ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

New Physics below the Fermi Scale

Mikhail Shaposhnikov

CERN Physics Beyond Colliders

September 6, 2016

The LHC has discovered something quite unexpected (at least, up to now, ICHEP 2016): The Higgs boson and nothing else, confirming the Standard Model.

The LHC has discovered something quite unexpected (at least, up to now, ICHEP 2016): The Higgs boson and nothing else, confirming the Standard Model.

For 125 GeV Higgs mass the Standard Model is a self-consistent weakly coupled effective field theory for all energies up to the quantum gravity scale $M_P \sim 10^{19}$ GeV

Unexpected?

Google

Google

expectations for new physics at the LHC

Google

expectations for new physics at the LHC

http://lhc2008.web.cern.ch/lhc2008/nobel/

Nobel expectations for new physics at the LHC, 2008

What do leading figures in particle physics expect from the LHC?

"a super world"

I expect new discoveries that will give us clues about the unification of the forces, and maybe solve some of the many mysteries that the Standard Model (SM) leaves open.

I personally expect supersymmetry to be discovered at the LHC; and that enormous discovery, if it happens, will open up a new world - a super world.

"a Higgs, or more"

The first thing we expect - we hope to see - is the Higgs. I am practically certain that the Higgs exists. My friends here say it is almost certain that if it exists, the LHC will find it.

There could be more than one Higgs, several Higgs, and there could be a composite Higgs, but most of us think it should be an elementary particle...

My real dream is that the Higgs comes up with a set of particles that nobody has yet predicted and doesn't look in any way like the particles that all of us expect today. That would be the nicest of all possibilities. We would then really have work to do to figure out how to interpret those results.

"lots of new particles"

If we don't get the Higgs, that would in fact be a bit more interesting, but I am hoping that there will be lots of new particles and resonances that no one ever expected. That will be really exciting.

"the nature of dark matter"

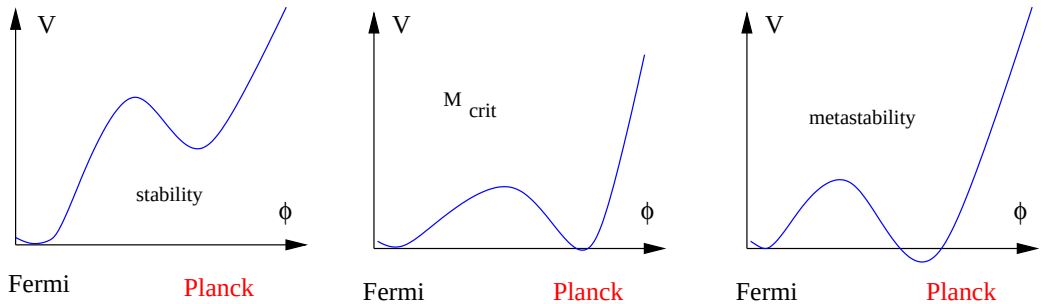
I am looking forward to hearing about the Higgs, because I'd like to see the Standard Model completed and understood. I'm also hoping that the LHC will begin to unveil extra dimensions, and that will have huge applications across the board.

But what I am really looking forward to is supersymmetry or something that shows what dark matter is made of, so I have really high hopes, perhaps too high hopes.

The LHC results must be reconciled with the evidence for new physics beyond the Standard Model:

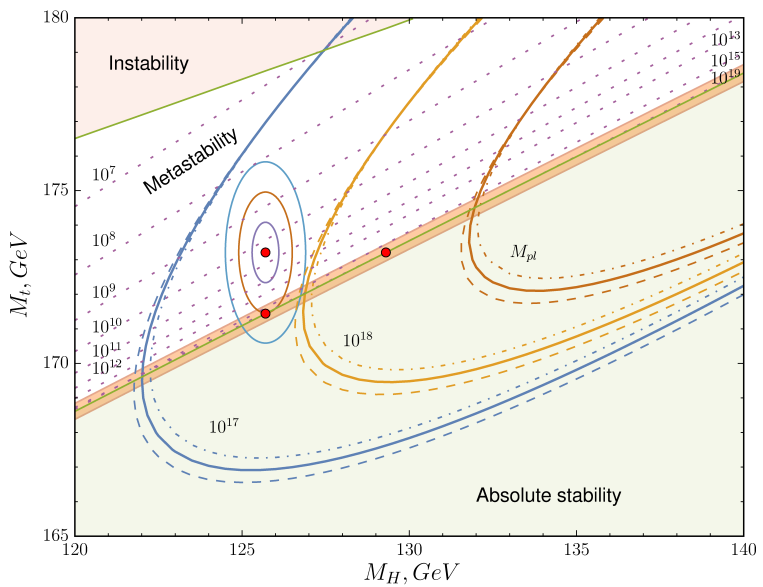
- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM). Talk by Graham
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)
- Cosmological inflation is absent in canonical variant of the SM
- Accelerated expansion of the Universe (?) - though can be “explained” by a cosmological constant. Talk by Burrage

