

# XXVII International Workshop on Deep Inelastic Scattering and Related Subjects

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## Book of Abstracts



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**Joint WG1+WG7: Structure Functions and PDFs + Future of DIS / 207**

## PDFSense: Mapping the PDF sensitivity of future facilities

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The publicly available PDFSense analysis package provides a variety of tools for quantifying the potential impact of experimental data on the extraction of PDFs. Our approach relies crucially on the Hessian correlation between theory-data residuals and the PDFs themselves, as well as on a newly defined quantity —the sensitivity— which represents an extension of the correlation and reflects both PDF-driven and experimental uncertainties. This offers a new means of understanding the influence of individual measurements in existing fits, as well as a predictive device for future facilities; toward this goal, we examine pseudo-data from the EIC, LHeC, and HL-LHC. Along the way, many new physics insights can be gained or reinforced.

**Joint WG1+WG7: Structure Functions and PDFs + Future of DIS / 247**

## Precision QCD with the LHeC and the FCC-eh

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The Large Hadron-electron Collider (LHeC) is a proposed upgrade of the LHC at CERN. An ERL will provide electrons to collide with the HL-LHC, HE-LHC and the FCC-hh proton beams to achieve centre-of-mass energies 1.3-3.5 TeV and luminosities  $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . These three configurations will extend the kinematic plane by more than one order of magnitude towards smaller  $x$  and larger  $Q^2$  than HERA. DIS measurements in such machines offer unprecedented possibilities to enlarge our knowledge on parton densities through a complete unfolding of all flavours in a single experimental setup to be compared with data from hadron colliders as an independent input and as a test of factorisation, and to determine  $\alpha_s$ . In this talk we review the most recent developments on these subjects.

**Joint WG1+WG7: Structure Functions and PDFs + Future of DIS / 120**

## Neutrino Telescopes as QCD Microscopes

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We present state-of-the-art predictions for the ultra-high energy (UHE) neutrino-nucleus cross-sections in charged- and neutral-current scattering. The calculation is performed in the framework of collinear

factorisation at NNLO, extended to include the resummation of small- $x$  BFKL effects. Further improvements are made by accounting for the free-nucleon PDF constraints provided by D-meson data from LHCb and assessing the impact of nuclear corrections and heavy-quark mass effects. The calculations presented here should play an important role in the interpretation of future data from neutrino telescopes such as IceCube and KM3NET, and highlight the opportunities that astroparticle experiments offer to study the strong interactions.

**Joint WG1+WG7: Structure Functions and PDFs + Future of DIS / 128**

## Towards Ultimate Parton Distributions at the High-Luminosity LHC

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In this talk, we present results from a detailed assessment of the ultimate constraining power of LHC data on the PDFs that can be expected from the complete dataset, in particular after the High-Luminosity (HL) phase. To achieve this, HL-LHC pseudo-data for different projections of the experimental uncertainties are generated, and the resulting constraints on the PDF4LHC15 set are quantified by means of the Hessian profiling method. We find that HL-LHC measurements can reduce PDF uncertainties by up to a factor of 2 to 4 in comparison to state-of-the-art fits, leading to few-percent uncertainties for important observables such as the Higgs boson transverse momentum distribution via gluon-fusion. Our results illustrate the significant improvement in the precision of PDF fits achievable from hadron collider data alone. In addition, we apply the same methodology to the final anticipated data sample from the proposed LHeC, and compare these with the HL-LHC projections, demonstrating an encouraging complementarity between the projected HL-LHC and LHeC constraints.

**Joint WG1+WG7: Structure Functions and PDFs + Future of DIS / 191**

## The SHiP experiment at CERN

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The SHiP Collaboration has proposed a general-purpose experimental facility operating in beam dump mode at the CERN SPS accelerator. The SHiP experiment incorporates a muon shield based on magnetic sweeping and two complementary apparatuses. The detector immediately downstream of the muon shield is optimised both for recoil signatures of light dark matter scattering and for physics with neutrino interactions, and consists of a spectrometer magnet housing a layered detector system with heavy target plates, emulsion film technology and electronic high precision tracking. The second detector system aims at measuring the visible decays of hidden sector particles to both fully reconstructible final states and to partially reconstructible final states with neutrinos, in a nearly background free environment. Using the high-intensity beam of 400 GeV protons, the experiment is capable of integrating  $2 \cdot 10^{20}$  protons in five years, which allows probing dark photons, dark scalars



and pseudo-scalars, and heavy neutrinos with GeV-scale masses at sensitivities which exceed those of existing and projected experiments. The tau neutrino deep-inelastic scattering cross-sections will be measured with a statistics a thousand times larger than currently available, with the extraction of the  $F_4$  and  $F_5$  structure functions, never measured so far, and allow for new tests of lepton non-universality with sensitivity to BSM physics. Following the review of the Technical Proposal, the CERN SPS Committee and the CERN Research Board recommended in 2016 that the experiment and the beam dump facility studies proceed to a Comprehensive Design phase. A proposal to the European Strategy for Particle Physics Update was recently submitted.

**Joint WG2+WG4: Small-x and Diff + Hadronic and EW / 143**

## Recent CMS results on the Soft QCD and Forward Physics

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Merged abstract

**Joint WG2+WG4: Small-x and Diff + Hadronic and EW / 161**

## Accessing double parton scatterings with associated-quarkonium production

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I will review how associated-quarkonium production can help us study double parton scatterings.

**Joint WG2+WG4: Small-x and Diff + Hadronic and EW / 352**

## Double parton scattering: theory progress

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Double parton scattering is the process in which one has two hard scatterings in an individual proton-proton collision. It can compete in rate with single scattering in certain kinematic regions and/or for certain processes, reveals new information on proton structure, and becomes more important as collider energy grows. I review recent progress in the theoretical description of double parton scattering. This includes progress towards numerical predictions using a recently-developed full QCD framework, as well as calculation of higher order corrections in this framework.

**Joint WG2+WG4: Small-x and Diff + Hadronic and EW / 63**

## Measurements of multiparton interactions at ATLAS

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Measurements of multiple parton scattering in proton-proton collisions provide insight into the structure and long-range low-momentum scale interactions of the proton. In this talk we present two recent measurements using proton-proton collision data collected by the ATLAS experiment. The first measurement determines the double-parton scattering contribution to four-lepton events at  $\sqrt{s}=8$  TeV. An artificial neural net is used to optimise the analysis and an upper limit on the double-parton scattering fraction is set at 0.042, which corresponds to an effective cross section of 1mb. In the second measurement, the underlying event activity is studied in events containing a Z-boson in  $\sqrt{s}=13$  TeV data. Unfolded differential cross sections are presented for charged particle multiplicity and charged particle transverse momentum in regions of azimuth measured with respect to the Z-boson direction. The data are compared to a wide variety of predictions from Monte Carlo event generators.

**Joint WG2+WG7: Small-x and Diff + Future of DIS / 288**

## Probing transversity GPDs in diffractive electroproduction on the proton and deuteron at an electron-ion collider

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A future electron-ion collider (EIC) with forward detectors would allow for measurements of coherent production of two vector mesons on proton and deuteron targets. In kinematics where the two vector mesons are separated by a large rapidity gap, one vector meson is produced at large transverse momenta and the other is transversely polarized, this process can probe the transversity generalized parton distributions of the respective targets. We show estimates for  $a$  cross sections of the  $\gamma^* N \rightarrow \rho\rho N'$ ,  $\gamma^* D \rightarrow \rho\omega N$  and  $\gamma^* D \rightarrow \rho\phi N$  processes at EIC kinematics, illustrating the feasibility of these measurements.

**Joint WG2+WG7: Small-x and Diff + Future of DIS / 47**

## Collinearly improved impact-parameter dependent Balitsky-Kovchegov evolution

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The Balitsky-Kovchegov equation has been successfully used to describe a wide range of processes in diffraction, saturation physics and many others. It has a wide use both in phenomenology and theory and its solution (the scattering amplitude) has received significant attention in the past years. However, the impact-parameter dependent solutions have been shown to exhibit so-called Coulomb tails, which spoil its phenomenological use due to an unphysical growth of the target. In this study we show, that choosing the recently proposed collinearly improved kernel suppresses the effect of the Coulomb tails and enables us to describe simultaneously the structure function data as well as vector meson photo-production. As an example of the application of these new

scattering amplitudes we present the impact-parameter dependent Weizsacker-Williams gluon distribution which can be measured at the future facilities such as the EIC.

**Joint WG2+WG7: Small-x and Diff + Future of DIS / 248**

## Determination of diffractive parton densities at the LHeC and the FCC-eh

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The Large Hadron-electron Collider (LHeC) is a proposed upgrade of the LHC at CERN. An ERL will provide electrons to collide with the HL-LHC, HE-LHC and the FCC-hh proton and ion beams to achieve per nucleon centre-of-mass energies 1.3-3.5 (0.8-2.2) TeV and luminosities  $\sim 10^{34(33)} \text{ cm}^{-2}\text{s}^{-1}$ . These three configurations will enlarge the kinematic plane by more than one order of magnitude towards smaller  $x$  and larger  $Q^2$  than HERA, which translates into a range of available momentum fraction of the diffractive exchange with respect to the hadron down to  $10^{-4} - 10^{-5}$  for a wide range of the momentum fraction of the parton with respect to the diffractive exchange. Here we show the large possibilities that they offer for the determination of diffractive parton densities DPDFs in proton and nuclei. Using the same framework and methodology previously employed at HERA and under very conservative assumptions for the luminosities and systematic errors, we find an improvement in the extraction of DPDFs from fits to reduced cross sections for inclusive coherent diffraction in  $ep$  by about an order of magnitude. We analyse the sensitivity to kinematic cuts and variations of the fit framework. We also note sensitivity to the shape of the gluon distribution, and to physics beyond linear twist-2 DGLAP evolution at moderate  $Q^2$ . For  $eA$ , we find that an extraction of the currently unmeasured nuclear DPDFs is possible with similar accuracy to that in  $ep$ .

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## Measuring the Weizsäcker-Williams distribution of linearly polarized gluons at an electron-ion collider through dijet azimuthal asymmetries

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The production of a hard dijet with small transverse momentum imbalance in semi-inclusive DIS probes the conventional and linearly polarized Weizsäcker-Williams (WW) transverse momentum dependent (TMD) gluon distributions. The latter, in particular, gives rise to an azimuthal dependence of the dijet cross section. In this talk I will discuss the feasibility of a measurement of these TMDs through dijet production in DIS on a nucleus at an electron-ion collider using a Monte Carlo generator to sample quark-antiquark dijet configurations based on leading-order parton level cross sections. The WW gluon distributions is obtained as a solution of the nonlinear small-x QCD evolution equations. The quark-antiquark dijet configurations are then fragmented to hadrons using PYTHIA, and final-state jets are subsequently reconstructed. I will report on background studies and on the effect of kinematic cuts introduced to remove beam jet remnants. The estimates on required luminosity to measure the distribution of linearly polarized gluons with a statistical accuracy of 5% will be provided.

**Joint WG2+WG7: Small-x and Diff + Future of DIS / 253**

## **Sub-eikonal spin corrections and $g_1$ structure function at low- $x$**

**Author:** Giovanni Antonio Chirilli<sup>1</sup>

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Most of the progress in high-energy Quantum Chromodynamics has been obtained within the eikonal approximation and infinite Wilson-line operators. Evolution equations of Wilson lines with respect to the rapidity parameter encode the dynamics of the hadronic processes at high energy. However, even at high energy many interesting aspects of hadron dynamics are not accessible within the eikonal approximation, the spin physics being an obvious example. The higher precision reached by the experiments and the possibility to probe spin dynamics at future Electron Ion Colliders make the study of deviations from eikonal approximation especially timely.

I will present the high-energy sub-eikonal corrections and the low- $x$   $g_1$  structure function through the high-energy Operator Product Expansion.

**Joint WG3+WG5: Higgs and BSM + HF Physics / 363**

## **New Physics implications of the B-physics anomalies**

**Author:** Javier Fuentes-Martin<sup>1</sup>

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Recent experimental measurements hint for possible new physics effects in B-meson decays, the so-called B-anomalies. New physics explanations of the anomalies generically imply large effects also in other observables, both at low-energies and at high-pT. I will review new physics scenarios able to address these anomalies and discuss their smoking-gun signatures. The possible connection of these anomalies with the SM flavor puzzle will also be addressed.

**Joint WG3+WG5: Higgs and BSM + HF Physics / 361**

## **B-flavour anomalies in $b \rightarrow sll$ and $b \rightarrow clnu$ transitions at LHCb**

**Author:** Alessandra Gioventu<sup>1</sup>

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The concept of lepton universality, where the muon and tau particles are simply heavier copies of the electron, is a key prediction in the Standard Model (SM). In models beyond the SM, lepton universality can be naturally violated with new physics particles that couple preferentially to the second and third generation leptons. Over the last few years, several hints of lepton universality violation have been seen in both  $b \rightarrow c$  and  $b \rightarrow s$  semileptonic beauty decays. This presentation will review these anomalies and give an outlook for the near future. Other probes of NP in highly suppressed b-hadron decays will also be discussed.

**Joint WG3+WG5: Higgs and BSM + HF Physics / 9**

## Heavy flavors at Belle II: status and plans

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The Belle II experiment at the SuperKEKB energy-asymmetric  $e^+e^-$  collider is a substantial upgrade of the B factory facility at the Japanese KEK laboratory.

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.

With this data set, Belle II will be able to measure the Cabibbo-Kobayashi-Maskawa (CKM) matrix, the matrix elements and their phases, with unprecedented precision and explore flavor physics with  $B$  and charmed mesons, and  $\tau$  leptons. Belle II has also a unique capability to search for low mass dark matter and low mass mediators. We also expect exciting results in quarkonium physics with Belle II.

From February to July of this year, the machine has completed a commissioning run, achieved a peak luminosity of  $5.5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ , and Belle II has recorded a data sample of about  $0.5 \text{ fb}^{-1}$ .

Regular operations are expected to start in March 2019.

In this presentation, we will review the status of the Belle II detector, the results of the commissioning run and the near-term prospects for physics at Belle II.

**Joint WG3+WG5: Higgs and BSM + HF Physics / 15**

## Search for new physics in CP violation with beauty and charm decays at LHCb

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Precision measurements of CP violating observables in the decays of b and c hadrons are powerful probes to search for physics beyond the Standard Model.

The most recent results on CP violation in the decay, mixing and interference of both b and c hadrons obtained by the LHCb Collaboration with Run I and years 2015-2016 of Run II are reviewed. In particular world best constraints and world first measurements are provided for CKM elements, unitarity angles and charm parameters.

**Joint WG3+WG7: Higgs and BSM + Future of DIS / 250**

## Higgs physics at the LHeC and the FCC-eh

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The Large Hadron-electron Collider (LHeC) is a proposed upgrade of the LHC at CERN. An ERL will provide electrons to collide with the HL-LHC, HE-LHC and the FCC-hh proton beams to achieve centre-of-mass energies 1.3-3.5 TeV and luminosities  $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . These large luminosities and

the corresponding CC and NC cross sections for Higgs production make the LHeC a Higgs factory. In this talk we present the latest results on the determination of Higgs couplings, both in DIS at the LHeC and the FCC-eh, and in combination with their hadronic counterparts HL-LHC/FCC-hh, pointing out the strong synergies. We also show the implication that a precise determination of PDFs at the LHeC and FCC-eh has on Higgs physics.

**Joint WG3+WG7: Higgs and BSM + Future of DIS / 300**

## Searches for Long Lived Particle Searches - Present and Future

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Since a few years the LHC experiments started to give a special focus on searches for unusual signatures, namely long lived particles that would traverse the experiments our decay in the detectors. Several of these searches are conducted now in the ATLAS, CMS, LHCb and MoEDAL experiments. New experiments for the LHC are presently being proposed to extend substantially the phase space for these searches.

At the same time also future fixed target experiments are proposed to complement these LHC searches, for the low mass region and very small couplings.

In this contribution we will give a review of the present searches and the plans for new experiments to cover a larger phase space of particle types, masses and couplings.

**Joint WG3+WG7: Higgs and BSM + Future of DIS / 252**

## BSM physics at the LHeC and the FCC-eh

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The Large Hadron-electron Collider (LHeC) is a proposed upgrade of the LHC at CERN. An ERL will provide electrons to collide with the HL-LHC, HE-LHC and the FCC-hh proton beams to achieve centre-of-mass energies 1.3-3.5 TeV and luminosities  $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . These large luminosities provide most interesting possibilities for BSM studies. In this talk we present the latest results on the determination of anomalous couplings involving top, Higgs and W,Z bosons in high-energy DIS at the LHeC and the FCC-eh, on studies on sterile neutrinos and other new physics models. We also show the complementarity with the corresponding studies at the HL-LHC.

**Joint WG6+WG7: Spin + Future of DIS / 256**

## Opportunities for spin physics at EIC

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This talk will discuss opportunities to measure spin effects at a high-energy Electron-Ion Collider (EIC). Various types of spin distributions (PDFs, TMDs, GTMDs) will be considered and promising observables will be discussed, in particular those with heavy quark final states.

**Joint WG6+WG7: Spin + Future of DIS / 211**

## The SoLID program in JLab

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The SoLID (Solenoidal Large Intensity Detector) program is proposed at JLab to be capable of running experiments with both high luminosity ( $10^{37} - 10^{39} \text{ cm}^{-2} \text{ s}^{-1}$ ) and large acceptance, exploiting the full potential of the 12 GeV energy upgrade at JLab. The spectrometer is designed with a capability of reconfiguration to optimize for either Parity-Violating Deep Inelastic Scattering (PVDIS) or Semi-Inclusive Deep Inelastic Scattering (SIDIS) /threshold production of the  $J/\psi$  meson. In this talk we will present the rich physics programs followed by an overview of the SoLID instrumentation and the current status.

**Joint WG6+WG7: Spin + Future of DIS / 132**

## Future SIDIS measurements with a transversely polarized deuteron target at COMPASS

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Since 2005, measurements of the SIDIS process off transversely polarised protons performed by the HERMES and COMPASS Collaboration have shown that the Collins and the Sivers asymmetries are clearly different from zero, a milestone in the knowledge of the nucleon structure.

Only few data were collected in the early phase of the COMPASS experiment on a deuteron ( $^6\text{LiD}$ ) target and more recently at JLab on  $^3\text{He}$ . The poor statistical significance of the deuteron data have in so far strongly limited the knowledge of the transversity distribution and of the Sivers function of the d and sea quarks in particular.

For this reason the COMPASS Collaboration has proposed to perform a new measurement of SIDIS on transversely polarised deuterons with an accuracy comparable with that of the existing proton data. The measurement, which will be performed in 2021, soon after the CERN Long Shut-down 2, will conclude the COMPASS exploratory phase of the study of the transverse spin structure of the nucleons and will provide measurements which will stay unique for many years.

The expected outcome from this new measurement and projections for the extraction of the transversity PDFs and for the evaluation of the tensor charge will be presented.

**Joint WG6+WG7: Spin + Future of DIS / 304**

## Studies of nucleon structure with CLAS12

**Author:** Harut Avakian<sup>None</sup>

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The detailed understanding of the orbital structure of partonic distributions, encoded in partonic Transverse Momentum Distributions (TMDs), has been widely recognized as one of the key objectives of the JLab 12 GeV upgrade, and a driving force behind the construction of the Electron Ion Collider.

Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles. The understanding of the contributions to the final transverse-momentum dependence of different azimuthal moments in the cross section will require detailed studies of different contributions.

In this talk, we present an overview of the latest developments and future studies of variety of spin-dependent and independent observables in single and di-hadron production accessible in semi-inclusive DIS using the CLAS12 detector at Jefferson Lab.

**Joint WG6+WG7: Spin + Future of DIS / 158**

## **STAR Forward Upgrade Program**

**Author:** Zhenyu Ye<sup>1</sup>

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Polarized proton-proton and proton-nucleus collisions at Relativistic Heavy Ion Collider (RHIC) presents a unique opportunity to study the partonic and spin structure of the nucleon and nuclei. The STAR experiment at RHIC has measured at mid-pseudorapidity ( $-1 < \eta < 2$ ) spin asymmetries in production cross section of pions, jets, as well as W and Z bosons, providing important experimental inputs to understand both the longitudinal and transverse spin structures of the nucleon. STAR is now working on improving its particle detection in the forward direction ( $2.5 < \eta < 4$ ) with a suite of tracking and calorimetry detectors. These new forward detectors, together with the existing mid-rapidity ones, will allow STAR to explore the low-x and high-x regimes with unprecedented precision. In this talk, the planned STAR forward detector upgrade and physics program will be presented.

**Plenary Session / 326**

## **Practical Informations on the Workshop**

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**Plenary Session / 323**

## **Proton structure and PDFs**

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**Plenary Session / 324**

## **Conference Opening**

**Plenary Session / 325**



## **Spin and 3D structure**

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**Plenary Session / 328**

## **QCD at colliders**

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**Plenary Session / 329**

## **News on Monte Carlo generators**

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**Plenary Session / 330**

## **Low-x and forward physics**

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**Plenary Session / 332**

## **Altarelli Prize talk 1**

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**Plenary Session / 333**

## **Altarelli Prize talk 2**

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**Plenary Session / 334**

## **Heavy flavour physics and hadron spectroscopy**

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**Plenary Session / 335**

## **Heavy ion physics**

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**Plenary Session / 336**

## **Higgs, EW and BSM physics**

**Plenary Session / 337**

## **From HERA to the future of DIS**

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**Plenary Session / 331**

## **Altarelli Prize ceremony**

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**Plenary Session / 344**

## **Concluding Talk**

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**Plenary Session / 345**

## **report from the IAC**

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**Plenary Session / 338**

## **WG1 Summary**

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**Plenary Session / 339**

## WG2 Summary

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**Plenary Session / 340**

## WG3 Summary

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**Plenary Session / 341**

## WG4 Summary

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**Plenary Session / 342**

## WG5 Summary

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**Plenary Session / 346**

## **Report from the LOC**

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**Plenary Session / 343**

## **WG7 Summary**

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**Plenary Session / 347**

## **WG6 Summary**

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**Plenary Session / 327**

## **Conference Opening**

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**WG1:Structure Functions and Parton Densities / 115**

## **NNLO QCD fits to extract PDFs from HERA inclusive and jet data**

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NNLO predictions for jet production in Deep Inelastic Scattering have recently become available. These are used to extend the QCD HERAPDF2.0 Jets fits, that were made to extract PDFs from inclusive HERA data and HERA jet data, from NLO to NNLO. In addition new jet data sets have become available since the publication of HERAPDF2.0 and these are also considered.

**WG1:Structure Functions and Parton Densities / 187**

## Updates of PDFs using the MMHT framework.

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We discuss the updates to the MMHT2014 PDFs. These are due to inclusion of ever-increasing amounts of LHC data, and simultaneously the treatment of more cross sections fully at NNLO. We also present the final results of our inclusion of QED effects in parton distributions.

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## New CTEQ global analysis with high precision data from the LHC

**Authors:** Tie-Jiun Hou<sup>1</sup>; Sayipjamal Dulat<sup>2</sup>; Joey Huston<sup>3</sup>; Jun Gao<sup>4</sup>; Marco Guzzi<sup>5</sup>; Tim Hobbs<sup>6</sup>; Pavel Nadolsky<sup>6</sup>; Jon Pumplin<sup>3</sup>; Carl Schmidt<sup>3</sup>; Ibrahim Sitiwaldi<sup>2</sup>; Dan Stump<sup>3</sup>; Keping Xie<sup>6</sup>; C.-P. Yuan<sup>3</sup>

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We present the new CTEQ-TEA global analysis of Quantum Chromodynamics (QCD). In this analysis, parton distribution functions (PDFs) of the nucleon are determined within the Hessian method at the next-to-next-to-leading order (NNLO) in perturbative QCD, based on the most recent measurements from the Large Hadron Collider (LHC) and a variety of world experimental collider data. Next-to-leading order (NLO) and leading order (LO) PDFs are also determined. Because of difficulties in fitting both the ATLAS 7 and 8 TeV  $W$  and  $Z$  vector boson production cross section data, we present two families of PDFs, named CT18 and CT18Z PDFs respectively, without and with the ATLAS 7 TeV  $W$  and  $Z$  measurements. We study the impact of the CT18 family of PDFs on the theoretical predictions of standard candle cross sections at the LHC and the role of PDF uncertainties.

**WG1:Structure Functions and Parton Densities / 302****Update of the ABM16 PDF fit****Authors:** Sergey Alekhin<sup>1</sup>; Johannes Bluemlein<sup>2</sup>; S. Moch<sup>3</sup><sup>1</sup> *Hamburg University*<sup>2</sup> *DESY*<sup>3</sup> *UHH***Corresponding Authors:** sven-olaf.moch@desy.de, johannes.bluemlein@desy.de, sergey.alekhin@desy.de

We report an update of the NNLO ABMP16 PDFs aimed to include recent data on the Drell-Yan process, single- and pair-production of the top quarks at the LHC, and the heavy-quark semi-inclusive DIS production with a main focus on the small-x PDFs. The parameters of QCD Lagrangian, strong coupling constants and the heavy quark masses, are determined simultaneously with the PDFs and interplay emerging between various fit ingredients is discussed.

**WG1:Structure Functions and Parton Densities / 291****The PDF interpretation of the measurement of a vector boson produced in association with jets at the ATLAS detector****Author:** ATLAS Collaboration<sup>None</sup>

We present a PDF interpretation of events containing a vector boson produced in association with jets at a proton-proton collider, performed using ATLAS data from 2012 at a centre-of-mass energy of 8 TeV, together with ATLAS data on inclusive vector boson production at 7 TeV. The results are given relative to the ATLASepWZ16 PDF set, with consequences for the strangeness content of the sea. Systematic correlations between the input ATLAS data sets are fully accounted. The resulting PDF set is called ATLASepWZWjets19.

**WG1:Structure Functions and Parton Densities / 127****Nuclear Uncertainties in the Determination of Proton PDFs****Authors:** Richard David Ball<sup>1</sup>; Emanuele Roberto Nocera<sup>2</sup>; Rosalyn Pearson<sup>1</sup><sup>1</sup> *Edinburgh University*<sup>2</sup> *The University of Edinburgh***Corresponding Authors:** r.l.pearson@sms.ed.ac.uk, emanuele.nocera@ed.ac.uk, rdb@ph.ed.ac.uk

We show how theoretical uncertainties due to nuclear effects may be incorporated into global fits of proton parton distribution functions (PDFs) that include deep-inelastic scattering and Drell-Yan data on nuclear targets. We specifically consider the CHORUS, NuTeV and E605 data included in the NNPDF3.1 fit, which used Pb, Fe and Cu targets, respectively. We show that the additional uncertainty in the proton PDFs due to nuclear effects is small, as expected, and in particular that the effect on the  $\bar{d}/\bar{u}$  ratio, the total strangeness  $s + \bar{s}$ , and the strange valence distribution  $s - \bar{s}$  is negligible.

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**Soft correction to inclusive DIS cross-section at four-loops****Authors:** Andreas Vogt<sup>1</sup>; Goutam Das<sup>2</sup>; S. Moch<sup>3</sup><sup>1</sup> *University of Liverpool*<sup>2</sup> *DESY*<sup>3</sup> *UHH***Corresponding Authors:** andreas.vogt@liv.ac.uk, gkdgoutam@gmail.com, sven-olaf.moch@desy.de

We study the threshold corrections for inclusive deep-inelastic scattering and resummation to N<sup>4</sup>LL accuracy. Using the form factor at four loops in the large-nc limit we are able to derive the soft-virtual coefficients at the four loops in large-nc approximation. We have presented the expression for resummation coefficients B<sub>4q</sub> coefficient for quarks which enters first time in the resummed exponent at this order. We study the effect of N<sup>4</sup>LL corrections for both resummed (exponentiated) as well as in the expansion of the coefficient function in tower expansion of logarithms. The addition of B<sub>4q</sub> coefficient stabilises the logarithmic expansion of the coefficient function. The extra logarithm at the fourth order changes the soft-virtual cross-section by less than 1%. However the perturbative convergence is seen to be improved with the addition of higher logarithms as expected.

