Seesaw Models, CLFV and Leptogenesis

Emiliano Molinaro

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Outline

- Introduction: neutrino oscillations
- Neutrino mass and mixing
- Origin of neutrino mass: seesaw scenarios
- Low energy signatures of type I seesaw
- Leptogenesis: standard scenario
- Baryogenesis through neutrino oscillations
- Summary and outlook

Neutrino oscillations

It is a well-established experimental fact that neutrinos and antineutrinos, which enter in charged current and neutral current weak interactions, appear in Nature in three different *types* or *flavours*: electron (ν_e), muon, (ν_μ), and tauon, (ν_τ)

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Experiments with solar, atmospheric, reactor and accelerator neutrinos have shown compelling evidences for the existence of **neutrino oscillations**: *quantum mechanical phenomenon* resulting in transitions in flight between different flavour (anti)neutrinos ν_e, ν_μ, ν_τ, due to the non-zero neutrino masses and mixing

Nobel Prize in Physics 2015

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

Neutrino mass and mixing

Compelling experimental evidence of Physics beyond the Standard Model

atmospheric neutrinos:

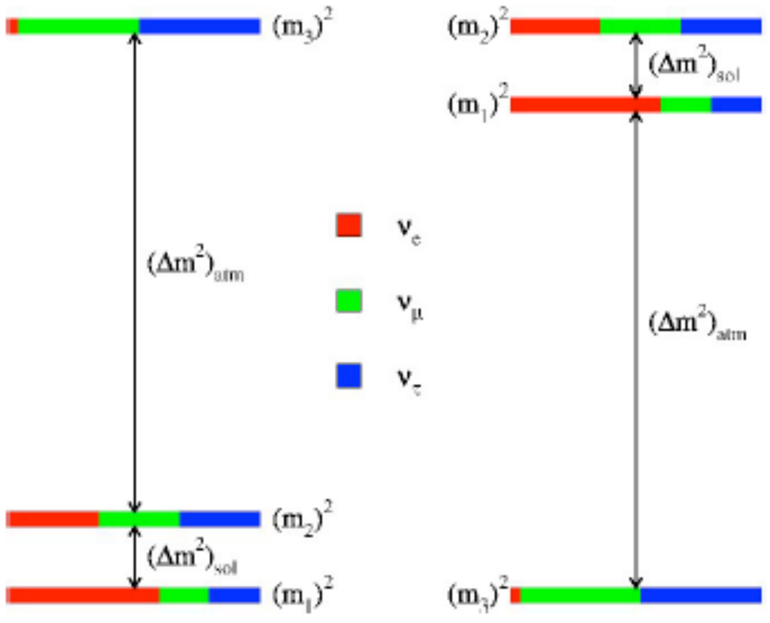
Super-Kamiokande: $|\Delta m_A^2| \sim O(10^{-3}\ \mathrm{eV}^2)$ and $\theta_{23} \cong \pi/4$

solar neutrinos:

SNO, SK and KamLAND: $\Delta m_S^2 \sim O(10^{-5}\ \mathrm{eV}^2)$ and $\theta_{12} \cong \arcsin(\sqrt{0.3})$

reactor and accelerator neutrinos:

Daya Bay, RENO, T2K, MINOS, Double CHOOZ: $\theta_{13} \neq 0$ at 10σ, $\theta_{13} \sim 0.15$ **in 2012**



1. at least two massive neutrinos ν_j with masses $m_j \neq 0$
2. existence of neutrino mixing:

$$\nu_{\ell \mathrm{L}}(x) = \sum_j (U_{\mathrm{PMNS}})_{\ell j}\, \nu_{j\mathrm{L}}(x), \quad \ell = e, \mu, \tau$$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \mathrm{diag}(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}})$$

Pontecorvo - Maki - Nakagawa - Sakata lepton mixing matrix

Neutrino mass and mixing

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{\rm CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

from 1409.5439

see also
M.C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz, 1209.3023
D.V. Forero, M. Tortola, J. Valle, 1205.4018
G.L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, A.M. Rotunno, 1205.5254