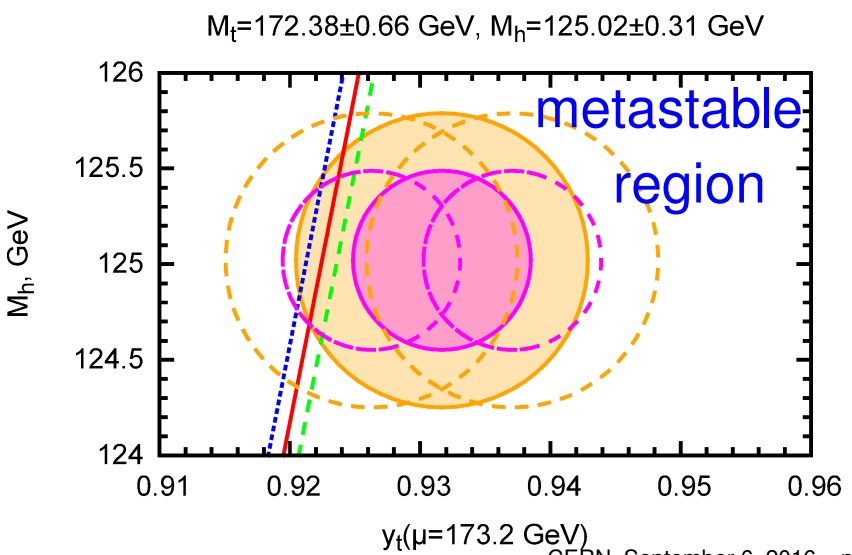
- Marginal evidence (less than 2σ) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling