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**Investigation of parton densities at very high  $x$** **Author:** Allen Caldwell<sup>1</sup><sup>1</sup> *Max-Planck-Institut fur Physik (DE)***Corresponding Author:** caldwell@mpp.mpg.de

The knowledge of the proton parton densities for large  $x$  is very important in the search for new physics signals at the LHC. For Bjorken- $x$  larger than 0.6 they are however poorly constrained by the data used in extracting the proton parton density functions (PDFs) and different pdf sets have large uncertainties, and differ considerably, in this regime. We compare the pdf sets most widely used by the LHC community to the ZEUS high- $x$  data. This data has not been previously used in PDF set determinations. Due to the small expected and observed numbers of events in this kinematic regime, Poisson statistics is used in the evaluation of the probabilities assigned to the different PDF sets. A wide variation is found in the ability of the PDF sets to predict the observed results.

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**A statistical description of theory uncertainty from missing higher orders****Author:** Marco Bonvini<sup>1</sup><sup>1</sup> *INFN, Rome 1 Unit***Corresponding Author:** marco.bonvini@cern.ch

Theory uncertainty from missing higher orders is usually estimated using scale variation. While scale variation is certainly a good tool to guess the size of the next perturbative order, it lacks of a statistical (probabilistic) interpretation and it often underestimates the actual uncertainty. Having

a statistical definition of theory uncertainties is not only need for a fair comparison with data in precision physics: it is also a useful tool for extracting PDFs accounting also for theory uncertainties. A few years ago Cacciari and Houdeau proposed a Bayesian model to give a statistical meaning to theory uncertainties. The idea was excellent, but it has some limitations, which in turn make it not very well performing, especially for LHC physics. In this talk I will present two new Bayesian models: one is an improved version of the Cacciari-Houdeau model, and the other is inspired by scale variation. I will further show how scale dependence can be removed from a finite-order result within the context of these models. As a proof of concept, I will apply the methods to inclusive Higgs production in gluon fusion, for which four perturbative orders are known, and which is characterised by large perturbative corrections. The results are very interesting and promising.

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## Constraining the Sea Quark Distributions Through $W^\pm$ Cross Section Ratio Measurements at STAR

**Author:** Matt Posik<sup>None</sup>

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Over the past several years, parton distribution functions (PDFs) have become more precise. However there are still kinematic regions where more data are needed to help constrain global PDF extractions, such as the ratio of the sea quark distributions  $\bar{d}/\bar{u}$  near the valence region. Furthermore, current measurements appear to suggest different high- $x$  behaviors of this ratio. The  $W$  cross section ratio ( $W^+/W^-$ ) is sensitive to the unpolarized quark distributions at large  $Q^2$  set by the  $W$  mass. Such a measurement can be used to help constrain the  $\bar{d}/\bar{u}$  ratio. The STAR experiment at RHIC is well equipped to measure the leptonic decays of  $W$  bosons, in the mid-pseudorapidity range ( $|\eta| \leq 1$ ), produced in proton-proton collisions at  $\sqrt{s} = 500/510$  GeV. At these kinematics STAR is sensitive to quark distributions near  $x$  of 0.16. STAR can also measure  $W^+/W^-$  in a more forward region ranging from  $1.0 < \eta < 1.5$ , which extends the sea quark sensitivity to higher  $x$ . RHIC runs from 2011 through 2013 have collected about  $350 \text{ pb}^{-1}$  of integrated luminosity, and an additional  $350 \text{ pb}^{-1}$  from the 2017 run. This talk will present preliminary results of the 2011-2013  $W^+/W^-$  cross section ratio measurements.

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## A new simple PDF parametrisation: improved description of the HERA data

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We consider a new parametrisation for the parton distribution functions (PDFs) that is more flexible in the small- $x$  region. We implement it in the `xFitter` open-source PDF fitting tool, and compare it to the default `xFitter` parametrization, widely used for many PDF studies, and notably for the HERAPDF determination. We find that we can describe the combined inclusive HERA I+II data using NNLO theory with a significantly higher quality than HERAPDF2.0: the  $\chi^2$  is reduced by more than 60 units, having used only four more parameters than in the HERAPDF2.0 parametrisation, and the resulting PDFs are more in line with other mainstream PDF sets. Our results highlight a significant parametrisation bias in the default `xFitter` parametrisation, which would lead to even more dramatic effects when used for higher energy colliders, where the small- $x$  region is more relevant. We also find that the inclusion of  $\log(1/x)$  resummation, that was shown in previous



studies to lead to similar improvements in the fit quality, further reduces the  $\chi^2$  by approximately 30 extra units.

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## A review of recent developments for APPLgrid

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A brief review of developments for APPLgrid to allow PDF fits other than to the proton, or other non standard proton fits is presented. These include changes to allow fitting of the photon density within the proton, and changes to facilitate the use of distinct PDF sets for each of the incoming hadrons in hadron-hadron interactions.

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## Fracture Functions in different kinematic regions and their factorizations

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Fracture functions are parton distributions of a hadron in the presence of an almost collinear particle observed in the final state. They are important ingredients in QCD factorization for processes where a particle is produced diffractively. Different kinds of fracture functions are used for a process in different kinematic regions depending on the scale of the momentum transfer. We take the production of a lepton pair combined with a diffractively produced particle in hadron collisions to discuss this. These fracture functions can be factorized further with twist-2 parton distribution functions and fragmentation functions if there are large energy scales involved. We perform explicit calculations at one loop to illustrate the factorization in the case that the diffractively produced particle is a photon. The complete perturbative coefficients are obtained. Evolution equations for both the integrated and transverse momentum dependent fracture functions are derived from our explicit results. They agree with expectations. These equations can be used for re-summations of large log terms in perturbative expansions. Our results also provide a connection between factorizations with fracture functions and those with twist-2 parton distribution and fragmentation functions.

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## Recent QCD results from the xFitter project

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We present recent results from the xFitter project—an open-source software framework for the determination of PDFs and the analysis of QCD physics. xFitter has been used for a variety of LHC studies including the measurement of the strange PDF, which we briefly summarize. Additionally, charged current DIS charm production provides a complementary perspective on  $s(x)$ . We make use of the xFitter tools to study the present  $s(x)$  constraints, and then use LHeC pseudo-data to infer how these might improve. Furthermore, as xFitter implements both Fixed Flavor and Variable Flavor number schemes, we can examine the impact of these different theoretical choices. This study provides a practical illustration of the many features of xFitter.

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## The fast reproduction of fully differential cross sections at NNLO in deep inelastic scattering at HERA using fast interpolation grids

**Authors:** Mark Sutton<sup>1</sup>; Klaus Rabbertz<sup>2</sup>; Alexander Yohei Huss<sup>3</sup>; Daniel Britzger<sup>4</sup>; Claire Gwenlan<sup>5</sup><sup>1</sup> University of Sussex (GB)<sup>2</sup> KIT - Karlsruhe Institute of Technology (DE)<sup>3</sup> CERN<sup>4</sup> Max-Planck-Institut für Physik München<sup>5</sup> University of Oxford (GB)**Corresponding Authors:** sutt@cern.ch, c.gwenlan1@physics.ox.ac.uk, alexander.yohei.huss@cern.ch, klaus.rabbertz@cern.ch

The APPLgrid and fastNLO projects provide a fast and flexible way to reproduce the results of perturbative QCD cross section calculations with any input PDF, renormalisation or factorisation scale, and different values for the strong coupling constant. Recent developments in the generation of fast interpolation grids using the DIS process with the NNLOJET generator through the standardised interface to the interpolation grids are reported. Results using precision interpolations grids for a number of jet production processes at HERA are presented and an exemplary application – that of a determination of the strong coupling constant,  $\alpha_s(M_Z)$ , in next-to-next-to-leading order QCD from inclusive jet cross section data in electron-proton collisions is presented.

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## Recent developments with APPLfast project for fully differential NNLO cross sections at the LHC and the distribution of fast interpolation grids

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Fast interpolation grid technology provides a fast and flexible way to reproduce the results of perturbative QCD cross section calculations with any input PDF, choice of scales, or strong coupling. Recent developments in the APPLfast interface between the NNLOJET QCD calculation with both APPLgid and fastNLO are reported including the release of development versions of grids for QCD cross sections at the LHC including jet production, and Z production at high ET. The ploughshare utility, used as the standard source for the distribution of the NNLO APPLfast grids is also discussed.

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## A QCD analysis for nuclear PDFs at NNLO

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In this talk, a new QCD analysis for nuclear parton distribution functions (nPDFs) at next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) will be presented. The framework of the analysis, including the form of the parametrisation as well as the included DIS datasets, will be discussed. The results of this QCD analysis will be compared to the existing nPDF sets and to the fitted data. The presented framework is based on an open-source tool, xFitter, which has been modified to be applicable also for a nuclear PDF analysis. The required modifications will be covered as well. Finally, an outlook for the next developments of the QCD analysis for nuclear PDFs will be given.

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## Constraints for nuclear PDFs from the LHCb D-meson data

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We quantify the impact of LHCb D-meson measurements at  $\sqrt{s} = 5$  TeV on the EPPS16 and nCTEQ15 nuclear PDFs. In our study, the theoretical description of D-meson production is based on the recently developed SACOT- $m_T$  variant of the general-mass variable-flavour-number formalism, and the impact on PDFs is estimated via profiling methods. We pay a special attention on the theoretical uncertainties known to us, and are led to exclude the  $p_T < 3$  GeV region from our main analysis. The LHCb data can be accommodated well within EPPS16/nCTEQ15, and the data provide stringent constraints on the gluons at the shadowing/antishadowing regions. No evidence of non-linear effects beyond standard DGLAP evolution is found even if the full kinematic region down to zero  $p_T$  is considered.

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## Parton distribution functions from lattice QCD

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Parton distribution functions (PDFs) are important quantities that characterize the structure of hadrons at high energy. Calculating them from first principles have been a long standing challenge in hadron physics and particle physics. In the past few years, rapid progress has been made in directly computing PDFs from lattice QCD. In this talk, I will summarize the current status of lattice calculation of PDFs. The state-of-the-art lattice results on nucleon PDFs have shown a reasonable agreement with phenomenological results extracted from the experimental data.

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## Extracting the Neutron Structure Function from Global DIS Data

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The CJ (CTEQ-Jefferson Lab) collaboration provides a global fit of parton distribution functions with a special emphasis on the large  $x$  region. The latest CJ15 global analysis implemented deuteron nuclear corrections at the parton level, and included data that were sensitive specifically to the neutron. These nuclear corrections allow for a calculation of the  $F_2$  structure functions of the proton, deuteron, and neutron from PDFs. In this work we re-estimated the uncertainties in the DIS  $F_2$  data utilized in CJ15, and collected an extended set of existing high-precision, small  $Q^2$ , large  $x$  DIS data from JLab 6 GeV experiments. We employed the CJ15 calculation to remove nuclear effects from deuteron data where the proton was available from the same experiment, and thereby constructed a global data set for the  $F_2$  neutron structure function. In this talk we will present the extracted  $F_2$  neutron data sets, as well as select applications such as a new evaluation of the GSR sum rule, and a new neutron excess correction factor.

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## nCTEQ PDFs and the strange PDF at LHC

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Extraction of the strange quark PDF is a long standing puzzle. We use nCTEQ nPDFs with uncertainties to examine W/Z production at the LHC

and try to study both the nuclear corrections and the flavor differentiation. This complements the information from neutrino-DIS data. Additionally, we look ahead to future facilities such as EIC, LHeC, and LHC upgrades and use a new tool, PDFSense, to estimate the impact.

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## Measurement of photon production at ATLAS

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The production of prompt isolated photons at hadron colliders provides stringent tests of perturbative QCD and can be used to evaluate probability density functions of partons in the proton. In this talk, we present the measurements of the isolated-photon plus two jets and the inclusive isolated-photons cross sections, both measured using proton-proton collision data collected by the ATLAS experiment at  $\sqrt{s}=13$  TeV. A ratio of photon cross sections at  $\sqrt{s}=8$  and  $\sqrt{s}=13$  TeV will also be presented. The results are compared with state-of-the-art theory predictions, indicating several interesting discrepancies.

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## ATLAS Jet Measurements for PDFs and their Uncertainties

**Author:** ATLAS Collaboration<sup>None</sup>

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Jet measurements play an essential role in PDF fits and the available measurements will be briefly summarized. The primary experimental uncertainties in these measurements are the knowledge of the jet energy scale and resolution. The analyses used to evaluate these uncertainties will be described and how they are combined to form the set of uncertainties that dominate these measurements. How these uncertainties should be correlated between ATLAS measurements and those of other experiments in PDF fits will be discussed. Estimated projections towards higher luminosity will also be briefly discussed.

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## Differential jet cross sections at the CMS experiment

**Author:** CMS Collaboration<sup>None</sup>

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We present measurements of differential jet cross sections over a wide range in transverse momenta from inclusive jets to multi-jet final states. Studies on the impact that these measurements have on the determination of the strong coupling  $\alpha_s$  as well as on parton density functions are reported.

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## Charm production in charged current deep inelastic scattering at HERA

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Charm production in charged current deep inelastic scattering has been measured for the first time in  $e^\pm p$  collisions, using data collected with the ZEUS detector at HERA, corresponding to an integrated luminosity of  $358 \text{ pb}^{-1}$ . Results are presented separately for  $e^+p$  and  $e^-p$  scattering at a centre-of-mass energy of  $\sqrt{s} = 318 \text{ GeV}$  within a kinematic phase-space region of  $200 \text{ GeV}^2 < Q^2 < 60000 \text{ GeV}^2$  and  $y < 0.9$ , where  $Q^2$  is the squared four-momentum transfer and  $y$  is the inelasticity of deep inelastic scattering. The measured cross sections of electroweak charm production, although not statistically significant, are consistent with expectations.

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## Measurement of W and Z boson production at ATLAS

**Author:** ATLAS Collaboration<sup>None</sup>

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Precision measurements of the production cross sections of W and Z bosons in proton-proton collisions provide stringent tests of perturbative QCD and yield important information about the parton distribution functions (PDFs) for quarks within the proton. We report measurements of fiducial integrated and differential cross sections for inclusive  $W^+$ ,  $W^-$  and Z boson production, analysed in the electron and muon decay channels, using data collected at center-of-mass energies of 2.76 and 5.02 TeV. The measurement of the  $W^+$  and  $W^-$  cross sections, in bins of the absolute lepton rapidity, and the associated charge asymmetry are also presented. The study is performed using data collected at  $\sqrt{s} = 8 \text{ TeV}$ . If available, a measurement of the transverse momentum distribution of Drell-Yan lepton pairs, performed using 13 TeV data, will also be reported. The measurements are compared with (next-to-)next-to-leading-order QCD cross-section calculations.

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## Impact of LHC top-quark pair measurements to CTEQ-TEA PDF analysis

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Detailed studies have been carried out on the impact of top pair production data from the LHC on the gluon PDF, in the context of the CTEQ-TEA global PDF fit. The data includes single differential distributions from ATLAS at and double differential distributions from CMS, both at 8 TeV. The relative impact of different physical observables related to top quark production was considered. All

analyses have been carried out at NNLO using fastNNLO tables constructed by the authors of the NNLO top production cross section.

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### Production of $W^+W^-$ and $t\bar{t}$ pairs via photon-photon processes in proton-proton scattering

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We discuss the production of  $W^+W^-$  pairs and  $t\bar{t}$  quark-antiquark pairs in proton-proton collisions induced by two-photon fusion including, for a first time, transverse momenta of incoming photons. The unintegrated inelastic fluxes (related to proton dissociation) of photons are calculated based on modern parametrizations of deep inelastic structure functions in a broad range of  $x$  and  $Q^2$ .

We focus on processes with single and double proton dissociation. Highly excited remnant systems hadronize producing particles that can be vetoed in the calorimeter. We calculate the associated effective gap survival factors. We observe approximate factorisation:  $S_{R,DD} \approx S_{R,SD}^2$  when imposing rapidity veto. For the  $W^+W^-$  final state, the remnant fragmentation leads to a taming of the cross section when the rapidity gap requirement is imposed. Also for  $t\bar{t}$  quark-antiquark pairs such a condition reverses the hierarchy observed for the case when such condition is taken into account. Our results imply that for the production of such heavy objects as  $t$  quark and  $\bar{t}$  antiquark the virtuality of the photons attached to the dissociative system are very large ( $Q^2 < 10^4 \text{ GeV}^2$ ).

1. M. Luszczak, L. Forthomme, W. Schafer, A. Szczurek, arXiv:1810.12432; JHEP (2019) in print.
2. L. Forthomme, M. Luszczak, W. Schafer, A. Szczurek, Phys.Lett. B789 (2019) 300-307.
3. M. Luszczak, W. Schafer, A. Szczurek, JHEP 1805 (2018) 064.

## WG1:Structure Functions and Parton Densities / 348

### Heavy-flavour production processes relevant for PDF fits

**Authors:** Maria Vittoria Garzelli<sup>1</sup>; Sergey Alekhin<sup>2</sup>; Giuseppe Bevilacqua<sup>3</sup>; Adam Kardos<sup>4</sup>; S. Moch<sup>2</sup>; Oleksandr Zenaiev<sup>2</sup>

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We present recent developments in the theoretical description of processes leading to the production of heavy flavours, which, together with the most recent experimental data, are of interest for further constraining present fits of Parton Distribution Functions. We compare different approaches, and, for selected cases, we show the impact of using the MSbar scheme as an alternative to the on-shell scheme for renormalizing the heavy-quark masses.

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## **PB TMD distributions from fits to DIS precision data**

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We present a new determination of Transverse Momentum Dependent (TMD) parton distributions applying the Parton Branching method. The PB TMDs are obtained from fits to precision DIS data using DGLAP splitting functions at leading and higher order. In addition the CCFM splitting function will be applied to include small  $x$  effects. Applications of these new TMD distributions will be discussed.

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## **PDFs with theoretical uncertainties**

**Authors:** Cameron Voisey<sup>1</sup>; NNPDF collaboration<sup>None</sup>

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A significant limitation in current PDF determinations is that the impact of theoretical uncertainties is not systematically accounted for. I will present a framework for the inclusion of additional sources of theoretical uncertainty in PDF fits, and present the first study of the effects of Missing Higher Order Uncertainties, which are estimated using scale variations, on PDFs in the context of the NNPDF approach.

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## **Combined analysis of collinear PDFs and FFs**

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Global QCD analyses of PDFs and fragmentation functions (FFs) have traditionally been performed in completely independent studies. The JAM Collaboration, in contrast, has embarked on a systematic program to simultaneously extract PDFs and FFs from a wide range of processes using Monte Carlo methods. In this talk I will report new results on spin-averaged and spin-dependent PDFs and FFs from a simultaneous analysis of the world's high-energy scattering data, including for the first time data from unpolarized and polarized semi-inclusive DIS reactions

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## Current status of spin-dependent parton distributions

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Since the first measurements by the EMC that triggered the so-called “proton spin crisis”, many experimental programs have been carried out to understand the spin of the nucleon in terms of its partonic degrees of freedom. It is still today an active research area in QCD phenomenology, with ongoing programs at COMPASS, RHIC and Jefferson Lab measuring spin observables to be analyzed within a QCD global analysis framework. In this talk I will review existing global QCD analyses of spin-dependent PDFs from various groups around the world.

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## First determination of nuclear PDFs using Neural Networks

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We present a first determination of the nuclear parton distribution functions (nPDF) based on the NNPDF methodology: nNNPDF1.0. This nPDF analysis is based on neutral-current deep-inelastic structure function data, and is performed using NNLO QCD calculations with heavy quark mass effects. For the first time in the NNPDF fits, the  $\chi^2$  minimisation is carried out using stochastic gradient descent with reverse-mode automatic differentiation (backpropagation) by means of the TensorFlow library. The nNNPDF1.0 set satisfies the boundary condition that for  $A = 1$  the proton PDFs (NNPDF3.1) and their uncertainties must be reproduced, which imposes significant constraints specially for low- $A$  nuclei. We validate the robustness of the fitting methodology by means of closure tests, assess their perturbative stability, and compare our results with other recent nPDF analyses. We find that the evidence for nuclear PDF modifications in heavy nuclei is at most at the one-sigma level. Our results represent the first-ever nPDF determination obtained using a methodology consistent with that of state-of-the-art proton PDF fits, and provide the backbone for subsequent global nPDF analyses which also include data from proton-nucleus collisions.

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## Large-log resummation in the VFN scheme of the DIS heavy-quark production

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We consider impact of the large-log resummation emerging at the large momentum transfer  $Q$  in the variable-flavour-number (VFN) scheme description when it is applied to analysis of the semi-inclusive DIS production of the charm and bottom quarks. Matching of the VFN scheme with the fixed-flavour-number (FFN) one at small  $Q$  is also discussed and phenomenological relevance of these two approaches at various  $Q$  is compared.

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## On the Consistent Use of Scale Variations in PDF Fits and Predictions

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We present an investigation of the theoretical uncertainties in parton distribution functions (PDFs) due to missing higher-order corrections in the perturbative predictions used in the fit, and their relationship to the uncertainties in subsequent predictions made using the PDFs. We consider in particular the standard approach of factorization and renormalization scale variation, and derive general results for the consistent application of these at the PDF fit stage. To do this, we use the fact that a PDF fit may be recast in a physical basis, where the PDFs themselves are bypassed entirely, and one instead relates measured observables to predicted ones. In the case of factorization scale variation we find that in various situations there is a high degree of effective correlation between the variation in the fit and in predicted observables. In particular, including such a variation in both cases can lead to an exaggerated theoretical uncertainty. More generally, a careful treatment of this correlation appears mandatory, at least within the standard scale variation paradigm. For the renormalization scale, the situation is less straightforward, but again we highlight the potential for correlations between related processes in the fit and predictions to enter at the same level as between processes in the fit or prediction alone.

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## Status of the measurement of the flavor dependence of light-quark sea in the SeaQuest experiment

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E-906/SeaQuest is a fixed-target experiment at Fermilab designed to measure the flavor dependence of the light-quark sea in nucleons at high Bjorken- $x$ . Previous experiments have shown a surprising drop of the  $\bar{d}/\bar{u}$  ratio at high Bjorken- $x$  and SeaQuest was designed to extend the measurement to higher Bjorken- $x$  with a 120 GeV proton beam. The Drell-Yan process is used as a probe of nucleon's sea quark distributions using liquid hydrogen and deuterium targets. By detecting forward Drell-Yan events ( $x_F > 0$ ) the anti-quark distribution of the nucleon can be measured. Data collection has been completed and extensive studies to determine the various contributions of the dimuon yields are being carried out. The status of the analysis towards a  $\bar{d}/\bar{u}$  measurement up to Bjorken- $x \sim 0.45$  will be reported.

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### The LHC experimental data in the CT18 global QCD analysis

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The sheer volume of the LHC experimental data sensitive to the hadronic structure presents a formidable challenge for the global QCD analysis. In the CT18 global analysis, we implemented new approaches to streamline identification of the LHC experiments that have the greatest promise for constraining parton distributions in the nucleon at the next-to-next-to-leading order accuracy. Toward this goal, we augment the global PDF fits with fast data surveys in the Hessian approach using new computer programs ePump and PDFsense, as well as with detailed Lagrange Multiplier studies. A combination of these techniques delivers a detailed map of constraints on the hadron structure from multiple experiments.

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### Efficient interpolation and evolution of parton distribution functions

**Authors:** Markus Diehl<sup>1</sup>; Riccardo Nagar<sup>2</sup>; Frank Tackmann<sup>3</sup>

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We present an efficient numerical solution of the DGLAP equations for single and double parton distribution functions (PDFs and DPDs), based on the Chebyshev interpolation of these functions. For PDF evolution, our method allows for a higher numerical accuracy using a considerably smaller number of grid points compared to other methods. The DPD evolution is realized using an affordable number of grid points, and allows for two independent renormalization scales for the two partons. Both methods include NNLO DGLAP kernels and flavor matching.

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**Using Forward-backward Drell-Yan Asymmetry in PDF Determinations****Author:** Juri Fiaschi<sup>1</sup>**Co-authors:** Elena Accomando<sup>2</sup>; Stefano Moretti<sup>3</sup>; Francesco Hautmann<sup>4</sup>; xFitter developers<sup>1</sup> *Westfälische Wilhelms-Universität Münster*<sup>2</sup> *Southampton University*<sup>3</sup> *Science and Technology Facilities Council STFC (GB)*<sup>4</sup> *University of Antwerp (BE)***Corresponding Authors:** fiaschi@uni-muenster.de, francesco.hautmann@desy.de, stefano.moretti@cern.ch, e.accomando@soton.ac.uk

Measurements of the forward-backward asymmetry in neutral-current Drell-Yan di-lepton production have primarily been used for determinations of the weak mixing angle  $\theta_W$ .

We investigate the possibility of using the reconstructed forward-backward asymmetry to place constraints on the determination of the parton distribution functions (PDFs). We perform this study using the open-source QCD platform xFitter. We explore the constraints on the flavour structure of quark distributions and the role of appropriate selection cuts on lepton rapidities both near the Z-boson peak and away from it.

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**Recent developments from APFEL++****Author:** Valerio Bertone<sup>1</sup><sup>1</sup> *NIKHEF***Corresponding Author:** valerio.bertone@cern.ch

In this contribution I will present the latest developments concerning the APFEL++ program. APFEL++ is a C++ rewriting of the Fortran 77 evolution code APFEL, it is based on a completely new code design and guarantees a better performance along with an optimal memory management. This makes APFEL++ suitable for a wide range of tasks: from the solution of the DGLAP evolution equations to the computation of deep-inelastic-scattering (DIS) and single-inclusive-annihilation cross sections. Also more complex computations, like semi-inclusive DIS and Drell-Yan cross sections, are easily implementable/implemented in APFEL++. In this talk I will discuss some recent results including the use of APFEL++ to implement transverse-momentum resummation applied to Drell-Yan and semi-inclusive DIS.

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**Testing collinear factorization in a spectator model with mass corrections****Author:** Juan Guerrero<sup>1</sup>**Co-author:** Alberto Accardi<sup>2</sup><sup>1</sup> *Hampton University/Jefferson Lab*<sup>2</sup> *Hampton U. and Jefferson Lab*

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In perturbative QCD, the masses of the hadrons involved in high energy reactions can usually be neglected. However, in the case of production of Kaons in electron-proton collisions at low (and not so low) beam energies this may not be a good approximation. In particular, a recent proposal to include hadron masses in theoretical calculations shows how these Hadron Mass Corrections can explain a large discrepancy observed in measurements performed at the HERMES and COMPASS experiments. In this talk, I will present spectator model calculations designed to test the range of validity of the approximations needed in the proposed factorization scheme.

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## Determination of proton parton distribution functions using ATLAS data

**Author:** ATLAS Collaboration<sup>None</sup>

We present a fit to determine parton distribution functions (PDFs) using inclusive  $W^\pm$  and  $Z/\gamma^*$  boson and top-antitop production measurements from ATLAS in combination with deep-inelastic scattering data from HERA. The ATLAS  $W$  and  $Z$  boson data exhibit sensitivity to the valence quark distributions and the light quark sea composition, whereas the top-quark pair production data have sensitivity to the gluon distribution. The impact of the top-antitop production data is increased by fitting several distributions simultaneously. To achieve this, full information on the systematic and statistical correlations between data points in different spectra is required. The information on statistical correlations, both between bins and between the different top spectra are made available, and the impact of the top-quark pair production data using these correlations is assessed.

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## Recent PDFs results from top quark pair and single top t-channel differential cross sections in CMS

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Differential measurements of top quark pair ( $t\bar{t}$ ) and single top quark (t-channel) production cross sections are presented using data collected by CMS. The cross sections are measured as a function of various kinematic observables of the top quarks and the jets and leptons of the event final state. The results are confronted with precise theory calculations. For the first time, multidifferential  $t\bar{t}$  cross sections are presented and used to constrain simultaneously the top quark pole mass,  $\alpha_S$ , and PDFs.

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## Parton Branching TMDs with angular ordering condition and their application to Z boson $p_T$ spectrum

**Authors:** Aleksandra Anna Lelek<sup>1</sup>; Hannes Jung<sup>2</sup>; Francesco Hautmann<sup>3</sup>; Lissa Keersmaekers<sup>4</sup>; Aron Mees van Kampen<sup>4</sup>

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We study the effects of angular ordering constraint on collinear and transverse momentum dependent (TMD) parton distributions functions (PDFs) obtained within the Parton Branching (PB) method. We compare it with virtuality and  $p_t$  ordering definitions. We study the effect of ordering choice on predictions for Z boson  $p_t$  spectrum, especially at low  $p_t$  and we demonstrate the advantage of the angular ordering. We compare the PB formalism with another existing and commonly used approaches as Kimber-Martin-Ryskin-Watt (KMRW) and Collins-Soper-Sterman (CSS). Especially, we identify the CSS Sudakov coefficients with the terms in the PB Sudakov form factor.

