TESTING LEPTOGENESIS AT SHIP, LHC AND BELLE II

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TU München

based on
arXiv:1502.00477 [hep-ph]
arXiv:1404.7114 [hep-ph]
arXiv:1208.4607 [hep-ph]

2013 review arXiv:1303.6912 [hep-ph], update arXiv:1502.06891 [hep-ph]

22. 6. 2015
invisibles2015 workshop, Madrid, Spain

The **Standard Model** and **General Relativity** together explain *almost* all phenomena observed in nature, but. . .

- gravity is not quantised
- a handful of observations remain unexplained
  - neutrino oscillations
  - baryon asymmetry of the universe
  - dark matter
  - accelerated cosmic expansion (Dark Energy, inflation)

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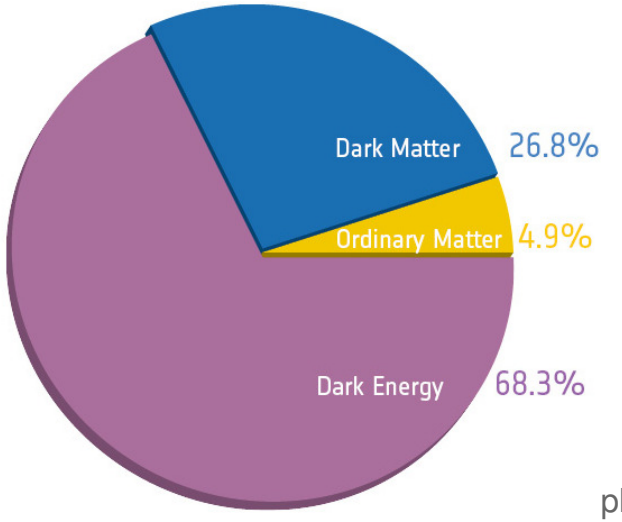

planck.cf.ac.uk

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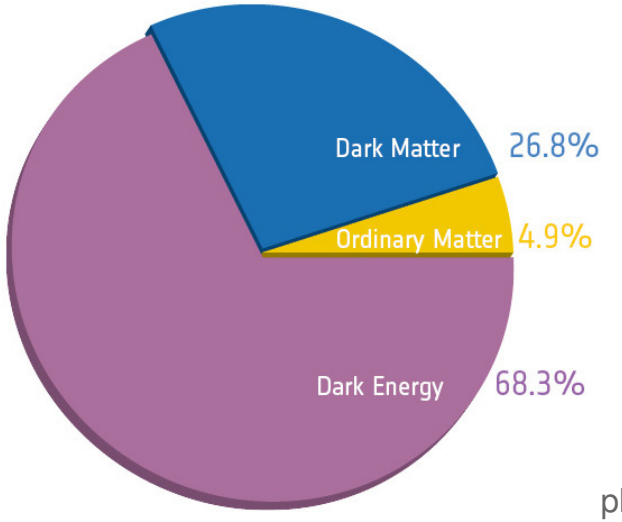
  - baryon asymmetry of the universe - leptogenesis?
  - dark matter - sterile neutrinos?
  - accelerated cosmic expansion (Dark Energy, inflation)



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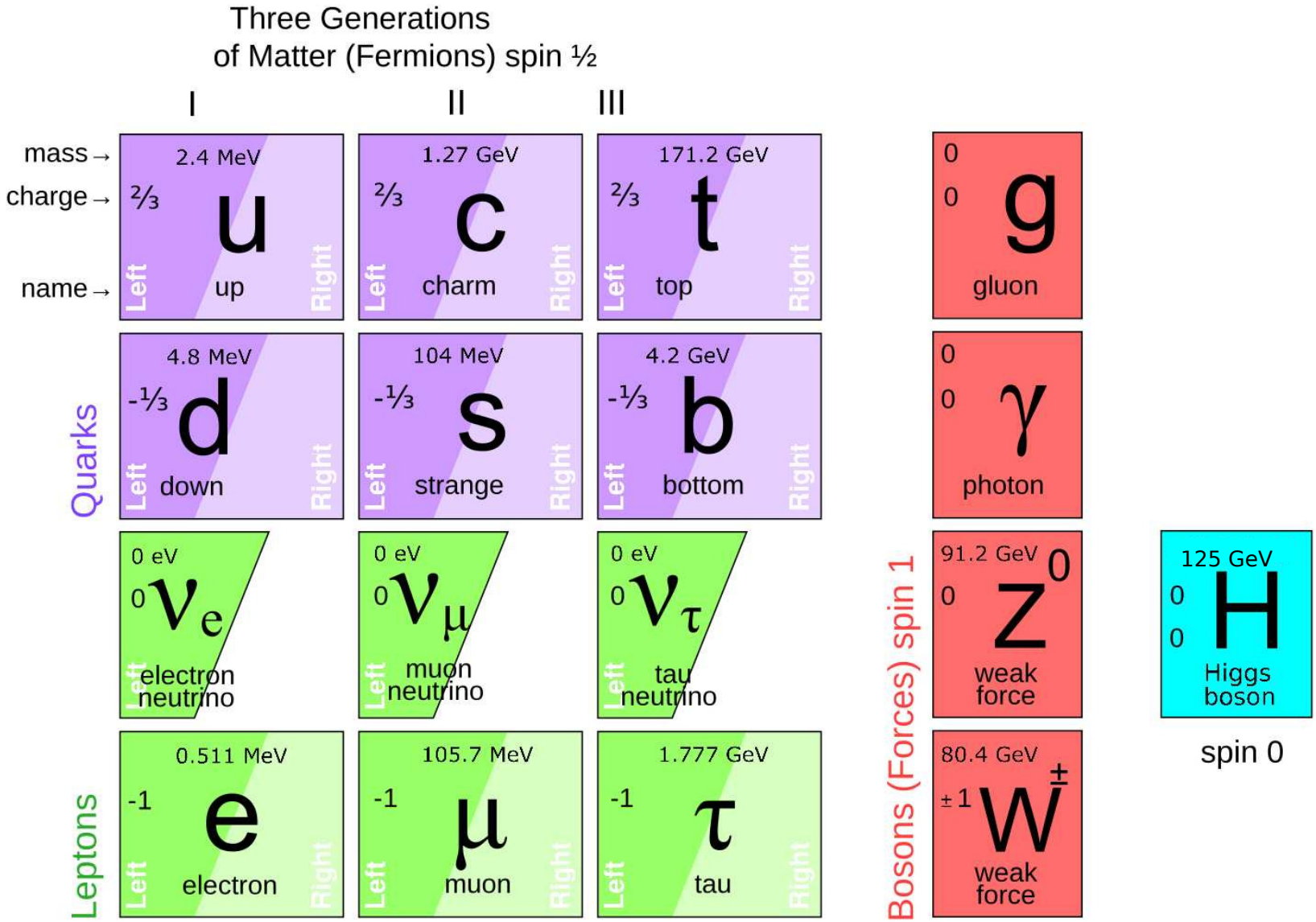
Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
0
0
g
gluon
Quarks
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
0
γ
photon
Left
Right
0 eV
0
ν_e
electron neutrino
0 eV
0
ν_μ
muon neutrino
0 eV
0
ν_τ
tau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