Bednyakov et al, '15

Vacuum is unstable at 1.3σ



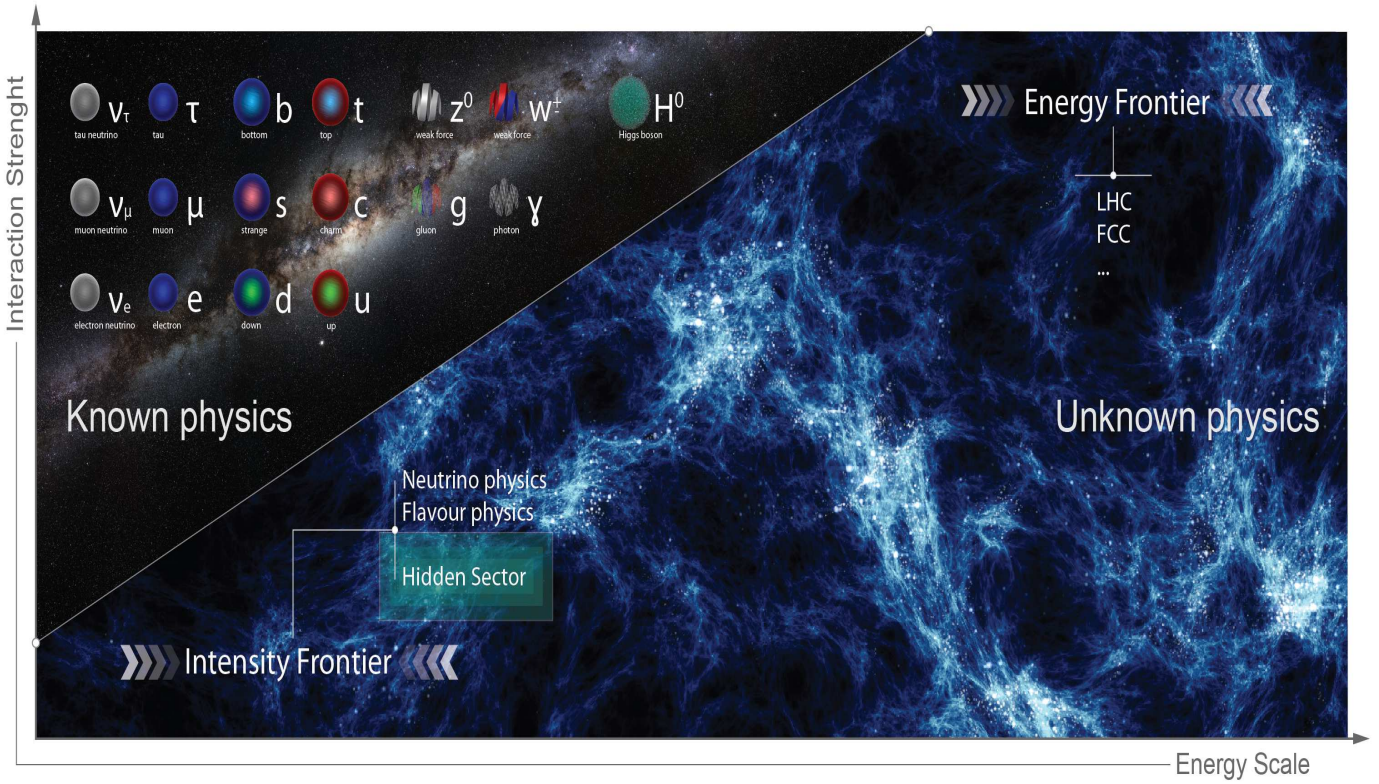


Where is new physics?

Energy scale of new physics from experiment or theory:

- Neutrino masses and oscillations: the masses of right-handed see-saw neutrinos can vary from $\mathcal{O}(1)$ eV to $\mathcal{O}(10^{15})$ GeV
- Dark matter, absent in the SM: the masses of DM particles can be as small as $\mathcal{O}(10^{-22})$ eV (super-light scalar fields) or as large as $\mathcal{O}(10^{20})$ GeV (wimpzillas, Q-balls).
- Baryogenesis, absent in the SM: the masses of new particles, responsible for baryogenesis (e.g. right-handed neutrinos), can be as small as $\mathcal{O}(10)$ MeV or as large as $\mathcal{O}(10^{15})$ GeV
- Higgs mass hierarchy : models related to SUSY, composite Higgs, large extra dimensions require the presence of new physics right above the Fermi scale , whereas the models based on scale invariance (quantum or classical) may require the absence of new physics between the Fermi and Planck scales