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## Results from proton-lead and fixed-target collisions at LHCb

**Author:** Katharina Mueller<sup>1</sup>

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In the last years the LHCb experiment established itself as an important contributor to heavy ion physics by exploiting some of its specific features.

Production of particles, notably heavy flavour states, can be studied in p-p, p-Pb and Pb-Pb collisions at LHC energies in the forward rapidity region (pseudorapidity between 2 and 5), providing measurements which are highly complementary to the other LHC experiments. Moreover, owing to its forward geometry, the detector is also well suited to study fixed-target collisions, obtained by impinging the LHC beams on gas targets with different mass numbers. This configuration allows to study pA collisions at the relatively unexplored scale of  $\sqrt{s_{NN}} \sim 100$  GeV, and can also provide valuable inputs to cosmic ray physics.

An overview of the unique measurements obtained so far by the LHCb ion program will be given, with emphasis on the most recent results.

**WG2: Small-x and Diffraction / 54**

## Recent ALICE results on coherent J/psi photoproduction in ultra-peripheral Pb-Pb collisions

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<sup>1</sup> *Petersburg Nuclear Physics Institut (RU)*

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The strong electromagnetic fields of Pb nuclei, accelerated at the LHC, can be used to measure photon-induced interactions in a new kinematic regime. Photon-induced processes are usually studied in ultra-peripheral Pb-Pb collisions where hadronic interactions are strongly suppressed. Coherent charmonium photoproduction is of particular interest since it is sensitive to poorly known gluon shadowing effects in target Pb ions. In this contribution, recent ALICE results on the coherent J/psi photoproduction in ultra-peripheral Pb-Pb collisions from LHC Run 2 will be presented. The implications for the study of nuclear gluon shadowing will be discussed. In addition projections for heavy vector meson photoproduction measurements in LHC Run 3 and 4 will be presented.

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## Soft QCD and Central Exclusive Production at LHCb

**Author:** Katharina Mueller<sup>1</sup>

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The forward acceptance of LHCb,  $2.0 < y < 5.0$ , provides complementary reach to the general purpose detectors at the LHC for the study of Soft QCD processes. In addition, the installation of a series of scintillating pad detectors (Herschel), bracketing the LHCb detector along the beamline, for Run 2 of the LHC, with dedicated triggers, has significantly enhanced LHCb's sensitivity to central exclusive production (CEP). Recent LHCb measurements of the pp inelastic cross-section, minimum bias properties, and particle production in CEP will be presented.

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## Photon-photon fusion measurements at ATLAS

**Authors:** ATLAS Collaboration<sup>None</sup>; Samira Hassani<sup>1</sup>

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Photon-photon fusion is a rare process at hadron and ion colliders. It is particularly interesting as a remarkably clean interaction with little (if any) remnant activity from the interacting particles. In this talk we present the status of photon-photon fusion measurements at the ATLAS detector, focussing on two types of analyses. In the first type of analysis, the ATLAS inner tracking detectors and calorimeters are used to define an interaction with little hadronic activity (so-called rapidity gaps). In the second, the ATLAS Forward Proton (AFP) detectors are used to tag intact protons from the photon-photon fusion process, that are scattered at small angles in diffractive and electromagnetic processes. These detectors can operate during standard high-luminosity LHC runs and collect large amounts of integrated luminosity. The AFP detectors and their performance during 2017 and 2018 operations will be presented.

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## Recent CMS and CMS-TOTEM results on diffraction

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Merged abstract

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## Recent CMS results on exclusive processes

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Merged abstract

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## Results and prospects with the CMS-TOTEM Precision Proton Spectrometer

**Author:** CMS Collaboration<sup>None</sup>

Merged abstract

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## Gradient corrections to the classical McLerran-Venugopalan model

**Author:** Douglas Wertepny<sup>1</sup>

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In the Color Glass Condensate framework the profile of the target is modelled by the saturation scale,  $Q_s(\vec{b})$ . In the literature it is commonly assumed that the length scale of the fluctuations of the saturation scale,  $l_{fluc.}$ , is large. One implication of this approximation is that the gluon dipole cannot couple to gradients of the saturation scale. Using the McLerran-Venugopalan (MV) model in the classical limit we find that there are two different ratios of relevance to the suppression of gradient corrections, the ratio of the length scale of the fluctuations to the quantum cutoff,  $\frac{1}{l_{fluc.}\Lambda_{QCD}}$ , and to the size of the gluon dipole,  $\frac{r_{dip.}}{l_{fluc.}}$ . In large system where  $\frac{1}{l_{fluc.}\Lambda_{QCD}} \ll 1$  the quantum scale successfully cuts off all the gradient corrections. In small systems or systems with large gradients,  $\frac{1}{l_{fluc.}\Lambda_{QCD}} \sim 1$ , the gradient expansion is controlled by the size of the gluon dipole,  $\frac{r_{dip.}}{l_{fluc.}}$ . We find that when  $\frac{r_{dip.}}{l_{fluc.}} \ll 1$  all but the second harmonic (quadrupole moment) are suppressed. This means that there is no justification for ignoring coupling to the gradients of the saturation scale. We finish by calculating the leading order gradient contribution to the classical McLerran-Venugopalan model for a gaussian distribution.

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## Forward Drell-Yan and backward jet production as a probe of the BFKL dynamics

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The forward Drell-Yan (DY) lepton pair production together with a backward jet is proposed as a new way to study the BFKL effects due to a large rapidity gap between the two systems. Predictions for



quantities to be measured are computed using the leading order DY impact factors and the BFKL kernel with a consistency condition which takes into account an important part of the next-to-leading order corrections.

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## Inclusive production of two rapidity-separated heavy quarks as a probe of BFKL dynamics

**Authors:** Andr e Dafne Bolognino<sup>1</sup>; Francesco Giovanni Celiberto<sup>2</sup>; Michael Fucilla<sup>None</sup>; Dmitry Ivanov<sup>None</sup>; Beatrice Murdaca<sup>None</sup>; Alessandro Papa<sup>3</sup>

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The inclusive photoproduction of two heavy quark–antiquark pairs, separated by a large rapidity interval, is proposed as a new channel for the manifestation of the Balitsky–Fadin–Kuraev–Lipatov (BFKL) dynamics. The extension to the hadroproduction case will also be discussed.

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## Diffraction PDF determination from HERA inclusive and jet data at NNLO QCD

**Authors:** Radek Zlebcik<sup>1</sup>; Daniel Britzger<sup>2</sup>; Stefan Schmitt<sup>1</sup>; Sergey Levonian<sup>1</sup>

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A new fit of diffractive parton distribution functions (DPDFs) to the HERA inclusive and jet data in diffractive deep-inelastic scattering (DDIS) at next-to-next-to-leading order accuracy (NNLO) is presented. The inclusion of the most comprehensive dijet cross section data, together with their NNLO predictions, provide enhanced constraints to the gluon component of the DPDF, which is of particular importance for diffractive PDFs. Compared to previous HERA fits, the presented fit includes the high-precision HERA-II data of the H1 collaboration, which corresponds to a 40-fold increase in luminosity for inclusive data (six-fold increase for jet data). In addition to the inclusive sample at nominal centre-of-mass energy  $\sqrt{s} = 319$ , inclusive H1 data at 252 and 225 GeV are included. The extracted DPDFs are compared to previous DPDF fits, and are used to predict cross sections for a large number of available measurements and different observables.

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## Diffractive Dijet Production and Wigner Distributions from the Color Glass Condensate

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We present results for the diffractive dijet production cross section in e+p collisions within the color glass condensate framework to leading logarithmic accuracy. The framework includes a spatially dependent McLerran-Venugopalan initial configuration at relatively large  $x$ , combined with explicit numerical solution of the JIMWLK equations. We focus in particular on the dependence of the dijet cross section on the relative angle between the nucleon recoiled momentum and the dijet transverse momentum, and compare to correlations between impact parameter and momentum in the gluon Wigner distribution which are related to the experimental dijet cross section[1]. We extract the magnitude of the elliptic modulation and determine its  $x$ -dependence, which is dominated by the growth of the proton with decreasing  $x$ . We also compare results to the IPSat model and a simple extension of it, which includes correlations between the dipole transverse separation vector and the impact parameter direction. Our results are presented in Ref.[2]

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## Unequal rapidity correlators in the dilute limit of JIMWLK

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Unequal rapidity correlations can be studied within the stochastic Langevin picture of JIMWLK evolution in the Colour Glass Condensate effective field theory. By evolving the classical field in the direct and complex conjugate amplitudes, the Langevin formalism can be used to study two-particle production at large rapidity separations. The evolution between the rapidities of the two produced particles can be expressed as a linear equation, even in the full nonlinear limit. In addition, the Langevin formalism for two-particle correlations reduces to a BFKL picture in the dilute limit and in momentum space, providing an interpretation of BFKL evolution as a stochastic process for colour charges.

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## Forward particle production: from trijet to NLO dijet

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Using the formalism of the light-cone wave function in perturbative QCD together with the hybrid factorization, we compute the cross-section for three (and two) particle production at forward rapidities in proton-nucleus collisions. We focus on the quark channel, in which the three produced partons – a quark accompanied by a gluon pair, or two quarks plus one antiquark – are all generated via two successive splittings starting with a quark that was originally collinear with the proton. The three partons are put on-shell by their scattering off the nuclear target, described as a Lorentz-contracted “shockwave”. By using the three-parton component of the quark light-cone wave function, together with the loop corrections, we can then present our progress on the computation of the next-to-leading order correction to the cross-section for the production of a pair of jets.

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## EPR paradox and quantum entanglement at sub-nucleonic scales

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In quantum mechanics, Einstein, Podolsky, and Rosen (EPR) formulated an apparent paradox of quantum theory in 1935. They considered two quantum mechanical systems were first brought to interaction, then later separated to large distance. A measurement of a physical observable in one system would have an immediate effect on the conjugate observable in the other system, even when they are causally disconnected. Therefore, EPR concluded that there is an inconsistency in the quantum theory. In the parton model formulated by Bjorken, Feynman, and Gribov, the partons inside of a nucleon are viewed as “quasi-free” particles when they are boosted into the infinite momentum frame, where the parton probed by the virtual photon is causally disconnected from the rest of the nucleon. Since the parton and the rest of the nucleon have to form a color-singlet state due to confinement, we encounter the EPR paradox at sub-nucleonic states for the first time. In this work we propose a resolution of this apparent paradox via quantum entanglement. We test this idea by measuring the entanglement entropy of the system using data from proton-proton collisions at the Large Hadron Collider, and our results provide a strong direct indication of quantum entanglement at sub-nucleonic scales.

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## BFKL Pomeron loops in photoproduction and hadroproduction of J/psi at large transverse momenta

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We analyze contributions to diffractive photoproduction and inclusive hadroproduction of J/psi with large transverse momentum coming from cut BFKL Pomeron loops in the corresponding cross sections. In this framework the diffractive photoproduction is described by the diffractive cut of two Pomeron exchange. For the hadroproduction we consider a gluon to J/psi transition mediated by an exchange of two gluons with a partonic target. After inclusion of the small x evolution, the latter process may be described as an exchange of two cut BFKL Pomerons, and it is related to the diffractive photoproduction. We study in detail properties of the diffractive cut and of the double

cut of the Pomeron loop. The obtained results are compared to experimental data on diffractive J/psi photoproduction at HERA and to the J/psi hadroproduction data from the LHC.

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## Hard diffraction and fluctuations in small-x evolution

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We present new quantitative predictions for the distribution of the total invariant mass produced diffractively in dipole-nucleus scattering at large relative rapidity. We show that the shape of this distribution is intimately related to the properties of the fluctuations in the small-x partonic evolution. This observable can potentially be measured at a future electron-ion collider.

*Based on Phys.Rev.Lett. 121 (2018) no.8, 082001; Phys.Rev. D98 (2018) no.3, 034021 and work in progress.*

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## Exclusive $\rho(770)$ photoproduction at HERA

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Exclusive photoproduction of  $\rho(770)$  vector mesons is studied using the H1 detector at HERA. A sample of about 700000 decays  $\rho \rightarrow \pi^+\pi^-$  was collected in the years 2006-2007, using the H1 fast track trigger. It corresponds to an integrated luminosity of  $1.3 \text{ pb}^{-1}$ . The sample is used to study cross-sections as a function of the invariant mass  $m_{\pi\pi}$  of the decay pions, the photon-proton collision energy  $W$  and the momentum transfer at the proton vertex  $t$ . The phase-space restrictions are  $0.5 < m_{\pi\pi} < 1.3 \text{ GeV}$ ,  $20 < W < 80 \text{ GeV}$  and  $|t| < 1.5 \text{ GeV}^2$ . Reactions where the proton stays intact are statistically separated from those where the proton dissociates to a low-mass hadronic system. The observed cross-section dependencies are parameterized using fits and are compared to expectations from phenomenological models.

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## Towards a determination of the low x gluon via exclusive HVM production

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I will discuss how the theoretical stability of exclusive HVM photoproduction has been improved through a systematic taming of the known  $\overline{MS}$  coefficient functions by accounting for a not so power suppressed correction encoded within a ' $Q_0$ ' cut. The phenomenological implications of this will be emphasised allowing for, ultimately, the inclusion of the exclusive data into a global fitter framework to provide constraints on the small  $x$  gluon. Time permitting, I will also present preliminary results for exclusive HVM electroproduction.

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## The Tensor Pomeron and Low- $x$ Deep Inelastic Scattering

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The tensor-pomeron model is applied to low- $x$  deep-inelastic lepton-nucleon scattering and photoproduction. We consider c. m. energies in the range 6 - 318 GeV and  $Q^2 < 50 \text{ GeV}^2$ . In addition to the soft tensor pomeron, which has proven quite successful for the description of soft hadronic high-energy reactions, we include a hard tensor pomeron. We also include  $f_2$ -reggeon exchange which turns out to be particularly relevant for real-photon-proton scattering at c. m. energies in the range up to 30 GeV. The combination of these exchanges permits a description of the absorption cross sections of real and virtual photons on the proton in the same framework. In particular, a detailed comparison of this two-tensor-pomeron model with the latest HERA data for  $x < 0.01$  is made. Our model gives a very good description of the transition from the small- $Q^2$  regime where the real or virtual photon behaves hadron-like to the large- $Q^2$  regime where hard scattering dominates. Our fit allows us, for instance, a determination of the intercepts of the hard pomeron as  $1.3008^{(+73)}_{(-84)}$ , of the soft pomeron as  $1.0935^{(+76)}_{(-64)}$ , and of the  $f_2$  reggeon. We find that in photoproduction the hard pomeron does not contribute within the errors of the fit. We show that assuming a vector instead of a tensor character for the pomeron leads to the conclusion that it must decouple in real photoproduction.

arXiv:1901.08524

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## Non-eikonal corrections to multi-particle production in the CGC

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We consider the non-eikonal corrections to particle production in the Color Glass Condensate originating from relaxing the shockwave approximation for the target which takes into account its finite longitudinal thickness. We derive a modified expression of the Lipatov vertex that accounts for these corrections. This expression is employed to compute single, double and triple gluon production in the Glasma graph limit valid for the scattering of two dilute objects, at all orders in the expansion in the number of colors. We justify and generalize previous results, and discuss the possible implications of these non-eikonal corrections on particle correlations.

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## Small-x physics in ultraperipheral collisions at the LHC

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We argue that ultraperipheral collisions at the LHC allow to study effects color fluctuations (CF) of the strength of interaction of photon in large and small size configurations. We make predictions for the distribution over the number of wounded nucleons  $v$  in the inelastic photon-nucleus scattering and in events with charm production. We show that CFs lead to a dramatic enhancement of this distribution at  $v=1$  and large  $v>10$ . We also study the implications of different scales and CFs in the photon wave function on the total transverse energy  $\Sigma_{ET}$  and neutron production in inelastic  $\gamma A$  scattering with different triggers. Our predictions can be tested in proton-nucleus and nucleus-nucleus ultraperipheral collisions at the LHC and will help to map CFs, whose first indications have already been observed at the LHC.

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## On correlators of Reggeon fields in high energy QCD

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We discuss Dyson-Schwinger hierarchy of the equations for the correlators of reggeized gluon fields in the framework of Lipatov's high energy QCD effective action formalism. The non-linear corrections to the two-field correlators are presented and correspondence between the correlators of reggeized gluon fields and Wilson line operators of longitudinal gluon fields is established, the connection between the JIMWLK-Balitsky formalism and Lipatov's effective action approach is also considered.

We demonstrate mechanisms of the reggeization breaking and present example of the calculations of an one-loop subleading vertex of the reggeized gluons interactions which is responsible for this violation of the gluon's propagator reggeization.

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## Measurements of single diffraction using the ALFA forward spectrometer at ATLAS

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Inclusive single diffractive dissociation ( $pp \rightarrow pX$ ) is studied using data collected by the ATLAS experiment at the LHC. The intact proton is reconstructed and measured in the ALFA forward spectrometer, while charged particles from the dissociative system ( $X$ ) are reconstructed and measured using the ATLAS inner tracking detector and calorimeters. Differential cross sections are presented as a function of the proton fractional momentum loss, the four-momentum transfer squared, and the size of a rapidity gap measured from the edge of the ATLAS calorimeters. The results are interpreted in the framework of Regge phenomenology.

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## One-loop corrections to multiscale effective vertices in the EFT for Multi-Regge processes in QCD

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The gauge-invariant EFT for Multi-Regge processes in QCD [1,2] has been introduced to facilitate the computation of NLO corrections in the BFKL approach. The main difficulty in this approach is the appearance of rapidity divergences (RDs) in loop integrals, which are not regularized by dimensional regularization and require separate regularization, see Ref. [3] for more details. We will discuss the technique of calculation of one-loop quantities with more than one scale of virtuality in this approach. New results to be presented include:

- 1) general analysis of the conditions of appearance of RDs,
- 2) results for rapidity-divergent scalar integrals with two scales of virtuality,
- 3) one-loop corrections to effective vertices of scattering of virtual photon on Reggeized quark and one-loop correction for the Green's function with external Reggeized and QCD gluons with insertion of gauge-invariant operator  $F_{\mu\nu}F^{\mu\nu}$ . Last results will be applied in the NLO calculation of DIS structure functions in the Parton Reggeization Approach [4,5].

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## Differential and total cross sections of high energy proton-proton scattering in holographic QCD

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We investigate the high energy proton-proton scattering in the framework of holographic QCD, which is an effective approach to QCD constructed based on the AdS/CFT correspondence. In our model setup, the involved nonperturbative partonic dynamics is described by the Pomeron exchange, which is realized applying the Reggeized spin 2 particle propagator together with the proton gravitational form factor obtained from the bottom-up AdS/QCD model. Our model includes only three adjustable parameters, and we determine them by fitting both the differential and total cross sections simultaneously to the experimental data, focusing on the Regge regime. The resulting differential and total cross sections are consistent with the data, including the ones recently measured at  $\sqrt{s} = 13$  TeV by the TOTEM collaboration at the LHC. Our results imply that the present framework works well in the considered TeV scale, and further applications to other high energy scattering processes, in which the involved strong interaction can be approximated by the Pomeron exchange, are possible. This work will be presented as a paper soon.

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## Production of $J/\psi$ quarkonia in color evaporation model based on $k_T$ -factorization

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We discuss the  $k_T$ -factorization approach for  $c\bar{c}$  production in the context of the color evaporation model for  $J/\psi$  meson production. We use a new approach to color evaporation model (CEM) for quarkonium production. The production of  $c\bar{c}$  pairs is performed within  $k_T$ -factorization approach using different unintegrated gluon distribution functions (UGDF) from the literature. We include all recent improvements to color evaporation model. We cannot describe simultaneously mid and forward rapidity data measured at the LHC when using the KMR UGDF based on collinear MMHT2014lo PDF with the same normalization parameter. Furthermore we get somewhat too hard distribution in

$J/\psi$  transverse momentum. Correcting the standard KMR-MMHT2014lo distributions for saturation effects at small values of  $x$  improves  $J/\psi$  rapidity distributions. When using CT14lo collinear PDFs a better agreement with the LHCb data can be achieved without clear need for implementing saturation effects. We get poor description of the large transverse momentum distributions of  $J/\psi$  with the JH-2013 CCFM-based UGDF. Here explicit inclusion of  $2 \rightarrow 3$  processes considerably improves the situation. Similar effects are discussed in the context of the KMR UGDF. More details of the studies can be found in Ref.[1].

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## Searching for odderon in exclusive reactions: $pp \rightarrow ppp\bar{p}$ , $pp \rightarrow pp\phi\phi$ and $pp \rightarrow pp\phi$

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Recent results of the TOTEM collaboration [1] suggest that the odderon exchange can be responsible for a disagreement of theoretical calculations and the TOTEM data [2] for elastic  $pp$  scattering. It is premature to draw conclusions. Here we present our recent studies for three different processes in  $pp$  collisions where the odderon may show up. We apply recently proposed tensor-pomeron and vector-odderon model for soft high-energy processes [3].

The first study concerns CEP of  $p\bar{p}$  pairs [4]. Here the odderon exchange may lead to asymmetries for proton and antiproton. It seems, however that the effect from subleading reggeons competes with the odderon. In the process  $pp \rightarrow pp\phi\phi$  [5] the odderon does not couple to protons. For the  $pp \rightarrow pp\phi$  reaction [6] the odderon-pomeron fusion is an alternative to the photon-pomeron fusion. We consider also other subleading processes to understand the WA102 experimental data [7] and check room left for the odderon exchange. The interference of photoproduction and odderon contributions can explain azimuthal correlations between protons. Upper limit for odderon exchange is obtained. Predictions for the LHC will be presented.

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**WG2: Small-x and Diffraction / 110****Measurement of the Psi(2S) to J/Psi cross section ratio in photoproduction with the ZEUS detector at HERA****Author:** Alessia Bruni<sup>1</sup><sup>1</sup> *Universita e INFN, Bologna (IT)***Corresponding Author:** alessia.bruni@bo.infn.it

The exclusive photoproduction reaction  $\gamma p \rightarrow \psi(2S)p$  has been studied with the ZEUS detector in  $ep$  collisions at HERA using an integrated luminosity of  $350 \text{ pb}^{-1}$ , in the kinematic range  $30 < W < 180 \text{ GeV}$ ,  $Q^2 < 1 \text{ GeV}^2$ ,  $|t| < 5 \text{ GeV}^2$ , where  $W$  is the photon-proton centre-of-mass energy,  $Q^2$  - the photon virtuality and  $t$  -four-momentum transfer at the proton vertex. The  $\psi(2S)$  mesons were identified via the decay channels:  $\psi(2S) \rightarrow \mu^+\mu^-$  and  $J/\psi\pi^+\pi^-$  with  $J/\psi \rightarrow \mu^+\mu^-$ . The ratio of the production cross sections  $R = \sigma(\psi(2S))/\sigma(J/\psi)$  was measured as a function of  $W$  and compared to predictions of the perturbative QCD.

**WG2: Small-x and Diffraction / 227****Transverse Spin Asymmetries in the  $p^\uparrow p \rightarrow p\pi^0 X$  Process at STAR****Author:** Christopher Dilks<sup>1</sup><sup>1</sup> *Duke University*

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A significant sample of  $p^\dagger p \rightarrow p\pi^0 X$  events have been observed at STAR in  $\sqrt{s} = 200$  GeV transversely polarized  $pp$  collisions, where an isolated  $\pi^0$  is detected in the forward pseudorapidity range  $2.65 < \eta < 3.9$  along with the forward-going proton  $p$ , which scatters with a near-beam forward pseudorapidity into Roman Pot detectors. The sum of the  $\pi^0$  and the scattered proton energies is consistent with the incident proton energy of 100 GeV, indicating that no further particles are produced in this direction. It is postulated that the forward incident proton may have fluctuated into a  $p + \pi^0$  system, with an angular momentum correlated with the initial proton spin. The backward-going proton interacts with the  $p + \pi^0$  system, which then separates such that the  $\pi^0$  has a transverse momentum of  $\sim 2$  GeV/ $c$  and the proton has a transverse momentum of  $\sim 0.2$  GeV/ $c$ , while the backward proton shatters into the remaining particles  $X$ , all in the backward direction. Correlations between the  $\pi^0$  and scattered proton will be presented, along with single spin asymmetries which depend on the azimuthal angles of both the pion and the proton. This is the first time that spin asymmetries have been explored for this process, and a model to explain their azimuthal dependence is needed.

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## Searches for Dark Matter at the LHC in forward proton mode

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We analyze in detail the LHC prospects for charged electroweakino searches, decaying to leptons, in compressed supersymmetry scenarios, via exclusive photon-initiated pair production. This provides a potentially increased sensitivity in comparison to inclusive channels, where the background is often overwhelming. We pay particular attention to the challenges that such searches would face in the hostile high pile-up environment of the LHC, giving close consideration to the backgrounds that will be present. The signal we focus on is the exclusive production of same-flavour muon and electron pairs, with missing energy in the final state, and with two outgoing intact protons registered by the dedicated forward proton detectors installed in association with ATLAS and CMS. We present results for slepton masses of 120–300 GeV and slepton-neutralino mass splitting of 10–20 GeV, and find that the relevant backgrounds can be controlled to the level of the expected signal yields. The most significant such backgrounds are due to semi-exclusive lepton pair production at lower masses, with a proton produced in the initial proton dissociation system registering in the forward detectors, and from the coincidence of forward protons produced in pile-up events with an inclusive central event that mimics the signal. We also outline a range of potential methods to further suppress these backgrounds as well as to enlarge the signal yields.

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## DIS structure functions at low x in the dipole factorization: including massive quarks at NLO

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Deep Inelastic Scattering (DIS) is the cleanest tool available to probe the content of a fast proton or nucleus. In the regime of low Bjorken  $x$ , one enters in the nonlinear regime of gluon saturation where the gluons are better described within the framework of Color Glass Condensate (CGC) and the dipole factorization. This framework allows to resum coherent multiple scattering on the target, and also to resum the high-energy leading logarithms (LL).

So far, phenomenological studies have been performed successfully at LO + LL resummation in the dipole factorization using HERA data for proton DIS. However, in order to reach precision, NLO corrections with massive quarks (which is known to be sizable in DIS at NLO) should be included as well as high-energy NLL resummations. This is important not only to extract as much knowledge as possible out of the HERA data, but also in prevision of future electron-proton and/or electron-nucleus colliders.

In this talk, we will discuss the calculation of the massive quark contribution to the NLO corrections to DIS structure functions on a dense target in the dipole factorization picture. In particular, we will present the complete result for the longitudinal structure function at NLO including massive quarks in that setup.

**WG2: Small- $x$  and Diffraction / 135**

## Impact of the Double-Logarithmic contribution to Pomeron on the small- $x$ behaviour of the DIS Structure Function $F_1$

**Author:** Boris Ermolaev<sup>1</sup><sup>1</sup> Ioffe Institute (RU)**Corresponding Author:** boris.ermolaev@cern.ch

Pomeron was introduced in the framework of the phenomenological Regge theory. It governs the high-energy asymptotics of various hadronic processes and the small- $x$  behavior of  $F_1$  in particular.

The best-known contribution to the QCD Pomeron comes from the BFKL equation which sums Leading Logarithmic (LL) contributions i.e. the single-logarithmic (SL) contributions  $\sim (\alpha_s \ln(1/x))^n$  multiplied by the overall factor  $1/x$ .

The high-energy asymptotics of this resummation is known as the BFKL Pomeron. It predicts that small- $x$   $F_1 \sim x^{-(1+\Delta)}$ , where  $\Delta$  is the intercept of the BFKL Pomeron.

In contrast, we calculate  $F_1$  in the Double-Logarithmic approximation (DLA), accounting for contributions  $\sim (\alpha_s \ln^2(1/x))^n$  as well as double-logs of  $Q^2$ . Such terms are not accompanied by the overall factor  $s$ , so their contribution to asymptotics of  $F_1$  is  $\sim x^{-\Delta_{DL}}$  without the factor  $x^{-1}$ . It looks negligibly small compared to the

BFKL exponent  $1 + \Delta$ . By this reason the DL contribution to Pomeron was offhandedly ignored by the HEP

community. However, we demonstrate that the intercept  $\Delta_{DL}$  proves to be so large that its value compensates for the lack of  $x^{-1}$ , which makes the DL Pomeron and BFKL Pomeron be equally important.

It means that DL Pomeron should participate in theoretical analysis of all HEP results where the BFKL Pomeron has been involved.

