ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Sterile Neutrinos as the Origin of Dark and Baryonic Matter

Mikhail Shaposhnikov

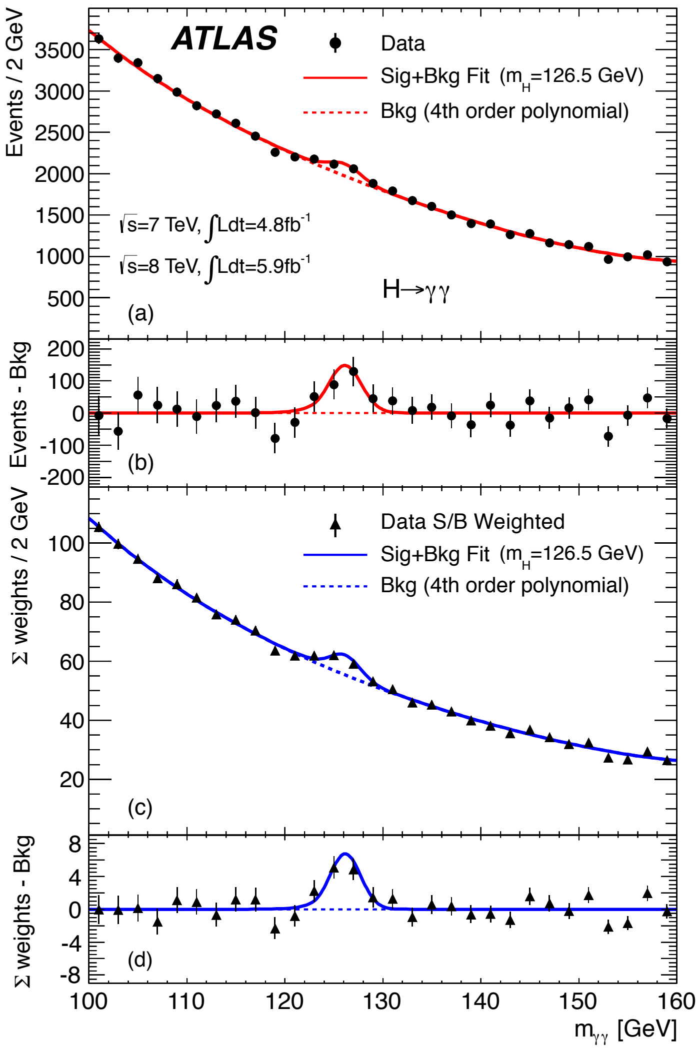
BNL, 21 June 2016

Outline

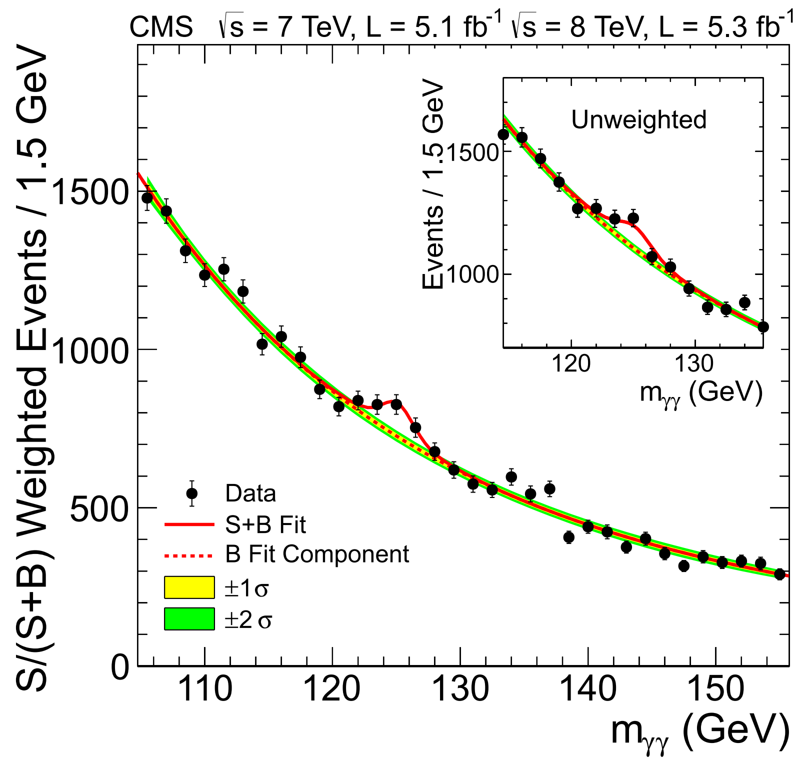
- Setting up the scene: LHC and new physics
- Standard Model and heavy neutral leptons (HNL or sterile neutrinos)
- Dark matter from HNL
- Baryon asymmetry of the Universe from HNL
- How to search for HNL?
- SHiP and FCC-ee
- Conclusions