Neutrino masses: Seesaw mechanism

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \bar{\nu}_R F^\dagger L \tilde{H}^\dagger - \frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

Minkowski 1979, Gell-Mann/Ramond/Slansky 1979, Mohapatra/Senjanovic 1979, Yanagida 1980

$$\Rightarrow \frac{1}{2}(\overline{\nu_L}\ \overline{\nu_R^c}) \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

two sets of Majorana mass states with mixing $\theta = m_D M_M^{-1} = vFM_M^{-1}$

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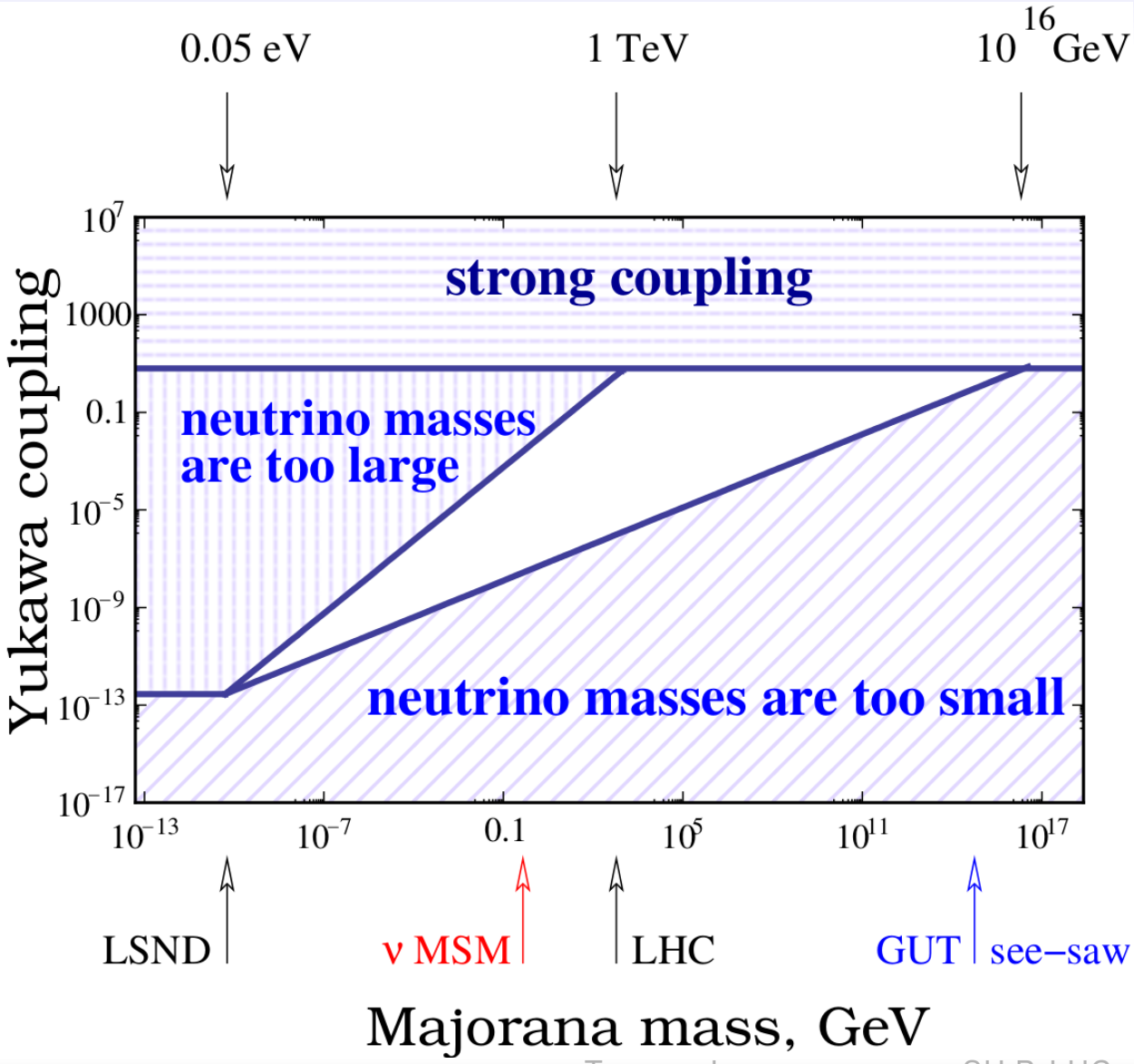
- three light neutrinos $\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
  - mostly "active" SU(2) doublet
  - light masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$
- three heavy neutrinos $N \simeq \nu_R + \theta^T \nu_L^c$
  - mostly "sterile" singlets
  - heavy masses $\boldsymbol{M_N \simeq M_M}$
- Majorana masses M_M introduce new mass scale(s)
- new heavy states only interact via small mixing $\theta \ll 1$

ν-oscillation data and the seesaw scale



The low scale seesaw

Pros:

- some theoretical arguments (no new scale Asaka/Shaposhnikov, classical scale invariance Khoze/Ro,. . .)
- allows for leptogenesis
  - during ν_R decay Pilaftsis 9707235
  - during ν_R production Akhmedov/Rubakov/Smirnov 9803255, Asaka/Shaposhnikov 0505013 without mass degeneracy MaD/Garbrecht 1206.5537, Canetti/MaD/Garbrecht 1404.7114
- new states can be found at colliders Gorbunov/Shaposhnikov, Kersten/Smirnov, Atre/Han/Pascoli/Zhang, Dev/Pilaftsis/Yang, Izaguirre/Shuve, Castillo-Felisola/Dib/Helo/Kovalenko/Ortiz, Ng/de la Puente/Pan, others. . .