**WG2: Small-x and Diffraction / 221****Non-linear evolution in QCD at low-x beyond leading order****Author:** Dionysios Triantafyllopoulos<sup>1</sup>**Co-authors:** Bertrand Ducloue<sup>2</sup>; Edmond Iancu<sup>3</sup>; Alfred Mueller<sup>4</sup>; Gregory Soyez<sup>5</sup><sup>1</sup> *ECT\*/FBK*<sup>2</sup> *IPhT Saclay*<sup>3</sup> *Université Paris-Saclay (FR)*<sup>4</sup> *Columbia University*<sup>5</sup> *IPhT, CEA Saclay***Corresponding Authors:** bertrand.ducloue@ipht.fr, ahm4@columbia.edu, trianta@ectstar.eu, edmond.iancu@cea.fr, gregory.soyez@cern.ch

The NLO Balitsky-Kovchegov (BK) equation describing the high-energy evolution of the scattering between a dilute projectile and a dense target suffers from instabilities unless it is supplemented by a proper resummation of large (anti-)collinear logarithms. Earlier studies showed that if one expresses the evolution in terms of the rapidity of the dilute projectile, the dominant anti-collinear contributions can be resummed to all orders. However, in phenomenological applications, the results must be re-expressed in terms of the rapidity of the dense target. We show that although they lead to stable evolution equations, resummations expressed in the rapidity of the dilute projectile show a strong, unwanted, scheme dependence when their results are translated in terms of the target rapidity. Here, we work directly in the rapidity of the dense target where anti-collinear contributions are absent but where new, collinear, instabilities arise. These are milder since disfavoured by the typical BK evolution. Studying several prescriptions for resumming these new double logarithms, we find only little scheme dependence. The resummed equations are non-local in rapidity and can be extended to full NLO accuracy.

**WG2: Small-x and Diffraction / 261****Mass renormalization in light-front perturbation theory****Author:** Guillaume Beuf<sup>None</sup>**Co-authors:** Risto Sakari Paatelainen<sup>1</sup>; Tuomas Lappi<sup>2</sup><sup>1</sup> *CERN*<sup>2</sup> *University of Jyväskylä***Corresponding Authors:** risto.sakari.paatelainen@cern.ch, tuomas.v.v.lappi@jyu.fi, guillaume.beuf@gmail.com

In order to understand more precisely the gluon saturation phenomenon at low  $x$  and the kinematical range in which it happens, higher order corrections need to be included. With that goal in mind, the NLO corrections to DIS structure functions in the dipole factorization and to various particle production processes at the LHC have been recently calculated, as well as the BK and JIMWLK evolutions at NLL accuracy. These calculations are often done in light-front perturbation theory, which simplifies the inclusion of gluon saturation effects. So far, for simplicity, almost all of these calculations have been restricted to the case of massless quarks. However, the charm and bottom quarks are known to give a sizable contribution to DIS at HERA, and should thus be considered.

The main new issue arising in the NLO calculations with massive quarks is the quark mass renormalization. Indeed, there was a longstanding confusion in the literature about mass renormalization in gauge theories in light-front perturbation theory, leading to inconsistent results. I will present how mass renormalization can be properly done for QCD and QED in light-front perturbation theory, by using a Lorentz-invariant UV regularization procedure.

## WG2: Small-x and Diffraction / 229

**Coherent  $J/\psi$  photoproduction in ultra-peripheral collisions at STAR**Author: Jaroslav Adam<sup>1</sup><sup>1</sup> Creighton University (US)

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Ultra-peripheral nucleus-nucleus collisions (UPC) are mediated by strong electromagnetic fields, offering the opportunity to study photon-nucleus processes at RHIC. Coherent  $J/\psi$  photoproduction is of particular interest for its sensitivity to nuclear gluon distribution. The  $J/\psi$  mesons are heavy enough to be described by perturbative Quantum Chromodynamics (pQCD), where coherent cross section, at the first order, is proportional to the square of the nuclear gluon distribution. This makes coherent  $J/\psi$  cross section an ideal probe to phenomena of gluon saturation and nuclear gluon shadowing.

In this talk, we present a brief overview of the topic and preliminary results of exclusive coherent  $J/\psi$  photoproduction in Au+Au UPC at  $\sqrt{s_{NN}} = 200$  GeV at central rapidity  $|\eta| < 1$ , where the photoproduction was tagged at the trigger level by forward neutrons emitted as a result of electromagnetic excitation of the nuclei.

## WG2: Small-x and Diffraction / 220

**High-energy effects in forward inclusive dijet and hadron-jet production**Authors: Alessandro Papa<sup>1</sup>; Andr e Dafne Bolognino<sup>2</sup>; Dmitry Ivanov<sup>None</sup>; Francesco Giovanni Celiberto<sup>3</sup>; Mohammed M.A. Mohammed<sup>4</sup><sup>1</sup> Universita' della Calabria & INFN-Cosenza<sup>2</sup> Universit  della Calabria & INFN gruppo collegato Cosenza<sup>3</sup> Universit  di Pavia and INFN, Sezione di Pavia<sup>4</sup> Universit  della Calabria and INFN-Cosenza

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Semi-hard processes serve as a special testing ground for calculations of high-energy scatterings in perturbative QCD. In this kinematic limit, the enhanced effect of energy logarithms calls for an all-order resummation procedure. The most natural language to resum these large logarithms, both in the leading and the next-to-leading approximation, is elegantly embodied by the BFKL approach. Pursuing the goal to single out the validity region of the high-energy resummation, and to possibly disentangle BFKL effects from the ones coming from a DGLAP-inspired, fixed-order description, we will first present our recent results for cross section and azimuthal correlations in the Mueller-Navelet jet production. Then, with the aim of enriching the final-state exclusiveness, we will give new predictions, tailored on the CMS and CASTOR acceptances, for forward inclusive hadron-jet correlations.

## WG2: Small-x and Diffraction / 353

**Elastic and Total Cross-Section Measurements by TOTEM**

**Authors:** TOTEM Collaboration<sup>None</sup>; Frigyes Janos Nemes<sup>1</sup>

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The TOTEM experiment at the LHC has measured proton-proton elastic scattering in dedicated runs at  $\sqrt{s} = 2.76, 7, 8$  and 13 TeV centre-of-mass LHC energies. The proton-proton total cross-section has been derived for each energy using a luminosity independent method. TOTEM has excluded a purely exponential differential cross-section for elastic proton-proton scattering with significance greater than  $7\sigma$  in the  $|t|$  range from 0.027 to 0.2 GeV<sup>2</sup> at  $\sqrt{s} = 8$  TeV. The  $\rho$  parameter has been measured at  $\sqrt{s} = 8$  TeV via the Coulomb-nuclear interference, and was found to be  $\rho = 0.12 \pm 0.03$ . The measurement has been repeated at 13 TeV and the result  $\rho = 0.09 \pm 0.01$  probes the existence of a colourless three-gluon bound state. The measured 2.76 TeV differential cross-section by TOTEM provides evidence for the colourless 3-gluon bound state, when compared to the D0 experiment ppbar result at 1.96 TeV (neglecting the small energy difference between TOTEM and D0).

**WG3: Higgs and BSM Physics in Hadron Collisions / 234**

## Bounding the Higgs width through interference effects

**Authors:** Enrico Bothmann<sup>1</sup>; Silvan Kuttimalai<sup>2</sup>; Stefan Hoeche<sup>2</sup>

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The Higgs decay width can be constrained by exploiting interference effects of the  $pp \rightarrow H \rightarrow \gamma\gamma$  signal with the  $pp \rightarrow \gamma\gamma$  continuum background, which leads to a width-dependent shift of the Higgs mass peak. I review a study in which my collaborators and I investigate the reach of an analysis that determines the reference mass by measuring the di-photon final state at high transverse momenta, using a full particle-level prediction calculated with the Monte-Carlo event generator Sherpa. We also propose a yet more powerful technique based on a direct fit to the experimentally observable  $m_{\gamma\gamma}$  line shape.

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## Constraining Lorentz Violation with DIS at HERA and the EIC

**Author:** Enrico Lunghi<sup>1</sup>

**Co-authors:** nathan sherrill<sup>2</sup>; Alan Kostelecky<sup>3</sup>; Alexandre Vieira<sup>4</sup>

<sup>1</sup> Indiana University (US)

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I present the theory of high energy hadron-lepton interactions in presence of a background which breaks Lorentz invariance (this parameterization of Lorentz violation is known in the literature as the Standard Model Extension). I apply this theory to the calculation of Lorentz violating effects in DIS and present the expected bounds that can be obtained by sidereal time analyses of existing HERA and future EIC data.

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## Prospects for Heavy Scalar Searches at the LHeC

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

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The prospects of the proposed Large Hadron electron Collider (LHeC) in the search for heavy neutral scalar particles are discussed.

A minimal model is considered with one additional complex scalar singlet that interacts with the Standard Model (SM) via mixing with the Higgs doublet, giving rise to a SM-like Higgs boson  $h_1$  and a heavy scalar particle  $h_2$ .

Both scalar particles are produced via vector boson fusion and can be tested via their decays into pairs of SM particles, analogously to the SM Higgs boson.

Using multivariate techniques we show that the LHeC is sensitive to  $h_2$  with masses between 200 and 800 GeV to squared scalar mixings as small as  $O(0.001)$ .

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## Searches for Light Higgs Bosons at the CMS Experiment

**Author:** CMS Collaboration<sup>None</sup>

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The searches for light pseudoscalar Higgs bosons pair produced from the decay of the 125 GeV Higgs boson and resulting in various final states ( $4\mu$ ,  $4\tau$ ,  $2\mu 2\tau$ ,  $2b 2\tau$ ) according to the mass of the light boson and searches for low mass scalar bosons below 125 GeV in decays to photon pairs will be summarised. The analyses are performed using data collected with the CMS experiment at the LHC from pp collisions at centre-of-mass energy of 13 TeV.

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## Measurement of $t\bar{t}H$ production at CMS

**Author:** CMS Collaboration<sup>None</sup>

The production of a Higgs boson in association with a pair of top quarks ( $t\bar{t}H$ ) is presented. In particular the final states with multileptons targeting the  $WW$ ,  $ZZ$  and  $\tau\tau$  decays of the Higgs boson, are reported. The data set analyzed corresponds  $41.4 \text{ fb}^{-1}$  of pp collisions recorded by the CMS experiment in 2017. Machine learning and matrix element techniques are used to enhance the sensitivity of the analysis. The results are also combined with those obtained in the 2016 data set. leading to an observed (expected) signal rate for the combined fit of  $0.96_{-0.31}^{+0.34}$  ( $1.00_{-0.27}^{+0.30}$ ) times the

expected rate in the standard model, which corresponds to an observed (expected) significance of  $3.2 \sigma$  ( $4.0 \sigma$ ).

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## **Measurements and searches of Higgs boson decays to two leptons at the ATLAS experiment**

**Author:** Quentin Buat<sup>1</sup>

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Testing the couplings of the Higgs boson to fermions is an important part to understand the origin of fermion masses. The talk presents cross section measurements in Higgs boson decays to two tau leptons, as well as a search for Higgs boson decays to two muons. Both analyses are based on pp collision data collected at 13 TeV.

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## **Combined Higgs boson measurements at the ATLAS experiment**

**Author:** Aurelio Juste Rozas<sup>1</sup>

<sup>1</sup> *ICREA and IFAE (ES)*

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The most precise measurements of Higgs boson cross sections, using the framework of simplified template cross sections, are obtained from a combination of the measurements performed in the different Higgs boson decay channels. This talk presents the combined measurements, as well as their interpretation.

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## **Searching for leptoquarks with the ATLAS detector**

**Author:** Vojtech Pleskot<sup>1</sup>

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Leptoquarks 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 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 with the ATLAS detector, covering all three generations, and highlight their complementarity.



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## **Higgs boson production in association with a $t\bar{t}$ pair at the ATLAS experiment**

**Authors:** Aurelio Juste Rozas<sup>1</sup>; Ana Elena Dumitriu<sup>2</sup>

<sup>1</sup> *ICREA and IFAE (ES)*

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The measurement of Higgs boson production in association with a  $t\bar{t}$  pair is essential to understand the top-quark couplings to the Higgs boson. This talks presents the analyses using Higgs boson decays to  $b\bar{b}$  pairs, to two Z bosons, to other multi-lepton final states, and to a pair of photons, using pp collision data collected at 13 TeV.

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## **Dark Matter searches with CMS**

**Author:** CMS Collaboration<sup>None</sup>

**Corresponding Author:** david.vannerom@cern.ch

Recent results on searches for Dark Matter are reported, including  $H \rightarrow \text{inv}$ .

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## **Expected physics reach of the upgraded ATLAS experiment for the HL-LHC**

**Author:** Ben Harry Smart<sup>1</sup>

**Co-author:** ATLAS Collaboration

<sup>1</sup> *Science and Technology Facilities Council STFC (GB)*

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The Large Hadron Collider (LHC) has been successfully delivering proton-proton collision data at the unprecedented center of mass energy of 13 TeV. An upgrade is planned to increase the instantaneous luminosity delivered by LHC in what is called HL-LHC, aiming to deliver a total of about 3000/fb of data to the ATLAS detector. To cope with the expected data-taking conditions ATLAS is planning major upgrades of the detector. In this contribution we present an overview of the physics reach expected for a wide range of measurements and searches at the HL-LHC for the ATLAS experiment, including Higgs coupling, di-Higgs boson production sensitivity, Vector Boson Scattering prospects as well as discovery potential for electroweak SUSY and other exotic benchmark scenarios. Such studies formed the basis of the ATLAS Collaboration input to the recent HL/HE-LHC Yellow-Report. An executive summary of this report was then submitted as input to the European Strategy process.

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## ATLAS Searches for Resonances Decaying to Boson Pairs

**Author:** Jana Schaarschmidt<sup>1</sup>

**Co-author:** ATLAS Collaboration

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

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Many extensions to the Standard Model predicts 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 resonant diboson resonances (including HH) have been performed in final states with different numbers of leptons, photons, jets and b-jets where new jet substructure techniques to disentangle the hadronic decay products in highly boosted configuration are being used. This talk summarizes recent ATLAS searches with up to 140fb<sup>-1</sup> of 13 TeV LHC Run 2 data.

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### Searches for BSM physics in leptonic final states using the ATLAS detector

**Author:** ATLAS Collaboration<sup>None</sup>

**Corresponding Author:** paolo.mastrandrea@cern.ch

Many theories beyond the Standard Model predict new particles, including new gauge bosons or heavy Majorana or Dirac neutrinos, which decay to well isolated leptons. Searches for new physics models with these signatures, are performed using the ATLAS experiment at the LHC.

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### Searches for squarks and gluinos at the LHC

**Authors:** ATLAS Collaboration<sup>None</sup>; CMS Collaboration<sup>None</sup>

**Corresponding Author:** maria.giulia.ratti@cern.ch

The talk will present the most recent results on inclusive searches for supersymmetric squarks (including direct stop and sbottom pair production) and gluinos at the LHC, possibly including R-parity violating scenarios and the description of special reconstruction techniques needed in these searches.

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### Searches for electroweak SUSY and for long-lived particles at the LHC

**Authors:** ATLAS Collaboration<sup>None</sup>; CMS Collaboration<sup>None</sup>; Hideyuki Oide<sup>1</sup>

<sup>1</sup> *INFN-Genova*

The talk presents results from searches for gaugino and slepton pair production at the LHC, possibly including R-Parity violating scenarios, and from searches for long-lived particles (excluding the ones from exotics Higgs decays), which can be detected through abnormal specific energy loss, appearing or disappearing tracks, displaced vertices, long time-of-flight or late calorimetric energy deposits.

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## Recent measurements of Higgs to bosons decays at the LHC

**Authors:** ATLAS Collaboration<sup>None</sup>; CMS Collaboration<sup>None</sup>

**Corresponding Author:** tulay.cuhadar.donszelmann@cern.ch

In Run2 precise measurements of the Higgs production and its properties have been carried out using the Higgs decays to bosons. Recent results from the LHC will be discussed, including measurements of different Higgs production modes and differential cross section measurements.

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## HH non-resonant production searches at the LHC

**Authors:** ATLAS Collaboration<sup>None</sup>; CMS Collaboration<sup>None</sup>

**Corresponding Author:** muhammad.bilal.kiani@cern.ch

This talk will discuss the most recent results for the search of double Higgs non-resonant production at the LHC.

The sensitivity reached, which is still one order of magnitude above than the SM prediction, allows excluding already significant regions of the BSM phase space. Interpretation of searches results with a dedicated EFT approach will be showed. A particular focus will be also given to the recent improvements of the analysis techniques and their prospects for the full Run2 analyses.

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## Finite quark mass effects for the production of Higgs-boson with Dijet

**Author:** Marian Heil<sup>1</sup>

<sup>1</sup> IPPP, Durham

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At the LHC the dominant production channel for the Higgs-boson with two jets is through gluon fusion, which is therefore also the dominant background for measuring the Higgs-boson production through weak boson fusion. To reduce the gluon fusion component WBF cuts require a large invariant mass of the dijet system. Thus the predictions become sensitive to a high energy logarithm. We present new calculations in the framework for High Energy Jets to resume such logarithms, while keeping the full quark mass dependences in the gluon to Higgs-boson coupling.

Compared to the infinite top mass approximation we found a reduction of 10% in the cross-section after WBF cuts.

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## Exotic Higgs decays searches at the LHC

**Author:** Scott Snyder<sup>1</sup>

**Co-authors:** ATLAS Collaboration ; CMS Collaboration

<sup>1</sup> Brookhaven National Laboratory (US)

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Several direct searches for exotic Higgs decays, which will be a clear sign of BSM physics, are performed at the LHC (lepton flavour violation, long-lived particles, low-mass scalars, semi-invisible...). This talk will discuss the most recent searches performed at the LHC, the interpretation of the results and prospects for the full LHC Run2 analyses.

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## Higgs to fermion decays measurements at LHC

**Authors:** ATLAS Collaboration<sup>None</sup>; CMS Collaboration<sup>None</sup>

**Corresponding Author:** grab@phys.ethz.ch

The understanding of the Higgs coupling to fermions is among the main goals of the Run2 at the LHC. This talk will present the most recent results from LHC on this topic. Prospects for the full Run2 analyses and for CP measurements of the  $Hff$  vertex will be also discussed.

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## Dark Matter searches with ATLAS

**Author:** ATLAS Collaboration<sup>None</sup>

The presence of a non-baryonic dark matter component in the Universe is inferred from the observation of its gravitational interaction. If dark matter interacts weakly with the Standard Model it would be produced at the LHC, escaping the detector and leaving a large missing transverse momentum as their signature. The ATLAS detector has developed a broad and systematic search program for dark matter production in LHC collisions. The results of these searches on 13 TeV pp data and their interpretation will be presented, including the search for the Higgs boson decaying to invisible final states.

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## Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

**Author:** CMS Collaboration<sup>None</sup>

Evidence for the light-by-light scattering process,  $\gamma\gamma \rightarrow \gamma\gamma$ , in ultraperipheral PbPb collisions at a centre-of-mass energy per nucleon pair of 5.02 TeV is reported. The analysis is conducted using a

data sample corresponding to an integrated luminosity of  $390 \mu\text{b}^{-1}$  recorded by the CMS experiment at the LHC. Light-by-light scattering processes are selected in events with two photons exclusively produced, each with transverse energy  $ET > 2 \text{ GeV}$ , pseudorapidity  $|\eta| < 2.4$ , diphoton invariant mass  $m_{\gamma\gamma} > 5 \text{ GeV}$ , diphoton transverse momentum  $p_{T\gamma\gamma} < 1 \text{ GeV}$ , and diphoton acoplanarity below 0.01. After all selection criteria are applied, 14 events are observed, compared to expectations of  $11.1 \pm 1.1$  (theo) events for the signal and  $4.0 \pm 1.2$  (stat) for the background processes. The excess observed in data relative to the background-only expectation corresponds to a significance of 4.1 standard deviations, and has properties consistent with those expected for the light-by-light scattering signal. The  $m_{\gamma\gamma}$  distribution is used to set new exclusion limits on the production of pseudoscalar axion-like particles, via the  $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$  process, in the mass range  $m_a = 5\text{--}90 \text{ GeV}$ .

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## A Monte Carlo analysis of the SMEFT in the top quark sector

**Author:** Emma Slade<sup>1</sup>

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

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We present a novel framework to carry out global analyses of the Standard Model Effective Field Theory (SMEFT) at dimension-six: SMEFiT. The SMEFiT approach is based on the Monte Carlo replica method to derive a faithful estimate of the experimental and theoretical uncertainties and enables one to construct the probability distribution in the space of the SMEFT degrees of freedom.

As a proof of concept of the SMEFiT methodology, we present an extensive study of the constraints on the SMEFT provided by top quark production measurements from the LHC. Our analysis includes more than 30 independent measurements from 10 different processes at  $\sqrt{s} = 8$  and 13 TeV, including inclusive  $t\bar{t}$  and single-top production and the associated production of top quarks with vector bosons and the Higgs boson.

State-of-the-art theoretical calculations are adopted both for the SM and the SMEFT contributions, where in the latter case NLO QCD corrections are included for the majority of processes. We derive bounds for the 34 degrees of freedom relevant for the interpretation of top quark data and compare these bounds with previously reported constraints. Our study illustrates the significant potential of LHC precision measurements to constrain physics beyond the Standard Model in a model-independent way, and pave the way towards a global analysis of the SMEFT.

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## FCNC and EFT interpretations in CMS

**Author:** CMS Collaboration<sup>None</sup>

Top quark production can probe physics beyond the SM in different ways. Some processes, and especially certain angular correlations, are sensitive to the existence of anomalous top quark couplings. In the SM, flavour-changing neutral currents (FCNC) are forbidden at tree level and are strongly suppressed in loop corrections. Several extensions of the SM incorporate significantly enhanced FCNC behaviour that can be directly probed in top quark processes. Current approaches adopting an EFT framework allow describing effects of new physics in a model independent way. This talks reviews the current limits on FCNC searches in the top sector, and EFT interpretations.

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## NA62 sensitivity to heavy neutral leptons in the low scale seesaw model

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The sensitivity of beam dump experiments to heavy neutral leptons depends on the relative strength of their couplings to individual lepton flavours in the Standard Model. We study the impact of present neutrino oscillation data on these couplings in the minimal type I seesaw model and find that it significantly constrains the allowed heavy neutrino flavour mixing patterns. We estimate the effect that the DUNE experiment will have on these predictions. We then discuss implication that this has for the sensitivity of the NA62 experiment when operated in the beam dump mode and provide sensitivity estimates for different benchmark scenarios. We find that the sensitivity can vary by almost two orders of magnitude for general choices of the model parameters, but depends only weakly on the flavour mixing pattern within the parameter range that is preferred by neutrino oscillation data.

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## Searches for Resonances Decaying to Quarks using the ATLAS detector

**Author:** ATLAS Collaboration<sup>None</sup>

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Many theories beyond the Standard Model predict new phenomena which decay to light or heavy quarks. Such final states are of particular interest at the LHC since new phenomena produced in parton collisions are likely to produce final states with (at least) two partons. Various strategies are employed to probe high and low resonance masses. This talk will present the latest searches performed by the ATLAS experiment with 13 TeV data.

**WG3: Higgs and BSM Physics in Hadron Collisions / 48**

## Search for supersymmetry in final states with photons and missing transverse momentum in pp collisions at 13 TeV using the CMS detector

**Author:** CMS Collaboration<sup>None</sup>

**Corresponding Author:** peter.major@cern.ch

Supersymmetry (SUSY) is a theoretical favored extension of the standard model (SM) since it provides explanations for several issues. Models with general gauge mediation (GGM), have the additional benefit of naturally suppressing flavor violations in the SUSY sector. Many of those models predict the production of events with photons and significant missing transverse momentum. The results of a search for new physics in final states with photons and missing transverse momentum are reported. The data sample corresponds to an integrated luminosity of 35.9 fb<sup>-1</sup> collected at a center-of-mass energy of 13 TeV using the CMS detector at the CERN LHC. The analysis exploits data-driven

techniques for the estimation of different backgrounds and the results are used to set cross section limits on gluino and squark pair production in the GGM model framework. This analysis gives a substantial improvement in sensitivity compared to the search performed by the CMS collaboration on the smaller 2015 dataset.

### WG3: Higgs and BSM Physics in Hadron Collisions / 156

## A Heavy Metal Path to New Physics

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We show that heavy ion collisions at the LHC provide a promising environment to search for signatures with displaced vertices in well-motivated New Physics scenarios. The lower instantaneous luminosity in heavy ion collisions allows to operate the LHC experiments with very loose triggers. For scenarios in which long-lived particles are produced in the decay of light particles, this can increase the number of observable events by several orders of magnitude. If ions lighter than Pb are used, as it is currently discussed in the heavy ion community for unrelated reasons, this can lead to a higher sensitivity per time of running than in pp collisions. We illustrate that explicitly for heavy neutrinos in the Neutrino Minimal Standard Model. Another advantage of heavy ion collisions is the fact that there is no pile up, i.e., the average number of simultaneous interactions per bunch crossing is well below unity. This entirely removes the problem of mis-identifying the location of the primary vertex, which may be the key to trespass the systematics wall due to background uncertainties in the cases where background contamination mostly comes from SM particles that originate from different parts of the interaction region. This provides strong motivation to further explore the possibility to search for New Physics in heavy ion collisions.

### WG3: Higgs and BSM Physics in Hadron Collisions / 216

## Can New Physics hide in the proton PDFs

**Authors:** Shayan Iranipour<sup>1</sup>; Maria Ubiali<sup>None</sup>; Juan Rojo<sup>2</sup>; Celine Catherine A Degrande<sup>None</sup>; Stefano Carrazza<sup>3</sup>

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A major recent breakthrough in global fits of the quark and gluon structure of the proton has been the inclusion of a significant amount of precision LHC measurements. While these data sets provide important constraints, especially on the poorly-known gluon and antiquark PDFs, it is crucial to avoid any contamination from potential beyond the Standard Model (BSM) effects that could be present in the high  $E$  or  $p_T$  tails of the fitted distributions. This problem is particularly acute for LHC data from Runs II and III, as well as for the future high-luminosity run, where many PDF-sensitive observables will reach into the few TeV region. In this talk, I present a first quantitative

analysis aiming to study whether or not BSM effects can be reabsorbed into the fitted PDFs, as well as the possibility of using the global QCD fit to simultaneously constrain both the proton structure and BSM dynamics.

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## Limits on contact interactions and leptoquarks at HERA

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High-precision HERA data corresponding to a luminosity of around  $1 \text{ fb}^{-1}$  have been used in the framework of  $eeqq$  contact interactions (CI) to set limits on possible high-energy contributions beyond the Standard Model to electron–quark scattering. Measurements of the inclusive deep inelastic cross sections in neutral and charged current  $ep$  scattering were considered. The analysis of the  $ep$  data has been based on simultaneous fits of parton distribution functions including contributions of CI couplings to  $ep$  scattering. Several general CI models and scenarios with heavy leptoquarks were considered. Improvements in the description of the inclusive HERA data were obtained for a few models. Since a statistically significant deviation from the Standard Model cannot be established, limits in the TeV range were set on all models considered.

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## Low scale type II seesaw: Present constraints and prospects for displaced vertex searches

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The type II seesaw mechanism is an attractive way to generate the observed light neutrino masses. It postulates a  $SU(2)_L$ -triplet scalar field, which develops an induced vacuum expectation value after electroweak symmetry breaking, giving masses to the neutrinos via its couplings to the lepton  $SU(2)_L$ -doublets. When the components of the triplet field have masses around the electroweak scale, the model features a rich phenomenology. We discuss the current allowed parameter space of the minimal low scale type II seesaw model, taking into account all relevant constraints, including charged lepton flavour violation as well as collider searches.

We point out that the symmetry protected low scale type II seesaw scenario, where an approximate “lepton number”-like symmetry suppresses the Yukawa couplings of the triplet to the lepton doublets, is still largely untested by the current LHC results.

In part of this parameter space the triplet components can be long-lived, potentially leading to a characteristic displaced vertex signature where the doubly-charged component decays into same-sign charged leptons. By performing a detailed analysis at the reconstructed level we find that already at the current run of the LHC a discovery would be possible for the considered parameter point,

via dedicated searches for displaced vertex signatures.

The discovery prospects are further improved at the HL-LHC and the FCC-hh/SppC.



