rates measured using  $t\bar{t}$  and  $g \rightarrow b\bar{b}$  splitting in multi-jet events.

**Flavor Physics and CP Violation / 393**

## Analysis of $B_c \rightarrow D^{(*)} \tau \bar{\nu}_\tau$ processes

**Authors:** Anupama Bhol<sup>1</sup>; Suchismita Sahoo<sup>2</sup>; Soram Robertson Singh<sup>3</sup>

<sup>1</sup> *Govt. Women's College Baripada-757001, India*

<sup>2</sup> *Central University of Karnataka*

<sup>3</sup> *Manipur University*

**Corresponding Author:** suchismita8792@gmail.com

We present a comprehensive study on rare semileptonic  $B_c \rightarrow D^{(*)} \tau \bar{\nu}_\tau$  decays involving  $b \rightarrow u \tau \bar{\nu}_\tau$  quark level transitions in an effective field theory approach. We consider the presence of an additional (pseudo)vector and (pseudo)scalar type interactions which can be either complex or real and constrain the new couplings using the existing data on  $R_{D^{(*)}}$ ,  $R_{J/\psi}$ ,  $R_\pi^l$ ,  $\text{Br}(B_{u,c} \rightarrow \tau \bar{\nu}_\tau)$  and  $\text{Br}(B \rightarrow \pi \tau \bar{\nu}_\tau)$  parameters. In order to segregate the sensitivity of new coefficients, we check the effects of these couplings on the branching ratios, lepton non-universality and various angular observables of  $B_c \rightarrow D^{(*)} \tau \bar{\nu}_\tau$  processes.

**Flavor Physics and CP Violation / 6**

## Flavour Anomalies at LHCb

**Corresponding Author:** miriam.lucio.martinez@cern.ch

The flavour anomalies in the  $b \rightarrow sll$  transition receive large attention. Apart from the recent update on lepton-flavour-universality, LHCb has new results on the rare decay  $B_s \rightarrow \mu\mu$ , angular distributions of charged B mesons decaying to  $K\mu\mu$  and  $Phimumu$ , and analyses of radiative and B decays to  $Kee$  at low- $q^2$ , and most recently on the  $B_s \rightarrow Phimumu$  decay rate with full run-2 data.

**Flavor Physics and CP Violation / 237**

## Semileptonic B decays and related study at Belle

**Author:** Youngjoon Kwon<sup>1</sup>

<sup>1</sup> *Yonsei University*

**Corresponding Author:** yjkwon63@yonsei.ac.kr

Though the Belle experiment has stopped data taking more than a decade ago, new results on  $B$  meson decays are still being obtained. This is in part due to new experimental tools elaborated for Belle II applied to the Belle data set, such as the FEI (Full Event Interpretation) hadronic and semileptonic tag which enables new measurements of  $B \rightarrow D^* \ell \nu$ ,  $B \rightarrow D^{**} \ell \nu$  and  $B \rightarrow X \ell \nu$ . Other analyses are motivated by the progress in theory such as the measurement of  $q^2$  moments in  $B \rightarrow X_c \ell \nu$ , which allows for a determination of  $|V_{cb}|$  up to the order  $1/m_b^4$ . The talk covers the study of semileptonic  $B$  decay results and related analyses, such as a new high-precision test of QCD factorisation with  $\mathcal{B}(\bar{B}^0 \rightarrow D^{(*)+} \pi^-)$  and  $\mathcal{B}(\bar{B}^0 \rightarrow D^{(*)+} K^-)$ , with Belle data set.

**Flavor Physics and CP Violation / 113**

## Imprint of SUSY in radiative B-meson decays

**Authors:** Helmut Eberl<sup>1</sup>; Keisho Hidaka<sup>2</sup>; Elena Ginina<sup>1</sup>; Akimasa Ishikawa<sup>3</sup>

<sup>1</sup> *HEPHY, Vienna*

<sup>2</sup> *Tokyo Gakugei University*

<sup>3</sup> *IPNS, KEK*

**Corresponding Author:** hidaka@u-gakugei.ac.jp

We study the supersymmetric (SUSY) effects on  $C_7(\mu_b)$  and  $C_7'(\mu_b)$  which are the Wilson coefficients (WC) for  $b \rightarrow s \gamma$  at  $b$  quark mass scale  $\mu_b$  and are closely related to radiative B meson decays. The SUSY-loop contributions to  $C_7(\mu_b)$  and  $C_7'(\mu_b)$  are calculated at leading order (LO) in the Minimal Supersymmetric Standard Model (MSSM) with general quark flavor violation (QFV). For the first time we perform a systematic MSSM parameter scan for the WCs  $C_7(\mu_b)$  and  $C_7'(\mu_b)$  respecting all the relevant constraints, i.e. the theoretical constraints from vacuum stability conditions and the experimental constraints, such as those from  $K$ - and  $B$ -meson data and electroweak precision data, as well as recent limits on SUSY particle masses and the 125 GeV Higgs boson data from LHC experiments. From the parameter scan, we find the following:

- (1) The MSSM contribution to  $\text{Re}(C_7(\mu_b))$  can be as large as  $\sim \pm 0.05$  which could correspond to about  $3\sigma$  significance of New Physics (NP) signal in the future LHCb-Upgrade and Belle II experiments.
- (2) The MSSM contribution to  $\text{Re}(C_7'(\mu_b))$  can be as large as  $\sim -0.08$  which could correspond to about  $4\sigma$  significance of NP signal in the future LHCb-Upgrade and Belle II experiments.
- (3) These large MSSM contributions to the WCs are mainly due to (i) large scharm-stop mixing and large scharm/stop involved trilinear couplings  $T_{U23}$ ,  $T_{U32}$  and  $T_{U33}$ , (ii) large sstrange-sbottom mixing and large sstrange-sbottom involved trilinear couplings  $T_{D23}$ ,  $T_{D32}$  and  $T_{D33}$  and (iii) large bottom Yukawa coupling  $Y_b$  for large  $\tan \beta$  and large top Yukawa coupling  $Y_t$ .

In case such large NP contributions to the WCs are really observed in the future experiments at Belle II and LHCb-Upgrade, this could be the imprint of QFV SUSY (the MSSM with general QFV) and would encourage to perform further studies of the WCs  $C_7'(\mu_b)$  and  $C_7^{MSSM}(\mu_b)$  at higher order (NLO/NNLO) level in this model.

Note: This work is based on collaboration with Helmut Eberl, Elena Ginina (HEPHY, Vienna) and Akimasa Ishikawa (Belle II, KEK).  
Reference: arXiv:2106.15228 [hep-ph] (under submission to a journal)

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## Results and Prospects of Radiative and Electroweak Penguin Decays at Belle II

Author: Yo Sato<sup>1</sup>

<sup>1</sup> KEK IPNS

Corresponding Author: yosato@post.kek.jp

In the recent years, several measurements of  $B$ -decays with flavor changing neutral currents, i.e.  $b \rightarrow s$  transitions hint at deviations from the Standard Model (SM) predictions. These decays are forbidden at tree-level in the SM and can only proceed via suppressed loop level or box diagrams. Rare decays of  $B$  mesons are an ideal probe to search for phenomena beyond the SM, since contributions from new particles can affect the decays on the same level as SM particles.

The Belle II experiment is a substantial upgrade of the Belle detector and operates at the SuperKEKB energy-asymmetric  $e^+e^-$  collider. Radiative  $b \rightarrow s\gamma$  decays is already been observed and inclusive photon spectra is also obtained with only a small dataset of Belle II. Early measurements related to the electro-weak penguin  $b \rightarrow s\ell\ell$  and  $b \rightarrow s\nu\bar{\nu}$  decays has also been performed. We will discuss the results obtained with the current dataset along with the prospects for the searches of these radiative and electroweak penguin decays with the expected  $50 ab^{-1}$  full dataset of Belle II.

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## Mixing and CP violation at LHCb

Corresponding Author: adam.davis@cern.ch

The latest results of beauty and charm meson decays from LHCb are presented. This includes the latest time-integrated CP violation measurements with information on the  $(K\pi)$  puzzle and on the CKM angle  $\gamma$ , and time-dependent CP violation measurements. In addition recent determinations of CKM elements, the legacy result on  $B_s$  mixing, and the first observation of the mass difference in the  $D_0$  system will be discussed.

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## Measurement of the very rare $K^+$ to $\pi^+$ $\nu\bar{\nu}$ decay

Corresponding Author: zuzana.kucerova@cern.ch

The decay  $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ , with a very precisely predicted branching ratio of less than  $10^{-10}$ , is among the best processes to reveal indirect effects of new physics.

The NA62 experiment at CERN SPS is designed to study the  $K^+ \rightarrow \pi^+ \nu\bar{\nu}$  decay and to measure its branching ratio using a decay-in-flight technique. NA62 took data in 2016, 2017 and 2018, reaching the sensitivity of the Standard Model for the  $K^+ \rightarrow \pi^+ \nu\bar{\nu}$  decay by the analysis of the 2016 and 2017 data, and providing the most precise measurement of the branching ratio to date by the analysis of

the 2018 data. This measurement is also used to set limits on  $\text{BR}(K^+ \rightarrow \pi^+ X)$ , where  $X$  is a scalar or pseudo-scalar particle.

The final result of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  branching ratio measurement and its interpretation in terms of  $K^+ \rightarrow \pi^+ X$  decay from the analysis of the full 2016-2017-2018 data set is presented, and future plans and prospects reviewed.

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### Search for lepton number and flavour violation in $K^+$ and $\pi^0$ decays

**Corresponding Author:** lubos.bician@cern.ch

The NA62 experiment at CERN collected a large sample of charged kaon decays into final states with multiple charged particles in 2016-2018. This sample provides sensitivities to rare decays with branching ratios as low as  $10^{-11}$ .

Results from searches for lepton flavour/number violating decays of the charged kaon and the neutral pion to final states containing a lepton pair based on this data set are presented.

#### Flavor Physics and CP Violation / 124

### Search for $\pi^0$ decays to invisible particles at the NA62 experiment

**Corresponding Author:** akleimen@cern.ch

A study of a sample of  $4 \cdot 10^9$  tagged  $\pi^0$  mesons from  $K^+ \rightarrow \pi^+ \pi^0 (\gamma)$  is performed at the NA62 experiment at CERN, searching for the decay of the  $\pi^0$  to invisible particles. No signal is observed in excess of the expected background fluctuations. An upper limit of  $4.4 \cdot 10^{-9}$  is set on the branching ratio at 90% C.L. improving on previous results by a factor of 60.

#### Flavor Physics and CP Violation / 126

### New measurement of radiative decays at the NA62 Experiment at CERN

**Corresponding Author:** dmitry.madigozhin@cern.ch

The NA62 experiment at CERN reports new results from studies of radiative kaon decays  $K^+ \rightarrow \pi^0 e^+ \nu_e (\text{Ke}3\gamma)$ , using a data sample recorded in 2017-2018. The sample comprises  $O(100k)$   $\text{Ke}3\gamma$  candidates with sub-percent background contaminations. Preliminary results with the most precise measurement of the and branching ratios and T-asymmetry measurement in the  $\text{Ke}3\gamma$  decay, are presented.

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## Physics Reach of Rare Charm Baryon Decays

**Authors:** Gudrun Hiller<sup>1</sup>; Marcel Golz<sup>1</sup>; Tom Magorsch<sup>1</sup>

<sup>1</sup> *TU Dortmund*

**Corresponding Author:** marcel.golz@tu-dortmund.de

Rare  $|\Delta c| = |\Delta u| = 1$  processes constitute unique flavor probes in the up-sector of the Standard Model. Semileptonic FCNC decays of charmed baryons, such as  $\Lambda_c \rightarrow p\mu^+\mu^-$ , offer a large set of clean null test observables such as CP-asymmetries, lepton-universality ratios, missing energy modes, lepton flavor violating modes and angular observables. In these observables any signal cleanly indicates Physics Beyond the Standard Model. A variety of rare charm baryon modes exists ( $\Lambda_c \rightarrow p\mu^+\mu^-$ ,  $\Xi_c^{0,+} \rightarrow \Sigma^{0,+}\mu^+\mu^-$ ,  $\Xi_c^0 \rightarrow \Lambda^0\mu^+\mu^-$ ,  $\Omega_c^0 \rightarrow \Xi^0\mu^+\mu^-$ ) and complements similar analyses of charmed meson decays.

Along with sizable charm production rates at current flavor facilities, null test searches provide a formidable road in the search for New Physics scenarios, such as leptoquarks,  $Z'$ - or SUSY-models. We present an overview of null test opportunities with rare charm baryon decays and give sensitivities to New Physics contributions.

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## Lattice QCD results on the hadronic contributions to the muon g-2

**Author:** Luchang Jin<sup>1</sup>

<sup>1</sup> *UCONN / RBRC*

**Corresponding Author:** ljin.luchang@gmail.com

Fermilab has just announced a new experimental result for muon g-2. The statistical uncertainty of the new result is similar to the previous BNL result and the central value is consistent. The combined value is now 4.2 standard deviation away from the Standard Model prediction. For the Standard Model prediction, the two hadronic contributions, HVP (hadronic vacuum polarization) and HLbL (hadronic light-by-light) are the dominant sources of uncertainty. I will review the lattice calculations in determining these two hadronic contributions.

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## Solving flavor anomalies in the 2HDM with flavor symmetries

**Author:** Fanrong Xu<sup>1</sup>

<sup>1</sup> *Jinan University*

**Corresponding Author:** fanrongxu@jnu.edu.cn

The  $3.1\sigma R_K$  anomaly after Moriond 2021 and  $3.3\sigma \Delta a_\mu$  from Fermilab Muon g-2 Experiment implicate that the lepton flavor universality violation (LFUV) may play a role in the exploration of new physics. Aiming at solving these flavor anomalies both in quark and lepton sectors, a specific Two-Higgs Doublet Model (2HDM) with particular U(1) gauge symmetry, which is designed to get rid of the redundancy in generic 2HDM-III Yukawa couplings, is proposed and investigated. Among three additional new particles in the flavor gauged 2HDM, FCNC processes can be induced by heavy neutral scalar and  $Z'$  only in down-type quark sector, which provide solutions to anomalies in  $b \rightarrow s\ell\bar{\ell}$

and anomalous magnetic dipole moment (AMDM) for leptons. The charged Higgs, on the other hand, explains anomalies in  $b \rightarrow c\ell\nu$  processes. Combining other typical flavor observables, the allowed parameter space for explaining all the three different types of flavor anomalies, within one consistent UV-complete model, can be obtained.

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## A Flavorful Composite Higgs Model : Connecting B anomalies with the hierarchy problem

Author: Yi Chung<sup>1</sup>

<sup>1</sup> University of California, Davis

Corresponding Author: yichung@ucdavis.edu

Lack of new states at the TeV scale challenges all kinds of solutions to the hierarchy problem but the current B anomalies might be a new guidance. One possible solution to the neutral current B anomalies is a TeV-scale  $Z'$  boson of the broken  $U(1)_F$  gauged flavor symmetry, which might imply the connection between the two problems. In this talk, I will realize this idea based on a  $SU(4)/Sp(4)$  composite Higgs model. The symmetry breaking by the strong dynamics introduces the composite Higgs doublet as pseudo-Nambu-Goldstone bosons. At the same time, the  $U(1)_F$  gauged flavor symmetry as a subgroup of  $SU(4)$  is also broken by the strong dynamics, which introduced a  $Z'$  boson at the TeV scale as desired. The allowed parameter space to explain the B anomalies without violating other experimental constraints is probed. The UV origin of the  $U(1)_F$  flavor symmetry will also be discussed.

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## New physics in $b \rightarrow se^+e^-$ : A model independent analysis

Authors: Ashutosh Alok<sup>1</sup>; Suman Kumbhakar<sup>2</sup>; Jyoti Saini (P15PH002)<sup>None</sup>; Sankagiri Umasankar<sup>3</sup>

<sup>1</sup> IIT Jodhpur

<sup>2</sup> IISc Bangalore

<sup>3</sup> IIT Bombay

Corresponding Author: suman@phy.iitb.ac.in

The lepton universality violating flavor ratios  $R_K/R_{K^*}$  indicate new physics either in  $b \rightarrow s\mu^+\mu^-$  or in  $b \rightarrow se^+e^-$  or in both. If the new physics is only  $b \rightarrow se^+e^-$  transition, the corresponding new physics operators, in principle, can have any Lorentz structure. In this work, we perform a model independent analysis of new physics only in  $b \rightarrow se^+e^-$  decay by considering effective operators either one at a time or two similar operators at a time. We include all the measurements in  $b \rightarrow se^+e^-$  sector along with  $R_K/R_{K^*}$  in our analysis. We show that various new physics scenarios with vector/axial-vector operators can account for  $R_K/R_{K^*}$  data but those with scalar/pseudoscalar operators and with tensor operators can not. We also show that the azimuthal angular observable  $P_1$  in  $B \rightarrow K^*e^+e^-$  decay is most suited to discriminate between the different allowed solutions.

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## Angular Distribution of polarised $\Lambda_b$ decay with NP operators

**Author:** RIA SAIN<sup>1</sup>**Co-author:** Diganta Das<sup>2</sup><sup>1</sup> *INSTITUTE OF MATHEMATICAL SCIENCES*<sup>2</sup> *IIT Hyderabad***Corresponding Author:** riasain@imsc.res.in

The recent anomalies in  $b \rightarrow s\ell^+\ell^-$  transitions could originate from some New Physics beyond the Standard Model. Either to confirm or to rule out this assumption, more tests of  $b \rightarrow s\ell^+\ell^-$  transition are needed.

$\Lambda_b \rightarrow \Lambda\ell^+\ell^-$  decay provides us complimentary information of this mode in contrast to the mesonic decay. We will discuss how the polarized  $\Lambda_b$  decay to a  $\Lambda$  and a dilepton pair offers a plethora of observables that are suitable to discriminate New Physics from the Standard Model. In this talk, we will give an overview of how the angular distribution of the  $\Lambda_b$  decay is calculated and present a full angular analysis of a polarized  $\Lambda_b$  decay to a  $\Lambda(\rightarrow p\pi)\ell^+\ell^-$  final state.

The full angular analysis performed with new scalar and pseudo-scalar operators supplemented with the Standard Model operator basis provides us with 2 new observables which were not present while considering only SM and its chirality flipped counterparts. The full angular distribution is calculated by retaining the mass of the final state leptons. At the low hadronic recoil, we use the Heavy Quark Effective Theory framework to relate the hadronic form factors which lead to simplified expression of the angular observables where short- and long-distance physics factorize. Using the factorized expressions of the observables, we construct a number of test of short- and long-distance physics including null tests of the Standard Model and its chirality flipped counterparts that can be carried out using experimental data. We provide the

the expected experimental precision on these angular observables achievable at the future LHCb. This is mainly based on the paper "Phys.Rev.D 104 (2021) 1, 013002".

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### A closer look at the extraction of $|V_{ub}|$ from $b \rightarrow \pi l \nu$

**Authors:** Aritra Biswas<sup>1</sup>; Ipsita Ray<sup>1</sup>; Soumitra Nandi<sup>1</sup>; Sunando Kumar Patra<sup>2</sup><sup>1</sup> *IIT Guwahati*<sup>2</sup> *Bangabasi Evening College***Corresponding Author:** ipsitaray02@gmail.com

To extract the Cabibbo-Kobayashi-Maskawa (CKM) matrix element  $|V_{ub}|$ , we have re-analyzed all the available inputs (data and theory) on the  $b \rightarrow \pi l \nu$  decays including the newly available inputs on the form-factors from light cone sum rule (LCSR) and Lattice QCD (LQCD) approach. We have commented on the effect of outliers on the fits. After removing the outliers and creating a comparable group of data-sets, we mention a few scenarios in the extraction of  $|V_{ub}|$ . Our best results for  $|V_{ub}|^{exc.}$  are  $(3.94 \pm 0.14) \times 10^{-3}$  and  $(3.93^{+0.14}_{-0.15}) \times 10^{-3}$  in frequentist and Bayesian approaches, respectively, which are consistent with the most recent inclusive determination by Belle within  $1\sigma$  confidence interval.

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### Explaining the Cabibbo Angle Anomaly

**Author:** Claudio Andrea Manzari<sup>1</sup><sup>1</sup> *Universitaet Zuerich (CH)*

**Corresponding Author:** claudio.andrea.manzari@cern.ch

The first row of the Cabibbo-Cobayashi-Maskawa (CKM) matrix shows a discrepancy of  $\sim 3\sigma$  with unitarity, known as the "Cabibbo Angle Anomaly" (CAA). After reviewing the origin and status of the anomaly, I investigate the various possibilities to explain it in the context of physics beyond Standard Model (BSM) which can be broadly grouped into three categories: modifications of four-fermion contact operators, modifications of the leptonic W vertices and modifications of the W vertices with quarks. In addition, I also discuss the phenomenological implications in the electroweak (EW) precision observables and low energy observables testing lepton flavour universality (LFU) which have to be taken into account in order to assess the viability of these solutions. Then, I review concrete realizations of BSM physics proposed to solve the CAA, which highlight the correlation with other existing anomalies such as  $b \rightarrow s\ell\ell$  and  $\tau \rightarrow \mu\nu\nu$ , providing interesting predictions to be tested experimentally in the near future.

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## $B \rightarrow K\nu\bar{\nu}$ measurements and beyond the Standard Model theories

**Author:** Rusa Mandal<sup>1</sup>

**Co-authors:** Nilendra Deshpande<sup>2</sup>; Rahul Sinha<sup>3</sup>; Thomas Browder<sup>4</sup>

<sup>1</sup> *Siegen University*

<sup>2</sup> *University of Oregon*

<sup>3</sup> *The Institute of Mathematical Sciences*

<sup>4</sup> *University of Hawaii*

**Corresponding Author:** rusa.mandal@gmail.com

Semileptonic flavor changing neutral current transitions with a pair of neutrinos in the final state are very accurately determined in the standard model. The most recent Belle II result on  $B \rightarrow K\nu\bar{\nu}$  uses an innovative inclusive tagging technique; this together with previous BaBar and Belle results indicates a possible enhancement in the branching fraction of  $B^+ \rightarrow K^+\nu\bar{\nu}$ . We have explored the possibilities of such an enhancement as a signal of new physics within several scenarios such as leptoquark and generic  $Z'$  models, which can also explain some of the other tensions observed in neutral as well as charged current  $B$ -decays.

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## ATLAS measurements of CP violation and rare decays processes with beauty mesons

**Corresponding Author:** maria.smizanska@cern.ch

The ATLAS experiment has performed measurements of B-meson rare decays proceeding via suppressed electroweak flavour changing neutral currents, and of mixing and CP violation in the neutral  $B_s$  meson system.

This talk will focus on the latest results from the ATLAS collaboration, such as rare processes  $B^0_s \rightarrow \mu\mu$  and  $B^0 \rightarrow \mu\mu$ , and CP violation in the  $B_s^0 \rightarrow J/\psi\phi$  decays. In the latter, the Standard Model predicts the CP violating mixing phase,  $\phi_s$ , to be very small and its SM value is very well constrained, while in many new physics models large  $\phi_s$  values are expected. The latest measurements of  $\phi_s$  and several other parameters describing the  $B_s^0 \rightarrow J/\psi\phi$  decays will be reported.

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## **QCD corrections to Bs mixing in leptoquark models**

**Authors:** Andreas Crivellin<sup>1</sup>; Javier Virto<sup>2</sup>; Jordi Folch Eguren<sup>3</sup>

<sup>1</sup> *PSI*

<sup>2</sup> *University of Barcelona*

<sup>3</sup> *University of Barcelona/TU Dortmund*

**Corresponding Author:** jfoeeg@gmail.com

Scalar Leptoquark models can explain the current anomalies in B physics. However, one of the main constraints on these models comes from Bs-mixing.

We analyse the QCD corrections to the Bs-mixing process within a scalar leptoquark model, going at 2-loop level. In order to examine the effect of this process we use a low energy EFT, and compute the Wilson coefficients at NLO.

**Flavor Physics and CP Violation / 315**

## **New Physics Implications of LHCb Data on b to s transitions**

**Author:** Nazila Mahmoudi<sup>1</sup>

<sup>1</sup> *Lyon University*

**Corresponding Author:** nazila@cern.ch

We present new physics implications of LHCb measurements of bsll observables within a model-independent approach and make projections for future measurements that indicate that LHCb will be in the position to discover lepton non-universality with the Run 3 data in a single observable. Moreover, we present global fits of rare B-decays within multidimensional fits involving up to all the relevant 20 Wilson coefficients and compare different scenarios via likelihood ratio tests, applying Wilks' theorem.

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## **A Supersymmetric Solution to the $R_{K^{(*)}}$ Anomalies**

**Author:** Mustafa Tabet<sup>None</sup>

**Co-author:** Ulrich Nierste

**Corresponding Author:** mustafa.tabet@kit.edu

The latest measurement of the ratio  $R_K$  at LHCb provides evidence for lepton flavour non-universal interactions beyond the Standard Model.

A popular extension of the Standard Model is the R-parity conserving Minimal Supersymmetric Standard Model (MSSM), however, it is widely claimed in the literature that an explanation of these anomalies is not possible within this model.

In this talk, I will show contrary to the claims that it is not only possible to relax the tensions, but also to explain the longstanding (g-2) anomaly of the muon at the same time.

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## Potential Signatures and Combined Constraints for First Generation Leptoquarks

**Authors:** Andreas Crivellin<sup>1</sup>; Luc Schnell<sup>2</sup>

<sup>1</sup> *PSI*

<sup>2</sup> *ETH Zurich, École Polytechnique de Paris, LPTHE Sorbonne Université*

**Corresponding Author:** luschnel@student.ethz.ch

We present potential signatures and combined constraints for leptoquarks which couple to first generation fermions, considering both low energy precision observables and LHC direct searches. Including all ten leptoquark representations, five scalar and five vector ones, we study at the precision frontier the constraints from  $K \rightarrow \pi \nu \nu$ ,  $K \rightarrow \pi e^+ e^-$ ,  $K^0 - \bar{K}^0$  and  $D^0 - \bar{D}^0$  mixing, as well as from experiments sensitive to parity-violating interactions (APV, QWEAK and COHERENT). We include LHC searches for  $s$ -channel single resonant production, pair production and Drell-Yan-like signatures of leptoquarks. Particular emphasis is placed on the recent CMS analysis of lepton flavour universality violation in non-resonant di-lepton pairs. The excess in electron events could be a hint at first generation leptoquarks,  $t$ -channel contributions from  $\tilde{S}_1, S_2, S_3, \tilde{V}_1, V_2$  ( $\kappa_2^{RL} \neq 0$ ) and  $V_3$  can explain the excess without violating other bounds. Regarding the so-called ‘‘Cabibbo angle anomaly’’, we observe that the present constraints are too restrictive to allow for a resolution via direct leptoquark contributions to super-allowed beta decays.

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## Planck-safe U(1)’ Extensions Explaining RK(\*)

**Authors:** Rigo Bause<sup>1</sup>; Gudrun Hiller<sup>2</sup>; Tim Höhne<sup>1</sup>; Daniel Litim<sup>3</sup>; Tom Steudtner<sup>1</sup>

<sup>1</sup> *TU Dortmund*

<sup>2</sup> *Technische Universität Dortmund (DE)*

<sup>3</sup> *University of Sussex*

**Corresponding Author:** tim.hoehne@tu-dortmund.de

We report on a new class of flavorful  $Z'$ -extensions of the standard model, which explain the recent hints for lepton universality violation in  $R_{K^{(*)}}$ -data.

The models feature new vector-like fermions as well as additional scalar fields around the electroweak scale or above.

On top of well-known theoretical and phenomenological constraints, we require stable and Landau-pole free coupling constant evolution up to the Planck scale.

We identify viable ‘‘Planck safe’’ benchmark scenarios and discuss phenomenological implications.

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## A Supersymmetric Flavor Clockwork

**Authors:** Sri Aditya Gadam<sup>1</sup>; Wolfgang Altmannshofer<sup>2</sup>

<sup>1</sup> *University of California, Santa Cruz*

<sup>2</sup> *UC Santa Cruz (SCIPP)*

**Corresponding Author:** sgadam@ucsc.edu

Clockwork models can explain the flavor hierarchies in the Standard Model quark and lepton spectrum.

We construct supersymmetric versions of such flavor clockwork models. The zero modes of the clockwork are identified with the fermions and sfermions of the Minimal Supersymmetric Standard Model. In addition to generating a hierarchical fermion spectrum, the clockwork also predicts a specific flavor structure for the soft SUSY breaking sfermion masses. We find sizeable flavor mixing among first and second generation squarks. Constraints from Kaon oscillations require the masses of either squarks or gluinos to be above a scale of  $\sim 3$  PeV.

**Flavor Physics and CP Violation / 215**

## Stringy origin of modular flavor symmetry and spontaneous CP violation

**Author:** Hajime Otsuka<sup>1</sup>

**Co-authors:** Tatsuo Kobayashi<sup>2</sup>; Keiya ISHIGURO<sup>3</sup>

<sup>1</sup> KEK, Tsukuba

<sup>2</sup> Hokkaido University

<sup>3</sup> Tsukuba, Graduate U. Adv. Studies (SOKENDAI)

**Corresponding Author:** hotsuka@post.kek.jp

We examine a common origin of four-dimensional flavor, CP, and  $U(1)_R$  symmetries in the context of heterotic string theory with standard embedding. We find that flavor and  $U(1)_R$  symmetries are unified into the  $Sp(2h+2, \mathbb{C})$  modular symmetries of Calabi-Yau threefolds with  $h$  being the number of moduli fields. Together with the  $\mathbb{Z}_2^{\text{CP}}$  CP symmetry, they are enhanced to  $GSp(2h+2, \mathbb{C})$  generalized symplectic modular symmetry.

We exemplify the  $S_3, S_4, T', S_9$  non-Abelian flavor symmetries on explicit toroidal orbifolds with and without resolutions and  $\mathbb{Z}_2, S_4$  flavor symmetries on three-parameter examples of Calabi-Yau threefolds. Thus, non-trivial flavor symmetries appear in not only the exact orbifold limit but also a certain class of Calabi-Yau threefolds. These flavor symmetries are further enlarged to non-Abelian discrete groups by the CP symmetry.

We also discuss the spontaneous CP violation in the context of Calabi-Yau flux compactifications.

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## Taming the $\epsilon_K$ in Little Randall Sundrum Models

**Authors:** Giancarlo D'Ambrosio<sup>None</sup>; Mathew Thomas<sup>1</sup>; Ashwani Kushwaha<sup>2</sup>; Sudhir Kumar Vempati<sup>3</sup>

<sup>1</sup> IISER, Trivandrum

<sup>2</sup> Indian Institute of Science

<sup>3</sup> Centre for High Energy Physics, Indian Institute of Science

**Corresponding Author:** thomas.mathewarun@gmail.com

The Randall Sundrum (RS) models receive significant constraints from the neutral Kaon system. The CP violating observable  $\epsilon_K$ , in Randall Sundrum scenario, requires the lightest KK gluon to be heavier than  $\sim 24$  TeV. The constraint is even stronger in the Little Randall Sundrum models (LRS),  $\sim 32$  TeV. The LRS models are motivated for their possible visibility at the Large Hadron Collider (LHC). We show that the stringent constraints from K-physics can be

relaxed in the LRS models, in the presence of the Brane Localised Kinetic Terms (BLKT). In particular, for a range of values, a UV BLKT could significantly modify the lightest KK gluon wave function such that the limit can reduce to 5 TeV. We also show that such a relaxation of the constraints can also be achieved by imposing flavour symmetries ‘*ala* Minimal Flavour Protection.

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## Super-Soft CP Violation

**Author:** Alessandro Valenti<sup>1</sup>

**Co-author:** Luca Vecchi<sup>2</sup>

<sup>1</sup> *University of Padua*

<sup>2</sup> *EPFL - Ecole Polytechnique Federale Lausanne (CH)*

**Corresponding Author:** alessandrovalenti.bs@gmail.com

Scenarios assuming an exact CP symmetry in the UV do not suffer quality problems, and are thus interesting alternatives to PQ-based solutions to the Strong CP problem. However, to correctly reproduce the Standard Model quark masses and CP violation these models must feature a non-trivial coincidence between a priori unrelated CP-even and CP-odd mass scales. In this talk we elucidate the origin of this condition and show that it can be naturally addressed by a confining dynamic generated at the Planck scale. This approach is robust and very predictive: it features vector-like quarks below a few 10's of TeV and a dark sector that may lead to interesting cosmological signatures.

**Flavor Physics and CP Violation / 78**

## Anomaly-free leptophilic axionlike particle and its flavor violating tests

**Authors:** Aurora Melis<sup>None</sup>; María Luisa López-Ibáñez<sup>None</sup>; Oscar Manuel Vives Garcia<sup>1</sup>; Chengcheng Han<sup>2</sup>; Jinmin Yang<sup>3</sup>

<sup>1</sup> *Univ. of Valencia and CSIC (ES)*

<sup>2</sup> *SYSU*

<sup>3</sup> *Institute of Theoretical Physics (ITP)*

**Corresponding Author:** oscar.vives@uv.es

Motivated by the Xenon1T result, we study here a leptophilic flavor-dependent anomaly-free axion-like particle (ALP) and its effects on charged-lepton flavor violation. We present two representative models. The first one considers that the ALP originates from the flavon that generates the charged-lepton masses. The second model assumes a larger flavor symmetry such that more general mixings in the charged-lepton are possible, while maintaining flavor-dependent ALP couplings. We find that a keV ALP explaining the Xenon1T result is still viable for lepton flavor violation and stellar cooling astrophysical limits. On the other hand, if the Xenon1T result is confirmed, future charged-lepton flavor violation measurements can be complementary to probe such a possibility.

**Flavor Physics and CP Violation / 16**

## Minimal Froggatt-Nielsen Textures



**Author:** Alessio Mastroddi<sup>1</sup>

<sup>1</sup> INFN - National Institute for Nuclear Physics

**Corresponding Author:** alessio.mastroddi@roma3.infn.it

The flavour problem of the Standard Model can be addressed through the Froggatt-Nielsen (FN) mechanism. In this work, we develop an approach to the study of FN textures building a direct link between FN-charge assignments and the measured masses and mixing angles via unitary transformations in flavour space. We specifically focus on the quark sector to identify the most economic FN models able to provide a dynamical and natural understanding of the flavour puzzle. Remarkably, we find viable FN textures, involving charges under the horizontal symmetry that do not exceed one in absolute value (in units of the flavon charge). Within our approach, we also explore the degree of tuning of FN models in solving the flavour problem via a measure analogous to the Barbieri-Giudice one. We find that most of the solutions do not involve peculiar cancellations in flavour space.

**Flavor Physics and CP Violation / 15**

## Exploring the flavour structure of the high-scale MSSM

**Author:** Sokratis Trifinopoulos<sup>1</sup>

**Co-author:** Gino Isidori<sup>2</sup>

<sup>1</sup> SISSA

<sup>2</sup> Universitaet Zuerich (CH)

**Corresponding Author:** trifinos@yahoo.com

We analyse the sensitivity of quark flavour-changing observables to the MSSM, in a regime of heavy superpartners. We analyse four distinct and motivated frameworks characterising the structure of the soft-breaking terms by means of approximate flavour symmetries. We show that a set of six low-energy observables with realistic chances of improvement in the near future, namely  $\Delta M_{s,d}$ ,  $M_{s,d}$ ,  $\epsilon_K$ ,  $\epsilon'_K/\epsilon_K$ ,  $\mathcal{B}(K \rightarrow \pi\nu\bar{\nu})/\mathcal{B}(K \rightarrow \pi\pi)$ , and the phase of  $D-\bar{D}$  mixing, could play a very important role in characterising these frameworks for superpartner masses up to  $\mathcal{O}(100)$  TeV. We show that these observables remain very interesting even in a long-term perspective, i.e. even taking into account the direct mass reach of the most ambitious future high-energy colliders.

**Flavor Physics and CP Violation / 462**

## Sub-GeV dark matter model: $U(1)_{T3R}$ extension of SM

**Author:** Sumit Ghosh<sup>1</sup>

<sup>1</sup> Texas A & M University

**Corresponding Author:** ghosh@tamu.edu

Scenarios in which right-handed light Standard Model fermions couple to a new gauge group,  $U(1)_{T3R}$  can naturally generate a sub-GeV dark matter candidate. But such models necessarily have large couplings to the Standard Model, generally yielding tight experimental constraints. We show that the contributions to  $g_\mu - 2$  from the dark photon and dark Higgs largely cancel out in the narrow window where all the experimental constraints are satisfied, leaving a net correction which is consistent with recent measurements from Fermilab. These models inherently violate lepton universality, and UV completions of these models can include quark flavor violation which can explain  $R_{K^{(*)}}$  anomalies as observed at the LHCb experiment after

satisfying constraints on  $Br(B_s \rightarrow \mu^+ \mu^-)$  and various other constraints in the allowed parameter space of the model.  
This scenario can be probed by FASER, SeaQuest, SHiP, LHCb, Belle, etc.

**Flavor Physics and CP Violation / 96**

## Systematic approach to $g-2$ , B-anomalies and Dark Matter

**Authors:** Federico Mescia<sup>1</sup>; Giorgio Arcadi<sup>None</sup>; Lorenzo Calibbi<sup>None</sup>; Marco Fedele<sup>2</sup>

<sup>1</sup> *Universitat de Barcelona*

<sup>2</sup> *KIT*

**Corresponding Author:** giorgio.arcadi@uniroma3.it

We discuss a systematic classification of the models with the minimal field content to account for, at the same time, the  $g-2$  anomaly, the ones emerging in decays of B-mesons and, finally, a viable thermal Dark Matter. We will illustrate, in some specific examples, the strong complementarity among flavor and Dark Matter observables.

**Flavor Physics and CP Violation / 81**

## Implications of the Muon $g-2$ in flavour models

**Author:** María Luisa López Ibáñez<sup>None</sup>

**Co-authors:** Oscar Manuel Vives Garcia<sup>1</sup>; Aurora Melis; Lorenzo Calibbi

<sup>1</sup> *Univ. of Valencia and CSIC (ES)*

**Corresponding Author:** maloi2@uv.es

The confirmation of the discrepancy between the Muon  $g-2$  experiment at Fermilab and the Standard Model prediction points to New Physics not far above the TeV scale. Flavour symmetries broken at low energies can account for it, although relevant constraints then arise from flavour-violating observables. Here I discuss the profound implications of this result over the structure of the charged-lepton mass matrix and apply these ideas to several discrete flavour groups popular in the lepton sector.

**Flavor Physics and CP Violation / 311**

## Renormalizable models of flavor-specific scalars

**Authors:** Ahmed Ismail<sup>None</sup>; Ayres Freitas<sup>1</sup>; Brian Thomas Batell<sup>None</sup>; Mudit Rai<sup>1</sup>; David McKeen<sup>2</sup>

<sup>1</sup> *University of Pittsburgh*

<sup>2</sup> *TRIUMF*

**Corresponding Author:** mur4@pitt.edu

New light singlet scalars with flavor-specific couplings represent a phenomenologically distinctive and flavor-safe alternative to the well-studied possibility of Higgs-portal scalars. However, in contrast to the Higgs portal, flavor-specific couplings require an ultraviolet completion involving new

heavy states charged under the Standard Model gauge symmetries, leading to a host of additional novel phenomena. Focusing for concreteness on a scenario with up quark-specific couplings, we investigate two simple renormalizable completions, one with an additional vector-like quark and another featuring an extra scalar doublet. We consider the implications of naturalness, flavor- and CP-violation, electroweak precision observables, and direct searches for the new states at the LHC. These bounds, while being model-dependent, are shown to probe interesting regions in the parameter space of the scalar mass and its low-energy effective coupling, complementing the essential phenomenology of the low-energy effective theory at a variety of low and medium energy experiments.

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## Complementarity of muon charged lepton flavour violating processes in the MRSSM

**Author:** Uladzimir Khasianevich<sup>1</sup>

**Co-authors:** Dominik Stöckinger<sup>1</sup>; Hyejung Stöckinger-Kim<sup>1</sup>; Wojciech Kotlarski<sup>1</sup>

<sup>1</sup> *TU Dresden*

**Corresponding Author:** uladzimir.khasianevich@tu-dresden.de

The Minimal R-symmetric Supersymmetric Standard Model possesses interesting features, which makes it an attractive alternative to the MSSM. Some of them can be observed in and are reflected by the lepton flavour violation processes. Notably, there is no  $\tan\beta$ -enhancement for  $g-2$  of the muon and other dipole operators, resulting in very different predictions for lepton observables compared to the MSSM.

In the view of forthcoming experiments the bounds obtained from muon  $g-2$  and flavour violating observables on the model parameter regions are studied. In particular, we consider the influence of Yukawa-like lambda parameters of the superpotential and the off-diagonal entries of slepton mass matrices. Different scenarios are discussed, depending also on the mass spectra of the model and additional restrictions, imposed by the anomalous magnetic moment of the muon. We focus on the interplay between  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow e$  conversion and  $\mu \rightarrow 3e$  and  $g-2$  of the muon and show that all of these observables are important to constrain the parameter space.

**Flavor Physics and CP Violation / 376**

## Implications of the Muon Anomalous Magnetic Moment for 3-3-1 Models

**Author:** Yoxara Sánchez Villamizar<sup>1</sup>

<sup>1</sup> *IIP & DFTE - Federal University of Rio Grande do Norte (UFRN)*

**Corresponding Author:** yoxarasv@gmail.com

We explore the implications of  $g-2$  new result to five models based on the  $SU(3)_C \times SU(3)_L \times U(1)_N$  gauge symmetry and put our conclusions into perspective with LHC bounds. We show that previous conclusions found in the context of such models change if there are more than one heavy particle running in the loop. Moreover, having in mind the projected precision aimed by the  $g-2$  experiment at FERMILAB, we place lower mass bounds on the particles that contribute to muon anomalous magnetic moment assuming the anomaly is resolved otherwise. Lastly, we discuss how these models could accommodate such anomaly in agreement with existing bounds.

**Flavor Physics and CP Violation / 93**

## **g-2, hadronic vacuum polarization, the electroweak fit and new physics**

**Author:** Andreas Crivellin<sup>1</sup>

<sup>1</sup> *Universitaet Zuerich (CH)*

**Corresponding Author:** andreas.crivellin@cern.ch

Hadronic vacuum polarization is a key ingredient of the SM prediction for g-2. However, it also enters the global EW fit, linking both of them. In this talk I discuss this interplay as well as the possible presence of NP in the EW fit and g-2.

**Formal SUSY Theories / 248**

## **Line defects and link invariants**

**Author:** Fei Yan<sup>None</sup>

**Corresponding Author:** fyan.hepth@gmail.com

I will describe interplay between the study of supersymmetric line defects and the construction of link invariants. As an example, a certain UV-IR map for line defects in 4d N=2 theories of class-S motivates a new link “invariant” (with wall-crossing behaviors) for links in three-manifolds taking the form of a surface times a real line. This new link “invariant” gives a refined counting of the ground states for the bulk-defect system; moreover it provides a new way of computing familiar link polynomials. More generally, link invariants for links in a broad class of three-manifolds could be constructed by studying supersymmetric line defects in 3d N=2 theories. This talk is based on joint work with A. Neitzke, as well as work in progress with D. Gaiotto, A. Khan and G. Moore.

**Formal SUSY Theories / 170**

## **From SU(N) Seiberg-Witten Theory to Adjoint QCD**

**Author:** EMILY NARDONI<sup>1</sup>

**Co-authors:** Eric D’Hoker<sup>1</sup>; Thomas Dumitrescu<sup>1</sup>; Efrat Gerchkovitz<sup>1</sup>

<sup>1</sup> *University of California, Los Angeles*

**Corresponding Author:** enardoni@physics.ucla.edu

Standard lore suggests that four-dimensional SU(N) gauge theory with 2 massless adjoint Weyl fermions (“adjoint QCD”) flows to a phase with confinement and chiral symmetry breaking. In this talk, we will test and present new evidence for this lore. Our strategy involves realizing adjoint QCD in the deep IR of a renormalization group flow descending from SU(N) Seiberg-Witten theory, deformed by a soft supersymmetry-breaking mass for its adjoint scalars. A crucial role in the analysis is played by a dual Lagrangian that originates from the multi-monopole points of Seiberg-Witten theory, and which can be used to explore the phase diagram as a function of the supersymmetry-breaking mass. The semi-classical phases of this dual Lagrangian suggest that the softly broken SU(N) theory traverses a sequence of phases, separated by first-order transitions, that interpolate between the Coulomb phase of Seiberg-Witten theory and the confining, chiral symmetry breaking phase expected for adjoint QCD.