Cons:

- very small Yukawa couplings F or cancellations in m_ν
- accessible regime constrained from low energy observations, in particular $\nu \to e\gamma$, $0\nu\beta\beta$-decay, PMNS-unitarity

Ibarra/Molinaro/Petcov 1103.6217, Abada/Das/Teixeira/Vicente/Weiland 1311.2830, Basso/Fischer/van der Bij 1310.2057, Endo/Yoshinaga 1404.4498, Asaka/Eijima/Takeda 1506.00417, MaD/Garbrecht 1502.00477

Where to see the N_I

- **Indirect searches**
- **Direct searches**
- **Cosmology**: BBN and $N_{\rm eff}$

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  - neutrino oscillation data
  - LFV in rare lepton decays
  - violation of lepton universality,
  - (apparent) violation of CKM unitarity
  - neutrinoless double β-decay
  - EW precision data
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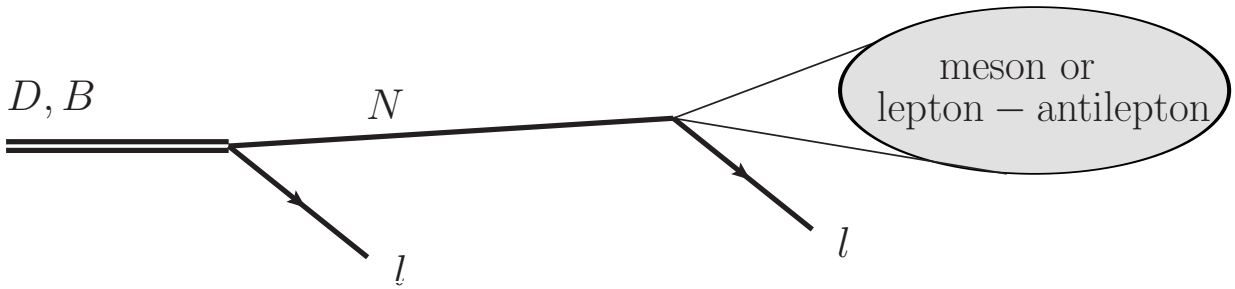
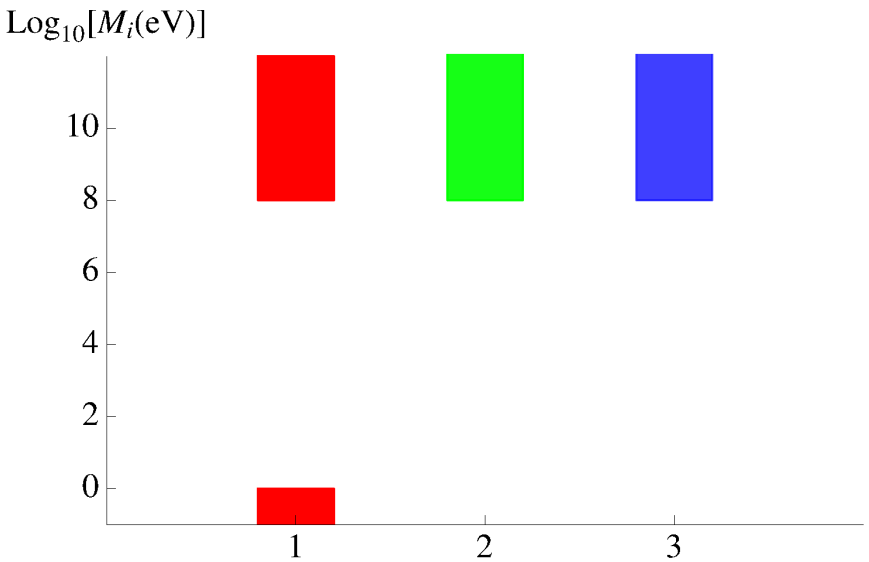
- **Direct searches**
  - LNV and LFV in gauge boson or meson decays

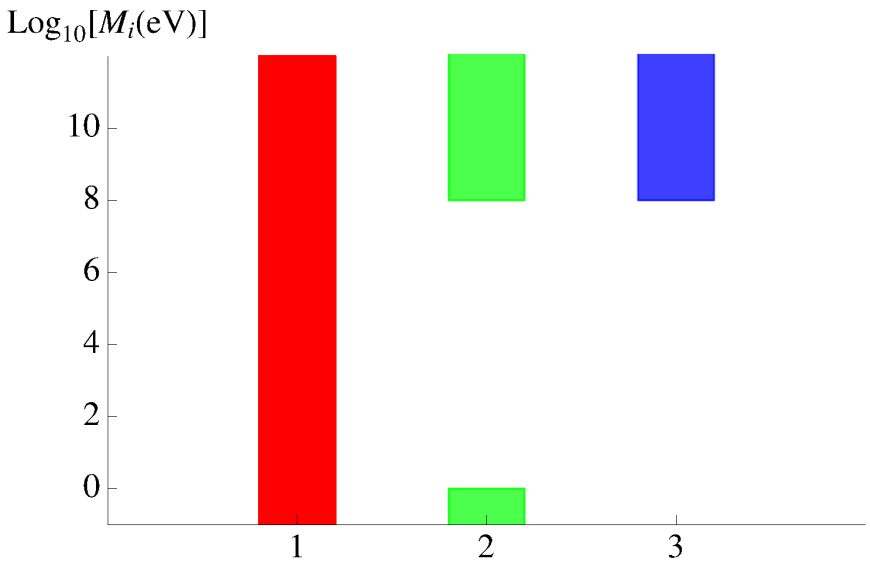


  - displaced vertices
  - peak searches, missing 4-momentum
- **Cosmology**: BBN and $N_{\rm eff}$