**WG3: Higgs and BSM Physics in Hadron Collisions / 235****Light charged Higgs boson production in future ep colliders**

**Authors:** Jaime Hernández-Sánchez<sup>1</sup>; Carlos Honorato<sup>2</sup>; Stefano Moretti<sup>3</sup>; Sebastian Rosado Navarro<sup>4</sup>; Omar Flores-Sánchez<sup>5</sup>

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The production of a light charged Higgs boson at the future Large Hadron electron Collider (LHeC) and Future Circular Collider in the mode hadron-electron (FCC-he) is studied, the main process  $e^+p \rightarrow \nu_e H^- q$  is considered, taking in account the decay channels  $H^- \rightarrow \bar{c}$  and  $H^- \rightarrow \tau \nu_{\tau}$  in the final state. We analyze these processes in the framework of the 2-Higgs Doublet Model Type III (2HDM-III) and assess the LHeC sensitivity to such  $H^-$  signals to opposite a variety of both reducible and irreducible backgrounds. The prospects for  $H^-$  detection in the 2HDM-III are promising.

**WG4: Hadronic and Electroweak Observables / 24****QCD Monte Carlo model tuning studies with CMS data at 13 TeV**

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New CMS PYTHIA 8 event tunes are presented. The new tunes are obtained using minimum bias and underlying event observables exploiting Monte Carlo configurations with consistent parton distribution functions and strong coupling constant values in the matrix element and the parton shower, at leading order (LO), next-to-leading order (NLO) and next-to-next-to-leading order (NNLO). Validation and performance studies are presented by comparing the predictions of the new tunes to a wide range of different CMS measurements at 7, 8 and 13 TeV with CMS.

**WG4: Hadronic and Electroweak Observables / 18****Effect of flavor-dependent partonic transverse momentum on the determination of the W mass at hadron colliders**

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Within the framework of transverse-momentum-dependent factorization, we investigate for the first time the impact of a flavor-dependent intrinsic transverse momentum of quarks on the production of

W bosons in hadronic collisions. We study the transverse-mass, lepton transverse momentum, and missing transverse momentum distributions of the W-decay products by means of a template-fit technique and we estimate the shift in the W boson mass induced by different choices of flavor-dependent parameters for the intrinsic quark transverse momentum. Our findings call for more detailed investigations of flavor-dependent non perturbative effects linked to the proton structure at hadron colliders.

#### WG4: Hadronic and Electroweak Observables / 11

### Jet Pull

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We discuss the jet shape variable pull and in particular, we present a first-principle prediction for the pull angle, which can help to probe the colour flow between jets. While the pull angle is not infra-red and collinear safe, it is Sudakov safe and therefore it can be calculated using all-order techniques, which share similarities to standard  $Q_T$  resummation. We compare our result with Monte Carlo result and with data collected by the ATLAS experiment.

#### WG4: Hadronic and Electroweak Observables / 20

### Local Analytic Sector Subtraction at NNLO

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I present a new local, analytic scheme for the subtraction of infrared singularities at next-to-next-to-leading order (NNLO) in QCD, which aims at reducing the complexity of the problem and features remarkable aspects. It works for any infrared-safe observable, it benefits from the partition of the radiative phase-space into sectors, the subtraction counterterms are local and can be analytically integrated. All these properties enable an efficient numerical implementation. Our scheme is currently designed for massless final state radiation only, but its extension to initial state radiation will allow for predictions at hadron-hadron and lepton-nucleon colliders.

#### WG4: Hadronic and Electroweak Observables / 40

### Electroweak physics with multibosons

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Measurements of multi-boson production at the LHC constitute precision tests of the Standard Model and unique probes of new physics through anomalous gauge couplings. These processes are also important backgrounds to Higgs measurements and searches for new particles. Relevant measurements from CMS are presented.

**WG4: Hadronic and Electroweak Observables / 23**

## V+jets production at CMS

**Author:** CMS Collaboration<sup>None</sup>

The production of vector bosons in association with jets is a stringent test of perturbative QCD and is a background process in searches for new physics. Total and differential cross-section measurements of vector bosons produced in association with jets in proton-proton collisions performed by the CMS collaboration at the LHC are presented. The measurements are compared to the predictions of event generators and theoretical calculations.

**WG4: Hadronic and Electroweak Observables / 39**

## Differential jet cross sections at the CMS experiment

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We present measurements of differential jet cross sections over a wide range in transverse momenta from inclusive jets to multi-jet final states. Studies on the impact that these measurements have on the determination of the strong coupling  $\alpha_s$  as well as on parton density functions are reported.

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## Amplitude Parton Showers and Non-global Logarithms

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I will present recent development of a new kind of parton shower algorithm at the amplitude level. An application of such an algorithm to the flexible resummation of non-global observables beyond leading-N is discussed, and prospects to a full parton shower implementation are presented, as well.

**WG4: Hadronic and Electroweak Observables / 44**

## Parton Shower based on TMD parton distributions

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We present a parton shower based on Transverse Momentum Dependent (TMD) parton distributions obtained with the Parton Branching method. We investigate how well the TMD parton shower reproduces the TMD parton distributions. Applications of the TMD parton shower to LHC processes will be presented.

**WG4: Hadronic and Electroweak Observables / 75**

## Measurements of dijet azimuthal decorrelations and extraction of $\alpha_S$ at ATLAS

**Author:** ATLAS Collaboration<sup>None</sup>

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The production of jets at hadron colliders provides stringent tests of perturbative QCD. We present a measurement of the rapidity and transverse momentum dependence of dijet azimuthal decorrelations, using the quantity  $R\Delta\phi$ . This quantity specifies the fraction of the inclusive dijet events in which the azimuthal opening angle of the two jets with the highest transverse momenta is less than a given value of the parameter  $\Delta\phi_{\text{max}}$ .  $R\Delta\phi$  is measured in proton-proton collisions at  $\sqrt{s}=8$  TeV as a function of the dijet rapidity interval, the event total scalar transverse momentum, and  $\Delta\phi_{\text{max}}$ . Predictions of a perturbative QCD calculation at next-to-leading order in the strong coupling with corrections for non-perturbative effects describe the data well in the whole kinematic region. The data are used to determine the strong coupling  $\alpha_S$  and to study its running for momentum transfers from 260 GeV to above 1.6 TeV. An analysis that combines data at all momentum transfers results in  $\alpha_S(m_Z)=0.1127-0.0027+0.0063$ .

**WG4: Hadronic and Electroweak Observables / 78**

## Precision electroweak measurements with ATLAS

**Author:** ATLAS Collaboration<sup>None</sup>

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The electroweak sector of the Standard Model can be tested via precision measurements of fundamental observables. Measurements of the Drell-Yan production of Z bosons at the LHC provide a benchmark of our understanding of perturbative QCD and electroweak processes. The ATLAS collaboration has recently used such measurements to evaluate the effective leptonic weak mixing angle using data collected during the Run-1 of the LHC at a centre-of-mass energy of 8 TeV. The result is  $\sin^2\theta_{\text{eff}}^l = 0.23140 \pm 0.00036$ , yielding a precision similar to that of the recently published Tevatron legacy result and to the most precise individual observable measurements from lepton colliders. If available, measurements useful for a precise determination of the W boson mass will also be presented.

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## Measurements of triboson production at ATLAS

**Author:** ATLAS Collaboration<sup>None</sup>

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A search for the production of three massive vector bosons in WWW, WWZ and WZZ final states is presented, using proton-proton collision data collected by the ATLAS experiment at  $\sqrt{s}=13$  TeV. The analysis utilises multiple search channels. WWW production is probed using a fully-leptonic decay channel, with three-charged leptons and missing transverse momentum, and a semi-leptonic decay channel with two-charged leptons and two hadronic jets. WWZ production is probed in both a fully leptonic decay channel (four charged leptons) and a semi-leptonic decay channel (three leptons and two hadronic jets), whereas WZZ production is probed using a semi-leptonic decay channel (four charged leptons and two hadronic jets). The signal strengths in each channel are extracted and combined in a global fit. The data are found to be in good agreement with the SM expectations.

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## Observation and measurements of vector-boson scattering with ATLAS

**Author:** ATLAS Collaboration<sup>None</sup>

**Corresponding Author:** francesco.conventi@cern.ch

The scattering of electroweak bosons tests the gauge structure of the Standard Model and is sensitive to anomalous quartic gauge couplings. In this talk, we present recent results on vector-boson scattering from the ATLAS experiment using proton-proton collisions at  $\sqrt{s}=13$  TeV. This includes the observation of WZ and same-sign-WW production via vector-boson scattering along with a measurement of VV production in semileptonic final states. If available, a measurement of  $Z\chi$  production via vector-boson scattering will also be presented. The results can be used to constrain new physics that manifests as anomalous electroweak-boson self interactions.

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## Monte Carlo generators for the modelling of multijet processes in ATLAS at 13 TeV

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Most of the interesting physics at the LHC involves final states with hadronic jets. We present new Monte Carlo event generator configurations used by the ATLAS experiment to model multijet processes in pp collisions at 13 TeV. The different generators are compared to each other and to 13 TeV ATLAS measurements in kinematic distributions sensitive both to the kinematic of hard process and to the effect of shower and non-perturbative effects. Recipes for evaluating uncertainties covering differences related to the matrix-element generator and matching, the shower radiation, and hadronisation effects are also presented.

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## Measurement of jet substructure observables using the ATLAS detector

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Theoretical calculations for jet substructure observables with accuracy beyond leading-logarithm have recently become available. Such observables are significant not only for probing a new regime of QCD at a hadron collider, but also for improving the understanding of jet substructure properties that are used in many searches for physics beyond the Standard Model. In this talk, we discuss a first measurement of such jet substructure quantities. The soft drop mass is measured in dijet events with the ATLAS detector at  $\sqrt{s}=13$  TeV, unfolded to particle-level and compared to Monte Carlo simulations. We also present a measurement of substructure variables in  $t\bar{t}$  and inclusive jet events, using data collected by the ATLAS experiment at  $\sqrt{s} = 13$  TeV. The measurements are performed with large-radius jets. They are corrected for detector effects, represented as particle-level distributions and are compared to the predictions of various Monte Carlo event generators. If available, a measurement of the Lund plane at  $\sqrt{s} = 13$  TeV, performed using charged particles, is also presented.

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## Low energy light-by-light scattering in heavy-ion UPC, a new possibility

**Authors:** Mariola Klusek-Gawenda<sup>1</sup>; Antoni Szczurek<sup>2</sup>; Rainer Schicker<sup>3</sup>

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So far light-by-light scattering ( $\gamma\gamma \rightarrow \gamma\gamma$ ) was not accessible for experiments because the corresponding cross section is rather low. Measurements of diphotons in ultra-peripheral collisions (UPCs) of lead-lead have been reported recently by the ATLAS [1] and CMS Collaborations [2]. Our theoretical results based on equivalent photon approximation in the impact parameter space [3] are in good agreement with the current data [1,2].

We will discuss how to extend such studies to lower  $\gamma\gamma$  energies where photoproduction of pseudoscalar and scalar resonances contribute to the two-photon final state. In addition, we consider the dominant background that arises from  $\gamma\gamma$  fusion into pairs of neutral pions [4]. Such  $\pi^0$ -pairs contribute to the background when only two of the four decay photons are within the experimental acceptance, the other two photons escape undetected. We will discuss in detail how to reduce the unwanted background.

We will present differential distributions and total cross section in ultra-peripheral Pb-Pb collisions at  $\sqrt{s_{NN}}=5.05$  and 5.52 TeV [5,6] and cross section for Ar-Ar collisions at the energy equal to 6.3 TeV [7]. Results for ALICE and LHCb acceptance will be presented.

[1] ATLAS Collaboration, Nature Phys. 13 (2017) 852

[2] CMS Collaboration, arXiv:1810.04602

[3] M.Klusek-Gawenda, P.Lebiedowicz, A.Szczurek, Phys.Rev.C93 (2016) 044907

[4] M.Klusek-Gawenda, A.Szczurek, Phys.Rev.C87 (2013) 054908

[5] M.Klusek-Gawenda, R.McNulty, R.Schicker, A.Szczurek, in preparation

[6] M.Klusek-Gawenda, EPJ Web Conf. 199 (2019) 05004

[7] Z.Citron et al., arXiv:1812.06772

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## Studying transverse momentum distributions with jets

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Semi-inclusive deep inelastic scattering will be a crucial channel to extract transverse momentum dependent distributions at future colliders. In this context, we recently developed a framework that uses jets (instead of single hadrons) to achieve reduced sensitivity to final-state non-perturbative effects. Moreover, a suitable non-standard jet definition allows us to apply the factorization formulas valid for hadrons to jets of arbitrary size, by just replacing fragmentation functions with the jet functions we computed. Besides presenting the framework, I will show numerical predictions at N<sup>2</sup>LL accuracy.

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## Towards transverse-momentum-dependent splitting functions in kT-factorization

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In this talk we review the project aiming and computing transverse-momentum-dependent splitting functions featuring correct collinear and high-energy limit that we started in refs. [arXiv:1711.04587, arXiv:1607.01507, arXiv:1511.08439]. At the moment we have obtained the real-emission parts of all the kernels (P<sub>gg</sub>, P<sub>gq</sub>, P<sub>qg</sub> and P<sub>qq</sub>) at LO. After introducing the methods used for defining and computing the real corrections we concentrate on the current effort aiming at calculating the virtual corrections and we present its current status.

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## ITMD factorization its phenomenological applications and its recent developments

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I would like to present application of Improved Transversal Momentum Dependent factorization to description of measurement of dijets production in forward rapidity region in p-p and p-Pb collisions. Furthermore recent results on constructing Transversal Momentum Dependent parton densities needed for calculation of 3 and for 4 jet final states will be presented.

**WG4: Hadronic and Electroweak Observables / 224****DIS with KaTie****Author:** Andreas van Hameren<sup>1</sup><sup>1</sup> *IFJ PAN***Corresponding Author:** hameren@ifj.edu.pl

KaTie is a parton level event generator that can deal with space-like initial-state partons, which occur in factorization prescriptions for hadron scattering that involve non-vanishing momentum components transverse to scattering hadrons. Since recently, it is possible to perform calculations with KaTie for deep inelastic scattering, including the possibility for a space-like initial-state parton. This update along with possible applications and some results will be discussed.

**WG4: Hadronic and Electroweak Observables / 315****Next-to-leading logarithmic processes in High Energy Jets****Author:** James Black<sup>1</sup><sup>1</sup> *IPPP***Corresponding Author:** james.a.black@durham.ac.uk

High Energy Jets (HEJ) provides all-order summation of the perturbative terms dominating the production of well-separated multiple jets at hadron colliders to leading log accuracy. We will present the first calculation of all the real next-to-leading high energy logarithms to the processes of pure jet and W-boson production in association with at least two jets. I will discuss the impact of the sub-leading channels on the predictions for experimentally measured distributions.

**WG4: Hadronic and Electroweak Observables / 174****Correlations in high-mass jets****Author:** Karoly Ueramoessy<sup>1</sup><sup>1</sup> *Chinese Academy of Sciences (CN)***Corresponding Author:** karoly.ueramoessy@cern.ch

I present the longitudinal and transverse momentum distributions, two particle eta-phi correlations and azimuthal anisotropy ( $v_2$ ) of pions in jets of high mass, obtained in a newly developed fragmentation model [1-4]. In this model, the jet mass is used as the fragmentation scale, and the scale evolution is calculated in the  $\phi^3$  theory. The initial form of the fragmentation function at starting scale  $Q_0$  is obtained in a model based on a micro-canonical statistics and superimposed negative-binomial multiplicity fluctuations.

[1] Eur.Phys.J. A53 (2017) no.2, 36

[2] PoS DIS2016 (2016) 054

[3] PoS DIS2017 (2018) 183

[4] Acta Phys.Polon. B48 (2017) 1225



**WG4: Hadronic and Electroweak Observables / 76****Measurement of jet fragmentation using the ATLAS detector****Author:** ATLAS Collaboration<sup>None</sup>

Gluon splitting to b-quark pairs is a unique probe of the properties of gluon fragmentation, as the identified b-tagged jets provide a proxy for the quark daughters of the initial gluon. We present a measurement of key differential distributions related to  $g \rightarrow b \bar{b}$  using data collected with the ATLAS detector at  $\sqrt{s}=13$  TeV. Track jets are used to probe angular scales below the standard  $R=0.4$  jet radius. The observables are unfolded to particle level in order to facilitate direct comparison with predictions from simulations and provide an important constraint to hadronization models. If available, a measurement of the properties of jet fragmentation performed with proton-proton collision data collected with the ATLAS detector at  $\sqrt{s}=13$  TeV will also be presented. Charged particle tracks are used to measure charged particle multiplicity, the jet charge, the summed fragmentation function, the momentum transverse to the jet axis, and the radial profile of the jet. Each observable is unfolded to correct for acceptance and detector effects. Exclusive interpretations in terms of quarks and gluons are provided in order to directly compare with state-of-the-art calculations.

**WG4: Hadronic and Electroweak Observables / 163****Towards a W boson mass measurement with LHCb****Authors:** Katharina Mueller<sup>1</sup>; Martina Pili<sup>2</sup><sup>1</sup> *Universitaet Zuerich (CH)*<sup>2</sup> *University of Oxford (GB)***Corresponding Author:** martina.pili@cern.ch

LHCb provides unique opportunities to study W and Z boson production at forward rapidities at the LHC.

It has recently been suggested that a new measurement of the W boson mass by LHCb would complement measurements by ATLAS and CMS.

All measurements of the W mass at the LHC are susceptible to PDF uncertainties, but there would be a partial cancellation of the overall PDF uncertainty when the LHCb result is included in an average with measurements by ATLAS and CMS.

Here we review measurements of W and Z boson production by LHCb, and report on a new study of the PDF uncertainty on the LHCb measurement of the W mass.

The latter study includes the proposal of a new approach which should reduce the PDF uncertainty by roughly a factor of two with LHCb Run 2 data.

**WG4: Hadronic and Electroweak Observables / 73****Measurements of inclusive WW and WZ production with ATLAS****Author:** ATLAS Collaboration<sup>None</sup>**Corresponding Author:** valerie.lang@cern.ch

Measurements of electroweak boson pair production at the LHC constitute a stringent test of the electroweak sector and provide a model-independent means to search for new physics at the TeV scale. In this talk, we present recent results for inclusive WW and WZ production in proton-proton collisions at  $\sqrt{s}=13$  TeV, including polarisation studies in the WZ final state. The precision measurements are compared to theoretical predictions at NLO (and NNLO) in perturbative QCD. The data

are sensitive to anomalous triple gauge couplings and are reinterpreted in terms of an effective field theory to constrain new physics beyond the Standard Model.

**WG4: Hadronic and Electroweak Observables / 167**

## **Z boson production in proton-lead collisions at the LHC accounting for transverse momenta of initial partons**

**Author:** Krzysztof Kutak<sup>1</sup>

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I would like to report on a calculation of inclusive Z boson production in proton-lead collisions at the LHC taking into account the transverse momenta of the initial partons. We use the framework of kT-factorization combining transverse momentum dependent parton distributions (TMDs) with off-shell matrix elements. In order to do it we need to construct appropriate TMDs for lead nuclei which is done using the parton branching method. Our computations are compared with data from CMS taken at  $\sqrt{s} = 5.02$  TeV. The results are in good agreement with the measurements especially the transverse momentum distribution of the Z boson.

**WG4: Hadronic and Electroweak Observables / 113**

## **Multiplicity dependence of azimuthal particle correlations as a probe of collectivity in deep inelastic electron-proton collisions at HERA**

**Author:** Iris Abt<sup>1</sup>

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Recent observations at RHIC and the LHC of two- and multi-particle correlations in high multiplicity relativistic proton-proton and proton-ion collisions and similarity of the results to those observed in central heavy-ion collisions are often interpreted as an evidence for collective particle production in small collision systems. These results motivate a study in even smaller systems, such as produced in relativistic electron-proton collisions. We present a measurement of two-particle correlations in collisions of electron beams at 27.5 GeV with beams of protons at 920 GeV, which corresponds to 318 GeV center-of-mass energy. A sample of events equivalent to the integrated luminosity of  $380 \text{ pb}^{-1}$  was recorded with the ZEUS experiment in 2003-2007. The correlations are measured for charged hadrons as a function of event multiplicity for the lab pseudo-rapidity range  $-1.5 < \eta_{\text{lab}} < 2$ . To probe the possible contribution due to collective effects, the correlations are studied as a function of the particle's pair separation in pseudo-rapidity and the pair mean transverse momentum. The observed correlations are compared to available Monte Carlo models of deep inelastic electron-proton scattering. Observations based on the analysis of the ZEUS data put a limit on the possible collective effects in high multiplicity electron-proton collisions.

**WG4: Hadronic and Electroweak Observables / 351**

## **Precise predictions for the production of jets in deep inelastic scattering**

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The production of hadronic jets in deep-inelastic lepton-proton scattering (DIS) is sensitive both to the strong and electroweak sectors of the Standard Model and constitutes one of the most precise probes to study the inner structure of the proton. It further provides crucial constraints on the flavour composition of the proton and thus in the extraction of parton distribution functions.

I will present precise QCD predictions to the jet-production process in DIS at  $O(\alpha_s^3)$  both for the neutral- and the charged-current process. These results pave the way for precision phenomenology using jet observables at future lepton-proton colliders.

**WG4: Hadronic and Electroweak Observables / 350**

## Recent results on Kaon decays from NA48/2

**Author:** NA48/2 Collaboration<sup>None</sup>

Final results of recent NA48/2 measurements are presented.

The charged kaon semileptonic form factors have been precisely measured from 4.4 million  $Ke_3$  and 2.3 million  $K\mu_3$  events collected in 2004.

In addition, the first observation of the  $K^{*-} \rightarrow \pi^+ \pi^0 e^- e^-$  decay is reported, with a sample of about 4900 candidates and less than 5% background.

The measured branching ratio in the full kinematic region is  $(4.24 \pm 0.14) \times 10^{-6}$ , in good agreement with ChPT predictions.

**WG4: Hadronic and Electroweak Observables / 354**

## Precise predictions for diboson production at the LHC

**Author:** Marius Wiesemann<sup>1</sup>

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Diboson measurements at the LHC require precision that can be reached only by state-of-the-art perturbative computations. In this talk, I will review the most important higher-order corrections to diboson processes and their consistent combination. This involves NNLO QCD corrections, NLO EW corrections and NLO QCD corrections to the loop-induced  $gg$  contribution, all of which are necessary to reach the percent-level precision goal set by the LHC experiments. Also the combination of NNLO QCD with all order results is discussed for diboson production.

**WG4: Hadronic and Electroweak Observables / 367**

## EFT in vector-boson scattering

**Author:** Raquel Gomez Ambrosio<sup>1</sup>

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In this talk we investigate how new physics effects can be systematically included in the family of vector boson processes (VBF, VBS, diboson), by means of the Standard Model Effective Field Theory (SMEFT) parametrisation. We discuss which effects can be searched for in LHC Run-2 and HL-LHC, and how this set of processes involving electroweak vertices and very energetic jets can be used to add extra information on the currently available fits.

**WG4: Hadronic and Electroweak Observables / 349**

## Latest results from NA62

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$K \rightarrow \pi \nu \bar{\nu}$  is one of the theoretically cleanest meson decay where to look for indirect effects of new physics complementary to LHC searches. The NA62 experiment at CERN SPS is designed to measure the branching ratio of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay with 10% precision. NA62 took data in 2015-2018; the analysis of a partial data set allows to reach the Standard Model sensitivity. The status of the experiments will be reviewed, and prospects will be presented.

Owing to the high beam-energy and a hermetic detector coverage, NA62 also has the opportunity to directly search for a variety of long-lived beyond-the Standard Model particles, such as Axion-like Particles and Dark Photons. In this talk we will review the status of invisible vector boson searches from  $\pi^0$  decays. The status and prospects of searches for lepton flavour and lepton number violation in kaon decays at the NA62 experiment we also be presented.

**WG4: Hadronic and Electroweak Observables / 355**

## On the $t\bar{t}\gamma/t\bar{t}$ cross section ratio at the LHC

**Authors:** Heribertus Bayu Hartanto<sup>1</sup>; Manfred Kraus<sup>2</sup>; Torsten Weber<sup>3</sup>; Malgorzata Maria Worek<sup>4</sup>; Giuseppe Bevilacqua<sup>None</sup>

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We study the ratio of the cross sections for  $t\bar{t}\gamma$  and  $t\bar{t}$  production at the LHC. We argue that, due to correlations between the theoretical uncertainties in the numerator and in the denominator, a very precise determination of this observable can be achieved at NLO QCD accuracy, with an uncertainty comparable to that of typical NNLO QCD computations. Thus, the ratio has an interesting potential to shed light on possible new physics that can reveal itself only when sufficiently precise theoretical predictions are available.

Our analysis is based on fully realistic NLO QCD simulations of  $t\bar{t}\gamma$  and  $t\bar{t}$  production in the dilepton decay channel, including complete off-shell effects and non-resonant contributions. Focusing on the case of the LHC at 13 TeV, we present numerical results for inclusive and differential cross section ratios. We also quantify the impact of the theoretical uncertainties

related to renormalization/factorization scales as well as to different choices of parton distribution functions.

**WG4: Hadronic and Electroweak Observables / 368**

## Measurements of inclusive neutral diboson production with ATLAS

**Corresponding Author:** valerie.lang@cern.ch

In this talk, we present a number of recent measurements of inclusive  $ZZ$  and  $Z\gamma$  production in proton-proton collisions at  $\sqrt{s}=13$  TeV at ATLAS. The unfolded differential cross section for  $ZZ \rightarrow 4l$  as a function of the four-lepton invariant mass is presented and compared to state-of-the-art Standard Model calculations. If available, an additional measurement of  $ZZ$  production will be presented for events in which the  $ZZ$  system decays to two charged leptons and two neutrinos. We also report measurements of  $Z$ -boson production in association with a high-energy photon, using the  $Z$ -boson decay to neutrinos and (if available) the  $Z$  boson decay to  $b$ -quarks. The data in all these measurements can be used to search for triple- and quartic- neutral gauge boson interactions, which are forbidden at tree-level in the Standard Model. No excess is observed relative to the Standard Model expectation, and upper limits are set on the strength of  $ZZ\gamma$  and  $Z\gamma\gamma$  couplings.

**WG5: Physics with Heavy Flavours / 13**

## Heavy-flavour hadron production at LHCb

**Authors:** Hans Dembinski<sup>1</sup>; for the LHCb collaboration<sup>None</sup>

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The LHCb experiment allows to measure the production and polarisation of charm and beauty hadrons including quarkonia in various collision systems in collider and fixed-target mode. The forward rapidity acceptance in the laboratory frame and the covered  $Q^2$  range test perturbative QCD calculations with their factorisation assumptions and put constraints on parton densities in unique kinematic regimes. In this talk, recent measurements on inclusive production in  $pp$  and  $pPb$  collisions in collider mode at different centre-of-mass-energies and fixed-target mode will be presented.

**WG5: Physics with Heavy Flavours / 17**

## Heavy flavour spectroscopy and exotic states at the LHC

**Author:** Katharina Mueller<sup>1</sup>

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The spectroscopy of excited hadronic states in the beauty sector, double heavy hadrons and quarkonia provides a rich proofing ground for effective theories of the strong interaction. The decays of these states also provide a source of exotic hadrons, especially in the charmonium mass region. The

unique data samples collected during Run I and II of the LHC open new possibilities for precision studies of these states. Recent results from LHCb on heavy hadron spectroscopy, including exotic mesons and baryons will be presented.

**WG5: Physics with Heavy Flavours / 55**

## Spectroscopy of conventional hadrons at e+e- machines

**Author:** Shohei Nishida<sup>1</sup>

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The largest data sample accumulated by the Belle experiment at KEKB asymmetric energy e+e- collider provides an opportunity to perform studies of hadron spectroscopy. We present new measurements on charmed baryons such as  $\Xi_c^0$ ,  $\Lambda_c$ , as well as other charmed mesons and strange baryons. In this presentation, we also cover recent results on hadron spectroscopy from Babar and BES III.

**WG5: Physics with Heavy Flavours / 56**

## Results from Charm baryon spectroscopy at LHCb, Belle and BESIII

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The spectroscopy of charm baryons provides a rich proving ground for effective theories of the strong interaction. This talk will present recent measurements of charmed baryons at LHCb, BESIII, and Belle. Discoveries of previously unobserved states in recent years will be discussed, along with precise determinations of the properties of known states.

**WG5: Physics with Heavy Flavours / 104**

## Production of quarkonia and heavy flavour states in ATLAS

**Author:** ATLAS Collaboration<sup>None</sup>

**Corresponding Author:** paolo.iengo@cern.ch

Associated production of vector boson with quarkonia is a key observable for understanding the quarkonium production mechanisms, including the separation of single and double parton scattering components. This talk will present the latest differential measurements from ATLAS of associated-quarkonium production. In addition, recent results on heavy flavour production measurements are reported in the Bu and Bc systems.