The scene : LHC discoveries

July 4, 2012, Higgs at ATLAS and CMS



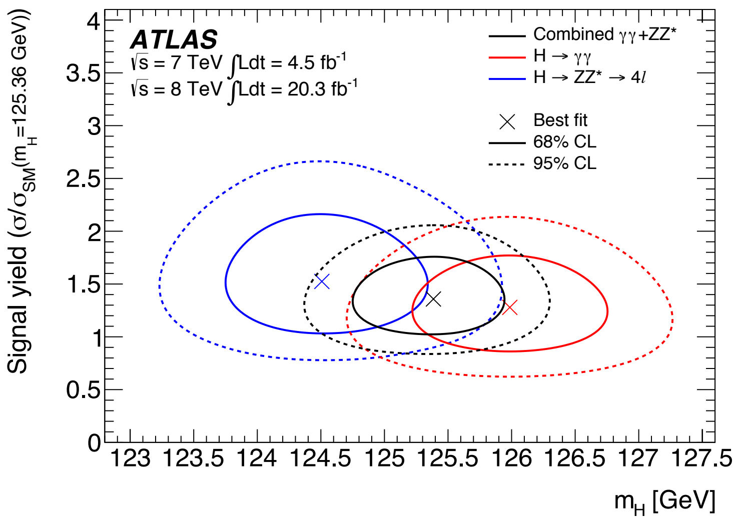
CMS

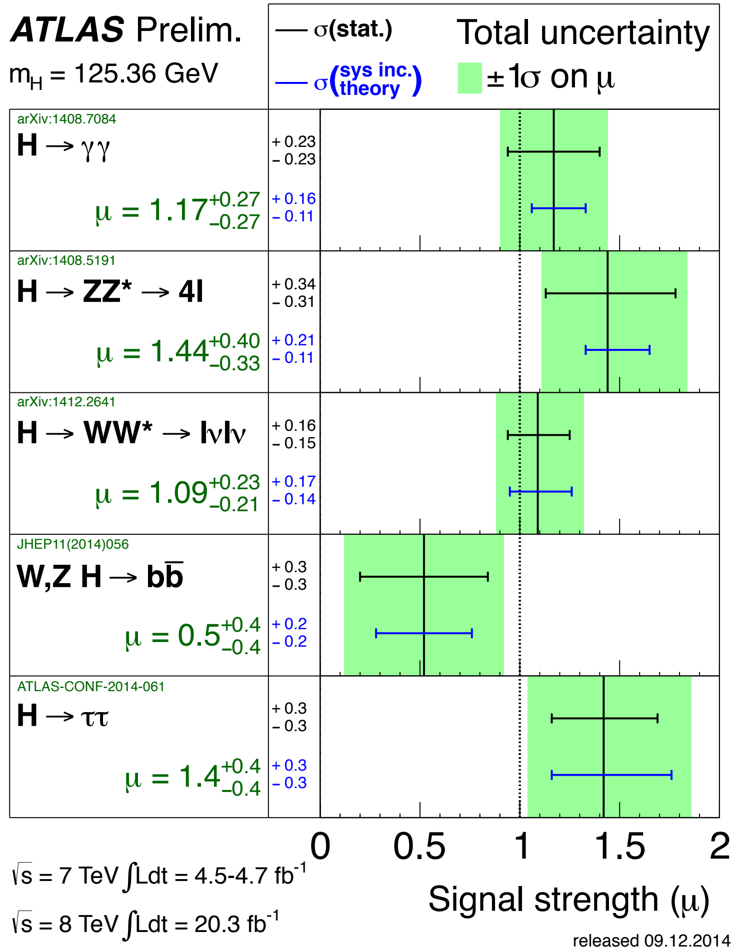


Higgs boson properties

Atlas - $M_H = 125.36 \pm 0.41$ GeV

CMS - $M_H = 125.03 \pm 0.29$ GeV

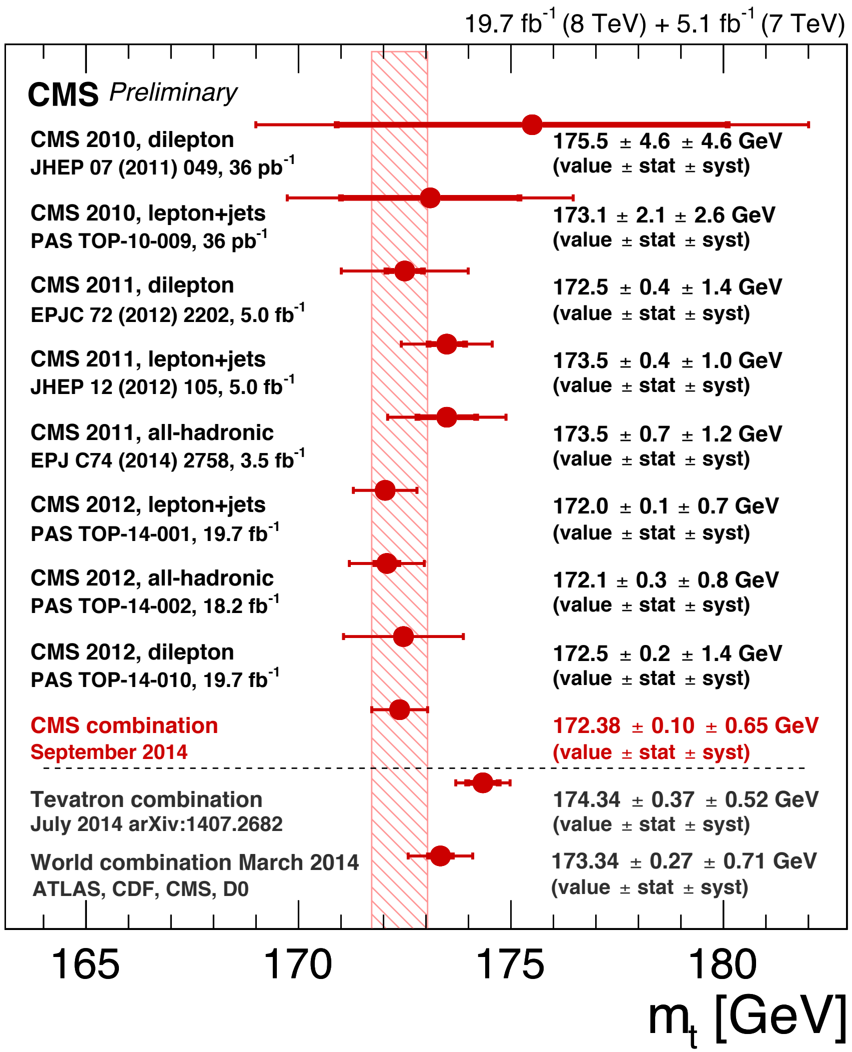




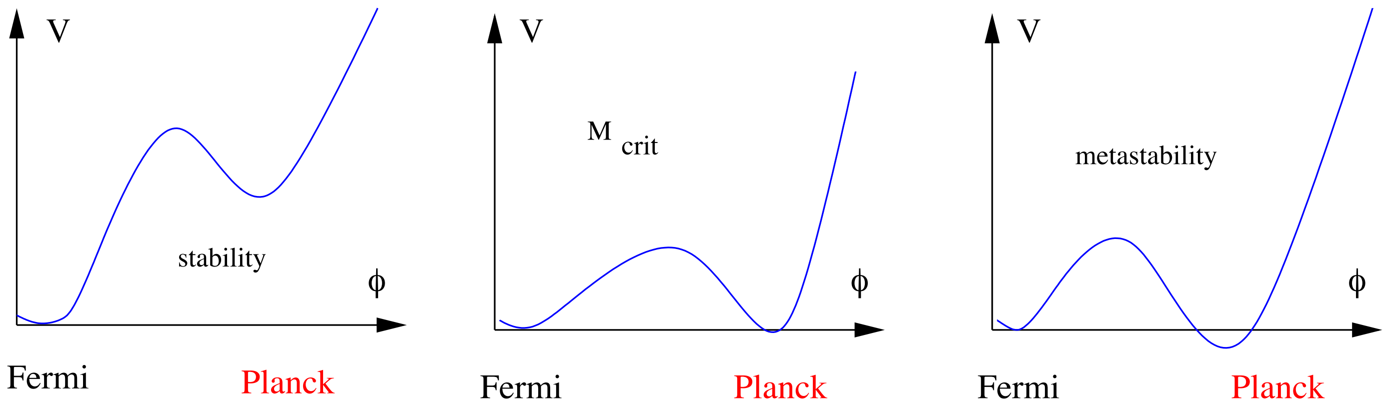
New resonance properties are consistent with those of the Higgs boson of the Standard Model

Determination of top quark mass

Monte Carlo mass: $m_t = \mathbf{172.38 \pm 0.10 \pm 0.65}$ GeV



Important fact: The combination of top-quark and Higgs boson masses is very close to the stability bound of the SM vacuum* (95'), to the Higgs inflation bound** (08'), and to asymptotic safety values for M_H and M_t *** (09'):