Bounds from cosmology: N_{eff} and BBN



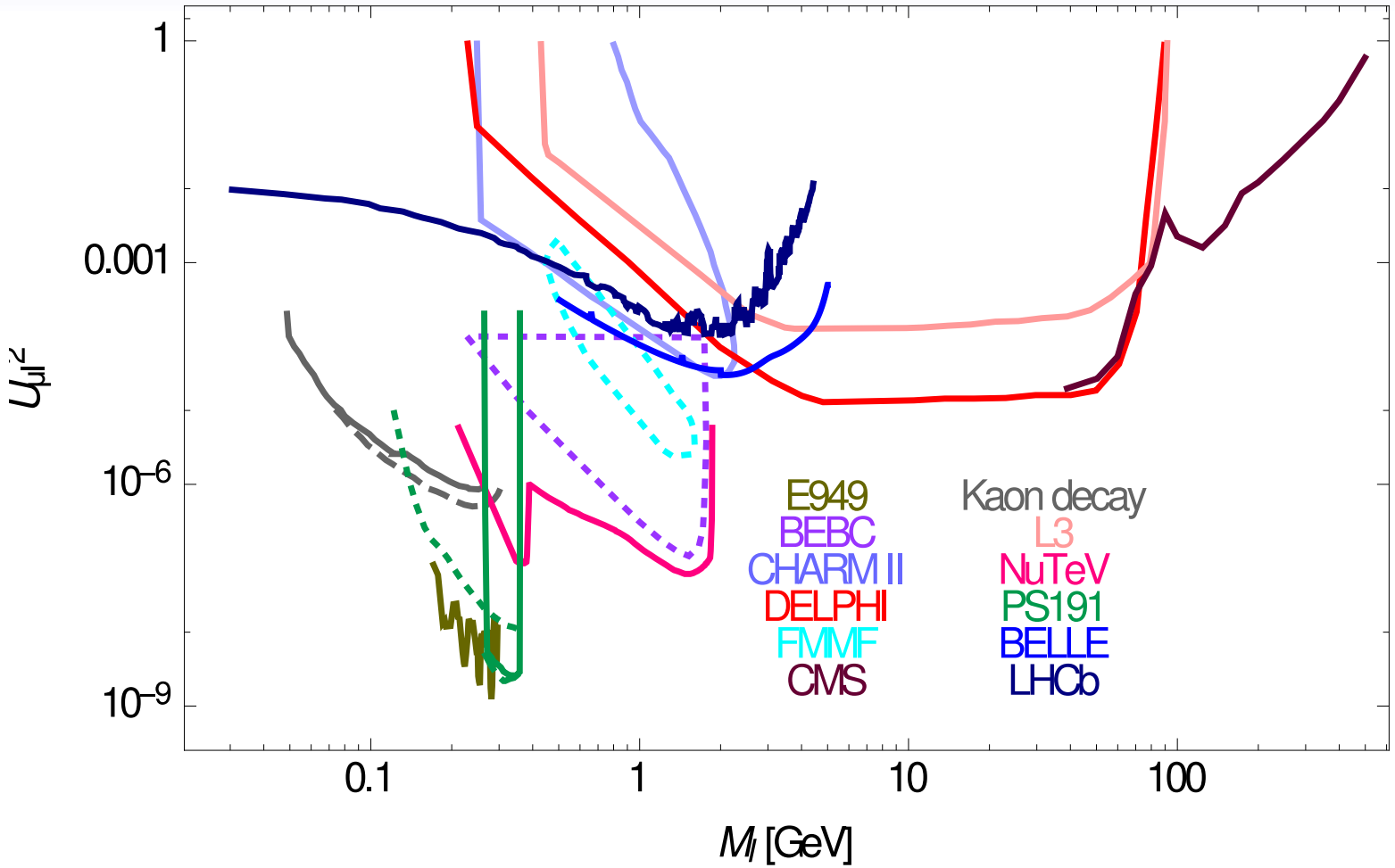
$m_{\text{lightest}} > 10^{-3} eV$



$m_{\text{lightest}} < 10^{-3} eV$

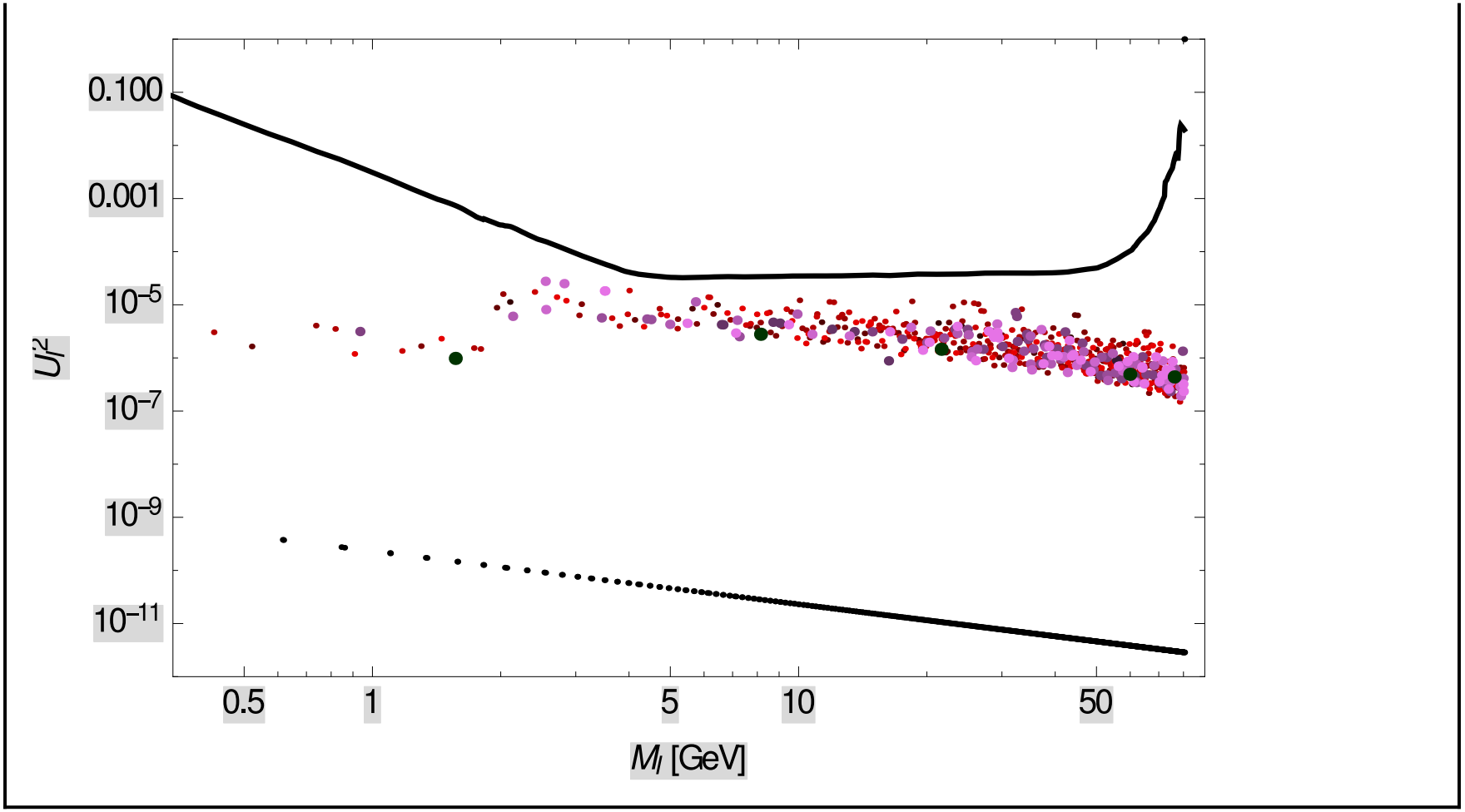
from Hernandez/Kevic/Lopez-Pavon 1406.2961