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**Shifted Quiver Yangians and Representations from BPS Crystals****Author:** Dmitrii Galakhov<sup>1</sup><sup>1</sup> *Kavli IPMU***Corresponding Author:** dmitrii.galakhov@ipmu.jp

We introduce a class of new algebras, the shifted quiver Yangians, as the BPS algebras for type IIA string theory on general toric Calabi-Yau three-folds. We construct representations of the shifted quiver Yangian from general subcrystals of the canonical crystal. We derive our results via equivariant localization for supersymmetric quiver quantum mechanics for various framed quivers, where the framings are determined by the shape of the subcrystals. Our results unify many known BPS state counting problems, including open BPS counting, non-compact D4-branes, and wall crossing phenomena, simply as different representations of the shifted quiver Yangians. Furthermore, most of our representations seem to be new, and this suggests the existence of a zoo of BPS state counting problems yet to be studied in detail.

Formal SUSY Theories / 107

**Counting BPS states with exponential networks****Authors:** Mauricio Romo<sup>1</sup>; Pietro Longhi<sup>2</sup>; Sibasish Banerjee<sup>3</sup><sup>1</sup> *Tsinghua*<sup>2</sup> *ETH Zurich*<sup>3</sup> *Bonn***Corresponding Author:** longhip@ethz.ch

I will describe a framework for computing the BPS spectrum of M-theory on a local Calabi-Yau threefold times  $R^4 \times S^1$ . Exponential Networks define counts of special Lagrangians in the mirror Calabi-Yau, thereby leading to a proposal for computing related DT invariants from geometric data of mirror curves. I will briefly sketch a connection to BPS quivers and a computation of the Kontsevich-Soibelman invariant of wall-crossing for the local Hirzebruch surface  $F_0$ .

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**Non-unitary TQFTs from 3D  $\mathcal{N} = 4$  rank 0 SCFTs****Authors:** Dongmin Gang<sup>1</sup>; Sungjoon Kim<sup>2</sup>; Kimyeong Lee<sup>3</sup>; Myungbo Shim<sup>4</sup>; Masahito Yamazaki<sup>5</sup><sup>1</sup> *Seoul National University*<sup>2</sup> *POSTECH*<sup>3</sup> *KLAS*<sup>4</sup> *Kyung Hee University*<sup>5</sup> *Kavli IPMU***Corresponding Author:** mbshim1213@khu.ac.kr

We propose a novel procedure of assigning a pair of non-unitary topological quantum field theories (TQFTs),  $\text{TFT}_{\pm}[\mathcal{T}_{\text{rank } 0}]$ , to a (2+1)D interacting  $\mathcal{N} = 4$  superconformal field theory (SCFT)  $\mathcal{T}_{\text{rank } 0}$  of

rank 0, i.e. having no Coulomb and Higgs branches. The topological theories arise from particular degenerate limits of the SCFT. Modular data of the non-unitary TQFTs are extracted from the supersymmetric partition functions in the degenerate limits. As a non-trivial dictionary, we propose that  $F = \max_{\alpha} \left( -\log |S_{0\alpha}^{(+)}| \right) = \max_{\alpha} \left( -\log |S_{0\alpha}^{(-)}| \right)$ , where  $F$  is the round three-sphere free energy of  $\mathcal{T}_{\text{rank } 0}$  and  $S_{0\alpha}^{(\pm)}$  is the first column in the modular S-matrix of  $\text{TFT}_{\pm}$ . From the dictionary, we derive the lower bound on  $F$ ,  $F \geq -\log \left( \sqrt{\frac{5-\sqrt{5}}{10}} \right) \simeq 0.642965$ , which holds for any rank 0 SCFT. The bound is saturated by the minimal  $\mathcal{N} = 4$  SCFT proposed by Gang-Yamazaki, whose associated topological theories are both the Lee-Yang TQFT. We explicitly work out the (rank 0 SCFT)/(non-unitary TQFTs) correspondence for infinitely many examples.

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## Schur index in closed-form and free fields

**Authors:** Wolfger Peelaers<sup>1</sup>; Yiwen Pan<sup>None</sup>

<sup>1</sup> *Oxford University*

**Corresponding Author:** ai.roswell@gmail.com

Flavored Schur indices of 4d  $\mathcal{N}=4$  SCFTs encode many crucial information of the associated VOAs. For Lagrangian theories, the indices can be written as a multi-contour-integral of one-loop factor  $Z$ . In this talk, we will show that for 4d  $\mathcal{N}=4$  theories, some special residues of  $Z$  coincide with the free field characters of the  $\text{bc}\beta\gamma$  systems, proposed by Bonetti, Meneghelli and Rastelli, that realize the associated VOAs. These residues serve automatically as additional solutions to the flavored modular differential equations. This result inspires an elementary method to rewrite the Schur indices in closed-form, in terms of finite sums and products of theta functions and their derivatives.

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## Feigin-Semikhatov duality and its applications

**Author:** Shigenori Nakatsuka<sup>1</sup>

**Co-authors:** Thomas Creutzig<sup>2</sup>; Naoki Genra<sup>1</sup>; Ryo Sato<sup>3</sup>

<sup>1</sup> *The University of Tokyo*

<sup>2</sup> *University of Alberta*

<sup>3</sup> *Academia Sinica*

**Corresponding Author:** shigenori.nakatsuka@ipmu.jp

In this talk, we investigate relationships between two families of  $\mathcal{W}$ -algebras, that is, the subregular  $\mathcal{W}$ -algebra for  $\mathfrak{sl}_n$  and the principal  $\mathcal{W}$ -superalgebra for  $\mathfrak{sl}_{1|n}$  in terms of their algebraic structure and representation theory.

The very beginning case is the Kazama-Suzuki coset construction of  $\mathcal{N} = 2$  superconformal algebra in terms of WZW model of  $\mathfrak{sl}_2$  whose inverse construction was invented by Feigin-Semikhatov-Tipunin by using a lattice theory.

The relationship of these two algebras are generalized to the above mentioned two families of  $\mathcal{W}$ -superalgebras.

It was originally conjectured by Feigin and Semikhatov and recently by Gaiotto and Rapcak in a much wider context of chiral algebras appearing at two dimensional boundary of four dimensional super Yang-Mills theory with various boundary conditions.

Firstly, I explain that the Heisenberg cosets of these two (super)algebras are isomorphic, which is conjectured by Gaiotto and Rapcak.  
 Secondly, I enhance this duality to the reconstruction of these two algebras from the other, which is the honest generalization of Kazama-Suzuki coset construction.  
 Then I explain the correspondence between the representation theory of these two algebras together with the isomorphisms between the superspaces of logarithmic intertwining operators.  
 Finally, I explain the levels when these two algebras give rational (super)conformal field theories and the classification of simple modules and the fusion rules. In this case, the duality of the fusion rules is explicitly written down in terms of duality of two lattices appearing as simple currents of respective representation theory.

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## S-type Operations, Line Defects and 3D Mirror Symmetry beyond ADE quivers

**Author:** Anindya Dey<sup>1</sup>

<sup>1</sup> *Johns Hopkins*

**Corresponding Author:** adey5@jhu.edu

I will present a systematic field theory prescription for constructing 3D  $N=4$  mirror pairs involving quiver gauge theories beyond the well-known ADE examples. The construction involves a certain generalization of the S operation, which arises in the context of the 3d  $SL(2, \mathbb{Z})$  action on a CFT with a  $U(1)$  0-form symmetry. I will show how this construction can be used to find Lagrangian descriptions for a large class of Argyres-Douglas theories compactified on a circle. I will also discuss how the prescription can be extended to include half-BPS line operators and determine the associated mirror maps, which were previously known only for the A-type quiver gauge theories.

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## Superconformal theories from S-fold geometries

**Author:** Simone Giacomelli<sup>1</sup>

<sup>1</sup> *University of Oxford*

**Corresponding Author:** simone.giacomelli@maths.ox.ac.uk

The term S-folds denotes F-theory compactifications which involve non-trivial S-duality transformations. In this talk I will discuss 4d  $N=2$  preserving S-folds and the worldvolume theories on D3-branes probing them. They consist of two new infinite series of superconformal theories whose distinction lies in the discrete torsion carried by the S-fold and in the difference in the asymptotic holonomy of the gauge bundle on the 7-brane. These models are connected by an interesting web of RG flows and their Higgs branches provide new examples of instanton moduli spaces.

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## Tetrahedron instantons

**Authors:** Elli Pomoni<sup>1</sup>; Wenbin Yan<sup>2</sup>; Xinyu Zhang<sup>3</sup>

<sup>1</sup> DESY<sup>2</sup> Yau Mathematical Sciences Center, Tsinghua University<sup>3</sup> Deutsches Elektronen-Synchrotron DESY**Corresponding Author:** xinyu.zhang@desy.de

I will describe my work arXiv:2106.11611 with Elli Pomoni and Wenbin Yan. We introduce and study tetrahedron instantons, which can be realized in string theory by D1-branes probing a configuration of intersecting D7-branes in flat spacetime with a nonzero constant background B-field. Physically they capture instantons on  $C^3$  in the presence of the most general intersecting codimension-two supersymmetric defects. Moreover, we construct the tetrahedron instantons as particular solutions of general instanton equations in noncommutative field theory. We analyze the moduli space of tetrahedron instantons and discuss the geometric interpretations. We compute the instanton partition function, which lies between the higher-rank Donaldson-Thomas invariants on  $C^3$  and the partition function of the magnificent four model.

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## 5d SCFTs from singularities

**Author:** Yinan Wang<sup>1</sup><sup>1</sup> Peking University**Corresponding Author:** ynwang@pku.edu.cn

5d SCFTs can be constructed from M-theory on canonical threefold singularities. The Coulomb and Higgs branch information of the SCFT are encoded in the resolution and deformation of the singularity, respectively. I'm going to present the recent progress on isolated hypersurface singularities and non-isolated singularities.

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## Compactifying 5d superconformal field theories to 3d

**Author:** Gabi Zafrir<sup>1</sup>**Co-authors:** Orr Sela ; Matteo Sacchi<sup>1</sup> University of Milano-Bicocca**Corresponding Author:** gabi.zafrir@unimib.it

The study of the strong coupling behavior of quantum field theory is very challenging, with theories exhibiting interesting and mysterious strong coupling phenomena like dualities and symmetry enhancement. The tool of dimensional reduction, where the theories are realized through the compactification of a higher dimensional theory, can be used to give an organizing principle for these phenomena. In this talk I will describe the recent progress in the study of such relations between five dimensional SCFTs and three dimensional  $\mathcal{N} = 2$  theories. Specifically, I consider the compactification of the so-called rank 1 Seiberg  $E_{N_f+1}$  5d SCFTs on tori and tubes with flux in their global symmetry, formulate a conjecture for the resulting 3d theories and put them to various consistency checks. This leads to many new and interesting cases of peculiar strong coupling behavior of 3d supersymmetric field theories like symmetry enhancement.



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**On Twisted Elliptic Genera****Author:** Kaiwen Sun<sup>None</sup>**Co-authors:** Kimyeong Lee ; Xin Wang

We study the elliptic genera of twisted 6d  $(1,0)$  SCFTs from several approaches: 2d localization, modular bootstrap, Higgsing and twisted elliptic blowup equations. The twist is made when the 6d gauge algebra has outer automorphism symmetry. Upon twisted circle compactification, nontrivial 5d Kaluza-Klein theories appear. We provide a universal method to compute the twisted elliptic genera of the 6d theories and find novel properties such as spectral flow symmetry.

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**Instanton counting in BCD-type gauge theories****Authors:** Ruidong Zhu<sup>1</sup>; Satoshi Nawata<sup>2</sup><sup>1</sup> *Soochow University*<sup>2</sup> *Fudan University***Corresponding Author:** nickzrd@gmail.com

Localization method together with ADHM construction provide a powerful way to compute the exact partition function of 8 SUSY gauge theories. In particular, Nekrasov's partition function is interesting because of the non-perturbative corrections from instantons. It is, however, known to be difficult to perform the integrals in an analytic way that appear in the computation of instanton partition functions of BCD-type gauge theories. In this talk, we propose an analytic expression for these integrals in the unrefined limit in the form of summation over Young diagrams. Our results are inspired by the topological vertex formalism in topological string theory.

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**Confinement in Non-Lagrangian 4d  $\mathcal{N}=1$  Theories****Authors:** Lakshya Bhardwaj<sup>None</sup>; Max Hubner<sup>None</sup>; Sakura Schafer-Nameki<sup>None</sup>**Corresponding Author:** lakshyabhardwaj15@gmail.com

I will describe a method for computing confinement in  $4d \mathcal{N} = 1$  theories that can be obtained by deforming  $4d \mathcal{N} = 2$  of Class S. Such theories generically do not admit a conventional Lagrangian description. The confinement for this class of  $4d \mathcal{N} = 1$  theories can be captured in topological properties of a complex curve, known as  $\mathcal{N} = 1$  curve, which can be understood as the spectral curve associated to a generalized Hitchin system.

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**4d superconformal theories with  $a=c$** **Author:** Jaewon Song<sup>1</sup>

<sup>1</sup> KAIST**Corresponding Author:** jws611@gmail.com

We study a set of four-dimensional  $N=2$  superconformal field theories (SCFTs) labeled by a pair of simply-laced Lie groups. For some special choices, the resulting theories have identical central charges ( $a=c$ ) without taking any large  $N$  limit. Moreover, we find that the Schur indices for such theories can be written in terms of that of  $N=4$  super Yang-Mills theory upon rescaling fugacities.

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## Maximally twisted eleven-dimensional supergravity

**Author:** Fabian Hahner<sup>1</sup>**Co-author:** Richard Eager<sup>1</sup> Universität Heidelberg**Corresponding Author:** fhahner@mathi.uni-heidelberg.de

In this talk I explain how the maximal twist of eleven-dimensional supergravity in the free perturbative limit can be computed directly in the BV formalism. The maximal twist exists on manifolds of  $G_2 \times SU(2)$  holonomy and is partially topological. After a short introduction to the BV formalism and twisting, I describe the  $L_\infty$  action of the supersymmetry algebra on the component fields of the supergravity multiplet. Decomposing these transformations and the BV differential under  $G_2 \times SU(2)$ , the twisted theory can be identified. The result takes a simple form as conjectured by Costello. The talk is based on arxiv:2106.15640.

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## Maximally twisted eleven-dimensional supergravity

**Authors:** Fabian Hahner<sup>None</sup>, Richard Eager<sup>None</sup>**Corresponding Author:** reager@gmail.com

We perform the maximal twist of eleven-dimensional supergravity. This twist is partially topological and exists on manifolds of  $G_2 \times SU(2)$  holonomy. Our derivation starts with an explicit description of the Batalin-Vilkovisky complex associated to the three-form multiplet in the pure spinor superfield formalism. We then determine the  $L_\infty$  module structure of the supersymmetry algebra on the component fields. We twist the theory by modifying the differential of the Batalin-Vilkovisky complex to incorporate the action of a scalar supercharge. We find that the resulting free twisted theory is given by the tensor product of the de Rham and Dolbeault complexes of the respective  $G_2$  and  $SU(2)$  holonomy manifolds as conjectured by Costello.

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## Twisting perturbative supergravity via pure spinor superfields

**Authors:** Ingmar Saberi<sup>None</sup>; Brian Williams<sup>1</sup>

<sup>1</sup> *University of Edinburgh***Corresponding Author:** i.saberi@physik.uni-muenchen.de

Pure spinor superfields provide a clean and powerful way of constructing and understanding supermultiplets, in any dimension and with any amount of supersymmetry, by using the algebraic geometry of the variety of square-zero elements in the corresponding supersymmetry algebra. This variety also classifies the possible twists of a supermultiplet. As such, it is natural to try and compute twists directly in a pure spinor superfield description. We show that this gives a general way of understanding the form of the twisted multiplets, which is related to the local geometry of the space of square-zero elements in the neighborhood of the twisting supercharge: in other words, the space of possible deformations of the selected twist to a further twist. The technique is efficient and requires essentially no detailed computations. Applications include new computations of the holomorphic twists of the eleven-dimensional and type IIB supergravity multiplets, verifying conjectures of Costello and Li.

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## G<sub>2</sub> instantons in twisted M-theory

**Authors:** Jihwan Oh<sup>1</sup>; Michele del Zotto<sup>2</sup>; Yehao Zhou<sup>3</sup><sup>1</sup> *University of Oxford*<sup>2</sup> *Uppsala University*<sup>3</sup> *Perimeter Institute***Corresponding Author:** jihwanoh254@gmail.com

Computing Donaldson-Thomas partition function of a G<sub>2</sub> manifold has been a long standing problem. The key step for the problem is to understand the G<sub>2</sub> instanton moduli space. I will discuss a string theory way to study the G<sub>2</sub> instanton moduli space and explain how to compute the instanton partition function for a certain G<sub>2</sub> manifold. An important insight comes from the twisted M-theory on the G<sub>2</sub> manifold. This talk is based on a work in progress with Michele del Zotto and Yehao Zhou.

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## 4d Chern-Simons Theory as a 3d Toda Theory, and a 3d-2d Correspondence

**Author:** Meer Ashwinkumar<sup>1</sup><sup>1</sup> *The University of Tokyo (Kavli IPMU)***Corresponding Author:** meer.ashwinkumar@ipmu.jp

We show that the four-dimensional Chern-Simons theory studied by Costello, Witten and Yamazaki, is, with Nahm pole-type boundary conditions, dual to a boundary theory that is a three-dimensional analogue of Toda theory with a novel 3d W-algebra symmetry. By embedding four-dimensional Chern-Simons theory in a partial twist of the five-dimensional maximally supersymmetric Yang-Mills theory on a manifold with corners, we argue that this three-dimensional Toda theory is dual to a two-dimensional topological sigma model with A-branes on the moduli space of solutions to the Bogomolny equations. This furnishes a novel 3d-2d correspondence, which, among other mathematical implications, also reveals that modules of the 3d W-algebra are modules for the quantized algebra of certain holomorphic functions on the Bogomolny moduli space.

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## Higher-order constraints for N=1 and N=2 superfields and non-linear SUSY

**Author:** Yermek Aldabergenov<sup>1</sup>

**Co-authors:** Auttakit Chatrabhuti ; Hiroshi Isono<sup>1</sup>; Ignatios Antoniadis<sup>2</sup>

<sup>1</sup> *Chulalongkorn University*

<sup>2</sup> *UPMC*

**Corresponding Author:** aldyermek@gmail.com

We study real higher-order constraints for  $calN = 1$  and  $calN = 2$  chiral superfields, which describe spontaneously broken (to  $calN = 0$ ) and non-linearly realized supersymmetry in the presence of a light axion of a spontaneously broken global  $U(1)$ . For  $calN = 1$  the constraint is of third order, while for  $calN = 2$  it is of fifth order and can be imposed on abelian vector or tensor (linear) multiplet. In both cases the constraint eliminates a single real scalar (saxion) in terms of goldstino field(s).

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## Counterexamples to the Nelson-Seiberg theorem

**Author:** Zheng Sun<sup>1</sup>

<sup>1</sup> *Sichuan University*

**Corresponding Author:** sun\_ctp@scu.edu.cn

The Nelson-Seiberg theorem and its extension relate supersymmetry breaking and R-symmetries in Wess-Zumino models, and found applications in phenomenology model building. We show that there are counterexample models with generic superpotential coefficients and non-generic R-charge assignment for fields. These models have more R-charge 2 fields than R-charge 0 fields, but give SUSY vacua with spontaneous R-symmetry breaking. So they are counterexamples to both the Nelson-Seiberg theorem and its extensions. The pattern of R-charge assignment is discussed, and we provide a sufficient condition for counterexamples.

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## Supersymmetry and Computational Complexity

**Author:** Marcos Crichigno<sup>1</sup>

**Co-author:** Chris Cade

<sup>1</sup> *Imperial College London*

**Corresponding Author:** p.crichigno@imperial.ac.uk

I will discuss various aspects of supersymmetric systems from the point of view of the theory of computational complexity. These include the claim that computing the Witten index of N=2 quantum mechanics is #P-complete and thus intractable. I will also discuss the complexity of finding supersymmetric ground states of local SUSY Hamiltonians and its implications for the problem of computing certain cohomology groups.

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**A high-quality axion from the non-minimal SU(6) GUT****Author:** NING CHEN<sup>1</sup>**Co-authors:** ZHAOLONG TENG ; YUTONG LIU<sup>1</sup> *Nankai University***Corresponding Author:** chenning\_symmetry@nankai.edu.cn

We propose an SU(6) GUT, which enjoys a global symmetry of  $SU(2) \times U(1)_{PQ}$ . The GUT breaking to the SM gauge symmetry undergoes two stages. The second stage of symmetry breaking scale corresponds to the axion physics scale. By studying the Peccei-Quinn quality constraint, we show an upper bound to the axion decay constant to be consistent with the classical axion window. The QCD axion, which has a KSVZ-type coupling to the vector-like quarks, has a DFSZ-type effective di-photon couplings, and can be probed by the upcoming IAXO experiment. Some other issues of the SU(6) GUT will be discussed as well.

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**Perturbativity aspects of the minimal SO(10) Higgs model****Author:** Michal Malinský<sup>1</sup>**Co-authors:** Kateřina Jarkovská <sup>2</sup>; Timon Mede <sup>3</sup>; Vasja Susič <sup>4</sup><sup>1</sup> *IPNP, Charles University, Prague*<sup>2</sup> *Institute of Particle and Nuclear Physics, Charles University, Prague, CZ*<sup>3</sup> *JSI, Ljubljana, Slovenia*<sup>4</sup> *Basel University***Corresponding Author:** malinsky@ipnp.troja.mff.cuni.cz

We shall present a brand new study of the minimal renormalizable SO(10) Higgs model focusing on its perturbativity aspects. With an essentially complete grip on the one-loop corrections to its scalar spectrum one can identify the symmetry breaking chains featuring an intermediate  $SU(4) \times SU(2) \times U(1)$  symmetry as a practically unique option for a potentially realistic model building.

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**Neutron-antineutron oscillation as a probe of baryogenesis****Authors:** Chandan Hati<sup>1</sup>; Julia Harz<sup>2</sup>; Kare Fridell<sup>2</sup><sup>1</sup> *Technical University of Munich*<sup>2</sup> *Technical University of Munich (TUM)***Corresponding Author:** kare.fridell@tum.de

Neutron-antineutron ( $n\text{-}\bar{n}$ ) oscillation is a baryon number violating process for which new constraints will be set in future experiments at ESS and DUNE. We study the impact of a potential  $n\text{-}\bar{n}$  oscillation discovery on the baryon asymmetry of the Universe in an effective field theory framework. We extend our analysis by a simplified model connected to GUT for one of two possible UV-complete topologies of the  $n\text{-}\bar{n}$  operator, and make a connection to resonant production at the

LHC. We find that successful baryogenesis can be realized in regions of parameter space that are currently unexplored but will be probed by future  $n\lambda\text{-}\bar{n}$  oscillation experiments.

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## **Towards the minimal non-supersymmetric E6 GUT**

**Authors:** Borut Bajc<sup>1</sup>; Kaladi Babu<sup>2</sup>; Vasja Susic<sup>3</sup>

<sup>1</sup> *Jožef Stefan Institute*

<sup>2</sup> *Oklahoma State University*

<sup>3</sup> *Basel University*

Although the minimal supersymmetric GUT has been proposed already some years ago, its non-supersymmetric counterpart is, strangely enough, not yet known. In this talk I will present some attempts in constructing the minimal non-supersymmetric E6 scalar potential which leads to the SM at low energy. This includes Higgs representations 27 and 351', as well as the more involved 650.

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## **Some phenomenological aspects of 6D SUSY SO(10) with magnetic flux**

**Author:** Ketan Patel<sup>1</sup>

<sup>1</sup> *Physical Research Laboratory*

**Corresponding Author:** ketan.hep@gmail.com

Supersymmetric SO(10) theory with extra abelian symmetry in six spacetime dimensions can explain the multiplicity of quarks and lepton flavours. Bulk superfields charged under extra U(1) give rise to multiple 4D fields through magnetic flux compactification. Details of how the realistic fermion mass pattern arises in such a framework will be discussed and its prediction for the heavy and light neutrino mass scale will be outlined. The framework also predicts specific flavour patterns in proton decay somewhat different from usual 4D SO(10) GUT models. The effective theory below the GUT scale is a two-Higgs-doublet model with a pair of Higgsino and leads to particular predictions for the scalar spectrum.

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## **Pseudo-Goldstone Dark Matter in SO(10)**

**Authors:** Nobuchika Okada<sup>1</sup>; Digesh Raut<sup>2</sup>; Qaisar Shafi<sup>None</sup>

<sup>1</sup> *University of Alabama*

<sup>2</sup> *University of Delaware*

**Corresponding Author:** theeguess@gmail.com

We propose a pseudo-Goldstone boson dark matter (pGDM) particle in  $SO(10)$  grand unified theory (GUT). Due to its Goldstone nature, this pGDM evades the direct DM detection experiments which, otherwise, severely constrain the parameter space of DM models. In  $SO(10)$ , the pGDM is embedded as a linear combination of the Standard Model (SM) singlet scalars in  $\mathbf{16}_H$  and  $\mathbf{126}_H$  representations. We consider two scenarios for the intermediate route of  $SO(10)$  symmetry breaking (SB) to the SM:  $SU(5) \times U(1)_X$  and Pati-Salam the  $SU(4)_c \times SU(2)_L \times SU(2)_R$  gauge groups. The vacuum expectation value of  $\mathbf{126}_H$ , which triggers the breaking of  $U(1)_X$  and 4-2-2 symmetry in the two scenarios, respectively, determines the pGDM lifetime whose astrophysical lower bound provides one of the most stringent constraints. The proton lifetime in the  $SU(5)$  case is predicted to be  $4.53 \times 10^{34}$  years, which lies well within the sensitivity reach of the Hyper-Kamiokande experiment.

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## The Standard Model and Dark Matter in Structures of Generalised Proper Time

Author: David Jackson<sup>None</sup>

Corresponding Author: david.jackson.th@gmail.com

Attempts to account for the elementary properties of matter through a structure of extra spatial dimensions date from the theory of Kaluza 100 years ago. In more recent years, while there is still no clear evidence that extra dimensions of space exist, the origin of the structure of the Standard Model has become a central question in fundamental particle physics. We describe how a new approach, with a further generalisation from the local 4-dimensional spacetime geometry to a general form for proper time, leads directly and efficiently to Standard Model structures. This generalisation naturally makes use of unique mathematical structures involving the octonion algebra and the exceptional Lie groups that are also seen in some SUSY models. As an additional feature of the theory a natural candidate for dark matter, itself a further major mystery in physics, can also be directly identified.

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## Supersymmetric grand unified theories with Higgsino-like neutralino dark matter and its implication to the proton decay search at the Hyper-Kamiokande

Authors: Nobuchika Okada<sup>1</sup>; Osamu Seto<sup>2</sup>

<sup>1</sup> University of Alabama

<sup>2</sup> Hokkaido University

Corresponding Author: okadan@ua.edu

Imposing the gauge coupling unification and the Higgsino-like neutralino dark matter in our Universe, we perform a parameter scan for a simple parameter set in the Minimal Supersymmetric Standard Model, namely, the universal sfermion mass ( $m_0$ ) and the universal gaugino mass at the GUT scale ( $M$ ). We find that sparticle masses in the range of 10-100 TeV result in the lifetime of proton decay mediated by the GUT gauge bosons that can be tested in the Hyper-Kamiokande experiment in the near future.

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## Viable Full Unification of the Standard Model into $E_8$

**Authors:** Alfredo Aranda<sup>None</sup>; Francisco J. de Anda N.<sup>None</sup>; António Morais<sup>None</sup>; Roman Pasechnik<sup>None</sup>

**Corresponding Author:** franciscojosede@ gmail.com

A 10 dimensional model with  $\mathcal{N} = 1$  SUSY and  $E_8$  as a gauge symmetry will be presented. It will be shown that through the orbifold  $6/(\mathbb{Z}_3 \times F_3)$ , only the Standard Model remains after compactification, with feasible Yukawa couplings. Gauge coupling unification can be achieved at energies as low as  $M_{GUT} = 10^7 GeV$  with a viable proton lifetime. Therefore the highly predictive extra dimensional GUT model can be within reach of near future experiments.

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## Minimal SU(5) Unification

**Authors:** Ilja Doršner<sup>1</sup>; shaikh saad<sup>2</sup>

<sup>1</sup> *University of Split*

<sup>2</sup> *University of Basel*

**Corresponding Author:** shaikh.saad@okstate.edu

A minimal model of  $SU(5)$  Grand Unification is proposed. The model is entirely built out of the first five lowest dimensional  $SU(5)$  representations. Charged and neutral fermion mass generation mechanisms are non-trivially linked together. The main predictions of the model are that (i) the neutrinos are Majorana particles, (ii) one neutrino is massless, (iii) the neutrinos have normal mass ordering, and (iv) there are four new scalar multiplets at or below a 120TeV mass scale. An improvement of the current  $p \rightarrow \pi^0 e^+$  lifetime limit by a factor of 2, 15, and 96 would require these four scalar multiplets to reside at or below the 100 TeV, 10 TeV, and 1 TeV mass scales, respectively.

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## Light Pseudo-Goldstone Higgs from SUSY SO(10) GUT

**Author:** Zurab Tavartkiladze<sup>1</sup>

<sup>1</sup> *Ilia State University*

**Corresponding Author:** zurab.tavartkiladze@gmail.com

A new mechanism for the Higgs doublet being the light pseudo-Goldstone mode within SUSY SO(10) GUT will be presented.

Considered model exploits additional symmetries, which guarantee desirable symmetry breaking and natural all-order hierarchy. Some phenomenology, including a realistic fermion pattern, nucleon stability and gauge coupling unification, will be also discussed.

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## An asymptotically safe SU(5) GUT

**Authors:** Alberto Tonero<sup>1</sup>; Carlos Mauricio Nieto Guerrero<sup>None</sup>; Marco Fabbrichesi<sup>2</sup>; Ugo Alessandri<sup>3</sup>

<sup>1</sup> *Carleton University*

<sup>2</sup> *INFN - National Institute for Nuclear Physics*



<sup>3</sup> *Jena University***Corresponding Author:** alberto.tonero@gmail.com

**Abstract:** In this talk I will present a model in which we minimally extend the Standard Model field content by adding new vector-like fermions at the TeV scale to allow gauge coupling unification at a realistic scale. We embed the model into a  $SU(5)$  GUT that is asymptotically safe and features an interacting fixed point for the gauge coupling. There are no Landau poles of the  $U(1)$  gauge and Higgs couplings. Gauge, Yukawa and Higgs couplings are retraced from the fixed point and matched at the GUT scale to those of the Standard Model rescaled up to the same energy. All couplings, their fixed point values and critical exponents always remain in the perturbative regime.

**Grand Unified Theories / 244**

## Nucleon decay fingerprints from SUSY GUT models (using SusyTCProton)

**Authors:** Christian Hohl<sup>1</sup>; Vasja Susic<sup>1</sup>; Stefan Antusch<sup>1</sup><sup>1</sup> *University of Basel***Corresponding Author:** vasja.susic@unibas.ch

Ratios of nucleon decay rates between different channels can provide rich information about the specific GUT model realization in nature. To investigate this fingerprint in the context of SUSY GUTs and D=5 proton decay, we developed the software package *SusyTCProton*, which is an extension of the module *SusyTC*, itself to be used as a package of *REAP*. It takes the effective dimension 5 operators in the superpotential at the GUT scale as input, and assuming MSSM below the unification scale, computes the proton (neutron) partial decay rates into 7 (5) different decay channels.

We demonstrate the utility of this software on a pair of toy SUSY GUT models with different flavor structures. Performing a numerical fit and a subsequent MCMC analysis, we find that both models provide an equally good fit to the low energy data, while they differ in their prediction for nucleon decay fingerprints, making it possible, at least in principle, to experimentally distinguish between them.

The talk is based on 2011.15026 [hep-ph].

**Grand Unified Theories / 328**

## $SU(5) \times U(1)_{PQ}$ Majoron-axion model

**Authors:** Digesh Raut<sup>1</sup>; Nobuchika Okada<sup>2</sup>; Qaisar Shafi<sup>None</sup><sup>1</sup> *University of Delaware*<sup>2</sup> *University of Alabama***Corresponding Author:** theeguess@gmail.com

We propose a  $SU(5) \times U(1)_{PQ}$  Majoron-axion model free of the axion domain wall, axion dark matter isocurvature, and  $SU(5)$  monopole problems. The vectorlike fermions in the model are essential to achieving successful unification of the SM gauge couplings as well as the viability of the inflation scenarios. The  $SU(5)$  symmetry is broken at  $M_{GUT} \simeq (4-7) \times 10^{15}$  GeV and the proton lifetime  $\tau_p$  is estimated to be well within the expected sensitivity of the future Hyper-Kamiokande experiment,  $\tau_p \gtrsim 1.3 \times 10^{35}$  years. Meanwhile, the CASPEr experiment can search for the axion.

**Gravitational Waves as Probes for New Physics / 396****Observation of a multimode quasi-normal spectrum from a perturbed black hole****Author:** Alex Nielsen<sup>1</sup><sup>1</sup> *University of Stavanger***Corresponding Author:** alex.b.nielsen@uis.no

When two black holes merge, the late stage of gravitational wave emission is a superposition of exponentially damped sinusoids. According to the black hole no-hair theorem, this ringdown spectrum depends only on the mass and angular momentum of the final black hole. An observation of more than one ringdown mode can test this fundamental prediction of general relativity. Here we provide strong observational evidence for a multimode black hole ringdown spectrum using the gravitational wave event GW190521, with a Bayes factor of  $\sim 40$  preferring two fundamental modes over one. The dominant mode is the 22-mode, and the sub-dominant mode corresponds to the 33-mode. We estimate the redshifted mass and dimensionless spin of the final black hole. The detection of the two modes disfavors a binary progenitor with equal masses. We find that the final black hole is consistent with the no hair theorem and constrain the fractional deviation from general relativity of the sub-dominant mode's frequency.

**Gravitational Waves as Probes for New Physics / 348****Primordial gravitational waves and primordial black holes****Author:** Wu Puxun<sup>None</sup>

Primordial gravitational waves (GWs) can be generated during different eras of early cosmic evolution, including inflation, cosmic phase transition, reheating/preheating, and so on. In this talk, I will first introduce the amplified GWs through parametric resonance during inflation in the Cherns-Simons gravity. Then, I will introduce the scalar induced GWs accompanied with the production of primordial black holes. Two different theoretical models how to enhance the curvature perturbations will be discussed.

**Gravitational Waves as Probes for New Physics / 379****Local constraints on the dark sector by future missions to Uranus and Neptune****Authors:** Lorenz Zwick<sup>1</sup>; Deniz Soyuer<sup>1</sup>; Prasenjit Saha<sup>2</sup><sup>1</sup> *University of Zurich*<sup>2</sup> *Universität Zürich***Corresponding Author:** deniz.soyuer@uzh.ch

Recent years have seen many publications underlining the importance of space missions to Uranus and Neptune in the following decade. Proposed mission plans would have a cruise time around 10 years, which can be utilized to search for low-frequency gravitational wave signals by observing the Doppler shift in the Earth-spacecraft radio link. Our recent work (Soyuer et al. 2020) demonstrates that detection of a supermassive black hole binary could be possible via Doppler tracking, and that a mission concurrent with LISA would improve gravitational wave source localization by an order of magnitude compared to LISA alone.

These prospective ice giant missions could also be utilized to constrain the dark sector. Modifications to the third Kepler-law and deviations from the inverse square law of gravity can be tested by observing the extra perihelion precession of Uranus and Neptune, which allows probing the local dark matter density, modified gravity (MOND) scenarios and Yukawa-like interactions. As of now, the extraprecession measurements of ice giants are done via ephemerides measurements, which have large uncertainties and provide looser constraints with respect to constraints by other planets. Current upper bound on the local dark matter density lies around  $\rho_{\text{DM}} \sim 10^{-20} \text{ g/cm}^3$ . However, Doppler tracking missions to Uranus and Neptune with radio ranging accuracy of a few meters can improve this upper bound by 2 to 3 orders of magnitude via the extraprecession technique. Moreover, estimates coming from the spacecraft cruise time energy budget could yield an even better estimate than the ephemerides measurements, potentially providing evidence for dark matter or shedding light on modified gravity scenarios.

**Gravitational Waves as Probes for New Physics / 175**

## Probing String-inspired Quadratic Gravity with Gravitational Waves

**Authors:** Kent Yagi<sup>1</sup>; Albert Bryant<sup>1</sup>; Zack Carson<sup>1</sup>; Kostas Glampedakis<sup>2</sup>; Brian Seymour<sup>3</sup>; Hector Silva<sup>4</sup>

<sup>1</sup> *University of Virginia*

<sup>2</sup> *University of Murcia*

<sup>3</sup> *California Institute of Technology*

<sup>4</sup> *Max Planck Institute for Gravitational Physics*

**Corresponding Author:** ky5t@virginia.edu

One natural extension of General Relativity is to introduce a quadratic-curvature correction to the action that is coupled to a scalar field. Such quadratic gravity includes Einstein-dilaton Gauss-Bonnet and dynamical Chern-Simons gravity that are motivated by certain types of string theory. The scalar field induces additional interaction and radiation to compact binary systems. In this talk, I will explain how well one can probe quadratic gravity with current and future gravitational wave observations.

**Gravitational Waves as Probes for New Physics / 36**

## Bridging the microhertz gap with asteroids: opportunities and challenges for gravitational wave detection

**Author:** Michael A. Fedderke<sup>1</sup>

**Co-authors:** Peter W. Graham<sup>2</sup>; Surjeet Rajendran<sup>1</sup>

<sup>1</sup> *The Johns Hopkins University*

<sup>2</sup> *Stanford University*

**Corresponding Author:** mfedderke@jhu.edu

The science case for a broad program of gravitational wave (GW) detection across all frequency bands is exceptionally strong. At present, there is a dearth of coverage by existing and proposed searches in the GW frequency band lying between the peak sensitivities of PTAs and LISA, roughly 0.1-100 microhertz. In this talk, I will outline a conceptual mission proposal to access this band. I will demonstrate that a few carefully chosen asteroids which orbit in the inner Solar System can act as excellent naturally occurring gravitational test masses despite the environmental noise sources. As such, a GW detector can be constructed by ranging between these asteroids using optical or radio links. At low frequencies, I will discuss how gravity gradient noise arising from the combined

motion of the other  $\sim 10^6$  asteroids in the inner Solar System sharply cuts off the sensitivity of this proposal. Sensitivity in the middle of this band is mostly limited by various solar perturbations to the asteroid test masses, while the high-frequency sensitivity is limited by noise in the ranging link. The projected strain-sensitivity curve that I will present indicates significant potential reach in this frequency band for a mission of this type.

**Gravitational Waves as Probes for New Physics / 459**

## Stochastic gravitational wave background in quantum gravity

**Authors:** Gianluca Calcagni<sup>None</sup>; Sachiko Kuroyanagi<sup>None</sup>

**Corresponding Author:** sachiko96@gmail.com

Inflation generically predicts a gravitational wave background originating from quantum fluctuations of the space-time metric. I will discuss quantum gravity models which predict a blue-tilted spectrum, such as non-local Starobinsky inflation, and present how future interferometer experiments help to constrain the models.

**Gravitational Waves as Probes for New Physics / 460**

## Probing spacetime geometry with gravitational waves

**Authors:** Gianluca Calcagni<sup>None</sup>; Gianmassimo Tasinato<sup>1</sup>; M. Arzano<sup>None</sup>; Maria Sakellariadou<sup>2</sup>; Nicola Tamanini<sup>3</sup>; Sachiko Kuroyanagi<sup>None</sup>

<sup>1</sup> *Swansea University*

<sup>2</sup> *University of London (GB)*

<sup>3</sup> *IPhT CEA/Saclay*

**Corresponding Author:** calcagni@iem.cfmac.csic.es

We review recent results about tests of quantum gravity with gravitational waves, using modified dispersion relations and the luminosity distance of standard sirens. Theoretical models predicting signals observable with LIGO-Virgo-KAGRA and LISA are discussed. The gravitational-wave physics of a recent nonlocal theory with fractional operators and infrared corrections to gravity is presented for the first time.

**Gravitational Waves as Probes for New Physics / 213**

## Stabilities of black hole solutions in vector-tensor theories

**Author:** Shinji Tsujikawa<sup>1</sup>

<sup>1</sup> *Waseda*

We study static and spherically symmetric black hole solutions in two classes of vector-tensor theories: generalized Proca theory and Einstein-Aether theory. We formulate the odd-parity black hole perturbations in these theories by expanding the corresponding action up to second order and discuss whether or not black holes with vector hair suffer ghost

or Laplacian instabilities.

We apply these results to concrete black hole solutions known in the literature and show that some of those solutions can be excluded by the violation of stability conditions.

Our general formulation of odd-parity perturbations is useful to study the propagation of gravitational waves during the inspiral and ringdown phases of binary BHs.

## Gravitational Waves as Probes for New Physics / 317

### Gravitational wave propagation beyond general relativity: waveform distortions and decoherence

**Authors:** Jose Maria Ezquiaga<sup>1</sup>; Macarena Lagos<sup>2</sup>; Meng-Xiang Lin<sup>1</sup>; Wayne Hu<sup>1</sup>

<sup>1</sup> *University of Chicago*

<sup>2</sup> *Columbia University*

**Corresponding Author:** mxlin@uchicago.edu

We study the cosmological propagation of gravitational waves (GW) beyond general relativity (GR) across homogeneous and isotropic backgrounds. We consider scenarios in which GWs interact with an additional tensor field and use a parametrized phenomenological approach that generically describes their coupled equations of motion. We analyze four distinct classes of derivative and non-derivative interactions: mass, friction, velocity, and chiral. We apply the WKB formalism to account for the cosmological evolution and obtain analytical solutions to these equations. We corroborate these results by analyzing numerically the propagation of a toy GW signal. We then proceed to use the analytical results to study the modified propagation of realistic GWs from merging binary black holes, assuming that the GW signal emitted is the same as in GR.

We generically find that tensor interactions lead to copies of the originally emitted GW signal, each one with its own possible modified dispersion relation.

These copies can travel coherently and interfere with each other leading to a scrambled GW signal, or propagate incoherently and lead to echoes arriving at different times at the observer that could be misidentified as independent GW events.

Depending on the type of tensor interaction, the detected GW signal may exhibit amplitude and phase distortions with respect to a GW waveform in GR, as well as birefringence effects.

We discuss observational probes of these interactions with both individual GW events, as well as population studies for both ground- and space-based detectors.

## Gravitational Waves as Probes for New Physics / 285

### Probing the existence of ultralight bosons with black hole superradiance

**Authors:** Nils Siemonsen<sup>1</sup>; William East<sup>1</sup>

<sup>1</sup> *Perimeter Institute*

**Corresponding Author:** nsiemonsen@perimeterinstitute.ca

In the presence of an ultralight bosonic field, spinning black holes are unstable to superradiance. The rotational energy of the black hole is converted into an oscillating boson cloud, which dissipates through the emission of nearly monochromatic gravitational radiation. Thus, gravitational wave observations by ground- or space-based detectors can be used to probe the existence of dark particles weakly coupled to the Standard Model. We demonstrate how these waveforms are obtained utilizing methods from black hole perturbation theory, outline different gravitational wave search strategies for these sources, show current bounds on the existence of ultralight bosonic clouds based

on these searches, and touch on how more complicated couplings to the Standard Model may affect the observational signatures.

### Gravitational Waves as Probes for New Physics / 342

## Gravitational Wave Gastronomy

**Authors:** Anish Ghosal<sup>1</sup>; David Dunsky<sup>2</sup>; Graham White<sup>3</sup>; Hitoshi Murayama<sup>4</sup>; Yuki Sakakihara<sup>5</sup>

<sup>1</sup> *Indian Institute of Technology-Madras, Chennai*

<sup>2</sup> *UC Berkeley*

<sup>3</sup> *IPMU*

<sup>4</sup> *University of California Berkeley (US)*

<sup>5</sup> *Sun Yat-sen University*

**Corresponding Author:** ddunsky@berkeley.edu

The symmetry breaking of grand unified gauge groups in the early universe often leaves behind relic topological defects such as cosmic strings, domain walls, or monopoles. For some symmetry breaking chains that produce domain walls, the accompanied presence of strings can lead to the destruction of the domain wall network, alleviating tension with present-day cosmology and to unique gravitational wave signatures. In this talk, I will discuss these gravitational wave signals which arise when a domain wall network is “eaten” by cosmic strings that nucleate as holes on the wall or when a string network is “eaten” by domain walls that attach to the strings.

