Status of the νMSM (neutrino Minimal extension of the SM)

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Flavour Physics Conference

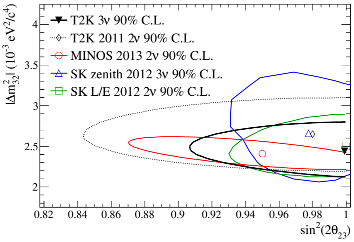
Xth Rencontres du Vietnam

Quy Nhon, Vietnam

Outline

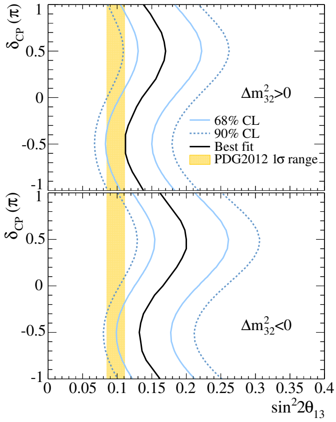
1. Neutrino oscillations: NP is below EW scale
2. Scheme: seesaw type I
3. νMSM: 3 in 1 flask
   (neutrino oscillations, dark matter, baryon asymmetry of the Universe)
4. “Heavy” Neutral Leptons
5. Dark Matter neutrino
6. Summary

Neutrino oscillations: masses and mixing angles



“atmospheric” 2×2 sector

1308.0465



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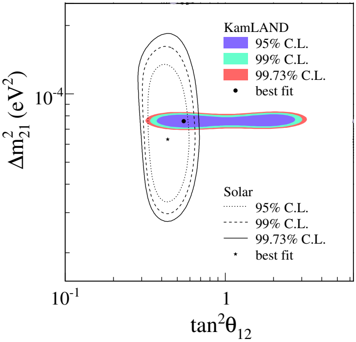


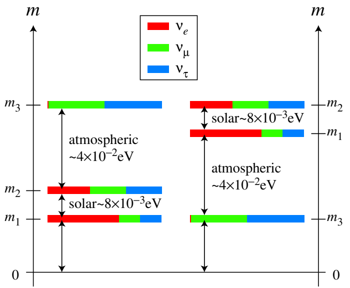
“solar” 2×2 sector

0801.4589

“Normal” and “Inverted” neutrino mass hierarchies

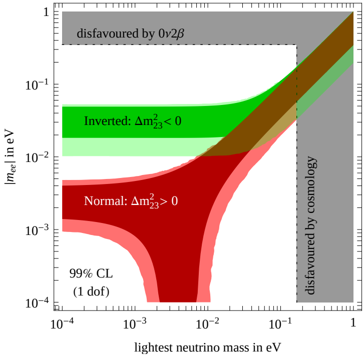
Only two squared mass differences are determined, there are options for masses. . .

may be, the hierarchy will be fixed by T2K & Noνae & JUNO



normal inverted
hierarchy

neutrinoless 2β-decay $Z->(Z+2)+2e^-$ CP ??



may be Cosmology will help...
Planck (2014)? . . . EUCLID (galaxy survey)

$|m_{ee}| = \left|\sum U^2_{ei} m_i\right|$, for Majorana masses

Sterile neutrinos: NEW ingredients

One of the optional physics beyond the SM:

sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

Attractive features:

- possible to achieve within renormalizable theory
- only $N = 2$ Majorana neutrinos needed
- massive sterile neutrinos can explain via seesaw why active ones are so light
- sterile neutrino (Majorana) masses violate lepton symmetry
  produce baryon asymmetry via leptogenesis
- dark matter (with $N \geq 3$ at least)
- 1 eV sterile neutrino might be responsible for neutrino anomalies. . . ?
  not a dark matter ($N \geq 4$?)