**WG5: Physics with Heavy Flavours / 170****Results of the XYZ states from experiments****Authors:** Peirong Li<sup>None</sup>; Liang Yan<sup>1</sup><sup>1</sup> *Universita e INFN Torino (IT)***Corresponding Author:** liang.yan@cern.ch

Recent years tremendous progress has gained in the study of the exotic states (so called XYZ) in both experiment and theory. In this talk, we will review the experimental results of the XYZ study.

**WG5: Physics with Heavy Flavours / 232****Quarkonium results in heavy-ion collisions****Author:** Roberta Araldi<sup>1</sup><sup>1</sup> *Universita e INFN Torino (IT)*

Quarkonium states are powerful tools to study the properties of the quark-gluon plasma (QGP), since their production is strongly affected by the dense and hot medium created in heavy-ion collisions.

In nucleus-nucleus interactions at LHC energies, charmonia reveal a smaller suppression with respect to the one measured at lower energies, as at RHIC and SPS. This observation points to the existence of two competing mechanisms, a suppression and a (re)combination process, affecting quarkonium production.

The role played by these mechanisms is confirmed by the measurement of a significant  $J/\psi$  elliptic flow ( $v_2$ ) in semi-central collisions. The large observed  $v_2$  is also suggestive of a strong participation of the charm quarks to the medium collectivity.

In the bottomonium sector, a hint for a sequential suppression of  $\Upsilon$  states is observed at RHIC and LHC, allowing a first theory-based attempt to extract the QGP temperature.

Proton-nucleus interactions allow us to address the influence of cold nuclear effects on quarkonium production. Mechanisms such as the modification of the parton distribution functions in nuclei or the coherent energy loss of the  $q\bar{q}$  pair in the medium are relevant for describing the production of quarkonium ground states. On the contrary, final state mechanisms, possibly related to the presence of a dense medium, are required to explain the stronger suppression of the excited quarkonium states.

In this talk, a review of the large wealth of increasingly precise data, from RHIC and LHC experiments, will be presented, together with a comparison to the state-of-the-art theory models.

**WG5: Physics with Heavy Flavours / 10****Quarkonium studies at Belle II****Author:** Ida Peruzzi<sup>1</sup><sup>1</sup> *Laboratori Nazionali di Frascati dell'INFN*

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The Belle II experiment at the SuperKEKB energy-asymmetric  $e^+e^-$  collider is a substantial upgrade of the B factory facility at the Japanese KEK laboratory. 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 of this year, the machine has completed a commissioning run, achieved a peak luminosity of  $5.5 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ , and Belle II has recorded a data sample of about  $0.5 \text{ fb}^{-1}$ . Belle II is uniquely capable of studying the so-called “XYZ” particles: heavy exotic hadrons consisting of more than three quarks. First discovered by Belle, these now number in the dozens, and represent the emergence of a new category within quantum chromodynamics. This talk will present the prospects of Belle II to explore both exotic and conventional quarkonium physics.

**WG5: Physics with Heavy Flavours / 309**

## Heavy flavor/quarkonium production at the LHC

**Author:** Hee Sok Chung<sup>1</sup>

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We review theoretical approaches to heavy flavor and quarkonium production mechanisms in hadron colliders. We discuss the application of the factorization theorem to heavy flavor production, and introduce implementations of the formalism in phenomenological calculations. For heavy quarkonium production, we give an overview of various production mechanisms, including phenomenological models and nonrelativistic effective field theory calculations.

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## Heavy-flavor hadron production in heavy-ion collisions

**Author:** Petr Chaloupka<sup>1</sup>

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Measurements with hadrons containing heavy quarks are indispensable when studying the properties of the medium created in high-energy nuclear collisions. High-statistics data collected by experiments at RHIC and LHC allow to perform comprehensive studies of the hot and dense QCD matter using heavy quarks as probes and put under scrutiny models describing various aspects of production of heavy-flavor hadrons.

In this talk I will give an overview of the most recent experimental results on heavy flavor production from RHIC and LHC experiments in pp, pA, and AA collisions in range of energies from  $\sqrt{s_{NN}}=200 \text{ GeV}$  to 8 TeV and discuss their physics interpretation.

**WG5: Physics with Heavy Flavours / 12**

## B-flavour anomalies in $b \rightarrow sll$ and $b \rightarrow clnu$ transitions at LHCb



**Author:** Katharina Mueller<sup>1</sup>

<sup>1</sup> *Universitaet Zuerich (CH)*

The concept of lepton universality, where the muon and tau particles are simply heavier copies of the electron, is a key prediction in the Standard Model (SM). In models beyond the SM, lepton universality can be naturally violated with new physics particles that couple preferentially to the second and third generation leptons. Over the last few years, several hints of lepton universality violation have been seen in both  $b \rightarrow c$  and  $b \rightarrow s$  semileptonic beauty decays. This presentation will review these anomalies and give an outlook for the near future. Other probes of NP in highly suppressed  $b$ -hadron decays will also be discussed.

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## Top quark pair and single top t-channel differential cross sections in CMS

**Author:** CMS Collaboration<sup>None</sup>

Differential measurements of top quark pair ( $t\bar{t}$ ) and single top quark (t-channel) production cross sections are presented using data collected by CMS. The cross sections are measured as a function of various kinematic observables of the top quarks and the jets and leptons of the event final state. The results are confronted with precise theory calculations. For the first time, multidifferential  $t\bar{t}$  cross sections are presented and used to constrain simultaneously the top quark pole mass,  $\alpha_S$ , and PDFs.

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## Measurements of the top quark mass using the ATLAS detector at the LHC

**Author:** ATLAS Collaboration<sup>None</sup>

The latest measurements of the top quark mass using the ATLAS experiment are presented. A measurement based on a multi-dimensional template fit that can constrain the uncertainties on the energy measurements of jets is presented and combined with measurements using dilepton and all-hadronic events. In addition an analysis of the top quark mass using leptonic kinematic variables is discussed. The measurement uses a novel technique to measure the top quark mass with minimal dependence on hadronic jets. The measurements that use precision theoretical QCD calculations for both inclusive  $t\bar{t}$  production and  $t\bar{t}$  production with an additional jet to extract the top quark mass in the pole-mass scheme are also presented.

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## Top quark pair property measurements using the ATLAS detector at the LHC

**Author:** ATLAS Collaboration<sup>None</sup>

Precise measurements of the properties of the top quark test the Standard Model (SM) and can be used to constrain new physics models. The top-quark is predicted in the SM to decay almost exclusively into a W boson and a b-quark. We present a wide range of searches for non-SM top quark decays

using the 13 TeV ATLAS datasets, including  $t \rightarrow q$  H and  $t \rightarrow q$  Z. In addition, measurements of the spin correlation and colour flow in  $t\bar{t}$  production are also presented.

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## Top quark pair-production cross-section measurements with the ATLAS detector

**Author:** ATLAS Collaboration<sup>None</sup>

Measurements of the inclusive and differential top-quark pair cross sections in proton-proton collisions at 13 TeV with the ATLAS detector at the Large Hadron Collider are presented. The inclusive measurements reach high precision and are compared to the best available theoretical calculations. Differential measurements of the kinematic properties of the top quark production are also discussed. These measurements, including results using boosted top quarks, probe our understanding of top quark pair production in the TeV regime. The results, unfolded to particle and parton level, are compared to predictions of Monte Carlo generators implementing NLO matrix elements matched with parton showers and NNLO QCD theory calculations.

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## Measurement of $t\bar{t}$ with additional jets with the ATLAS detector

**Author:** ATLAS Collaboration<sup>None</sup>

Measurements of the production cross-section of top-antitop quark pairs with additional jets provide important tests of quantum chromodynamics (QCD) predictions.

The ATLAS experiment has measured several final state observables that are sensitive to additional radiation in top-quark-antiquark final states at 13 TeV. These measurements are compared to predictions of modern Monte Carlo generators based on NLO QCD matrix element or LO multi-leg matrix elements.

The process of a  $t\bar{t}$  pair produced in association with jets originating from b-quarks (b-jets) is particularly important to measure, as there are many uncertainties in the calculation of the process due to the relevance of multiple energy scales. The ATLAS Collaboration has performed fiducial cross-section measurements in the dilepton and lepton-plus-jets  $t\bar{t}$  decay channels. Results are presented at particle level in the form of inclusive cross-sections of  $t\bar{t}$  final states with three and four b-jets as well as differential cross-sections as a function of global event properties and properties of b-jet pairs.

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## Open heavy-flavour production with ALICE at the LHC.

**Author:** Annelies Marianne Veen<sup>1</sup>

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Heavy quarks (charm and beauty) are unique probes for studies of the properties of the Quark-Gluon Plasma (QGP) formed in high-energy Pb-Pb collisions, since they are almost exclusively produced in hard scattering processes in the initial stages of the collision and thus experience the full evolution

of the QGP.

In order to distinguish the effects of the QGP from possible Cold Nuclear Matter (CNM) effects, such as shadowing,  $k_T$  broadening and initial-state energy loss, comparisons are made between results in p-Pb and Pb-Pb which are both studied with respect to pp collisions. Measurements in pp collisions do not only provide a reference p-Pb and Pb-Pb measurements, but also constitute as an excellent test of next-to-leading-order perturbative QCD calculations in the TeV energy regime.

Furthermore, studies of heavy-flavour production as a function of charged-particle multiplicity in small systems shed light on the possible presence of collective effects at high multiplicities in such systems, as well as on the dependence of CNM effects on the collision geometry.

The ALICE detector at the LHC studies open heavy-flavour production at mid-rapidity via hadronic and semi-electronic decays, and via semi-muonic decays at forward rapidity. In this contribution, we will present recent results on heavy-flavour production in pp, p-Pb and Pb-Pb collisions with ALICE.

**WG5: Physics with Heavy Flavours / 109**

## Measurement of beauty production from dimuon events at HERA

**Author:** Achim Geiser<sup>1</sup>

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Beauty production in events containing two muons in the final state has been measured with the ZEUS detector at HERA II. A low transverse-momentum threshold for muon identification, in combination with the large rapidity coverage of the ZEUS muon system and the upgraded ZEUS tracker, gives access to almost the full phase space for beauty production. The total cross section for beauty production in  $ep$  collisions at  $\sqrt{s} = 318$  GeV has been measured. Differential cross sections and a measurement of  $b\bar{b}$  correlations are also obtained. All are compared to previous beauty cross-section measurements, Monte Carlo models and next-to-leading-order QCD predictions. The previous ZEUS measurements are confirmed with higher precision.

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## Explaining the Flavour Anomalies with Leptoquarks

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The recent intriguing hints for new physics in semi-leptonic B decays point towards lepton flavor universality (LFU) violating extensions of the SM. Prime candidates for such new particles are leptoquarks which can provide the desired effects. After a review of the current experimental and theoretical situation, the phenomenology of the vector leptoquark SU(1) singlet, which was proposed already a long time ago in the context of the famous Pati-Salam model, is discussed. A focus will be laid on important loop-effects, which allow for LFU conserving new physics alongside of LFU violating one.

**WG5: Physics with Heavy Flavours / 258****Radiative leptonic decay  $B \rightarrow \gamma \ell \nu_\ell$  with subleading power corrections****Author:** Yao Ji<sup>1</sup>**Co-authors:** Martin Beneke<sup>2</sup>; Vladimir Braun<sup>1</sup>; Yan-Bing Wei<sup>3</sup><sup>1</sup> *University of Regensburg*<sup>2</sup> *Technical University Munich*<sup>3</sup> *Nankai University*

We discuss the QCD predictions for the radiative decay  $B \rightarrow \gamma \ell \nu_\ell$  with an energetic photon in the final state by taking into account the  $1/E_\gamma, 1/m_b$  power-suppressed hard-collinear and soft corrections from higher-twist  $B$ -meson light-cone distribution amplitudes (LCDAs). The soft contribution is estimated through a dispersion relation and light-cone QCD sum rules. The analysis of theoretical uncertainties and the dependence of the decay form factors on the leading-twist LCDA  $\phi_+(\omega)$  shows that the latter dominates. The radiative leptonic decay is therefore well suited to constrain the parameters of  $\phi_+(\omega)$ , including the first inverse moment,  $1/\lambda_B$ , from the expected high-statistics data of the BELLE II experiment.

**WG5: Physics with Heavy Flavours / 364****Rare top production  $ttW, ttZ, tt\gamma, tttt$  at the LHC****Author:** Joscha Knolle<sup>1</sup><sup>1</sup> *Deutsches Elektronen-Synchrotron (DE)***Corresponding Author:** joscha.knolle@cern.ch

A comprehensive set of measurements of top quark pair and single top quark production in association with EWK bosons (W, Z or  $\gamma$ ) is presented. The results are compared to theory predictions and re-interpreted as searches for new physics inducing deviations from the standard model predictions using an effective field theory approach. 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.

**WG5: Physics with Heavy Flavours / 365****Top properties at the LHC****Author:** Baptiste Ravina<sup>1</sup><sup>1</sup> *University of Sheffield (GB)***Corresponding Author:** baptiste.ravina@sheffield.ac.uk

Measurements of top quark properties using data collected by the LHC are presented. Among them, latest results on top mass,  $t\bar{t}$  spin correlations and charge asymmetries will be discussed.

**WG5: Physics with Heavy Flavours / 362****Theory: Top properties at the LHC****Author:** Markus Schulze<sup>1</sup><sup>1</sup> *Argonne National Laboratory***Corresponding Authors:** schulze@pha.jhu.edu, schulze@particle.uni-karlsruhe.de, markus.schulze@anl.gov

I give an overview talk on recent theoretical studies of top quark properties. Starting from basic quantities such as the top quark mass and spin correlations, I discuss more sophisticated quantities related to the electroweak interactions and dipole moments. These couplings can be probed at the LHC in a multitude of different ways. I will present some of the most recent ideas and proposals.

**WG5: Physics with Heavy Flavours / 366****Single top production at the LHC****Author:** CMS Collaboration <sup>None</sup>**Corresponding Author:** achim.geiser@cern.ch

Latest results on inclusive and differential single top quark production cross sections are presented using proton-proton collision data collected by the LHC. The single top quark analyses investigate separately the production of top quarks via t-channel exchange, in association with a W boson (tW) or via the s-channel. Final states with at least one charged lepton and one b-jet are explored to measure inclusive production cross sections. The sensitivity of some these measurements to PDFs and extraction of standard model parameters is also described.

**WG5: Physics with Heavy Flavours / 358****Top pairs at the LHC****Author:** Sergio Grancagnolo<sup>1</sup><sup>1</sup> *Humboldt University of Berlin (DE)***Corresponding Author:** sergio.grancagnolo@cern.ch

Latest results on inclusive top quark pair production cross sections are presented using proton-proton collision data collected at the LHC. The inclusive measurements reach high precision and are compared to the best available theoretical calculations. Differential measurements of the kinematic properties of the top quark production are also discussed. These measurements, including results using boosted top quarks, probe our understanding of top quark pair production in the TeV regime. The results, unfolded to particle and parton level, are compared to predictions of Monte Carlo generators implementing NLO matrix elements matched with parton showers and NNLO QCD theory calculations.

**WG5: Physics with Heavy Flavours / 274****Direct determination of top quark width with bb4l**

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In the context of the Standard Model (SM) of particle physics, the relationship between the mass of top quark and its width has been precisely calculated. However, the uncertainty from current direct measurements of the width is nearly 50%. A new approach for directly measuring the top quark width is presented, using events away from the resonance peak.

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## Constraining gluon PDFs and TMDs with quarkonium production

**Authors:** Melih Arslan Ozcelik<sup>1</sup>; Miguel Echevarria<sup>2</sup>; Jean-Philippe Lansberg<sup>3</sup>; Cristian Pisano<sup>4</sup>; Andrea Signori<sup>5</sup>

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We explore how the positivity of the  $P_T$ -integrated  $\eta_c$ -hadroproduction cross section computed at NLO in  $\alpha_s$  can set up constraints on the  $x$  dependence of both gluon PDFs and TMDs at low scales. We also discuss the phenomenological implications on other quarkonium-production cross sections computed at NLO in both collinear and TMD factorisations.

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## Enhanced production of $\Lambda_c$ in proton-proton collisions at the LHC

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We calculate the cross section for the production of  $D$  mesons and  $\Lambda_c$  baryons in pp collisions at the LHC. The cross section for production of  $c\bar{c}$  pairs is calculated within the  $k_T$ -factorization approach. We show that our approach well describes the  $D^0$ ,  $D^+$ , and  $D_s$  experimental data. We try to understand recent ALICE and LHCb data for  $\Lambda_c$  production with the  $c \rightarrow \Lambda_c$  independent parton fragmentation approach. Although one can agree with the ALICE data using the standard estimation of model uncertainties, one cannot describe simultaneously the ALICE and the LHCb data with the

same set of parameters. The fraction  $f_{c \rightarrow \Lambda_c}$  necessary to describe the ALICE data is much larger than the average value obtained from  $e^+e^-$  or  $ep$  experiments. No drastic modification of the shape of the fragmentation function is allowed by the new ALICE and LHCb data for  $\Lambda_c$  production. We also discuss a possible dependence of the  $\Lambda_c/D^0$  baryon-to-meson ratio on rapidity and transverse momentum as recent observations by the ALICE and LHCb collaborations seem to suggest. Three different effects are considered: the value of the  $\varepsilon_c^\Lambda$  parameter in the Peterson fragmentation function for  $c \rightarrow \Lambda_c$ , a kinematical effect related to the hadronization prescription, and a possible feed-down from higher charmed-baryon excitations. It seems very difficult, if not impossible, to understand the ALICE data within the considered independent parton fragmentation scheme.

[1] R. Maciula and A. Szczurek, Phys. Rev. D98, no. 1, 014016 (2018).

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### Hadroproduction of open heavy flavour for PDF analyses

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Due to the large masses of the charm and bottom quarks, their production cross sections are calculable within the perturbative QCD. This makes the heavy-quark mesons important observables in high-energy collisions of protons and nuclei. However, the available calculations for heavy-flavored-meson hadroproduction have been somewhat problematic in reliably describing the cross sections across the full kinematic range from zero to very high  $p_T$ . This has put some question marks on the robustness of LHC heavy-flavored-meson measurements in studying the partonic structure of the colliding hadrons and nuclei. Here, we introduce SACOT- $m_T$  - a novel scheme for open heavy-flavour hadroproduction within the general-mass variable-flavour-number formalism, that solves this problem. The introduced scheme is an analogue of the SACOT- $\chi$  scheme in deeply-inelastic scattering and thereby well suited for PDF analyses.

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### Theory: top production at the LHC

**Author:** Rene Poncelet<sup>1</sup>

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This talk reviews the current theory status of top-quark production at the LHC. The production of top-quarks, the heaviest elementary particle known, is studied in great detail by the experiments ATLAS and CMS. It provides unique possibilities to extend our knowledge about the Standard Model and beyond. To make most of the precise data available, precise theory predictions for inclusive/fiducial and differential cross sections are required and allow to investigate the top-quark properties in an unprecedented detail. Recent progress in fixed order perturbation theory as well as in resummation techniques are discussed.

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## Sivers function at NLO

**Authors:** Scimemi Ignazio<sup>None</sup>; Tarasov Andrey<sup>None</sup>; Vladimirov Alexey<sup>None</sup>

The Sivers function is benchmark for spin physics. The systematic calculation of this observable in QCD has been object of many studies. We discuss here a methodology for calculation which allows to rederive systematically the NLO calculation and that can be used for all other twist-3 TMDs.

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## High-z proton and kaon multiplicity ratios on deuteron target

**Authors:** Marcin Stolarski<sup>1</sup>; COMPASS Collaboration<sup>None</sup>

<sup>1</sup> *LIP Laboratorio de Instrumentacao e Fisica Experimental de Part*

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Recently COMPASS has reported unexpected results concerning K<sup>-</sup> over K<sup>+</sup> multiplicity ratio for kaons produced in DIS with a large fraction of the virtual-photon energy, PLB 786 (2018) 390. The obtained ratio is significantly below the lower limit given by NLO pQCD.

In order to provide more information about the observed phenomenon we will show for the first time results concerning pbar over p multiplicity ratio for protons produced in DIS with a large fraction of the virtual-photon energy. In addition the kaon multiplicity ratio will be presented in an extended kinematic phase-space with respect to the one used in the aforementioned paper.

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## Transverse single-spin asymmetry with a $\sin \phi_{S_h}$ modulation for proton and lambda production in SIDIS at subleading twist

**Author:** Wenjuan Mao<sup>1</sup>

**Co-authors:** Yongliang Yang<sup>2</sup>; Zhun Lu<sup>2</sup>

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We investigate the transverse single-spin asymmetry with a  $\sin \phi_{S_h}$  modulation for the transversely polarized proton and lambda production in semi-inclusive inelastic scattering process, where  $\phi_{S_h}$  is the azimuthal angle of the transverse spin of the final hadron. Theoretically, the spin asymmetry can be interpreted by the convolution of the twist-3 transverse momentum dependent distributions and twist-2 fragmentation functions. In this work, three different origins in terms of the  $hH_1$  term, the  $f^\perp D_{1T}^\perp$  term and the  $g^\perp G_{1T}$  term are taken into account simultaneously for this asymmetry.

We calculate the twist-3 quark transverse momentum dependent distributions  $h$ ,  $f^\perp$  and  $g^\perp$  by using the quark spectator diquark model, and we investigate the role of the fragmentation functions  $H_1$ ,  $D_{1T}^\perp$  and  $G_{1T}$  in the  $\sin \phi_{S_h}$  asymmetry as well. We also predict the numerical results of the asymmetries for the proton and the lambda production at JLab with a 12 GeV beam and at COMPASS with a 160 GeV beam, separately. From the comparison of the different sources for the asymmetry, we find that, the distribution  $h$  and the fragmentation function  $H_1$  give the dominant contribution to the  $\sin \phi_{S_h}$  asymmetry for proton production, while the distribution  $f^\perp$  might be probed by the convolution with  $D_{1T}^\perp$  in the lambda production at JLab 12 GeV.



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## Comments on the perturbative and non-perturbative contributions in unpolarized SIDIS.

**Authors:** J. Osvaldo Gonzalez H.<sup>1</sup>; mariaelena boglione<sup>1</sup>; Andrea Simonelli<sup>1</sup>

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The extraction of unpolarized transverse momentum dependent functions (TMDs) has received a lot of attention in recent years. A successful extraction of these functions requires careful consideration of the interplay between perturbative and non-perturbative components in the definitions of the TMDs. In this talk, I will discuss how our knowledge of the unpolarized TMDs may be improved in light of recent developments. For concreteness, I will focus on the case of the most recent SIDIS data by the COMPASS collaboration.

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## Spectrally novel fragmentation function sum rules

**Authors:** Alberto Accardi<sup>1</sup>; Andrea Signori<sup>2</sup>

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We connect at the operator level the inclusive gauge-invariant quark propagator and the quark to single hadron fragmentation correlator in QCD. Exploiting a new spectral decomposition for the quark propagator, we then derive a complete set of momentum sum rules for the quark fragmentation functions into a single unpolarized hadron up to twist-three. Known results are recovered, and new sum rules discovered.

The spectral decomposition of the jet correlator also allows one to define a gauge-invariant dressed quark (or “jet”) mass. Remarkably, the mass sum rules for the  $E$  and  $\tilde{E}$  twist-3 fragmentation functions provide an experimental gateway to this jet mass and its interaction-dependent component, which can thus be potentially measured in deep-inelastic processes and shed light on the dynamical generation of mass in QCD.

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## Update on phenomenological extraction of the proton tensor charge

**Author:** Marco Radici<sup>None</sup>

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The tensor charge, namely the first Mellin moment of the chiral-odd transversity parton distribution, is not connected to operators entering the Standard Model Lagrangian at tree level. It could represent a low-energy footprint of new physics happening at much higher scales, hence it is important to know it with very high precision. I will present the latest results obtained by extracting the transversity distribution from a global analysis of pion-pair production in deep-inelastic scattering and in proton-proton collisions. In particular, I will discuss the impact of pseudodata connected to

future more precise measurements at both medium-low and high parton fractional momenta, and I will compare the projected results with recent lattice calculations of the valence and isovector components of the tensor charge.

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## Inclusion of the $3P_0$ model in PYTHIA 8

**Authors:** Albi Kerbizi<sup>1</sup>; Leif Lönnblad<sup>2</sup>

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We present our work on the inclusion of spin effects in the hadronization part of the PYTHIA 8 event generator. These effects are restricted to the emission of pseudoscalar mesons and are obtained from the propagation of the quark polarization along the fragmentation chain according to the rules of the  $^3P_0$  model.

The interface between PYTHIA 8 and the  $^3P_0$  model and the results on the Collins asymmetry obtained from simulations of the polarized SIDIS process are presented.

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## The gluon Sivers function and its process dependence from RHIC data

**Authors:** Cristian Pisano<sup>1</sup>; Umberto D'Alesio<sup>2</sup>; Carlo Flore<sup>3</sup>; Francesco Murgia<sup>4</sup>; Pieter Tael<sup>5</sup>

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Within the so-called color gauge invariant generalized parton model (CGI-GPM), which includes initial (ISI) and final state (FSI) interactions in a transverse momentum dependent formalism, we present a phenomenological analysis of available data on single spin asymmetries for pion and  $D$ -meson production in  $pp$  collisions at RHIC. This allows us, for the first time, to put preliminary constraints on the two universal types of gluon Sivers function entering the model. Predictions for single spin asymmetries in  $J/\psi$  and direct photon production, as well as a comparison with the simpler generalized parton model (without ISI and FSI), are also presented.

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## Longitudinal double-spin asymmetries in semi-inclusive deep-inelastic scattering of electrons and positrons by protons and deuterons

**Author:** Gunar Schnell<sup>1</sup>

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A comprehensive collection of results on longitudinal double-spin asymmetries is presented for charged pions and kaons produced in semi-inclusive deep-inelastic scattering of electrons and positrons on the proton and deuteron, based on the full HERMES data set. The dependence of the asymmetries on hadron transverse momentum and azimuthal angle extends the sensitivity to the flavor structure of the nucleon beyond the distribution functions accessible in the collinear framework. No strong dependence on those variables is observed. In addition, the hadron charge-difference asymmetry is presented, which under certain model assumptions provides access to the helicity distributions of valence quarks.

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## Relating TMDs & collinear twist-3 functions in the CSS formalism

**Author:** Leonard Gamberg<sup>None</sup>

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In this talk I will present our work on an improved implementation of the Collins Soper Stermann formalism for combining transverse-momentum-dependent (TMD) factorization and collinear factorization in semi-inclusive DIS (SIDIS). I will focus on our recent extension to the case of polarized observables; in particular the Sivers contribution to the transversely polarized target cross section. We demonstrate how one recovers the expected leading-order collinear twist-3 result from a (weighted)  $q_T$ -integral of the differential cross section. We are also able to re-derive at leading order the well-known relation between the TMD Sivers function and the (collinear twist-3) Qiu-Sterman function within this framework. This relation allows for the interpretation that the first moment of the Sivers function describes the average transverse momentum of unpolarized quarks in a transversely polarized spin-1/2 target.

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## Extraction of unpolarized transverse momentum dependent parton distribution functions (TMDPDF)

**Authors:** Alexey Vladimirov<sup>None</sup>; Valerio Bertone<sup>1</sup>; Ignazio Scimemi<sup>2</sup>

<sup>1</sup> *NIKHEF*

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I present the latest extraction of unpolarized quark transverse momentum dependent parton distribution functions (TMDPDFs) and the non-perturbative part of TMD evolution kernel from the global analysis of Drell-Yan and  $Z$ -boson production data. The analysis is performed at the next-to-next-to-leading order (NNLO) in perturbative QCD, using the  $\zeta$ -prescription. The estimation of the error-propagation from the experimental uncertainties to non-perturbative function is made by the replica method. The importance of the inclusion of the precise LHC data and its influence on the determination of non-perturbative functions is discussed.

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## The impact of the errors of collinear functions in describing un-integrated SIDIS data.

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

**Co-authors:** J. Osvaldo Gonzalez H.<sup>2</sup>; Mariaelena Boglione<sup>3</sup>

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Describing qT-dependent SIDIS distributions requires consideration of two different regimes which involve two different factorization schemes. In both cases, the necessary ingredients include parton distribution and fragmentation functions (PDFs and FF), which are traditionally extracted in statistical analyses with collinear observables. In this talk I will present examples of how the errors in the extraction of collinear PDFs and FFs may affect the successful description of the qT-dependent SIDIS distributions.