Origin of neutrino mass and mixing

- From data on the invisible Z decay width: 3 flavour active neutrinos $\nu_{\ell L}$, $\ell = e, \mu, \tau$
- The number of mass eigenstate ν_j can be larger than 3 (*sterile neutrinos ?*), *but* at least 3 of the ν_j should be "light":

$$m_{1,2,3} < 1 \text{ eV and } m_1 \neq m_2 \neq m_3$$

- ^{3}H $\beta-$decay experiments and astrophysical observations

$$m_j \lesssim 0.5 \text{ eV} \qquad m_j/m_{\ell,q} \lesssim 10^{-6}$$

- Important questions:
  1. *Are neutrinos Majorana or Dirac particles ?*
  2. *What is the mass ordering ?*
  3. *Is there CP violation in the neutrino sector ?*
  4. *Is there a new fundamental mass scale Λ in particle physics ?*

Origin of neutrino mass and mixing

Why do neutrinos have a non-zero tiny mass ?

Symmetry principles give us an answer, even if the dynamics involved is not understood

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Electroweak Theory + Quantum Chromodynamics:

- Lorentz invariance
- Gauge invariance: SU(3)xSU(2)xU(1)
- Renormalizability

The Standard Model is not sufficiently "complicated" to violate baryon and lepton number conservation (except for tiny quantum effects unobservable at the temperature of the present universe)

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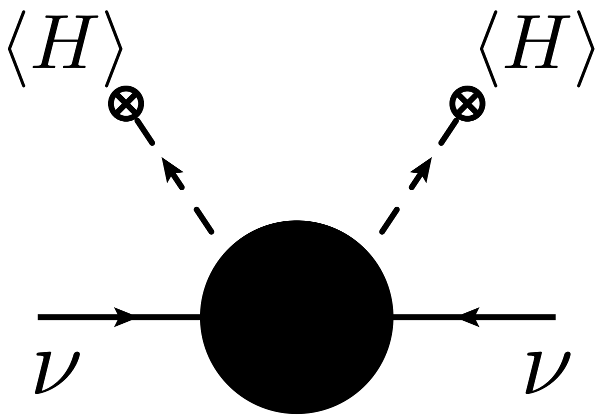
We can relax the renormalizability requirement and introduce all the possible interaction operators which are allowed by gauge and Lorentz symmetries (*effective field theories*).
In this case we introduce *new scales* in the theory, suppressing the new interactions.

When we do experiments to detect neutrino oscillations or proton decay, what we are measuring are the *non-renormalizable effective interactions* added to the renormalizable part of the Standard Model

Seesaw mechanisms

Why do neutrinos have a non-zero tiny mass ?



Weinberg, PRD 22 (1980) 1694

$$\frac{c_{\ell\ell'}}{\Lambda}\left(\overline{\psi^c_{\ell L}}\widetilde{H}^*\right)\left(\widetilde{H}^\dagger\psi_{\ell' L}\right)$$

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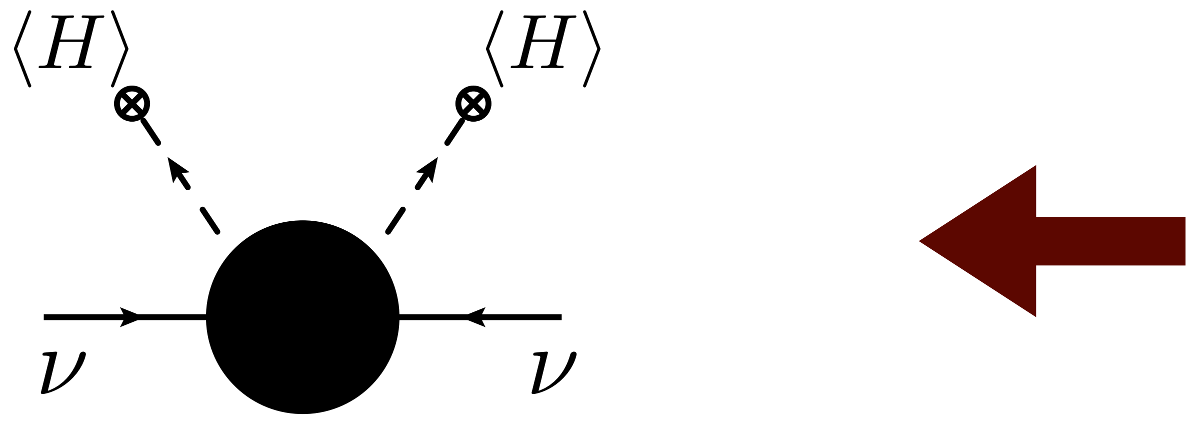