### Gravitational Waves as Probes for New Physics / 54

## Collider and GW complementarity in the 2HDM

**Authors:** AJAY Kaladharan<sup>1</sup>; Dorival Gonçalves<sup>1</sup>; Yongcheng Wu<sup>1</sup>

<sup>1</sup> *Oklahoma State University*

**Corresponding Author:** kaladharan.ajay@okstate.edu

We study electroweak phase transition and resultant GWs of a CP conserving 2HDM with a softly broken  $Z_2$  symmetry. We analysed the parameter space of both type I and type II 2hdm without relying on any decoupling limit. We observe  $M_{H^\pm} \approx M_H$  or  $M_{H^\pm} \approx M_A$  favours SFOEWPT in 2HDM. In addition to di-Higgs production, scalar to fermion decay channel is also important to probe phase transition behaviour in 2HDM. We also comment about the shape of potential leading to SFOEWPT in 2hdm.

### Gravitational Waves as Probes for New Physics / 370

## Tentative evidence for echoes from GW190521

**Author:** Jahed Abedi<sup>1</sup>

**Co-authors:** Luís F. Longo ; Niayesh Afshordi

<sup>1</sup> *University of Stavanger*

**Corresponding Author:** jahedabedi@gmail.com

GW190521 in a class of its own is a different signal, being the most massive BBH event observed to date. The exceptionally dominant ringdown of this event and its large mass makes it a plausible candidate to search for GW echoes. In this letter we perform an unprecedented search in two different platforms, satisfying a physical template (matched filtering and MCMC with PyCBC) and model agnostic search (Coherent WaveBurst-cWB). We expect the existence of post-merger horizon mode frequencies  $m \times \Omega_H$  (with  $m=2$  for quadrupolar gravitational radiation) as a consequence of BBH merger non-linear dynamics and Planck scale Boltzmann reflection near the would be event horizon. In this search, with a careful bayesian inference approach using dynamic nested sampling MCMC algorithm, we found  $\ln \mathcal{B}_{\text{IMR}}^{\text{IMRE}} = +2.0$  evidence for such frequencies and their echoes in GW190521. On the other hand, the results obtained via cWB supports that main event and the echo are preferably co-localized,  $\mathcal{B}_{\text{nonco-loc}}^{\text{co-loc}} \approx 7.1$ . Additionally, accounting for all the “look-elsewhere” effects, we find tentative evidence for GW echoes at false detection probability of  $2.5 \times 10^{-3}$ , using cWB pipeline.

**Gravitational Waves as Probes for New Physics / 156**

## On the origin of the LIGO “mystery” noise and the high energy particle physics desert

**Author:** Niayesh Afshordi<sup>None</sup>

**Corresponding Author:** nafshordi@perimeterinstitute.ca

One of the most ubiquitous features of quantum theories is the existence of zero-point fluctuations in their ground states. For massive quantum fields, these fluctuations decouple from infrared observables in ordinary field theories. However, there is no “decoupling theorem” in Quantum Gravity, and we recently showed that the vacuum stress fluctuations of massive quantum fields source a red spectrum of metric fluctuations given by  $\sim \text{mass}^5/\text{frequency}$  in Planck units. I show that this signal is consistent with the reported unattributed persistent noise, or “mystery” noise, in the Laser Interferometer Gravitational-Wave Observatory (LIGO), for the Standard Model of Particle Physics. If this interpretation is correct, then it implies that: 1) This will be a fundamental irreducible noise for all gravitational wave interferometers, and 2) There is no fundamental weakly-coupled massive particle heavier than those in the Standard Model.

**Gravitational Waves as Probes for New Physics / 380**

## Constrain extra dimensions with shortcuts

**Author:** Zi-Chao Lin<sup>1</sup>

**Co-authors:** Liu Yu-Xiao<sup>1</sup>; Hao Yu<sup>2</sup>

<sup>1</sup> Lanzhou University

<sup>2</sup> Chongqing University

**Corresponding Author:** linzch12@lzu.edu.cn

Extra dimensions are expected to solve some long-standing problems in the Standard Model of particle physics. Searching for their traces in our Universe helps to promote our understanding on the physics. Taking advantage of the source property of gravitational waves (GWs), extra dimensions might leave observable effects on GWs. Thus the observation of GWs becomes a new way to probe and study extra dimensions. In the report, we will shortly review the history and viewpoint of extra dimensions, traditional experiments on testing extra dimensions, and some researches on extra dimensions through GWs. We then introduce the conception of shortcuts, which is a new feature

of GWs in extra dimensions. Finally, we shall show what we could learn on extra dimensions from detections of GW170817 and its counterpart GRB 170817A.

**Gravitational Waves as Probes for New Physics / 362**

## **Imprints of black hole area quantization in gravitational waves.**

**Authors:** Adrian del Rio Vega<sup>1</sup>; Ivan Agullo<sup>2</sup>; Jorge Pullin<sup>2</sup>; Michele Maggiore<sup>3</sup>; Vítor Cardoso<sup>4</sup>

<sup>1</sup> *Penn State*

<sup>2</sup> *Louisiana State University*

<sup>3</sup> *Universite de Geneve (CH)*

<sup>4</sup> *IST*

**Corresponding Author:** axd570@psu.edu

We argue that black hole area quantization, in the form predicted by Bekenstein and Mukhanov, could leave observable imprints in the gravitational-wave signal of a binary black hole merger by affecting the absorption properties of the black holes. These imprints include gravitational-wave echoes after the ringdown stage, and suppressed tidal heating during the inspiral phase. This phenomenology is within reach of future gravitational-wave detectors, and could be used to bound the fundamental quantum of black hole area.

**Gravitational Waves as Probes for New Physics / 305**

## **Gravitational Imprints from Heavy Kaluza-Klein Resonances**

**Author:** Mariano Quiros Carcelen<sup>1</sup>

<sup>1</sup> *The Barcelona Institute of Science and Technology (BIST) (ES)*

**Corresponding Author:** quiros@ifae.es

We consider Kaluza-Klein (KK) resonances with masses  $m_{KK}$  at the multi-TeV scale, out of reach of LHC. The backreaction of the radion field on the gravitational metric is taken into account by using the superpotential formalism. The confinement/deconfinement first order phase transition leads to a gravitational wave stochastic background which mainly depends on the scale  $m_{KK}$  and the number of colors,  $N$ , in the dual theory. Its power spectrum peaks at a frequency that depends on the amount of tuning required in the electroweak sector. It turns out that the present and forthcoming gravitational wave observatories can probe scenarios where the KK resonances are very heavy.

**Gravitational Waves as Probes for New Physics / 372**

## **Exploring fundamental physics with gravitational wave observations**

**Author:** Bangalore Sathyaprakash<sup>1</sup>

<sup>1</sup> *The Pennsylvania State University*



**Corresponding Author:** bss25@psu.edu

Gravitational wave observations provide a plethora of opportunities to explore questions in fundamental physics and physics beyond the standard model. Multimessenger observation of gravitational waves and electromagnetic radiation from distant sources can be used to test modified theories of gravity, measure cosmological parameters, ascertain the nature of dark matter and dark energy. Gravitational waves emitted in the aftermath of neutron star collisions potentially carry the signature of QCD phase transition. Axionic clouds around black holes could lead to continuous gravitational waves with characteristic signature. In this talk I will describe the different aspects of fundamental physics that is accessible to the gravitational-wave window.

**Gravitational Waves as Probes for New Physics / 307**

## Effective picture of cosmic bubble expansion

**Authors:** Rong-Gen Cai<sup>1</sup>; Shao-Jiang Wang<sup>None</sup>

<sup>1</sup> ITP-CAS

**Corresponding Author:** leoneo.schwang@gmail.com

We derive an effective equation-of-motion for an expanding bubble wall in the thermal plasma with a general form of the thermal friction. The efficiency factor for gravitational waves productions from colliding bubble walls is obtained with a special interest for the strong first-order phase transition.

**Gravitational Waves as Probes for New Physics / 152**

## Gravitational waves produced by astrophysical sources and propagation through cosmic distances in inhomogeneous universe

**Authors:** Anzhong Wang<sup>1</sup>; Bowen Li<sup>1</sup>; Jared Fier<sup>1</sup>; Shinji Mukohyama<sup>2</sup>; Tao Zhu<sup>3</sup>; Xiongjun Fang<sup>4</sup>

<sup>1</sup> Baylor University

<sup>2</sup> Kyoto University

<sup>3</sup> Zhejiang University of Technology

<sup>4</sup> Hunan Normal University

**Corresponding Author:** jared\_fier@baylor.edu

Gravitational waves produced by astrophysical sources and propagation through cosmic distances in inhomogeneous universe

In this talk, we shall present our recent studies of gravitational waves (GWs) first produced by remote compact astrophysical sources and then propagating in our inhomogeneous universe through cosmic distances, before arriving at detectors. To describe such GWs properly, we first introduce three scales,

$\lambda$ ,  $L_c$  and  $L$ , denoting, respectively, the typical wavelength of GWs, the scale of the cosmological perturbations, and the size of the observable universe. For GWs to be detected by the current and foreseeable detectors, the condition  $\lambda \ll L_c \ll L$  holds. Then, such GWs can be approximated as high-frequency GWs and be well separated from the background  $\gamma_{\mu\nu}$  by averaging the spacetime curvatures over a scale  $\ell$ , where  $\lambda \ll \ell \ll L_c$ , and  $g_{\mu\nu} = \gamma_{\mu\nu} + \epsilon h_{\mu\nu}$  with  $\epsilon \simeq \text{cal}O(\lambda/L)$ , and  $h_{\mu\nu}$  denotes the GWs. In order for the backreaction of the GWs to the background spacetimes to be negligible, we must assume that  $|h_{\mu\nu}| \ll 1$ , in addition to the condition  $\epsilon \ll 1$ , which are also the conditions for the linearized Einstein field equations for  $h_{\mu\nu}$  to be valid. Such studies can

be significantly simplified by properly choosing gauges, such as the spatial ( $\chi_{0\mu} = 0$ ), traceless ( $\gamma^{\mu\nu}\chi_{\mu\nu} = 0$ ), and Lorentz ( $\nabla^\nu\chi_{\mu\nu} = 0$ ) gauges, where  $\chi_{\mu\nu} \equiv h_{\mu\nu} - h\gamma_{\mu\nu}/2$ , and  $\nabla^\nu$  denotes the covariant derivative with respect to  $\gamma_{\mu\nu}$ . We show that these three different gauge conditions can be imposed simultaneously, even when the background is not vacuum, as long as the high-frequency GW approximation is valid. However, to develop the formulas that can be applicable to as many cases as possible, we first write down explicitly the linearized Einstein field equations for  $\chi_{\mu\nu}$  by imposing only the spatial gauge. Then, applying these formulas together with the geometrical optics approximation to such GWs, we find that they still move along null geodesics and its polarization bi-vector is parallel-transported, even when both the cosmological scalar and tensor perturbations are present. In addition, we also calculate the gravitational integrated Sachs-Wolfe effects due to these two kinds of perturbations, whereby the dependences of the amplitude, phase and luminosity distance of the GWs on these perturbations are read out explicitly.

J. Fier, X.-J. Fang, B.-W. Li, S. Mukohyama, A. Wang, T. Zhu, Gravitational wave cosmology I: high frequency approximation, Phys. Rev. D (2021) [arXiv:2102.08968].

## Gravitational Waves as Probes for New Physics / 146

### What are gravitational waves telling us about fundamental physics?

**Author:** Nicolas Yunes<sup>1</sup>

<sup>1</sup> *University of Illinois at Urbana-Champaign*

**Corresponding Author:** nyunes@illinois.edu

The recent gravitational wave observations of the collision of black holes and neutron stars have allowed us to pierce into the extreme gravity regime, where gravity is simultaneously unfathomably large and wildly dynamical. These waves encode a trove of information about physics that is prime for the taking, including potential revelations about the validity of Einstein's theory and possible string-inspired extensions. In this talk, I will describe some of the physics inferences we have made from gravitational wave observations, and the future inferences that will come next.

## Gravitational Waves as Probes for New Physics / 327

### Finding sound shells in LISA mock data using likelihood sampling

**Authors:** Felix Giese<sup>1</sup>; Jorinde van de Vis<sup>2</sup>; Thomas Konstandin<sup>1</sup>

<sup>1</sup> *DESY*

<sup>2</sup> *Deutsches Elektronen-Synchrotron DESY*

**Corresponding Author:** jorinde.van.de.vis@desy.de

I discuss to what extent LISA can observe features of gravitational wave spectra originating from cosmological first-order phase transitions. I focus on spectra which are of the form of double-broken power laws. These spectra are predicted by hydrodynamic simulations and also analytical models such as the sound shell model. I argue that the ratio of the two break frequencies is an interesting observable since it can be related to the wall velocity while overall amplitude and frequency range are often degenerate for the numerous characteristics of the phase transition. The analysis uses mock data obtained from the power spectra predicted by the simplified simulations and the sound shell model and analyzes the detection prospects using  $\chi^2$ -minimization and likelihood sampling. I point out that the prospects of observing two break frequencies from the electroweak phase transition is hindered by a shift of the spectrum to smaller frequencies for strong phase transitions.

Finally, I also highlight some differences between signals from the sound shell model compared to simulations.

#### Gravitational Waves as Probes for New Physics / 329

### Gravitational waves from bubble collisions in first order phase transitions

**Author:** Marek Lewicki<sup>1</sup>

<sup>1</sup> *University of Warsaw*

**Corresponding Author:** marek.lewicki@fuw.edu.pl

We will discuss energy budget of first order phase transitions and identify models capable of supporting extreme supercooling necessary to feature bubble collisions as the main source of gravitational waves. We will also review the new semi-analytical calculation of the spectrum appropriate in such strong transitions.

#### Gravitational Waves as Probes for New Physics / 352

### Gravitational Wave Echo of Relaxion Trapping

**Authors:** Abhishek Banerjee<sup>1</sup>; Eric Madge<sup>1</sup>; Gilad Perez<sup>2</sup>; Pedro Schwaller<sup>None</sup>; Wolfram Ratzinger<sup>3</sup>

<sup>1</sup> *Weizmann Institute of Science*

<sup>2</sup> *Weizmann Institute*

<sup>3</sup> *Johannes Gutenberg Universität Mainz*

**Corresponding Author:** eric.madge-pimentel@weizmann.ac.il

In order to solve the hierarchy problem, the relaxion must remain trapped in the correct minimum, even if the electroweak symmetry is restored after reheating. In this scenario, the relaxion starts rolling again until the back-reaction potential, with its set of local minima, reappears. Depending on the time of barrier-reappearance, Hubble friction alone may be insufficient to re-trap the relaxion in a large portion of the parameter space. Thus, an additional source of friction is required, which might be provided by coupling to a dark photon. The dark photon experiences a tachyonic instability as the relaxion rolls, which slows down the relaxion by backreacting to its motion, and efficiently creates anisotropies in the dark photon energy-momentum tensor, sourcing gravitational waves. We calculate the spectrum of the resulting gravitational wave background from this new mechanism, and evaluate its observability by current and future experiments. We further investigate the possibility that the coherently oscillating relaxion constitutes dark matter and present the corresponding constraints from gravitational waves.

#### Gravitational Waves as Probes for New Physics / 461

### Baryogenesis and gravity waves from a UV-completed electroweak phase transition

**Authors:** Avi Friedlander<sup>1</sup>; James Cline<sup>2</sup>; Kimmo Juhani Kainulainen<sup>3</sup>; Benoit Laurent<sup>4</sup>; Dong-Ming He<sup>None</sup>

<sup>1</sup> *Queen's University*

<sup>2</sup> McGill University, (CA)

<sup>3</sup> University of Jyväskylä (FI)

<sup>4</sup> CEA / DAM Ile de France (FR)

**Corresponding Author:** kimmo.kainulainen@cern.ch

We study gravity wave production and baryogenesis at the electroweak phase transition in a real singlet scalar extension of the Standard Model, including vectorlike top partners, to generate the CP violation needed for electroweak baryogenesis (EWBG). The singlet makes the phase transition strongly first order through its coupling to the Higgs boson, and it spontaneously breaks CP invariance through a dimension-five contribution to the top quark mass term, generated by integrating out the heavy top quark partners. We improve on previous studies by incorporating updated transport equations, compatible with large bubble wall velocities. The wall speed and thickness are computed directly from the microphysical parameters rather than treating them as free parameters, allowing for a first-principles computation of the baryon asymmetry. The size of the CP-violating dimension-five operator needed for EWBG is constrained by collider, electroweak precision, and renormalization group running constraints. We identify regions of parameter space that can produce the observed baryon asymmetry or observable gravitational wave (GW) signals. Contrary to standard lore, we find that for strong deflagrations, the efficiencies of large baryon asymmetry production and strong GW signals can be positively correlated. However, we find the overall likelihood of observably large GW signals to be smaller than estimated in previous studies. In particular, only detonation-type transitions are predicted to produce observably large gravitational waves.

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## Stochastic GWs from cosmological phase transitions

**Author:** Thomas Markus Konstandin<sup>None</sup>

**Corresponding Author:** thomas.konstandin@desy.de

I will discuss the current status of the production of stochastic GW backgrounds by cosmological phase transitions. Main focus will be the differences between fully hydrodynamic simulations and the recently presented hybrid approach. I will also touch on recent results on the energy budget of the phase transition and the LISA sensitivity forecasts using likelihood sampling.

Based on arXiv: 2004.06995, 2010.00971, 2107.06275.

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## Gravitational waves from first-order phase transitions: A hybrid simulation, and signal enhancement from density perturbations

**Authors:** Ryusuke Jinno<sup>1</sup>; Thomas Konstandin<sup>1</sup>; Henrique Rubira<sup>1</sup>; Jorinde van de Vis<sup>2</sup>

<sup>1</sup> DESY

<sup>2</sup> Deutsches Elektronen-Synchrotron DESY

**Corresponding Author:** ryusukejinno@gmail.com

Over the next few decades, we will have an exciting opportunity to detect GWs from the early Universe with space interferometers. In this talk, we first propose an efficient numerical scheme to calculate GWs from sound waves in first-order phase transitions, which reveals more detailed structure of the spectrum. Based on this simulation, we next discuss the possibility of the enhancement of the GW signal in the presence of density perturbations. The first part is based on 2010.00971 with

T. Konstandin and H. Rubira (DESY), while the second part is based on an ongoing work with T. Konstandin, H. Rubira, and J. van de Vis (DESY).

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## **Gravitational Wave Production right after a Primordial Black Hole Evaporation**

**Author:** Keisuke Inomata<sup>1</sup>

**Co-authors:** Takahiro Terada<sup>2</sup>; Kyohei Mukaida<sup>3</sup>; Masahiro Kawasaki<sup>4</sup>; Tsutomu Yanagida<sup>5</sup>

<sup>1</sup> *University of Chicago*

<sup>2</sup> *Institute for Basic Science*

<sup>3</sup> *DESY*

<sup>4</sup> *The University of Tokyo*

<sup>5</sup> *T. D. Lee Institute*

**Corresponding Author:** inomata@uchicago.edu

We discuss the footprint of evaporation of primordial black holes (PBHs) on stochastic gravitational waves (GWs) induced by scalar perturbations. We consider the case where PBHs once dominated the Universe but eventually evaporated before the big bang nucleosynthesis. The reheating through the PBH evaporation could end with a sudden change in the equation of state of the Universe compared to the conventional reheating caused by particle decay. We show that this “sudden reheating” by the PBH evaporation enhances the induced GWs, whose amount depends on the length of the PBH-dominated era and the width of the PBH mass function. We also explore the possibility to constrain the primordial abundance of the evaporating PBHs by observing the induced GWs. This presentation will be based on our paper, arXiv:2003.10455.

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## **Stochastic Gravitational Waves from String Cosmology**

**Author:** Robert Brandenberger<sup>1</sup>

<sup>1</sup> *McGill University*

**Corresponding Author:** rhb@physics.mcgill.ca

I will argue that the slope of the spectrum of gravitational waves may provide us evidence of superstring effects in early universe cosmology. Both String Gas Cosmology and the S-Brane Mediated Ekpyrotic scenario predict a blue tilt of the tensor spectrum.

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## **Testing gravitational theories with broken Lorentz symmetry by gravitational wave observations**

**Authors:** Chao Zhang<sup>1</sup>; Xiang Zhao<sup>None</sup>; Anzhong Wang<sup>2</sup>

<sup>1</sup> *Zhejiang University of Technology*<sup>2</sup> *Baylor University***Corresponding Author:** c\_zhang@baylor.edu

Lorentz symmetry is the cornerstone of modern physics, and is consistent with all experiments carried out so far. However, due to various motivations, gravitational theories with Lorentz symmetry breaking have been proposed, and one of the examples is the Horava-Lifshitz theory, motivated by the quantization of gravity. Another example is the Einstein-aether ( $\alpha$ -) theory, which is a vector-tensor theory with the vector (aether) field being always timelike and unity. The  $\alpha$ -theory is self-consistent (such as free of ghosts and instability), and satisfies all the experimental tests carried out so far. Its Cauchy problem is well-posed, and energy is always positive (at least as far as the hypersurface-orthogonal aether field is concerned). In addition, black holes exist and can be formed from gravitational collapse of realistic matter.

In this talk, we shall present our recent studies of gravitational waves (GWs) produced by massive and compact objects in  $\alpha$ -theory, including their waveforms, polarizations, response function, its Fourier transform, and energy loss rate through three different channels of radiation, the scalar, vector and tensor modes. Combination of such theoretical predictions with observations of GWs can bring severe constraints on the theory.

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## Universal $10^{20}$ Hz stochastic gravitational waves from photon spheres of black holes

**Author:** Kaishu Saito<sup>1</sup>**Co-authors:** Jiro Soda<sup>1</sup>; Hirotaka Yoshino<sup>2</sup><sup>1</sup> *Kobe University*<sup>2</sup> *Kobe University and Osaka city University***Corresponding Author:** 184s151s@stu.kobe-u.ac.jp

We show that photon spheres of supermassive black holes generate high-frequency stochastic gravitational waves through the photon-graviton conversion.

Remarkably, the frequency is universally determined as  $m_e \sqrt{m_e/m_p} \simeq 10^{20}$  Hz in terms of the proton mass  $m_p$  and the electron mass  $m_e$ .

It turns out that the density parameter of the stochastic gravitational waves  $\Omega_{\text{gw}}$  could be  $10^{-12}$ . Since the existence of the gravitational waves from photon spheres is robust, it is worth seeking methods of detecting high-frequency gravitational waves around  $10^{20}$  Hz.

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## Gravity and cosmology beyond general relativity and gravitational waves

**Author:** Shinji Mukohyama<sup>None</sup>**Corresponding Author:** s.mukohyama@gmail.com

After motivating gravity and cosmology beyond general relativity, I will review some theories and their phenomenologies, including gravitational wave physics.

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## **Renormalization group analysis of the self-interacting axion cloud**

**Author:** Hidetoshi Omiya<sup>1</sup>

<sup>1</sup> *Kyoto University*

**Corresponding Author:** omiya@tap.scphys.kyoto-u.ac.jp

There are strong interests in considering ultra-light scalar fields (especially axion) around a rapidly rotating black hole because of the possibility of observing gravitational waves from axion condensate (axion cloud) around black holes. Motivated by this consideration, we propose a new method to study the dynamics of an ultra-light scalar field with self-interaction around a rapidly rotating black hole, which uses the dynamical renormalization group method. We find that for relativistic clouds, a saturation of the superradiant instability by the scattering of the axion due to the self-interaction does not occur in the weakly non-linear regime when we consider the adiabatic growth of the cloud from a single superradiant mode. This may suggest that an explosive phenomenon called the Bosenova may inevitably happen for relativistic axion clouds, at least once in its evolutionary history.

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## **Probing beyond standard model physics from gravitational waves**

**Author:** Tanmay Kumar Poddar<sup>1</sup>

<sup>1</sup> *Physical Research Laboratory*

**Corresponding Author:** tanmaypoddar06@gmail.com

The orbital period loss of Hulse-Taylor binary system was the first indirect evidence of gravitational wave (GW) which confirms Einstein's general theory of relativity to a very good extent. However the uncertainty in the measurement of GW from observation and GR prediction allows us to probe physics beyond the standard picture. In this talk I will discuss about probing beyond standard model physics from GW observation and some other astrophysical phenomena.

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## **Primordial gravitational waves revealed by a spinning axion**

**Authors:** Geraldine Servant<sup>1</sup>; Peera Simakachorn<sup>2</sup>; Yann Gouttenoire<sup>3</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron (DE)*

<sup>2</sup> *Universität Hamburg and DESY*

<sup>3</sup> *Deutsches Elektronen-Synchrotron DESY*

**Corresponding Author:** peera.simakachorn@desy.de

A fast-spinning axion can dominate the Universe at early times and generates the so-called kination era. The presence of kination imprints a smoking-gun spectral enhancement in the primordial gravitational-wave (GW) background. Current and future-planned GW observatories could constrain particle theories that generate the kination phase. Surprisingly, the viable parameter space

allows for a kination era at the PeV-EeV scale and generates a peaked spectrum of GW from either cosmic strings or primordial inflation, which lies inside ET and CE windows.

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## **Fast Gravitational Wave Burst from Axion Clumps**

**Author:** Yun-Long Zhang<sup>1</sup>

<sup>1</sup> *NAOC, Beijing*

**Corresponding Author:** zhangyunlong001@gmail.com

The axion objects such as axion mini-clusters and axion clouds around spinning black holes induce parametric resonances of electromagnetic waves through the axion-photon interaction. In particular, it has been known that the resonances from the axion with the mass around  $\mu\text{eV}$  may explain the observed fast radio bursts (FRBs). Here we argue that similar bursts of high frequency gravitational waves, which we call the fast gravitational wave bursts (FGBs), are generated from axion clumps with the presence of gravitational Chern-Simons (CS) coupling. The typical frequency is half of the axion mass, which in general can range from kHz to GHz. We also discuss the secondary gravitational wave production associated with FRB, as well as the possible host objects of the axion clouds, such as primordial black holes. Future detections of FGBs together with the observed FRBs are expected to provide more evidence for the axion.

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## **Probing GHz gravitational waves with magnons**

**Authors:** Asuka Ito<sup>1</sup>; Jiro Soda<sup>2</sup>

<sup>1</sup> *Tokyo institute of technology*

<sup>2</sup> *Kobe University*

**Corresponding Author:** aito@cts.nthu.edu.tw

In the era of gravitational wave astronomy/cosmology, it is important not only to improve the sensitivity of existing detectors but also to extend detectable frequency range with novel methods. We show that gravitational waves can induce resonant spin precessions of electrons (magnon) in the presence of an external magnetic field. This phenomenon, we call it graviton-magnon resonance, enables us to probe gravitational waves in the GHz frequency range. Furthermore, we give upper limits on GHz gravitational waves by utilizing measurements of resonance fluorescence of magnons.

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## **Towards the precise prediction of the phase transition gravitational wave**

**Author:** Fa Huang Huang<sup>1</sup>

<sup>1</sup> *SunYat-Sen university*



**Corresponding Author:** huangfp8@sysu.edu.cn

After the discovery of Higgs boson and gravitational wave (GW), the phase transition GW becomes a new and realistic approach to explore new physics and the fundamental physics. However, current predictions on the phase transition GW have large uncertainties from energy budget, bubble wall velocity and so on. We study how to obtain more precise phase transitional GW

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## **Testing the dispersion of gravitational waves using b-EMRI systems**

**Author:** Xian Chen<sup>None</sup>

**Corresponding Author:** chenxianpku@gmail.com

Binary extreme-mass-ratio inspiral (b-EMRIs) consists of a stellar-mass binary black hole orbiting around a supermassive massive black hole. Such a three-body system emits simultaneously low-frequency (milli-Hertz) gravitational waves and high-frequency (hundred Hertz) ones. Therefore, it is ideal for testing the dispersion of gravitational waves. In this talk, I will show how such systems could be produced naturally in astrophysical environments, via the processes of either tidal capture or planetary-like migration. By coordinating ground-based and future space-borne gravitational-wave observatories, we could constrain the dispersion of gravitational waves, and hence the mass of gravitons, to a precision that is ten times better than the current limit.

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## **From the merger rate of Primordial Black Hole Binaries to the Primordial Power Spectrum of curvature perturbation on small scales**

**Author:** Zhang Ying-li<sup>None</sup>

**Corresponding Author:** yingli@tongji.edu.cn

The properties of primordial curvature perturbations on small scales are still unknown while those on large scales have been well probed by the observations of the cosmic microwave background anisotropies and the large scale structure. We propose the reconstruction method of primordial curvature perturbations on small scales through the merger rate of binary primordial black holes, which could form from large primordial curvature perturbation on small scales.

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## **Search for ultralight dark matter and cosmological phase transition using pulsar timing arrays**

**Author:** Qiang Yuan<sup>1</sup>

<sup>1</sup> Purple Mountain Observatory, CAS

**Corresponding Author:** yuanq@pmo.ac.cn

Pulsar timing arrays record the arrival time of radio pulses from dozens of millisecond pulsars. The pulsars of different sky locations construct a network that is sensitive to gravitational waves and

dark matter signals. There are three Pulsar timing arrays in the world, PPTA, EPTA and NANOGrav, that are actively gathering pulsar timing data with very high precision. In this talk, we use the recent PPTA data to search for ultralight dark photon dark matter signal and the phase transition gravitational wave background signal. We find that in both cases, the sensitivity of the current PPTA data exceeds the current limit in the low-frequency range, and a fair amount of parameter space can therefore be probed.

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## Detecting primordial black hole as dark matter by induced gravitational waves

**Author:** Shi Pi<sup>1</sup>

<sup>1</sup> *ITP, CAS*

**Corresponding Author:** shi.pi@itp.ac.cn

Primordial black holes (PBHs) may form when the high peaks of the primordial density perturbation re-enter the Hubble horizon, while at the same time gravitational waves induced by the density perturbation at second order are generated. Currently observational constraints make it possible for asteroid-mass PBHs to be all dark matter, whose concomitant induced GWs are in the millihertz band. I will show that if all or a large portion of the PBHs are composed of dark matter, the corresponding induced gravitational wave energy spectrum must be detectable by space-borne interferometers like LISA, irrespective of linear local non-Gaussianity of the scalar perturbation.

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## Primordial black holes and gravitational waves

**Author:** Sai Wang<sup>1</sup>

<sup>1</sup> *IHEP, CAS*

**Corresponding Author:** wangsai@ihep.ac.cn

I will report the current progress in our works on the detection of primordial black holes (PBHs) with gravitational waves, including the transients and the stochastic background of gravitational waves (SGWB). The observations of gravitational waves by LIGO open a new window to probe the PBHs, which could be a viable candidate of cold dark matter. We find that the scenario of PBHs can explain the merger rates of GW200105 and GW200115, which were claimed to be neutron star-black hole binaries. As a second observational window, SGWB can be also capable of constraining the abundance of PBHs through observations of SGWBs from the coalescing binaries and the enhanced curvature perturbations.

**Gravity and Supergravity / 475**

## Sequestered Inflation

**Author:** Renata Kallosh<sup>1</sup>

<sup>1</sup> *Stanford university*

**Corresponding Author:** kallosh@stanford.edu

I describe the Sequestered Inflation as presented in the recent works with M. Gunaydin, A. Linde, Y. Yamada and T. Wrase in 2008.01494, 2108.08491, 2108.08492. We construct supergravity models allowing to sequester the phenomenology of inflation from the Planckian energy scale physics. The procedure consists of two steps: At Step I we study supergravity models associated with string theory or M-theory and find supersymmetric Minkowski vacua with flat directions. The corresponding massless Goldstone supermultiplets are related to the symmetries of flux superpotentials. At Step II we uplift these flat directions to inflationary plateau potentials using the nilpotent multiplet. The sequestered models include seven hyperbolic disks. Their predictions are among the main B-mode targets for future CMB experiments.

**Gravity and Supergravity / 549**

## Quantum gravity microstates from Fredholm determinants

**Author:** Clifford Johnson<sup>1</sup>

<sup>1</sup> *University of Southern California and Princeton University*

**Corresponding Author:** johnson1@usc.edu

This talk describes how to go well beyond the perturbative correspondence between JT gravity and large N matrix models (discovered by Saad, Shenker and Stanford) to uncover detailed information about the individual microscopic states of the matrix model. This corresponds to data about the underlying microstates of the gravity system, which are crucial in the regime where the smooth spacetime description is inadequate. This system is therefore a fully tractable model of quantum gravity where the phenomenon of emergent spacetime is manifest. The key new tool in this context is a Fredholm determinant, which can be computed using numerical methods.

**Gravity and Supergravity / 477**

## Thermodynamics of Supersymmetric Black Holes in AdS(5)

**Author:** Finn Larsen<sup>1</sup>

<sup>1</sup> *Michigan U*

**Corresponding Author:** larsenf@umich.edu

Supersymmetric black holes have zero temperature but their dependence on chemical potentials defines conventional thermodynamics. The phase diagram for supersymmetric AdS black holes is reminiscent of Schwarzschild-AdS, featuring a cusp, a minimal “temperature”, and a Hawking-Page transition. This talk presents a complete phase diagram and discusses the confinement/deconfinement transition for supersymmetric black holes in AdS(5) and their N=4 SYM dual.

**Gravity and Supergravity / 487**

## Microscopic description of brane gauginos

**Author:** Gary Shiu<sup>None</sup>

**Corresponding Author:** shiu@physics.wisc.edu

Different aspects of explicit dS proposals in string theory have recently come under intense scrutiny. One key ingredient is D7-brane gaugino condensation, which can be straightforwardly treated using effective 4d supergravity. However, it is also desirable to derive the relevant scalar potential directly from a 10d Lagrangian which captures the interactions among the various localized sources and the background fields. While progress in this endeavour has recently been made, issues related to divergences and non-localities related to the quartic gaugino coupling have remained problematic in the available proposals. I will discuss an explicitly local and finite D7-brane quartic gaugino term which reproduces the relevant part of the 4d supergravity action upon dimensional reduction. This is both a step towards a more complete understanding of 10d type-IIB supergravity as well as specifically towards better control of dS constructions in string theory involving gaugino condensation.

**Gravity and Supergravity / 489**

## Geometry and physics on the boundary of the supergravity landscape

**Author:** Ling Lin<sup>1</sup>

<sup>1</sup> *CERN*

**Corresponding Author:** ling.lin@cern.ch

The landscape of supergravity theories arising from string compactifications is highly constrained by the internal geometry. In this talk, I will argue that, rather than being a limitation of string model building, these geometric constraints reflect physical consistency conditions that delineate the landscape from the swampland. I will focus on constructions of 8d and 6d supergravity theories via F-theory, and discuss geometric restrictions on the possible gauge symmetries, including the global structure of the gauge group. As I will explain in the talk, the corresponding physical consistency conditions are related to (generalized) global symmetries.

**Gravity and Supergravity / 485**

## Duality and Higher Derivatives

**Author:** Olaf Hohm<sup>1</sup>

<sup>1</sup> *Humboldt U Berlin*

**Corresponding Author:** ohohm@physik.hu-berlin.de

TBA

**Gravity and Supergravity / 488**

## The Unreasonable Effectiveness of Higher-Derivative Supergravity in AdS<sub>4</sub> Holography

**Author:** Nikolay Bobev<sup>1</sup>

<sup>1</sup> *KU Leuven Association*

**Corresponding Author:** nikolay.bobev@kuleuven.be

I will describe the four-derivative corrections to four-dimensional  $N=2$  minimal gauged supergravity and show that they are controlled by two constants. Interestingly, the solutions of the equations of motion in the two-derivative theory are not modified by the higher-derivative corrections. I will use this to arrive at a general formula for the regularized on-shell action for any asymptotically locally AdS<sub>4</sub> solution of the theory and show how the higher-derivative corrections affect black hole thermodynamic quantities in a universal way. I will employ these results in the context of holography to derive new explicit results for the subleading corrections in the large  $N$  expansion of supersymmetric partition functions on various compact manifolds for a large class of three-dimensional SCFTs arising from M2-branes. I will also briefly discuss possible extensions and generalizations of these results.

**Gravity and Supergravity / 483**

## S-fold solutions from D=4 supergravity vacua

**Author:** Mario Trigiante<sup>1</sup>

<sup>1</sup> *Politecnico di Torino*

**Corresponding Author:** mario.trigiante@polito.it

In this talk I will review the construction of new S-fold solutions of Type IIB string theory starting from vacua of a maximal four-dimensional supergravity with a suitable dyonic gauging. The global properties of certain moduli are analyzed.

**Gravity and Supergravity / 473**

## Local SUSY, an unconventional approach

**Author:** Jorge Zanelli<sup>1</sup>

<sup>1</sup> *CECS, Valdivia*

**Corresponding Author:** z@cecs.cl

Unconventional SUSY connects spacetime and internal symmetries, combining spin-1 gauge field and spin-1/2 matter particles in a single Lie superalgebra-valued connection. In this representation, states do not come in Bose-Fermi pairs, avoiding the doubling of particles and fields. If the local symmetry contains the Lorentz group, gravity is inevitably included, but there are no spin-3/2 or higher fundamental fields. Local SUSY is a conditional symmetry of the action, like local Poincaré or AdS invariances that depend on the nature of the spacetime background. The resulting systems are remarkably simple, closely resembling a standard quantum field theory and SUSY still emerges as a contingent symmetry, dependent on the features of the vacuum/ground state. We illustrate the general construction with some examples.

**Gravity and Supergravity / 478**

## Gravitino production during inflation

**Author:** Lorenzo Sorbo<sup>1</sup>

<sup>1</sup> *University of Massachusetts, Amherst*

**Corresponding Author:** sorbo@physics.umass.edu

In this talk I will review the dynamics of supergravity models in inflation, focusing especially on the amplification of the modes of the gravitino induced by the time-dependent background. In particular, I will show that in certain well-motivated models in supergravity, gravitinos are produced during inflation, and in their turn source scalar metric perturbations. This process modifies the tensor-to-scalar ratio, allowing to revive models of inflation that, in the absence of supersymmetry, are ruled out by observation.

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## Odd-dimensional analogue of the Euler characteristic

When compact manifolds  $X$  and  $Y$  are both even dimensional, their Euler characteristics obey the Kunneth formula  $\chi(X \times Y) = \chi(X)\chi(Y)$ . In terms of the Betti numbers of  $b_p(X)$ ,  $\chi(X) = \sum_p (-1)^p b_p(X)$ , implying that  $\chi(X) = 0$  when  $X$  is odd dimensional. We seek a linear combination of Betti numbers, called  $\rho$ , that obeys an analogous formula  $\rho(X \times Y) = \chi(X)\rho(Y)$  when  $Y$  is odd dimensional. The unique solution is  $\rho(Y) = -\sum_p (-1)^p b_p(Y)$ . Physical applications include: (1)  $\rho \rightarrow (-1)^m \rho$  under a generalized mirror map in  $d = 2m+1$  dimensions, in analogy with  $\chi \rightarrow (-1)^m \chi$  in  $d = 2m$ ; (2)  $\rho$  appears naturally in compactifications of M-theory. For example, the 4-dimensional Weyl anomaly for M-theory on  $X^4 \times Y^7$  is given by  $\chi(X^4)\rho(Y^7) = \rho(X^4 \times Y^7)$  and hence vanishes when  $Y^7$  is self-mirror. Since, in particular,  $\rho(Y \times S^1) = \chi(Y)$ , this is consistent with the corresponding anomaly for Type IIA on  $X^4 \times Y^6$ , given by  $\chi(X^4)\chi(Y^6) = \chi(X^4 \times Y^6)$ , which vanishes when  $Y^6$  is self-mirror; (3) In the partition function of p-form gauge fields,  $\rho$  appears in odd dimensions as  $\chi$  does in even.

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## Non-relativistic Gravity and Supergravity

**Author:** E.A. Bergshoeff<sup>1</sup>

<sup>1</sup> *Rijksuniversiteit Groningen*

**Corresponding Author:** e.a.bergshoeff@rug.nl

In this talk I will show that Newtonian gravity is not the unique non-relativistic gravity theory that can be defined by taking a limit of (matter coupled) general relativity. I will discuss several extensions of Newtonian gravity including non-relativistic gravity theories involving geometries with a higher co-dimensional foliation and with non-zero torsion. Using these extensions, I will show how a non-relativistic limit of 10D supergravity can be defined that can be identified with the effective low-energy approximation of a non-relativistic superstring theory. Using this identification I will discuss several aspects of non-relativistic superstring theory using field theory techniques.

**Gravity and Supergravity / 492**

## Three notions of brane gravity localisation

**Author:** Kellogg Sheffield Stelle<sup>1</sup>

<sup>1</sup> *Imperial College (GB)*

**Corresponding Author:** k.stelle@imperial.ac.uk

Effectively generating a lower-dimensional theory of gravity or supergravity on a subsurface brane worldvolume within a noncompact transverse space requires certain special conditions for the transverse space structure. Three different scenarios emerge, depending crucially on the nature of boundary conditions that are imposed on solutions as one transversely approaches the brane worldvolume. Genuinely lower-dimensional behaviour at long worldvolume distances can be compatible with short-distance higher-dimensional structure, but this requires a specific type of boundary condition compatible with the existence of normalisable transverse-space zero modes is chosen.

**Gravity and Supergravity / 476**

## **Double Field Theory and Pseudo-Supersymmetry**

**Author:** Christopher Pope<sup>1</sup>

<sup>1</sup> *High Energy Phys.Group Blackett-Lab Imp.Coll.*

**Corresponding Author:** pope@physics.tamu.edu

TBA

**Gravity and Supergravity / 70**

## **Beyond of the Poincaré Chern-Simons hypergravity, in (2+1) dimensions.**

**Authors:** David Tempo<sup>1</sup>; Evelyn Rodríguez<sup>2</sup>; Javier Matulich<sup>3</sup>; Patrick Concha<sup>4</sup>; Ricardo Caroca<sup>5</sup>

<sup>1</sup> *Universidad Católica de Temuco*

<sup>2</sup> *Universidad del Bío-Bío*

<sup>3</sup> *Université Libre de Bruxelles and International Solvay Institutes*

<sup>4</sup> *Universidad Católica de la Santísima Concepción*

<sup>5</sup> *Universidad Católica de la Santísima Concepción, Chile*

**Corresponding Author:** rcaroca@ucsc.cl

We study the minimal coupling of Chern-Simons gravity based on the Maxwell symmetry with massless spin-5/2 gauge fields, in three dimensions. It is shown the simplest hyper-Maxwell superalgebra and its corresponding Chern-Simons gravity, which contains a massless spin-2 fields which is coupled with a massless Majorana fermion spin-5/2. For certain combinations of  $osp(1/4)$  and  $sp(4)$  algebras, we find two different alternatives for hypersymmetric extensions of the Maxwell algebra, using the Inönü-Wigner contraction procedure. The hyper-Maxwell Chern-Simons actions was constructed for each case, which show interactions of non-propagating spin-4 fields with one or two spin-5/2 gauge fields.

**Gravity and Supergravity / 470**

## **The anomaly that was not meant IIB**

**Author:** Miguel Montero<sup>1</sup>

<sup>1</sup> *Harvard U*

**Corresponding Author:** mmontero@g.harvard.edu

Type IIB supergravity famously has a discrete duality group, which is an exact symmetry of the full type IIB string theory. This symmetry has potential quantum anomalies, which could render the theory inconsistent. In this talk I will describe how we computed these anomalies in recent work, and show they are nonvanishing, but remarkably, they can be cancelled by a subtle modification of the IIB Chern-Simons term in what amounts to a new variant of the Green-Schwarz mechanism. This can only happen because of some “miraculous cancellations” that depend on the details of the IIB supergravity spectrum. I will also describe alternative ways to cancel this anomaly, presenting variant versions of IIB string theory which have the same IIB supergravity as the low-energy limit, but which differ at the nonperturbative level. These theories may or may not be in the Swampland.

**Gravity and Supergravity / 486**

## **(Supergravity) Anomalies as Obstructions**

**Author:** Ruben Minasian<sup>1</sup>

<sup>1</sup> *Saclay, SPHT*

**Corresponding Author:** ruben.minasian@ipht.fr

In the first part of the talk I will review the relation between the anomalies in six dimensions and the Chern-Simons couplings in five. These determine in particular the central charges of string-like BPS objects that cannot be consistently decoupled from gravity, a.k.a. supergravity strings. In the second part of the talk I will review how requiring that the worldsheet theory of the supergravity strings imposes bounds on the admissible theories of quantum gravity.

**Gravity and Supergravity / 471**

## **Uses and Limitations of Supergravities with “New Fayet-Iliopoulos” and “Liberated” Terms**

**Author:** Massimo Porrati<sup>1</sup>

<sup>1</sup> *NYU*

**Corresponding Author:** massimo.porrati@nyu.edu

This talk reviews recent work done in collaboration with H. Jang on recently discovered new supergravity actions. Besides the standard ones, they contain new terms that become singular when auxiliary fields vanish. Constraints on the magnitude of such new terms are found by standard low-energy effective field theory consistency checks. After discussing those constraints I will present a realization of supergravity inflation that uses the new Kaehler-invariant Fayet-Iliopoulos term recently introduced by Antoniadis, Chatrabhuti, Isono and Knoops.