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## Exclusive photoproduction of a photon pair with a large invariant mass

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The electromagnetic probe has proven to be a very efficient way to access the three-dimensional structure of the nucleon, particularly thanks to the exclusive Compton processes. We explore the hard photoproduction of a large invariant mass diphoton in the kinematical regime where the diphoton is nearly forward and its invariant mass is the hard scale enabling to factorize the scattering amplitude in terms of generalized parton distributions. We calculate unpolarized cross sections and the angular asymmetry triggered by a linearly polarized photon beam.

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## Pion and Kaon multiplicities in SIDIS from COMPASS

**Author:** Nicolas Pierre<sup>1</sup>

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We present preliminary COMPASS results on pion and kaon multiplicities produced in semi-inclusive deep inelastic scattering of 160 GeV muons off a pure proton (LH<sub>2</sub>) target. The results constitute a

large data set of more than 600 points for pions and 600 for kaons, covering a large  $x$ ,  $Q^2$  and  $z$  domain in a fine binning. The results from the sum of the  $z$ -integrated multiplicities  $M^{\pi^+} + M^{\pi^-}$  and  $M^{K^+} + M^{K^-}$  and their ratio  $M^{\pi^+}/M^{\pi^-}$  and  $M^{K^+}/M^{K^-}$  are presented versus  $x$  and compared to previous COMPASS results on deuteron and other experiments like EMC and HERMES.

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## Linearly polarized gluons TMDPDFs at NNLO in QCD

**Author:** Sergio Leal Gómez<sup>1</sup>

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One of the most striking phenomena arising from the extension of collinear factorization (inspired in Bjorken's parton model) to Transverse Momentum Dependent (TMD) factorization is the appearance of azimuthal modulation induced by the polarization of partons with nonzero transverse momentum even inside unpolarized hadrons. Linearly polarized gluons inside unpolarized hadrons is one of these cases. We present the perturbative calculation of the matching coefficient onto unintegrated PDF in the limit of large  $q_T$  (or small  $b_T$ ) at NNLO in QCD.

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## Frame-independent angular distributions as density matrix invariants

**Authors:** Oleg Teryaev<sup>1</sup>; Margarita Gavrilova<sup>1</sup>

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The dilepton angular distribution in vector particle decays can be described through a set of five SO(3) rotational-invariant observables. These observables are derived as invariants of the spacial part of the hadronic tensor (density matrix) expressed in terms of angular coefficients. The restrictions on the invariants following from the positivity of the hadronic tensor are obtained. Special cases of SO(2) rotations are considered. Calculation of invariants for available data on Z and  $J/\psi$  decays is performed.

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## Probing Dihadron Fragmentation Functions and Twist-3 Parton Distribution Functions at CLAS12

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

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Dihadron production in Semi-Inclusive Deep Inelastic Scattering (SIDIS) represents a novel probe for nucleon structure, as well as for spin-orbit correlations in hadronization. Measurements of the beam spin asymmetry from dihadron production provide access to the twist-3 PDF  $e(x)$ , which can be related to the transverse polarization dependence of the transverse force experienced by a struck quark in an unpolarized nucleon. This asymmetry also provides access to the transverse momentum dependent Dihadron Fragmentation Function (DiFF),  $G_1^\perp$ , which describes the azimuthal dependence of the final state hadrons on the helicity of the parent quark, and can be thought of as the DiFF analog of the wormgear PDF. The CLAS12 experiment recently took data with longitudinally polarized electrons scattering off an unpolarized proton target, and is currently taking data using a deuterium target. Recent results from CLAS12 will be discussed, along with prospects for upcoming measurements.

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## Nucleon properties from basis light front quantization

**Authors:** Chandan Mondal<sup>1</sup>; Xiqi Xu<sup>1</sup>; Jiangshan Lan<sup>1</sup>; Xingbo Zhao<sup>1</sup>; Yang Li<sup>2</sup>; Henry Lamm<sup>3</sup>; James Vary<sup>2</sup>

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The basis light front quantization (BLFQ) approach has been developed for solving many-body bound state problems in quantum field theories. We investigate several aspects of the nucleon properties such as electromagnetic form factors, generalized parton distributions (GPDs) etc. using the framework of BLFQ. We consider the light front wavefunctions obtained by diagonalizing the effective Hamiltonian consisting of the holographic QCD confinement potential, the longitudinal confinement, and a one-gluon exchange interaction with fixed coupling. The obtained results in BLFQ formalism are compared with the light-front quark-diquark model constructed from the soft-wall AdS/QCD prediction.

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## Studying gluon TMDs with J/ψ pair production at the LHC

**Authors:** Florent Scarpa<sup>1</sup>; Jean-Philippe Lansberg<sup>2</sup>; Cristian Pisano<sup>3</sup>; Marc Schlegel<sup>4</sup>; Daniel Boer<sup>None</sup>; Miguel Echevarria<sup>5</sup>; Hua-Sheng Shao<sup>6</sup>; Andrea Signori<sup>7</sup>

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We report on our recent study on the extraction of the gluon Transverse Momentum Dependent distributions (TMDs) inside unpolarised protons, using vector quarkonium pair production at the LHC. In this work, we show how  $J/\psi$  pair production is an ideal process to pin down the gluon TMDs and generate large azimuthal asymmetries ; we also present a first fit of the average  $k_T$  parameter for a Gaussian model of the TMD f1g using LHCb data. We add new results including the effect of the evolution of the gluon TMDs, for the kinematics relevant for the LHCb, CMS and ATLAS data.

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## Energy-momentum tensor densities in the bag model

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The form factors of the energy-momentum tensor can be accessed via studies of GPDs in hard exclusive reactions. In this talk we present recent results on the EMT densities in the bag model. The simplicity and lucidity of this quark model allow us to investigate many general concepts which have recently attracted interest, including shear, pressure, radial and tangential forces. We also present the first study of the D-term of a  $N^*$  resonance. The results from the bag model are theoretically consistent, and comply with all general requirements.

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## Nuclear-dependence of transverse, single-spin asymmetries in charged hadron production in PHENIX

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The PHENIX experiment at RHIC studied the  $A$ -dependence of transverse, single-spin asymmetries in production of charged hadrons in collisions of polarized protons with aluminum and gold nuclei, as well as with protons. The measurements covered forward rapidities, between 1.4 and 2.4, over the transverse-momentum range of 1.8 to 7 GeV/ $c$ . We report on the observation of a significant asymmetry in  $p + p$  collisions, while the asymmetry is smaller for  $p+Al$  and consistent with zero for  $p+Au$  collisions. This observed  $A$ -dependence can provide important clues regarding transverse-spin dynamics in nucleon structure and hadron production.

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## Applications of the WW-type approximation to SIDIS

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We explore the complete cross-section for the production of unpolarized hadrons in semi-inclusive deep-inelastic scattering up to power-suppressed  $\mathcal{O}(1/Q^2)$  terms in the Wandzura–Wilczek-type approximation, which consists in systematically assuming that  $\bar{q}gq$ -correlators are much smaller than  $\bar{q}q$ -correlators. Under the applicability of Wandzura–Wilczek-type approximations, certain relations among TMDs occur which will be used to approximate SIDIS cross-section by a smaller subset of TMDs. We further discuss the applicability of the Wandzura–Wilczek-type approximations on the basis of available data.

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## Towards extraction of GPDs from DVCS data

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I will present two complementary analyses of nearly all existing Deeply Virtual Compton Scattering (DVCS) data allowing to explore the proton structure within the framework of Generalised Parton Distributions (GPDs). The first analysis is based on a classic approach, where parameterisations of DVCS amplitudes are constructed in a model-dependent way to fulfil the basic properties of GPDs. The second analysis starts from a model-independent extraction of DVCS amplitudes, which latter are interpreted in the language of GPDs. Both analyses allow to access the nucleon tomography and the so-called subtraction constant, which is related to the energy-momentum tensor and the mechanical forces acting on partons inside the proton. The usage of the neural network technique in the second analysis allows to reduce and estimate the model dependency. The work is done within the PARTONS framework being the modern tool for generic GPD studies.

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## New way to access the quark fragmentation functions in electron-positron annihilation

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The description of the polarized quark hadronization process is one of the most challenging problems in strong interactions. The various single hadron and dihadron fragmentation functions, that quantify this process, are determined by analyzing the inclusive production of hadrons in electron-positron annihilation process. These, in turn, are used to extract the transverse momentum dependent parton distribution functions from the experiments on semi-inclusive deep inelastic scattering process, elucidating the spin-orbit correlations in nucleon.

In this talk we present a framework for new measurement of polarized quark fragmentation functions in electron-positron annihilation process. This measurement offers a number of exciting opportunities to improve our understanding of the polarized quark hadronization and test the universality of the fragmentation functions, and can be performed at the upcoming BELLE II experiment.

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## Understanding the large $p_T$ spectrum in SIDIS

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With the upgrade of JLab 12 GeV, a new era for the exploration of partonic degrees of freedom in hadronic physics has started. In particular SIDIS is a key reaction to understand partonic structure of hadrons and the physics of hadronization provided a solid understanding and consistency of QCD factorization theorems to describe the data. In this talk I will review a recent progress to understand the physics of the large  $p_T$  spectrum in SIDIS in particular at COMPASS kinematics.

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## Measurement of the Longitudinal Single Spin Asymmetries for $W$ Boson Production in Polarized Proton-Proton Collisions at $\sqrt{s} = 510$ GeV at STAR

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The production of  $W$  bosons in longitudinally polarized proton-proton collisions at the Relativistic Heavy Ion Collider (RHIC) provides an ideal tool to study the spin-flavor structure of the proton, through the measurement of the parity-violating single-spin asymmetry,  $A_L$ . STAR has measured  $A_L$  for  $W$  boson production from datasets taken in 2011 and 2012 which provided significant constraints on the helicity distribution functions of  $\bar{u}$  and  $\bar{d}$  quarks. In 2013 the STAR experiment collected a large data sample of  $250 \text{ pb}^{-1}$  which is about three times larger than the total integrated luminosity from previous years. The final  $A_L$  results from the 2013 STAR data sample will be reported along with the combined results from the 2011–2013 data sets, and the impact of these results on the light sea quark helicity distribution functions.

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## Constraining the Polarized Gluon Distribution Function of the Proton with Recent STAR Measurements

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The contribution of the gluon helicity to the spin of the proton is being studied through the use of the unique capability of the Relativistic Heavy Ion Collider (RHIC) to collide polarized protons at  $\sqrt{s} = 200$  GeV and  $\sqrt{s} = 510$  GeV. The kinematic coverage of the Solenoidal Tracker At RHIC (STAR) allows access to gluons through quark-gluon and gluon-gluon scattering processes which dominate particle production at low and medium transverse momentum. The polarized gluon distribution function,  $\Delta g$ , can be constrained through a global analysis by measuring the longitudinal double-spin asymmetry ( $A_{LL}$ ) of inclusive jet and di-jet production.

Published inclusive jet results from 2009 at mid-rapidity ( $|\eta| < 1$ ) at  $\sqrt{s} = 200$  GeV have been used in global analyses and suggest a statistically significant non-zero truncated first moment of  $\Delta g$  for  $x > 0.05$ . An additional data sample of  $33 \text{ pb}^{-1}$  has been collected in 2015. This new data sample is 65% larger than the previous sample and will improve the precision of  $\Delta g$  for  $x > 0.05$ . The status of this new inclusive jet analysis will be presented along with the status of di-jet measurements and previous measurements at  $\sqrt{s} = 510$  GeV which will further constrain  $\Delta g$  at lower  $x$ .

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## Beam-helicity asymmetries in semi-inclusive deep-inelastic single-hadron production from unpolarized hydrogen and deuterium targets

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A measurement of beam-helicity asymmetries for single-hadron production in deep-inelastic scattering is presented. Data from the scattering of 27.6 GeV electrons and positrons off gaseous hydrogen and deuterium targets were collected by the HERMES experiment. The asymmetries for charged pions and kaons as well as for protons and anti-protons are presented binned either separately or simultaneously in the Bjorken scaling variable, the hadron transverse momentum, and the fractional energy.

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## SIDIS Pion Beam Spin Asymmetries with CLAS 12 at 10.6 GeV

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The CLAS12 detector at Jefferson Laboratory (JLab) started data taking with a polarized 10.6 GeV electron beam, interacting with an unpolarized liquid hydrogen target in February 2018. One of the

first quantities which could be extracted from the new data is the moment  $A_{LU}^{sin(\phi)}$  corresponding to the polarized electron beam spin asymmetry in semi-inclusive deep inelastic scattering.  $A_{LU}^{sin(\phi)}$  is a twist-3 quantity which provides information about the quark gluon correlations in the nucleon. The talk will present a simultaneous study of all three pion channels ( $\pi^+$ ,  $\pi^0$  and  $\pi^-$ ) over a large kinematic range with virtualities  $Q^2$  ranging from 1 GeV<sup>2</sup> up to 8 GeV<sup>2</sup>. Preliminary results for the measurement in a large range of  $z$ ,  $x_B$ ,  $P_T$  and  $Q^2$ , including up to now not measured kinematic regions will be presented.

\*The work is supported by DOE grant no: DE-FG02-04ER41309.

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## Transverse momentum dependent multiplicities of hadrons produced in DIS at COMPASS

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The multiplicities of charged hadrons produced in the deep inelastic scattering (DIS) of muons off a proton target as a function of the hadron transverse momentum  $P_{hT}$  are being measured by COMPASS using the data collected in 2016 and 2017 with a 160 GeV/c muon beam and a liquid hydrogen target. Preliminary results of this analysis using a fraction of the full collected sample and a limited kinematic range will be shown. Namely, the range of photon virtuality  $Q^2 > 1$  (GeV/c)<sup>2</sup>, Bjorken variable  $0.003 < x < 0.4$  and fractional hadron energy  $0.2 < z < 0.8$  is covered. The hadron transverse momentum squared extends in the region  $0.02$  (GeV/c)<sup>2</sup>  $< P_{hT}^2 < 1$  (GeV/c)<sup>2</sup>, where the results offer an insight in the transverse motion of partons, as well as in the high- $P_{hT}^2$  region up to 3 (GeV/c)<sup>2</sup>, where higher-order perturbative QCD contribution is expected to dominate. The results complement our previous ones, obtained with an isoscalar target in the same kinematic range.

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## Fragmentation related measurements at Belle

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The Belle experiment at the asymmetric e+e- collider KEKB provides a large data set not only for the exploration of flavor physics but also for precision QCD studies. The clean initial state is particularly well suited to investigate the process of high-energetic partons fragmenting into final state hadrons. Various results related to unpolarized and polarized fragmentation functions have been obtained in the previous years. A new measurement studies the creation of transverse momentum with respect to the fragmenting parton in the fragmentation process. Such transverse momentum dependent functions are the main input in learning about the three-dimensional structure of the nucleon using other reactions such as hadron collisions or semi-inclusive DIS.

In particular for the future electron-ion collider this information is essential as in e+e- annihilation only the fragmentation process can be singled out. The latest results show that the transverse momentum width of the extracted single hadron cross sections has a nontrivial fractional energy dependence as well as an interesting dependence on hadron type.

The latest results on this measurement and previous fragmentation function related results will be presented.

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## Transversely polarized Drell-Yan measurements at COMPASS

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The exploration of the transverse spin structure of the nucleon by measuring spin (in)dependent azimuthal asymmetries in semi-inclusive DIS and in Drell-Yan processes is one of the main objectives of the COMPASS experiment at CERN (SPS, M2 beamline). During the first phase of the experiment (2002-2011) a series of SIDIS measurements were performed, using a longitudinally polarized muon beam impinging on transversely polarized <sup>6</sup>LiD or NH<sub>3</sub> targets. As a part of the COMPASS-II programme, in 2015 and 2018 the experiment performed Drell-Yan measurements with a  $\pi^-$  beam interacting with a transversely polarized  $NH_3$ . The measurement of the Sivers and other azimuthal asymmetries at the same hard scale in polarized SIDIS and Drell-Yan provides a unique possibility to test predicted in QCD (pseudo-)universal features of transverse momentum dependent parton distribution functions. In this talk the results of the first ever polarized Drell-Yan measurements performed by COMPASS will be presented together with related SIDIS results and model predictions.

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## Transversity distributions from difference asymmetries in semi-inclusive DIS.

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In recent years information on the transversity distribution  $h_1$  has been obtained combining the Collins asymmetry results from semi-inclusive deep inelastic scattering (SIDIS) data on transversely polarized nucleon targets and the information on the fragmentation function of a transversely polarized quark from the asymmetries measured in  $e^+e^-$  annihilation into hadrons. An alternative method was proposed long time ago, which does not require the  $e^+e^-$  data, but allows one to get ratios of the  $u$  and  $d$  quark transversity distributions from the SIDIS data alone. The method utilizes the ratio of the difference of the Collins asymmetries of positively and negatively charged hadrons produced on transversely polarized proton and deuteron targets. We have applied this method to the COMPASS proton and deuteron data, and extracted the ratio  $h_1^d/h_1^u$ . Our results are very close to those obtained in a previous point-by-point extraction based both on SIDIS and  $e^+e^-$  data. Thus the new method strengthens the validity of the determination and of the procedures presented in earlier works on the subject.

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## Transverse Single-Spin Asymmetries of Midrapidity Eta Mesons at PHENIX

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Transverse single-spin asymmetries (TSSAs) of proton-proton collisions have a history of revealing the richness of QCD. Large TSSAs were originally discovered in fixed target experiments in the mid 1970s. However they have been found to persist in collisions up to  $\sqrt{s} = 510$  GeV and transverse momenta up to about 7 GeV/c, well into the perturbative regime of QCD, and yet their origin remains poorly understood. The large TSSA measurements led to the development of both transverse momentum dependent descriptions and collinear twist-3 descriptions of nonperturbative spin-momentum correlations in the nucleon as well as in the process of hadronization. As hadrons, eta mesons are sensitive to both initial- and final-state nonperturbative effects for a mix of parton flavors. Their comparison to neutral pions may provide information on potential effects due to strangeness, isospin, or mass. The status of the TSSA of eta mesons at midrapidity for 200 GeV proton-proton collisions from the PHENIX 2015 data set will be shown.

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## Sivers Asymmetry in $\pi N$ Drell-Yan process at COMPASS within TMD factorization

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We study the differential cross section in the unpolarized  $\pi^- N$  Drell-Yan process, using transverse momentum dependent factorization up to next-to-logarithmic order of QCD and extract the non-perturbative Sudakov form factor for the pion in the evolution formalism of the unpolarized TMD distribution function, by fitting the experimental data collected by the E615 Collaboration at Fermilab. With the extracted Sudakov factor, we investigate the Sivers asymmetry in the pion-induced single polarized Drell-Yan process in the theoretical framework of the transverse momentum dependent factorization up to next-to-leading logarithmic order of QCD. Within the TMD evolution formalism of parton distribution functions, the extracted nonperturbative Sudakov form factor for the pion distribution functions as well as the one for the Sivers function of the proton are applied to numerically estimate the Sivers asymmetry in the  $\pi^- p$  Drell-Yan at the kinematics of the COMPASS at CERN.

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## Lepton angular distributions of Drell-Yan process in pQCD and a geometric approach

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Measuring lepton angular distributions of Drell-Yan process provides a powerful tool to explore the reaction mechanisms and related parton distributions. For example, the Lam-Tung relation has been proposed as a benchmark of the pQCD effect in Drell-Yan process. Nevertheless, the violation of Lam-Tung relation was observed in the measurements of fixed-target experiments. Precision data of  $\gamma^*/Z$  production from LHC collider experiments are recently available. Strong transverse-momentum and rapidity dependencies are observed for the angular coefficients. Violation of Lam-Tung relation appears in the large transverse-momentum regions.

In this talk, we present a comparison of data with the fixed-order pQCD calculations by which the baseline of pQCD effects is illustrated. Then using an intuitive geometric approach, we show that these dependencies can be readily understood. The violation of the Lam-Tung relation, appearing at large transverse-momentum region, is attributed to the presence of a “non-coplanarity” effect. This interpretation is consistent with the appearance of violation beyond LO-QCD effect in the pQCD calculation.

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## Probing the Gluon Sivers Function through direct photon production at RHIC

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We study the production of prompt-photons at RHIC in the context of a generalised parton model framework, with a view to obtain information on the gluon Sivers function (GSF). At RHIC energy ( $\sqrt{s} = 200$  GeV), the Compton process,  $gq \rightarrow \gamma q$  contributes significantly to the production of direct-photons at midrapidity and dominates it in the negative (backward) rapidity region. We find that for direct photons, asymmetries of upto 10% are allowed by a maximal gluon Sivers function. However, the asymmetry obtained using existing fits of the GSF available in literature is negligible. We also estimate the impact that photons produced via fragmentation can have on the signal and find that their inclusion can dilute the asymmetry by between 10-50% of the direct-photon value. Finally, using the Colour-Gauge Invariant generalised parton model (CGI-GPM) approach, we consider the effects of initial state and final state interactions which can affect the universality of the Sivers functions in different processes. We find that the inclusion of these effects leads to the size of the gluon contributions being roughly halved. However, in the backward region which we are interested in, the sizes of the quark contributions are suppressed even further, leading to increased dominance of the gluon contributions.

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## Polarized gluon TMDs at small x

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Flavor, spin and partonic transverse momenta are important characteristics for parton distribution functions (PDFs), allowing a proliferation of possibilities. This proliferation can provide novel information into the non-perturbative structure of nucleons as well as new probes for high energy processes. Wilson lines are an important ingredient in the operator definitions of transverse momentum dependent PDFs (TMDs). We focus on the small  $x$  behavior of unpolarized and linearly polarized gluon TMDs with different gauge link structures for unpolarized and transversely polarized nucleons. For this we employ generalized TMD correlators (GTMDs) involving non-forward matrix elements of Wilson loops. As an example of the richness of GTMDs, we note that the  $C$ -odd parts can generate odd harmonics in the two-particle azimuthal correlations in peripheral proton-nucleus collisions.

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## **J/psi polarization in $p+p$ collisions at PHENIX**

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The  $J/\psi$ , a bound state of charm and anti-charm quark with spin 1 state, decays into spin  $\frac{1}{2}$  lepton pairs with a large branching ratio. Its production in  $p+p$  collisions shed light on inner workings of charmonium production that is dominated by gluon-gluon interaction at RHIC energy. Hadronization of charmonium in unpolarized  $p+p$  collisions is also accessible in robust nonrelativistic QCD formalism due to the large energy scale of heavy quark mass relative to the hadronization scale. Measuring how the spin of a decay lepton aligns with the spin of charmonium can test and map out various production mechanisms. In the past, the PHENIX saw non-sizeable polarization in  $J/\psi$  mesons produced in forward rapidity at  $\sqrt{s} = 510$  GeV and efforts continue to measure polarization at mid-rapidity. Status of mid-rapidity measurements of  $J/\psi$  to decay di-electrons spin alignment for  $p+p$  collisions from data taken at  $\sqrt{s} = 510$  GeV in 2013 will be presented.

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## **The angular momentum decomposition in the scalar diquark model.**

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One of the challenges of hadronic physics is to fully understand the structure of the proton. In particular, there is nowadays a great interest in the decomposition of its total angular momentum into orbital angular momentum (OAM) and intrinsic spin, as well as identifying contributions from valence quarks, sea quarks and gluons.

The most common decompositions of OAM are the Jaffe-Manohar (canonical) and Ji (kinetic) decompositions, which differ in the way contributions are attributed to quarks and gluons. Using perturbation theory, explicit one-loop calculations found that the difference between such decompositions vanishes. We show within the diquark model in QED that the difference appears at two-loop level, supporting the interpretation of such a difference as originating from the torque exerted by the spectator system on the struck quark.

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**NLO corrections to heavy flavour distributions in polarized deep-inelastic scattering****Author:** Felix Hekhorn<sup>1</sup>**Co-author:** Marco Stratmann<sup>1</sup><sup>1</sup> *University Tübingen***Corresponding Authors:** marco.stratmann@uni-tuebingen.de, felix.hekhorn@uni-tuebingen.de

We present a first calculation of the heavy flavour contribution to the longitudinally polarized DIS structure function  $g_1^Q$ , differential in the transverse momentum or the rapidity of the observed heavy antiquark  $\bar{Q}$ . The results are obtained at next-to-leading order accuracy with a newly developed parton-level Monte Carlo generator that also allows one to study observables associated with the heavy quark pair such as its invariant mass distribution or their correlation in azimuthal angle. First phenomenological studies are presented in a kinematic regime relevant for a future Electron-Ion Collider with a particular emphasis on the sensitivity to the helicity gluon distribution. Finally, we also provide first NLO results for the full neutral-current sector of DIS, i.e., including contributions from  $Z$ -boson exchange.

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**EXCLUSIVE SINGLE-PHOTON MUONPRODUCTION AT COMPASS****Author:** Antoine Vidon<sup>1</sup><sup>1</sup> *CEA-Saclay/IRFU/SPhN***Corresponding Author:** antoine.vidon@cern.ch

Part of the COMPASS-II program is dedicated to the investigation of Generalized Parton Distributions (GPDs) via lepton-induced hard exclusive reactions, in particular Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production. Data have been taken in 2016 -17 using a high intensity muon beam of 160 GeV and a 2.5 m-long liquid hydrogen target surrounded by a barrel-shaped time-of-flight system to detect the recoiling particles and optimize the selection of exclusive events.

The DVCS cross-section and its  $|t|$ -dependence are extracted from the sum of cross-sections measured with opposite beam charge and polarization. From a pilot measurement, a first estimate of the transverse extension of partons in the proton in the sea quark range ( $x_{Bj} \sim 0.06$ ), where no world data was available up to now, will be reported. The analysis method and the preliminary results from a part of the long run will be discussed.

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**First data on Deeply Virtual Compton Scattering with CLAS12 at 10.6 GeV Electron Beam****Author:** Francesco Bossu<sup>1</sup><sup>1</sup> *CEA-Saclay*



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Generalized Parton Distributions (GPDs) provide the opportunity to obtain a 3-dimensional description of a nucleon in terms of its constituent partons. Moreover, GPDs are related, via QCD-based sum rules, to total angular momentum, mass and pressure distributions inside the nucleon. GPDs are experimentally accessible via the deeply virtual Compton scattering (DVCS), i.e. the absorption of a highly virtual photon by the proton and the subsequent emission of a high-energy photon.

At Jefferson Lab, the brand new CLAS12 spectrometer has been commissioned and has collected its first DVCS data with a 10.6 GeV continuous electron beam in winter 2017 - spring 2018. Its central part, containing the cylindrical silicon and micromegas trackers within a 5T-solenoidal field surrounding the liquid hydrogen target, is ideal to detect the recoil proton of a DVCS event. The forward detectors, placed in a toroidal magnetic field, detect the associated scattered electron and high energy photon. A first look at the data collected so far with CLAS12 for DVCS studies on unpolarized proton target will be presented together with projections for the full run.

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## Re-assessment of the nucleon Boer-Mulders function

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The presently published Boer-Mulders (BM) function, for a given quark flavour, was extracted from data on semi-inclusive deep inelastic scattering (SIDIS) using the simplifying assumption that it is proportional to the Sivers function for that flavour. We argued that such an assumption is theoretically unacceptable and replaced it with an analogous, theoretically acceptable, relation for the BM valence quark combinations. This modified assumption, as we showed recently [Phys. Rev. D 97 056018, (2018)], is compatible with the COMPASS SIDIS deuteron data on particle-antiparticle difference asymmetries,  $A_{UU}^{\cos \phi_h, h-\bar{h}}$  and  $A_{UU}^{\cos 2\phi_h, h-\bar{h}}$ . Our results suggested that the published information on the BM function might be incorrect. In the present paper, using the standard factorized exponential form for the  $k_{\perp, BM}$ -dependence of the Boer-Mulders function, but here for the sum of the valence quarks  $Q_V(x_B, Q^2) \equiv u_V(x_B, Q^2) + d_V(x_B, Q^2)$ , namely,  $f_{BM}^{Q_V} \equiv \Delta f_{BM}^{Q_V}(x_B, Q^2) F(k_{\perp, BM})$ , we have made the minimal assumption that only the  $k_{\perp, BM}$  dependence is the same as in the Sivers case, and we have extracted its collinear part  $\Delta f_{BM}^{Q_V}(x_B, Q^2)$  from the above mentioned data. We show that, indeed, this differs significantly from the same function constructed using the presently published data on the BM function.