Bounds from Colliders



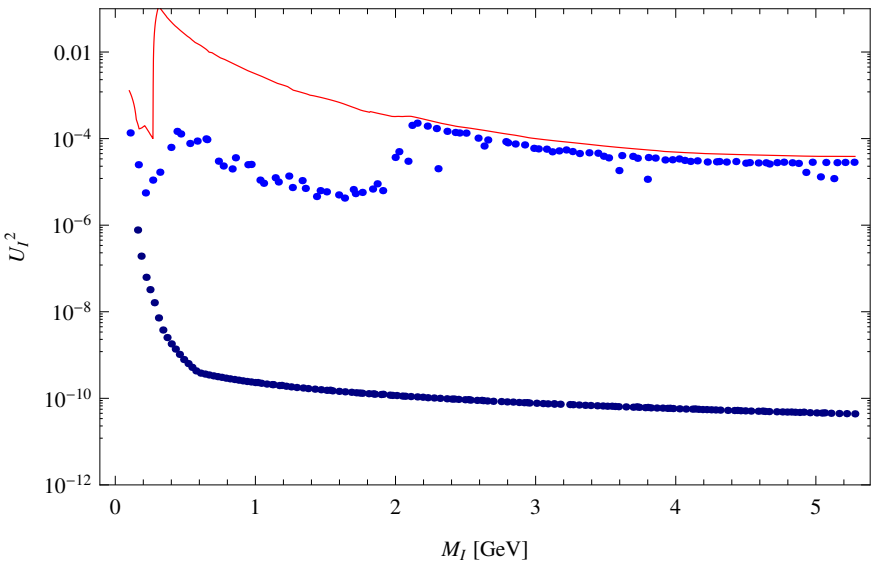
plot from MaD/Garbrecht 1502.00477

Combining direct and indirect bounds: EW scale

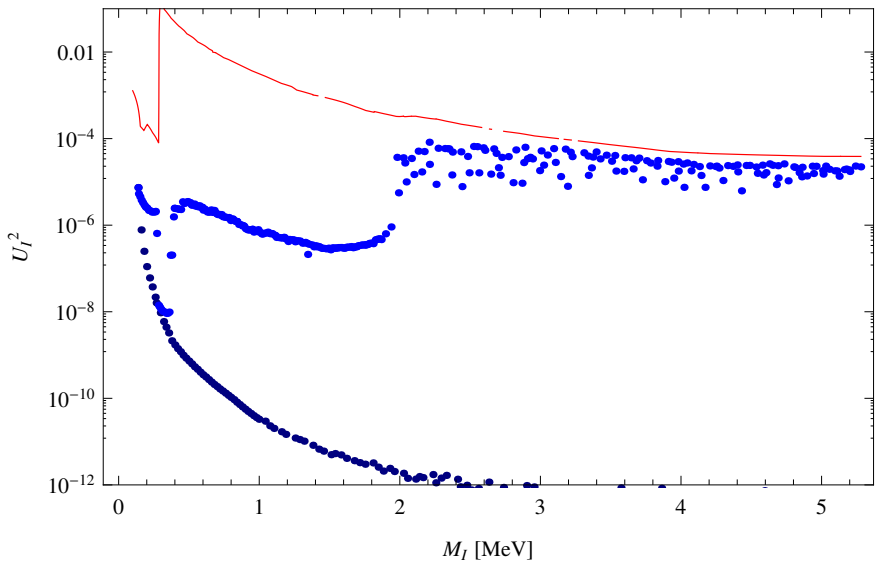


to be updated in arXiv:1502.00477 [hep-ph]