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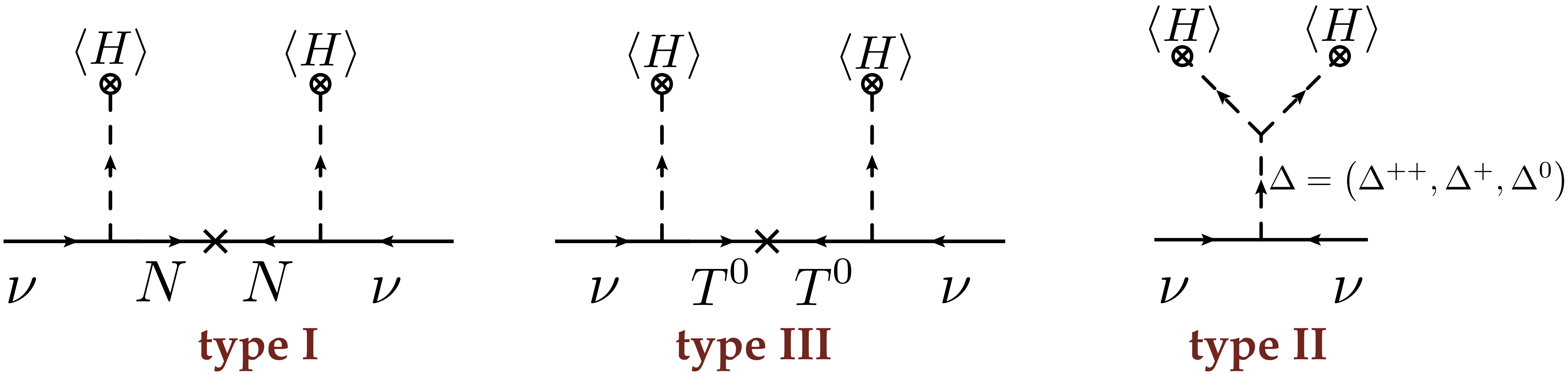

direct tests: probing new physics at energy frontier
indirect tests: probing new physics at the intensity frontier

Baryon Asymmetry of the Universe

$$\eta \equiv \left. \frac{n_B - n_{\bar{B}}}{n_\gamma} \right|_0 , \quad \eta_{10} = 10^{10}\eta = 274\,\Omega_B\,h^2$$