Disappointing feature:

Major part of parameter space is UNTESTABLE

Outline

Sterile neutrino lagrangian

Most general renormalizable with 2(3...) right-handed neutrinos N_I

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

Parameters to be determined from experiments

9(7): active neutrino sector

- 2 Δm_{ij}^2: oscillation experiments
- 3 θ_{ij}: oscillation experiments
- 1 CP-phase: oscillation experiments
- 2(1) Majorana phases: $0\nu ee$, $0\nu\mu\mu$
- 1(0) m_ν: $^3\text{H} \to ^3\text{He} + e + \bar{\nu}_e$, cosmology, ...

11: $N = 2$ sterile neutrinos (works if $m_\nu = 0$!!!)

- 2: Majorana masses M_{N_I}
- 9: New Yukawa couplings $f_{\alpha I}$ which form
  - 2: Dirac masses $M^D = f\langle H\rangle$
  - 3+1: mixing angles
  - 2+1: CP-violating phases

4 new parameters in total
help with leptogenesis

18: $N = 3$ sterile neutrinos:

- 3: Majorana masses M_{N_I}
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9 new parameters in total
both BAU and DM are possible

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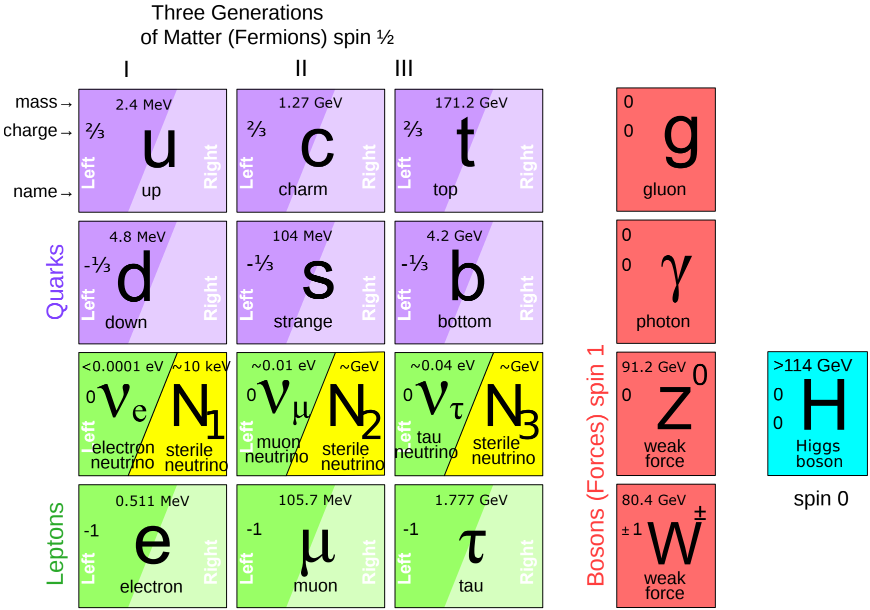

Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
0
0
g
gluon
Quarks
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
0
γ
photon
<0.0001 eV
~10 keV
0
νe
N1
electron neutrino
sterile neutrino
~0.01 eV
~GeV
0
νμ
N2
muon neutrino
sterile neutrino
~0.04 eV
~GeV
0
ντ
N3
tau neutrino
sterile neutrino
91.2 GeV
0
0
Z
weak force
>114 GeV
0
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
80.4 GeV
±1
W±
weak force
Bosons (Forces) spin 1
Left
Right

Seesaw type I mechanism: $M_N \gg m_{active}$

$$\mathcal{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I \;+\; \text{h.c.}$$

where $I = 1,2,3$ and $\alpha = e,\mu,\tau$ $\quad \tilde{H}_a = \varepsilon_{ab} H_b^*$

When Higgs gains $\langle H\rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathcal{L}_N \to \frac{1}{2}\left(\overline{\nu}_\alpha\,,\overline{N}_I^c\right)\begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^T}{\sqrt{2}} & \hat{M}_N \end{pmatrix}\left(\nu_\alpha^c\,,N_I\right)^{\mathrm{T}} \;+\; \text{h.c.}$$