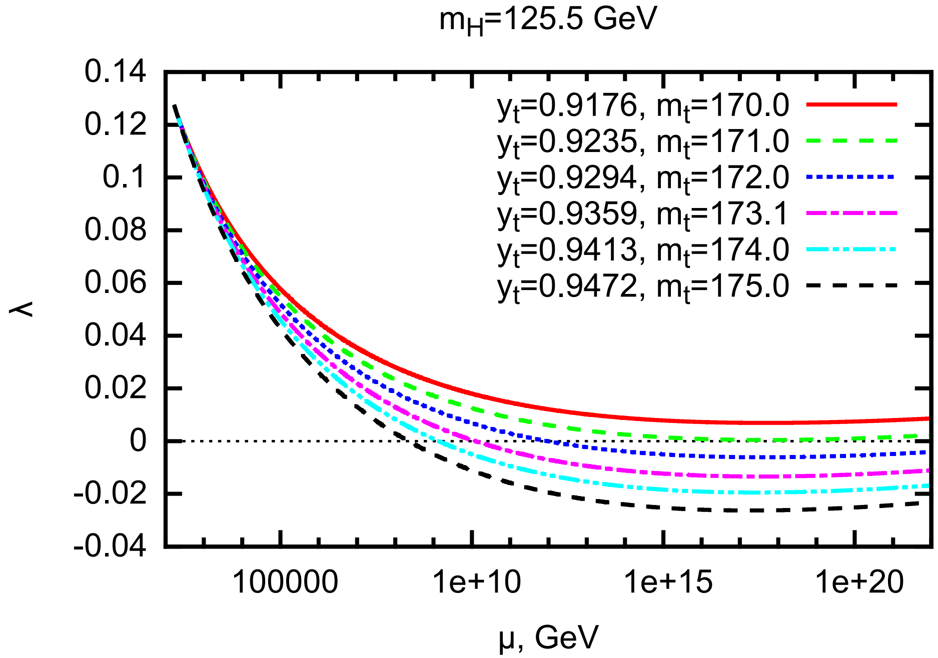


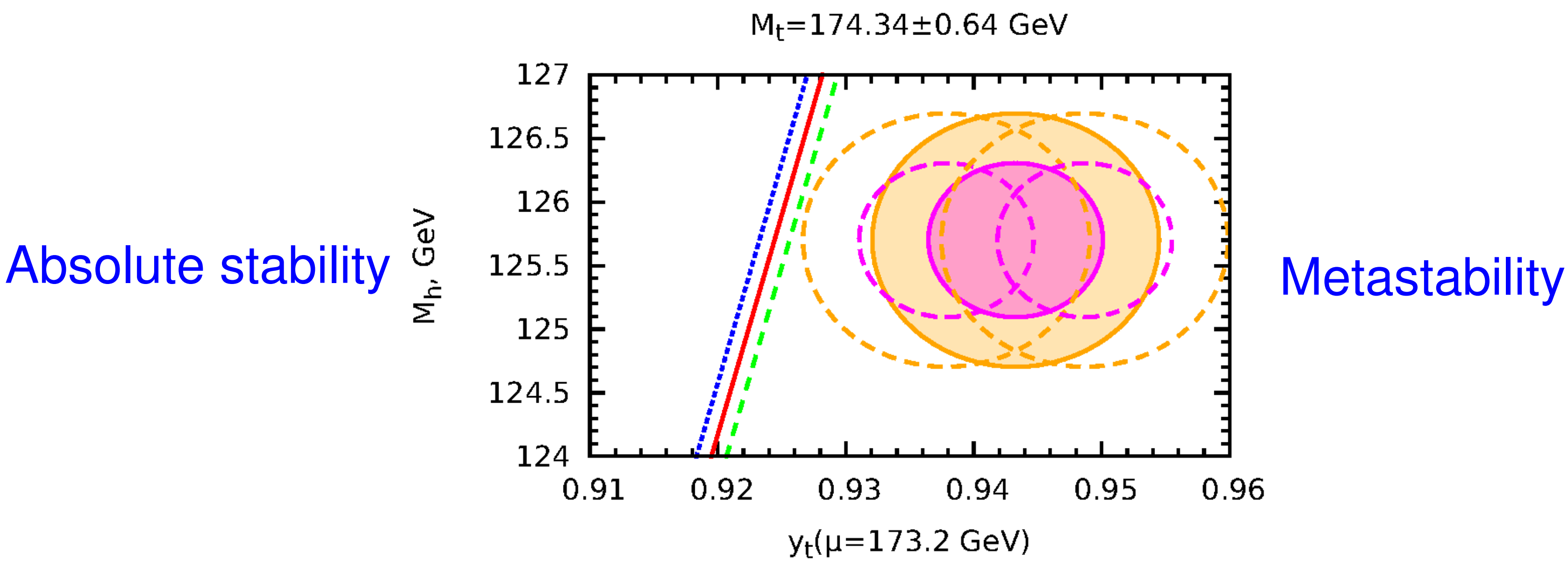
* Froggatt, Nielsen

** Bezrukov, MS

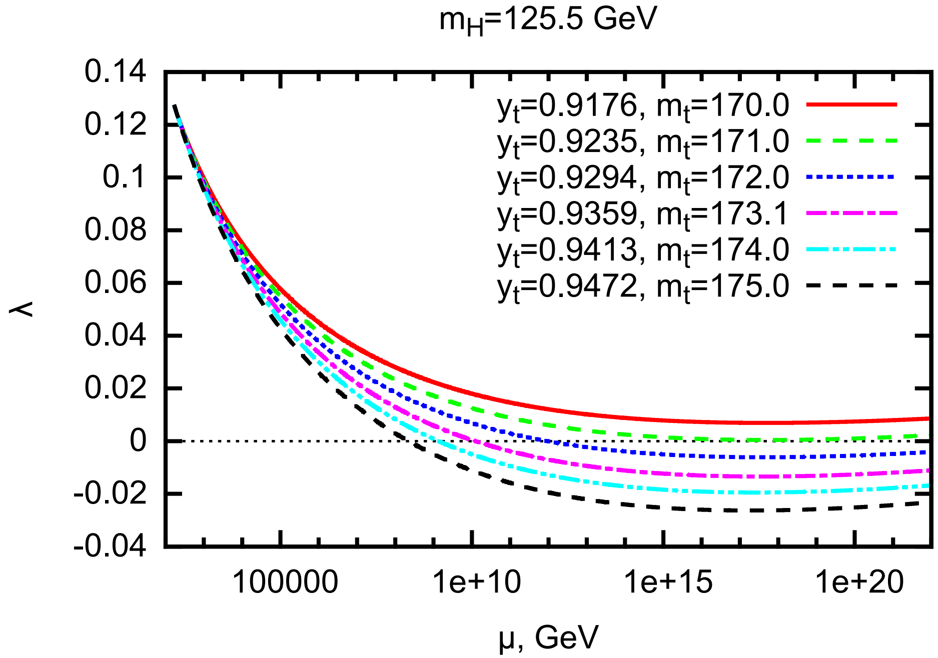
De Simone, Hertzberg, Wilczek

*** Wetterich, MS

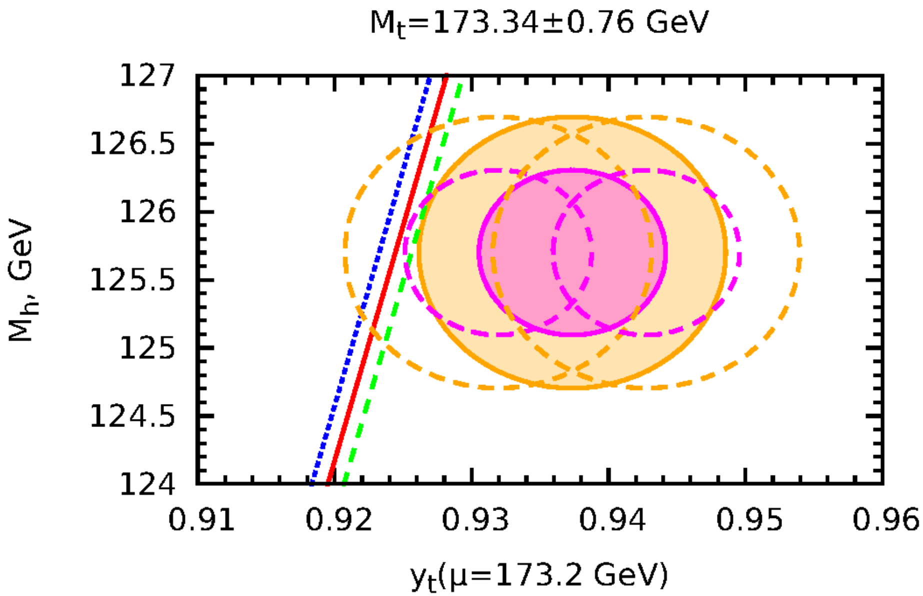




TEVATRON 2014: $m_t = 174.34 \pm 0.37 \pm 0.52$ GeV

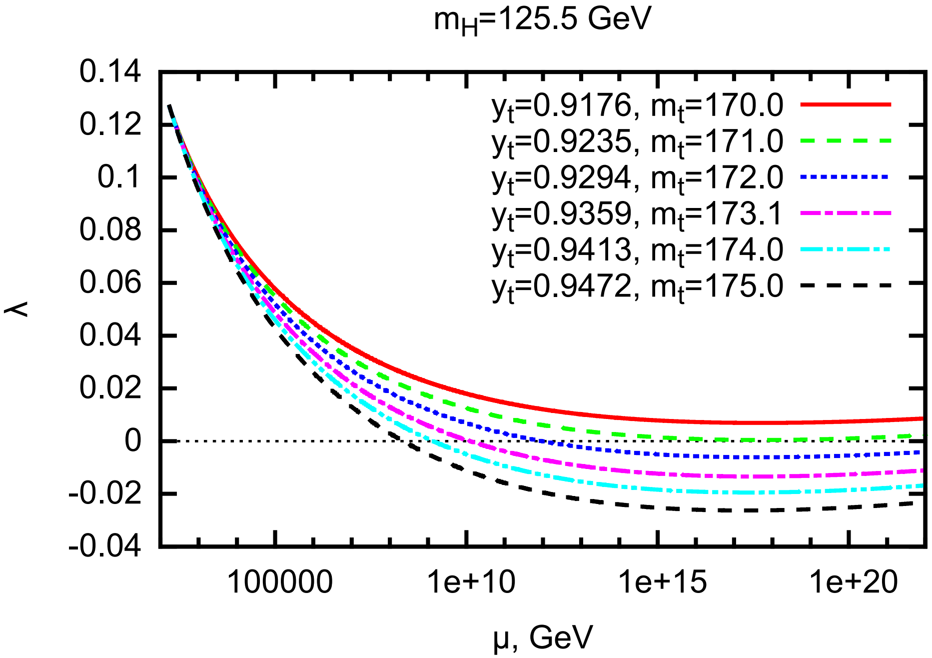


Absolute stability

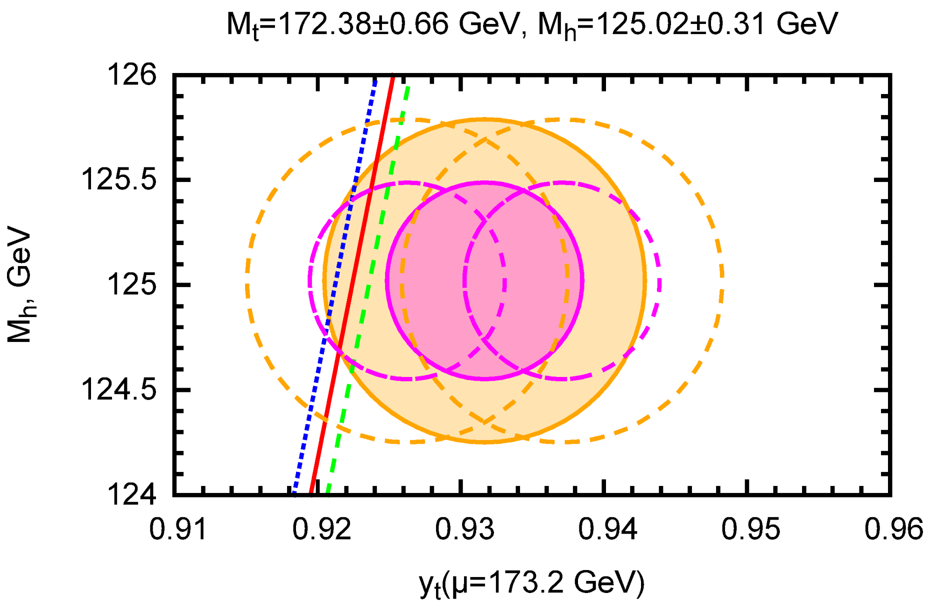


Metastability

PDG 2014: $m_t = \mathbf{173.34 \pm 0.27 \pm 0.71\ GeV}$



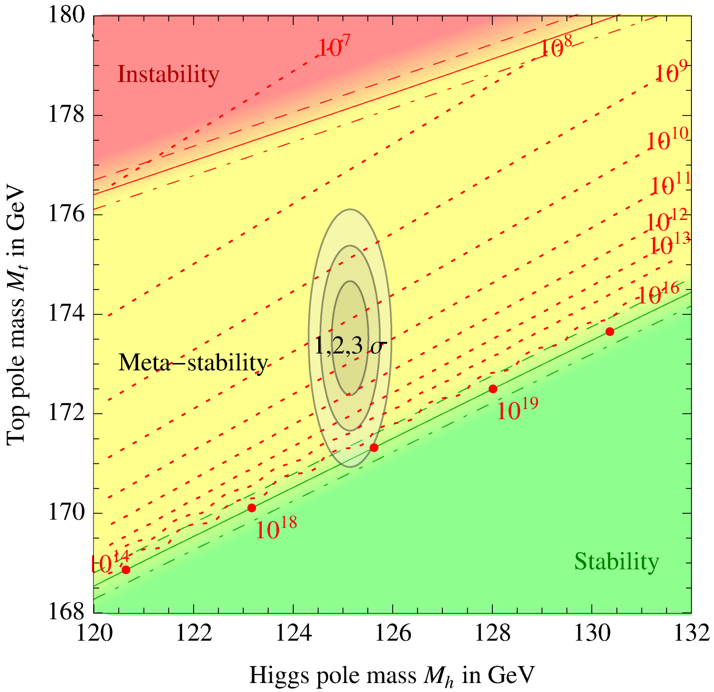
Absolute stability



Metastability

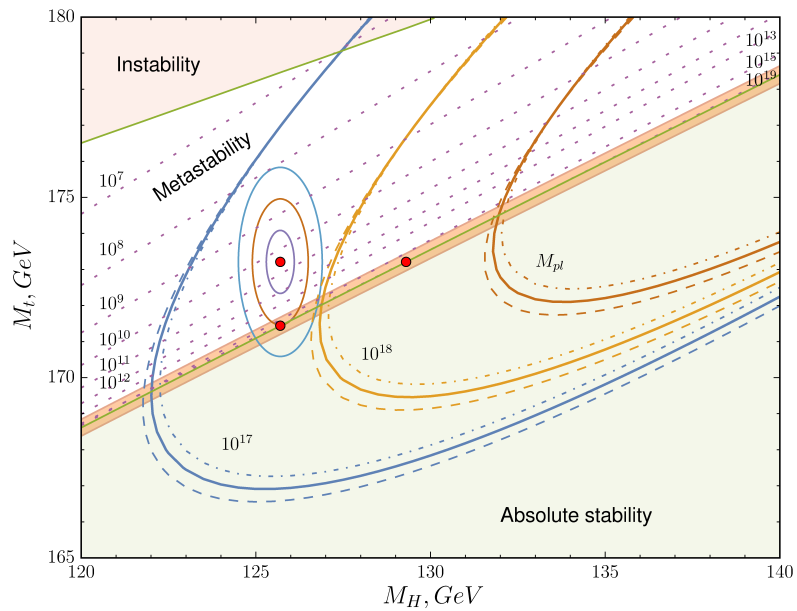
CMS 2014: $m_t = \mathbf{172.38 \pm 0.10 \pm 0.65\ GeV}$