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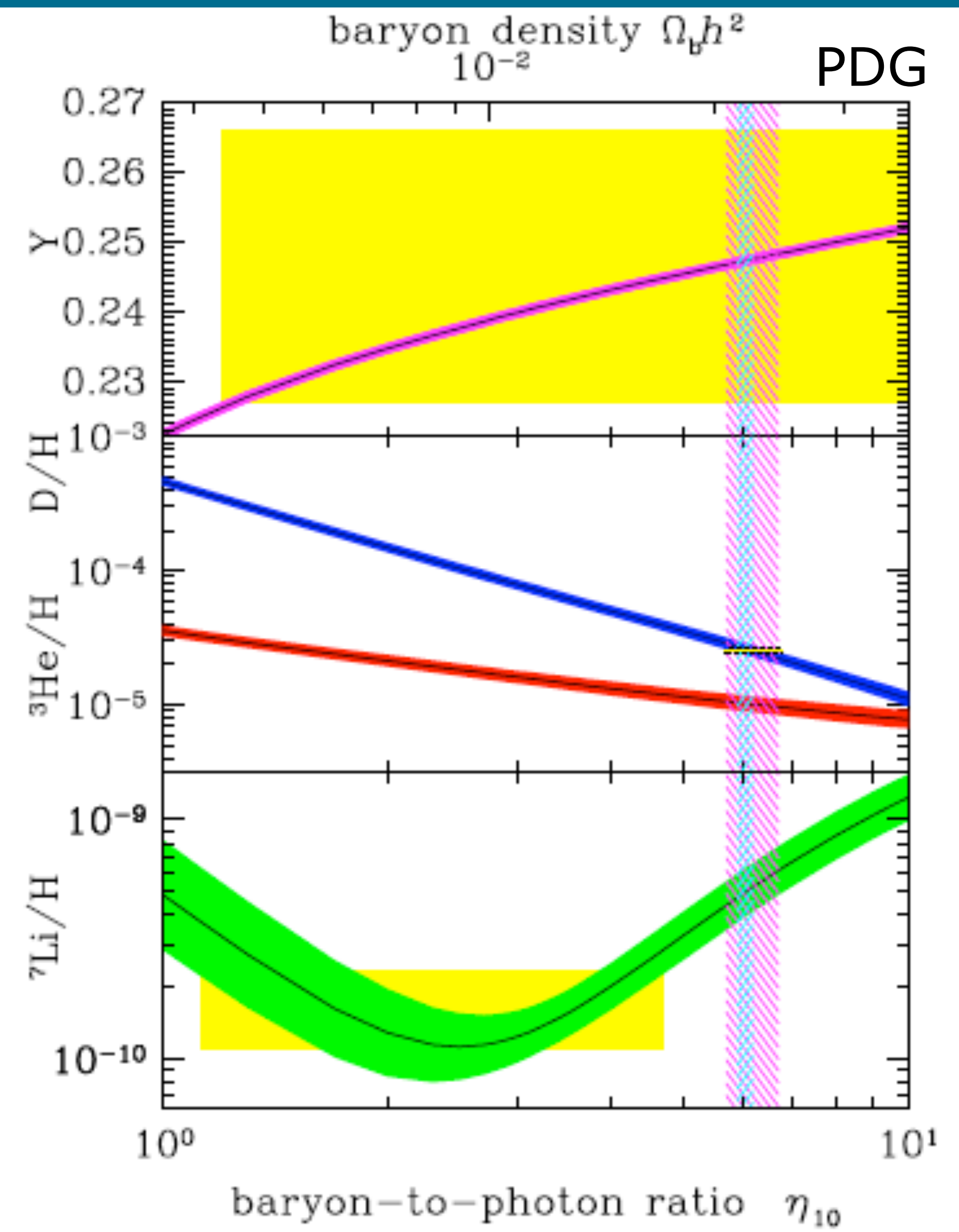
from primordial nucleosynthesis of light elements (@ T ≲ 1 MeV) :