New Physics, experimentally

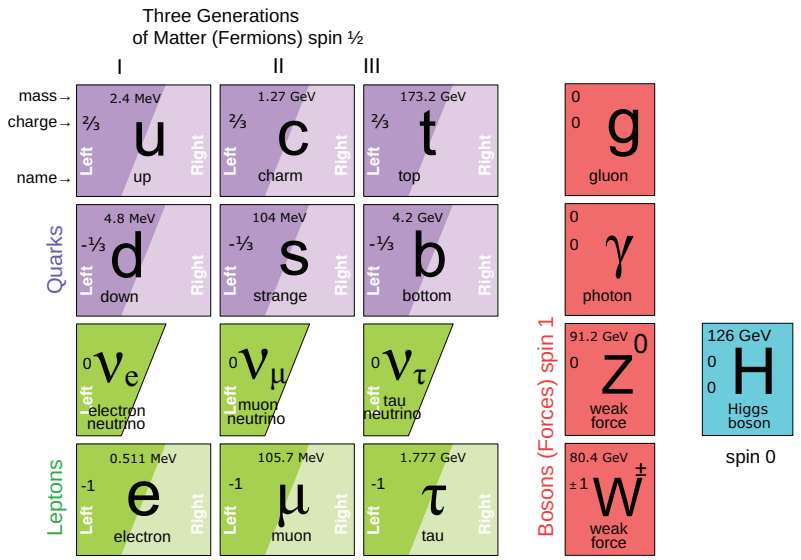


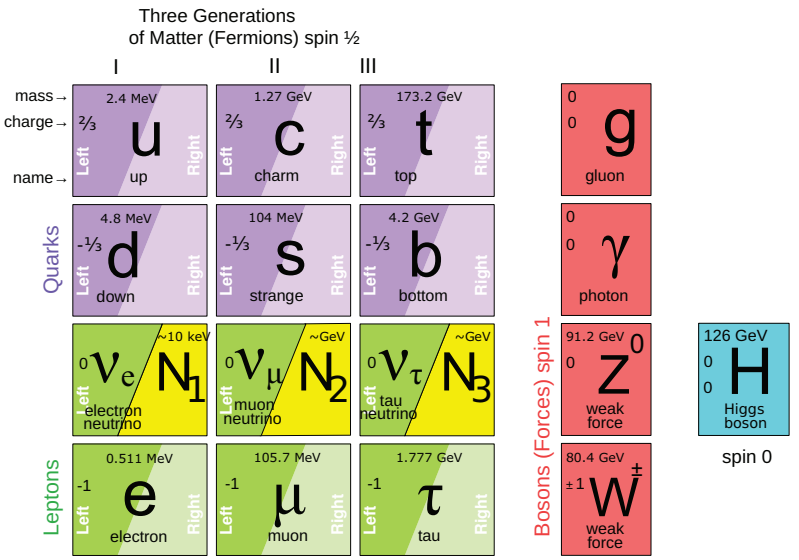
- Direct searches for new relatively strongly interacting particles: high energy frontier.
  - LHC is the best and the only option at the moment. Future accelerators.
- Indirect searches for new relatively strongly interacting particles : precision frontier.
  - Charged lepton flavour violation
  - Proton decay, $n\bar{n}$ oscillations
  - Flavour physics, LHCb, NA62 $K \to \pi\nu\nu$,...
  - EDM of proton and neutron, strong CP-violation or BSM, g-2. Talks by Pospelov, Bowcock.
- Direct searches for new feably interacting particles: intensity frontier. Talks by Gninenko, Golutvin, Spadaro

Superweakly interacting new physics below the Fermi scale

- Light messengers between the SM and heavy sectors such as SUSY, extra dimensions, new strong dynamics.
- Light Dark matter and/or light particles in the hidden sector
- Absence of new particle thresholds between the Fermi and Planck scales? Then all the experimental BSM problems should be explained by light particles.

An example: νMSM





N = Heavy Neutral Lepton - HNL, Majorana fermion

Role of N_1 with mass in keV region: dark matter

Role of N_2, N_3 with mass in 100 MeV – 100 GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

Predictions, 2005-2009

Prediction	assumptions	status
No deviations from SM at LHC	structure of νMSM	OK
SM Higgs boson with $M_H > 127 \pm 2$ GeV	Higgs inflation	OK within 2σ
SM Higgs boson with $M_H = 127 \pm 2$ GeV	asymptotic safety	OK within 2σ
No WIMPS	structure of νMSM	OK
DM is a keV scale HNL , $N \to \nu\gamma$	structure of νMSM	3.5 keV X-ray line?
New particles - HNL	structure of νMSM	constraints only
Unitarity of PMNS matrix	structure of νMSM	OK
no light sterile ν	structure of νMSM	OK
neutrino mass $m_1 \lesssim 10^{-5}$ eV	dark matter	constraints only
No visible $\mu \to e\gamma,\ \mu \to 3e, etc$	BAU	OK
$N_\nu = 3$	structure of νMSM	OK, Planck
spectral index $n_s = 0.967$	Higgs inflation	OK, Planck
small tensor to scalar ratio $r = 0.003$	Higgs inflation	Planck, constraints only
no non-Gaussianities	Higgs inflation	Planck, constraints only

Contradictions to experiments?

Contradictions to experiments?

- Anomalous muon magnetic dipole moment, 3.6σ deviation from the SM and νMSM, 2004.

Contradictions to experiments?