Buttazzo et al, ’13, ’14



Vacuum is unstable at $\mathbf{2.8\sigma}$

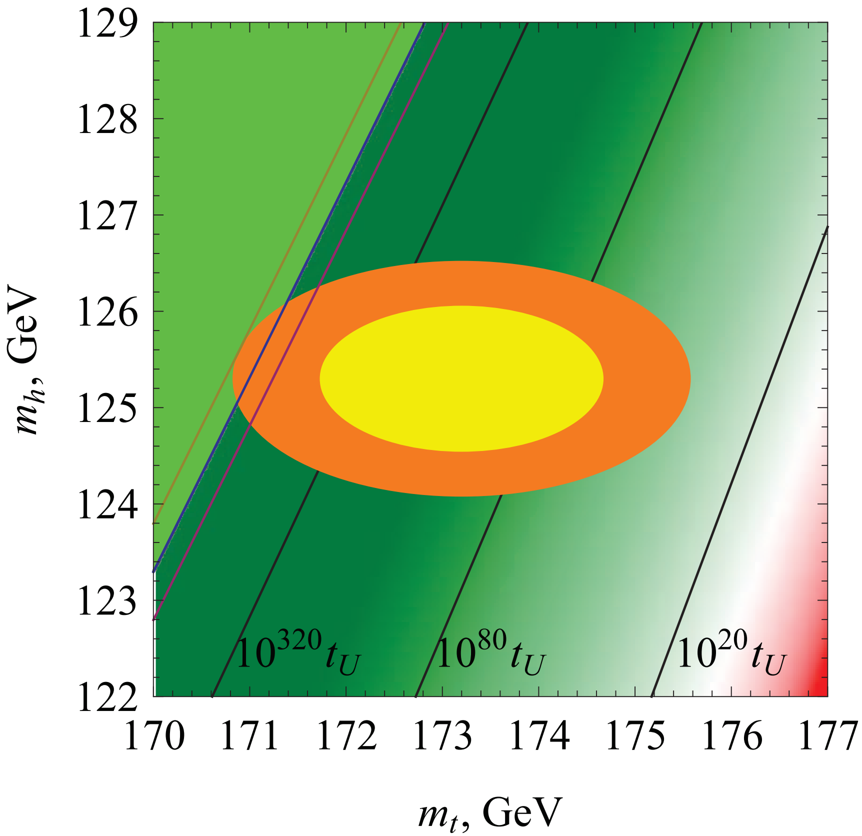
Bednyakov et al, ’15



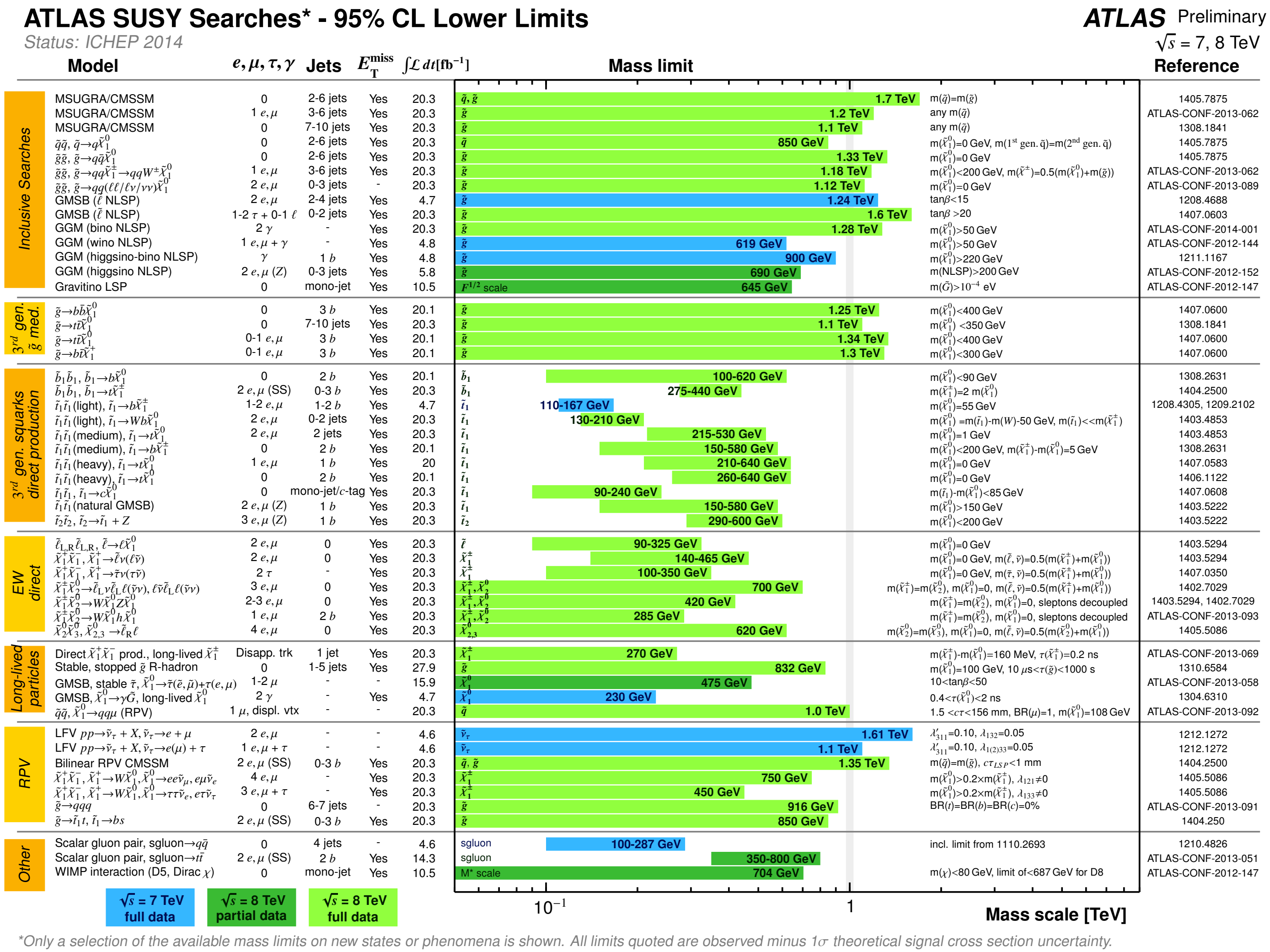
Vacuum is unstable at $\mathbf{1.3\sigma}$

Main uncertainty: top Yukawa coupling, relation between the MC mass and the top Yukawa coupling allows for ± 1 GeV in M_{top}. Alekhin et al, Frixione et al.

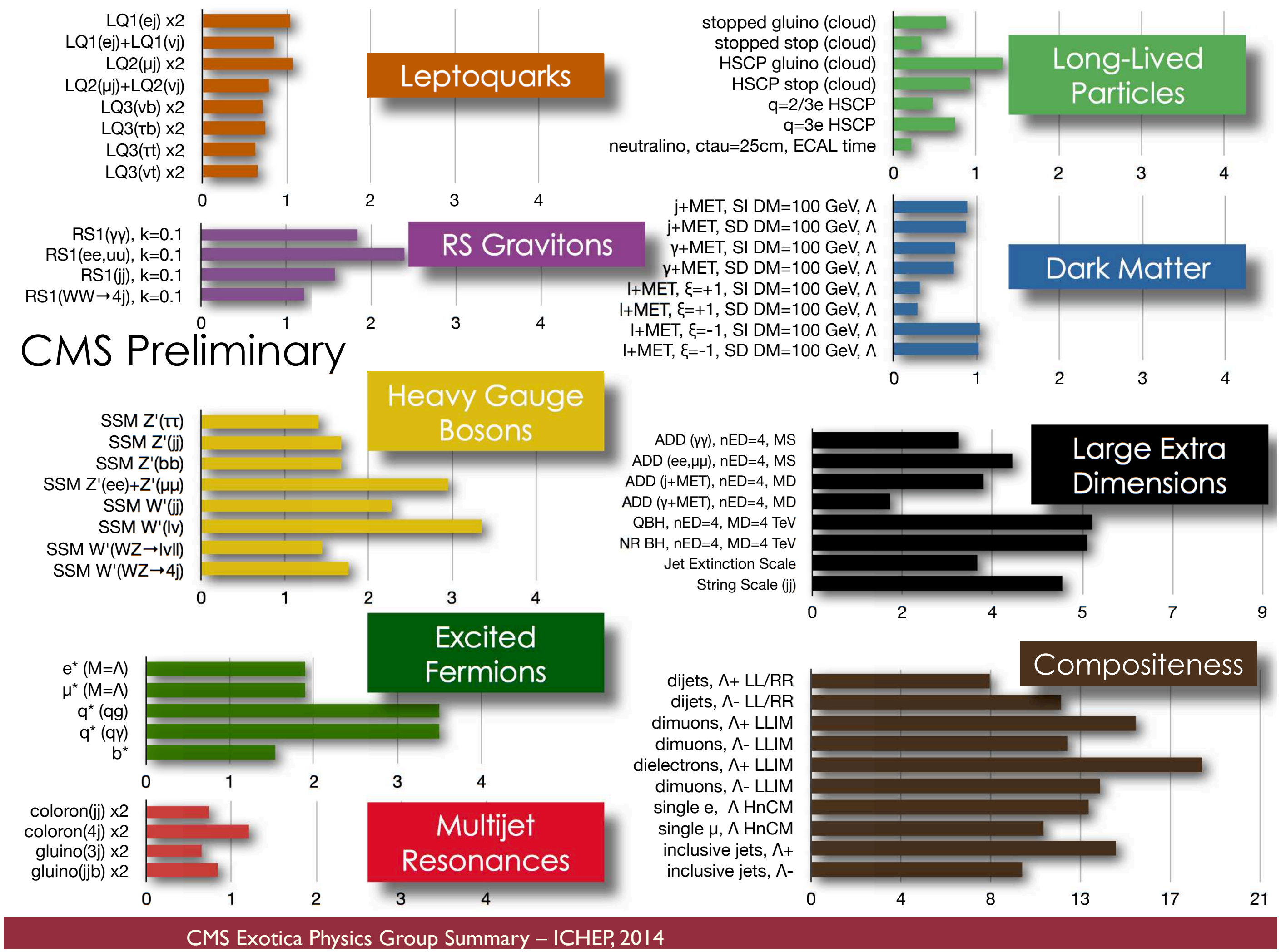
Vacuum lifetime



Searches for new physics, SUSY



Searches for new physics, exotics



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- The masses of the top quark and of the Higgs boson, the Nature has chosen, make the SM a self-consistent effective field theory all the way up to the Planck scale
- End of high energy physics?

Experimental evidence for BSM physics

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- Neutrino masses and oscillations, absent in the Standard Model
- Most of the matter in the universe is dark : no particle physics candidate in the SM
- The Universe is asymmetric: it contains baryons, but there is no antimatter in amounts comparable with matter. This cannot be explained in the SM.

How to reconcile the evidence for new physics without spoiling the success of the Standard Model?

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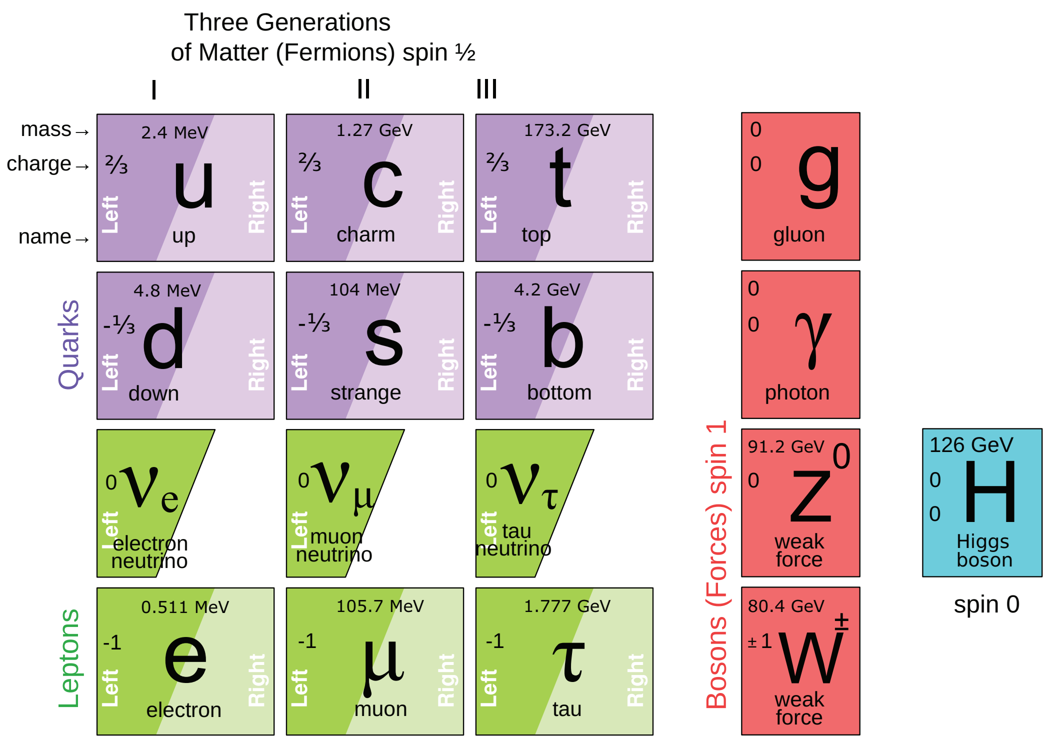
the SM


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass→
charge→
name→
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
173.2 GeV
⅔
t
top
Quarks
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
νe
electron
neutrino
0
νμ
muon
neutrino
0
ντ
tau
neutrino
Leptons
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
Left
Right
Bosons (Forces) spin 1
0
0
g
gluon
0
0
γ
photon
91.2 GeV
0
Z0
weak
force
80.4 GeV
±1
W±
weak
force
126 GeV
0
0
H
Higgs
boson
spin 0

The missing piece: sterile neutrinos

Most general renormalizable (see-saw) Lagrangian

$$L_{see-saw} = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \, \bar{L}_\alpha N_I \Phi - \frac{M_I}{2} \, \bar{N}_I^c N_I + h.c.,$$

Assumption: all Yukawa couplings with different leptonic generations are allowed.

$I \leq \mathcal{N}$ - number of new particles - HNLs - cannot be fixed by the symmetries of the theory.