Then for off-diag $\ll$ diag $\quad$ ($\hat{M}_D = v\,\frac{\hat{f}}{\sqrt{2}} \ll M_N$) we find the eigenvalues:

$$\simeq \hat{M}_N \qquad \text{and} \qquad \hat{M}^\nu = -\hat{M}_D\frac{1}{\hat{M}_N}\hat{M}_D^T \propto \left(\frac{\text{off-diag}}{\text{diag}}\right)^2 M_N \lll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I}N_I$

active-active mixing: (PMNS-matrix U) $\qquad U^T\hat{M}^\nu U = diag\,(m_1\,,m_2\,,m_3)$

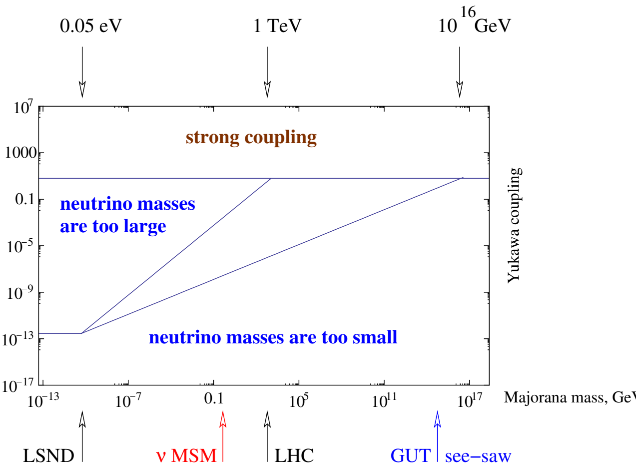
active-sterile mixing: $\qquad \theta_{\alpha I} = \frac{M_{D_{\alpha I}}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1$

Outline

Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

Is not fixed: lighter sterile neutrinos with smaller Yukawas

With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get $f \sim 1$, hierarchy in sterile neutrino masses, etc



T.Asaka, M.Shaposhnikov (2005)

νMSM implies

- 2 “heavy” neutral leptons of 0.1-50 GeV
  – responsible for seesaw
  – responsible for leptogenesis (must be degenerate $\Delta M \sim 100$ keV)
- 1 “light” sterile neutrinos of 2-50 keV
  – form dark matter

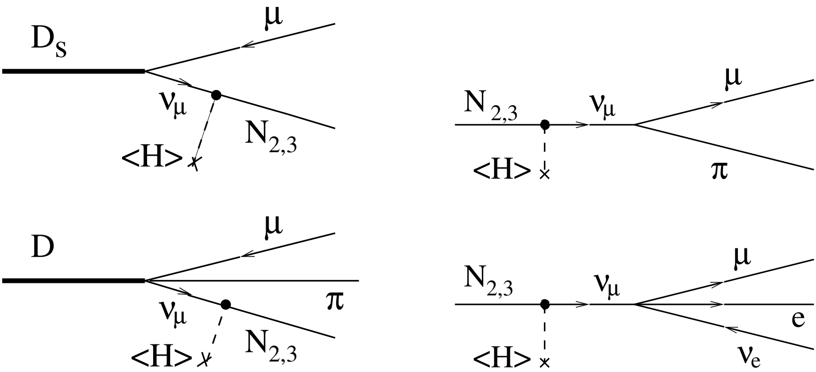
BSM is below EW scale:

– no gauge hierarchy

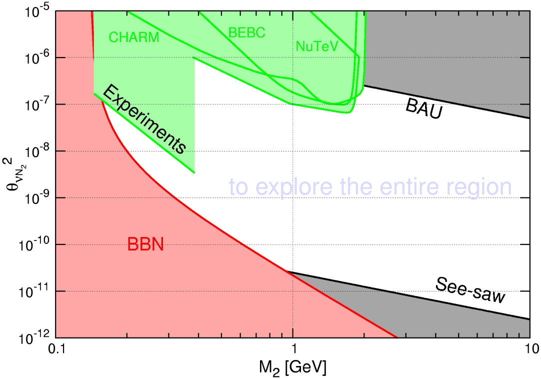
– available for direct tests

Outline

Production and decays (if $M_N < 5\,\mathrm{GeV}$)