$$5.7 \;\leq\; \eta_{10} \;\leq\; 6.7 \quad \text{at } 95\% \text{ CL}$$

$$0.021 \;\leq\; \Omega_B\,h^2 \;\leq 0.025$$



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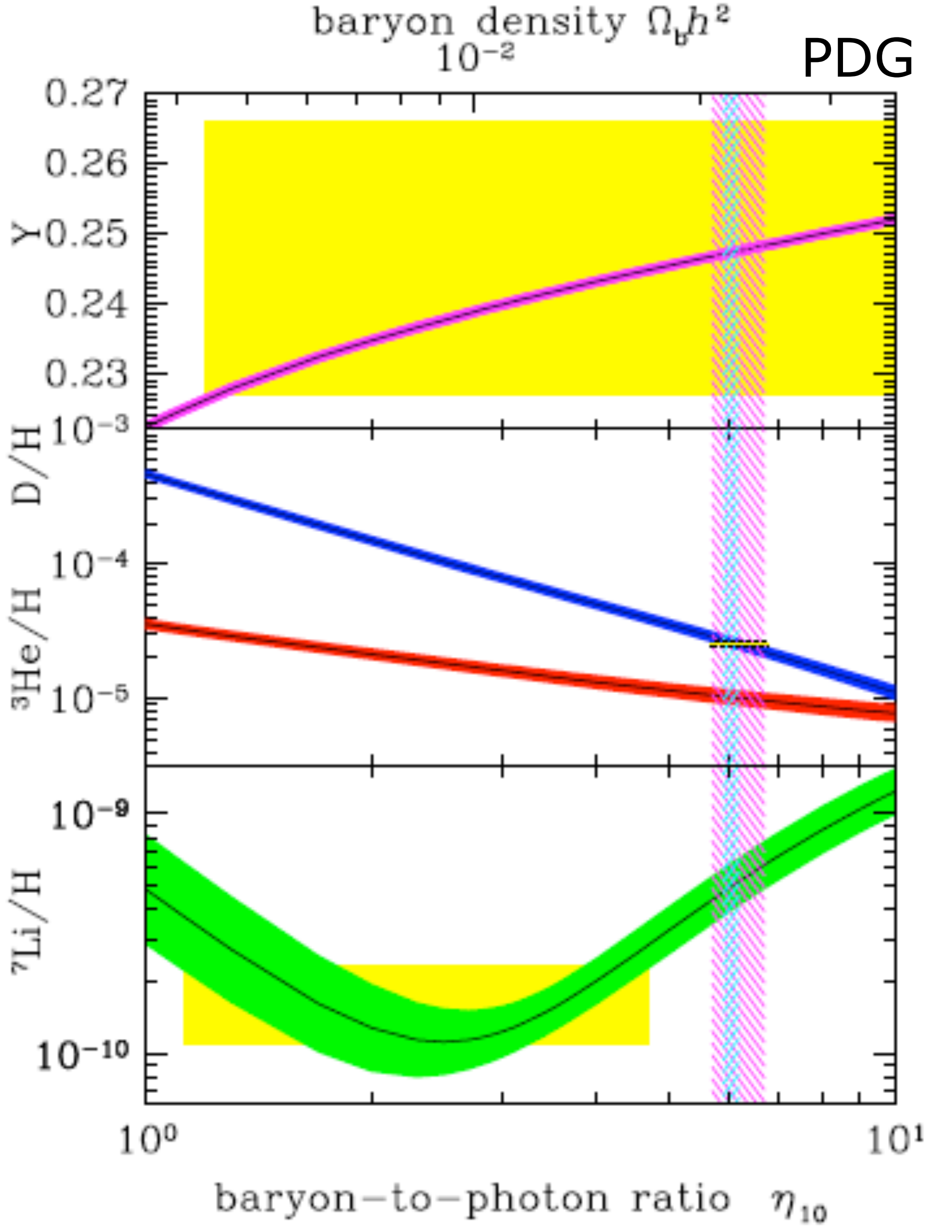
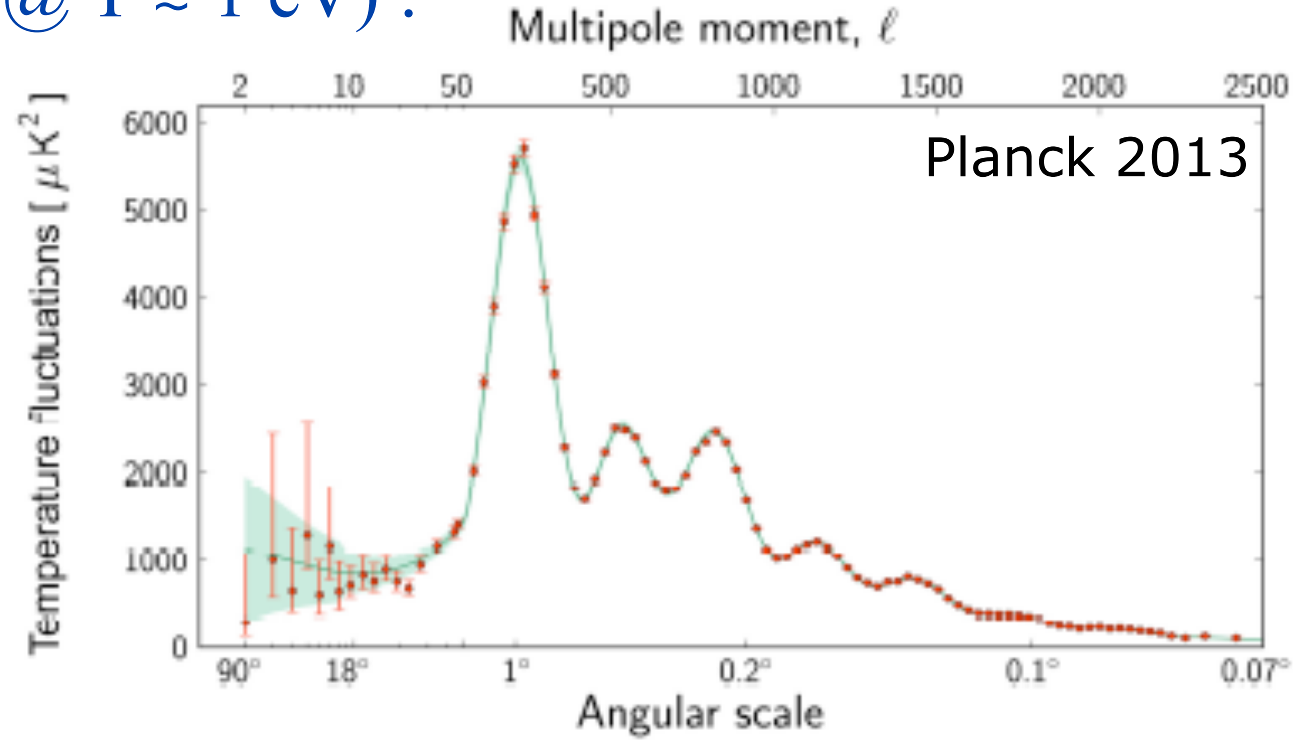