Present direct and indirect constraints: GeV scale



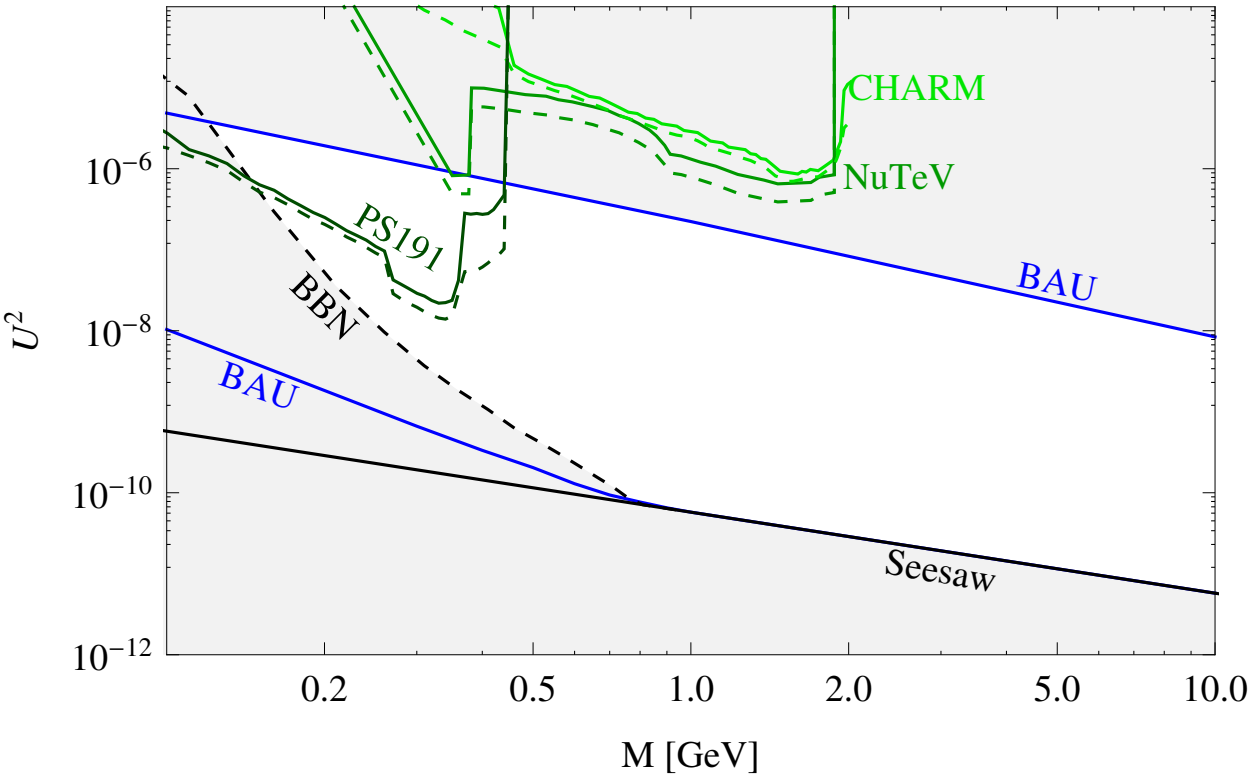
$m_{\text{lightest}} = 0.23\text{eV}$



$m_{\text{lightest}} = 0\text{eV}$

plot from MaD/Garbrecht 1502.00477

Leptogenesis with 2 GeV scale RH neutrinos

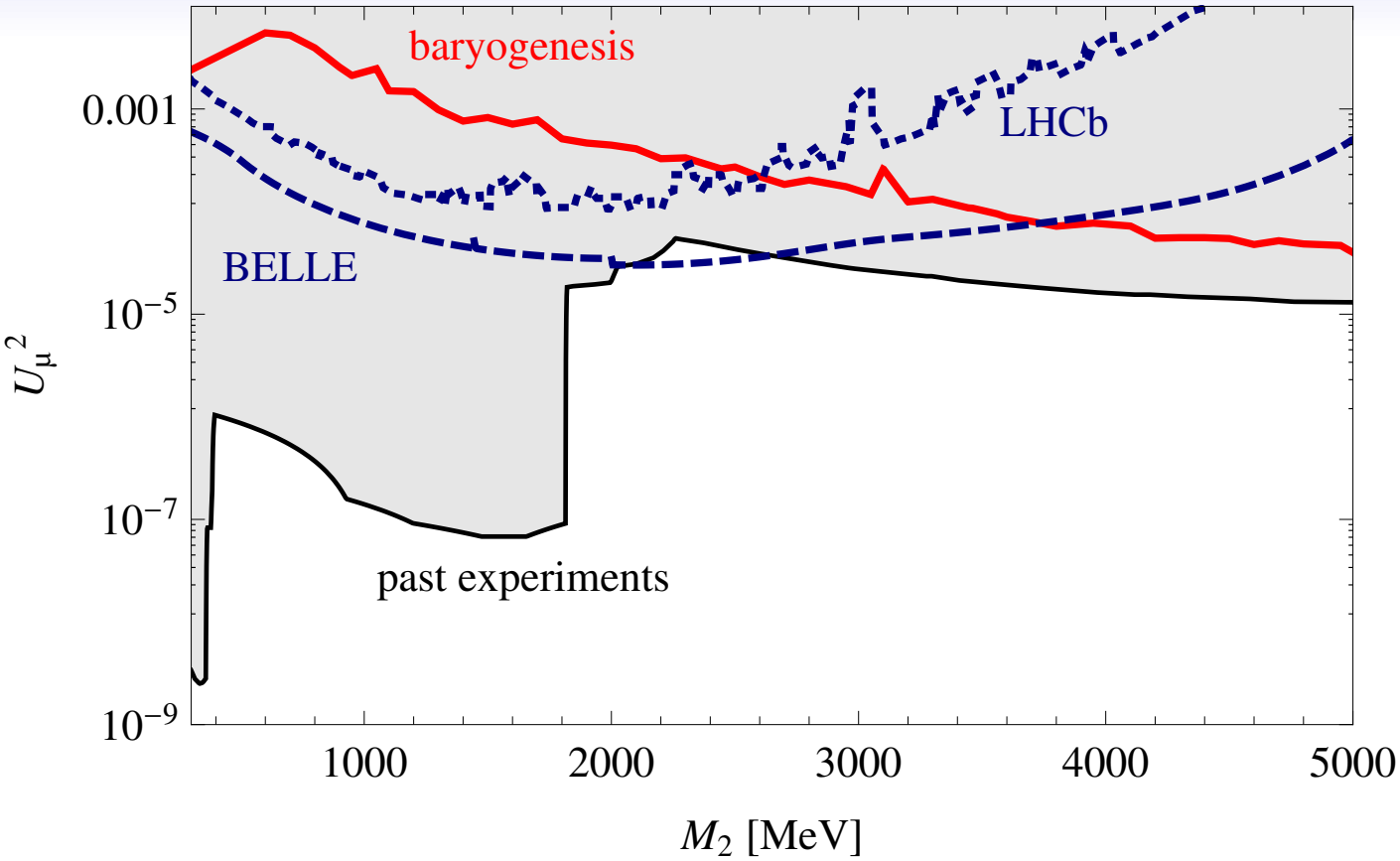


Canetto/MaD/Frossard/Shaposhnikov 1208.4607

Requires mass degeneracy and small mixing. . .