Probing leptogenesis SHiP upgrading to Aerocarrier



to explore the entire region

D.G, M.Shaposhnikov (2007)

lower bound at $\times 10^{-4}$

$$\mathrm{Br}\,(D \to lN) \lesssim 2 \times 10^{-8}$$
$$\mathrm{Br}\,(D_s \to lN) \lesssim 3 \times 10^{-7}$$
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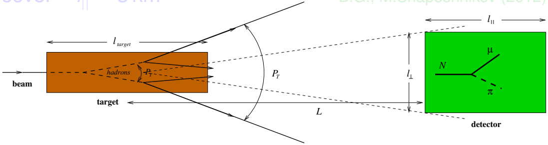
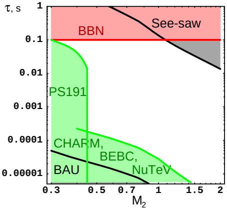
For 10^{20} PoT at 400 GeV (SPS) detectors have to cover $l_{||} \sim 3$ km

D.G., M.Shaposhnikov (2012)





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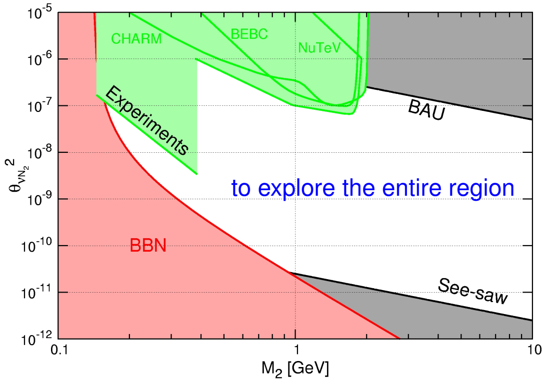

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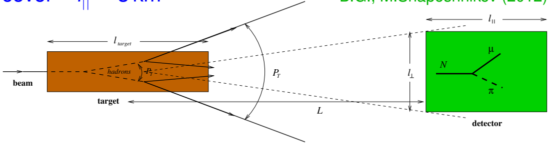
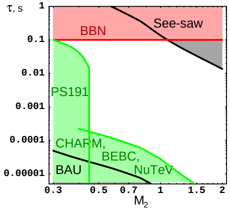


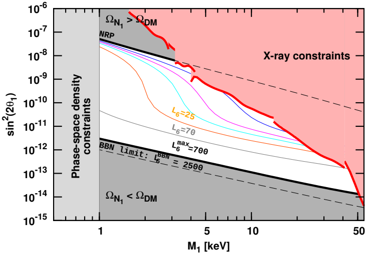


Outline

SubEW sterile neutrinos: $M_N \simeq 1$ keV-50 GeV νMSM

T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

- At $T > 100$ GeV active-sterile neutrino oscillations produce lepton asymmetry in the early Universe, if $\Delta M_N \ll M_N$ $\longrightarrow$ baryogenesis E.Akhmedov, V.Rubakov, A.Smirnov (1998)
- Lightest sterile neutrino may comprise Dark Matter
  - production in primordial plasma due to mixing with active neutrinos is ruled out from searches at X-ray telescopes



$$\Gamma_{N\to\nu\gamma} \simeq 5.5\times 10^{-22}\theta_1^2 \left(\frac{M_1}{1\ \text{keV}}\right)^5 \text{s}^{-1}$$