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## Studying twist-2 GPDs through quasi-distributions in a scalar di-quark model

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Studying light-cone (standard) parton distribution functions (PDFs) through Euclidean correlators in lattice QCD is currently a very active field of research. In particular, the quasi-distributions (quasi-PDFs) suggested by Ji have attracted a lot of attention. Quasi-PDFs converge to their respective standard distributions if the hadron momentum goes to infinity. We explore the quasi-distribution approach for twist-2 generalized parton distributions (GPDs) in a frequently used diquark spectator model. Our analytical expressions of the quasi-GPDs reduce to their corresponding standard ones in the large-momentum limit, substantiating them to be practical tools to predict features of standard GPDs. We illustrate numerical results of quasi-GPDs and of quasi-PDFs. Our focus is to test how well the quasi-distributions agree with their standard counterparts for finite hadron momenta. By discussing the sensitivity of our results to model parameters, we highlight robust features of the quasi-GPDs and quasi-PDFs that one may extract from this model study. We also discuss moments of quasi-distributions which recently attracted a lot of attention. Our contribution is based on published work and new results.

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## Lensing function relation in Hadrons

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The transverse momentum parton distribution  $f_{1T}^\perp$ , known as Sivers function, is odd under the naive time-reversal transformation and gives rise to a transverse single spin asymmetry (tSSA) in semi-inclusive DIS (SIDIS). An intuitive picture to understand the origin of this asymmetry is to relate the average Sivers transverse momentum to the impact parameter parton distribution  $E$ , which describes the distortion of the spatial distribution of partons in the transverse plane. The connection between the two functions is realised through the “lensing” function, that arises from the final-state interactions between the active quark and the spectator partons.

However, this picture for the tSSA is valid only using a particular model for the proton. As a matter of fact, no relations between impact parameter distributions and transverse momentum distributions can exist in QCD. The relation is expected to be an artefact of the model, however it was not clear which features of the model originate it.

In this talk, I will present an argument that helps to understand the origin of this relation in models. To this aim, I will first discuss the pion case, as a prototype of a bound two-body system, and then the results for the proton, treated as both a quark-diquark state and a three-quark state.

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## Measurement of the azimuthal modulations of hadrons in unpolarized SIDIS events.

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In 2016 and 2017, together with DVCS data, the COMPASS Collaboration has collected a considerable amount of Deep Inelastic Scattering events scattering a 160 GeV/c muon beam off a liquid hydrogen target. A first analysis of a small

subsample of these data has allowed to extract preliminary results on the amplitudes of three azimuthal modulations,  $A_{UU}^{\cos \phi_h}$ ,  $A_{UU}^{\cos 2\phi_h}$  and  $A_{LU}^{\sin \phi_h}$ . The first two modulations are particularly important since they carry information on the intrinsic transverse momentum  $k_{\perp}$  of the quarks and on the correlations between the quark spin and  $k_{\perp}$ , expressed by the Boer-Mulders TMD PDFs. The kinematic dependence of these amplitudes as a function of the Bjorken variable  $x$ , of the fraction of virtual photon energy carried by the hadron  $z$  and of the component  $P_{hT}$  of the hadron momentum orthogonal to the virtual photon direction will be shown and discussed.

These preliminary results confirm the strong kinematic dependencies observed in previous measurements. Perspectives for the full analysis will also be given.

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## Off-shell initial state effects and gauge invariance in the Drell-Yan process

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We discuss production of Drell-Yan lepton pairs at hadron colliders in the framework of the Parton Reggeization Approach, which includes off-shell initial state effects in a gauge-invariant way. Other possible prescriptions to restore gauge-invariance of hard-scattering coefficient with off-shell initial-state partons are also investigated and significant differences for the resulting structure functions are found, especially for the  $F_{UU}^{(\cos 2\phi)}$ . We compare our numerical results for  $q_T$ -spectra of the lepton pair with experimental data, obtained by E-288 collaboration ( $\sqrt{S} = 19.4$  and  $23.8$  GeV) and find a good agreement. Also we perform predictions for the Drell-Yan structure functions at NICA  $pp$ -collider ( $\sqrt{S} = 24$  GeV).

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## On the $\sin \phi_R$ azimuthal asymmetry single longitudinal-spin asymmetry in dihadron production in SIDIS

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We study the single longitudinal-spin asymmetry of dihadron production in semi-inclusive deep inelastic scattering process in which the transverse momentum of the final-state hadron pairs is integrated out. In Particular, we investigate origins of the  $\sin \phi_R$  azimuthal asymmetry for which we take into account the coupling of the twist-3 distributions  $h_L$  and the dihadron fragmentation function (DiFF)  $H_{1,ot}^{sphericalangle}$  as well as the coupling of the helicity distribution  $g_1$  and the twist-3 DiFF

$\tilde{G}^{sphericalangle}$ . To this end The unknown twist-3 dihadron fragmentation function  $\tilde{G}^{sphericalangle}$  is calculated in a spectator model which is successful in describing the dihadron production in unpolarized process. We estimate the  $\sin \phi_R$  asymmetry of dihadron production in SIDIS at the kinematics of COMPASS and compare it with the preliminary COMPASS data. In addition, we make a prediction on the  $\sin \phi_R$  asymmetry at the typical kinematics of future EIC. Although the asymmetry is dominated by the  $h_L H_1^{sphericalangle}$  term, we find that the contribution from the  $g_1 \tilde{G}^{sphericalangle}$  term should also be taken into account in certain kinematical region.

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## Measurement of $q_T$ -weighted transverse-spin-dependent azimuthal asymmetries at COMPASS

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COMPASS is a fixed-target experiment in operation at the CERN North Area (SPS, M2 beam-line) since 2002. An important part of its broad physics programme is dedicated to the exploration of the transverse spin-structure of the nucleon studying target spin-(in)dependent azimuthal asymmetries arising in the Semi-Inclusive DIS (SIDIS) and Drell-Yan (DY) cross-sections. Recently, COMPASS has also extracted the transverse spin-dependent azimuthal asymmetries (TSAs) weighted with the transverse momentum of the detected hadron (SIDIS,  $p_{T,h}$ ) and the virtual photon (DY,  $q_T$ ). In the transverse momentum dependent (TMD) QCD approach, the conventional TSAs are interpreted as convolutions of the beam pion and of the transversely polarized target proton TMD parton distribution functions (PDFs), while the  $q_T$ -weighted TSAs can be interpreted directly in terms of their products.

In 2015 and 2018 the Collaboration performed two years of Drell-Yan data taking with a 190 GeV/c  $\pi^-$  beam impinging on a transversely polarized  $\text{NH}_3$  target. The analysis of the  $q_T$ -weighted TSAs performed on these two data-sets is presented in this paper. The results are then compared with the expectation based on the weighted Sivers asymmetry measured in the SIDIS process. Similarly, also the Boer–Mulders function of the pion and proton are investigated.

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## The TOPSiDE Detector Concept for the EIC

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After an introduction to the EIC (parameters, physics goals, and status) and a quick overview of the various detector concepts being developed for the EIC, I will introduce the TOPSiDE detector concept. TOPSiDE aims at the detection and identification of all particles created in electron-proton/ion collisions at the EIC while achieving the best possible momentum/energy resolution. The measurement of hadronic jets exploits the advantages offered by Particle

Flow Algorithms (PFAs), which in turn require imaging calorimetry. Particle identification is achieved through time-of-flight measurements in the tracker and the electromagnetic calorimeter, necessitating the deployment of ultra-fast silicon sensors. Simulation studies showed that timing resolutions of 10 picoseconds are required to achieve pion-kaon separation up to 7 GeV/c.

I will review the ongoing detector R&D efforts to realize TOPSiDE and also some of the benchmark physics processes being studied to validate the concept.

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## Using the proposed RHIC-EIC proton beam to drive plasma wakefields

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Initial simulations investigating using the RHIC-EIC proton beam as the drive beam in a plasma wakefield acceleration experiment are presented. The proton beam enters the plasma and undergoes self-modulation, forming a series of microbunches. These microbunches resonantly drive electron density perturbations within the plasma, exciting a longitudinal electric field with accelerating gradients in excess of  $\text{GVm}^{-1}$ . Injecting electrons into the resulting wakefield offers an efficient method for accelerating electron bunches for use in the proposed EIC collider.

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## Precision measurements of fundamental interactions with (anti)neutrinos

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A technique has been recently proposed to achieve a control of the neutrino targets and fluxes comparable to electron scattering experiments. In particular, it allows precise measurements of high statistics samples of (anti)neutrino-hydrogen interactions and of various nuclear targets. The planned high intensity LBNF/DUNE beams give access to a broad mixture of measurements of electroweak parameters, QCD and hadron structure of nucleons and nuclei, nuclear physics, form factors, structure functions and cross-sections, as well as searches for new physics or verification of existing outstanding inconsistencies. Such a program of precision measurements and searches would nicely complement the efforts in the fixed-target, collider, and nuclear physics communities, elevating the near site of DUNE to a general physics facility for a broad range scientific studies.

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## Gluon TMDs in quarkonium production at an EIC

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We describe two recent ideas to probe gluon TMDs in electron-proton collisions using quarkonium production. In the first one, we study the semi-inclusive production of a  $j/\psi$  or  $\psi(2S)$  meson in deep-inelastic scattering off a (un)polarized proton. In the regime where the small transverse momentum of the quarkonium is much smaller than the virtuality of the process, the cross section is directly sensitive to the gluon TMDs of the proton, which can be disentangled using the different azimuthal modulations that appear. We discuss the role of the long-distance matrix elements (LDMEs), which appear in the color octet production mechanism in non-relativistic QCD (NRQCD), and look at the low- $x$  limit in which the gluon contribution is enhanced. Finally, we discuss recent progress in the calculation of quarkonium + jet production, where the quarkonium and the jet are almost back to back in the transverse plane

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## PERLE: status and plans

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PERLE is a facility to be built at LAL Orsay, providing very intense beams of electrons with energies up to 1 GeV using an Energy Recovery Linac in racetrack configuration. Its applications are multiple, going from accelerator science as a proof of concept for a multipass high-current energy recovery machine, to component testing, BSM, EW, hadron and nuclear physics with electrons and photon beams, material science, etc. In this talk we review the status of the project.

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## Jets and Jet Substructure at an EIC

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The goal of the planned high-energy high-luminosity polarized electron-ion collider (EIC) is a detailed understanding of the QCD dynamics that underlie the nucleons and nuclei. With advances in experimental technique and theoretical understanding over the past several decades, jets have become precision tools in the exploration of QCD in collider environments. Therefore, precision jet measurements have the potential to be important components of the electron-hadron and electron-nucleus EIC physics programs. One property of jets that may prove especially useful is that their substructure, i.e. their internal energy distribution, can be rigorously defined and studied systematically. This contribution will discuss possible uses for substructure observables at an EIC as well as outline various experimental aspects of their measurement.

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## Energy and atomic number scan in electron-ion collisions

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The DIS of leptons with different energy on hadrons, light and heavy nuclei is discussed. It should allow one to explore the transitions between different ways of description of QCD matter and dualities between them.

In particular, the interplay between the description of azimuthal asymmetries in terms of Wigner functions and collective flows and corresponding duality between the statistical and dynamical approaches to the similar phenomena may be revealed.

The special attention is paid to the aspects of hadronic and nuclear structure manifested due to the emerging large non-inertial effects and possible experimental separation of the effects of rotation and acceleration.

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## Prospects of Simulating Jet Physics at an EIC within the JETSCAPE framework

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A high-energy high-luminosity polarized electron-ion collider (EIC) is the Nuclear Science Advisory Committee's highest priority for new facility construction. A dedicated  $e + A$  Monte Carlo event generator is especially crucial during the process of identifying observables and the experimental needs they would pose to detector designs. The JETSCAPE collaboration recently released version 1.0 of an innovative modular event generator and simulation framework with a unified interface and a comprehensive suite of model implementations for all stages of ultra-relativistic heavy ion collisions from initial state through hadronization.

A key feature of the framework design is modularity and agnosticism regarding the underlying physics assumptions. It thus promises to be an ideal candidate to serve as a platform for developing Monte Carlo models of electron-ion collisions specifically because it allows to concentrate on one specific aspect, such as medium interaction or hadronization, while leaving other modules unchanged. An overview of necessary modifications and baseline performance for electron+proton collisions will be presented alongside first feasibility tests for medium interaction models.

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## Top and Electro-Weak physics at the LHeC and the FCC-eh

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The Large Hadron-electron Collider (LHeC) is a proposed upgrade of the LHC at CERN. An ERL will provide electrons to collide with the HL-LHC, HE-LHC and the FCC-hh proton beams to achieve centre-of-mass energies 1.3-3.5 TeV and luminosities  $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . These large luminosities and the corresponding cross sections provide huge possibilities for precision measurements of top couplings and EW parameters. In this talk we present the latest results on the determination of SM and anomalous top couplings in top-energy DIS at the LHeC and the FCC-eh, and compare them with the results at LHC and the prospects at the HL-LHC. We also show the implications that a precise determination of PDFs at the LHeC and FCC-eh has on the extraction of EW parameters at hadronic colliders.

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## The Large Hadron-electron Collider: status and plans

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The Large Hadron-electron Collider (LHeC) is a proposed upgrade of the LHC at CERN. An Energy Recovery Linac in racetrack configuration will provide 60 GeV electrons to collide with the HL-LHC proton and ion beams and, eventually, with those from the HE-LHC and the FCC-hh. Such configurations will yield electron-proton (nucleus) collisions with per nucleon centre-of-mass energies 1.3-3.5 (0.8-2.2) TeV and luminosities  $\sim 10^{34(33)} \text{ cm}^{-2}\text{s}^{-1}$ . In this talk we will review the status of the accelerator, detector and physics studies.

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## Accessing the high- $x$ content of protons and heavy nuclei in the fixed-target mode at the LHC

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Using the LHCb and ALICE detectors in the fixed-target mode at the LHC offers unprecedented possibilities to study the quark, gluon and heavy-quark content of the proton and nuclei in the poorly known region of the high-momentum fractions. We review our projections for studies of Drell-Yan, charm, beauty and quarkonium production with both detector set-ups used with various nuclear targets and the LHC proton beams. Based on this, we show the expected improvement in the determination of the quark, charm and gluon proton and nuclear PDFs as well as discuss the implication for a better understanding of the cold-nuclear-matter effects in hard-probe production in proton-nucleus collisions.

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## Quarkonium production and TMDs at LHC



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In this contribution we briefly discuss an ongoing phenomenological programme on quarkonium production in unpolarised and polarised proton-proton collisions in a fixed target setup at LHCb, the LHCSpin project.

Within a TMD approach, we will consider in particular: the relative role of the NRQCD color-singlet and color-octet production mechanisms, both for unpolarised and polarised quarkonium production; the study of transverse single spin asymmetries as a tool for learning about the almost unknown gluon Sivers function.

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## Proton Radius in High-Energy Muon Scattering

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The proton radius can be determined by measuring the slope of the electric form factor at small squared four-momentum transfer  $Q^2$ . Numerous elastic-scattering and laser-spectroscopy measurements of the proton radius have been performed with contradicting results, the so-called proton radius puzzle. We propose to measure the proton radius in high-energy elastic muon-proton scattering at the M2 beam line of CERN's Super Proton Synchrotron in the year 2022. A high precision measurement at low  $Q^2$  realized with a high-pressure hydrogen TPC can contribute to a solution of the puzzle, especially in view of the systematics of this approach compared to electron scattering. In the year 2018, a test measurement with silicon tracking detectors upstream and downstream of a prototype TPC was performed to study the feasibility employing both detector systems. We present results of the on-going analysis and discuss ideas for a possible setup in 2022.

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## Shear forces and tensor polarization

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The shear forces in deuteron are related to tensor polarization and may be studied in both exclusive and inclusive processes. They are related to sum rules for tensor spin structure functions and provide the new probe of gravity coupling to quarks and gluons and Equivalence Principle (EP). The HERMES data are compatible with validity of EP separately to quarks and gluons. The more accurate tests in hadronic and nuclear collisions, including NICA complex at JINR, are discussed.

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## Towards enhanced databases for High Energy Physics

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The accumulation of a large amount of new experimental data at an impressive rate at present and future collider experiments has led to important questions concerning data storage and organization, their public access and usability, as well as their effective and efficient usage in order to discriminate between different theories. For the last thirty years, the HEPData database has been the reference database for the worldwide community of elementary particle physicists, from DIS to fixed-target and collider experts. Using as a basis a dump of HEPData\*, we discuss possible paths to enhance the capabilities of databases for High Energy Physics. Our starting point is the reorganization of the data in a different scheme, which allows for the application of OLAP techniques to automatically extract information at a multidimensional level, answering to complex queries. The feedback of the DIS community is important for understanding specific needs, towards an even more effective storage, extraction and presentation of the data and information of their interest.

\*Note: the HEPdata dump on which this work is based was kindly provided us by K. Ellis, F. Krauss and G. Watt (IPPP, Durham), with whom further collaboration is foreseen for the future.

**WG7: Future of DIS / 245**

## A detector for the LHeC and the FCC-eh

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The Large Hadron-electron Collider (LHeC) is a proposed upgrade of the LHC at CERN. An ERL will provide electrons to collide with the HL-LHC, HE-LHC and the FCC-hh proton and ion beams to achieve per nucleon centre-of-mass energies 1.3-3.5 (0.8-2.2) TeV and luminosities  $\sim 10^{34(33)} \text{ cm}^{-2}\text{s}^{-1}$ . Such a machine offers the opportunity to build a state-of-the-art HEP detector to be operative in the 2030s. The present design of the detectors for the three configurations will be discussed.

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## Overview of physics possibilities at future DIS facilities

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In this contribution I will provide an overview of the physics possibilities in the future DIS machines: EIC, LHeC and FCC-eh.

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## Next-generation spin physics measurements with polarized deuteron and spectator tagging

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A future EIC with forward detectors would enable measurements of DIS on the deuteron with detection of a forward proton/neutron (spectator tagging) over a wide kinematic range. Spectator tagging controls the nuclear configuration during the DIS process and permits an accurate differential treatment of nuclear effects. When combined with deuteron polarization, the method enables next-generation measurements of neutron spin structure and nuclear partonic structure. We summarize recent progress in the development of the spectator tagging program for the EIC. This includes (a) a theoretical framework for precise extraction of neutron spin structure with spectator tagging (realistic deuteron structure, S and D waves) and assessment of the impact of experimental deuteron polarization (using  $-1/0/+1$  spin states or only  $+1/-1$  spin states) [1]; (b) novel tensor-polarized deuteron structure functions in spectator tagging, representing genuine  $A = 2$  effects in nuclear partonic structure.

[1] W. Cosyn, C. Weiss, arXiv:1902.03678 [hep-ph]; in progress.

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## The LHCSpin project

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The LHCSpin project aims to bring both unpolarized and polarized physics at the LHC through the installation of a gaseous fixed target at the upstream end of the LHCb detector. The forward geometry of the LHCb spectrometer is perfectly suited for the reconstruction of particles produced in fixed-target collisions. The fixed-target configuration, with center-of-mass energies ranging from  $\sqrt{s}=115$  GeV in pp interactions to  $\sqrt{s_{NN}}=72$  GeV in collisions with Pb beams, allows to cover a wide backward rapidity region, including the poorly explored high x-Bjorken and high negative x-Feynman regimes. The project has several ambitious goals regarding new-era quantitative searches in QCD through the study of the nucleon's internal dynamics in terms of both quarks and gluons degrees of freedom. In particular, the use of transversely polarized H and D targets will allow to study the quarks TMDs

in pp collisions at unique kinematic conditions. Furthermore, being LHCb specifically designed for heavy-flavor physics, efficiently reconstructed final states with c- or b-quarks (e.g. in inclusive quarkonia production) will provide access to the so-far unknown gluons TMDs. The status of the project is presented along with a selection of physics opportunities.

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## **Spectroscopy, gluon structure and polarisability of kaons in the new QCD facility at the M2 beam line at CERN SPS**

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The new planned QCD facility at the M2 beam line of the CERN SPS, will be a successor of COMPASS, and will have a broad experimental programme addressing fundamental issues leading to significant improvements in our understanding of strong interactions. After a brief summary of the planned research in hadron partonic structure and hadron spectroscopy, the presentation will focus on two items of the programme, foreseen after CERN accelerator long shutdown 3: the spectroscopy and the gluon content of kaons (the latter via prompt-photon production) and low energy tests of QCD employing the Primakoff reactions or the first ever measurements of the kaon polarisability. A unique tool for these measurements is a high-energy, high-intensity radio-frequency separated hadron beams which could be made possible by a major upgrade of the M2 beam line.

An experimental backbone of the new facility will be the upgraded multi-purpose two-stage magnetic spectrometer of COMPASS in the experimental hall EHN2. Individual instrumentation with modern detector architecture will be constructed and installed in that hall.

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## **Meson and Hadron structure in the new QCD facility at the M2 beam line at CERN**

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The new planned QCD facility at the M2 beam line of the CERN SPS will have a broad experimental programme addressing fundamental issues leading to significant improvements in our understanding of strong interactions. The presentation will be focused on the Drell-Yan programme, which aims

to make a major step forward in the determination of the nearly unknown pion and kaon parton distribution functions (PDFs). The improved knowledge of the onset of the sea and gluon distributions in the meson will help in explaining the differences between the gluon contents of pions, kaons and nucleons, and hopefully provide clues to understand the mechanism that generates the hadron masses.

The possibility to combine an antiproton beam with a transversally polarised proton target to study TMD PDFs will also be discussed. The M2 secondary hadron beam line at the CERN SPS provides an exclusive opportunity for such measurements.

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## Vector mesons production off nuclei at the new planned QCD facility at CERN

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The production of light vector mesons  $V = \rho, \omega, \varphi, K^*$  off nuclei targets with pion, kaon and muon beams at the new planned QCD facility at the M2 beam line of the CERN SPS will be presented. Whereas in the charge exchange reaction  $\pi^- + p \rightarrow V + n$  vector mesons are produced mainly longitudinally polarized (helicity  $\lambda = 0$ ) the investigation of their production off nuclei  $\pi^- + A \rightarrow V + A'$  allows to extract the total cross section of the longitudinally polarized vector meson interaction with nucleon  $\sigma_L(VN)$ , a value of which has not yet been measured.

The vector mesons production by muons off nuclei using capabilities of COMPASS-like detector would allow to separate the effect of virtual photon shrinking (color transparency) from the effect caused by different absorption of transverse (helicity  $\lambda = \pm 1$ ) and longitudinal (helicity  $\lambda = 0$ ) vector mesons in nuclei. Such measurements are of a current interest as they are complement to investigations of vector mesons photoproduction off nuclei the experimental realization of which is recently proposed at JLAB.

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## Challenges in the US EIC Detector and Interaction Region Design

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The Electron-Ion Collider (EIC) project is rapidly marching towards its approval stage in the US.

The anticipated design goals of the collider, with the luminosity 2-3 orders of magnitude higher than that at HERA, polarized electron and proton beams, as well as nuclear beams from light to heavy species, pose several technological challenges by itself.

Equally demanding are the requirements for the Interaction Region (IR) and the physics detector(s) that will be needed to carry out the compelling EIC physics program: hermetic coverage in tracking, calorimetry and particle ID within a pseudorapidity range of up to  $\pm 4$ , substantial angular and momentum acceptance in the hadron-going direction, as well as high quality hadronic calorimetry among others.

In my talk I will give an overview of the detector concepts with typical configurations considered for an EIC, providing a connection between physics requirements, simulations and the ongoing EIC

Detector R&D Program. I will outline areas where R&D beyond the current state-of-the-art is required. The talk will also cover the activities carried out within the EIC User Group IR Working group, aimed on evaluating the feasibility of high precision bunch-by-bunch luminosity measurements with an anticipated repetition rate 1-2 orders of magnitude higher than at HERA, as well as on the modeling of various sources of expected backgrounds.

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## eA collisions at the LHeC and nuclear parton densities

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The Large Hadron-electron Collider (LHeC) is a proposed upgrade of the LHC at CERN. An Energy Recovery Linac in racetrack configuration will provide 60 GeV electrons to collide with the HL-LHC ion beams and, eventually, with those from the HE-LHC and the FCC-hh. Such configurations will yield electron-nucleus collisions with per nucleon centre-of-mass energies 0.8-2.2 TeV and luminosities  $\sim 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ . They will extend the kinematic plane by about four orders of magnitude towards smaller  $x$  and larger  $Q^2$  than presently existing DIS and DY fixed target data. DIS measurements in such configurations offer unprecedented possibilities to enlarge our knowledge on parton densities through a complete unfolding of all flavours. In this talk we will present the latest results on the determination of nPDFs in a single experimental setup. We will also comment on the comparison with data from hadron colliders where precise factorisation tests can be performed.

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## Parton-pseudo distribution functions from Lattice QCD

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The light-cone definition of Parton Distribution Functions (PDFs) does not allow for a direct ab initio determination employing methods of Lattice QCD simulations that naturally take place in Euclidean spacetime. In this presentation we focus on pseudo-PDFs where the starting point is the equal time hadronic matrix element with the quark and anti-quark fields separated by a finite distance. We focus on Ioffe-time distributions, which are functions of the Ioffe-time  $v$ , and can be understood as the Fourier transforms of parton distribution functions with respect to the momentum fraction variable  $x$ . We present lattice results for the case of the nucleon and we also perform a comparison with the pertinent phenomenological determinations.

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## Parton distribution functions from Lattice QCD

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In this talk, I will discuss the computation of collinear PDFs in the framework of Lattice QCD, using the so-called quasi-PDF approach introduced by Xiangdong Ji in 2013 and intensively developed thereafter. We employed twisted mass fermions with light quark mass set to its physical value. The relevant matrix elements obtained on the lattice were non-perturbatively renormalized and converted to the  $\overline{MS}$  scheme at the scale of 2 GeV. A matching process was applied together with nucleon mass corrections, leading to the reconstruction of light-cone PDFs. We observe a similar behavior between the lattice and phenomenological data, and for both types of polarized PDFs a nice overlap for a range of Bjorken- $x$  values. This presents a major success for the emerging field of direct calculations of quark distributions using Lattice QCD.

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## An EIC proposed in China (EicC)

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Recently, an Electron-Ion Collider was proposed in China based on the High-Intensity Heavy Ion Accelerator Facility (HIAF) which is currently under construction. The first phase of EicC will be an e-p/e-A collider with center-of-mass energy around 10-20 GeV for e-p. Both electron and proton (light nucleus) beams will be polarized with a luminosity of  $1.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ . EicC will have a capability for an upgrade in both energy and luminosity. In this talk an early-stage preliminary conceptual design and selected physics topics at the EicC-I will be presented. The current status and future plan will also be discussed.

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## Status and Perspectives of a US-based Electron-Ion Collider (EIC)

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Understanding the properties of nuclear matter and its emergence through the underlying partonic structure and dynamics of quarks and gluons requires a new experimental facility in hadronic physics known as the Electron-Ion Collider (EIC). A US-based facility capable of colliding high-energy polarized electron and ion beams at high luminosity has been envisaged for a long time

and articulated as the highest priority for new construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.

The EIC will address some of the most profound questions concerning the emergence of nuclear properties by precisely imaging gluons and quarks inside protons and nuclei such as the distribution of gluons and quarks in space and momentum, their role in building the nucleon spin and the properties of gluons in nuclei at high energies. Two facility concepts have been presented to address these conditions, at Brookhaven National Laboratory and Jefferson Laboratory taking advantage of existing accelerator infrastructure and accelerator expertise.

The US Department of Energy requested the review of the science case of a future EIC program by the US National Academy of Sciences (NAS). This review process started in January 2017 and concluded with the release of a report which was publicly presented on July 24, 2018, stating that ‘the committee unanimously finds that the science that can be addressed by an EIC is compelling, fundamental and timely’.

The status and perspectives of a US-based EIC facility will be discussed in this presentation.

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## **Unraveling the 3D/spin structure of the nucleons with a fixed-target experiment at the LHC**

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A fixed-target experiment using the LHC beams with an (un)polarized target would offer a unique opportunity to study the 3-dimensional (3D) and spin structure of the nucleon. Recent studies have shown that a number of spin and azimuthal asymmetries are large enough to be precisely measured, allowing to constrain several non-perturbative functions which encode the internal structure of the nucleon, as the quark and gluon Sivers functions.

In this talk I will review the ground-breaking spin physics program developed by the AFTER@LHC study group. I will confront the state-of-the-art theoretical predictions with the potential of a fixed-target experiment at the LHC to unravel the nucleon structure through different high-energy processes, using LHCb-like and ALICE-like detectors.