**Gravity and Supergravity / 481**

## **Branes Wrapped on Spindles**



**Author:** Jerome Gauntlett<sup>1</sup>

<sup>1</sup> *Imperial College London*

**Corresponding Author:** j.gauntlett@imperial.ac.uk

We discuss supergravity solutions that are holographically dual to supersymmetric CFTs that arise when various branes wrap a spindle. A spindle is a specific two dimensional orbifold: a two sphere with quantised conical deficits at each of the poles. We construct solutions describing the wrapped branes in gauged supergravity and then uplift them to D=10 and D=11 supergravity. Remarkably, in some cases the higher dimensional solutions are free from all orbifold singularities. For the case of D3 and M5 branes wrapping spindles we can calculate the central charge of the CFT that arises both from the gravity solution and from a field theory computation and find exact agreement. For the case of M2 branes there is an interesting connection with D=4 accelerating black holes.

**Gravity and Supergravity / 484**

## Kaluza-Klein spectrometry for supergravity

**Author:** Henning Samtleben<sup>1</sup>

<sup>1</sup> *ENS Lyon*

**Corresponding Author:** henning.samtleben@ens-lyon.fr

I review new tools for the computation of Kaluza-Klein mass spectra associated with compactifications around various background geometries relevant for string theory. This includes geometries with little to no remaining symmetries, hardly accessible to standard methods. The new tools build on exceptional field theory, the duality covariant formulation of supergravity. Applications include the identification of non-supersymmetric AdS4 vacua which are perturbatively stable at all Kaluza-Klein levels.

**Gravity and Supergravity / 474**

## TBA

**Author:** John Joseph M Carrasco<sup>1</sup>

<sup>1</sup> *Northwestern U*

**Corresponding Author:** carrasco@northwestern.edu

TBA

**Gravity and Supergravity / 472**

## Higher Derivative 6D Supergravity and Quaternionic Kahler Spaces

**Author:** Ergin Sezgin<sup>1</sup>

<sup>1</sup> *Texas A & M University*

**Corresponding Author:** sezgin@tamu.edu

I will describe the construction of a curious 4-derivative extension of 6D,  $N=(1,0)$  supergravity coupled to hypermultiplets whose scalar fields parametrize a quaternionic projective space. Surprisingly, we find that the inclusion of the Riemann-squared term is not allowed. Dimensional reduction of Bergshoeff-de Roo heterotic supergravity with Riemann-squared terms, on the other hand, suggests that such an inclusion should be possible if the scalars parametrize a Grassmannian coset. To compare the two cases, I will describe the dimensional reduction of BdR supergravity on 4-torus followed by a consistent truncation to  $(1,0)$  supersymmetry. In this case, we can see that the Riemann-squared term and 4-derivative scalar field couplings co-exist, but we also encounter an obstacle due to presence of certain terms in the fermionic sector that break the expected  $SO(4) \times SO(4)$  composite local symmetry down to its diagonal  $SO(4)$  subgroup.

**Gravity and Supergravity / 14**

## Unimodular vs Nilpotent Superfield Approach to Pure dS Supergravity

**Author:** Silvia Nagy<sup>1</sup>

<sup>1</sup> *University of Nottingham*

**Corresponding Author:** silvynagy@googlemail.com

I will present a novel solution to the long-standing issue of obtaining de Sitter spacetimes from a pure Supergravity theory. Our model is based on the first superspace formulation of unimodular gravity, in conjunction with a (super)-Stueckelberg construction. I will then present a comparison between our model and other proposals in the literature, based on constrained superfields. Even though the approaches are very different, I will show that the two proposals converge towards the same theory, thus offering a tantalising glimpse of a more general framework.

[Based on JHEP 01 (2021) 146 and Proc.Roy.Soc.Lond.A 476 (2020) 2237, 20200035]

**Gravity and Supergravity / 482**

## de Sitter, supergravity and the Swampland

**Author:** Gianguido Dall'Agata<sup>1</sup>

<sup>1</sup> *Padua U*

**Corresponding Author:** gianguido.dallagata@pd.infn.it

I will discuss recent progress in finding and classifying de Sitter vacua in supergravity. I will also comment on the evidence that models with de Sitter vacua with massless gravitini in the swampland.

**Gravity and Supergravity / 490**

## Superconformal approach to $N=4$ supergravity

**Author:** Bindusar Sahoo<sup>1</sup>

<sup>1</sup> *IISER, India***Corresponding Author:** bsahoo@iisertvm.ac.in

In this talk I will start with a brief introduction of N=4 supergravity and the known results about the anomalies and divergences of N=4 supergravity in the literature. From there I will motivate the necessity for studying N=4 supergravity from the superconformal approach and discuss a systematic way to construct N=4 conformal supergravity. Then I will discuss how to use the superconformal results in the construction of N=4 Poincare supergravity with higher derivative corrections which would be relevant from the point of view of the above mentioned study of anomalies and divergences in N=4 supergravity. I will end with some future directions.

**Gravity and Supergravity / 479**

## A Penrose limit for type IIB AdS<sub>6</sub> solutions

**Author:** Michael Gutperle<sup>1</sup><sup>1</sup> *UCLA***Corresponding Author:** gutperle@ucla.edu

In this talk I review recent work on constructing a Penrose limit for the warped type IIB  $AdS_6 \times S^2 \times \Sigma_2$  solutions and determining the spectrum of the Green-Schwarz string in the background.

**Gravity and Supergravity / 3**

## Scattering amplitudes of massive spin-2 particles in Extra Dimensional theories

**Authors:** DIPAN SENGUPTA<sup>1</sup>; R. SEKHAR CHIVUKULA<sup>2</sup>; DENNIS FOREN<sup>3</sup>; KIRTIMAAN MOHAN<sup>4</sup>; ELIZABETH SIMMONS<sup>2</sup><sup>1</sup> *UNIVERSITY OF CALIFORNIA, San Diego*<sup>2</sup> *UC San Diego*<sup>3</sup> *MSU AND UC San Diego*<sup>4</sup> *MSU***Corresponding Author:** disengupta@physics.ucsd.edu

We describe the computation of the scattering amplitudes of massive spin-2 Kaluza-Klein excitations in a gravitational theory with a single compact extra dimension, whether flat or warped. These scattering amplitudes are characterized by intricate cancellations between different contributions: although individual contributions may grow as fast as  $O(s^5)$ , the full results grow only as  $O(s)$ . We demonstrate that the cancellations persist for all incoming and outgoing particle helicities and examine how truncating the computation to only include a finite number of intermediate states impacts the accuracy of the results. We also carefully assess the range of validity of the low energy effective Kaluza-Klein theory. In particular, for the warped case we demonstrate directly how an emergent low energy scale controls the size of the scattering amplitude, as conjectured by the AdS/CFT correspondence

**Lepton Colliders / 172**

## Precision Test of the Muon-Higgs Coupling at a High-energy Muon Collider

**Authors:** Jürgen Reuter<sup>1</sup>; Keping Xie<sup>2</sup>; Nils Kreher<sup>None</sup>; Tao Han<sup>2</sup>; Tobias Striegl<sup>None</sup>; Wolfgang Kilian<sup>3</sup>; Yang Ma<sup>2</sup>

<sup>1</sup> DESY Hamburg, Germany

<sup>2</sup> University of Pittsburgh

<sup>3</sup> University of Siegen

**Corresponding Author:** kex10@pitt.edu

An open question in particle physics is whether the Higgs mechanism generates the masses of all the fermions by the Yukawa interactions. We propose to scrutinize the muon Yukawa coupling at a high-energy muon collider. By the subtle interplay between the muon Yukawa coupling in the high-energy production of multiple (vector and Higgs) bosons, we show that it is possible to measure the muon Yukawa coupling to an accuracy of ten percent for a 10 TeV collider and a few percent for a 30 TeV machine.

**Lepton Colliders / 347**

## Deeply Learned Preselection of Dijet Higgs Decays at Future Lepton Colliders

**Author:** Wenxing Zhang<sup>None</sup>

**Co-author:** Nakai Yuichiro

**Corresponding Author:** 1820927213@qq.com

We propose a method to improve the efficiency of preselection in Higgs signal searches at CEPC. For this propose we developed three machine learning algorithms including boosted decision tree algorithm, fully-connected neural networks and convolutional neural networks. Among all these algorithms, we found the fully-connected neural networks gives the best prediction on Higgs signals. Using such algorithms, we improve the signal strength of s-tagging events from cut-based result,  $\mu_{ss} \sim 100$ , to FCNN result  $\mu_{ss} \sim 10$ .

**Lepton Colliders / 330**

## Longitudinally polarized ZZ scattering at the Muon Collider

**Authors:** Congqiao Li<sup>1</sup>; Tianyi Yang<sup>1</sup>; Zhe Guan<sup>1</sup>; Meng Lu<sup>2</sup>; Fanqiang Meng<sup>1</sup>; Jie Xiao<sup>1</sup>; Qiang Li<sup>1</sup>; Sitian Qian<sup>1</sup>

<sup>1</sup> Peking University (CN)

<sup>2</sup> Sun Yat-Sen University (CN)

**Corresponding Author:** tianyi.y@cern.ch

Measuring longitudinally polarized vector boson scattering in, e.g., the ZZ channel is a promising way to investigate the unitarization scheme from the Higgs and possible new physics beyond the Standard Model. However, at the LHC, it demands the end of the HL-LHC lifetime luminosity, 3000/fb, and advanced data analysis technique to reach the discovery threshold due to its small production rates. Instead, there could be great potential for future colliders. In this paper, we perform a Monte Carlo study and examine the projected sensitivity of longitudinally polarized ZZ scattering

at a TeV scale muon collider. We conduct studies at 14 TeV and 6 TeV muon colliders respectively and find that a 5 standard deviation discovery can be achieved at a 14 TeV muon collider, with 3000/fb of data collected. While a 6 TeV muon collider can already surpass HL-LHC, reaching 2 standard deviations with around 4000/fb of data. The effect from lepton isolation and detector granularity is also discussed, which may be more obvious at higher energy muon colliders, as the leptons from longitudinally polarized Z decays tend to be closer.

**Lepton Colliders / 150**

## Electroweak Precision Physics at the FCC-ee

**Corresponding Author:** jan.eysermans@cern.ch

The Future Circular Collider with electron-positron beams (FCC-ee) should provide improvements of the electroweak precision measurement concerning Z, W, H, and their masses by a large factor over the present status. The unparalleled experimental precision would open, via Electroweak loop corrections, a broad discovery potential for new, at least weakly interacting particles up to high energy scales. The Z boson mass and width, as well as the Z to bb partial width, and the forward-backward asymmetries for leptons and quarks can be measured with high precision with the run at the Z pole, where the instantaneous luminosity is expected to be five to six orders of magnitude larger than LEP. As a result, a precise determination of the effective weak mixing angle, as well as of the running electromagnetic coupling can be extracted directly from the data. Considerable improvements of the strong coupling constant determination will be possible with the measurements of the hadronic widths of the Z and W bosons.

**Lepton Colliders / 144**

## Testing CP-violation in the scalar sector at lepton colliders

**Author:** Ying-nan Mao<sup>1</sup>

<sup>1</sup> *Wuhan University of Technology*

**Corresponding Author:** ynmao@whut.edu.cn

We proposed a novel method to test the CP-violation in scalar sector at Higgs factories. Based on the CP-properties' analysis, if we have already discovered two scalars, the existence of three vertices  $H_1ZZ$ ,  $H_2ZZ$ , and  $H_1H_2Z$  at tree level becomes the evidence for us to confirm CP-violation. At a lepton collider, all four components of energy-momentum can be reconstructed, and thus all these vertices can be measured model-independently.

**Lepton Colliders / 135**

## An unambiguous test of positivity at lepton colliders

**Author:** Jiayin Gu<sup>1</sup>

<sup>1</sup> *JGU Mainz*

**Corresponding Author:** jiagu@uni-mainz.de

The diphoton channel at lepton colliders,  $e^+e^-(\mu^+\mu^-) \rightarrow \gamma\gamma$ , has a remarkable feature that the leading new physics contribution comes only from dimension-eight operators. This contribution is subject to a set of positivity bounds, derived from fundamental principles of Quantum Field Theory, such as unitarity, locality, analyticity and Lorentz invariance. These positivity bounds are thus applicable to the most direct observable – the diphoton cross sections. This unique feature provides a clear, robust, and unambiguous test of these principles. We estimate the capability of various future lepton colliders in probing the dimension-eight operators and testing the positivity bounds in this channel. We show that positivity bounds can lift certain flat directions among the effective operators and significantly change the perspectives of a global analysis. We also perform a combined analysis of the  $\gamma\gamma/Z\gamma/ZZ$  processes in the high energy limit and point out the important interplay among them.

Based on 2011.03055

**Lepton Colliders / 130**

## Probing QFT bedrock principles and the inverse problem @ future lepton colliders

**Authors:** Benjamin Fuks<sup>1</sup>; Cen Zhang<sup>2</sup>; Shuang-Yong Zhou<sup>3</sup>; Yiming Liu<sup>None</sup>

<sup>1</sup> *Centre National de la Recherche Scientifique (FR)*

<sup>2</sup> *Institute of High Energy Physics, Chinese Academy Sciences*

<sup>3</sup> *University of Science & Technology China*

**Corresponding Author:** benjamin.fuks@cern.ch

We consider the positivity bounds on dimension-8 four-electron operators and study two related phenomenological aspects at future lepton colliders. First, if positivity is violated, probing such violations will revolutionize our understanding of the fundamental pillars of quantum field theory and the S-matrix theory. Second, the positive nature of the dimension-8 parameter space allows us to either directly infer the existence of UV-scale particles together with their quantum numbers or exclude them in a model-independent way. We demonstrate with realistic examples how those possibilities can be achieved.

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## Status of physics studies at the CEPC

**Author:** Manqi Ruan<sup>1</sup>

<sup>1</sup> *Chinese Academy of Sciences (CN)*

**Corresponding Author:** manqi.ruan@cern.ch

The Circular Electron Positron Collider is designed to deliver 1 M Higgs boson, 100 M W boson, 1 Tera Z boson in roughly 10 years of data taking. It is not only a machine for precision measurement but also a Discovery machine. To quantify its physics potential and comparative advantages compared to other facilities, intensive physics studies have been performed, aiming at CEPC physics white papers in a few years.

This report will briefly introduce the status and highlights of recent CEPC physics studies.

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**Fermion pair production at  $e^-e^+$  linear collider experiments in GUT inspired gauge-Higgs unification****Author:** Naoki Yamatsu<sup>1</sup>**Co-authors:** Shuichiro Funatsu<sup>2</sup>; Hisaki Hatanaka; Yutaka Hosotani<sup>3</sup>; yuta orikasa<sup>1</sup> *Kyushu University*<sup>2</sup> *Central China Normal University*<sup>3</sup> *Osaka University***Corresponding Author:** yamatsu.naoki@phys.kyushu-u.ac.jp

In gauge-Higgs unification (GHU), the 4D Higgs boson appears as a part of the fifth dimensional component of 5D gauge field. Recently, an  $SO(11)$  GUT inspired  $SO(5) \times U(1) \times SU(3)$  GHU model has been proposed. In the GHU, Kaluza-Klein (KK) excited states of neutral vector bosons, photon,  $Z$  boson and  $Z_R$  boson, appear as neutral massive vector bosons  $Z'$ s. The  $Z'$  bosons in the GHU couple to quarks and leptons with large parity violation, which leads to distinctive polarization dependence in, e.g., cross sections and forward-backward asymmetries in  $e^-e^+ \rightarrow \mu^-\mu^+, q\bar{q}$  processes.

In the talk, we discuss fermion pair production in  $e^-e^+$  linear collider experiments with polarized  $e^-$  and  $e^+$  beams in the GUT inspired GHU. Deviations from the SM are shown in the early stage of ILC 250 GeV experiments. The deviations can be tested for the KK mass scale up to about 15 TeV. This talk is mainly based on Phys.Rev.D102(2020)015029.

## Lepton Colliders / 151

**Quark Pair Production at Lepton Colliders: Experimental challenges****Author:** Adrian Irlles<sup>1</sup><sup>1</sup> *IFIC CSIC/UV***Corresponding Author:** adrian.irlles@ific.uv.es

We will discuss the experimental challenges and prospects for precision measurements of observables associated to quark pair production at  $e^+e^-$  Higgs/Top Factories (with focus in the ILC)

## Lepton Colliders / 148

**Flavor Physics at FCC-ee****Corresponding Author:** clement.helsens@cern.ch

Z-pole operation at FCC-ee offers a unique laboratory for flavor physics, with the anticipated production of  $10^{12}$  b-quarks and the opportunity for triggerless data-taking in a clean  $e^+e^-$  collision environment. Using new simulation and analysis tools developed for FCC-ee physics and performance studies, theoretically compelling beauty, charm, and tau decay modes are studied in order to evaluate key performance metrics and expected yields. Comparisons with LHCb Upgrade and Belle-II are performed, in order to highlight areas within flavor physics where FCC-ee measurements can be highly impactful.

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## Probing the minimal $U(1)_X$ model at future electron-positron colliders via the fermion pair-production channel

**Authors:** Arindam Das<sup>1</sup>; Bhupal Dev<sup>None</sup>; Sanjoy Mandal<sup>None</sup>; Yutaka Hosotani<sup>None</sup>

<sup>1</sup> Hokkaido University

**Corresponding Author:** dasarindamphysics@gmail.com

The minimal  $U(1)_X$  extension of the Standard Model (SM) is a well-motivated new physics scenario, where the anomaly cancellation requirement dictates the new neutral gauge boson ( $Z'$ ) couplings with the SM fermions in terms of two scalar charges ( $x_H$  and  $x_\Phi$ ). In this paper, we investigate the SM charged fermion pair production mechanism for different values of these scalar charges in the  $U(1)_X$  scenario at future electron-positron colliders, i.e.  $e^+e^- \rightarrow f\bar{f}$ . Apart from the standard photon and  $Z$  boson exchange for this process, this model features a  $t$ -channel (or both  $s$  and  $t$ -channel for  $f = e^-$ )  $Z'$ -boson exchange, which interferes with the SM processes. Considering the dilepton and dijet signatures from the heavy resonance we estimate the bounds on the  $U(1)_X$  coupling ( $g'$ ) and the  $Z'$  mass ( $M_{Z'}$ ). Considering the LEP-II results and prospective International Linear Collider (ILC) bounds on the effective scale for the four fermion interaction we estimate the reach on  $M_{Z'}/g'$  for different center of mass energies. We study the angular distributions, forward-backward ( $\mathcal{A}_{FB}$ ), left-right ( $\mathcal{A}_{LR}$ ) and left-right forward-backward ( $\mathcal{A}_{LR,FB}$ ) asymmetries of the  $f\bar{f}$  final states which can show substantial deviations from the SM results, even for a multi-TeV  $Z'$ . This provides a powerful complementary way to probe the heavy  $Z'$  parameter space beyond the direct reach of the Large Hadron Collider (LHC), as well as an effective way to determine the  $U(1)_X$  charges.

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## Radiation Amplitude Zero and Production of Leptoquark at Electron-Proton and Electron-Photon colliders

**Author:** Anirban Karan<sup>1</sup>

**Co-authors:** Priyotosh Bandyopadhyay<sup>2</sup>; Saunak Dutta<sup>2</sup>

<sup>1</sup> IIT Hyderabad

<sup>2</sup> Indian Institute of Technology Hyderabad

**Corresponding Author:** kanirban@iith.ac.in

Radiation Amplitude Zero (RAZ) is a well-known phenomenon in electroweak sector 1. The tree-level single photon amplitudes for various electroweak processes vanish at certain regions of phase space depending on the electric charges and four-momenta of the external particles [2]. Using this fact we perform PYTHIA based analyses to probe the signature of leptoquarks [3], which have gained much attention in recent years in explaining flavour anomalies, at  $ep$  [4] and  $e\gamma$  [5] colliders. While the position of zero in case of  $ep$  collider depends only on the charge of leptoquark, the same at  $e\gamma$  collider involves the mass of leptoquark and energy of collision too. We find that these two colliders are complementary to each other in a sense that the leptoquarks showing zero at one colliders do not exhibit the null zone at the other one. The effects of non-monochromatic photons at  $e\gamma$  collider have also been studied.

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## Millicharged particles at electron colliders

**Authors:** Jinhan Liang<sup>1</sup>; Zuowei Liu<sup>1</sup>; Yue Ma<sup>None</sup>; Yu Zhang<sup>2</sup>

<sup>1</sup> Nanjing University

<sup>2</sup> Anhui University

**Corresponding Author:** jinhanliang@smail.nju.edu.cn

We propose to search for millicharged particles in electron colliders operated with the center-of-mass energies at  $\mathcal{O}(1-10)$  GeV, which include Belle II, BESIII, BaBar, and also the proposed experiment STCF. We use the monophoton final state to probe the parameter space of millicharged particles at electron colliders. We find that electron colliders have sensitivity to the previously unexplored parameter space for millicharged particles with MeV-GeV mass:  $\epsilon < \mathcal{O}(10^{-1})$  for  $0.5 \text{ GeV} < m < 3.5 \text{ GeV}$  in BaBar,  $\epsilon < \mathcal{O}(10^{-3})$  for  $0.1 \text{ GeV} < m < 1.5 \text{ GeV}$  in BESIII,  $\epsilon < 10^{-3} - 10^{-2}$  for  $0.1 \text{ GeV} < m < 4 \text{ GeV}$  in Belle II, and  $\epsilon < \mathcal{O}(10^{-4})$  for  $1 \text{ MeV} < m < 1 \text{ GeV}$  in STCF.

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## Probing Dark Matter with ILC

**Corresponding Author:** filip.zarnecki@fuw.edu.pl

The International Linear Collider offers a number of unique opportunities for searches for dark matter and dark sector particles potentially related to realization of supersymmetry in Nature. The collider program will offer important capabilities, but also, the ILC will enable new fixed-target experiments using the high-energy electron and positron beams, both beam dump experiments and dedicated experiments using single beams. This talk will describe the expectations for these programs, which address all of the possible dark sector portals.

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## Feebly-interacting particles at the muon collider

**Author:** Federico Meloni<sup>1</sup>

<sup>1</sup> Deutsches Elektronen-Synchrotron (DE)S

**Corresponding Author:** federico.meloni@cern.ch

The search for new physics with very feeble interaction strength is stimulating a vibrant experimental program. This talk will present the opportunities that could be exploited at a future high-energy muon collider and highlight the experimental challenges arising from this specific collision environment. Finally, recent results studying the reach of such machine in models predicting long-lived charged winos and higgsinos will be presented.

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**Sensitivity to invisible scalar decays at CLIC****Author:** Krzysztof Mekala<sup>1</sup>**Co-author:** Aleksander Filip Zarnecki<sup>1</sup><sup>1</sup> *University of Warsaw***Corresponding Author:** k.mekala@student.uw.edu.pl

An electron-positron Higgs factory is regarded as the highest-priority next large-scale collider facility. Among others, two linear collider projects are being considered: the Compact Linear Collider (CLIC) and the International Linear Collider (ILC). Reaching energies at the TeV scale, both machines would allow us not only to study Higgs boson and top quark properties with very high precision but could also result in the direct or indirect discovery of New Physics. SM-like Higgs boson or new heavy scalar decays with the emission of invisible dark matter particles could be the only way to observe Beyond the Standard Model effects at achievable energy scales and establish the connection between the Standard Model and New Physics sectors.

We studied the possibility of measuring the invisible Higgs boson and additional heavy scalar decays with CLIC running at 380 GeV and 1.5 TeV. The analysis is based on the WHIZARD event generation and fast simulation of CLIC detector response with DELPHES. We estimated the expected limits on the invisible decays of the 125 GeV Higgs boson, as well as the cross section limits for the production of an additional neutral scalar, assuming its invisible decays, as a function of its mass. The results obtained are one order of magnitude more stringent than the current limits coming from the LHC.

## Lepton Colliders / 224

**Probing a bino NLSP at lepton colliders****Author:** mengchao zhang<sup>1</sup><sup>1</sup> *IBS-CTPU***Corresponding Author:** mczhangchina@gmail.com

We consider a scenario where light bino is the next-to-lightest supersymmetric particle (NLSP) and gravitino/axino is the lightest supersymmetric particle (LSP). For a bino mass less than or around hundred GeV, it can be pair produced at the future lepton colliders through t-channel slepton exchange, subsequently decaying into a gravitino/axino plus a photon. We study the prospects to look for such binos at the future colliders and find that a bino mass around 100 GeV can be probed at the  $2\sigma$  ( $5\sigma$ ) level for a slepton below 2 TeV (1.5 TeV) with a luminosity  $5.6 \text{ ab}^{-1}$ . For a bino mass around 10 GeV, a slepton mass less than 4.5 TeV (3.5 TeV) can be probed at the  $2\sigma$  ( $5\sigma$ ) level, which is much beyond the reach of the LHC for direct slepton searches.

## Lepton Colliders / 289

**Implication of Higgs/EW precision on 2HDM****Authors:** Shuaolong Li<sup>None</sup>; Shufang Su<sup>1</sup>; Tao Han<sup>2</sup>; wei su<sup>3</sup>; Yongcheng Wu<sup>4</sup><sup>1</sup> *University of Arizona*<sup>2</sup> *University of Pittsburgh*

<sup>3</sup> *university of Adelaide*<sup>4</sup> *Oklahoma State University***Corresponding Author:** weisv@alumni.itp.ac.cn

Studying the properties of Standard Model (SM) –like Higgs boson becomes one important window to explore the physics beyond the SM. In this work, we present studies about the implications of the Higgs and Z-pole precision measurements at future Higgs Factories. We perform a global fit to various Higgs search channels to obtain the 95% C.L. constraints on the model parameter spaces of Two Higgs Double Model (2HDM). In the 2HDM, we analyse tree level effects as well as one-loop contributions from the heavy Higgs bosons. The strong constraints on  $\cos(\beta - \alpha)$ ,  $m_\Phi$  and heavy Higgs mass splitting can be complementary to direct search of the LHC and Z pole precision measurements. We also explore its effects on the electroweak phase transition of 2HDM. We compare the sensitivity of various future Higgs factories, namely Circular Electron Positron Collider (CEPC), Future Circular Collider (FCC)-ee and International Linear Collider (ILC).

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## Heavy Higgs Bosons in 2HDM at a Muon Collider

**Authors:** Shuailong Li<sup>None</sup>; Shufang Su<sup>1</sup>; Tao Han<sup>2</sup>; Yongcheng Wu<sup>3</sup>; wei su<sup>4</sup><sup>1</sup> *University of Arizona*<sup>2</sup> *University of Pittsburgh*<sup>3</sup> *Oklahoma State University*<sup>4</sup> *University of Adelaide***Corresponding Author:** shufang@email.arizona.edu

We study the discovery potential of the non-Standard Model (SM) heavy Higgs bosons in the Two-Higgs-Doublet Models (2HDMs) at a multi-TeV muon collider and explore the discrimination power among different types of 2HDMs.

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## Testing electroweak phase transition at muon colliders

**Authors:** Ke-Pan Xie<sup>1</sup>; Wei Liu<sup>2</sup><sup>1</sup> *Seoul National University*<sup>2</sup> *Nanjing University of Science and Technology***Corresponding Author:** wei.liu@cern.ch

We study the complementarity of the proposed multi-TeV muon colliders and the near-future gravitational wave (GW) detectors to the first order electroweak phase transition (FOEWPT), taking the real scalar extended Standard Model as the representative model. A detailed collider simulation shows the FOEWPT parameter space can be greatly probed via the vector boson fusion production of the singlet, and its subsequent decay to the di-Higgs or di-boson channels. Especially, almost all the parameter space yielding detectable GW signals can be probed by the muon colliders. Therefore, if we could detect stochastic GWs in the future, a muon collider could provide a hopeful crosscheck to identify their origin. On the other hand, there is considerable parameter space that escapes GW detections but is within the reach of the muon colliders. The precision measurements of Higgs couplings could also probe the FOEWPT parameter space efficiently.

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## **A collinear factorisation approach at e+e- colliders**

**Author:** Stefano Frixione<sup>1</sup>

<sup>1</sup> *INFN*

**Corresponding Author:** stefano.frixione@cern.ch

I discuss the physics that underpins QED collinear-factorisation formulae, in particular the PDFs, and some applications of the latter to the simulation of e+e- collision processes

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## **The partonic picture at high-energy lepton colliders**

**Authors:** Keping Xie<sup>1</sup>; Tao Han<sup>1</sup>; Yang Ma<sup>1</sup>

<sup>1</sup> *University of Pittsburgh*

**Corresponding Author:** mayangluon@pitt.edu

After the triumph of discovering the Higgs boson at the CERN Large Hadron Collider, people are getting increasingly interested in studying the Higgs properties in detail and searching for the physics beyond the Standard Model (SM). A multi-TeV lepton collider provides a clean experimental environment for both the Higgs precision measurements and the discovery of new particles. In high-energy leptonic collisions, the collinear splittings of the leptons and electroweak (EW) gauge bosons are the dominant phenomena, which could be well described by the parton picture. In the parton picture, all the SM particles should be treated as partons that radiated off the beam particles, and the electroweak parton distribution functions (EW PDFs) should be adopted as a proper description for partonic collisions of the initial states. In our work, both the EW and the QCD sectors are included in the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) formalism to perturbatively resum the potential large logarithms emerging from the initial-state radiation (ISR). I will show the results of QCD jet production as well as some other typical SM processes at a possible high-energy electron-positron collider and a possible high-energy muon collider obtained using the PDFs.

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## **Higgs measurement at the Future Circular Colliders**

**Author:** Sylvie Braibant<sup>None</sup>

Precision measurements and searches for new phenomena in the Higgs sector are among the most important goals in particle physics. Experiments at the Future Circular Colliders (FCC) are ideal to study these questions. Electron-positron collisions (FCC-ee) up to an energy of 365 GeV provide the ultimate precision with studies of Higgs boson couplings, mass, total width, and CP parameters, as well as searches for exotic and invisible decays. Very high energy proton-proton collision (up to 100 TeV) provided by the FCC-hh will allow studying the Higgs self-coupling. There is a remarkable complementarity of the FCC-ee and FCC-hh colliders, which in combination offer the best possible overall study of the Higgs boson properties.

**Lepton Colliders / 214**

## Higgs Precision at CEPC

**Author:** Yaquan Fang<sup>1</sup>

<sup>1</sup> *Chinese Academy of Sciences (CN)*

**Corresponding Author:** yaquan.fang@cern.ch

As Higgs factory, Higgs study is one of the main physics goal at the CEPC. This presentation will present the latest Higgs results at CDR and new updates afterwards. In addition, the impact of 360 GeV run on CEPC Higgs physics will be addressed as well. Finally, some comparison with other colliders on physics will be discussed.

**Lepton Colliders / 495**

## Supersymmetry at the Muon Collider

**Author:** Nathaniel Craig<sup>1</sup>

<sup>1</sup> *UC Santa Barbara*

**Corresponding Author:** ncraig@physics.ucsb.edu

The talk will address the potential of the muon collider to probe Supersymmetry and related ideas for physics Beyond the Standard Model.

**Lepton Colliders / 196**

## Prospects for SUSY Searches @ CEPC

**Author:** Da Xu<sup>1</sup>

<sup>1</sup> *IHEP, CAS*

**Corresponding Author:** xuda@ihep.ac.cn

The proposed Circular Electron Positron Collider (CEPC) with a center-of-mass energy  $\sqrt{s} = 240$  GeV will serve as a Higgs factory, while it can offer good opportunity for new physics search at low energy, which is challenging in hadron colliders but motivated by some theory models such as dark matter. This talk will cover electroweak SUSY and slepton search prospects at CEPC.

**Lepton Colliders / 185**

## SUSY global fits with future colliders using GAMBIT

**Author:** yang zhang<sup>None</sup>

**Corresponding Author:** yang.phy@foxmail.com

We study the impact of future electron-positron colliders, such as CEPC, ILC and FCC- $ee$ , on global fits of the simplest supersymmetric models, such as the CMSSM and pMSSM-7, using GAMBIT and publicly available data published by the GAMBIT Community. From the impact of the additional likelihoods, we discuss the discovery prospects and reaches of future colliders.

**Lepton Colliders / 88**

## **Searching for long-lived light neutralinos at future lepton colliders**

**Authors:** Kechen Wang<sup>1</sup>; Zeren Simon Wang<sup>2</sup>

<sup>1</sup> *Wuhan University of Technology*

<sup>2</sup> *National Tsing Hua University*

**Corresponding Author:** wzs@mx.nthu.edu.tw

Future lepton colliders such as the Circular Electron Positron Collider (CEPC) and FCC (Future Circular Collider)-ee would run as high-luminosity  $Z$ -boson factories, which offer a unique opportunity to study long-lived particles which couple to  $Z$ -bosons. We consider the long-lived lightest neutralinos in the R-parity-violating supersymmetry, produced from  $Z$ -boson decays, and show the sensitivity limits of not only the near detectors at the CEPC and FCC-ee but also proposed far-detector experiments at these colliders. We find the near detectors at the future  $Z$ -factories can outperform the ATLAS experiment at the high-luminosity Large Hadron Collider (LHC) and the proposed LHC experiments with far detectors (AL3X, CODEX-b, FASER, and MATHUSLA), and that new experiments with far detectors at future lepton colliders may extend and complement the sensitivity reaches of the default near detectors.

**Lepton Colliders / 493**

## **Towards a Muon Collider**

**Corresponding Author:** elias.metral@cern.ch

After the recent update of the European Strategy an International Muon Collider Collaboration is forming. The talk will give an overview of the project and the plans of the collaboration. It will highlight some of the challenges and the technologies to address them.

**Lepton Colliders / 494**

## **Muon Colliders Physics Potential Overview**

**Author:** Dario Buttazzo<sup>None</sup>

**Corresponding Author:** dario.buttazzo@pi.infn.it

The talk will summarise the status of the muon collider physics potential assessment

**Lepton Colliders / 216**

## **Status of the CEPC Project**

**Author:** Haijun Yang<sup>1</sup>

<sup>1</sup> *Shanghai Jiao Tong University (CN)*

**Corresponding Author:** haijun.yang@cern.ch

The discovery of the Higgs boson marked the beginning of a new era in HEP. Precision measurement of the Higgs boson properties and exploring new physics beyond the Standard Model using Higgs as a tool become a natural next step beyond the LHC. Among the proposed Higgs factories worldwide, the Circular Electron Positron Collider (CEPC) is proposed by the Chinese HEP community and to be hosted in China. The CEPC will be located in a tunnel with 100km circumference. It will operate at CME of 240 GeV as a Higgs factory. It can also operate at lower energy as W and Z boson factory. In this talk, the recent progress about CEPC accelerator and detector R&D, and study of physics potential will be presented.

**Neutrino Physics and Leptons / 238**

## Results on Lepton Flavor Universality and Lepton Flavor Violation at Belle

**Corresponding Authors:** hulya.atmacan@gmail.com, atmacaha@ucmail.uc.edu

The study of the lepton flavor universality (LFU) and searches for lepton flavor violation (LFV) attract attention as a probe for the new physics signal. We present the study of LFU violation observables  $R_K$  and  $R_{K^*}$  in electroweak penguin  $B$  decays  $B \rightarrow K^{(*)}\ell^+\ell^-$  ( $\ell = e, \mu$ ). We also present search for  $B \rightarrow K^*\tau^+\tau^-$  as well as LFV decays  $B \rightarrow \ell\tau$ ,  $\tau \rightarrow \ell\gamma$  and  $\Upsilon(1S) \rightarrow \ell\tau$ . All these results are based on data collected by the Belle experiment at the KEKB asymmetric-energy  $e^+e^-$  collider.

**Neutrino Physics and Leptons / 123**

## Search for $K^+$ decays to a lepton and invisible particles

**Corresponding Author:** artur.shaikhiev@cern.ch

The NA62 experiment at CERN reports searches for  $K^+ \rightarrow e+N$ ,  $K^+ \rightarrow \mu+N$  and  $K^+ \rightarrow \mu+\nu X$  decays, where  $N$  and  $X$  are massive invisible particles, using the 2016-2018 data set.

The  $N$  particle is assumed to be a heavy neutral lepton, and the results are expressed as upper limits of  $O(10^{-9})$  and  $O(10^{-8})$  of the neutrino mixing parameter  $|U_{e4}|^2$  and  $|U_{\mu 4}|^2$ , improving on the earlier searches for heavy neutral lepton production and decays in the kinematically accessible mass range. The  $X$  particle is considered a scalar or vector hidden sector mediator decaying to an invisible final state, and upper limits of the decay branching fraction for  $X$  masses in the range 10-370 MeV/ $c^2$  are reported for the first time, ranging from  $O(10^{-5})$  to  $O(10^{-7})$ .

An improved upper limit of  $1.0 \cdot 10^{-6}$  is established at 90% CL on the  $K^+ \rightarrow \mu+\nu\nu$  branching fraction.

**Neutrino Physics and Leptons / 109**

## The Radiative SUSY Seesaw Mechanism

**Author:** Pablo Candia da Silva<sup>1</sup>

**Co-author:** Apostolos Pilaftsis<sup>2</sup>

<sup>1</sup> The University of Manchester

<sup>2</sup> *University of Manchester (GB)*

**Corresponding Author:** pablo.candiadasilva@manchester.ac.uk

In this talk we first review the radiative seesaw scenario in the context of inverse seesaw models, in which small lepton number violating parameters generate radiatively at the one-loop order the observed small light neutrino masses. Then, we show how the supersymmetric version of this radiative mechanism offers cancellations among the one-loop contributions to neutrino masses thanks to a SUSY non-renormalization theorem, thereby relaxing dramatically the size of the lepton number violating parameters in such models. Finally, we discuss the phenomenological and cosmological implications of this radiative SUSY seesaw scenario.

**Neutrino Physics and Leptons / 300**

## Can CE $\nu$ NS experiments probe Dirac vs Majorana nature of neutrinos?

**Authors:** Chandan Hati<sup>1</sup>; Frank Deppisch<sup>2</sup>; Julia Harz<sup>3</sup>; Kare Fridell<sup>3</sup>; Patrick Bolton<sup>2</sup>; Suchita Kulkarni<sup>4</sup>

<sup>1</sup> *Technische Universität München, James-Franck-Straße 1, D-85748*

<sup>2</sup> *University College London*

<sup>3</sup> *Technical University of Munich (TUM)*

<sup>4</sup> *University of Graz*

**Corresponding Author:** c.hati@tum.de

Coherent Elastic Neutrino Nucleus Scattering (CE $\nu$ NS) provide a novel window to probe new physics connected with the well established non-vanishing neutrino masses. In this talk we will discuss how in the presence of a transition magnetic moment of neutrinos the CE $\nu$ NS experiments have the potential to shed light on the nature of neutrinos: Dirac vs Majorana. In particular, we will take the NUCLEUS experiment as an example to demonstrate that through a study of differential energy distribution of the final states the CE $\nu$ NS experiments can potentially achieve such a feat.

**Neutrino Physics and Leptons / 261**

## Recent Astroparticle and Beyond the Standard Model Results from MicroBooNE

**Authors:** Ivan Lepetic<sup>1</sup>; David Marsden<sup>2</sup>

<sup>1</sup> *Rutgers University*

<sup>2</sup> *University of Manchester*

MicroBooNE is an 85-ton active mass liquid argon time projection chamber (LArTPC) at Fermilab. Its excellent calorimetry and resolution (both spatial and energy), along with its exposure to two neutrino beamlines make it a powerful detector not just for neutrino physics, but also for Beyond the Standard Model (BSM) physics and astroparticle physics. The experiment has competitive sensitivity to heavy neutral leptons possibly present in the leptonic decay modes of kaons, and also to scalar bosons that could be produced in kaon decays in association with pions. In addition, MicroBooNE serves as a platform for prototyping searches for rare events in the future Deep Underground Neutrino Experiment (DUNE). This talk will explore the capabilities of LArTPCs for BSM physics and astroparticle physics and highlight some recent results from MicroBooNE.



## Neutrino Physics and Leptons / 29

**Explicit Perturbations to the Stabilizer  $\tau = \{\mathrm{rm} \ i\}$  of Modular  $A^{\prime}_5$  Symmetry and Leptonic CP Violation****Authors:** Shun Zhou<sup>1</sup>; Xin Wang<sup>2</sup><sup>1</sup> *IHEP, CAS*<sup>2</sup> *Institute of High Energy Physics***Corresponding Author:** wangx@ihep.ac.cn

The finite modular symmetry provides us with an attractive and novel way to understand lepton flavor mixing, and has recently attracted a lot of attention. In a class of neutrino mass models with modular flavor symmetries, it has been observed that CP symmetry is preserved at the stabilizer of the modulus parameter  $\tau = i$ , whereas significant CP violation emerges within the neighbourhood of this stabilizer. In this work, we first construct a viable model with the modular  $A'_5$  symmetry, and explore the phenomenological implications for lepton masses and flavor mixing. Then, we introduce explicit perturbations to the stabilizer at  $\tau = i$ , and present both numerical and analytical results to understand why a small deviation from the stabilizer leads to large CP violation. As low-energy observables are very sensitive to the perturbations to model parameters, we further demonstrate that the renormalization-group running effects play an important role in confronting theoretical predictions at the high-energy scale with experimental measurements at the low-energy scale.

## Neutrino Physics and Leptons / 402

**Light particles with baryon and lepton numbers****Author:** Julian Heeck<sup>None</sup>**Corresponding Author:** heeck@virginia.edu

We consider light new particles  $\chi$  and  $\phi$  that carry baryon and lepton numbers. If these particles are lighter than nucleons they lead to exotic decays such as  $p \rightarrow \pi^+ \chi$  and  $p \rightarrow e^+ \phi$ , not yet fully constrained by dedicated searches. For  $\chi$  and  $\phi$  masses in the GeV range, proton decays are kinematically forbidden but other decays of the forms  $\text{baryon} \rightarrow \text{meson} + \chi$ ,  $\text{meson} \rightarrow \text{baryon} + \bar{\chi}$ , and  $\text{baryon} \rightarrow \text{anti-lepton} + \phi$  involving heavy initial hadrons are allowed. This opens up the possibility to search for apparent baryon number violation not just in underground experiments such as Super-Kamiokande and DUNE but also in decays of heavy hadrons in charm and  $B$  factories.

## Neutrino Physics and Leptons / 184

**Leptogenesis from  $SU(5)$  GUT with  $\mathcal{T}_{13}$  Family Symmetry****Author:** Moinul Rahat<sup>1</sup><sup>1</sup> *University of Florida***Corresponding Author:** mrahat@ufl.edu

In a seesaw scenario, GUT and family symmetry can severely constrain the structure of the Dirac and Majorana mass matrices of neutrinos. We will discuss an interesting case where these matrices are related in such a way that definite predictions for light neutrino masses are achieved without specifying the seesaw scale. This opens up the possibility to consider both high- and low-scale leptogenesis. We will explore both of these possibilities in an  $SU(5) \times \mathcal{T}_{13}$  model and show that

sub-GeV right-handed neutrinos with active-sterile mixing large enough to be probed by DUNE can explain baryon asymmetry of the Universe through resonant leptogenesis.

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## Realistic neutrino mixing in a scotogenic model using $S_3$ symmetry

Author: Soumita Pramanick<sup>1</sup>

<sup>1</sup> National Centre for Nuclear Research (NCBJ), Warsaw, Poland

Corresponding Author: soumita509@gmail.com

[This is talk will be on Phys.Rev. D100 (2019) no.3, 035009 by Soumita Pramanick]

Using  $S_3 \times Z_2$  symmetry a scotogenic model for realistic neutrino mixing at one-loop level will be discussed. In this model, there are two right-handed neutrinos. It was found when these two right-handed neutrinos are mixed maximally one can obtain the form of the left-handed Majorana neutrino mass matrix with  $\theta_{13} = 0$ ,  $\theta_{23} = \pi/4$  and the solar mixing  $\theta_{12}$  can have any value like that of Tribimaximal (TBM), Bimaximal (BM) and Golden Ratio (GR) or any other mixing scenario.

A little shift from the maximal mixing between the two right-handed neutrino states can yield the realistic neutrino mixing angles i.e., non-zero  $\theta_{13}$ , deviation of  $\theta_{23}$  from  $\pi/4$  and small corrections to  $\theta_{12}$ .

Thus this scotogenic mechanism at one-loop level produces non-zero  $\theta_{13}$  by shifting from maximal mixing between the two-right handed neutrinos. The model also has two inert  $SU(2)_L$  doublet scalars odd under  $Z_2$ , the lightest among which can become a dark matter.