- Anomalous muon magnetic dipole moment, 3.6σ deviation from the SM and νMSM, 2004. Will be checked by muon $g-2$ experiment at FNAL.

Contradictions to experiments?

- Anomalous muon magnetic dipole moment, 3.6σ deviation from the SM and νMSM, 2004. Will be checked by muon $g-2$ experiment at FNAL.

- LSND and MiniBooNE evidences for light sterile neutrino, 1998-2012.

Contradictions to experiments?

- Anomalous muon magnetic dipole moment, 3.6σ deviation from the SM and νMSM, 2004. Will be checked by muon $g-2$ experiment at FNAL.

- LSND and MiniBooNE evidences for light sterile neutrino, 1998-2012. Disfavoured by the recent results from IceCube neutrino observatory, 2016

Contradictions to experiments?

- Anomalous muon magnetic dipole moment, 3.6σ deviation from the SM and νMSM, 2004. Will be checked by muon $g-2$ experiment at FNAL.
- LSND and MiniBooNE evidences for light sterile neutrino, 1998-2012. Disfavoured by the recent results from IceCube neutrino observatory, 2016
- BICEP2 gravitational waves from inflation, 2014.

Contradictions to experiments?

- Anomalous muon magnetic dipole moment, 3.6σ deviation from the SM and νMSM, 2004. Will be checked by muon $g-2$ experiment at FNAL.
- LSND and MiniBooNE evidences for light sterile neutrino, 1998-2012. Disfavoured by the recent results from IceCube neutrino observatory, 2016
- BICEP2 gravitational waves from inflation, 2014. Disappeared in 2015.

Contradictions to experiments?

- Anomalous muon magnetic dipole moment, 3.6σ deviation from the SM and νMSM, 2004. Will be checked by muon $g-2$ experiment at FNAL.
- LSND and MiniBooNE evidences for light sterile neutrino, 1998-2012. Disfavoured by the recent results from IceCube neutrino observatory, 2016
- BICEP2 gravitational waves from inflation, 2014. Disappeared in 2015.
- 750 GeV digamma excess, 2015.

Contradictions to experiments?

- Anomalous muon magnetic dipole moment, 3.6σ deviation from the SM and νMSM, 2004. Will be checked by muon $g-2$ experiment at FNAL.
- LSND and MiniBooNE evidences for light sterile neutrino, 1998-2012. Disfavoured by the recent results from IceCube neutrino observatory, 2016
- BICEP2 gravitational waves from inflation, 2014. Disappeared in 2015.
- 750 GeV digamma excess, 2015. Disappeared in 2016.