a narrow line $(\delta E_\gamma/E_\gamma \sim v \sim 10^{-3})$

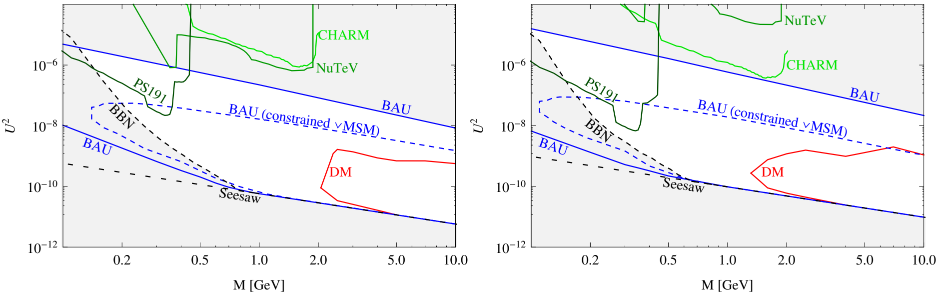
at $E_\gamma = M_N/2$

  - Possible for 1-50 keV (WDM-CDM range) either with fine-tuning in M_{N_I} $(\Delta M_N \sim 10^{-7}\ \text{eV})$ to get $L \gg B$ and use the resonant production or with ANOTHER source of production, e.g. inflaton decays..

M.Shaposhnikov, I.Tkachev (2006), F.Bezrukov, D.G. (2009)

νMSM parameter space with resonant DM

Not an easy task (coherence, plasma, expansion, etc. . .)
concentrating in a particular region of parameter space
people calculated what happens and found
where inside that region BAU & Dark Matter
can be both explained for sure



L.Canetti, M.Drewes, M.Shaposhnikov 1208.4607

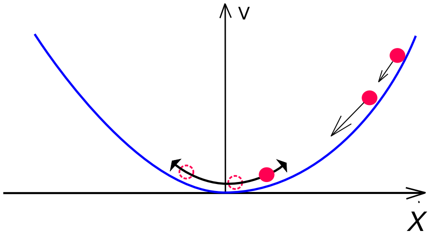
Inflation and νMSM: dark matter production ?

$$\ddot{X} + 3H\dot{X} + V'(X) = 0$$

$X_e > M_{Pl}$

scale-invariant scalar perturbations from exponentially stretched quantum fluctuations of X

$\delta\rho/\rho \sim 10^{-5}$ requires
$V = \beta X^4$: $\beta \sim 10^{-13}$



Chaotic inflation, A.Linde (1983)

DM production (inflaton gives mass)
from inflaton decays in plasma at $T \sim m_\chi$

M.Shaposhnikov, I.Tkachev (2006)

$$M_{N_I}\bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

Can be "naturally" Warm ($250\,\text{MeV} < m_\chi < 1.8\,\text{GeV}$)

F.Bezrukov, D.G. (2009)

$$M_1 \lesssim 15 \times \left(\frac{m_\chi}{300\text{ MeV}}\right) \text{keV}$$

Higgs Inflation and νMSM: dark matter ?

If $\lambda(\sim M_{Pl}) > 0$ & if non-minimally coupled to gravity $H^\dagger H R$ the SM Higgs field may serve as the inflaton

F.Bezrukov, M.Shaposhnikov (2007)

Then DM sterile neutrino may be produced via dim-5 operator

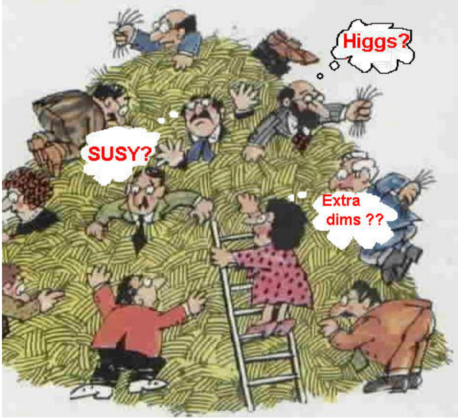
$$\mathscr{L} = \frac{\beta}{\Lambda} H^\dagger H \bar{N}^c N \; + \; \text{h.c.}$$