Let us play with $\mathcal{N}$ to see if having some number of HNLs is good for something

- $\mathcal{N} = 1$: Only one of the active neutrinos gets a mass

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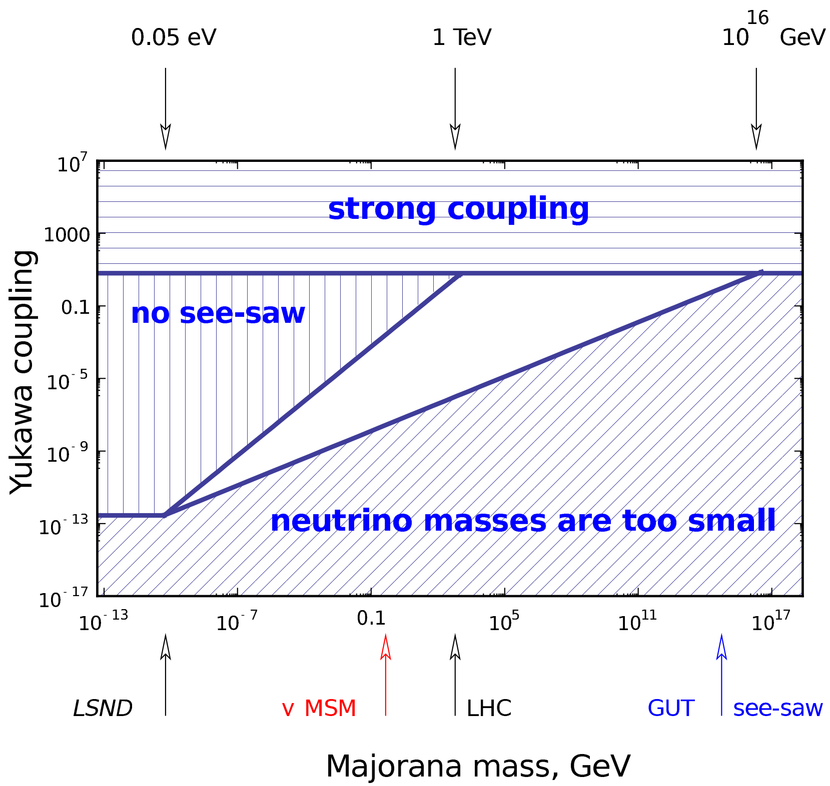
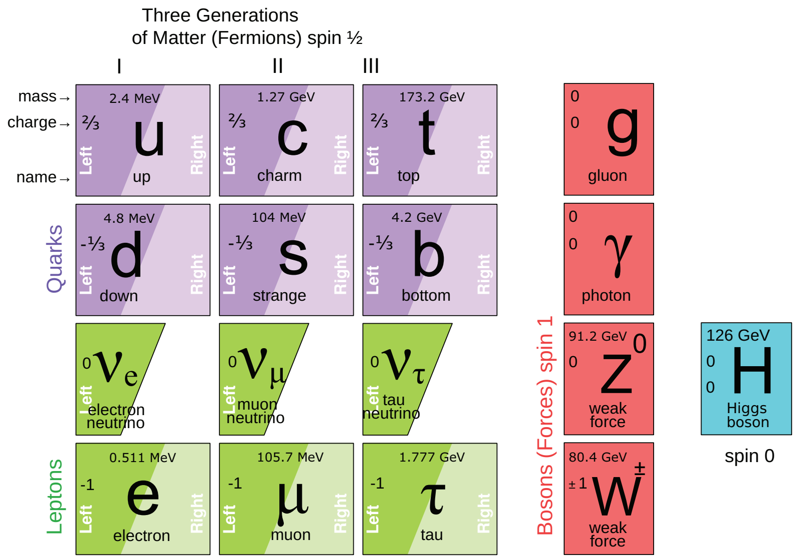
- $\mathcal{N} > \mathbf{3}$: Now you can do many things, depending on your taste - extra relativistic degrees of freedom in cosmology, neutrino anomalies, dark matter, different scenarios for baryogenesis, and different combinations of the above.

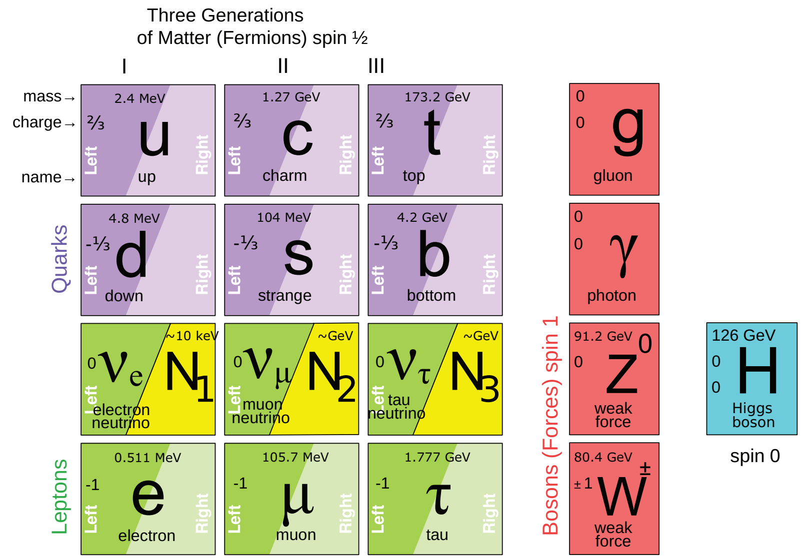
New mass scale and Yukawas

$$Y^2 = Trace[F^\dagger F]$$



$\mathcal{N} = 3$ with $M_I < M_W$: the νMSM





N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

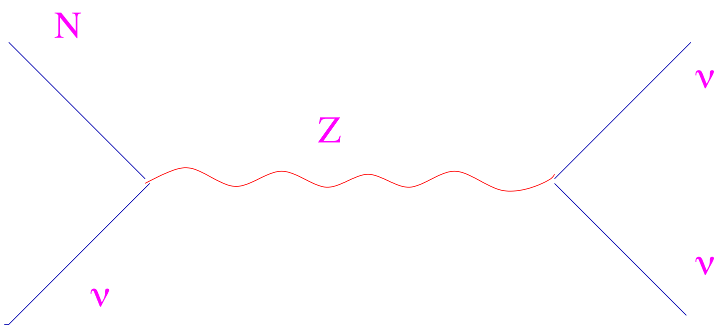
Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

What should be the properties of $N_{1,2,3}$ in the minimal setup - no any type of new physics between the Fermi and Planck scales ?

How to search for them experimentally?

DM candidate: the lightest Majorana ν, N_1

Yukawa couplings are small $\rightarrow$ sterile N can be very stable.



Main decay mode: $N \rightarrow 3\nu$.

For one flavour:

$$\tau_{N_1} = 5\times 10^{26}\,\text{sec}\left(\frac{1\text{keV}}{M_1}\right)^5\left(\frac{10^{-8}}{\Theta^2}\right)$$

$$\Theta = \frac{m_D}{M_I}$$

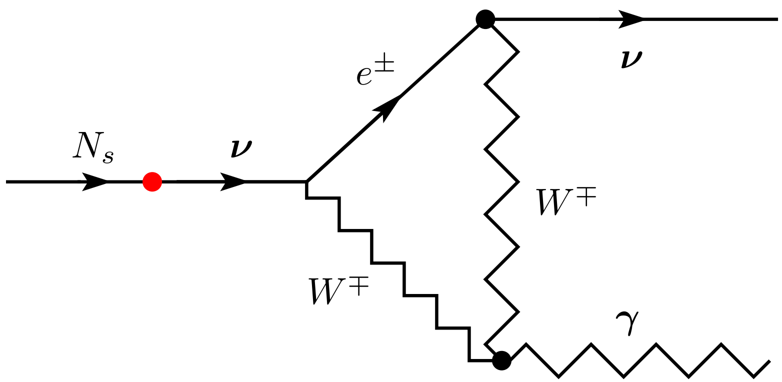
Dark Matter candidate: N_1

DM particle is not stable. Main decay mode $N_1 \rightarrow 3\nu$ is not observable.

Subdominant radiative decay channel: $N \rightarrow \nu\gamma$.

Photon energy:

$$E_\gamma = \frac{M}{2}$$



Radiative decay width:

$$\Gamma_{\mathrm{rad}} = \frac{9\,\alpha_{\mathrm{EM}}\,G_F^2}{256 \cdot 4\pi^4}\ \sin^2(2\theta)\,M_s^5$$

Dark Matter production

Cosmological production of sterile neutrinos

Sterile neutrino never equilibrates, since their interactions are very weak

$$\Omega_N h^2 \sim 0.1 \sum_I \sum_{\alpha=e,\mu,\tau} \left(\frac{|\Theta_{\alpha I}|^2}{10^{-8}}\right) \left(\frac{M_I}{1 \text{ keV}}\right)^2 .$$

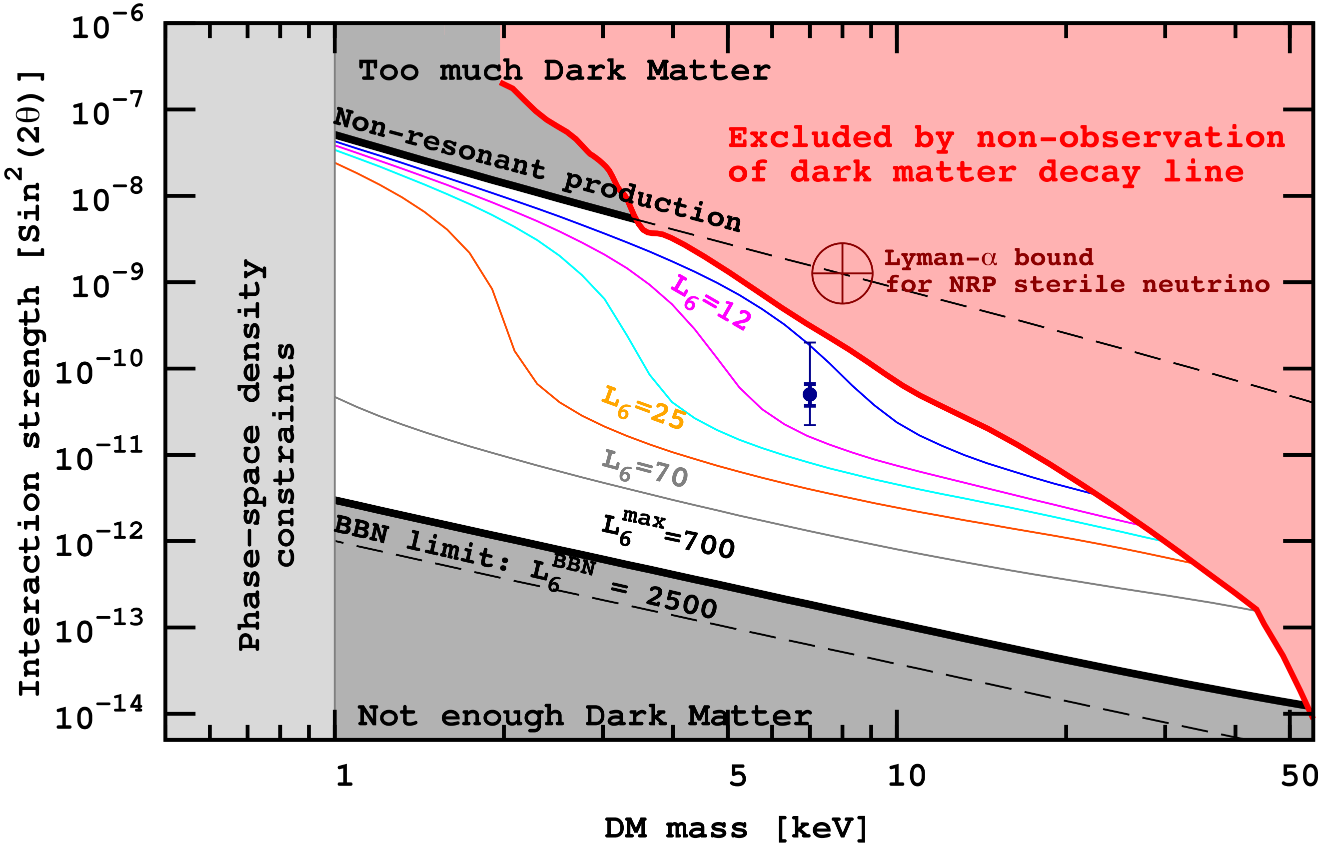
Production temperature $\sim 130 \left(\frac{M_I}{1 \text{ keV}}\right)^{1/3}$ MeV

Production rate depends on Yukawa couplings and on lepton asymmetry.