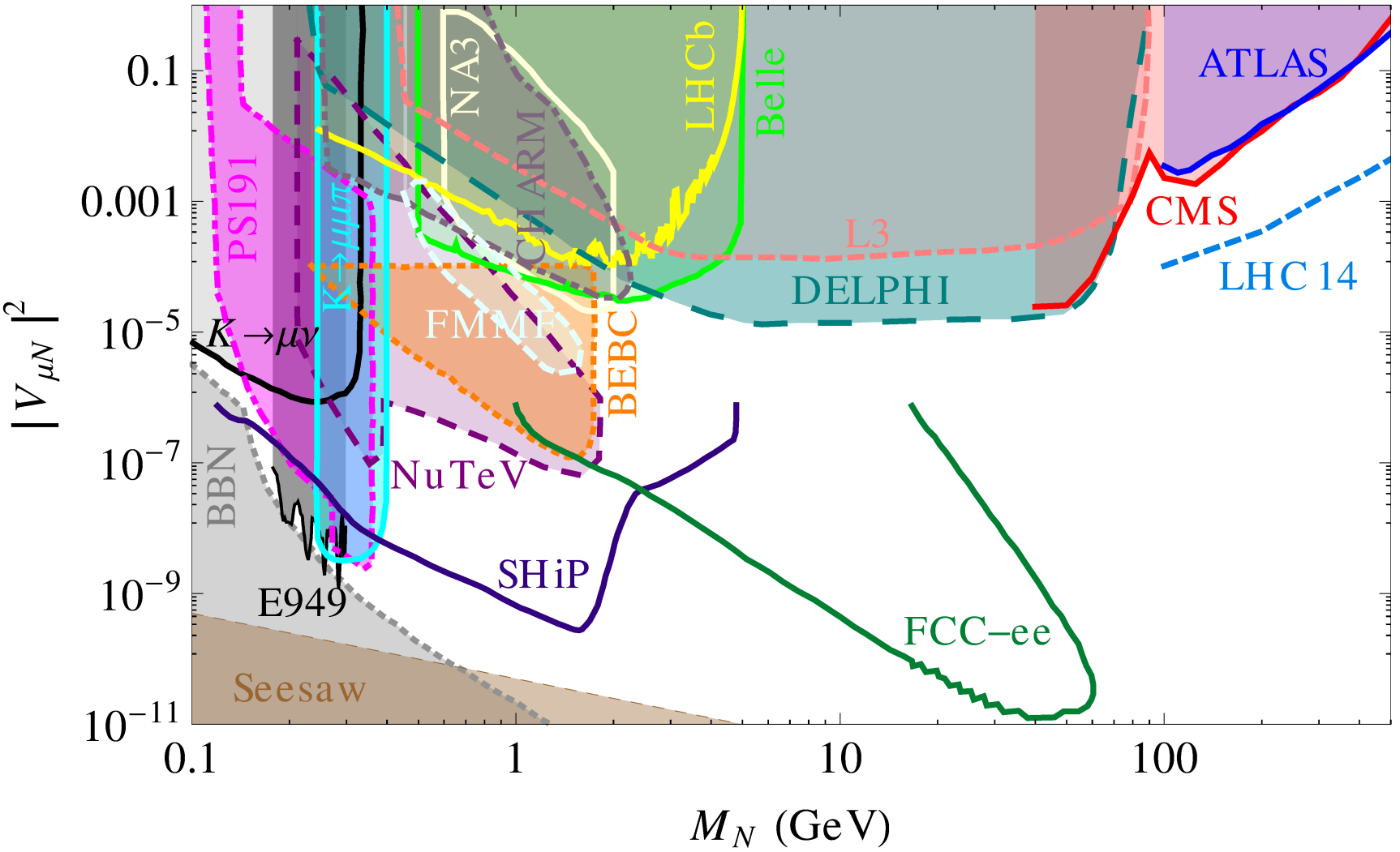
Theoretical challenges, similar to the Standard Model:

- UV completion, unification with gravity
- Why the Higgs and HNL masses are so much smaller than the Planck scale?
- Why the cosmological constant (or dark energy) is so tiny?
- Why θ_{QCD} is so small? Talk by Ringwald
- Origin and magnitude of Yukawa couplings
- ...

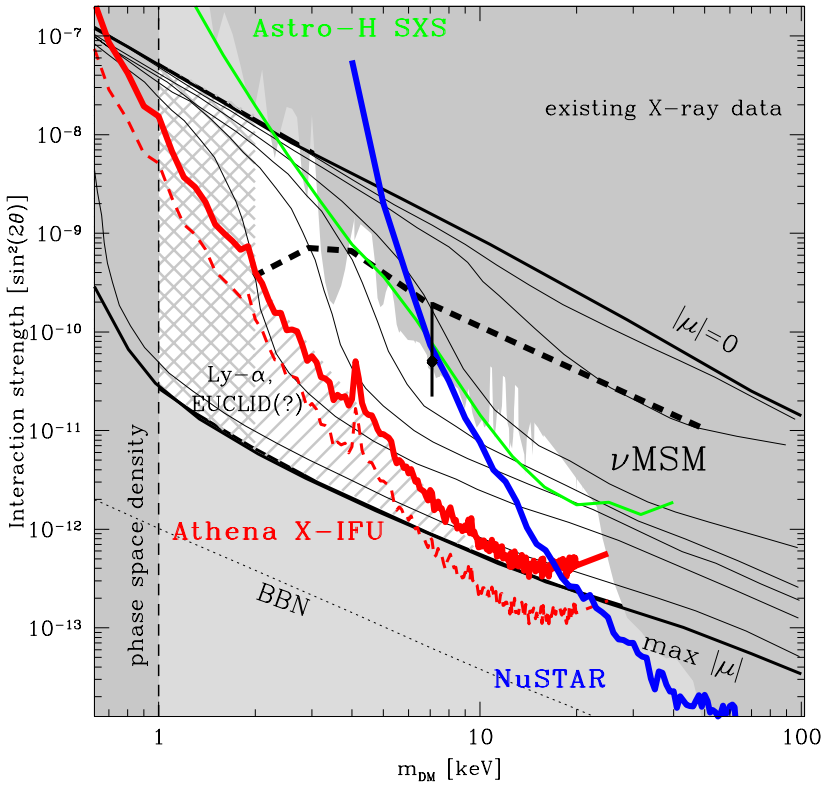
Experimental challenges:

- HNL production and decays are highly suppressed – dedicated experiments or analyses are needed:
  - Mass below ~ 2 GeV - Intensity frontier, CERN SPS.
  - Mass above ~ 2 GeV - FCC in e^+e^- mode in Z-peak, LHC
  - HNL's in beauty and charm decays: Belle, LHCb

Survey of constraints, $N_{2,3}$



- HNL (N_1) dark matter searches in X-rays, future after Astro-H failure
  - Micro-calorimeter on sounding rocket (2017): instrument with large field-of-view and very high spectral resolution
  - Large ESA X-ray mission (2028) – Athena + , X-ray spectrometer (X-IFU) with unprecedented spectral resolution



Although the νMSM is a minimal theory that can address the SM problems in a unified way the fact that it is minimal does not mean that it is correct.

HNLs are just an example of Hidden Sector particles, which appear in models with or without new physics above the Fermi scale. They can couple to SM via different “portals” - gauge-invariant operators:

$B_{\mu\nu}$ - vector portal, dimension 2: dark photon

$H^\dagger H$ - scalar portal, dimension 2: new scalars

$H^T L$ - neutrino portal, dimension 5/2: new leptons, HNLs

...

B-hypercharge field, H - Higgs field, L- leptonic doublet

- Pseudo-Nambu-Goldstone bosons, which are naturally light even if the scale of new physics is high.
  - Axion or axion-like particles (ALPS), Ringwald talk.
  - PNGBs of spontaneously broken global flavour symmetries : familons
  - String theory compactifications: axiverse with ALPs with masses taking values distributed across every scale of energy
- New vector particles, associated with extra gauge forces coming from Grand Unification. Gauging of accidental symmetries of the Standard Model, such as $B - L$.
  - Evoked for resolution of muon $g - 2$ discrepancy, Pospelov talk
  - Mediator of interaction with Dark matter, increasing its annihilation cross-section. Essential for light WIMPS

- Light scalars
  - DM candidates
  - composite states
  - Hidden Valley scenarios
  - ...
- Light SUSY particles
  - Unstable neutralino in models with R-parity breaking (then DM candidates - axino or axion)
  - Scalar and pseudoscalar sgoldstinos coming from SUSY breaking (e.g. no-scale SUGRA)
  - SUSY partners of axion: axino and saxion
  - ...

Common features of hidden particles

Production

- Meson decays
  - Dark photon A': $\eta,\ \rho,\ \pi, ... \to \gamma A'$
  - HNL, neutralino, axino N: $K, D, B \to N + lepton$
  - scalars, light inflaton, pseudoscalars, sgoldstino X: $K, D, B \to X + meson$
  - photino $\tilde{\gamma}$: $B \to K\tilde{\gamma}\tilde{\gamma}$
- Direct production, bremsstrahlung
  - Dark photon A': $q\ \bar{q} \to A',\ q\ g \to A'\ q$, $pp \to ppA'$
  - scalars S: $p + \mathrm{target} \to S + ...$
  - ALPs, saxions a: Drell-Yan $q\bar{q} \to \gamma^*$, followed by Primakoff $\gamma^* \to a\gamma$

Common features of hidden particles

Detection

- Hidden particle decays
  - Dark photon A': $A' \to l^+l^-, \quad A' \to \mathbf{hadrons}$
  - HNL, neutralino, axino N: $N \to meson + lepton, \ ...$
  - scalars, light inflaton, pseudoscalars, sgoldstino X: $X \to \gamma\gamma, \ l^+l^-, \ ...$
  - hidden photino $\tilde{\gamma}$: $\tilde{\gamma} \to \tilde{\gamma}' + l^+l^-$