where Λ is either M_{Pl} or $\Lambda = \Lambda(h)$

and no need for DM sterile-active neutrino (?) mixing…

Outline

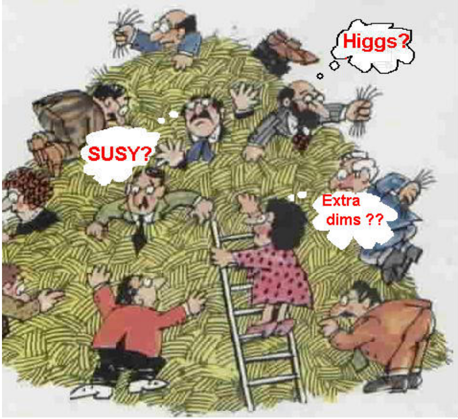
Searches at LHC



Finally…
Higgs boson has been recognized

Please LHC!
Pleeaassee!

Searches at LHC



Finally…
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Summary: intensity frontier

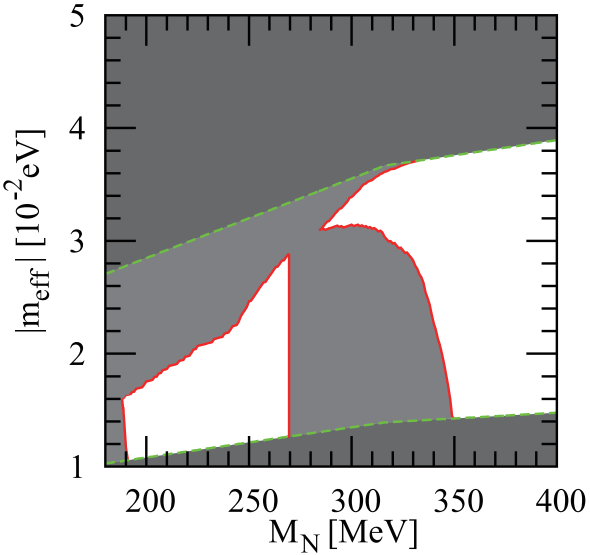
- We definitely need New Physics
- There are arguments in favour of NP below EW scale...

  True Extension of the Standard Model should at least

  - Reproduce the correct neutrino oscillations
  - Contain the viable DM candidate
  - Be capable of explaining the baryon asymmetry of the Universe
  - Have the inflationary mechanism operating at early times
- νMSM can do it
- and be directly tested right now (GeV mass scale) or later (for 10-100 GeV masses)

Backup slides

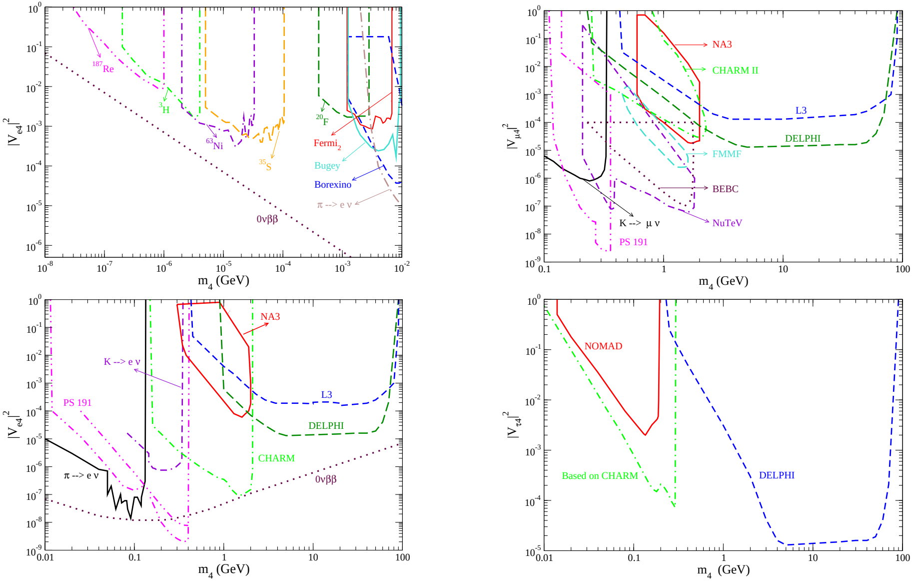
Leptogenesis in $2+1$ scheme: $0\nu2\beta$ decay region