Note: DM sterile neutrino does not contribute to the number of relativistic species! Perfect agreement with Planck measurements.

Constraints on DM sterile neutrino N_1

- Stability. N_1 must have a lifetime larger than that of the Universe
- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \;\; q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance
- Structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars and structure of dwarf galaxies
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton).

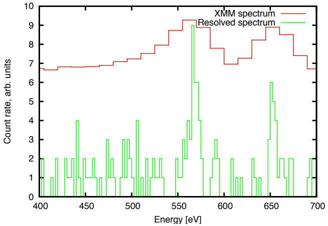


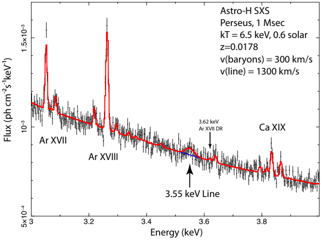
Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky , O. Ruchayskiy, D. Iakubovskyi, J. Franse. e-Print: arXiv:1402.4119

Next step for 3.5 keV line: Astro-H

- Astro-H – new generation X-ray spectrometer with a superb spectral resolution
- Launched 17 February 2016
- Calibration phase – about 1 year
- First observational/calibration target – Perseus galaxy cluster, where strong 3.5 keV line has been detected
- Expected to be able to confirm the presence of the 3.5 keV line in Perseus and distinguish it from atomic element lines (Potassium, Chlorium, etc.)





HOWEVER

Status of Astro-H

From Supplemental Handout on the Operation Plan of the X-ray Astronomy Satellite ASTRO-H

(1) On March 26th, attitude maneuver to orient toward an active galactic nucleus was completed as planned.

(2) After the maneuver, unexpected behavior of the attitude control system (ACS) caused incorrect determination of its attitude as rotating, although the satellite was not rotating actually. In the result, the Reaction Wheel (RW) to stop the rotation was activated and lead to the rotation of satellite. 【Presumed Mechanism 1】

(3)In addition, unloading(*) of angular velocity by Magnetic Torquer operated by ACS did not work properly because of the attitude anomaly. The angular momentum kept accumulating in RW. 【 Presumed Mechanism 2】

(4) Judging the satellite is in the critical situation, ACS switched to Safe Hold mode (SH), and the thrusters were used. At this time ACS provided atypical command to the thrusters by the inappropriate thruster control parameters. As a result, it thrusted in an unexpected manner, and it is estimated that the satellite rotation was accelerated.【 Presumed Mechanism 3】

(5)Since the rotation speed of the satellite exceeded the designed speed, parts of the satellite that are vulnerable to the rotation such as solar array paddles (SAPs), Extensible Optical Bench (EOB) and others separated off from the satellite. There is high possibility that the both SAPs had broken off at their bases and were separated. 【 Presumed Mechanism 4】

Considering the information above, JAXA concluded that the satellites functionality could not be restored and ceased recovery activities. (April 28)

Before its failure Astro-H had started its observational programme

- There are observations of the center of Perseus galaxy cluster
- Observations performed in calibration phase, so low efficiency (additional filters)
- However, the center of Perseus galaxy cluster exhibits one of the strongest signals at 3.5 keV (confirmed by several groups and observed with 3 instruments)
- The data has not been revealed by the collaboration, but based on some conference presentations we expect to see at least a 3σ signal
- **To summarize:** it can still be possible to confirm the presence of the 3.5 keV line in Perseus and distinguish it from atomic element lines (Potassium, Chlorium, etc.)

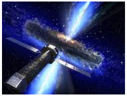
Future after Astro-H failure

Microcalorimeter on sounding rocket (2017)

- Instrument with large field-of-view and very high spectral resolution
- Very useful to resolve narrow lines from diffuse sources
- Can improve existing bounds by a factor of few in the mass range (5-15 keV) and partially probe 3.5 keV line region
- Fly time $\sim 10^2$ seconds pointing to some area in the sky $\Rightarrow$ can only explore a signal from Galactic dark matter halo

Athena+

- Large ESA X-ray mission (2028)
- X-ray spectrometer (X-IFU) – unprecedented spectral resolution
- Lifetime: 5–10 years
- Very large collecting area (10$\times$ that of XMM)



Baryon asymmetry

Sakharov conditions:

- Baryon number violation - OK due co complex vacuum structure in the SM and chiral anomaly
- CP-violation - OK due to new complex phases in Yukawa couplings
- Deviations from thermal equilibrium - OK as HNL are out of thermal equilibrium for $T > \mathcal{O}(100)$ GeV

Baryon asymmetry

Akhmedov, Rubakov, Smirnov; Asaka, MS

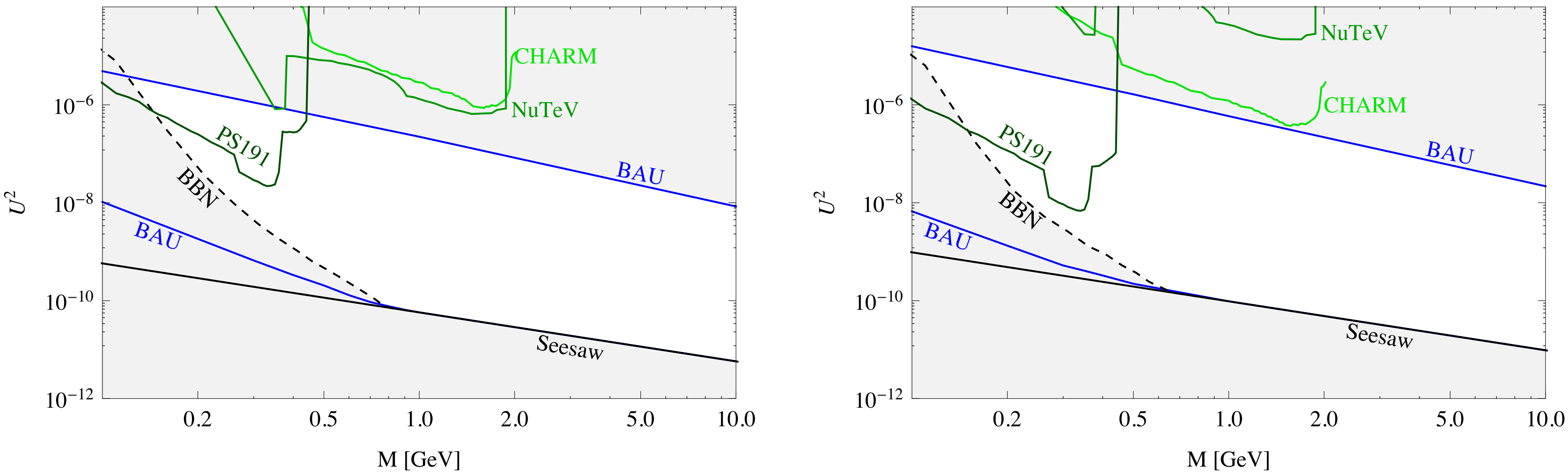
Idea - $N_{2,3}$ HNL oscillations as a source of baryon asymmetry.
Qualitatively:

- HNL are created in the early universe and oscillate in a coherent way with CP-breaking.
- Lepton number from HNL can go to active neutrinos.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

Constraints on BAU HNL $N_{2,3}$

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

- BAU generation requires out of equilibrium: mixing angle of $N_{2,3}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $N_{2,3}$ to active neutrinos cannot be too small
- BBN. Decays of $N_{2,3}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $N_{2,3}$ have not been seen

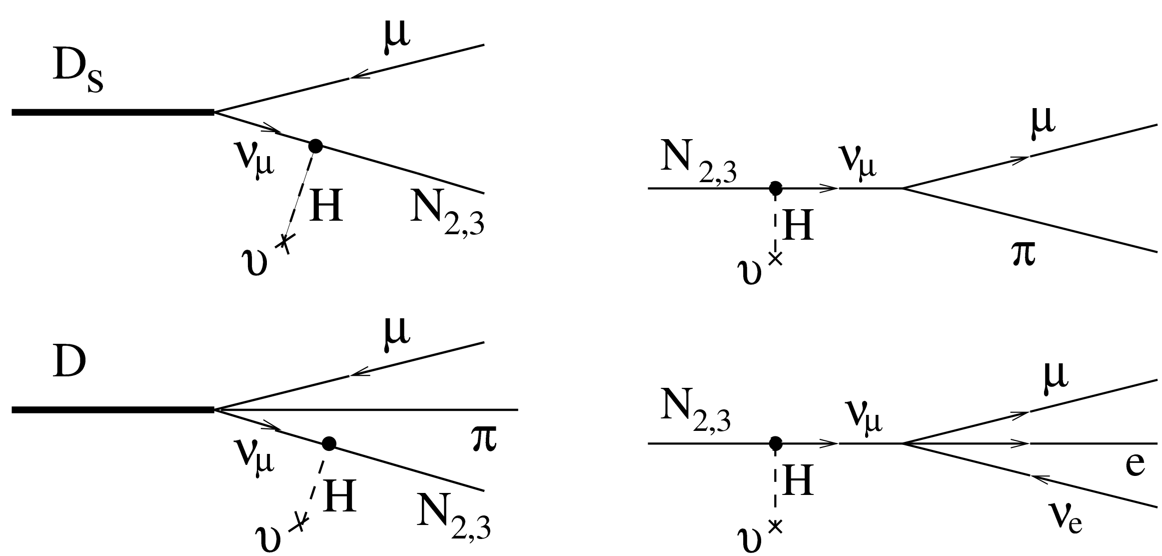


Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS).