from measurements of CMB anisotropies (@ T ≲ 1 eV) :



$$\eta_{10} = 6.047 \pm 0.074$$
$$\Omega_B\,h^2 = 0.02207 \pm 0.00027$$

Baryon Asymmetry of the Universe

Consistency of two independent measurements of BAU (*epochs with six orders of magnitude difference in temperature*) is a great success of hot Big Bang cosmology

From the theoretical side: What is the origin of the matter-antimatter asymmetry?

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From the theoretical side: What is the origin of the matter-antimatter asymmetry?

Inflationary cosmological model excludes the possibility of a fine-tuned initial condition

The baryon asymmetry must be generated dynamically (BARYOGENESIS)

Necessary conditions for baryogenesis: (Sakharov, 1967)

1. Baryon number violation

2. C and CP violation

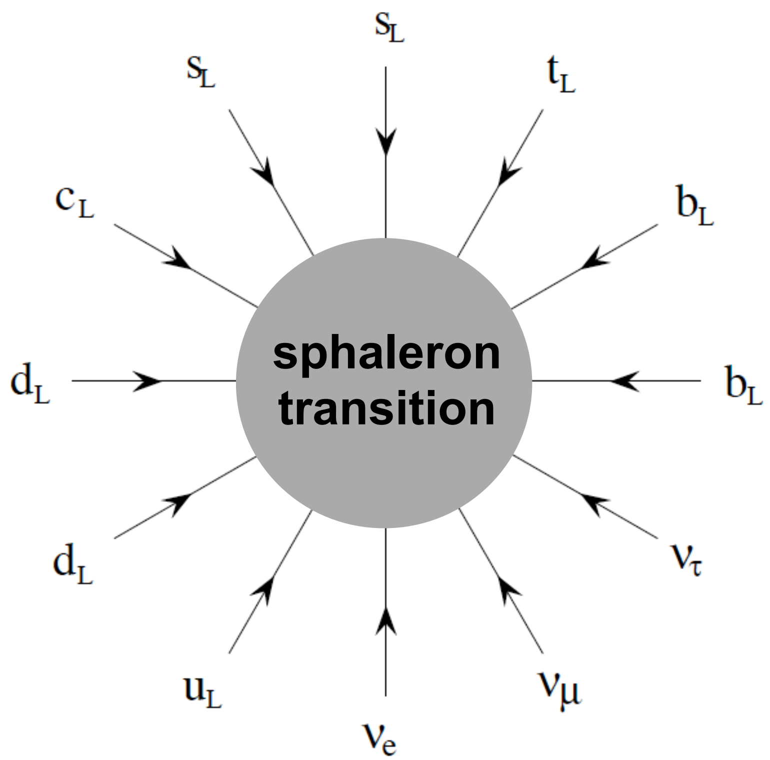
3. Out of equilibrium dynamics

observed BAU requires physics beyond the Standard Model

Leptogenesis

In the Standard Model baryon and lepton number are violated at non-perturbative level in the early Universe:

$$O_{B+L} \;=\; \prod_{k=1}^{3} \epsilon_{\alpha\beta}\,\epsilon_{\gamma\delta}\,\epsilon_{abc}\,\left[Q^a_\alpha\, Q^b_\beta\, Q^c_\gamma\, L_\delta\right]_k$$