Neutrino Physics and Leptons / 134

## A systematic approach to neutrino masses and their phenomenology

Author: Michael Schmidt<sup>1</sup>

<sup>1</sup> UNSW Sydney

Corresponding Author: m.schmidt@unsw.edu.au

We propose a model-independent framework to classify and study neutrino mass models and their phenomenology. The idea is to introduce one particle beyond the Standard Model which couples to leptons and carries lepton number together with an operator which violates lepton number by two units and contains this particle. This allows to study processes which do not violate lepton number, while still working with an effective field theory. The contribution to neutrino masses translates to a robust upper bound on the mass of the new particle. We compare it to the stronger but less robust upper bound from Higgs naturalness and discuss several lower bounds.

Neutrino Physics and Leptons / 38

## Radiative neutrino masses, lepton flavor mixing and muon $g - 2$ in a leptoquark model

**Author:** di zhang<sup>None</sup>

**Corresponding Author:** zhangdi@ihep.ac.cn

We propose a leptoquark model with two scalar leptoquarks  $S_1 (\bar{3}, 1, \frac{1}{3})$  and  $\tilde{R}_2 (3, 2, \frac{1}{6})$  to give a combined explanation of neutrino masses, lepton flavor mixing and the anomaly of muon  $g - 2$ , satisfying the constraints from the radiative decays of charged leptons. The neutrino masses are generated via one-loop corrections resulting from a mixing between  $S_1$  and  $\tilde{R}_2$ . With a set of specific textures for the leptoquark Yukawa coupling matrices, the neutrino mass matrix possesses an approximate  $\mu$ - $\tau$  reflection symmetry with  $(M_\nu)_{ee} = 0$  only in favor of the normal neutrino mass ordering. We show that this model can successfully explain the anomaly of muon  $g - 2$  and current experimental neutrino oscillation data under the constraints from the radiative decays of charged leptons.

**Neutrino Physics and Leptons / 31**

## Inverse Seesaw Model with a Modular $S_4$ Symmetry: Lepton Flavor Mixing and Warm Dark Matter

**Author:** Xinyi Zhang<sup>1</sup>

**Co-author:** Shun Zhou<sup>2</sup>

<sup>1</sup> *Institute of High Energy Physics, Chinese Academy of Sciences*

<sup>2</sup> *IHEP, CAS*

**Corresponding Author:** zhangxinyi@ihep.ac.cn

We present a systematic investigation on simple inverse seesaw models for neutrino masses and flavor mixing based on the modular  $S_4$  symmetry. Two right-handed neutrinos and three extra fermion singlets are introduced to account for light neutrino masses through the inverse seesaw mechanism and to provide a keV-mass sterile neutrino as the candidate for warm dark matter in our Universe. Considering all possible modular forms with weights no larger than four, we obtain twelve models, among which we find one is in excellent agreement with the observed lepton mass spectra and flavor mixing. Moreover, we explore the allowed range of the sterile neutrino mass and mixing angles, by taking into account the direct search of X-ray line and the Lyman- $\alpha$  observations. The model predictions for neutrino mixing parameters and the dark matter abundance will be readily testable in future neutrino oscillation experiments and cosmological observations.

**Neutrino Physics and Leptons / 60**

## Diagonal reflection symmetries and universal four-zero texture

**Author:** Masaki Yang<sup>1</sup>

<sup>1</sup> *Saitama University*

**Corresponding Author:** yang@krishna.th.phy.saitama-u.ac.jp

In this seminar, we consider a set of new symmetries in the SM:  $\{ \text{it diagonal reflection} \}$  symmetries  $R m_{u,\nu}^* R = m_{u,\nu}$ ,  $m_{d,e}^* = m_{d,e}$  with  $R = \text{diag}(-1, 1, 1)$ . These generalized  $CP$  symmetries predict the Majorana phases to be  $\alpha_{2,3}/2 \sim 0$  or  $\pi/2$ .

By combining the symmetries with the four-zero texture, the mass eigenvalues and mixing matrices of quarks and leptons are reproduced well.

This scheme predicts the normal hierarchy, the Dirac phase  $\delta_{CP} \simeq 203^\circ$ , and  $|m_1| \simeq 2.5$  or  $6.2$  [meV].

In this scheme, the type-I seesaw mechanism and a given neutrino Yukawa matrix  $Y_\nu$  completely determine the structure of the right-handed neutrino mass  $M_R$ . A  $u - \nu$  unification predicts the mass eigenvalues to be  $(M_{R1}, M_{R2}, M_{R3}) = (O(10^5), O(10^9), O(10^{14}))$  [GeV].

## Neutrino Physics and Leptons / 403

### Neutral Current Neutrino Interactions at FASER $\nu$

**Author:** Roshan Mammen Abraham<sup>1</sup>

<sup>1</sup> *Oklahoma State University*

**Corresponding Author:** rmammen@ostatemail.okstate.edu

The Forward Physics Facility (FPF) at LHC has the potential to explore the far-forward region at LHC. FASER $\nu$  is the dedicated program at FPF to study collider neutrinos. Charged current neutrino interactions have been extensively studied in the context of various experiments, including FASER $\nu$ . The presence of a charged lepton in the final state allows for easy identification of candidate signal events and incoming beam energy reconstruction. Neutral current neutrino interaction on the other hand have a neutrino in the final state. This imposes two challenges: a) differentiating signal from background, which is primarily neutral hadron induced in FASER $\nu$  and b) reconstructing incoming beam energy when the final state has missing energy. In this work, we propose to use machine learning tools to identify and reconstruct signal events. We show how a suitable choice of event observables and proper training of the neural network can allow us to constrain NC neutrino cross-section in the 100GeV- a few TeV range. We convert this cross-section sensitivity to limits on neutrino NSI.

## Neutrino Physics and Leptons / 338

### Probing non-standard neutrino interactions with low energy neutrino-electron elastic scattering in reactor experiments

**Authors:** Adrian Raphael Thompson<sup>1</sup>; Ankur Verma<sup>1</sup>; Bhaskar Dutta<sup>2</sup>; Sumit Ghosh<sup>1</sup>; Tianjun Li<sup>3</sup>

<sup>1</sup> *Texas A & M University*

<sup>2</sup> *Texas A&M University*

<sup>3</sup> *Chinese Academy of Sciences*

**Corresponding Author:** averma1@tamu.edu

Reactor experiments provide an excellent platform to investigate the atomic ionization effects induced by the unexplored neutrino interaction channels. Including the atomic effects in our calculations, we study the neutrino-electron scattering by reactor anti-neutrinos in low-energy electron recoil detectors such as Si/Ge in light of neutrino non-standard interactions with leptons. We find that the atomic and crystal effects in Si/Ge yields a sizable suppression to the neutrino-electron scattering rate when compared to the free-electron approximation. We present our sensitivity results for the light vector and scalar mediator case. The explanation of the excess in the recent Xenon1T result can also be investigated at the reactor experiments since the reactors have a similar energy flux profile to solar neutrinos with characteristic neutrino energies  $<1$  MeV.

## Neutrino Physics and Leptons / 220

## Coherent neutrino scattering and the Migdal effect

**Author:** Jiajun Liao<sup>1</sup>

**Co-authors:** Hongkai Liu ; Danny Marfatia

<sup>1</sup> *Sun Yat-sen University*

**Corresponding Author:** liaojiajun@mail.sysu.edu.cn

Recent measurements of the germanium quenching factor deviate significantly from the predictions of the standard Lindhard model for nuclear recoil energies below a keV. This departure may be explained by the Migdal effect in neutron scattering on germanium. In this talk, we will discuss the Migdal effect on the quenching factor, We show it can mimic the signal of a light  $Z'$  or light scalar mediator in coherent elastic neutrino-nucleus scattering experiments with reactor antineutrinos. It is imperative that the quenching factor of nuclei with low recoil energy thresholds be precisely measured close to threshold to avoid such confusion. This will also help in experimental searches of light dark matter.

**Neutrino Physics and Leptons / 310**

## 1 $\leftrightarrow$ 2 Processes of a Sterile Neutrino Around Electroweak Scale in the Thermal Plasma

**Author:** Yi-Lei Tang<sup>1</sup>

<sup>1</sup> *Sun Yat-Sen University*

**Corresponding Author:** tangyilei15@pku.edu.cn

In this talk I will show how we calculated the  $1 \leftrightarrow 2$  processes of a sterile neutrino with the mass  $\sim 100$  GeV in the early universe. This is essential for evaluating the corresponding leptogenesis processes. The Goldstone equivalence gauge is applied and its application in thermal plasma will be introduced.

**Neutrino Physics and Leptons / 40**

## Tau physics prospects at Belle II

**Author:** Marcela Garcia Hernandez<sup>None</sup>

**Corresponding Author:** mgarciah@fis.cinvestav.mx

The Belle II experiment is a substantial upgrade of the Belle detector and will operate at the SuperKEKB energy-asymmetric  $e^+e^-$  collider. The design luminosity of the machine is  $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$  and the Belle II experiment aims to record  $50 \text{ ab}^{-1}$  of data, a factor of 50 more than its predecessor. From February to July 2018, the machine has completed a commissioning run and main operation of SuperKEKB has started in March 2019. Belle II has a broad  $\tau$  physics program, in particular in searches for lepton flavour and lepton number violations (LFV and LNV), benefiting from the large cross section of the pair wise  $\tau$  lepton production in  $e^+e^-$  collisions. We expect that after 5 years of data taking, Belle II will be able to reduce the upper limits on LF and LN violating  $\tau$  decays by an order of magnitude. Any experimental observation of LFV or LNV in  $\tau$  decays constitutes an unambiguous sign of physics beyond the Standard Model, offering the opportunity to probe the underlying New Physics. In this talk we will review the  $\tau$  lepton physics program of Belle II.

**Neutrino Physics and Leptons / 25**

## **Testing the neutrino mass generation mechanism at the current and future colliders**

**Author:** Arindam Das<sup>1</sup>

<sup>1</sup> *Hokkaido University*

**Corresponding Author:** dasarindamphysics@gmail.com

The generation of the neutrino mass is an essential observation from the neutrino oscillation experiments. This indicates a major revision of the Standard Model which initiated with the massless neutrinos. A possible interesting scenario is the seesaw mechanism where SM gauge singlet Right Handed Neutrinos are introduced. Another interesting aspect is the extension of the SM with SU(2) triplet fermions. Alternatively a general U(1) extension of the SM is also an interesting idea which involves three generations of the SM singlet RHNs to generate the tiny neutrino mass through the seesaw mechanism. Additionally such models can contain a  $Z'$  boson which could be tested at the colliders through the pair production of the RHNs.

**New Developments in Quantum Field Theory / 117**

## **New positivity bounds from full crossing symmetry**

**Author:** Shuang-Yong Zhou<sup>1</sup>

<sup>1</sup> *University of Science & Technology China*

**Corresponding Author:** zhou.sy234@gmail.com

Positivity bounds are constraints on the Wilson coefficients of an effective field theory that can be extracted from fundamental properties of the S-matrix of the UV theory, notably the dispersion relation. We show that a new set of powerful bounds can be obtained by using the full crossing symmetry. In contradistinction to the previous s-u symmetric bounds, these new bounds can be applied to put upper and lower bounds on Wilson coefficients, and are much more constraining as shown in the lowest orders. These bounds can be applied generic effective field theories. As an example of applications, we show that theories with soft amplitude behaviour such as weakly broken Galileon theories can be excluded from admitting a standard UV completion.

**New Developments in Quantum Field Theory / 400**

## **The Breakdown of the Narrow Width Approximation and other Aspects of Timeline Processes in AdS**

**Authors:** Alexandria Costantino<sup>None</sup>; sylvain fichet<sup>None</sup>; Flip Tanedo<sup>1</sup>

<sup>1</sup> *UC Riverside*

**Corresponding Author:** lexicostantino@gmail.com

Working in a slice of AdS truncated by branes, it's well known that the propagator contains a tower of poles which correspond to narrow particles—KK modes. Does this picture of “a tower of narrow modes” hold to arbitrarily high energies when interactions are present? Generically these narrow modes will get a finite width which can grow with KK number, possibly becoming as large as the mass gap between the modes. What happens when these resonances overlap and mix at high energies,

and could this have implications for timelike processes? In my talk, I will address these questions and share some insights that we have gained in the pursuit of answers.

**New Developments in Quantum Field Theory / 351**

## **Constructing on-shell operator basis for all masses and spins**

**Co-author:** Jing Shu <sup>1</sup>

<sup>1</sup> *ITP-CAS*

We first propose a general method to construct the complete set of on-shell operator bases involving massive particles with any spins. To incorporate the non-abelian little groups of massive particles, the on-shell scattering amplitude basis should be factorized into two parts: one is charged, and the other one is neutral under little groups of massive particles. The complete set of these two parts can be systematically constructed by choosing some specific Young diagrams of Lorentz subgroup and global symmetry  $U(N)$  respectively ( $N$  is the number of external particles), without the equation of motion and integration by part redundancy. Thus the complete massive amplitude bases without any redundancies can be obtained by combining these two complete sets. Some examples are presented to explicitly demonstrate this method. This method is applicable for constructing amplitude bases involving identical particles, and all the bases can be constructed automatically by computer programs based on it.

**New Developments in Quantum Field Theory / 346**

## **A 3d disordered superconformal fixed point**

**Authors:** Cheng Peng<sup>None</sup>; Chi-ming Chang<sup>None</sup>; Mukund Rangamani<sup>None</sup>; Sean Colin-Ellerinc<sup>None</sup>

We initiate the study of a three dimensional disordered supersymmetric field theory. Specifically, we consider a  $N = 2$  large  $N$  Wess-Zumino like model with cubic superpotential involving couplings drawn from a Gaussian random ensemble. Taking inspiration from analyses of lower dimensional SYK like models we demonstrate that the theory flows to a strongly coupled superconformal fixed point in the infra-red. In particular, we obtain leading large  $N$  spectral data and operator product coefficients at the critical point. Moreover, the analytic control accorded by the model allows us to compare our results against those derived in the conformal bootstrap program and demonstrate consistency with general expectations.

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## **Multiparticle fields method for the description of the bound states scattering**

**Author:** Fedir Musonov<sup>1</sup>

**Co-authors:** Denis Domin<sup>1</sup>; Victor Tarasov<sup>1</sup>; Tetiana Zelentsova<sup>1</sup>

<sup>1</sup> *Odessa Polytechnic State University*

**Corresponding Author:** ne-tolik@ukr.net

All existing quantum field theories are formulated in terms of functions defined in the Minkowski space and possess the values from a set of operators. Such functions satisfy the equations which

conserve their form during the Lorentz transform. As a result of these two points, within such theories, it is impossible to construct an operator which could change the coordinate dependence of the state keeping the temporal dependence intact. For example, it is impossible to construct an operator which creates a particle with certain momentum only –it is only possible to construct an operator which creates a particle with certain energy-momentum. This makes it difficult to describe the bound states within the relativistic quantum theory. In addition, a relativistic theory of bound states scattering, built on top of such models, would result in the conservation of the total energy-momentum four-vector of the single-particle states (regardless of the quantization method and the method of dynamic problem solution –using the perturbation theory or not). So in QCD the total four-momentum of quarks and gluons in initial state will be equal to the total four-momentum of quarks and gluons in the final state. This is an obvious contradiction to the experiment, where the total four-momentum of hadrons is conserved, and not of their constituent particles. This problem is usually overcome using the parton model [1]. In this case the total four-momentum of hadron is given as a sum of the four-momenta of its constituent partons which do not interact with each other. This is obviously a way to only elude the mentioned problems, while the method of multiparticle fields aims at their solution. The basic idea of this method can be illustrated using the example of a two-particle field.

Consider a set of event pairs, where each pair is chosen from the Minkowski space for one of the particles. In [2] it was shown that the measurement of the quantum state of such particles must be done at the same time relative to the frame in which this measurement is done. So the multiparticle states are described on the subset of the Cartesian product of Minkowski spaces, which corresponds to the simultaneous events. We call it the subset of simultaneous events. We show that it is possible to derive the dynamic equations similar to the known Klein-Gordon-Fock and Dirac equations for the fields on such a subset. The solutions of the dynamical equations for the two-particle gauge field can be given in a form of two components. The first one plays the role of a potential of the particle interaction inside the bound particle, while the second one is the field which after the quantization describes the interaction between the bound particles. Curiously enough, the first component, which describes the interaction inside the bound particle, satisfies the dynamic equation which in its turn describes the confinement under certain boundary conditions, and the mechanism of spontaneous symmetry breaking under some others.

This model may serve as an effective field theory for the description of the elastic and inelastic scattering of hadrons.

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## New Developments in Quantum Field Theory / 80

### Exact solution studies of local and non-local Yang-Mills theories

**Author:** Marco Frasca<sup>None</sup>

**Corresponding Author:** mar.frasca@gmail.com

Local exact solutions for the scalar field theory, both for the classical and the quantum case have been recently obtained [1,3] by a technique devised by Bender, Savage and Milton [4]. This permits to derive the set of Dyson-Schwinger equations in a fully differential form. These methods can be applied also to the exact solution of the Yang-Mills theory [5] and corresponding confinement studies [6]. It is also possible to get a significant agreement for the spectrum of the theory [7] and to prove confinement in 2+1 dimensions [8].

Non-local quantum field theories have been studied recently as a promising approach to go beyond the Standard Model (e.g. see [9-11]). This approach is motivated by p-adic string field theory [12-14]. These theories have the properties of UV-completeness and have been proposed as a direction of UV-completion the non-local infinite-derivative theories, and are ghost-free, re-normalizable and



predicts conformal invariance at the quantum level [10, 15]. They are able to rescue dark matter models [11], move trans-planckian processes to sub-planckian [16] and improve inflationary behaviour of the Higgs field [17]. Along these same research avenues, we consider an infinite derivative non-local Yang-Mills theory and we show and we derive the set of Dyson-Schwinger equations in differential form till the 2P-correlation functions. Then, we provide a method to solve them, assuming that non-local effects are small at low-energies and taking into account only the leading order solutions [19] as we already show for the scalar field case [18]. The argument about confinement, put forward in [6], is then extended to this non local case [20]. It is seen that UV-limit is never reached in this case and the theory confines in the IR, the coupling running to infinity, without the appearance of a Landau pole. In these studies, we just assume that one has a proper local solutions to start from to get the corrections due to the non-locality. An immediate consequence of this approach is that the a mass gap is obtained and the spectrum of the theory becomes accessible analytically. In any case, the mass gap is diluted in the UV.

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## New Developments in Quantum Field Theory / 314

### Geometrizing Fermionic QFTs via Supermanifolds

**Author:** Sotirios Karamitsos<sup>1</sup>

**Co-authors:** Apostolos Pilaftsis<sup>2</sup>; Kieran Finn

<sup>1</sup> University of Pisa

<sup>2</sup> University of Manchester

**Corresponding Author:** sotirios.karamitsos@df.unipi.it

We always have the freedom to reparametrize any QFT without affecting the underlying physics, but this freedom is not always manifest in the way we write it down. Vilkovisky demonstrated that the standard definition of the effective action yields different off-shell results for different parametrizations of the same theory. This issue is neatly resolved through the covariant Vilkovisky-De Witt (VDW) formalism, which offers a geometric interpretation of a QFT as a (pseudo)Riemannian manifold, in which the fields take on the role of coordinates. Reparametrizations are therefore realized through diffeomorphisms in this field-space manifold, which leave the physics manifestly invariant. However, the application of this covariant formalism to fermionic degrees of freedom and the proper definition of the fermionic field space metric have been elusive. In this talk, I will demonstrate how the VDW formalism can be extended to take into account both scalar and fermion fields. This is made possible by promoting the field space manifold to a supermanifold, which is equipped with a supermetric. In this way, the space of QFTs becomes fully geometrized, and every theory can be written in a manifestly reparametrization-invariant manner.

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## To simplify complicated IBP reduction coefficients via improved Leinartas' algorithm

**Authors:** Dominik Bendle<sup>None</sup>; Janko Boehm<sup>None</sup>; Marcel Wittmann<sup>None</sup>; Rourou Ma<sup>None</sup>; Yang Zhang<sup>None</sup>; Yingxuan Xu<sup>None</sup>; Zihao Wu<sup>None</sup>

**Corresponding Author:** wuzihao@mail.ustc.edu.cn

We introduce improved Leinartas algorithm, to simplify multivariate rational functions via partial fraction decomposition. We use this algorithm to simplify IBP reduction coefficients, dramatically shorten the size of the coefficients. This algorithm can also be used to simplify rational functions in other fields of theoretical physics.

**New Developments in Quantum Field Theory / 222**

## Collider Physics tools for classical gravitational wave observables

**Author:** Enrico Herrmann<sup>1</sup>

**Co-authors:** Mao Zeng<sup>2</sup>; Michael Ruf<sup>3</sup>; Julio Parra-Martinez<sup>4</sup>

<sup>1</sup> *UCLA*

<sup>2</sup> *ETH Zürich*

<sup>3</sup> *Freiburg University*

<sup>4</sup> *Caltech*

**Corresponding Author:** eherrmann10@gmail.com

In this talk, I will review some of the recent developments in applying Quantum Field Theory ideas and scattering amplitudes technology to the study of classical gravitational observables that are relevant to e.g. the LIGO/VIRGO detectors. I will mostly focus on a particular framework, originally devised by Kosower, Maybee, and O'Connell, to extract classical physics from quantum observables. This particular avenue opens the possibility to transfer numerous advances from collider physics calculations, such as integration-by-parts relations, reverse unitarity, and (canonical) differential equations to evaluate the relevant Feynman integrals that appear in the classical gravitational observables of interest. We find surprising similarities between maximally supersymmetric gravity as well as pure Einstein gravity.

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## Recent Developments in N=4 Yang-Mills Scattering Amplitudes

**Author:** Anastasia Volovich<sup>1</sup>

<sup>1</sup> *Brown University (US)*

**Corresponding Author:** anastasia.volovich@cern.ch

I will review recent developments in N=4 Yang-Mills amplitudes.

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## Nonperturbative Negative Geometries: From the Amplituhedron to AdS

**Authors:** Jaroslav Trnka<sup>1</sup>; Johannes Henn<sup>None</sup>; Nima Arkani-Hamed<sup>2</sup>

<sup>1</sup> *UC Davis*

<sup>2</sup> *IAS*

**Corresponding Author:** jmhenn137@gmail.com

We consider scattering amplitudes in N=4 super Yang-Mills theory. Apart from any physics motivation about the exponentiation of infrared divergences, purely from the positive geometry of the loop Amplituhedron, we find that the logarithm of the amplitude appears as a natural object to look at. Thinking about ‘negative geometries’ gives a useful decomposition of the latter, different from usual Feynman diagrams. We define a new observable that can be defined directly in terms of negative geometries, and integrated directly in four dimensions. Purely from the perspective of the geometry, there is a clear separation in the complexity of different contributions. We compute analytically a particular class of terms to all loop orders, and extract their contribution to the cusp anomalous dimension. We find that our analytic result reproduces several qualitative features of the full answer.

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## Fermi-gas correlators of ADHM theory and triality symmetry

**Author:** Tadashi Okazaki<sup>None</sup>

**Co-author:** Yasuyuki Hatsuda<sup>1</sup>

<sup>1</sup> *Rikkyo University*

**Corresponding Author:** tadashi.okazaki.hep@gmail.com

We analytically study the Fermi-gas formulation of sphere correlation functions of the Coulomb branch operators for 3d  $\mathcal{N} = 4$  ADHM theory with a gauge group  $U(N)$ , an adjoint hypermultiplet and  $l$  hypermultiplets which can describe a stack of  $N$  M2-branes at  $A_{l-1}$  singularities. We find that the leading coefficients of the perturbative grand canonical correlation functions are invariant under a hidden triality symmetry conjectured from the twisted M-theory. The triality symmetry also helps us to fix the next-to-leading corrections analytically.

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## **New Developments for the Momentum Amplituhedron**

**Author:** David Damgaard<sup>1</sup>

<sup>1</sup> *LMU Munich*

**Corresponding Author:** d.damgaard@lmu.de

In the past decade our understanding of scattering amplitudes in maximally supersymmetric Yang Mills theory has increased dramatically. This enhanced understanding has led to a formulation of color-ordered scattering amplitudes as logarithmic differential forms on particular geometries, called positive geometries. In particular, the momentum amplituhedron is the geometry governing the tree-level amplitudes in spinor helicity space, and it allows for considering different orderings. In this talk, I will review the construction of the momentum amplituhedron as well as discuss some surprising recent results regarding how the Kleiss-Kuijff relations arise geometrically in this framework.

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## **Cluster Algebras for Feynman Integrals**

**Authors:** Dmitry Chicherin<sup>1</sup>; Georgios Papathanasiou<sup>2</sup>; Johannes Henn<sup>3</sup>

<sup>1</sup> *Max Planck Institute for Physics*

<sup>2</sup> *Deutsches Elektronen-Synchrotron DESY*

<sup>3</sup> *MPP Munich*

**Corresponding Author:** georgios.papathanasiou@desy.de

A wealth of physical information may be inferred from the singularities of scattering amplitudes. For the simplest interacting gauge theory, these singularities have been found to be encoded in beautiful mathematical objects known as cluster algebras. In this talk, I present evidence that cluster algebras may underlie the analytic structure of general quantum field theories. In particular, I show that they describe the singularities of a considerable number of Feynman integrals in dimensional regularization, most notably those governing Higgs plus jet amplitudes in QCD. This opens for the first time the exciting prospect of applications of cluster algebras to future collider physics calculations, for example via novel bootstrap methods that evade the formidable task of direct integration.

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## **Generalized Supersymmetric Pati-Salam Models from Intersecting D6-branes**

**Author:** Rui Sun<sup>1</sup>

**Co-authors:** Tianjun Li<sup>2</sup>; Lina Wu<sup>3</sup>; Adeel Mansha<sup>4</sup>; Weikun He<sup>1</sup>

<sup>1</sup> *KIAS*

<sup>2</sup> *Chinese Academy of Sciences*

<sup>3</sup> *School of Science, Xi'an Technological University*

<sup>4</sup> *ITP*

**Corresponding Author:** sunrui0310@gmail.com

We discuss the  $N = 1$  supersymmetric  $SU(12)_C \times SU(2)_L \times SU(2)_R$  models,  $SU(4)_C \times SU(6)_L \times SU(2)_R$  models, and  $SU(4)_C \times SU(2)_L \times SU(6)_R$  models from the Type IIA orientifolds on  $T^6/(\mathbb{Z}_2 \times \mathbb{Z}_2)$  with intersecting D6-branes. These gauge symmetries can be broken down to the Pati-Salam gauge symmetry  $SU(4)_C \times SU(2)_L \times SU(2)_R$  via three  $SU(12)_C/SU(6)_L/SU(6)_R$  adjoint representation Higgs fields, and further down to the Standard Model (SM) via the D-brane splitting and Higgs mechanism. We obtain three families of the SM fermions, and have the left-handed three-family SM fermion unification in the  $SU(4)_C \times SU(6)_L \times SU(2)_R$  models, and the right-handed three-family SM fermion unification in the  $SU(4)_C \times SU(2)_L \times SU(6)_R$  models.

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## The control issues of KKLT de Sitter construction in string theory

**Author:** Xin Gao<sup>1</sup>

**Co-authors:** Daniel Junghans ; Arthur Hebecker

<sup>1</sup> *Sichuan University*

**Corresponding Author:** xingao@scu.edu.cn

In this talk, I will introduce the problem of realizing de Sitter space in string compactifications, especially the proposal by Kachru, Kallosh, Linde and Trivedi (KKLT). We analyze to which extent the KKLT proposal for the construction of de Sitter vacua in string theory is quantitatively controlled. I will then explain why, according to our recent analysis, extended singularities in the bulk of the compact space appear to generically threaten the construction. In particular, we show that, requiring the curvature to be small in the conifold region, one is generically forced into a regime where the warp factor becomes negative in a large part of the Calabi-Yau orientifold. We call it the “bulk singular problem”.

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## Sharpening the Boundaries Between Flux Landscape and Swampland by Tadpole Charge

**Author:** Keiya Ishiguro<sup>1</sup>

**Co-author:** Hajime Otsuka<sup>2</sup>

<sup>1</sup> *Tsukuba, Graduate U. Adv. Studies (SOKENDAI)*

<sup>2</sup> *KEK, Tsukuba*

**Corresponding Author:** keyspire@ruri.waseda.jp

We investigate the vacuum structure of four-dimensional effective theory arising from Type IIB flux compactifications on a mirror of the rigid Calabi-Yau threefold, corresponding to a T-dual of the DeWolfe-Giryavets-Kachru-Taylor model in Type IIA flux compactifications. By analyzing the vacuum structure of this interesting corner of string landscape, it turns out that there exist perturbatively unstable de Sitter (dS) vacua in addition to supersymmetric and non-supersymmetric anti-de Sitter vacua. On the other hand, the stable dS vacua appearing in the low-energy effective action violate the tadpole cancellation condition, indicating a strong correlation between the existence of dS vacua and the flux-induced D3-brane charge (tadpole charge). We also find analytically that the tadpole charge constrained by the tadpole cancellation condition emerges in the scalar potential in

a nontrivial way. Thus, the tadpole charge would restrict the existence of stable dS vacua, and this fact underlies the statement of the dS conjecture. Furthermore, our analytical and numerical results exhibit that distributions of  $calO(1)$  parameters in expressions of several swampland conjectures peak at specific values.

**New Developments in String Theory / 50**

## Aligned Natural Inflation in Large Volume Scenario

**Author:** Kang Sin Choi<sup>1</sup>

<sup>1</sup> *Ewha Womans University*

**Corresponding Author:** kangsin@ewha.ac.kr

We embed aligned natural inflation and stabilize moduli in Large Volume Scenario. Scalar perturbation, weak gravity conjecture and Kahler condition of internal geometry constrains the model in interesting ways.

**New Developments in String Theory / 360**

## When Nekrasov partition function meets 5-brane web with O5-plane in the thermodynamic limit

**Authors:** Futoshi Yagi<sup>1</sup>; Xiaobin Li<sup>2</sup>

<sup>1</sup> *Southwest Jiaotong University*

<sup>2</sup> *Southwest Jiaotong University*

**Corresponding Author:** lixiaobin@home.swjtu.edu.cn

In this paper, we study 5d  $N = 1$   $Sp(N)$  gauge theory with  $N_f$  flavors based on 5-brane web diagram with O5-plane. On the one hand, we discuss Seiberg-Witten curve based on the dual graph of the 5-brane web with O5-plane. On the other hand, we compute the Nekrasov partition function based on the topological vertex formalism with O5-plane. Rewriting it in terms of profile functions, we obtain the saddle point equation for the profile function after taking thermodynamic limit. By introducing the resolvent, we derive the Seiberg-Witten curve and its boundary conditions as well as its relation to the prepotential in terms of the cycle integrals. They coincide with those directly obtained from the dual graph of the 5-brane web with O5-plane. This agreement gives further evidence for mirror symmetry which relates Nekrasov partition function with Seiberg-Witten curve in the case with orientifold plane and shed light on the non-toric Calabi-Yau 3-folds including D-type singularities.

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## Holographic Heavy-Heavy-Light Three-point functions Revisited

**Author:** Jun-Bao Wu<sup>1</sup>

<sup>1</sup> *Tianjin University*

**Corresponding Author:** junbao.wu@tju.edu.cn

We study correlation functions of D-branes and a supergravity mode in AdS, which are dual to structure constants of two sub-determinant operators with large charge and a BPS single-trace operator. Our approach is inspired by the large charge expansion of CFT and resolves puzzles and confusions in the literature on the holographic computation of correlation functions of heavy operators. In particular, we point out two important effects which are often missed in the literature; the first one is an average over classical configurations of the heavy state, which physically amounts to projecting the state to an eigenstate of quantum numbers. The second one is the contribution from wave functions of the heavy state. To demonstrate the power of the method, we first analyze the three-point functions in N=4 super Yang-Mills and reproduce the results in field theory from holography, including the cases for which the previous holographic computation gives incorrect answers. We then apply it to ABJM theory and make solid predictions at strong coupling. Finally we comment on possible applications to states dual to black holes and fuzzballs.

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## Three Point Functions in ABJM Theory-Weak Coupling Computation

**Author:** Peihe Yang<sup>1</sup>

<sup>1</sup> *Tianjin University*

**Corresponding Author:** peihe\_yang@tju.edu.cn

We develop an integrability-based framework to compute structure constants of two subdeterminant operators and a single-trace non-BPS operator in ABJM theory in the planar limit. In this part of work I will introduce them at weak coupling using a relation to an integrable spin chain. We first develop a nested Bethe ansatz for an alternating SU(4) spin chain that describes single-trace operators made out of scalar fields. We then apply it to the computation of the structure constants and show that they are given by overlaps between a Bethe eigenstate and a matrix product state. We conjecture that the determinant operator corresponds to an integrable matrix product state and present a closed-form expression for the overlap, which resembles the so-called Gaudin determinant. We also provide evidence for the integrability of general sub-determinant operators. The techniques developed in this paper can be applied to other quantities in ABJM theory including three-point functions of single-trace operators.

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## 4D effective action from non-Abelian DBI action with magnetic flux background

**Authors:** Rei Takahashi<sup>None</sup>; Shintaro Takada<sup>1</sup>; Tatsuo Kobayashi<sup>1</sup>; Tetsutaro Higaki<sup>2</sup>; Yoshihiko Abe<sup>None</sup>

<sup>1</sup> *Hokkaido University*

<sup>2</sup> *Keio University*

**Corresponding Author:** y.abe@gauge.scphys.kyoto-u.ac.jp

We derive 4D  $\mathcal{N} = 1$  supersymmetric effective theory from 10D non-Abelian Dirac-Born-Infeld action compactified on a six dimensional tori with magnetic flux on the D-branes. For the 10D action, we use a symmetrized trace prescription and focus on the bosonic part. 4D chiral fermions can arise via index theorem for the background flux. The gauge coupling and the matter Kähler metric are read from the 10D action, which depend on closed string moduli and the fluxes.

We read the superpotential from an F-term scalar quartic interaction derived from the 10D action, and discuss the contribution of the matter Kähler metric to the scalar potential is consistent with the supergravity formulation.

This talk is based on the collaboration with Tetsutaro Higaki, Tatsuo Kobayashi, Shintaro Takada and Rei Takahashi.

**New Developments in String Theory / 464**

## **A New Spin on the Weak Gravity Conjecture**

**Author:** Gregory Loges<sup>None</sup>

**Co-author:** Gary Shiu

**Corresponding Author:** gloges@wisc.edu

The mild form of the Weak Gravity Conjecture states that quantum or higher-derivative corrections should decrease the mass of large, extremal, charged black holes at fixed charge. This allows extremal black holes to decay, unless protected by a symmetry (such as supersymmetry). This conjecture can be reformulated as an integrated condition on the effective stress tensor capturing the effect of quantum or higher-derivative corrections. In addition to charged black holes, we also consider rotating BTZ black holes and show that this condition is satisfied as a consequence of the c-theorem, proving a spinning version of the Weak Gravity Conjecture.

**New Developments in String Theory / 267**

## **Moduli Stabilisation and the Statistics of SUSY Breaking in the Landscape**

**Author:** Kuver Sinha<sup>1</sup>

<sup>1</sup> *University of Oklahoma*

**Corresponding Author:** kuver.sinha@gmail.com

The statistics of the supersymmetry breaking scale in the string landscape has been extensively studied in the past finding either a power-law behaviour induced by uniform distributions of F-terms or a logarithmic distribution motivated by dynamical supersymmetry breaking. These studies focused mainly on type IIB flux compactifications but did not systematically incorporate the Kähler moduli. In this paper we point out that the inclusion of the Kähler moduli is crucial to understand the distribution of the supersymmetry breaking scale in the landscape since in general one obtains unstable vacua when the F-terms of the dilaton and the complex structure moduli are larger than the F-terms of the Kähler moduli. After taking Kähler moduli stabilisation into account, we find that the distribution of the gravitino mass and the soft terms is power-law only in KKLT and perturbatively stabilised vacua which therefore favour high scale supersymmetry. On the other hand, LVS vacua feature a logarithmic distribution of soft terms and thus a preference for lower scales of supersymmetry breaking. Whether the landscape of type IIB flux vacua predicts a logarithmic or power-law distribution of the supersymmetry breaking scale thus depends on the relative preponderance of LVS and KKLT vacua.

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## **The Standard Model Quiver in de Sitter String Compactifications**



**Authors:** Andreas Schachner<sup>1</sup>; Fernando Quevedo<sup>2</sup>; Iñaki García Etxebarria<sup>3</sup>; Michele Cicoli<sup>4</sup>; Michele Cicoli<sup>5</sup>; Pramod Shukla<sup>None</sup>; Roberto Valandro<sup>None</sup>

<sup>1</sup> *Cambridge University*

<sup>2</sup> *University of Cambridge*

<sup>3</sup> *Durham University*

<sup>4</sup> *Università di Bologna*

<sup>5</sup> *INFN - National Institute for Nuclear Physics*

**Corresponding Author:** as2673@cam.ac.uk

With the advent of the string landscape, the realisation of the Standard Model in general string theory compactifications to 4D has become a primary focus. This talk concerns novel constructions of the Standard Model in global set-ups of type IIB Calabi-Yau compactifications. We argue that the Standard Model quiver can be embedded into compact Calabi-Yau geometries through orientifolded D3-branes at del Pezzo singularities  $dP_n$  with  $n \geq 5$  in a framework including moduli stabilisation. To illustrate our approach, we explicitly construct a local  $dP_5$  model via a combination of Higgsing and orientifolding. This procedure reduces the original  $dP_5$  quiver gauge theory to the Left-Right symmetric model with three families of quarks and leptons as well as a Higgs sector to further break the symmetries to the Standard Model gauge group. We embed this local model in a globally consistent Calabi-Yau flux compactification with tadpole and Freed-Witten anomaly cancellations. The model features closed string moduli stabilisation with a de Sitter minimum from T-branes, supersymmetry broken by the Kähler moduli, and the MSSM as the low energy spectrum. We further discuss phenomenological and cosmological implications of this construction.

## New Developments in String Theory / 35

### Moduli-dependent Calabi-Yau and SU(3)-structure metrics from Machine Learning

**Authors:** Lara B. Anderson<sup>1</sup>; Mathis Gerdes<sup>None</sup>; Nikhil Raghuram<sup>2</sup>; Sven Krippendorff<sup>None</sup>; James Gray<sup>1</sup>

<sup>1</sup> *Virginia Tech*

<sup>2</sup> *Massachusetts Institute of Technology*

**Corresponding Author:** mathisgerdes@gmail.com

We use machine learning to approximate Calabi-Yau and SU(3)-structure metrics, including for the first time complex structure moduli dependence. Our new methods furthermore improve existing numerical approximations in terms of accuracy and speed. Knowing these metrics has numerous applications, ranging from computations of crucial aspects of the effective field theory of string compactifications such as the canonical normalizations for Yukawa couplings, and the massive string spectrum which plays a crucial role in swampland conjectures, to mirror symmetry and the SYZ conjecture. In the case of SU(3) structure, our machine learning approach allows us to engineer metrics with certain torsion properties. Our methods are demonstrated for Calabi-Yau and SU(3)-structure manifolds based on a one-parameter family of quintic hypersurfaces in  $P^4$ .

## New Tools in New Physics Searches / 161

### (S)ARGES – Advanced Renormalisation Group Equation Simplifier

**Authors:** Tom Steudtner<sup>1</sup>; Daniel Litim<sup>2</sup>

<sup>1</sup> *TU Dortmund*

<sup>2</sup> *University of Sussex*

**Corresponding Author:** tom2.steudtner@tu-dortmund.de

We present ARGES, a toolkit for obtaining renormalisation group equations in perturbation theory, as well as SARGES, its supersymmetric counterpart.

The programs can handle any perturbatively renormalisable four-dimensional quantum field theory, and have pioneered the approach of performing a symbolic rather than numeric computation. We highlight further notable features, such as input of unconventional scalar and Yukawa sectors, an interactive evaluation and disentanglement as well as capabilities to inject algebraic simplification rules.

**New Tools in New Physics Searches / 61**

## FlexibleDecay: An automated calculator of scalar decay widths

**Authors:** Alexander Voigt<sup>1</sup>; Dominik Stoeckinger<sup>2</sup>; Peter Athron<sup>None</sup>; Wojciech Kotlarski<sup>3</sup>

<sup>1</sup> *RWTH Aachen*

<sup>2</sup> *TU Dresden*

<sup>3</sup> *TU - Dresden*

**Corresponding Author:** wojciech.kotlarski@tu-dresden.de

We present FlexibleDecay, a tool to calculate decays of scalars in an arbitrary BSM model. The tool aims for high precision particularly in the case of Higgs boson decays. In the case of scalar and pseudoscalar Higgs boson decays the known higher order SM QED, QCD and EW effects are taken into account where possible. The program works in a modified  $\overline{\text{MS}}$  scheme that exhibits a decoupling property with respect to heavy BSM physics, with BSM parameters themselves treated in the  $\overline{\text{MS}}$ / $\overline{\text{DR}}$ -scheme allowing for an easy connection to high scale tests for, e.g., perturbativity and vacuum stability, and the many observable calculations readily available in  $\overline{\text{MS}}$ / $\overline{\text{DR}}$  programs. Pure BSM effects are taken into account at the leading order, including all one-loop contributions to loop-induced processes. The program is implemented as an extension to FlexibleSUSY, which determines the mass spectrum for arbitrary BSM models, and does not require any extra configuration from the user.

**New Tools in New Physics Searches / 369**

## MARTY, an independent software program for general symbolic calculations in Beyond the Standard Model physics

**Author:** Grégoire Uhlich<sup>None</sup>

**Corresponding Author:** g.uhlich@ipnl.in2p3.fr

We present MARTY (arXiv:2011.02478 [hep-ph]), the very first independent program automating the calculation of amplitudes, squared amplitudes and Wilson coefficients at the tree level and the one-loop level for general BSM models. This type of calculations requires a computer algebra system and could only be done, up to now, using Mathematica that is a commercial and closed software for symbolic manipulations. MARTY does not rely on Mathematica since it re-implements its own symbolic computation machinery. We show how to perform phenomenological analyses in general BSM scenarios using MARTY, for any domain of high energy physics.

## New Tools in New Physics Searches / 395

**Probing long-lived particles with SModelS v2**

**Authors:** Alicia Wongel<sup>1</sup>; Andre Lessa<sup>2</sup>; Gael Alguero<sup>3</sup>; Chanranjit K. Khosa<sup>4</sup>; Humberto Reyes-González<sup>5</sup>; Jan Heisig<sup>6</sup>; Neuhuber Philip<sup>None</sup>; Sabine Kraml<sup>7</sup>; Suchita Kulkarni<sup>8</sup>; Wolfgang Waltenberger<sup>9</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron (DE)*

<sup>2</sup> *CCNH - Univ. Federal do ABC*

<sup>3</sup> *LPSC, Grenoble*

<sup>4</sup> *University of Genova*

<sup>5</sup> *University of Genoa*

<sup>6</sup> *Université catholique de Louvain (UCL)*

<sup>7</sup> *LPSC Grenoble*

<sup>8</sup> *University of Graz*

<sup>9</sup> *Austrian Academy of Sciences (AT)*

**Corresponding Author:** gael.alguero@lpsc.in2p3.fr

The new developments in SModelS, an automated tool enabling the fast interpretation of simplified model results from the LHC, make it possible to include a wide range of constraints for long-lived particles and treat them at the same footing as the constraints from prompt searches. We present these new features of SModelS v2.x and the new experimental analyses included in its database, and showcase how they constrain different new physics scenarios, including electroweakinos in the MSSM, and scalar or fermionic dark matter in the scotogenic model. Finally, we also report on our SModelS/pyhf interface, allowing the usage of full likelihoods as published by ATLAS.

## New Tools in New Physics Searches / 252

**Machine learning Higgs tagger**

**Author:** Jinmian Li<sup>1</sup>

<sup>1</sup> *Sichuan University*

**Corresponding Author:** phyljm@gmail.com

Based on the jet image approach, which treats the energy deposition in each calorimeter cell as the pixel intensity, the Convolutional neural network (CNN) method has been found to achieve a sizable improvement in jet tagging compared to the traditional jet substructure analysis.

In this work, the Mask R-CNN framework is adopted to reconstruct Higgs jets in collider-like events, with the effects of pileup contamination taken into account. This automatic jet reconstruction method achieves higher efficiency of Higgs jet detection and higher accuracy of Higgs boson four-momentum reconstruction than traditional jet clustering and jet substructure tagging methods.