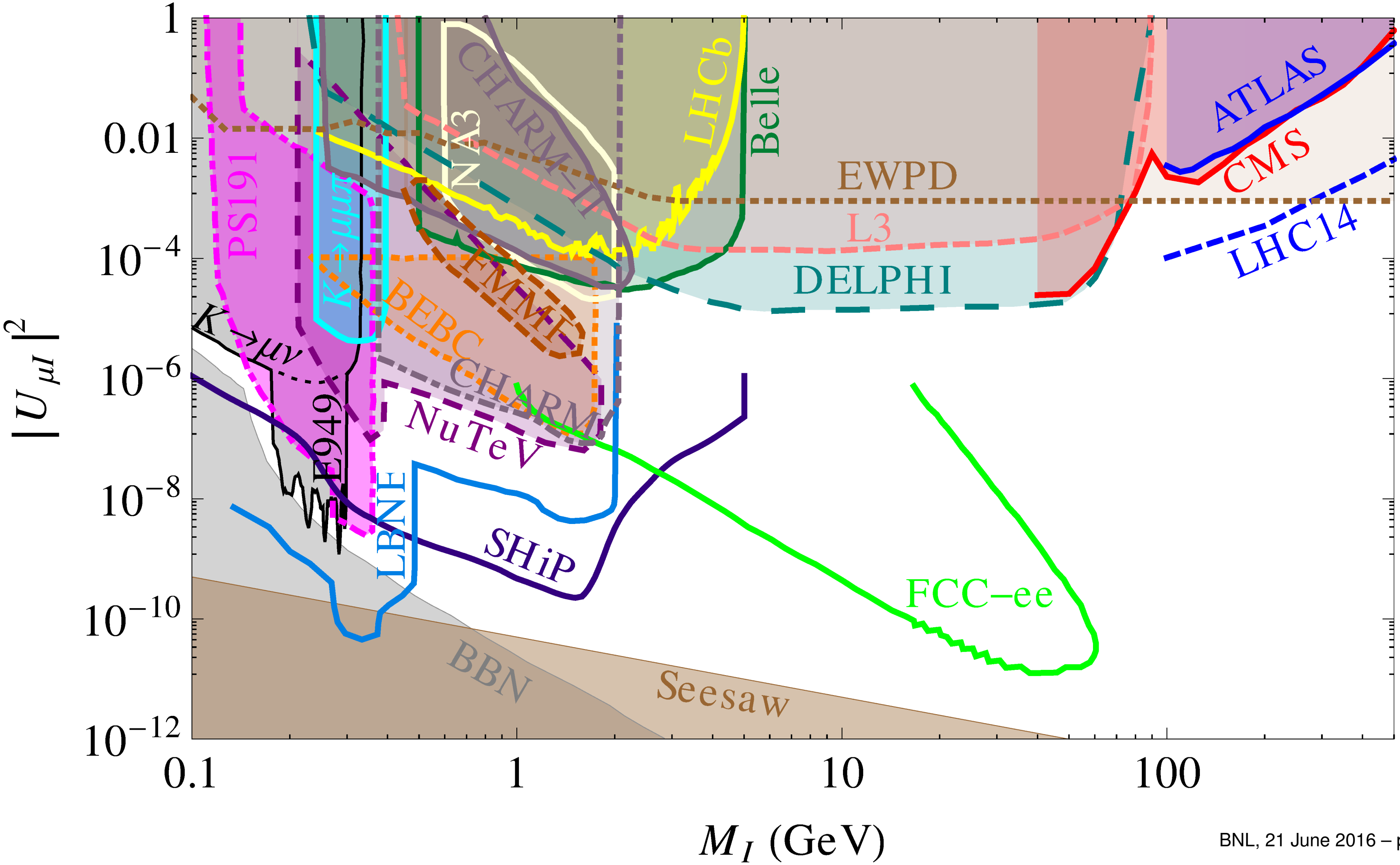
Experimental search for HNL

- Production
  - via intermediate (hadronic) state

    $p + \textbf{target} \to \textbf{mesons} + ...$, and then hadron$\to N + ...$
  - via Z-boson decays: $e^+e^- \to Z \to \nu N$
- Detection
  - Subsequent decay of N to SM particles



Survey of constraints



How to improve the bounds or to discover light very weakly interacting HNL's?

Dedicated experiments

Common features of all relatively light feebly interacting particles :

- Can be produced in decays of different mesons (π, K, charm, beauty)
- Can decay to SM particles (l^+l^-, $\gamma\gamma$, $l\pi$, etc)
- Can be long lived

Requirements to experiment:

- Produce as many mesons as you can
- Study their decays for a missing energy signal: charm or B-factories, NA62, BNL E949
- Search for decays of hidden sector particles - fixed target experiments
  - Have as many pot as you can, with the energy enough to produce charmed (or beauty) mesons
  - Put the detector as close to the target as possible, in order to catch all hidden particles from meson decays (to evade $1/R^2$ dilution of the flux)
  - Have the detector as large as possible to increase the probability of hidden particle decay inside the detector
  - Have the detector as empty as possible to decrease neutrino and other backgrounds

Most recent dedicated experiment - 1986, Vannucci et al

Volume 166B, number 4 PHYSICS LETTERS 23 January 1986

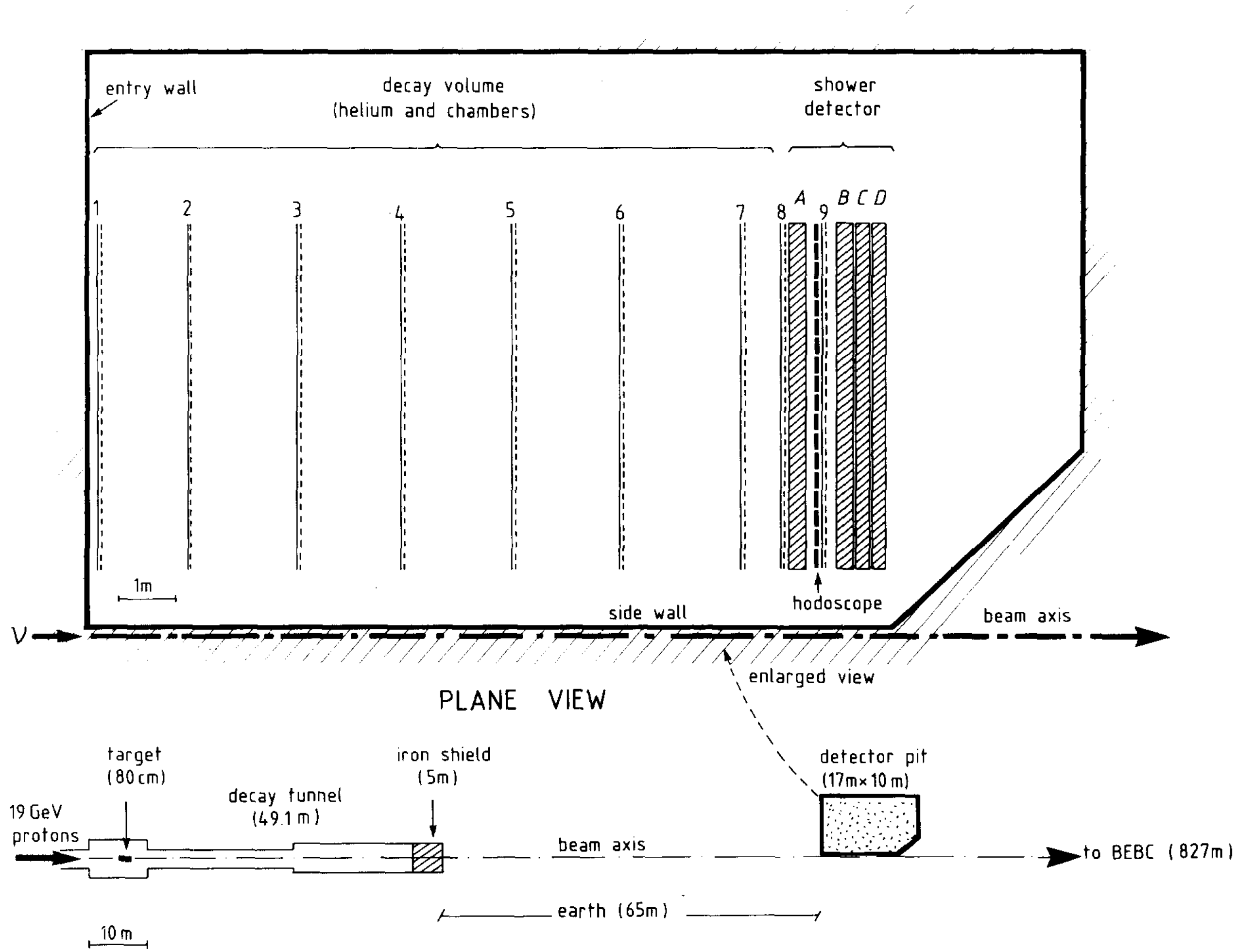


Fig. 1. Beam and layout of the detector.

No new particles are found with mass below K-meson, the best for many years constraints are derived, improved by BNL E949 in 2014