. . .but CP-violation may also be measurable Cvetic/Kim/Zamora-Saa 1403.2555

Leptogenesis with 3 GeV scale RH neutrinos

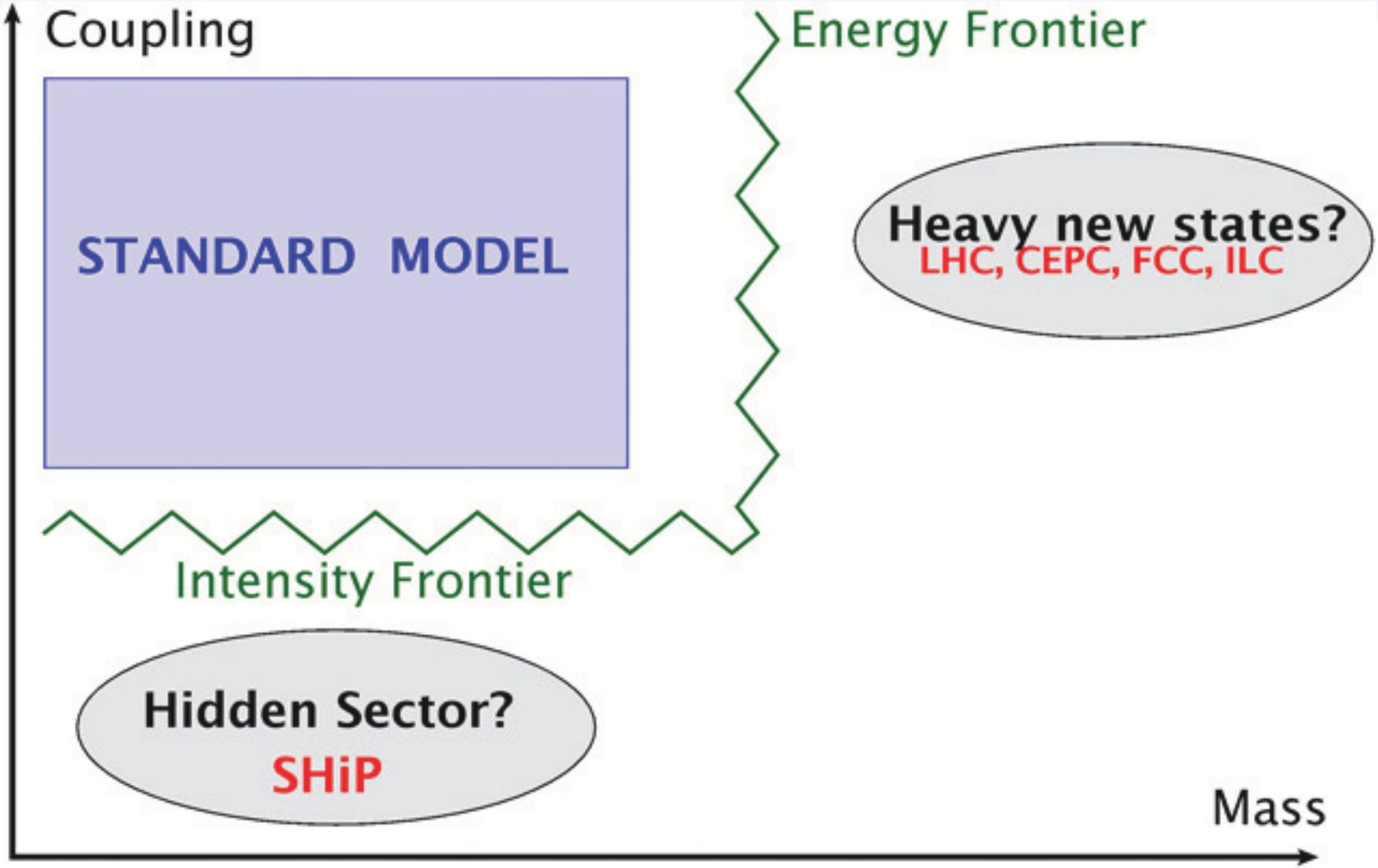


$M_1 = 1$ GeV, $M_3 = 3$ GeV plot updated from Canetti/MaD/Garbrecht 1404.7114

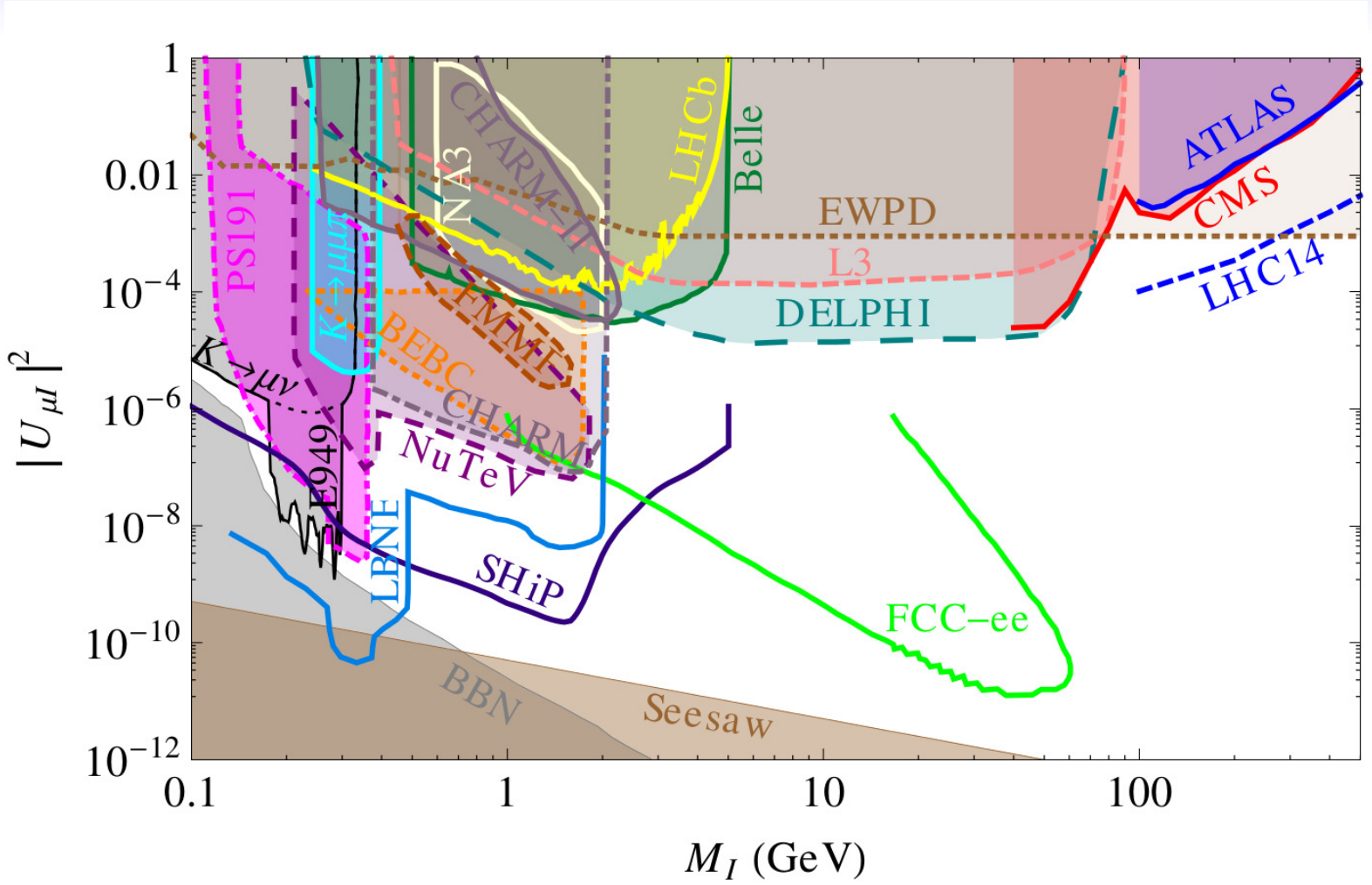
CP-violation may also be measurable Cvetic/Kim/Zamora-Saa 1403.2555

$\Rightarrow$ **LHCb, BELLE, SHIP may unveil the origin of matter!**

Where is the New Physics hiding?

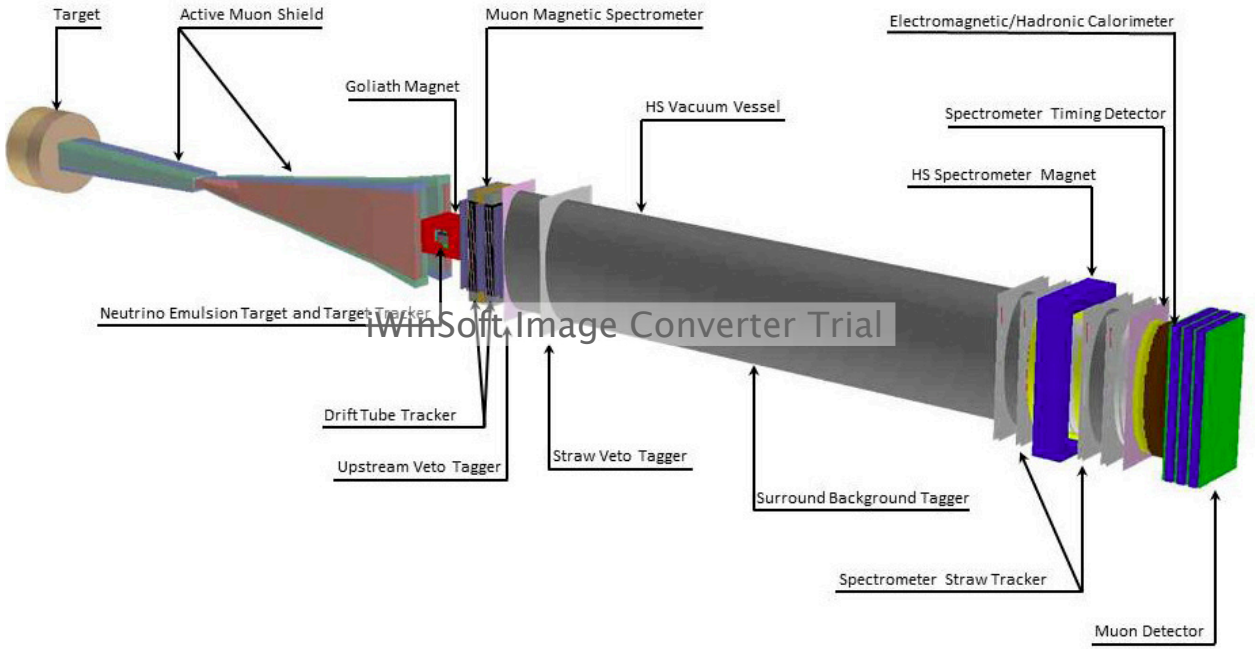


Future searches



Plot from arXiv:1504.04855 [hep-ph]

The SHiP Experiment



- intensity frontier experiment using CERN SPS beam
- fixed target experiment with strong shield
- technical report arXiv:1504.04956 [physics.ins-det]

The SHiP Experiment

Search for **Hi**dden **P**articles

- neutrino portal
- scalar / Higgs portal
- vector portal
- axion-like particles
- ν_τ physics
- LFV in τ-decays
- very light neutralino?
- your proposal!

see arXiv:1504.04855 [hep-ph] for details
great opportunity at the intensity frontier

Summary

- ν-oscillations are the only BSM signal seen in the lab
  definitely require new BSM degrees of freedom!
- the new particles are RH neutrinos, they may be related to
  cosmological puzzles (Dark Matter, baryogenesis, Dark Radiation)
- if new particles are below the electroweak scale, they can be found experimentally $\Rightarrow$ experimental search for exciting New Physics!
- even if they are heavier, indirect probes involve
  - neutrino oscillation experiments
  - neutrinoless double β-decay
  - lepton flavour violation
  - lepton universality violation
  - unitarity of the observed CKM matrix

We are looking forward to exciting new data. . .