Moreover, the Mask R-CNN trained on events containing a single Higgs jet is capable of detecting one or more Higgs jets in events of several different processes, without apparent degradation in reconstruction efficiency and accuracy.

The outputs of the network also serve as new handles for the  $t\bar{t}$  background suppression, complementing to traditional jet substructure variables.

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**FORESEE: FORward Experiment SENSitivity Estimator for the LHC and future hadron colliders**

**Authors:** Felix Kling<sup>1</sup>; Sebastian Trojanowski<sup>2</sup>

<sup>1</sup> SLAC

<sup>2</sup> National Centre for Nuclear Research, Poland

**Corresponding Author:** strojan@fuw.edu.pl

During the upcoming Run 3, a new experimental program will be initiated at the LHC in its far-forward region that will focus on the search for highly-displaced decays of light unstable BSM particles in the FASER detector and on studying interactions of high-energy neutrinos in the FASERnu and SND@LHC experiments. To fully exploit the relevant physics potential, the experimental efforts should be supplemented with a comprehensive program of theoretical and phenomenological studies. To facilitate this, in the talk, we will introduce a numerical package, namely the FORward Experiment SENSitivity Estimator, or FORESEE, which could be used to obtain the expected sensitivity reach for BSM models in various far-forward experiments. We will also comment on the similar prospects for the far-forward BSM searches in the future HE-LHC, SppC, and FCC-hh hadron colliders.

**New Tools in New Physics Searches / 27**

## Extracting Invisible Higgs signals at the LHC with Convolutional Neural Networks

**Authors:** Akanksaa Bhardwaj<sup>1</sup>; Aruna Nayak<sup>2</sup>; Partha Konar<sup>3</sup>; Vishal Singh Ngairangbam<sup>4</sup>

<sup>1</sup> University of Glasgow

<sup>2</sup> Institute of Physics, Bhubaneswar

<sup>3</sup> Physical Research Laboratory, Ahmedabad, Gujarat-380 009, INDIA

<sup>4</sup> Physical Research Laboratory

**Corresponding Author:** vishalngairangbam@gmail.com

We show that using the full tower information in the form of an image, a Convolutional Neural Network(CNN) can efficiently recognise Vector boson fusion(VBF) signal from non VBF backgrounds at the Large Hadron Collider(LHC). As a concrete example, we compare with existing state-of-the-art techniques currently in use, we show that deep-learning algorithms like a CNN can significantly improve the bounds on the invisible branching ratio of the recently discovered Higgs boson. This can help constrain many beyond the Standard Model(BSM) theories, which relies on the Higgs decaying to any new stable (or semi stable) particles which do not interact with the known Standard Model particles.

**Opening Remarks / 551**

## Picture taking

**Opening Remarks / 553**

## Opening remarks I

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## Opening remarks II

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## Acknowledgments

Corresponding Author: tli@itp.ac.cn

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## Baryogenesis and New Physics

Corresponding Author: elcwagner@gmail.com

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## Higgs measurements at ATLAS and CMS

Corresponding Author: antonio.de.maria@cern.ch

Since the Higgs boson discovery in 2012, a continuous effort has been made to study several of its properties like the coupling strengths, spin and charge-parity quantum numbers. The Higgs boson is not only a key ingredient of the Standard Model of particle physics to understand the mechanism which gives mass to other particles, but also to open new frontiers beyond the Standard Model.

The most recent measurements on the Higgs sector by ATLAS and CMS experiments at the LHC will be presented in this talk, including differential and Simplified Template cross-section measurements as well as coupling to the second generation fermions and di-Higgs production searches.

Plenary / 515

## The String Landscape and Particle Remnants

Corresponding Author: j.halverson@northeastern.edu

In this talk I will review some essential facts about the known landscape of string vacua and its potential implications for particle physics and cosmology. A central focus will be on string remnants, which are new particles that are apparently accidental consequences of the ultraviolet theory, not necessarily motivated by specific shortcomings of the standard models of particle physics or cosmology. A particular focus will be given to dark gauge sectors and axion-like particles, including their couplings to the photon.

Plenary / 528

## Exploring farther with long-lived particles

Corresponding Author: jshelton137@gmail.com

Plenary / 510

## Exploring suspersymmetric theories from scattering amplitudes

Corresponding Author: yutin@phys.ntu.edu.tw

In the past few years, the study of amplitudes have made inroads in connecting with classical dynamics of binary blackholes as well as the revival of the S-matrix bootstrap. We will give a brief overview of the major results on these two fronts and the new light they shed on supersymmetric theories.

Plenary / 511

## Grand Unified Theories

Corresponding Author: kaladi.babu@okstate.edu

I shall review the motivations for grand unification and summarize recent progress in this field.

Plenary / 500

## Recent Progress and Plan of PandaX Experiment

Corresponding Author: ning.zhou@cern.ch

PandaX experiment uses xenon as target to detect weak and rare physics signals, including dark matter and neutrinos. PandaX-II, 580kg liquid xenon completed successfully in 2019, and we are running a next generation experiment PandaX-4T with 4-ton xenon in the sensitive volume. In this talk, I will give an overview of the PandaX-4T experiment and commissioning. From 0.63 ton-year exposure data during commissioning, new constraints on the WIMP-nucleon spin-independent cross section is obtained.

Plenary / 504

## GAMBIT: The Global and Modular Beyond-the-Standard-Model Inference Tool

Corresponding Author: csaba.balazs@monash.edu

I give an update on GAMBIT, the Global And Modular Beyond-the-Standard-Models Inference Tool. After briefly motivating global fitting, I highlight why GAMBIT is a promising framework to help us identifying the new physics model beyond the standard models (BSM) of particle physics and cosmology. Focusing on the physics content, I give a non-technical introduction of the schematic structure and main features of the GAMBIT code, from the hierarchical database, through dependency resolution, to modules and backends. I finish the talk by describing the GAMBIT Universal Model Machine, the latest feature that GAMBIT 2.0 introduced.

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## Dark Matter (Mediators) at Colliders

Corresponding Author: drees@th.physik.uni-bonn.de

Thermal Dark Matter (DM) must have sizable couplings to lighter particles. This motivates Dark Matter searches at colliders. However, these 'lighter particles' need not include the particles humans can accelerate (basically electrons, u and d quarks, and gluons). Moreover, in most cases collider searches for the particle mediating the interaction of DM with lighter particles are more promising than searching for DM production. Special attention is paid to the production of mediators that do not couple to first generation fermions, and thus have to be produced in higher order processes.

Plenary / 522

## Challenges in supersymmetric cosmology

Corresponding Author: antoniad@lpthe.jussieu.fr

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## Progresses of the Dark Matter Particle Explorer

Corresponding Author: yuanq@pmo.ac.cn

The Dark Matter Particle Explorer (DAMPE) is a satellite-borne, calorimetric type, high-energy-resolution space cosmic ray and gamma-ray detector. It was launched in December 2015 and has been stably operating for more than five years. Its three major scientific objectives are dark matter indirect detection, cosmic ray physics and gamma-ray astronomy. Precise measurements of the all-electron, proton and Helium spectra in wide energy ranges have been obtained, shedding new light on the research of cosmic ray physics and dark matter properties. We will also present the current status of the mission and its recent physical results.

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## The Foundation of Unification Theory & Gravitational Wave Detections in Space

**Corresponding Author:** ylwu@itp.ac.cn

In this talk, I will report the recent progresses on the foundation of unification theory and the projects on the space-based gravitation wave detections. I shall briefly outline that the foundation of the hyperunified field theory based on the maximum coherence motion principle and maximum entangled-qubits motion principle as well as gauge and scaling invariance principle enables us to make issues on the long-standing open questions, such as: what is made to be the fundamental building block of nature? What is acted as the fundamental interaction of nature? what brings about the fundamental symmetry of nature? what is the basic structure of spacetime? how many dimensions does spacetime have? what makes time difference from space? why is there only one temporal dimension? why do we live in a universe with only four dimensional spacetime? Why are there leptons and quarks more than one family? why are the existed leptons and quarks the chiral fermions with maximum parity violation? how does the fundamental symmetry govern basic forces? what is the nature of gravity? how does early universe get inflationary expansion? what is a dark matter candidate? what is the nature of dark energy? what is the nature of Higgs boson? how can we understand three families of chiral type leptons and quarks? It is expected that the gravitational wave detections with LISA and Taiji projects in space provide a new window for exploring the gravitational universe and possible new phenomena of unification theory.

Plenary / 516

## **Aspects of Higgs and EW physics in SUSY: light LSP and Heavy Higgs**

**Corresponding Author:** rohini@iisc.ac.in

In this talk I will discuss the case of a light LSP (lighter than half the Higgs mass) in pMSSM, NMSSM as well as both these models extended with a right handed sneutrino. In addition I will point out some new strategies for heavy higgs searches in electroweakino final states as well as remind us of the importance of the precision calculations in the Higgs sector for the phenomenology.

Plenary / 513

## **(Non-)SUSY 2021 and Cosmology: overview and new developments**

**Corresponding Author:** evas@stanford.edu

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## **Quantum Gravity and the Swampland**

**Corresponding Author:** shiu@physics.wisc.edu

String theory seems to offer an enormous number of possibilities for low energy physics. The huge set of solutions is often known as the String Theory Landscape. In recent years, there has been increasing evidence that not all quantum field theories can be consistently coupled to gravity. Theories that cannot be ultraviolet completed in quantum gravity are said to be in the Swampland. In this talk, I'll discuss some conjectured properties of quantum gravity, evidences for them, and their phenomenological applications.



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## **Four-form relaxation of Higgs mass and its cosmological implications**

Corresponding Author: hminlee@cau.ac.kr

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## **SUSY Predictions from the String Landscape and the Naturalness**

Corresponding Author: baer@nhn.ou.edu

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## **Particle-Antiparticle Oscillations and Baryogenesis in SUSY**

Corresponding Author: sipek@physics.carleton.ca

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## **The First Results of the Fermilab Muon $g-2$ Experiment**

Corresponding Author: l.li@cern.ch

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## **Theoretical overview of muon $g-2$**

Corresponding Author: motoi.endo@kek.jp

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## **Future Colliders**

Corresponding Author: yfwang@mail.ihep.ac.cn

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## **Prospects of HL-LHC (ATLAS, CMS, LHCb)**

**Corresponding Author:** sezen.sekmen@cern.ch

**Plenary / 540**

## **EW/Top measurements at ATLAS and CMS**

**Corresponding Author:** aleksandra.dimitrievska@cern.ch

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## **Top Quark Physics**

**Corresponding Author:** qinghongcao@pku.edu.cn

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## **Collider Searches, Standard Model Effective Theory**

**Corresponding Author:** ian.lewis@ku.edu

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## **SUSY chargino/neutralino searches at ATLAS and CMS**

**Corresponding Author:** teruki.kamon@cern.ch

**Plenary / 533**

## **SUSY squark/gluino searches at ATLAS and CMS**

**Corresponding Author:** luigi.longo@cern.ch

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## **Other searches at ATLAS and CMS**

**Corresponding Author:** rachid.mazini@cern.ch

**Plenary / 535**

## **BSM Higgs searches at ATLAS and CMS**

**Corresponding Author:** aruna.nayak@cern.ch

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## **Precision axion physics with running axion couplings**

**Corresponding Author:** kchoi@ibs.re.kr

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## **Axion dark matter**

**Corresponding Author:** sikivie@phys.ufl.edu

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## **Gravitational Waves as Probes of New Fundamental Physics**

**Corresponding Author:** pedro.schwaller@uni-mainz.de

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## **Sub-GeV Dark Matter**

**Corresponding Author:** dutta@physics.tamu.edu

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## **Dark matter/Long-lived particles at ATLAS and CMS**

**Corresponding Author:** zeynep.demiragli@cern.ch

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## **Galactic Probes of Dark-Sector Physics**

**Corresponding Author:** mlisanti@princeton.edu

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## **Solar WIMP Search with the IceCube Neutrino Observatory**

Corresponding Author: jeffrey.lazar@icecube.wisc.edu

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## **Neutrino masses and Yukawa interactions**

Corresponding Author: xingzz@ihep.ac.cn

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## **Belle and Belle II results**

Corresponding Author: bhuyan@iitg.ac.in

Plenary / 538

## **Flavour physics: LHCb, ATLAS, CMS**

Corresponding Author: yuehong.xie@cern.ch

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## **B-physics anomalies and flavor hierarchies: a natural link**

Corresponding Author: gino.isidori@cern.ch

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## **Machine Learning and QCD**

Corresponding Author: plehn@uni-heidelberg.de

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## **Recent progress on jet structure for BSM**

Corresponding Author: nojiri@post.kek.jp

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## Aspirations and Prospects for Natural Supersymmetry

Corresponding Author: tata@phys.hawaii.edu

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## String Inflation

Corresponding Author: kallosh@stanford.edu

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## SUSY 2022 Announcement

Corresponding Author: leonta@uoi.gr

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## Why SUSY is great

Corresponding Author: hitoshi.murayama@ipmu.jp

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## Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum with the ATLAS experiment

Author: Yuta Okazaki<sup>1</sup>

Co-author: The ATLAS collaboration

<sup>1</sup> *Kyoto University (JP)*

Corresponding Author: yuta.okazaki@cern.ch

Searches for electroweakinos light enough to be produced at the LHC are well motivated by consideration on dark matter, naturalness and the recently observed muon  $g-2$  anomaly. This talk presents a search for electroweakinos in fully-hadronic final states to exploit the advantage of the large branching ratio, and the efficient background rejection by identifying the high- $p_T$  bosons using large-radius jets and jet substructure information. Compared to the more traditionally considered lepton final states, it allows to reach sensitivity to higher electroweakinos masses and to set strong limits on a variety of simplified models. For example, for the case of the wino-bino simplified model a wino mass up to 1060 GeV is excluded. Additionally, more concrete complete models and parameter scans are also considered.

Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 447

## Jet flavour tagging for the ATLAS Experiment

**Author:** Jonathan Shlomi<sup>1</sup>

<sup>1</sup> *Weizmann Institute of Science (IL)*

**Corresponding Author:** jonathan.shlomi@weizmann.ac.il

The ability to identify jets stemming from the hadronisation of b-quarks (b-jets) is crucial for the physics program of ATLAS. The higher pileup conditions and the growing interest for measurements including c-jets and for searches in the high transverse momentum regime make the task more and more complex. The algorithms responsible for establishing the jet's flavour are evolving quickly, exploiting powerful multivariate and deep machine learning techniques. Since the primary input to any such algorithm consists of charged-particle tracks within the jet, the identification of jets from heavy-flavor decays depends strongly on the tracking efficiency and resolution and the robustness of the track-jet association logic. Flavour-tagging techniques in ATLAS will be reviewed, presenting the state-of-the-art in terms of algorithms, with focus on the capability to reconstruct and select the relevant tracks produced in the ATLAS Inner Detector.

Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 326

## Highly Boosted Higgs Bosons and Unitarity in Vector-Boson Fusion at Future Hadron Colliders

**Author:** Zhijie Zhao<sup>1</sup>

**Co-authors:** Qi-Shu Yan<sup>2</sup>; Sichun Sun ; Xiaoran Zhao<sup>3</sup>; Wolfgang Kilian<sup>4</sup>

<sup>1</sup> *Institute of High Energy Physics, Chinese Academy of Sciences*

<sup>2</sup> *University of Chinese Academy of Sciences*

<sup>3</sup> *Rome Tre University*

<sup>4</sup> *University of Siegen*

**Corresponding Author:** zhaozhijie@ihep.ac.cn

We study the observability of new interactions which modify Higgs-pair production via vector-boson fusion processes at the LHC and at future proton-proton colliders. In an effective-Lagrangian approach, we explore in particular the effect of the operator  $h^2 W_{\mu\nu}^a W^{a,\mu\nu}$ , which describes the interaction of the Higgs boson with transverse vector-boson polarization modes. By tagging highly boosted Higgs bosons in the final state, we determine projected bounds for the coefficient of this operator at the LHC and at a future 27 TeV or 100 TeV collider. Taking into account unitarity constraints, we estimate the new-physics discovery potential of Higgs pair production in this channel.

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## Searches for new physics in events with jets in the final state in CMS

**Author:** Eirini Tziaferi<sup>1</sup>

<sup>1</sup> *National and Kapodistrian University of Athens (GR)*

**Corresponding Author:** e.tziaferi@cern.ch

Many new physics models, e.g., compositeness, extra dimensions, excited quarks, and dark matter mediators, are expected to manifest themselves in final states with jets. This talk presents searches in CMS for new phenomena in the final states that include jets, focusing on the recent results obtained using the full Run-II data-set collected at the LHC.

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## **Searches for vector-like quarks at CMS**

**Author:** Francesco Carnevali<sup>1</sup>

<sup>1</sup> *Universita e sezione INFN di Napoli (IT)*

**Corresponding Author:** francesco.carnevali@cern.ch

We present results of searches for vector-like quarks using proton-proton collision data collected with the CMS detector at the CERN LHC at a center-of-mass energy of 13 TeV. Single and pair production of vector-like quarks are studied, with decays into a variety of final states, containing top and bottom quarks, electroweak gauge and Higgs bosons. The presented searches make use of a wide variety of reconstructed objects, allowing to explore diverse signatures from multi-leptonic to fully hadronic. We set exclusion limits on the vector-like quark masses and cross sections, and for combinations of the vector-like quark branching ratios.

**Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 439**

## **Searches and techniques for boosted resonances (non-diboson) with the ATLAS detector**

**Author:** Miguel Villaplana<sup>1</sup>

<sup>1</sup> *IFIC - Univ. of Valencia and CSIC (ES)*

**Corresponding Author:** miguel.villaplana.perez@cern.ch

Many new-physics signatures at the LHC produce highly boosted particles, leading to close-by objects in the detector and necessitating jet substructure techniques to disentangle the hadronic decay products. This talk will illustrate the use of these techniques in recent ATLAS searches for heavy  $W'$  and  $Z'$  resonances in top-bottom and di-top final states, as well as searches for vector-like quarks, using the full Run 2 dataset. It will explain the techniques used, including new top-tagging techniques using machine learning and the use of large-radius jets containing electrons.

**Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 442**

## **Searches for new physics with leptons using the ATLAS detector**

**Author:** Christos Vergis<sup>1</sup>

<sup>1</sup> *University of Bonn (DE)*

**Corresponding Author:** christos.vergis@cern.ch

Many theories beyond the Standard Model predict new phenomena, such as  $Z'$ ,  $W'$  bosons, or heavy leptons, in final states with isolated, high-pt leptons (e/mu/tau). Searches for new physics with such signatures, produced either resonantly or non-resonantly, are performed using the ATLAS experiment at the LHC. This includes a novel search that exploits the lepton-charge asymmetry in events with an electron and muon pair. Lepton flavor violation (LFV) is a striking signature of potential beyond the Standard Model physics. The search for LFV with the ATLAS detector focuses on the decay of the Z boson into different flavour leptons (e/mu/tau). The recent 13 TeV pp results will be reported.

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## New bounds on sparticle masses through rare signals and collider searches

**Authors:** Humberto Gilmer<sup>1</sup>; Linda Carpenter<sup>1</sup>

<sup>1</sup> *Ohio State University*

**Corresponding Author:** gilmer.30@osu.edu

Though collider searches are constraining supersymmetric parameter space, generic model independent bounds on sneutrinos remain very low. We calculate new model independent lower bounds on general supersymmetric scenarios with sneutrino LSP and NLSPs. By recasting ATLAS LHC exotic searches in mono boson channels, we place an upper bound on the cross section on  $pp \rightarrow \tilde{\nu}\tilde{\nu} + V$  processes in mono- $\gamma$ , mono- $W/Z$  and mono-Higgs channels. We also evaluate the LHC discovery potential of sneutrinos in the HL-LHC 3 ab<sup>-1</sup> run. Lastly, we present preliminary results for similar constraints on higgsino LSPs by placing upper bounds on  $pp \rightarrow \tilde{\chi}^0\tilde{\chi}^0 + V$  process cross sections.

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## Non-Minimal Dark Sectors: Mediator-induced Decay Chains and Multi-Jet Collider Signatures

**Author:** Huayang Song<sup>1</sup>

**Co-authors:** Brooks Thomas<sup>2</sup>; David Yaylali<sup>1</sup>; Doojin Kim<sup>3</sup>; Keith Dienes<sup>1</sup>; Shufang Su<sup>1</sup>

<sup>1</sup> *University of Arizona*

<sup>2</sup> *Lafayette College*

<sup>3</sup> *Texas A&M University*

**Corresponding Author:** huayangs@email.arizona.edu

If the dark sector contains multiple components with similar quantum numbers which only communicate with the visible sector through a mediator, this mediator necessarily gives rise to dark-sector decays, with heavier dark components decaying to lighter components. Such successive decays can even give rise to relatively long dark decay chains with visible matter being produced at each step. In this talk, I discuss the collider signatures of such decay chains in a simple scenario where a multi-component dark sector is connected through a mediator to the Standard Model quarks. The properties of the multi-jet signatures arising in such scenarios are examined at both the parton and detector levels. Within relatively large regions of parameter space, these signatures are not excluded by existing mono-jet and multi-jet searches. Such decay cascades therefore represent a potential discovery route for multi-component dark sectors at current and future collider.



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**A Suppressed Higgs coupling in a classically conformal extension of the Standard Model****Authors:** Victor Baules<sup>1</sup>; Nobuchika Okada<sup>2</sup><sup>1</sup> *University of Alabama, The*<sup>2</sup> *University of Alabama***Corresponding Author:** vabaules@crimson.ua.edu

We consider a classically conformal  $U(1)$  extension of the Standard Model (SM).

The  $U(1)$  symmetry is radiatively broken by the Coleman-Weinberg mechanism, after which the  $U(1)$  Higgs field  $\phi$  drives electroweak symmetry breaking through a mixed quartic coupling with the SM Higgs doublet with coupling constant  $\lambda_{mix}$ .

We calculate the Higgs triple couplings in this system and find a suppression of the coupling  $g_{h\phi\phi}$  when compared to the naively expected value  $g_{h\phi\phi} \sim \lambda_{mix}v_h$  ( $v_h = 246$  GeV), likely due to the unique nature of the classically conformal potential.

We consider experimental signals for such conformal structure via the anomalous Higgs decay  $h \rightarrow \phi\phi$  and anomalous SM Higgs couplings.

Such specific conformal structure would allow for a sizeable anomalous SM Higgs coupling alongside a heavily suppressed  $h \rightarrow \phi\phi$  decay mode.

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**Light hidden mesons inspired by neutral naturalness and SUSY****Author:** LINGFENG LI<sup>1</sup><sup>1</sup> *HKUST***Corresponding Author:** iasfli@ust.hk

Confining hidden sectors are an attractive possibility for physics beyond the Standard Model (SM). They are especially motivated by neutral naturalness theories, which reconcile the lightness of the Higgs with the strong constraints on colored top partners. We study hidden QCD with one light quark flavor, coupled to the SM via effective operators suppressed by the mass of new electroweak-charged particles. This effective field theory is inspired by a new tripled top model of supersymmetric neutral naturalness. The hidden sector is accessed primarily via the Z and Higgs portals, which also mediate the decays of the hidden mesons back to SM particles. We find that exotic Z decays at the LHC and future Z factories provide the strongest sensitivity to this scenario, and we outline a wide array of searches. For a larger hidden confinement scale  $\sim$ GeV, the exotic Z decays dominantly produce final states with two hidden mesons. ATLAS and CMS can probe their prompt decays up to 3 TeV at the high luminosity phase, while a TeraZ factory would extend the reach up to 20 TeV through a combination of searches for prompt and displaced signals. For smaller confinement scale, the Z decays to the hidden sector produce jets of hidden mesons, which are long-lived. LHCb will be a powerful probe of these emerging jets. Furthermore, the light hidden vector meson could be detected by proposed dark photon searches.

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**Segregating BSM models at Present and Future Colliders based on Spin and Isospin Representations**

**Authors:** Anirban Karan<sup>1</sup>; Priyotosh Bandyopadhyay<sup>1</sup>; Saunak Dutta<sup>2</sup>

<sup>1</sup> *Indian Institute of Technology Hyderabad*

<sup>2</sup> *Delhi University*

**Corresponding Author:** saunak100@gmail.com

Theories Beyond the Standard Model (BSM) address the outstanding issues of the Standard Model (SM). These theories predict new particles with different spin and isospin representations within a similar mass range. We consider one such model, the Leptoquarks, well motivated by various anomalies observed in the flavour sector. These particles have integral spins, 0 or 1, and belong to either of the singlet, doublet or triplet representation of the weak isospin. We showed how the spin of a leptoquark pair produced at LHC and FCC, in a  $2 \rightarrow 2$  scattering can be distinguished from their angular signature at the rest frame of interaction<sup>1</sup>. Such frame can be successfully reconstructed from their decay products. We have also explored the other observables which indicate the spin of the leptoquarks. Once the spin determined, we consider the associated production of leptoquarks with a photon in electron-hadron colliders like LHeC and FCC-he where the notion of the Radiation Amplitude Zero (RAZ) has been exploited to determine the weak isospin representation of the leptoquarks<sup>[2]</sup>. We have proposed a strategy to segregate the signals of different member of the same isospin multiplets based on electromagnetic charge of the jets, originating from their respective decays. Finally, SM Backgrounds have been estimated and the signal significance for respective processes are calculated to present the reach of these colliders.

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## Investigating New Physics Models with Signature of Same-Sign Diboson + $E_T^{\cancel{e}}$

**Authors:** Cheng-Wei Chiang<sup>1</sup>; Dibyashree Sengupta<sup>2</sup>; Sudip Jana<sup>3</sup>

<sup>1</sup> *National Taiwan University*

<sup>2</sup> *University of Oklahoma*

<sup>3</sup> *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

**Corresponding Author:** dibyashreecbr@gmail.com

We investigate the prospect of searching for new physics via the novel signature of same-sign diboson +  $E_T^{\cancel{e}}$  at current and future LHC. We study three new physics models: (i) natural SUSY models, (ii) type-III seesaw model and (iii) type-II seesaw/Georgi-Machacek model. In the first two class of models, this signature arises due to the presence of a singly-charged particle which has lifetime long enough to escape detection, while in the third model this signature originates resonantly from a doubly-charged particle produced along with two forward jets that, most likely, would escape detection. We analyze in great detail the discovery prospects of the signal in these three classes of models in the current as well as the upcoming runs of the LHC (such as HL-LHC and HE-LHC) by showing a distinction among these scenarios.

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## Revisiting Type-II see-saw: Present Limits and Future Prospects at LHC

**Authors:** Kirtiman Ghosh<sup>1</sup>; Saiyad Ashanujjaman<sup>2</sup>

<sup>1</sup> *IoP*

<sup>2</sup> *Institute of Physics, Bhubaneswar*

**Corresponding Author:** saiya.a@iopb.res.in

The type-II see-saw mechanism based on the annexation of the Standard Model by weak gauge triplet of scalar field proffers a natural explanation for the very minuteness of neutrino masses. Noting that the phenomenology for the degenerate triplet Higgs spectrum is substantially contrasting than that for the non-degenerate one, we perform a comprehensive study for a wide range of the model parameter space parametrised by triplet Higgs vacuum expectation value ( $v_t$ ), the mass-splitting between the doubly and singly charged Higgs ( $\Delta m$ ) and the doubly charged Higgs mass ( $m_{H^{\pm\pm}}$ ). Considering all the Drell-Yan production mechanisms, some of which are often forsaken by both CMS and ATLAS, we derive the most stringent 95% CL lower limit on the doubly charged Higgs mass for a wide range of  $v_t$  and  $\Delta m$  by implementing already existing direct collider searches by CMS and ATLAS. Further, we propose a search strategy that yields improved limits for a significant part of the parameter space of  $v_t$  and  $\Delta m$ .

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## Minimal and non-minimal Universal Extra Dimension models in the light of LHC data at 13 TeV

**Authors:** Avnish<sup>1</sup>; Kirtiman Ghosh<sup>2</sup>; Saurabh Niyogi<sup>None</sup>; Tapoja Jha<sup>None</sup>

<sup>1</sup> *Institute of Physics*

<sup>2</sup> *Institute of Physics, Bhubaneswar, India.*

**Corresponding Author:** avnish@iopb.res.in

Universal Extra Dimension (UED) is a well-motivated and well-studied scenario. One of the main motivations is the presence of a dark matter (DM) candidate namely, the lightest level-1 Kaluza-Klein (KK) particle (LKP), in the particle spectrum of UED. The minimal version of UED (mUED) scenario is highly predictive with only two parameters namely, the radius of compactification and cut-off scale, to determine the phenomenology. Therefore, stringent constraint results from the WMAP/PLANCK measurement of DM relic density (RD) of the universe. The production and decays of level-1 quarks and gluons in UED scenarios give rise to multijet final states at the Large Hadron Collider (LHC) experiment. We study the ATLAS search for multijet plus missing transverse energy signatures at the LHC with 13 TeV center of mass energy and 139 inverse femtobarn integrated luminosity. In view of the fact that the DM RD allowed part of mUED parameter-space has already been ruled out by the ATLAS multijet search, we move on to a less restricted version of UED namely, the non-minimal UED (nmUED), with non-vanishing boundary-localized terms (BLTs). The presence of BLTs significantly alters the dark matter as well as the collider phenomenology of nmUED. We obtain stringent bounds on the BLT parameters from the ATLAS multijet plus missing transverse energy search.

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## Chasing the Higgs shape at HL-LHC

**Author:** Tirtha Sankar Ray<sup>1</sup>

<sup>1</sup> *IIT Kharagpur, India*

**Corresponding Author:** tirthasankar.ray@gmail.com

The Higgs boson may well be a composite scalar with a finite extension in space. Owing to the momentum dependence of its couplings the imprints of such a composite pseudo Goldstone Higgs may show up in the tails of various kinematic distributions at the LHC, distinguishing it from an elementary state. From the bottom up we construct the momentum dependent form factors to capture the interactions of the composite Higgs boson with the weak gauge bosons. We demonstrate their impact in the differential distributions of various kinematic parameters for the  $pp \rightarrow ZH \rightarrow llbb$  channel. We show that this channel can provide an important avenue to probe the Higgs' substructure at the HL-LHC.

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## Long-lived particles searches at LHCb

**Authors:** Federico Leo Redi<sup>1</sup>; LHCb Collaboration<sup>None</sup>

<sup>1</sup> EPFL - Ecole Polytechnique Federale Lausanne (CH)

**Corresponding Author:** federico.redi@cern.ch

The unique design of the LHCb detector with a flexible trigger and a precision vertex tracker, offers the possibility to search for long-lived particles with low masses and short lifetimes, in complementarity with other general-purpose detectors at the LHC.

Searches have been performed at LHCb, in fully leptonic and semi-leptonic final states. In particular, searches for long-lived particles produced in pairs from an exotic Higgs boson decay, and a search for heavy neutral leptons from a W boson decay, will be presented.

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## Search for a light $Z'$ at LHC in a neutrinophilic U(1) model

**Authors:** Waleed Abdallah<sup>1</sup>; Santosh Rai<sup>None</sup>; Tousik Samui<sup>None</sup>; anjan barik<sup>None</sup>

<sup>1</sup> Faculty of Science, Cairo University, Giza 12613, Egypt

**Corresponding Author:** anjanbarik3@gmail.com

We consider a neutrinophilic U(1) extension of the standard model (SM) which couples only to SM isosinglet neutral fermions, charged under the new group. The neutral fermions couple to the SM matter fields through Yukawa interactions. The neutrinos in the model get their masses from a standard inverse-seesaw mechanism while an added scalar sector is responsible for the breaking of the gauged U(1) leading to a light neutral gauge boson ( $Z'$ ) which has minimal interaction with the SM sector. We study the phenomenology of having such a light  $Z'$  in the context of neutrinophilic interactions as well as the role of allowing kinetic mixing between the new U(1) group with the SM hypercharge group. We show that current experimental searches allow for a very light  $Z'$  if it does not couple to SM fields directly and highlight the search strategies at the LHC. We observe that multi-lepton final states in the form of  $(4l + E/\gamma)$  and  $(3l + 2j + E/\gamma)$  could be crucial in discovering such a neutrinophilic gauge boson lying in a mass range of 200–500 GeV.

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## Looking for beyond the Standard Model interactions of neutrinos and light dark matter with secondary production

**Authors:** Felix Kling<sup>1</sup>; Krzysztof Jodlowski<sup>2</sup>; Leszek Roszkowski<sup>3</sup>; Sebastian Trojanowski<sup>None</sup>

<sup>1</sup> SLAC

<sup>2</sup> National Centre for Nuclear Research

<sup>3</sup> National Centre for Nuclear Research (PL)

**Corresponding Author:** krzysztof.jodlowski@ncbj.gov.pl

The search for beyond the Standard Model interactions of neutrinos and other light new physics species is one of the most promising experimental targets, which, in the high-energy regime, is also currently less explored. In the talk, we will discuss novel prospects for such studies that will be opened up thanks to a new far-forward physics program at the LHC to be initiated with the FASER experiment. We will illustrate this for GeV-scale heavy neutral leptons (HNLs) that could be produced in neutrino scatterings mediated by the dipole or light vector portal, but also for long-lived dark photons, dark Higgs bosons, and stable dark matter particles of similar mass that can be produced in interaction right in front of the detector. Such a secondary production of new physics species would also extend the reach of the proposed MATHUSLA and SHiP detectors. In all cases, we find good discovery prospects of BSM physics.

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## Enhanced Long-Lived Dark Photon Signals at the LHC

**Authors:** Mingxuan Du<sup>1</sup>; Van Que Tran<sup>1</sup>; Zuowei Liu<sup>1</sup>

<sup>1</sup> Nanjing University

**Corresponding Author:** mg1722004@smail.nju.edu.cn

We construct a model in which the standard model is extended by a hidden sector with two gauge  $U(1)$  bosons. A Dirac fermion  $\psi$  charged under both  $U(1)$  fields is introduced in the hidden sector which can be a subcomponent of the dark matter in the Universe. Stueckelberg mass terms between the two new gauge  $U(1)$  fields and the hypercharge gauge boson mediate the interactions between the standard model sector and the hidden sector. A remarkable collider signature of this model is the enhanced long-lived dark photon events at the LHC than the conventional dark photon models; the long-lived dark photons in the model can be discriminated from the background by measuring the time delay signal in the precision timing detectors which are proposed to be installed in the LHC upgrades and have an  $\mathcal{O}(10)$  pico-second detection efficiency. Searches with current LHCb data are also investigated. Various experimental constraints on the model including collider constraints and cosmological constraints are also discussed.

**Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 371****Charming ALPs****Author:** Christiane Scherb<sup>1</sup><sup>1</sup> *JGU Mainz***Corresponding Author:** cscherb@uni-mainz.de

Axion-like particles (ALPs) are ubiquitous in models of new physics explaining some of the most pressing puzzles of the Standard Model. However, until relatively recently, little attention has been paid to its interplay with flavour. In this work, we study in detail the phenomenology of ALPs that exclusively interact with up-type quarks at the tree-level, which arise in some well-motivated ultra-violet completions such as QCD-like dark sectors or Froggatt-Nielsen type models of flavour. Our study is performed in the low-energy effective theory to highlight the key features of these scenarios in a model independent way. We derive all the existing constraints on these models and demonstrate how upcoming experiments at fixed-target facilities and the LHC can probe regions of the parameter space which are currently not excluded by cosmological and astrophysical bounds. We also emphasize how a future measurement of the currently unavailable meson decay  $D \rightarrow \pi + \text{invisible}$  could complement these upcoming searches.

**Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 444****Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector****Author:** Stefano Giagu<sup>1</sup><sup>1</sup> *Sapienza Universita e INFN, Roma I (IT)***Corresponding Author:** stefano.giagu@cern.ch

Various theories beyond the Standard Model predict unique signatures that are difficult to reconstruct and for which estimating the background rate is also a challenge. Signatures from displaced decays anywhere from the inner detector to the muon spectrometer, as well as those of new particles with fractional or multiple values of the charge of the electron or high mass stable charged particles are all examples of experimentally demanding signatures. The talk will focus on the most recent results using 13 TeV pp collision data collected by the ATLAS detector. Prospects for HL-LHC will also be shown.

**Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 57****A search for the low-lying SUSY spectrum at the LHC consistent with the recent muon  $g-2$  result****Authors:** Amin Abou Ibrahim<sup>1</sup>; Michael Klasen<sup>None</sup>; Pran Nath<sup>2</sup><sup>1</sup> *Institute for theoretical physics, Münster University*<sup>2</sup> *Department of Physics***Corresponding Author:** aabouibr@uni-muenster.de

The recent experimental result on the muon  $g-2$  from Fermilab has confirmed the old Brookhaven result and increased the tension with the Standard Model. We investigate the electroweak sector of

supersymmetry to explain the muon  $g-2$  anomaly. We perform a scan of the SUGRA parameter space with the help of a neural network to identify the regions consistent with the  $g-2$  anomaly. It is shown that a gluino-driven radiative breaking of the electroweak symmetry is a natural outcome with the sleptons and weakinos being low-lying while the colored sector is heavy. To perform a SUSY search at the LHC using a set of benchmarks, we employ a deep neural network to train the signal and background. We show that benchmarks corresponding to slepton and sneutrino production can be discovered at HL-LHC and HE-LHC.

The talk is based on arXiv:2104.03839 [hep-ph].

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### Anomalous magnetic moments from asymptotic safety

**Authors:** Gudrun Hiller<sup>1</sup>; Clara Hormigos Feliu<sup>2</sup>; Daniel Litim<sup>3</sup>; Tom Steudtner<sup>2</sup>

<sup>1</sup> *Technische Universitaet Dortmund (DE)*

<sup>2</sup> *TU Dortmund*

<sup>3</sup> *University of Sussex*

**Corresponding Author:** tom2.steudtner@tu-dortmund.de

In this talk, we present an extension of the SM featuring vector-like leptons and uncharged scalars in the BSM sector. We show that this theory allows to accommodate for the discrepancies in both the muon and electron anomalous magnetic moments simultaneously, without explicit violation of lepton flavor universality. Moreover, the theory remains physical and predictive until the Planck scale and stabilizes the Higgs potential. We also highlight the most prominent phenomenological implications.

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### Distinguishing signatures of scalar leptoquarks at the LHC and Muon colliders

**Author:** Priyotosh Bandyopadhyay<sup>1</sup>

**Co-authors:** Rusa Mandal<sup>2</sup>; Anirban Karan

<sup>1</sup> *Indian Institute of Technology Hyderabad*

<sup>2</sup> *Siegen University*

**Corresponding Author:** bpriyo@phy.iith.ac.in

While the hunt for new states beyond the standard model (SM) goes on for various well motivated theories, the leptoquarks are among the most appealing scenarios at recent times due to a series of tensions observed in B-decays. We consider two scalar leptoquarks, one being a singlet and the other a triplet under the electroweak gauge group, and respectively contributes to charged and neutral current B-decays. The final state consisting of a b and  $\tau$  jets provides highest reach for the singlet leptoquark whereas for the triplet leptoquark  $1 - \text{jet} + 2\mu + p_T$  topology is the most optimistic signature at the hadron colliders. Various distinguishing signatures are studied which can easily discriminate different components of the triplet leptoquark. Establishing a direct connection with the neutral current B-anomalies, we perform simulations for these leptoquarks at the proposed multi-TeV muon collider where the background free environment can probe  $O(10^{-2})$  value of the leptoquark couplings to fermions up to the 10 TeV leptoquark mass range

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**Constraints on the B-anomalies-motivated  $U_1$  leptoquark parameters from the LHC data****Author:** Arvind Bhaskar<sup>1</sup>**Co-authors:** Diganta Das<sup>2</sup>; Tanumoy Mandal<sup>3</sup>; Subhadip Mitra<sup>1</sup>; Cyrin Neeraj<sup>4</sup><sup>1</sup> *International institute of information technology, Hyderabad*<sup>2</sup> *International Institute of information technology, Hyderabad*<sup>3</sup> *Indian Institutes of Science Education and Research, Thiruvananthapuram*<sup>4</sup> *International institute of information technology, Hyderabad***Corresponding Author:** arvind.bhaskar@research.iit.ac.in

The semileptonic B-decay anomalies could be a gateway to new physics. Of the theories and BSM models put forward, the vector charge-2/3  $U_1$  leptoquark (LQ) seems to be the best candidate to explain the anomalies seen in the  $R_{D^{(*)}}$  and  $R_{K^{(*)}}$  observables. In this talk, I will explore the LHC bounds on the  $U_1$  leptoquark model. I will present a list of possible scenarios with different coupling combinations that can contribute to the relevant operators. I will then discuss how the latest dilepton data and the direct search data can either limit or exclude these scenarios. Finally, I would show how an LQ of mass of about 1.5 TeV survives the LHC and other flavour bounds and explain the anomalies simultaneously.

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**Vector-Like Leptons and Inert Scalar Triplet: Lepton Flavor Violation,  $g-2$  and Collider Searches****Author:** Álvaro Jesus<sup>1</sup>**Co-authors:** Farinaldo Queiroz<sup>2</sup>; Sergei Kovalenko<sup>3</sup>; Clarissa Siqueira<sup>4</sup><sup>1</sup> *International Institute of Physics, Federal University of Rio Grande do Norte*<sup>2</sup> *International Institute of Physics -Natal*<sup>3</sup> *Universidad Andres Bello (CL)*<sup>4</sup> *Instituto de Física de São Carlos - Universidade de São Paulo (IFSC/USP)***Corresponding Author:** alvarosndj@gmail.com

We investigate simplified models involving an inert scalar triplet and vector-like leptons that can account for the muon  $g-2$  anomaly. These simplified scenarios are embedded in a model that features  $W'$  and  $Z'$  bosons, which are subject to stringent collider bounds. The constraints coming from the muon  $g-2$  anomaly are put into perspective with collider bounds, as well as bounds coming from lepton flavor violation searches. The region of parameter space that explains the  $g-2$  anomaly is shown to be within reach of lepton flavor violation probes and future colliders such as HL-LHC and HE-LHC.

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**Search for long-lived particles in CMS****Author:** Jingyu Luo<sup>1</sup>



<sup>1</sup> *Brown University (US)*

**Corresponding Author:** jingyu.luo@cern.ch

This talk discusses new techniques to detect signatures potentially originating from long-lived particles in the CMS detector, presents recent results from such searches in CMS using the full Run-II data-set of the LHC, and discusses prospects for Run-III.

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## **Tumblers: A Novel Collider Signature for Long-Lived Particles**

**Author:** Brooks Thomas<sup>1</sup>

**Co-authors:** Keith R. Dienes<sup>2</sup>; Doojin Kim<sup>3</sup>; Tara Leininger<sup>1</sup>

<sup>1</sup> *Lafayette College*

<sup>2</sup> *University of Arizona*

<sup>3</sup> *Texas A&M University*

**Corresponding Author:** thomasbd@lafayette.edu

In this talk, we point out a novel signature of physics beyond the Standard Model which could potentially be observed both at the LHC and at future colliders. This signature, which emerges naturally within many proposed extensions of the Standard Model, results from the multiple displaced vertices associated with the successive decays of unstable, long-lived particles along the same decay chain. We call such a sequence of displaced vertices a “tumbler.” We examine the prospects for observing tumblers at the LHC and assess the extent to which tumbler signatures can be distinguished from other signatures of new physics which involve multiple displaced vertices within the same collider event. As part of this analysis, we also develop a procedure for reconstructing the masses and lifetimes of the particles involved in the corresponding decay chains. We find that the prospects for discovering and distinguishing tumblers can be greatly enhanced by exploiting precision timing information 8212; information such as would be provided by the CMS timing layer at the HL-LHC. Our analysis therefore provides strong motivation for continued efforts to improve the timing capabilities of collider detectors at the LHC and beyond.

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## **Triggering long-lived particles in HL-LHC and the challenges in the first stage of the trigger system**

**Authors:** Biplob Bhattacharjee<sup>1</sup>; Swagata Mukherjee<sup>2</sup>; Rhitaja Sengupta<sup>1</sup>; Prabhat Solanki<sup>3</sup>

<sup>1</sup> *Indian Institute of Science*

<sup>2</sup> *Rheinisch Westfaelische Tech. Hoch. (DE)*

<sup>3</sup> *Indian Institute of Science, Bengaluru, India*

**Corresponding Author:** prabhats@iisc.ac.in

Triggering long-lived particles (LLPs) at the first stage of the trigger system is very crucial in LLP searches to ensure that we do not miss them at the very beginning. The future High Luminosity runs of the Large Hadron Collider will have an increased number of pile-up events per bunch crossing. There will be major upgrades in hardware, firmware and software sides, like tracking at level-1 (L1). The L1 trigger menu will also be modified to cope with pile-up and maintain the sensitivity to physics processes. In our study we found that the usual level-1 triggers, mostly meant for triggering prompt

particles, will not be very efficient for LLP searches in the 140 pile-up environment of HL-LHC, thus pointing to the need to include dedicated L1 triggers in the menu for LLPs. We consider the decay of the LLP into jets and develop dedicated jet triggers using the track information at L1 to select LLP events. We show in our work that these triggers give promising results in identifying LLP events with moderate trigger rates.