Proposal to Search for Heavy Neutral Leptons at the SPS arXiv:1310.1762

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

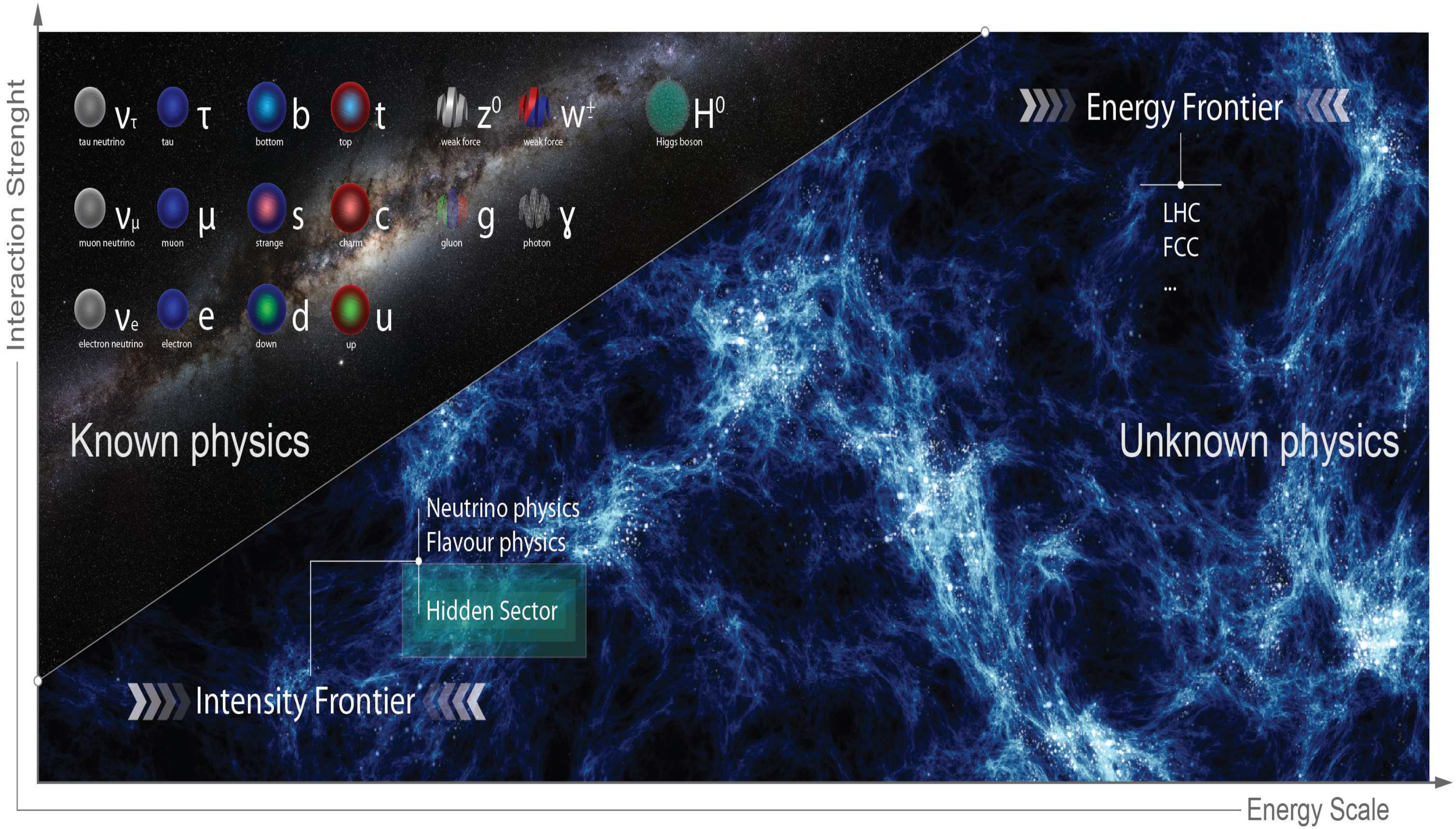
$$\Downarrow$$

General beam dump facility: Search for Hidden Particles

SHiP

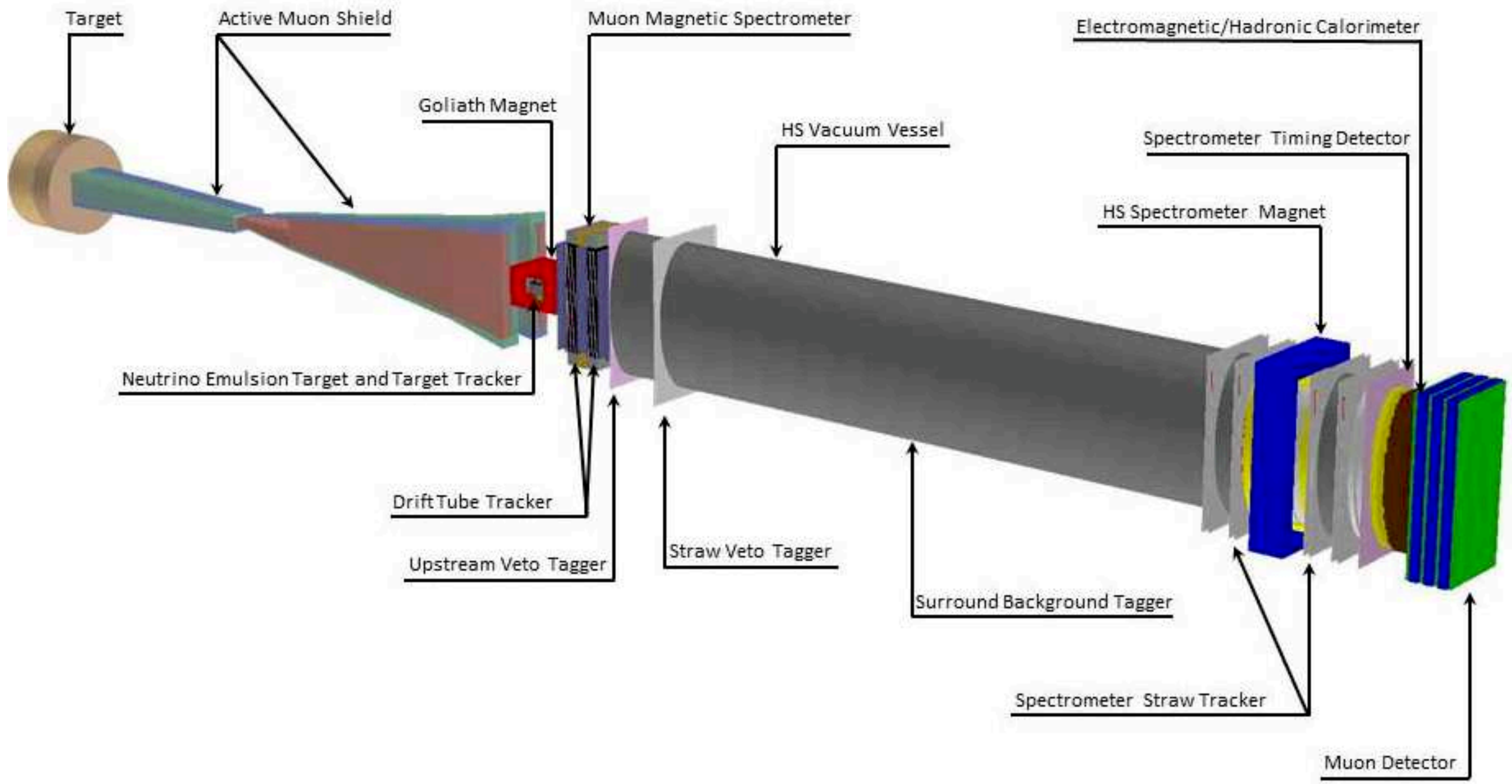
Search for Hidden Particles

Hidden sector: very weakly interacting relatively light particles: HNL, dark photon, scalars, ALPS, etc

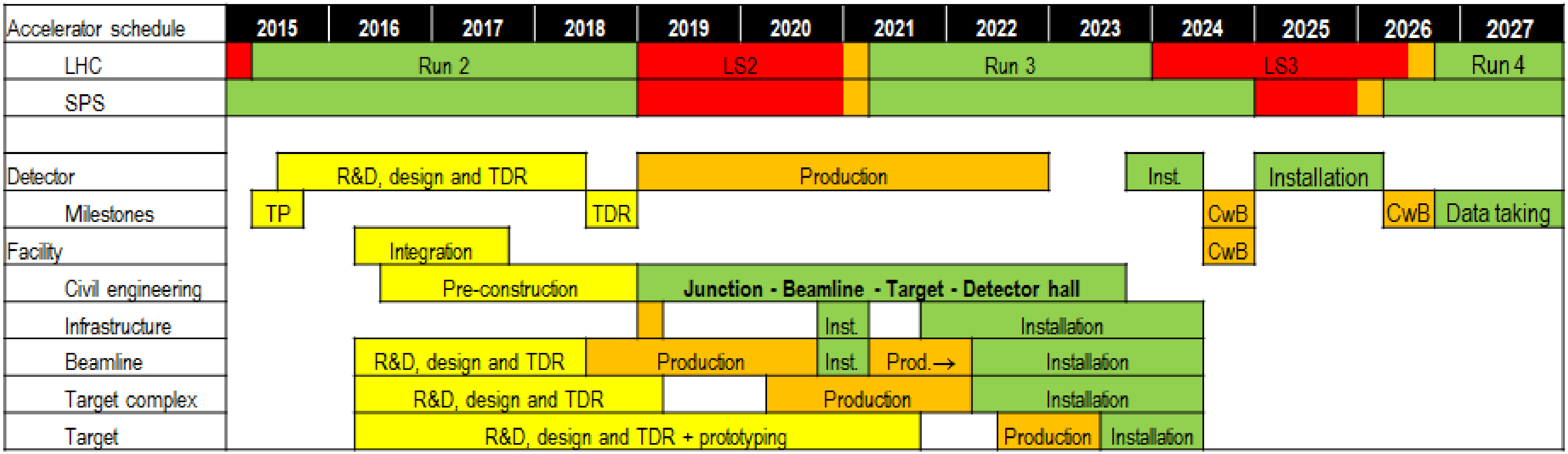


SHiP is currently a collaboration of 46 institutes from 15 countries

web-site: http://ship.web.cern.ch/ship/



SHiP schedule



FCC-ee Z-factory

Processes: $Z \to N\nu, \quad N \to lq\bar{q}$ (lepton + meson, lepton + 2 quark jets),

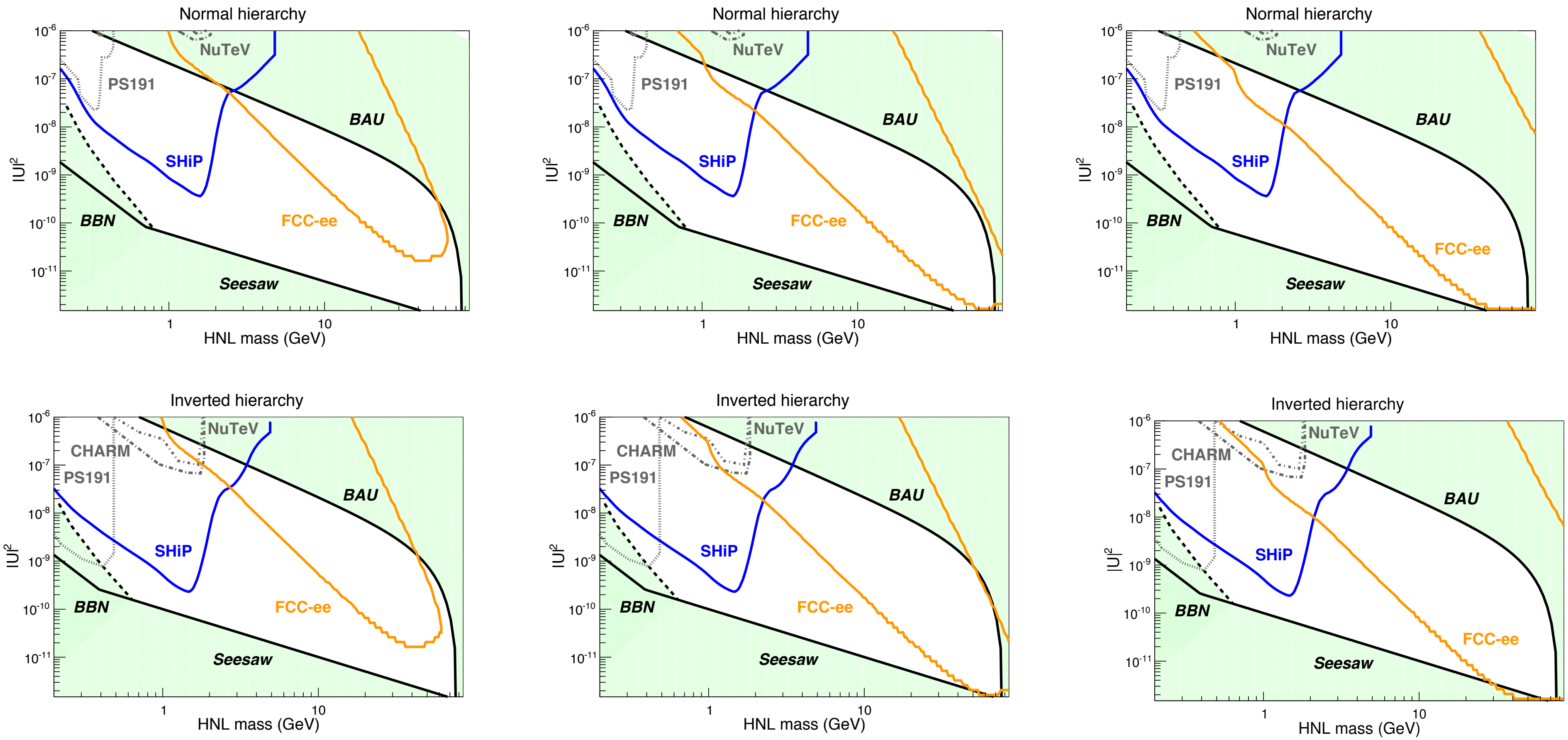
$$BR(Z \to \nu N) \simeq BR(Z \to \nu\nu)U^2, \qquad \Gamma_N \simeq \frac{G_F^2 M^5}{192\pi^3} U^2 A$$

Coefficient A counts the number of open channels, $A \sim 10$ for $M > 10$ GeV

Detector of size L:

- "short lived" N: decay length < L $\Longrightarrow$ constraint on U^2 may go down to $U^2 < 10^{-10}$ as the sensitivity will grow as the number of Z-decays! This works for $M \gtrsim 20$ GeV.
- "long lived" N: decay length exceeds the size of the detector $\Longrightarrow$ constraint on U^2 may go down to $U^2 < 4 \times 10^{-8}$ as the sensitivity will grow as the square root of the number of Z-decays. This works for lighter HNL.

SHiP and FCC-ee sensitivity



Decay length: 10-100 cm | 10-100 cm | 0.01-500 cm

$10^{12}\ Z^0$ | $10^{13}\ Z^0$ | $10^{13}\ Z^0$

Conclusions

- Heavy neutral leptons can be a key to (almost all) BSM problems:
  - neutrino masses and oscillations
  - dark matter
  - baryon asymmetry of the universe
- They can be found in Space and on the Earth
  - X-ray satellites
  - proton fixed target experiment - SHiP, $M \lesssim 2$ GeV
  - collider experiments at FCC-ee in Z-peak, $M \gtrsim 2$ GeV