Inverse hierarchy 1308.3550

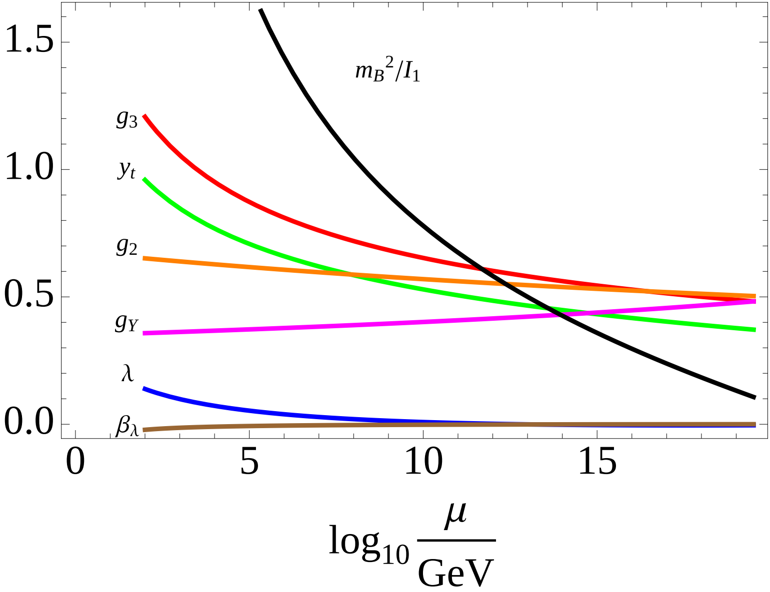
Present limits

0901.3589: 1) $0\nu\beta\beta$-bound is stronger by 10, 1205.3867 2) limits from LHCb and CMS

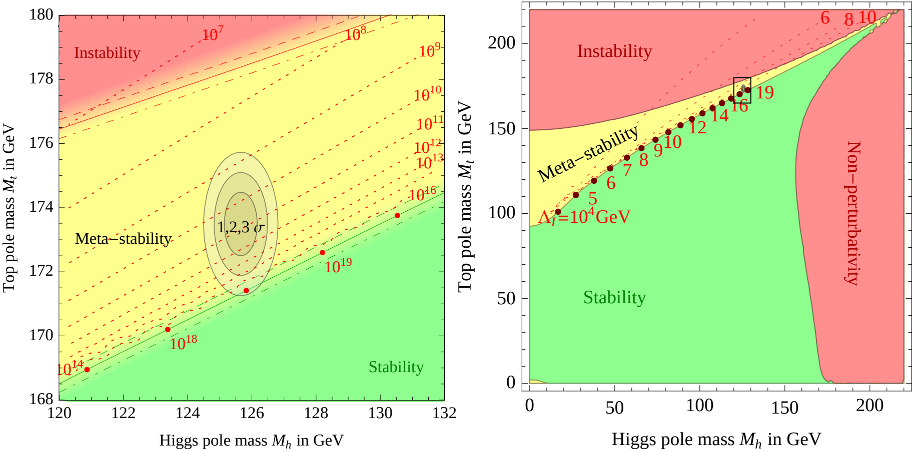


RG evolution of the SM couplings

1305.7055



How "natural" the 126 GeV...