For comprehensive study of possibilities at CERN SPS see:

IOP Publishing Reports on Progress in Physics
Rep. Prog. Phys. **00** (2016) 000000 (137pp) UNCORRECTED PROOF

Report on Progress

A facility to search for hidden particles at the CERN SPS: the SHiP physics case

Sergey Alekhin[1,2], Wolfgang Altmannshofer[3], Takehiko Asaka[4], Brian Batell[5], Fedor Bezrukov[6,7], Kyrylo Bondarenko[8], Alexey Boyarsky[8,68], Ki-Young Choi[9], Cristóbal Corral[10], Nathaniel Craig[11], David Curtin[12], Sacha Davidson[13,14], André de Gouvêa[15], Stefano Dell'Oro[16], Patrick deNiverville[17], P S Bhupal Dev[18], Herbi Dreiner[19], Marco Drewes[20], Shintaro Eijima[21], Rouven Essig[22], Anthony Fradette[17], Björn Garbrecht[20], Belen Gavela[23], Gian F Giudice[5], Mark D Goodsell[24,25], Dmitry Gorbunov[26,27], Stefania Gori[3], Christophe Grojean[28,29,69], Alberto Guffanti[30], Thomas Hambye[31], Steen H Hansen[32], Juan Carlos Helo[10,33], Pilar Hernandez[34], Alejandro Ibarra[20], Artem Ivashko[8,35], Eder Izaguirre[3], Joerg Jaeckel[36,69], Yu Seon Jeong[37], Felix Kahlhoefer[29], Yonatan Kahn[38], Andrey Katz[5,39,40], Choong Sun Kim[37], Sergey Kovalenko[10], Gordan Krnjaic[3], Valery E Lyubovitskij[41,42,43], Simone Marcocci[16], Matthew Mccullough[5], David McKeen[44], Guenakh Mitselmakher[45], Sven-Olaf Moch[46], Rabindra N Mohapatra[47], David E Morrissey[48], Maksym Ovchynnikov[35], Emmanuel Paschos[49], Apostolos Pilaftsis[18], Maxim Pospelov[3,17,69], Mary Hall Reno[50], Andreas Ringwald[29], Adam Ritz[17], Leszek Roszkowski[51], Valery Rubakov[26], Oleg Ruchayskiy[21,52,68], Ingo Schienbein[53], Daniel Schmeier[19], Kai Schmidt-Hoberg[29], Pedro Schwaller[5], Goran Senjanovic[54,55], Osamu Seto[56], Mikhail Shaposhnikov[21,68,69], Lesya Shchutska[45,69], Jessie Shelton[57], Robert Shrock[58], Brian Shuve[3], Michael Spannowsky[59], Andy Spray[60], Florian Staub[5], Daniel Stolarski[5], Matt Strassler[40], Vladimir Tello[54], Francesco Tramontano[61,62,69], Anurag Tripathi[61], Sean Tulin[63], Francesco Vissani[16,64], Martin W Winkler[65] and Kathryn M Zurek[66,67]

Conclusions

The search for new very weakly interacting particles with masses below the Fermi scale, inaccessible at LHC, can

- find particles that lead to neutrino masses and oscillations
- find particles that lead to baryon asymmetry of the Universe
- find particles that could inflate the Universe
- shed new light on the properties of dark matter

Whatever the LHC will bring us, we are in a “no lose” situation: New physics at the LHC - study it! No new physics at the LHC - a number of new experiments at high energy, precision, and high intensity frontiers, in cosmology and astrophysics will be needed - a lot to explore!

Carlo Rubbia, 2008: "Nature will tell"

I think Nature is smarter than physicists. We should have the courage to say: "Let Nature tell us what is going on."

Our experience of the past has demonstrated that in the world of the infinitely small, it is extremely silly to make predictions as to where the next physics discovery will come from and what it will be.

In a variety of ways, this world will always surprise us all. The next breakthrough might come from beta decay, or from underground experiments, or from accelerators.

We have to leave all this spectrum of possibilities open and just enjoy this extremely fascinating science.