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## Searches for vector-like quarks with the ATLAS detector

**Author:** Pekka Sinervo<sup>1</sup>

<sup>1</sup> *University of Toronto (CA)*

**Corresponding Author:** pekka.sinervo@utoronto.ca

Vector like quarks appear in many theories beyond the Standard Model as a way to cancel the mass divergence for the Higgs boson. The talk will focus on the most recent results using 13 TeV pp collision data collected by the ATLAS detector. This presentation will address the analysis techniques, in particular the selection criteria, the background modelling and the related experimental uncertainties. The results and the complementarity of the various searches, along with the phenomenological implications, will be discussed.

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## Searches for new physics in events with leptons in the final state in CMS

**Author:** Olena Karacheban<sup>1</sup>

<sup>1</sup> *Rutgers State Univ. of New Jersey (US)*

**Corresponding Author:** olena.karacheban@cern.ch

Many new physics models, e.g., compositeness, extra dimensions, extended Higgs sectors, supersymmetric theories, and dark sector extensions, are expected to manifest themselves in the final states with leptons and photons. This talk presents searches in CMS for new phenomena in the final states that include leptons and photons, focusing on the recent results obtained using the full Run-II data-set collected at the LHC.

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## Probing MeV-scale Scalar Bosons in association with TeV-scale Vectorlike Fermions in U(1)T3R at the LHC

**Authors:** Alfredo Gurrrola<sup>1</sup>; Teruki Kamon<sup>2</sup>; Bhaskar Dutta<sup>3</sup>; Dale Adam Julson<sup>1</sup>; Jason Kumar<sup>None</sup>

<sup>1</sup> *Vanderbilt University (US)*

<sup>2</sup> *Texas A & M University (US)*

<sup>3</sup> *Texas A&M University*

**Corresponding Author:** daleadamjulson@gmail.com

#### Abstract

Recently, there has been great interest in beyond-the-Standard Model (BSM) physics involving new low-mass matter and mediator particles. One such model, U(1)T3R, proposes a new U(1) gauge symmetry under which only right-handed fermions of the standard model are charged, as well as the addition of new vector-like fermions (e.g.,  $\chi_t$ ) and a new dark scalar particle ( $\phi$ ) whose vacuum expectation value breaks the U(1)T3R symmetry. For this work, we perform a feasibility study to

explore the mass ranges for which these new particles can be probed at the LHC. We consider the interaction  $pp \rightarrow \chi_t + t + \phi$  in which the top quark decays purely hadronically, the  $\chi_t$  decays semileptonically ( $\chi_t \rightarrow W + b \rightarrow l \nu b$ ), and the  $\phi$  decays to two photons. The proposed search is expected to achieve a discovery reach with signal significance greater than  $5\sigma$  for  $\chi_t$  masses up to 1.8 TeV and  $\phi$  masses as low as 1 MeV, assuming an integrated luminosity of 3000 fb<sup>-1</sup>.

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## On the feasibility of Bell Inequality violation at ATLAS experiment with flavor entanglement of B meson pairs from proton-proton collisions

**Authors:** Izumi Tsutsui<sup>1</sup>; Kunihiro Nagano<sup>2</sup>; Satoshi Higashino<sup>3</sup>; Tsubasa Ichikawa<sup>4</sup>; Yosuke Takubo<sup>2</sup>; Yuichiro Mori<sup>1</sup>

<sup>1</sup> KEK

<sup>2</sup> High Energy Accelerator Research Organization (JP)

<sup>3</sup> Kobe University (JP)

<sup>4</sup> Osaka University

**Corresponding Author:** yosuke.takubo@cern.ch

The Bell inequality is a principal touchstone of testing the local realism posited by Einstein at the time of the formation of quantum theory. The violations of the Bell inequality have been found with the measured system of photons, electrons or nucleons at low energies, which reject local realism. Extending to systems with higher energies will be important for establishing the nonlocal nature universally.

This talk will present a simulation study on the feasibility of the Bell test by means of flavor entanglement of a pair of B mesons in the ATLAS experiment at CERN. Our results show that it is capable to find the maximal violation of the Bell inequality at the time difference of 1.5 ps in the decays of the two entangled B mesons, rejecting yet again the local realism at the highest energy scale 14 TeV ever. This will be the first case of Bell inequality violation in particle physics experiment, given that the earlier analysis with the Belle experiment was found to be inconclusive, due primarily to the lack of selection process of spacelike events and the inability of independent identification of the decay times.

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## Missing Transverse Momentum Reconstruction in ATLAS

**Author:** Holly Pacey<sup>1</sup>

<sup>1</sup> University of Cambridge (GB)

**Corresponding Author:** holly.ann.pacey@cern.ch

Missing transverse momentum (MET) is a critical observable for physics searches in proton-proton collisions at the Large Hadron Collider. This talk describes these various novel approaches and their performance. ATLAS employs a suite of working points for missing transverse momentum (MET) reconstruction, and each is optimal for different event topologies. A new neural network can exploit various event properties to pick the optimal working point on an event-by-event basis and also combine complementary information from each of the working points. The resulting regressed “METNet” offers improved resolution and pileup resistance across a number of different topologies compared to the current MET working points. Additionally, image-based de-noising neural network techniques are studied; these also provide significant resolution improvements and pileup resistance.

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## Hadronic Reconstruction Techniques at ATLAS

**Author:** Mark Hodgkinson<sup>1</sup>

<sup>1</sup> *University of Sheffield (GB)*

**Corresponding Author:** mark.hodgkinson@cern.ch

The reconstruction and calibration of hadronic final states is an extremely challenging experimental aspect of measurements and searches at the LHC. This talk summarizes the latest results from ATLAS for jet reconstruction and calibration. New approaches to jet inputs better utilize relationships between calorimeter and tracking information to significantly improve the reconstruction of jet substructure. Additionally, a full suite of in-situ measurements of the jet energy scale and jet energy resolution for ATLAS’s new particle flow jets yield the lowest uncertainties yet in the high pileup conditions of the LHC Run 2. Finally, new machine learning approaches for various aspects of reconstruction will be discussed.

**Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 441**

## Searches for leptoquarks with the ATLAS detector

**Author:** Alexander Mann<sup>1</sup>

<sup>1</sup> *Ludwig-Maximilians-Universität München (DE)*

**Corresponding Author:** a.mann@lmu.de

Leptoquarks (LQ) are predicted by many new physics theories to describe the similarities between the lepton and quark sectors of the Standard Model and offer an attractive potential explanation for the lepton flavour anomalies observed at LHCb and flavour factories. The ATLAS experiment has a broad program of direct searches for leptoquarks, coupling to the first-, second- or third-generation particles. This talk will present the most recent 13 TeV results on the searches for leptoquarks and contact interactions with the ATLAS detector, covering flavour-diagonal and cross-generational final states.

**Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 422**

## Search for new resonances coupling to third generation quarks at CMS

**Author:** Andrea Piccinelli<sup>1</sup>

<sup>1</sup> *Universita e INFN, Perugia (IT)*

**Corresponding Author:** andrea.piccinelli@cern.ch

We present an overview of searches for new physics with top and bottom quarks in the final state, using proton-proton collision data collected with the CMS detector at the CERN LHC at a center-of-mass energy of 13 TeV. The results cover non-SUSY based extensions of the SM, including heavy gauge bosons or excited third generation quarks. Decay channels to vector-like top partner quarks are also considered. We explore the use of jet substructure techniques to reconstruct highly boosted objects in events, enhancing the sensitivity of these searches

**Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 23**

## Possible indications for new Higgs bosons in the reach of the LHC: N2HDM and NMSSM interpretations

**Authors:** Alexander Josef Grohsjean<sup>1</sup>; Thomas Biekötter<sup>2</sup>; Christian Schwanenberger<sup>1</sup>; Georg Ralf Weiglein<sup>1</sup>; Sven Heinemeyer<sup>3</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron (DE)*

<sup>2</sup> *Deutsches Elektronen-Synchrotron DESY*

<sup>3</sup> *CSIC (Madrid, ES)*

**Corresponding Author:** thomas.biekotter@desy.de

In several searches for additional Higgs bosons at the LHC, in particular the CMS search in the  $pp \rightarrow \phi \rightarrow t\bar{t}$  channel and the ATLAS search in the  $pp \rightarrow \phi \rightarrow \tau^+\tau^-$  channel, a local excess at the level of  $3\sigma$  or above has been observed at a mass scale of  $m_\phi \approx 400\text{GeV}$ . We investigate to what extent a possible signal in those channels could be accommodated in the Next-to-Two-Higgs-Doublet Model (N2HDM) or the Next-to Minimal Supersymmetric Standard Model (NMSSM). In a second step we furthermore analyse whether such a model could be compatible with both a signal at  $\approx 400\text{GeV}$  and at  $\approx 96\text{GeV}$ , where the latter possibility is motivated by observed excesses in searches for the  $b\bar{b}$  final state at LEP and the di-photon final state at CMS. The analysis for the N2HDM reveals that the observed excesses at  $\approx 400\text{GeV}$  in the  $pp \rightarrow \phi \rightarrow t\bar{t}$  and  $pp \rightarrow \phi \rightarrow \tau^+\tau^-$  channels point towards different regions of the parameter space, while one such excess and an additional Higgs boson at  $\approx 96\text{GeV}$  could simultaneously be accommodated. In the context of the NMSSM an experimental confirmation of a signal in the  $t\bar{t}$  final state would favour the alignment-without-decoupling limit of the model, where the Higgs boson at  $\approx 125\text{GeV}$  could be essentially indistinguishable from the Higgs boson of the SM. In contrast, a signal in the  $\tau^+\tau^-$  channel would be correlated with significant deviations of the properties of the Higgs boson at  $\approx 125\text{GeV}$  from the ones of a SM Higgs boson that could be detected with high-precision coupling measurements.

## Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 42

**A 96 GeV Higgs boson in the 2HDMS****Authors:** Cheng Li<sup>1</sup>; Gudrid Moortgat-Pick<sup>None</sup>; Steven Paasch<sup>1</sup>; Sven Heinemeyer<sup>2</sup><sup>1</sup> *Deutsches Elektronen-Synchrotron DESY*<sup>2</sup> *CSIC (Madrid, ES)***Corresponding Author:** cheng.li@desy.de

We discuss a  $\sim 3\sigma$  signal (local) in the light Higgs-boson search in the diphoton decay mode at  $\sim 96$  GeV as reported by CMS, together with a  $\sim 2\sigma$  excess (local) in the  $b\bar{b}$  final state at LEP in the same mass range. We interpret this possible signal as a Higgs boson in the 2 Higgs Doublet Model with an additional complex Higgs singlet (2HDMS). We find that the lightest CP-even Higgs boson of the 2HDMS type II can perfectly fit both excesses simultaneously, while the second lightest state is in full agreement with the Higgs-boson measurements at 125 GeV, and the full Higgs-boson sector is in agreement with all Higgs exclusion bounds from LEP, the Tevatron and the LHC as well as other theoretical and experimental constraints. We derive bounds on the 2HDMS Higgs sector from a fit to both excesses and describe how this signal can be further analyzed at the LHC and at future  $e^+e^-$  colliders, such as the ILC or CEPC. We analyze in detail the anticipated precision of the coupling measurements of the 96 GeV Higgs boson at the ILC.

## Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 264

**The forgotten channels: charged Higgs boson decays to a  $W^\pm$  and a non-SM-like Higgs boson****Author:** Jonas Wittbrodt<sup>1</sup>**Co-authors:** Tim Stefaniak<sup>2</sup>; Henning Bahl<sup>3</sup><sup>1</sup> *Lund University*<sup>2</sup> *DESY*<sup>3</sup> *Deutsches Elektronen-Synchrotron DESY***Corresponding Author:** jonas.wittbrodt@thep.lu.se

The presence of charged Higgs bosons is a generic prediction of multiplet extensions of the Standard Model (SM) Higgs sector. Focusing on the Two-Higgs-Doublet-Model (2HDM), we discuss the charged Higgs boson collider phenomenology in the theoretically and experimentally viable parameter space. While almost all existing experimental searches at the LHC target the fermionic decays of charged Higgs bosons, we point out that the bosonic decay channels — especially the decay into a non-SM-like Higgs boson and a  $W$  boson — often dominate over the fermionic channels. We propose several benchmark scenarios with distinct phenomenological features in order to facilitate the design of dedicated LHC searches for charged Higgs bosons decaying into a  $W$  boson and a non-SM-like Higgs boson.

## Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 321

**Displaced Higgs production in Type-III Seesaw at the LHC/FCC, MATHUSLA and Muon collider****Author:** Chandrima Sen<sup>1</sup>**Co-authors:** Priyotosh Bandyopadhyay<sup>2</sup>; Saunak Dutta<sup>1</sup>; Aleesha KT

<sup>1</sup> *Indian Institute of Technology, Hyderabad*

<sup>2</sup> *Indian Institute of Technology Hyderabad*

**Corresponding Author:** ph19resch11014@iith.ac.in

We explore the possibility of displaced Higgs production from the decays of the heavy fermions in the Type-III seesaw extension of the Standard Model at the LHC/FCC and the muon collider. The displaced heavy fermions and the Higgs boson can be traced back by measuring the displaced charged tracks of the charged leptons along with the  $b$ -jets. The prospects of the transverse and longitudinal displaced decay lengths are extensively studied in the context of the boost at the LHC/FCC. Due to the parton distribution function, the longitudinal boosts leads to larger displacement compared to the transverse one, which can reach MATHUSLA and beyond. Such measurements are indeed possible by the fully visible finalstate, which captures the complete information about the longitudinal momenta. The comparative studies are made at the LHC/FCC with the centre of mass energies of 14, 27 and 100 TeV, respectively. A futuristic study of the muon collider where the collision happens in the centre of mass frame is analysed for centre of mass energies of 3.5, 14 and 30 TeV. Contrary to LHC/FCC, here the transverse momentum diverges, however, the maximum reach in both the directions are identical due to the constant total momentum in each collision. The reach of the Yukawa couplings and fermion masses are reappraised for both the colliders.

**Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 421**

## Searches for heavy resonances decaying into Z, W, and Higgs bosons at CMS

**Author:** Qilong Guo<sup>1</sup>

<sup>1</sup> *Peking University (CN)*

**Corresponding Author:** qilong.guo@cern.ch

We present a summary of searches for new heavy resonances decaying into pairs or triplets of bosons, performed on proton-proton collision data collected with the CMS detector at the CERN LHC at a center-of-mass energy of 13 TeV. A common feature of these analyses is the boosted topology, namely the decay products of the considered bosons (both electroweak W, Z bosons and the Higgs boson) are expected to be highly energetic and close in angle, leading to a non-trivial identification of the quarks and leptons in the final state. The exploitation of jet substructure techniques allows to increase the sensitivity of the searches where at least one boson decays hadronically. Various background estimation techniques are adopted, based on data-MC hybrid approaches or relying only in control regions in data. Results are interpreted in the context of multiple scenarios beyond the standard model.

**Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 418**

## Search for new physics with unconventional signatures in CMS

**Author:** John Paul Chou<sup>1</sup>

<sup>1</sup> *Rutgers State Univ. of New Jersey (US)*

**Corresponding Author:** john.paul.chou@cern.ch

Many extensions of the standard model predict new particles with long lifetimes or other properties, that give rise to non-conventional signatures in the detector. We present recent results of searches for new physics from such non-conventional signatures obtained using data recorded by the CMS experiment using the full Run-II LHC data-set.

## Searches for the BSM Physics at the LHC and Future Hadronic Colliders / 325

**Uncovering quirk signal with energy loss inside tracker****Author:** Junle Pei<sup>1</sup>**Co-authors:** Jinmian Li ; Tianjun Li ; Wenxing Zhang<sup>1</sup> *Institute of Theoretical Physics, Chinese Academy of Sciences***Corresponding Author:** peijunle@mail.itp.ac.cn

A quirk propagating through a detector is subject to the Lorentz force, a new confining gauge force, and the frictional force from ionization energy loss. At the LHC, it was found that the monojet search and the coplanar search were able to constrain such a quirk signal. Inspired by the coplanar search proposed by S. Knapen et. al, we develop a new search that also utilizes the information of the relatively large ionization energy loss inside tracker. Our algorithm has improved efficiency in finding quirk signals with a wide oscillation amplitude. Because of our trigger strategy, the  $Z(\rightarrow \nu\nu)+\text{jets}$  process overlaid by pileup events is the dominant background. We find that the  $\sim 100 \text{ fb}^{-1}$  dataset at the LHC will be able to probe the colored fermion (scalar) quirks with masses up to  $\{2.1 (1.1) \text{ TeV}\}$ , and the color neutral fermion (scalar) quirks with masses up to  $\{450 (150) \text{ GeV}\}$ , respectively.

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**Machine Learning the Higgs-top CP Measurement****Authors:** Dorival Gonçalves<sup>1</sup>; Rahool Barman<sup>1</sup>; Felix Kling<sup>2</sup><sup>1</sup> *Oklahoma State University*<sup>2</sup> *SLAC***Corresponding Author:** rahool.barman@okstate.edu

We explore the direct Higgs-top CP structure via the  $pp \rightarrow t\bar{t}h$  channel with machine learning techniques, considering the clean  $h \rightarrow \gamma\gamma$  final state at the high luminosity LHC (HL-LHC). We show that a combination of a comprehensive set of observables, that include the  $t\bar{t}$  spin-correlations, with mass minimization strategies to reconstruct the  $t\bar{t}$  rest frame provide large CP-sensitivity.

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**Higgs as a probe of beyond the Standard Model physics****Author:** Arindam Das<sup>1</sup><sup>1</sup> *Hokkaido University***Corresponding Author:** dasarindamphysics@gmail.com

The minimal U(1) extension of the Standard Model (SM) is a simple and well-motivated extension of the SM, which supplements the SM with the seesaw mechanism for naturally generating the light neutrino masses and offers various interesting phenomenologies. In the model, the U(1) charge of each SM field is characterized by the U(1) charge of the SM Higgs doublet with a free parameter  $x$  and  $\phi$ . Due to the U(1) charge of the Higgs doublet, the Higgs boson has a trilinear coupling with the  $U(1)$  gauge boson ( $'$ ) due to  $\neq 0$ . With this coupling, a new process for the associated Higgs boson production with  $U(1)$  boson arises through a  $'$  boson in the  $h$ -channel at high



energy colliders. In this paper, we calculate the associated Higgs boson production at high energy colliders and show the interesting effects of the new  $\nu'$  boson mediated process, which can be tested in the future. Such models contain three SM singlet RHNs which generate the light neutrino mass through the seesaw mechanism after the  $U(1)$  breaking. We will also study the prospect of such RHN productions through the Higgs boson at the colliders which can probe a suitable neutrino mass generation mechanism.

**Split SUSY and High-Scale SUSY / 287**

## Testing Affleck Dine with Poltergeist Gravitational Waves

**Author:** Graham White<sup>1</sup>

<sup>1</sup> *IPMU*

**Corresponding Author:** graham.white@ipmu.jp

The Affleck Dine mechanism is a compelling explanation for the asymmetry between matter and anti-matter. Unfortunately, testing the mechanism is quite a challenge due to the high scales involved. We will argue that the Affleck-Dine condensate usually produces long lived Q-balls that cause an early period of matter domination. Because these Q-balls decay at a rate faster than exponential, they will produce sound waves in the plasma that enhance gravitational waves from inflation at a frequency that corresponds to the time of decay. The production of observable signals is very common, and the mechanisms that can produce a sufficiently fast transition from matter to radiation domination are limited. This implies a relatively generic test of the mechanism

**Split SUSY and High-Scale SUSY / 157**

## Electroweak Phase Transitions with BSM Fermions

**Authors:** Jonas Mueller<sup>1</sup>; M. Margarete Muehlleitner<sup>1</sup>; Martin Gabelmann<sup>2</sup>

<sup>1</sup> *KIT*

<sup>2</sup> *Karlsruhe Institute of Technology (KIT)*

**Corresponding Author:** martin.gabelmann@kit.edu

Negative results of searches for BSM physics at the LHC are pushing the soft-SUSY-breaking scale of colored superpartners beyond the TeV scale. On the contrary, there exist only very weak constraints on the masses of additional light fermions gauged under the SM gauge group. Therefore, split-/high-scale-SUSY scenarios are an appealing alternative to weak-scale SUSY since they automatically fulfil both experimental constraints by assuming a large separation between the soft-breaking squared-scalar and gaugino masses. However, heavy or even decoupled scalar masses are in general non-beneficial for the realisation of a strong first order electroweak phase transition (EWPT).

We study the impact of additional beyond-the-Standard Model (BSM) fermions, charged under the Standard Model (SM)  $SU(2) \times U(1)$  gauge group, on the EWPT in a 2-Higgs-Doublet-Model (2HDM) of type II. We find that the strength of the EWPT can be enhanced by about 40% compared to the default 2HDM. Therefore, additional light fermions are a useful tool to weaken the tension between increasing mass constraints on BSM scalars and the requirement of additional light scalar degrees of freedom to accommodate a strong first order EWPT. The findings are of particular interest for a variety of (non-minimal) split supersymmetry scenarios.

**Split SUSY and High-Scale SUSY / 45**

## **$N = 1$ trinification from dimensional reduction of $N = 1, 10D E_8$ over $SU(3)/U(1) \times U(1) \times Z_3$ and its phenomenological consequences**

**Authors:** George Manolakos<sup>1</sup>; George Zoupanos<sup>2</sup>; Gregory Patellis<sup>2</sup>

<sup>1</sup> NTUA

<sup>2</sup> National Technical University of Athens

**Corresponding Author:** giorgismanolakos@gmail.com

In this talk we will present an extension of the Standard Model that results from the dimensional reduction of the  $N = 1, 10D E_8$  group over a  $M4 \times B_0/Z_3$  space, where  $B_0$  is the nearly-Kähler manifold  $SU(3)/U(1) \times U(1)$  and  $Z_3$  is a freely acting discrete group on  $B_0$ . Using the Wilson flux breaking mechanism we are left in four dimensions with an  $N = 1 SU(3)^3$  gauge theory. Below the unification scale we have a two Higgs doublet model in a split-like supersymmetric version of the Standard Model, which yields third generation quark and light Higgs masses within the experimental limits and predicts the LSP  $\sim 1500\text{GeV}$ . The above is based on our recent work: Phys.Lett.B 813 (2021) 136031, 2009.07059 [hep-ph].

**Split SUSY and High-Scale SUSY / 204**

## **The Race to Find Split Higgsino Dark Matter**

**Author:** Benjamin Sheff<sup>None</sup>

**Co-authors:** James Daniel Wells<sup>1</sup>; Raymond Co<sup>2</sup>

<sup>1</sup> University of Michigan (US)

<sup>2</sup> University of Minnesota

**Corresponding Author:** ben1sheff@berkeley.edu

Higgsinos are a particularly compelling form of dark matter, and are on the verge of detection by multiple current experimental avenues. They can arise in models with decoupled scalars that enjoy the benefits of depending on very few parameters while still explaining gauge coupling unification, dark matter, and most of the hierarchy between the Planck and electroweak scales, and they remain undetected to past experiments. My talk will cover the reach for current and upcoming electron electric dipole moment experiments as compared to direct and indirect detection as avenues to observe higgsino dark matter models.

**Split SUSY and High-Scale SUSY / 212**

## **Gravitational Waves from Mini-Split SUSY**

**Author:** Bartosz Fornal<sup>1</sup>

**Co-authors:** Barmak Shams Es Haghi<sup>2</sup>; Jiang-Hao Yu<sup>3</sup>; Yue Zhao<sup>2</sup>

<sup>1</sup> Barry University

<sup>2</sup> University of Utah

<sup>3</sup> Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing

**Corresponding Author:** bfornal@barry.edu

I will show that color-breaking vacua may develop at high temperature in the Mini-Split SUSY scenario. This can lead to a nontrivial cosmological history of the universe, including strong first order phase transitions and domain wall production. Given the typical PeV energy scale associated with Mini-Split SUSY models, a stochastic gravitational wave background at frequencies around 100 Hz is expected. I will discuss the potential for detection of such a signal in future gravitational wave experiments.

**Split SUSY and High-Scale SUSY / 233**

## High-Scale Supersymmetry, Inflation, and Leptogenesis

**Author:** Sarunas Verner<sup>1</sup>

<sup>1</sup> *University of Minnesota*

**Corresponding Author:** nedzi002@umn.edu

In this talk, I discuss cosmological models that account for both inflation and the generation of net baryon asymmetry in the context of high-scale supersymmetry. Two different classes of inflationary models can be distinguished in which the gravitino mass is above or below the inflationary scale. When supersymmetry is broken at some high scale, the inflationary potential may be perturbed, which places restrictions on the model of inflation and supersymmetry breaking scale. Finally, I present the mass spectra of the inflationary sector and examine both thermal and non-thermal leptogenesis in high-scale supersymmetry.

**Split SUSY and High-Scale SUSY / 128**

## Expectations for SUSY from the landscape

**Author:** Howard Baer<sup>1</sup>

<sup>1</sup> *University of Oklahoma*

**Corresponding Author:** baer@nhn.ou.edu

In a fertile patch of the string landscape with the MSSM as the low energy EFT, it is expected that soft terms scan as a power law thus favoring large soft terms. This is to be balanced by the ABDS anthropic requirement that the pocket universe weak scale be not too far removed from our measured value. Under such conditions, the landscape predicts a Higgs mass of  $\sim 125$  GeV with sparticles beyond present LHC search limits and a higgsino as the LSP. Dark matter is expected to be mixed axion plus higgsino LSP.

**Split SUSY and High-Scale SUSY / 173**

## How Heavy can Neutralino Dark Matter be?

**Authors:** Feng Luo<sup>1</sup>; Hajime Fukuda<sup>2</sup>; Satoshi Shirai<sup>3</sup>

<sup>1</sup> *Sun Yat-sen University*

<sup>2</sup> *Lawrence Berkeley National Laboratory*

<sup>3</sup> *Kavli IPMU*

**Corresponding Author:** hfukuda@lbl.gov

What is the upper limit of the mass of the neutralino dark matter whose thermal relic is consistent with the observation? If the neutralino dark matter and colored sparticles are extremely degenerated in mass, with a mass difference less than the QCD scale, the dark matter annihilation is significantly increased and enjoys the “second freeze-out” after the QCD phase transition. In this case, the neutralino dark matter with a mass much greater than 100 TeV can realize the correct dark matter abundance. We study the dark matter abundance and its detection in the case of such highly degenerated mass spectrum of the neutralino dark matter and colored supersymmetric particles.

**Split SUSY and High-Scale SUSY / 141**

## Radiative Gravitino Production from Inflaton Decay

**Authors:** Keith A. Olive<sup>1</sup>; Kunio Kaneta<sup>2</sup>; Yann Mambrini<sup>None</sup>

<sup>1</sup> *University of Minnesota (US)*

<sup>2</sup> *KIAS*

**Corresponding Author:** kkaneta@kias.re.kr

In high-scale supersymmetry where all sparticles, except gravitino, are heavier than inflaton, an EeV-scale gravitino is suited for dark matter. Gravitino may be produced not only from scatterings of thermal particles but also from radiative decay of inflaton even when there is no direct coupling between the two. I will argue that in a viable inflation model based on no-scale supergravity, the latter can be a non-negligible contribution.

**Split SUSY and High-Scale SUSY / 140**

## A Minimal Supersymmetric SU(5) Missing-Partner Model

**Author:** Natsumi Nagata<sup>1</sup>

**Co-authors:** John Ellis<sup>2</sup>; Jason Evans<sup>3</sup>

<sup>1</sup> *University of Tokyo*

<sup>2</sup> *CERN*

<sup>3</sup> *University of Minnesota*

**Corresponding Author:** natsumi@hep-th.phys.s.u-tokyo.ac.jp

We explore a missing-partner model based on the minimal SU(5) gauge group with 75, 50 and 50 Higgs representations, assuming a super-GUT CMSSM scenario in which soft supersymmetry-breaking parameters are universal at some high scale above the GUT scale. We identify regions of parameter space that are consistent with the cosmological dark matter density, the measured Higgs mass and the experimental lower limit on proton lifetime. These constraints can be satisfied simultaneously along stop coannihilation strips. We find that the lifetime of the proton decay into  $K^+$  and neutrino is less than  $3 \times 10^{34}$  years throughout the allowed range of parameter space, within the range of the next generation of searches with the JUNO, DUNE and Hyper-Kamiokande experiments.

**Split SUSY and High-Scale SUSY / 65**

## Probing the Supersymmetric Grand Unified Theories at the Future Proton-Proton Colliders and Hyper-Kamiokande Experiment

**Author:** Shabbar Raza<sup>1</sup>

<sup>1</sup> *Federal Urdu University of Arts, Science and Technology, Karachi*

**Corresponding Author:** shabbar.raza@fuuast.edu.pk

Gauge coupling unification in the Supersymmetric Standard Models strongly implies the Grand Unified Theories (GUTs). With the grand desert hypothesis, we show that the supersymmetric GUTs can be probed at the future proton-proton (pp) colliders and Hyper-Kamiokande experiment. For the GUTs with the GUT scale  $M_{GUT} \leq 1.0 \times 10^{16}$  GeV, we can probe the dimension-six proton decay via heavy gauge boson exchange at the Hyper-Kamiokande experiment. Moreover, for the GUTs with  $M_{GUT} \geq 1.0 \times 10^{16}$  GeV, we for the first time study the upper bounds on the gaugino and sfermion masses. We show that the GUTs with anomaly and gauge mediated supersymmetry breakings are well within the reaches of the future 100 TeV pp colliders such as the FCC<sub>hh</sub> and SppC, and the supersymmetric GUTs with gravity mediated supersymmetry breaking can be probed at the future 160 TeV pp collider.

**Supersymmetry: Models, Phenomenology and Experimental Results / 398**

## Prospects for Chargino Searches and Measurements at the ILC

**Author:** Alain Bellerive<sup>1</sup>

<sup>1</sup> *Carleton University (CA)*

**Corresponding Author:** maria-teresa.nunez-pardo-de-vera@desy.de

The lighter chargino is a prime candidate to be the next-to-lightest SUSY particle (the NLSP). Even if up to now data from the LHC have not shown evidence of SUSY, the complementary nature of physics with e+e- collisions still offers many interesting scenarios in which SUSY can be discovered at the ILC. In this contribution we present the capability of the ILC for excluding or, respectively, discovering SUSY in the most challenging SUSY channels, such as higgsinos and winos at low mass differences. We also include evaluations of precision of model-parameter measurements as well as the constraints that these measurements put on parts of the sparticle-spectrum beyond direct reach, and how they contribute to discriminate between different models of SUSY breaking at high scale. The impact of low Pt hadrons from gamma-gamma beam induced interactions on the analysis of low deltaM higgsino processes is also presented. For the first time it is shown that, besides the fragile signature of such processes, they can be discovered and measured at the ILC even in presence of those overlay hadrons. The studies are based on the full detector simulation of the ILD concept and realistic accelerator conditions.

**Supersymmetry: Models, Phenomenology and Experimental Results / 399**

## Prospects for Stau Searches and Measurements at the ILC

**Author:** Alain Bellerive<sup>1</sup>

<sup>1</sup> *Carleton University (CA)*

**Corresponding Authors:** mikael.berggren@desy.de, mikael.berggren@cern.ch

The direct pair-production of the tau-lepton super-partner, stau, is one of the most interesting channels to search for SUSY. First of all the stau is with high probability the lightest of the scalar leptons. Secondly the signature of stau pair production signal events is one of the most difficult ones, yielding to the ‘worst’ and so most global scenario for the searches. The current model-independent stau limits comes from analysis performed at LEP but they suffer from the low energy of this facility. The LHC exclusion reach extends to higher masses for large mass differences, but under strong model assumptions. The ILC, a future electron-positron collider with energy up to 1 TeV, is a promising scenario for SUSY searches. The capability of the ILC for determining exclusion/discovery limits for the stau in a model-independent way is shown in this contribution, together with an overview of the current state-of-the-art. A detailed study of the ‘worst’ scenario for stau exclusion/discovery taking into account the effect of the stau mixing on stau production cross-section and efficiency is presented. For selected benchmarks, the prospect for measuring masses and polarized cross-sections will be shown. The studies were done using the *sgv* fast simulation adapted to the ILD detector concept at the ILC.

**Supersymmetry: Models, Phenomenology and Experimental Results / 336**

## Four-top quark signatures through the lens of color-octet scalars

**Author:** Taylor Murphy<sup>1</sup>

**Co-authors:** Linda Carpenter<sup>1</sup>; Matthew Smylie<sup>1</sup>

<sup>1</sup> *Ohio State University*

**Corresponding Author:** murphy.1573@osu.edu

We reinterpret two recent LHC searches for events containing four top quarks ( $t\bar{t}t\bar{t}$ ) in the context of supersymmetric models with Dirac gauginos and color-octet scalars (sgluons). We explore whether sgluon contributions to the four-top production cross section  $\sigma(pp \rightarrow t\bar{t}t\bar{t})$  can accommodate an excess of four-top events recently reported by the ATLAS collaboration. We also study constraints on these models from an ATLAS search for new phenomena with jets and missing transverse energy ( $E_T^{\text{miss}}$ ) sensitive to signals with four top quarks. We find that these two analyses provide complementary constraints, with the jets +  $E_T^{\text{miss}}$  search exceeding the four-top cross section measurement in sensitivity for sgluons heavier than about 800 GeV. We ultimately find that either a scalar or a pseudoscalar sgluon can currently fit the ATLAS excess in a range of reasonable benchmark scenarios, though a pseudoscalar in minimal Dirac gaugino models is ruled out. We finally offer sensitivity projections for these analyses at the HL-LHC, mapping the  $5\sigma$  discovery potential in sgluon parameter space and computing exclusion limits at 95% CL in scenarios where no excess is found.

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## muon $g-2$ and the B-physics anomalies in RPV supersymmetry and the discovery prospect at LHC

**Author:** Fang Xu<sup>None</sup>

**Co-authors:** Bhupal Dev ; AMARJIT Soni<sup>1</sup>

<sup>1</sup> *BNL*

**Corresponding Author:** xufang@wustl.edu

In R-parity violating supersymmetric scenario, assuming the third-generation superpartners to be the lightest (calling the scenario RPV3), we show that there are some benchmark scenarios in which

$R_{D^{(*)}}$ ,  $R_{K^{(*)}}$  and  $(g - 2)_\mu$  anomalies can be addressed and also can be detected at 14 TeV LHC or future hadron colliders. We consider  $\bar{t}\mu\bar{\mu}$  as our final state to be detected at hadron colliders because there is no simple Standard Model process can have this kind of final state and the background cross-section is thus very small.

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## Phenomenological predictions in supersymmetric scenarios with non-minimal flavour violation

**Authors:** Amine Boussejra<sup>None</sup>; Grégoire Uhlich<sup>None</sup>; Nazila Mahmoudi<sup>1</sup>

<sup>1</sup> *Universite Claude Bernard Lyon I (FR)*

**Corresponding Author:** g.uhlrich@ipnl.in2p3.fr

We present analytical one-loop contributions to  $(g - 2)$  and Wilson coefficients in Non-Minimal Flavor Violating (NMFV) MSSM scenarios. Evaluating numerically the general results in specific scenarios, we show which scenarios could be (dis-)favored by the experimental  $(g - 2)$  tension and flavor anomalies. These results provide important insights for BSM searches in general MSSM scenarios.

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## Gluino-SUGRA Type Scenarios In Light of FNAL Muon $g-2$ Anomaly

**Author:** Fei Wang<sup>1</sup>

**Co-authors:** Zhuang Li ; Guo-Li Liu ; Jin-Ming Yang ; Yang Zhang

<sup>1</sup> *ZhengZhou University*

**Corresponding Author:** feiwang@zzu.edu.cn

Gluino-SUGRA ( $\tilde{g}$ SUGRA), which is an economical extension of mSUGRA, adopts much heavier gluino mass parameter than other gauginos mass parameters and universal scalar mass parameter at the unification scale. It can elegantly reconcile the experimental results on the Higgs boson mass, the muon  $g - 2$ , the null results in search for supersymmetry at the LHC and the results from B-physics.

In this work, we propose several new ways to generate large gaugino hierarchy (i.e.  $M_3 \gg M_1, M_2$ ) for  $\tilde{g}$ SUGRA model building and then discuss in detail the implications of the new muon  $g - 2$  results with the updated LHC constraints on such  $\tilde{g}$ SUGRA scenarios. We obtain the following observations: (i) For the most interesting  $M_1 = M_2$  case at the GUT scale with a viable bino-like dark matter, the  $\tilde{g}$ SUGRA can explain the muon  $g - 2$  anomaly at  $1\sigma$  level and be consistent with the updated LHC constraints for  $6 \geq M_3/M_1 \geq 9$  at the GUT scale; (ii) For  $M_1 : M_2 = 5 : 1$  at the GUT scale with wino-like dark matter, the  $\tilde{g}$ SUGRA model can explain the muon  $g - 2$  anomaly at  $2\sigma$  level and be consistent with the updated LHC constraints for  $3 \geq M_3/M_1 \geq 4$  at the GUT scale; (iii) For  $M_1 : M_2 = 3 : 2$  at the GUT scale with mixed bino-wino dark matter, the  $\tilde{g}$ SUGRA model can explain the muon  $g - 2$  anomaly at  $2\sigma$  level and be consistent with the updated LHC constraints for  $6.7 \geq M_3/M_1 \geq 7.8$  at the GUT scale.

Based on 2106.04466

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## The new “MUON G-2” Result and Supersymmetry

**Authors:** Ipsita Saha<sup>1</sup>; Manimala Chakraborti<sup>None</sup>; Sven Heinemeyer<sup>2</sup>

<sup>1</sup> *Kavli IPMU*

<sup>2</sup> *CSIC (Madrid, ES)*

**Corresponding Authors:** ipsita.saha@ipmu.jp, mani.chakraborti@gmail.com, sven.heinemeyer@cern.ch

We confront the Minimal Supersymmetric Standard Model (MSSM) with the recent measurement of  $(g-2)_\mu$ , the Dark Matter (DM) relic density, DM direct detection limits and electroweak SUSY searches at the LHC. We demonstrate that various distinct regions of the parameter space can fulfill all experimental constraints. We present predictions for future pp and e+e- colliders to explore these regions.

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## Supersymmetric Alignment Models for muon g-2

**Authors:** Matthew Reece<sup>None</sup>; Motoo Suzuki<sup>1</sup>; Yuichiro Nakai<sup>None</sup>

<sup>1</sup> *ICRR*

**Corresponding Author:** m0t@icrr.u-tokyo.ac.jp

Hierarchical masses of quarks and leptons are addressed by imposing horizontal symmetries. In supersymmetric Standard Models, the same symmetries play a role in suppressing flavor violating processes induced by supersymmetric particles. Combining the idea of spontaneous CP violation to control contributions to electric dipole moments, the mass scale of supersymmetric particles can be lowered. We present supersymmetric models with U(1) horizontal symmetries and discuss CP and flavor constraints. Models with two U(1) symmetries are found to give a viable solution to the muon g-2 anomaly.

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## Muon g-2 and implications for physics beyond the SM

**Authors:** Csaba Balazs<sup>1</sup>; Dominik Stoeckinger<sup>2</sup>; Douglas Jacob<sup>1</sup>; Hyejung Stoeckinger-Kim<sup>2</sup>; Peter Athron<sup>None</sup>; Wojciech Kotlarski<sup>3</sup>

<sup>1</sup> *Monash University*

<sup>2</sup> *TU Dresden*

<sup>3</sup> *TU - Dresden*

**Corresponding Author:** dominik.stoeckinger@tu-dresden.de

In April the Fermilab Muon  $g - 2$  experiment reported its first measurement of the muon g-2, which is in full agreement with the previous BNL measurement and pushes the world average deviation from the Standard Model to a significance of  $4.2\sigma$ .

We provide an extensive survey of its impact on beyond the Standard Model physics. We compute predictions for g-2, dark matter and LHC searches in a wide range of simple models with up to three



new fields, that represent some of the few ways that large  $g-2$  can be explained. In addition, for the MSSM we exhaustively cover the scenarios where large  $g-2$  can be explained while simultaneously satisfying all relevant data from other experiments. Generally, the  $g-2$  result can only be explained by rather small masses and/or large couplings and enhanced chirality flips, which can lead to conflicts with limits from LHC and dark matter experiments.

Our results show that the new measurement excludes a large number of models and provides crucial constraints on others. Two-Higgs doublet and leptoquark models provide viable explanations of  $g-2$  only in specific versions and in specific parameter ranges. Among all models with up to three fields, only models with chirality enhancements can accommodate  $g-2$  and dark matter simultaneously. The MSSM can simultaneously explain  $g-2$  and dark matter for Bino-like LSP in several coannihilation regions. Allowing under abundance of the dark matter relic density, the Higgsino- and particularly Wino-like LSP scenarios become promising explanations of the  $g-2$  result.

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## Searches for R-parity violating SUSY with the CMS detector

**Author:** Christopher Madrid<sup>1</sup>

<sup>1</sup> *Fermi National Accelerator Lab. (US)*

**Corresponding Author:** cmadrid@fnal.gov

R-parity violation introduces many viable signatures to the search for supersymmetry at the LHC. The decay of supersymmetric particles can produce leptons or jets, while removing the missing transverse momentum signal common to traditional supersymmetry searches. The talk presents recent results from searches of supersymmetry in these unusual signatures of R-parity violation with the CMS detector.

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## Exploring the frontier of R-parity-violating supersymmetry with the ATLAS detector

**Author:** Lorenzo Felgioni<sup>1</sup>

<sup>1</sup> *CPPM, Aix-Marseille Université, CNRS/IN2P3 (FR)*

**Corresponding Author:** lorenzo@cppm.in2p3.fr

Supersymmetry models in which R-parity violation occurs predict a wide range of experimental signatures at the LHC, including many high-multiplicity final states without large missing transverse momentum. These models are motivated by the hierarchy problem and for some parameters naturally explain the lightness of the standard model neutrinos. Searches for RPV SUSY signatures require dedicated signal regions and innovative techniques to estimate the challenging backgrounds. This talk will highlight the latest results of searches conducted by the ATLAS experiment which target supersymmetric particles produced via both strong and electroweak processes in R-parity violating scenarios.

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## Search for R-parity violating supersymmetry in a final state containing leptons and many jets with the ATLAS experiment

**Author:** Martin Errenst<sup>1</sup>

<sup>1</sup> *Bergische Universitaet Wuppertal (DE)*

**Corresponding Author:** martin.errenst@cern.ch

R-parity-violating (RPV) SUSY models are well motivated theories, with fewer experimental constraints than many R-parity-conserving models, and allow for more natural supersymmetric mass spectra. This talk presents the latest result for a search for RPV SUSY in final states with at least one lepton and high number of jets, several of which may be b-jets. The analysis follows a general approach to be sensitive to a large variety of models for strong production of SUSY particles. Additionally, it introduces the use of novel machine learning techniques to reach sensitivity, for the first time at the LHC, for electroweak production of SUSY particles (including Higgsinos) with subsequent RPV prompt decays to quarks. These machine learning techniques are based on the distance correlation training and they play a key role also in the data-driven estimation of the backgrounds. The analysis sets impressive limits reaching as high as 2.4 TeV in gluino mass, 1.35 TeV in top-squark mass, and 320 (365) GeV in higgsino (wino) mass.

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## Multi-scalar signature of self-interacting dark matter in the NMSSM and beyond

**Author:** Cong Zhang<sup>1</sup>

**Co-authors:** Jinmian Li<sup>2</sup>; Junle Pei<sup>3</sup>

<sup>1</sup> *Sichuan University*

<sup>2</sup> *College of Physics, Sichuan University*

<sup>3</sup> *bCAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences; School of Physical Sciences, University of Chinese Academy of Sciences*

**Corresponding Author:** zhangcong.phy@gmail.com

As the standard model of the Big Bang cosmology, the  $\Lambda$ CDM model can account for most observations of the Universe, especially on the large scale structure of the Universe. However, the predictions on small scale structures exist some anomalies: missing satellites, cusp vs core, too big to fail. The issues can be resolved if the DM has strong self-interactions with light mediator ( $\sim 1$  MeV) where the cross section is constrained. The self-interacting DM with scalar mediator can be naturally realized in the NMSSM. In this work, we focus on the SIDM scenario in the general NMSSM, and discuss the possible LHC signatures of the SIDM in the NMSSM basing on our selected benchmark points.