1307.7879

Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$

$$\mathcal{L}^{(5)} = \frac{F_{\alpha\beta}}{4\Lambda} \bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \text{h.c.}$$

L_α are SM leptonic doublets, $\alpha = 1,2,3$, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a,b = 1,2$; in a unitary gauge $H^T = \left(0, (v+h)/\sqrt{2}\right)$ and

$$\mathcal{L}^{(5)}_{\nu\nu} = \frac{v^2 F_{\alpha\beta}}{4\Lambda} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.} = m_{\alpha\beta} \times \frac{1}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

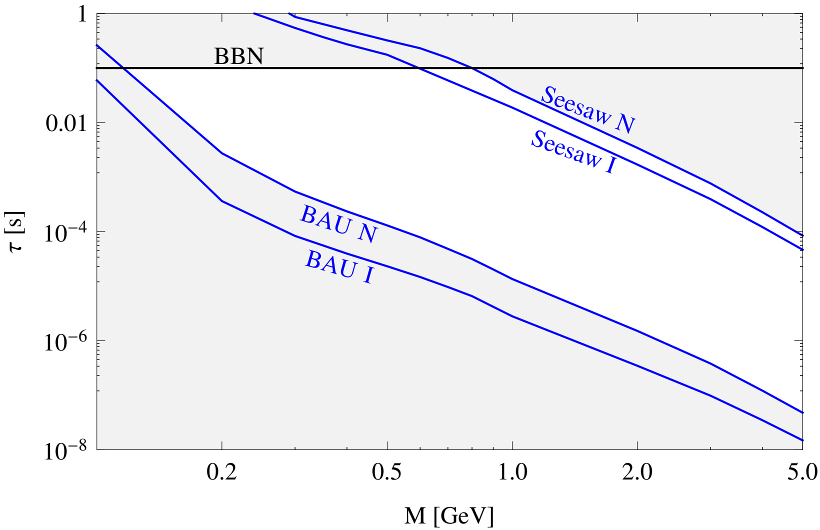
where

Λ is the scale of new dynamics

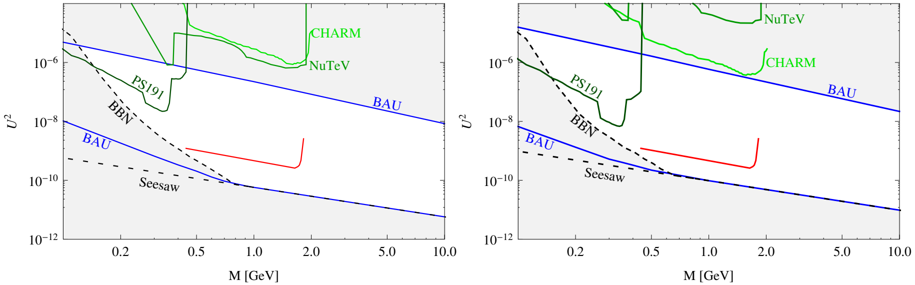
$F_{\alpha\beta}$ is the strength of new dynamics

only their ratio is fixed by the scale of active neutrino masses

νMSM: Heavy neutral lepton lifetime (1208.4607)

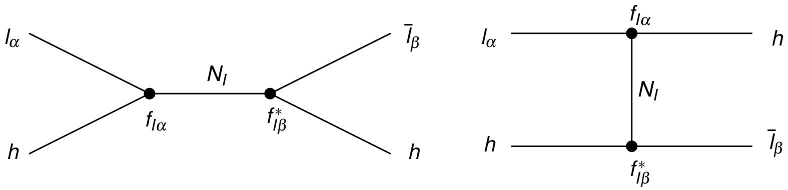


νMSM: Heavy neutral lepton mixing (1208.4607)



We get dim-5 operator at small momentum transfer

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N_I^c} N_I + \text{h.c.}$$



at $|Q_N^2| \ll M_N^2$ we arrive at effective interaction (dim-5 operator)

$$\Longrightarrow \quad \mathscr{L}^{(5)} = \frac{F_{\alpha\beta}}{4\Lambda}\bar{L}_\alpha \tilde{H} H^\dagger L_\beta^c + \text{h.c.} \qquad \text{where} \quad \frac{\hat{F}}{\Lambda} = \hat{f}^T \hat{M}_N^{-1} \hat{f}$$