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## Anapole Moment of Majorana Fermions and Implications for Direct Detection of Neutralino Dark Matter

**Authors:** Alejandro Ibarra<sup>None</sup>; Merlin Reichard<sup>1</sup>; Ryo Nagai<sup>2</sup>

<sup>1</sup> *Technical University of Munich (TUM)*

<sup>2</sup> *Osaka University*

**Corresponding Author:** m.reichard@tum.de

In many theories dark matter is assumed to be a Majorana fermion, for which the anapole moment can induce an effective interaction with targets in direct detection experiments via the exchange of a virtual photon. In this talk, I will present the novel contribution to the anapole moment of a generic Majorana fermion due to vectors in the one-loop expression. For this, the diagrams are evaluated by application of the background field method, ensuring a gauge- and gauge-parameter independent result. After the model-independent discussion I will focus on the anapole moment of the lightest neutralino in various MSSM scenarios and will highlight its implication for direct detection experiments of neutralino dark matter. Notably the here presented novel contribution can be significant in scenarios in which squarks and sleptons are heavy and the chargino mixing angles are non-degenerate.

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## A relatively light, highly bino-like dark matter in the $Z_3$ -symmetric NMSSM and recent LHC searches

**Authors:** AseshKrishna Datta<sup>1</sup>; Subhojit Roy<sup>2</sup>; Waleed Abdallah<sup>3</sup>

<sup>1</sup> Harish-Chandra Research Institute, India

<sup>2</sup> Harish-Chandra Research Institute, INDIA

<sup>3</sup> Department of Mathematics, Faculty of Science, Cairo University, Giza 12613, Egypt

**Corresponding Author:** subhotheory@gmail.com

A highly bino-like Dark Matter (DM), which is the Lightest Supersymmetric Particle (LSP), could be motivated by the stringent upper bounds on the DM direct detection rates. This is especially so when its mass is around or below 100 GeV for which such a bound tends to get most severe. Requiring not so large a higgsino mass parameter, that would render the scenario reasonably ‘natural’, prompts such a bino-like state to be relatively light. In the Minimal Supersymmetric Standard Model (MSSM), in the absence of comparably light scalars, such an excitation, if it has to be a thermal relic, is unable to meet the stringent experimental upper bound on its abundance unless its self-annihilation hits a funnel involving either the  $Z$ -boson or the Standard Model (SM)-like Higgs boson. We demonstrate that, in such a realistic situation, a highly bino-like DM of the popular  $Z_3$ -symmetric Next-to-Minimal Supersymmetric Standard Model (NMSSM) is viable over an extended range of its mass, from our targeted maximum in the vicinity of the mass of the top quark down to about 30 GeV. This is facilitated by the presence of comparably light singlet-like states that could serve as funnel (scalars) and/or coannihilating (singlino) states even as the bino-like LSP receives a minimal (but optimal) tempering triggered by suitably light higgsino states that, in the first place, evade stringent lower bounds on their masses that can be derived from the Large Hadron Collider (LHC) experiments only in the presence of a lighter singlino-like state. An involved set of blind spot conditions is derived for the DM direct detection rates by considering for the very first time the augmented system of neutralinos comprising of the bino, the higgsinos and the singlino which highlights the important roles played by the NMSSM parameters ‘ $\lambda$ ’ and  $\tan \beta$  in delivering a richer phenomenology.

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## Signals from Light Sneutrino Dark Matter at future $e^+e^-$ Colliders

**Authors:** Harri Waltari<sup>1</sup>; Stefano Moretti<sup>1</sup>; YI LIU<sup>2</sup>

<sup>1</sup> University of Southampton

<sup>2</sup> university of Southampton

**Corresponding Author:** yl1e19@soton.ac.uk

We study the possibility of measuring neutrino Yukawa couplings in the Next-to-Minimal Supersymmetric Standard Model supplemented with right-handed neutrinos (NMSSM<sub>r</sub>) when the lightest of such states is the Dark Matter (DM) candidate, by exploiting a ‘dijet + dilepton + Missing Transverse Energy’ (MET) signature. We show that, contrary to the minimal realisation of Supersymmetry (SUSY), the MSSM, wherein the DM candidate is typically a much heavier (fermionic) neutralino state, this extended model of SUSY offers one with a much lighter (bosonic) state as DM that can then be produced at the next generation of  $e^+e^-$  colliders with energies up to 500 GeV or so. The ensuing signal, mediated by (both neutral and charged)  $\tilde{\chi}$  into production and decay, is extremely pure so it also affords one with the possibility of extracting the Yukawa parameters of the (s)neutrino sector. Altogether, our results serve the purpose of motivating searches for light DM signals at such machines, where the DM candidate can have a mass around the Electro-Weak (EW) scale.

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## Probing mild-tempered neutralino dark matter through top-squark production at the LHC

**Authors:** Arnab Roy<sup>None</sup>; Monoranjan Guchait<sup>1</sup>; Seema Sharma<sup>2</sup>

<sup>1</sup> *Tata Institute of Fundamental Research*

<sup>2</sup> *Indian Institute of Science Education & Research*

**Corresponding Author:** arnab.roy@tifr.res.in

In Supersymmetry, the lightest neutralino turns out to be a promising WIMP dark matter(DM) candidate. In the Minimal Supersymmetric Standard Model(MSSM), a pure neutralino state can be a thermal DM if it has mass  $\mathcal{O}(1)$  TeV. So a WIMP dark matter(DM) of mass  $\mathcal{O}(100)$  GeV or less should be a “tempered neutralino”. Taking into account current constraints from direct detection(DD) experiments, it turns out that this DM should mostly be a bino-dominated “mild-tempered” neutralino, where a small Higgsino component is necessary to achieve the observed relic density. This DM candidate can be produced indirectly through heavier Higgsino-like electroweakino states, which, in turn, can appear from the decay of top-squark. Keeping that in mind, we shall discuss how in a DM motivated MSSM scenario at the LHC, a common robust feature is the presence of the Standard Model(SM) Higgs boson, along with  $t\bar{t}$  and the indispensable  $\cancel{E}_T$ . We shall also present how this “mild-tempered” neutralino DM can be probed at the LHC through a Higgs-mediated channel at the center of mass energy  $\sqrt{s} = 13$  TeV and integrated luminosity options  $\mathcal{L} = 300 \text{ fb}^{-1}$  and  $3000 \text{ fb}^{-1}$ .

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## Search for supersymmetry in compressed scenario’s with the CMS detector

**Author:** Denis Rathjens<sup>1</sup>

<sup>1</sup> *Texas A & M University (US)*

**Corresponding Author:** denis.rathjens@cern.ch

Results from the CMS experiment are presented for supersymmetry searches targeting so-called compressed spectra. Those have small mass splittings between the different supersymmetric partners. Such a spectrum presents unique experimental challenges. This talk describes the new techniques utilized by CMS to address such difficult scenarios. The searches use proton-proton collision data

with luminosity up to  $137 \text{ fb}^{-1}$  at the center of mass energy of 13 TeV collected during the LHC Run 2.

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## Searches for sleptons with the ATLAS detector

**Author:** Lorenzo Rossini<sup>1</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron (DE)*

**Corresponding Author:** lorenzo.rossini@cern.ch

Many supersymmetry models feature sleptons with masses below a TeV. Light sleptons can arise in well motivated dark matter models as well as proposed solutions to the observed anomalous muon magnetic moment. The talk presents recent ATLAS results from searches for slepton pair production in a variety of final states, including models in which R-parity is either conserved or violated, and results from searches in which sleptons appear in cascade decays from heavier supersymmetric particles.

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## Search for long-lived charginos based on a disappearing-track signature with the ATLAS experiment

**Author:** Paul Gessinger<sup>1</sup>

<sup>1</sup> *CERN*

**Corresponding Author:** paul.gessinger@cern.ch

The disappearing track signature, which arises from the decay of a long-lived charged particle to a neutral particle and particles with momenta below the reconstruction thresholds, is characteristic of many well-motivated models for physics beyond the standard model, including anomaly mediated SUSY breaking models, natural models of SUSY with light higgsinos, and dark matter models with mass-degenerate multiplets. This talk presents a search for disappearing tracks in the ATLAS detector using the full Run 2 dataset. The results are interpreted in the context of long-lived charginos produced either directly or in the cascade decay of heavy prompt gluino states.

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## ATLAS searches for supersymmetry with long-lived particles

**Author:** Emily Anne THOMPSON<sup>1</sup>

<sup>1</sup> *DESY*

**Corresponding Author:** emily.anne.thompson@cern.ch

Various Supersymmetry (SUSY) scenarios, including split SUSY and anomaly or gravity-mediated SUSY-breaking scenarios, lead to signatures with long-lived particles. Searches for these processes may target either the long lived particle itself or its decay products at a significant distance from the collision point. These signatures provide interesting technical challenges due to their special

reconstruction requirements as well as their unusual backgrounds. This talk will present recent results in long-lived SUSY searches using ATLAS Run 2 data.

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## Long lived NMSSM :Analysing some long lived NLSP signatures in the NMSSM

**Authors:** Amandip De<sup>1</sup>; Amit Adhikary<sup>1</sup>; Biplob Bhattacharjee<sup>1</sup>; Rahool Kumar Barman<sup>2</sup>; Rohini Godbole<sup>3</sup>; Suchita Kulkarni<sup>4</sup>

<sup>1</sup> *Indian Institute of Science*

<sup>2</sup> *Oklahoma State University*

<sup>3</sup> *Centre for Theoretical Studies (CTS)*

<sup>4</sup> *University of Graz*

**Corresponding Author:** deamandip93@gmail.com

We analyse NMSSM scenarios containing a singlino LSP dark matter. By systematically considering several NLSP compositions, we identify and classify regions of parameter space where NLSP exhibits a long lifetime due to suppressed couplings and leads to a displaced vertex signature at the colliders. We furthermore construct viable production and decay processes at the HL-LHC to search for such displaced vertices.

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## Searching for Compressed Top Partners in the CMS Open Data

**Authors:** Daneng Yang<sup>1</sup>; Haipeng An<sup>2</sup>; Zhen Hu<sup>3</sup>; Zhen Liu<sup>4</sup>

<sup>1</sup> *Department of Physics, Tsinghua University (CN)*

<sup>2</sup> *Tsinghua University*

<sup>3</sup> *Tsinghua University (CN)*

<sup>4</sup> *University of Minnesota*

**Corresponding Author:** anhp@mail.tsinghua.edu.cn

A cluster of *soft* displaced tracks corresponds to the dark matter co-annihilation regime. The long-lived regime is, in particular, motivated by the unexplored top partner physics. The background in this regime is extremely challenging to model using a traditional simulation method. We demonstrate the feasibility of handling the formidable background using the CMS Open Data. We perform this analysis to search for compressed and long-lived top partners in the 8 TeV CMS Open Data events with the integrated luminosity of  $11.6 \text{ fb}^{-1}$  and obtain new limits. With 15-30 GeV mass splitting between the top partner and the DM candidate, we exclude the top partner mass below 350 GeV, which is more stringent than the ATLAS and CMS results using 8 TeV data with  $20 \text{ fb}^{-1}$  luminosity. Our study also shows that the CMS Open Data can be a powerful tool to help physicists explore non-conventional new physics and even enable deriving new limits on exotic signals from data directly.

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## Probing Theories with Reduced Couplings at Future Colliders

**Authors:** George Zoupanos<sup>1</sup>; Grigorios Patellis<sup>None</sup>; Jan Henryk Kalinowski<sup>2</sup>; Myriam Mondragon<sup>3</sup>; Nicholas Tracas<sup>1</sup>; Sven Heinemeyer<sup>4</sup>; Wojciech Kotlarski<sup>5</sup>

<sup>1</sup> National Technical Univ. of Athens (GR)

<sup>2</sup> University of Warsaw (PL)

<sup>3</sup> Universidad Nacional Autonoma de Mexico UNAM

<sup>4</sup> CSIC (Madrid, ES)

<sup>5</sup> TU - Dresden

**Corresponding Author:** patellis@central.ntua.gr

The search for renormalization group invariant relations among parameters to all orders in perturbation theory constitutes the basis of the reduction of couplings concept. Reduction of couplings can be achieved in certain  $N = 1$  supersymmetric grand unified theories and few of them can even become finite at all loops. The resulting theories in which successful reduction of couplings has been achieved so far include: (i) a reduced version of the minimal  $N = 1$   $SU(5)$  model, (ii) an all-loop finite  $N = 1$   $SU(5)$  model, (iii) a two-loop finite  $N = 1$   $SU(3)^3$  model and finally (vi) a reduced version of the Minimal Supersymmetric Standard Model. We present a number of benchmark scenarios for each model and investigate their observability at existing and future hadron colliders. The heavy supersymmetric spectra featured by each of the above models are found to be beyond the reach of the 14 TeV HL-LHC. It is also found that the reduced version of the MSSM is already ruled out by the LHC searches for heavy neutral MSSM Higgs bosons. In turn, the discovery potential of the 100 TeV FCC-hh is investigated and found that large parts of the predicted spectrum of these models can be tested.

In this talk we will present results and updates from our recent work (Eur.Phys.J.C 81 (2021) 2,185: arXiv:2011.07900 [hep-ph]).

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## Probing heavy scalar in supersymmetric final states

**Authors:** Amit Adhikary<sup>1</sup>; Biplob Bhattacharjee<sup>1</sup>; Najimuddin Khan<sup>2</sup>; Rohini Godbole<sup>1</sup>; Suchita Kulkarni<sup>3</sup>

<sup>1</sup> Centre for High Energy Physics, Indian Institute of Science, Bengaluru, India

<sup>2</sup> Centre for High Energy Physics, Indian Institute of Science, Bangalore 560012, India

<sup>3</sup> Institute of Physics, NAWI Graz, University of Graz, Universitätsplatz 5, A-8010 Graz, Austria

**Corresponding Author:** amitadhikary@iisc.ac.in

We explore the supersymmetric (susy) final states coming from MSSM Higgs decaying via neutralinos and charginos, collectively called electroweakinos. They give rise to mono-(h/Z) + missing energy final states. We consider backgrounds coming from Standard Model (SM) and susy processes. The susy backgrounds have not been considered in this kind of analysis earlier, which comes from direct electroweakino production via SM mediators. Our study shows that the susy backgrounds have important ramifications in these analysis. They have appreciable production rates and significant kinematic overlap with the signal. The case of wino-like long-lived chargino decaying from MSSM Higgs is also discussed. These search can improve the sensitivity in disappearing charged track searches at the LHC because of the boost received from heavy Higgs bosons.

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## Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum with the ATLAS experiment

**Author:** Yuta OKAZAKI<sup>1</sup>

<sup>1</sup> *Kyoto U*

**Corresponding Authors:** okazaki.yuuta.22n@st.kyoto-u.ac.jp, yuta.okazaki@cern.ch

Searches for electroweakinos light enough to be produced at the LHC are well motivated by consideration on dark matter, naturalness and the recently observed muon  $g-2$  anomaly. This talk presents a search for electroweakinos in fully-hadronic final states to exploit the advantage of the large branching ratio, and the efficient background rejection by identifying the high- $p_T$  bosons using large-radius jets and jet substructure information. Compared to the more traditionally considered lepton final states, it allows to reach sensitivity to higher electroweakinos masses and to set strong limits on a variety of simplified models. For example, for the case of the wino-bino simplified model a wino mass up to 1060 GeV is excluded. Additionally, more concrete complete models and parameter scans are also considered.

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## **Electroweak SUSY in leptonic final states with the CMS detector**

**Author:** Kaitlin Salyer<sup>1</sup>

<sup>1</sup> *Boston University (US)*

**Corresponding Author:** ksalyer@bu.edu

Results from the CMS experiment are presented for electroweak production of supersymmetric partners with decays to leptonic final states. The searches use proton-proton collision data with luminosity up to 137 fb<sup>-1</sup> recorded by the CMS detector at center of mass energy 13 TeV during the LHC Run 2.

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## **Searches for supersymmetry in tau final states with the CMS detector**

**Author:** Saikat Karmakar<sup>1</sup>

<sup>1</sup> *Tata Institute of Fundamental Research-B, India*

**Corresponding Author:** saikat.karmakar@cern.ch

Results from the CMS experiment are presented for searches for supersymmetric particle production with tau leptons in the final state. The searches use proton-proton collision data with luminosity up to 137 fb<sup>-1</sup> recorded by the CMS detector at center of mass energy 13 TeV during the LHC Run 2.

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## **Searches for charginos and neutralinos with the ATLAS detector**



**Author:** Sara Alderweireldt<sup>1</sup>

<sup>1</sup> *The University of Edinburgh (GB)*

**Corresponding Author:** sara.alderweireldt@cern.ch

Charginos and neutralinos are often the lightest new particles predicted by a wide range of supersymmetry models, and the lightest neutralino is a well motivated and studied candidate for dark matter in models with R-parity conservation. The small direct production cross sections of electroweakinos leads to difficult searches, despite relatively clean final states. This talk will highlight the most recent results of searches performed by the ATLAS experiment for charginos and neutralinos, covering a variety of model parameters and final states.

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## Precise Higgs mass predictions for multi-scale hierarchies with FeynHiggs

**Author:** Henning Bahl<sup>1</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron DESY*

**Corresponding Author:** henning.bahl@desy.de

In this talk, I will give an overview of the status and recent developments of FeynHiggs. Focusing on the calculation of the SM-like Higgs boson mass in the MSSM, I will highlight some of the recent improvements in the effective field theory calculation that are relevant for multi-scale hierarchies. I.e., I will discuss the case of a heavy gluino as well as the case of light non-SM-like Higgs bosons (discussing also the effect of CP-violating phases).

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## Loop-corrected Higgs Masses in the NMSSM with Inverse Seesaw Mechanism

**Authors:** Anh Vu Phan<sup>1</sup>; Milada Margarete Mühlleitner<sup>None</sup>; Thi Nhung Dao<sup>1</sup>

<sup>1</sup> *ICISE*

**Corresponding Author:** phananhvu1609@gmail.com

The Next-to-Minimal Supersymmetric extension of the Standard Model (NMSSM) including additionally six leptonic singlet superfields can explain the small active neutrino masses via the inverse seesaw mechanism (ISS), while it still allows for large values of the neutrino Yukawa couplings with a mass scale of sterile neutrinos of order TeV. While  $R$ -parity is conserved in this model, lepton number is explicitly violated. The extended (s)neutrino sector therefore can affect the Higgs sector and the lepton flavor-violating observables through radiative corrections. We investigated these impacts by computing the complete one-loop corrections with full momentum dependence and consistently combined them with the dominant two-loop corrections at  $\mathcal{O}(\alpha_s \alpha_t + \alpha_t^2)$  to the Higgs boson masses and their mixings. We further computed the radiative decays  $l_i \rightarrow l_j + \gamma$ , and the oblique parameters  $S, T, U$  at one-loop level. In our numerical study, we showed that these impacts can be significant depending on the parameter space. We take into account the constraints from the Higgs data, the neutrino oscillation data, the lepton flavor-violating decays, and the oblique parameters to have a realizable analysis. Our computations have been implemented in the public Fortran code NMSSMCALC-nuSS that computes the Higgs mass spectrum as well as the Higgs boson decay widths including the state-of-the-art higher-order corrections.

**Supersymmetry: Models, Phenomenology and Experimental Results / 188****Two-Loop  $\mathcal{O}(\alpha_t + \alpha_\lambda + \alpha_\kappa)^2$  Corrections to the Higgs Boson Masses in the CP-Violating NMSSM****Authors:** Heidi Angelika Rzehak<sup>None</sup>; Martin Gabelmann<sup>1</sup>; Thi Nhung Dao<sup>2</sup>; Milada Muehlleitner<sup>3</sup><sup>1</sup> Karlsruhe Institute of Technology (KIT)<sup>2</sup> ICISE<sup>3</sup> Unknown**Corresponding Author:** dtnhung2008@gmail.com

The Higgs boson mass has turned into a precision observable with an uncertainty of a few hundred MeV at the LHC and provides an important constraint on the parameter space of supersymmetric models. To have sensible limits, the experimental accuracy has to be matched by the precision of the theory predictions. Consequently, a tremendous effort has been put in the computation of the higher-order corrections to supersymmetric Higgs boson masses.

In this talk, we report about our computation of the  $\mathcal{O}(\alpha_t + \alpha_\lambda + \alpha_\kappa)^2$  two-loop corrections to the Higgs boson masses of the CP-violating Next-to-Minimal Supersymmetric Standard Model (NMSSM) using the Feynman-diagrammatic approach. We discuss the renormalization schemes used for the Higgs sector and the top/stop sector, together with the treatment of the infrared divergences which appear in the gaugeless and zero momentum approximation. We present the numerical impact of the new corrections and their dependence on the renormalization scheme and the renormalization scale. Our new corrections have been implemented in the Fortran code `NMSSMCALC` that computes the Higgs mass spectrum of the CP-conserving and CP-violating NMSSM as well as the partial decay widths of the Higgs bosons including the state-of-the-art higher-order corrections. Our results mark another step forward in the program of increasing the precision in the NMSSM Higgs boson observables.

**Supersymmetry: Models, Phenomenology and Experimental Results / 101****Maximally Symmetric Three Higgs Doublet Model****Authors:** Aidin Masouminia<sup>1</sup>; Neda Darvishi<sup>2</sup>; Apostolos Pilaftsis<sup>3</sup><sup>1</sup> Durham University<sup>2</sup> University of Warsaw<sup>3</sup> University of Manchester (GB)**Corresponding Author:** neda.darvishi@fuw.edu.pl

I discuss the general Three-Higgs Doublet Model (3HDM) and identify all limits that lead to exact SM alignment. I focus on the most economic setting, called here the Maximally Symmetric Three-Higgs Doublet Model (MS-3HDM). The potential of the MS-3HDM obeys an  $\text{Sp}(6)$  symmetry, softly broken by bilinear masses and explicitly by hypercharge and Yukawa couplings through renormalisation-group effects, whilst the theory allows for quartic coupling unification up to the Planck scale. Besides the two ratios of vacuum expectation values,  $\tan\beta_{1,2}$ , the MS-3HDM is predominantly governed by only three input parameters: the masses of the two charged Higgs bosons and their mixing angle  $\sigma$ . Most remarkably, with these input parameters, we obtain definite predictions for the entire scalar mass spectrum of the theory, as well as for the SM-like Higgs-boson couplings to the gauge bosons and fermions. The predicted deviations of these couplings from their SM values might be probed at future precision high-energy colliders.

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## **Full NLO corrections to charged Higgs boson decays in the NMSSM**

**Authors:** Thi Nhung Dao<sup>1</sup>; Margarete Mühleitner<sup>2</sup>; Kodai Sakurai<sup>3</sup>; Shruti Patel<sup>4</sup>

<sup>1</sup> *ICISE*

<sup>2</sup> *Karlsruhe institute of Technology*

<sup>3</sup> *Tohoku University*

<sup>4</sup> *Karlsruhe institute of Technology*

**Corresponding Author:** kodai.sakurai.e3@tohoku.ac.jp

In light of the current situation that no direct sign of new particles has been observed so far, indirect searches of new particles become increasingly important.

Accurate theoretical predictions are inevitable in order to be able to indirectly find new physics and - in case of discovery - to identify the underlying model.

In this study, we calculated the full one-loop corrections to the decay widths of charged Higgs boson decays in the framework of the Next-to-Minimal Supersymmetric Model (NMSSM) with CP violation.

In this talk, we discuss the impact of the NLO corrections on the charged Higgs branching ratios in a wide range of parameter space that is compatible with the experimental constraints.

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## **Searches for third generation squarks with the CMS detector**

**Corresponding Author:** caleb.smith@ku.edu

Results from the CMS experiment are presented for searches for supersymmetric stop and sbottom production. A variety of final state decays are considered with an emphasis on targeting difficult to reach kinematic regions. The searches use proton-proton collision data with luminosity up to 137 fb<sup>-1</sup> recorded by the CMS detector at center of mass energy 13 TeV during the LHC Run 2

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## **Searches for direct pair production of third generation squarks with the ATLAS detector**

**Author:** Carlos Moreno Martinez<sup>1</sup>

<sup>1</sup> *Universitat Autònoma de Barcelona (ES)*

**Corresponding Author:** carlos.moreno.martinez@cern.ch

Naturalness arguments for weak-scale supersymmetry favour supersymmetric partners of the third generation quarks with masses light enough to be produced at the LHC. The ATLAS experiment has a variety of analyses devoted to direct production of stops and sbottoms, exploiting novel reconstruction and analysis techniques. This talk presents recent results from these searches and their interpretation in both supersymmetric models and simplified associated-production dark matter models.

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## **Phenomenological Study of the Semi-constrained NMSSM**

**Authors:** Jingya Zhu<sup>1</sup>; Kun Wang<sup>2</sup>

<sup>1</sup> *Henan University*

<sup>2</sup> *University of Shanghai for Science and Technology*

**Corresponding Author:** wk2016@whu.edu.cn

Based on 3 papers: arXiv:2002.05554, 2003.01662, 2011.12848

1. "A Novel Scenario in the Semi-constrained NMSSM," JHEP 06, 078 (2020)

2. "Funnel annihilations of light dark matter and the invisible decay of the Higgs boson," Phys. Rev. D 101, no.9, 095028 (2020)

3. "Higgsino Asymmetry and Direct-Detection Constraints of Light Dark Matter in the NMSSM with Non-Universal Higgs Masses," Chin. Phys. C 45, no. 4, 041003 (2021)

The fully constrained NMSSM is in tension with current experimental constraints. Therefore, we focus on a simple and elegant supersymmetric model: semi-constrained NMSSM (scNMSSM).

In order to better explore the parameter space of scNMSSM, we have developed a new search algorithm: the Heuristically Search (HS) and the Generative Adversarial Network (GAN).

We applied this very effective search algorithm to the parameter space of scNMSSM. For the first time (according to the current understanding), we successfully found a parameter space that satisfies all the theoretical and experimental constraints, and then we made analysis of the Higgs and dark matter properties.

We carefully studied the Higgs and dark matter LSP scenario in the scNMSSM. We found that in scNMSSM, there can be four funnel-annihilation mechanisms for the LSP in scNMSSM, which are the  $h_2$ ,  $Z$ ,  $h_1$  and  $a_1$  funnel. We also verified that the spin-dependent cross section is proportional to the square of higgsino asymmetry. And the higgsino-mass parameter  $\mu$  is smaller than about 335 GeV in the scNMSSM due to the current muon  $g-2$  constraint.

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## **Searches for strong production of supersymmetric particles with the ATLAS detector**

**Author:** Kazuki Todome<sup>1</sup>

<sup>1</sup> *Universita e INFN, Bologna (IT)*

**Corresponding Author:** kazuki.todome@cern.ch

Despite the absence of experimental evidence, weak-scale supersymmetry remains one of the best motivated and studied Standard Model extensions. This talk summarizes recent ATLAS results on inclusive searches for supersymmetric squarks of the first two generations and gluinos, focusing on decay modes in which R-parity is conserved and therefore the lightest SUSY particle is a stable dark matter candidate. The searches target final states including jets, leptons, photons, and missing transverse momentum.

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## **Vacuum (meta-)stability in the $\mu\nu$ SSM**

**Authors:** Georg Ralf Weiglein<sup>1</sup>; Thomas Biekötter<sup>2</sup>; Sven Heinemeyer<sup>3</sup>

<sup>1</sup> *Deutsches Elektronen-Synchrotron (DE)*

<sup>2</sup> *Deutsches Elektronen-Synchrotron DESY*

<sup>3</sup> *CSIC (Madrid, ES)*

**Corresponding Author:** thomas.biekotter@desy.de

We perform an analysis of the vacuum stability of the neutral scalar potential of the  $\mu$ -from- $\nu$  Supersymmetric Standard Model ( $\mu\nu$ SSM). As an example scenario, we discuss the alignment without decoupling limit of the  $\mu\nu$ SSM. We demonstrate that in this limit large parts of the parameter space feature unphysical minima that are deeper than the electroweak minimum. In order to estimate the lifetime of the electroweak vacuum, we calculate the decay rates for the tunneling process into each unphysical minimum. We find that in many cases the resulting lifetime is longer than the age of the universe, such that the considered parameter region is not excluded. On the other hand, we also find parameter regions in which the EW vacuum is short-lived, and we demonstrate how these regions are related to the presence of light right-handed sneutrinos.

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## Searches for supersymmetry in hadronic final states with the CMS detector

**Author:** Koushik Mandal<sup>1</sup>

<sup>1</sup> *Eotvos Lorand University (HU)*

**Corresponding Author:** koushik.mandal@cern.ch

Results from the CMS experiment are presented for searches for strong supersymmetric with decays to hadronic final states. The searches use proton-proton collision data with luminosity up to 137 fb<sup>-1</sup> recorded by the CMS detector at center of mass energy 13 TeV during the LHC Run 2.

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## Proton Lifetime in Minimal SU(5)

**Authors:** Cem Salih Un<sup>1</sup>; Ilia Gogoladze<sup>2</sup>; Kaladi Babu<sup>3</sup>

<sup>1</sup> *Bursa Uludag University*

<sup>2</sup> *University of Delaware*

<sup>3</sup> *Oklahoma State University*

**Corresponding Author:** cemsalihun@uludag.edu.tr

We will consider the proton decay in a class of minimal SU(5) GUTs mediated by color-triplets Higgsinos. Even though their masses are comparable with the GUT scale, they can still yield a shorter lifetime for the proton, especially in the low  $\tan\beta$  region. In this work, we consider several threshold effects from Planck-suppressed operators, which lead to heavier triplet Higgsinos as well as correcting the wrong fermion mass relations realized in SU(5) GUTs.

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## Diluting SUSY flavour problem on the Landscape

**Authors:** Emilian Dudas<sup>1</sup>; Priyanka Lamba<sup>2</sup>; Sudhir Kumar Vempati<sup>3</sup>

<sup>1</sup> *Ecole Polytechnique*

<sup>2</sup> *Indian Institute of Science, Bengaluru 560012, India*

<sup>3</sup> *Centre for High Energy Physics, Indian Institute of Science*

**Corresponding Author:** lpriyanka@iisc.ac.in

We consider an explicit effective field theory example based on the Bousso-Polchinski framework with a large number  $N$  of hidden sectors contributing to supersymmetry breaking. Each contribution comes from four form quantized fluxes, multiplied by random couplings. The soft terms in the observable sector in this case become random variables, with mean values and standard deviations which are computable. We show that this setup naturally leads to a solution of the flavor problem in low-energy supersymmetry if  $N$  is sufficiently large. We investigate the consequences for flavor violating processes at low-energy and for dark matter.

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## Linking the Supersymmetric Standard Model to the Cosmological Constant

**Author:** Yucheng QIU<sup>1</sup>

**Co-author:** S. -H. Henry Tye<sup>2</sup>

<sup>1</sup> *The Hong Kong University of Science and Technology*

<sup>2</sup> *HKUST, Cornell*

**Corresponding Author:** yqiuai@connect.ust.hk

String theory has no parameter except the string scale  $M_S$ , so the Planck scale  $M_{\text{Pl}}$ , the supersymmetry-breaking scale  $m_{\text{susy}}$ , the electroweak scale  $m_{\text{EW}}$  as well as the vacuum energy density (cosmological constant)  $\Lambda$  are to be determined dynamically at any local minimum solution in the string theory landscape. Here we consider a model that links the supersymmetric electroweak phenomenology (bottom up) to the string theory motivated flux compactification approach (top down). In this model, supersymmetry is broken by a combination of the racetrack Kahler uplift mechanism, which naturally allows an exponentially small positive  $\Lambda$  in a local minimum, and the anti-D3-brane in the KKLT scenario. In the absence of the Higgs doublets from the supersymmetric standard model, one has either a small  $\Lambda$  or a big enough  $m_{\text{susy}}$ , but not both. The introduction of the Higgs fields (with their soft terms) allows a small  $\Lambda$  and a big enough  $m_{\text{susy}}$  simultaneously. Since an exponentially small  $\Lambda$  is statistically preferred (as the properly normalized probability distribution  $P(\Lambda)$  diverges at  $\Lambda = 0^+$ ), identifying the observed  $\Lambda_{\text{obs}}$  to the median value  $\Lambda_{50\%}$  yields  $m_{\text{EW}} \sim 100$  GeV. We also find that the warped anti-D3-brane tension has a SUSY-breaking scale  $M_{\text{susy}} \sim 100 m_{\text{EW}}$  while the SUSY-breaking scale that directly correlates with the Higgs fields in the visible sector is  $m_{\text{susy}} \simeq m_{\text{EW}}$ .

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## Natural SUSY emergent from the landscape

**Author:** Howard Baer<sup>1</sup>

<sup>1</sup> *University of Oklahoma*

**Corresponding Author:** baer@nhn.ou.edu

We explain how the landscape can make predictions for Higgs and sparticle masses.

A power-law draw to large soft terms coupled with the ABDS anthropic condition that the derived weak scale be within a factor of a few of our measured value leads to  $m(h) \sim 125$  GeV with sparticles above present LHC limits. The spectra that emerges is that of radiatively driven natural SUSY. We show why such natural models are much more likely from the landscape than finetuned SUSY models.

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## Cosmological Implications of Supercooled Confinement

**Authors:** Filippo Sala<sup>1</sup>; Jason Baldes<sup>2</sup>; Yann Gouttenoire<sup>3</sup>; Geraldine Servant<sup>4</sup>

<sup>1</sup> CNRS and Sorbonne University

<sup>2</sup> Université Libre de Bruxelles

<sup>3</sup> Deutsches Elektronen-Synchrotron DESY

<sup>4</sup> Deutsches Elektronen-Synchrotron (DE)

**Corresponding Author:** yann.gouttenoire@gmail.com

A strongly-coupled sector can feature a supercooled confinement transition in the early universe. When fundamental quanta of the strong sector are swept into expanding bubbles of the confined phase, the distance between them is large compared to the confinement scale. The flux linking the fundamental quanta then deforms and stretches towards the wall, producing an enhanced number of composite states upon string fragmentation. The composite states are highly boosted in the plasma frame, which leads to additional particle production through the subsequent deep inelastic scattering. I will discuss the modelling of these dynamics and introduce the consequences for the abundance and energetics of particles in the universe and for bubble-wall Lorentz factors.

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## Gravitational waves and baryogenesis from a non-minimal composite Higgs model

**Author:** Andrea Guiggiani<sup>1</sup>

**Co-authors:** Stefania De Curtis<sup>2</sup>; Giuliano Panico<sup>3</sup>

<sup>1</sup> Università degli studi di Firenze

<sup>2</sup> Università e INFN, Firenze (IT)

<sup>3</sup> University of Florence and INFN Florence

**Corresponding Author:** andrea.guiggiani@unifi.it

A possible explanation of the origin of baryon asymmetry in the universe is provided by electroweak (EW) baryogenesis, where the asymmetry is generated during a first-order phase transition. This can be realized in the presence of new physics that modify the Higgs dynamics.

Non minimal Composite Higgs models based on the coset  $SO(6)/SO(5)$  offer a suitable extension of the SM Higgs sector that can realize baryogenesis.

The scalar sector of the theory is enriched by an additional scalar singlet field that triggers a “two-step” EW phase transition and introduces additional sources of CP-violation.

In this talk I will discuss the dynamics of the two-step phase transition, with particular focus on the conditions needed for baryogenesis.

An important requirement is the breaking of a discrete  $Z_2$  symmetry associated to the additional singlet, which controls the degeneracy of vacua and the amount of CP violation.

The current bounds on the electric dipole moments of the electron and the neutron impose very mild constraints on the amount of  $Z_2$  breaking, allowing for a successful EW baryogenesis in a large part of the parameter space.

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## Electroweak baryogenesis and gravitational waves in a composite Higgs model with high dimensional fermion representations

**Author:** Ke-Pan Xie<sup>1</sup>

**Co-authors:** Ligong Bian ; Yongcheng Wu<sup>2</sup>

<sup>1</sup> *Seoul National University*

<sup>2</sup> *Oklahoma State University*

**Corresponding Author:** kpxie@snu.ac.kr

We study electroweak baryogenesis in the  $SO(6)/SO(5)$  composite Higgs model with the third generation quarks being embedded in the  $20'$  representation of  $SO(6)$ . The scalar sector contains one Higgs doublet and one real singlet, and their potential is given by the Coleman-Weinberg potential evaluated from the form factors of the lightest vector and fermion resonances. We show that the resonance masses at  $O(1 \sim 10 \text{ TeV})$  can generate a potential that triggers the strong first-order electroweak phase transition (SFOEWPT). The CP violating phase arising from the dimension-6 operator in the top sector is sufficient to yield the observed baryon asymmetry of the universe. The SFOEWPT parameter space is detectable at the future space-based detectors.

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## Terazooming in on light (composite) axion like particles

**Author:** Abhishek Iyer<sup>1</sup>

**Co-authors:** Giacomo Cacciapaglia ; Aldo Deandrea<sup>2</sup>; Krishnamoorthy Sridhar<sup>3</sup>

<sup>1</sup> *IIT Delhi*

<sup>2</sup> *I*

<sup>3</sup> *TIFR*

**Corresponding Author:** iyerabhishek@physics.iitd.ac.in

The Tera-Z phase of future  $e^+e^-$  colliders, FCC-ee and CepC, is a goldmine for exploring  $Z$  portal physics. We focus on axion-like particles (ALPs) that can be produced via  $Z$  decays with a monochromatic photon. As a template model, we consider composite Higgs models with a light pseudo-scalar that couples through the Wess-Zumino-Witten term to the electroweak gauge bosons. For both photophilic and photophobic cases, we show that the Tera-Z can probe composite scales up to 100s of TeV, well beyond the capability of the LHC and current precision physics.

Our results also apply to generic ALPs and, in particular, severely constrain models that explain the muon  $g - 2$  anomaly.



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## Composite Dynamics in the Early Universe

**Authors:** Giuliano Panico<sup>None</sup>; Luigi Delle Rose<sup>1</sup>; Stefania De Curtis<sup>2</sup>

<sup>1</sup> *University of Florence*

<sup>2</sup> *INFN, Florence*

**Corresponding Author:** luigi.dellerose@fi.infn.it

We study the occurrence of a strong first-order electroweak phase transition in composite Higgs models. Minimal constructions realising this scenario are based on the coset  $SO(6)/SO(5)$  which delivers an extended Higgs sector with an additional scalar. In such models, a two-step phase transition can be obtained with the scalar singlet acquiring a vacuum expectation value at intermediate temperatures. A bonus of the Nambu-Goldstone boson nature of the scalar-sector dynamics is the presence of non-renormalisable Higgs interactions that can trigger additional sources of CP violation needed to realise baryogenesis at the electroweak scale. Another interesting aspect of this scenario is the generation of gravitational wave signatures that can be observed at future space-based interferometers.

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## Constraining a top-philic dark matter model featuring contact terms

**Author:** Lara Mason<sup>1</sup>

<sup>1</sup> *Universite Claude Bernard Lyon 1*

**Corresponding Author:** masonlara316@gmail.com

We investigate the astrophysical and collider constraints of an effective model featuring a scalar top-philic heavy dark matter candidate and a dimension-five contact interaction term, as motivated by possible underlying extensions of the Standard Model such as composite Higgs models. We show that the presence of contact interactions can have a major impact on the dark matter relic density as well as on its direct and indirect detection prospects, while the collider phenomenology of the model is unaffected. This underlines the complementarity of collider and cosmological constraints on dark matter models.

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## Vector boson scattering in composite Higgs models

**Author:** Diogo Buarque Franzosi<sup>1</sup>

<sup>1</sup> *Chalmers University of Technology*

**Corresponding Author:** diogo.buarque.franzosi@gmail.com

Deviations from the SM in high energy longitudinal vector boson scattering might be the first evidence of a composite electroweak symmetry breaking sector. In this talk I will discuss the theoretical expectations and experimental prospects for this process in composite Higgs models. I will also compare it with searches for scalars that are typical in this class of model.

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## Chiral models of composite axions and accidental Peccei-Quinn symmetry

**Author:** Alessandro Podo<sup>1</sup>

<sup>1</sup> *Columbia University*

**Corresponding Author:** ap3964@columbia.edu

The QCD axion, based on the existence of the anomalous Peccei-Quinn (PQ) symmetry, realizes a simple and elegant solution to the strong CP problem. However, explicit realizations are extremely sensitive to PQ-violating effects in the UV, which can destabilize the axion potential and spoil the solution. In this talk, we introduce a class of composite axion models that provide a natural solution to the strong CP problem. The PQ symmetry is not only accidental, but also naturally protected from higher dimensional operators by the gauge dynamics. The QCD axion emerges as the NGB of a strongly-interacting, chiral sector with no fundamental scalars, where all mass scales are generated dynamically. The model can be easily chosen to be compatible with a grand unified dynamics, and we discuss the case of non-supersymmetric SU(5) unification.

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## Phase transition and gravitational wave in strongly-coupled dark gauge sectors

**Author:** Chen Zhang<sup>1</sup>

**Co-authors:** Manuel Reichert ; Francesco Sannino ; Zhi-Wei Wang

<sup>1</sup> *INFN - National Institute for Nuclear Physics*

**Corresponding Author:** chen.zhang@fi.infn.it

Dark gauge sectors are well-motivated extensions of the Standard Model which may have interesting cosmological consequences. In this talk I will discuss the treatment of confinement and/or chiral phase transitions in dark QCD-like sectors, using Polyakov-extended chiral effective models. The implication for gravitational wave signatures in these type of theories will be explored.

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## Partial Compositeness from Partial Unification

**Author:** Vatani Shahram<sup>1</sup>

**Co-authors:** Giacomo Cacciapaglia ; Chen Zhang<sup>2</sup>

<sup>1</sup> *IP2I Lyon*

<sup>2</sup> *INFN - National Institute for Nuclear Physics*

**Corresponding Author:** vatani@ipnl.in2p3.fr

Providing an Ultra-Violet completion valid up to the Planck scale is of paramount importance to validate the composite Higgs paradigm, on a par with supersymmetry. We propose the first complete framework, based on partial unification of a confining hypercolor gauge group with the Standard Model color group, where couplings of the standard model fermions are mediated by both gauge and

scalar bosons. We demonstrate our approach by providing an explicit model based on a Techni-Pati-Salam (TPS) unification,  $SU(8)_C \times SU(2)_L \times SU(2)_R$ , able to generate masses for all fermion generations, including neutrinos, via partial compositeness. The TPS scenario features an  $Sp(4)$  hypercolor group, and lattice studies will be crucial to validate the model.

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## Natural composite Higgs model

**Author:** Teng Ma<sup>None</sup>

We present a simple mechanism for generating a Higgs quartic in composite Higgs models without a corresponding quadratic term. The extra quartic will originate from a Higgs dependent kinetic mixing between additional fermionic states. The mechanism can be naturally embedded to models with maximal symmetry as well as Twin Higgs models. The resulting Twin Higgs models will have a fully natural realistic Higgs potential, where the quartic mechanism will serve as the only source for the  $Z_2$  breaking, while the top and gauge sectors can remain exactly  $Z_2$  invariant.

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## A road to a beyond the Standard Model model

**Authors:** Giancarlo Rossi<sup>None</sup>; Roberto Frezzotti<sup>None</sup>

We describe examples of renormalizable field theories where the breaking of chiral symmetry at the UV cutoff leaves behind at low energy dynamically generated elementary particle masses in a way alternative to the Higgs mechanism. In this scenario 1) the scale of the elementary particle masses is set by the RGI scale of the theory 2) masses are kept “small” owing to an enhanced chiral symmetry enjoyed by the massless theory, thus solving the ‘t Hooft naturalness problem, 3) in order to match the experimental value of the top mass, a super-strongly interacting sector, gauge-invariantly coupled to standard matter, needs to exist with an RGI scale,  $\Lambda \gg \Lambda_{\text{QCD}}$ , of the order of a few TeV’s, 4) the peculiar dependence of the non-perturbatively generated masses upon the gauge couplings is such that it may offer a hint to solve the mass hierarchy problem, 5)  $\Lambda$  sets the order of magnitude of the electro-weak scale, 6) the 125 GeV resonance recently identified at LHC is interpreted as a  $\frac{1}{2} + \frac{1}{2} - \frac{1}{2}$  composite state bound by exchanges of super-strongly interacting particles to which the electro-weak bosons are coupled,

7) at  $(\text{momenta})^2 \ll \Lambda^2$  the couplings of the composite Higgs boson with quark, leptons and electro-weak bosons deviate from those of the Standard Model by  $O(\frac{1}{\Lambda^2})$  corrections, 8) with a reasonable choice of particle content, a theory extending the Standard Model with the inclusion of the new super-strong sector exhibits gauge coupling unification at a scale  $\sim 10^{18} \text{ GeV}$  making the proton life time comfortably larger than the present limit of  $1.7 \times 10^{34}$  years.