Operator invariant under gauge transformations and U(3) flavour rotations

$$\Delta B = \Delta L = \pm 3$$

In each electroweak sphaleron transition an SU(3) and $SU(2)_L$-singlet neutral object for each generation is created out of vacuum. Transition fast in the temperature range:

$$135 \text{ GeV} \;\lesssim\; T_{sph} \;\lesssim\; 10^{12} \text{ GeV}$$

Kuzmin, Rubakov, Shaposhnikov, 1985

$$\langle B\rangle_T \;=\; C\,\langle B-L\rangle_T \;=\; \frac{C}{C-1}\,\langle L\rangle_T$$

with $C = 28/79$ in the Standard Model.

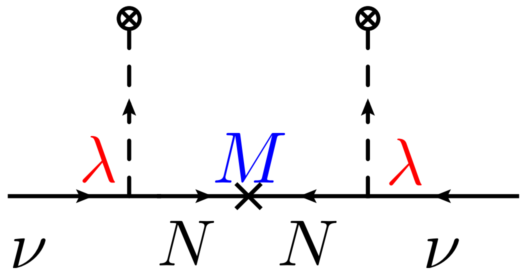
Lepton number asymmetry generated dynamically in the early Universe can also explain cosmological baryon asymmetry

Type I seesaw scenario

Minkowski, 1977
Yanagida, 1979
Gell-Mann, Ramond, Slansky, 1979
Mohapatra, Senjanovic, 1980

$$\mathcal{L}^{\rm seesaw}(x) = \mathcal{L}_{\rm Y}(x) + \mathcal{L}_{\rm M}^{\rm N}(x)$$

$$\begin{aligned}
\mathcal{L}_{\rm Y}(x) &= -\lambda_{\ell i}\,\overline{\psi}_{\ell L}(x)\,\widetilde{H}(x)\,N_{iR}(x) - h_\ell\,\overline{\psi}_{\ell L}(x)\,H(x)\,\ell_R(x) + \text{h.c.}\\
\mathcal{L}_{\rm M}^{\rm N}(x) &= -\frac{1}{2}\,M_i\,\overline{N_i}(x)\,N_i^C(x)\,, \qquad i \geq 2
\end{aligned}$$



At energies below the lightest N_i mass, the heavy Majorana fields are integrated out $\Longrightarrow$ *Majorana mass term* for the LH flavour neutrinos at $E \sim M_Z$:

$$m_\nu = -v^2\,\lambda\,M^{-1}\,\lambda^T = U_{\rm PMNS}^*\,Diag(m_1, m_2, m_3)\,U_{\rm PMNS}^\dagger$$

taking $|\lambda| \sim 1$ and $m_\nu \sim 10^{-2}$ eV $\Rightarrow M \sim 10^{14}$ GeV

$\Lambda \simeq M$ *is not related to the EWSB scale and can, in principle, take arbitrary values up to the Planck mass! Testing the see-saw mechanism???*

Low energy effects of RH neutrinos

$$m_\nu \simeq -m_D\, M^{-1}\, m_D^T \qquad m_D \simeq \lambda\, v$$

$$\text{naively for } M = 1 \text{ TeV} \curvearrowright m_D \approx 10^{-4} \text{ GeV} \Rightarrow \lambda \approx 10^{-6}$$

low energy effects very suppressed:

- tiny EDMs
- tiny lepton radiative decays
- tiny deviations from EW precision observables
- production cross-section at colliders is suppressed (except when RH neutrino has additional interactions, e.g. $U(1)_{B-L}$)

conversely, testing the seesaw mechanism at colliders and/or from low energy observables requires large Yukawa couplings. Again naively,

$$\lambda = 0.1, \qquad M = 1 \text{ TeV} \quad \Rightarrow \quad m_\nu \approx 0.1 \text{ GeV}$$

is it possible to have seesaw models at low scale consistent with light neutrino masses and sizeable Yukawa couplings ?

Mohapatra, '86
Mohapatra, Valle, '86
Pilaftsis, '92;'95
Pilaftsis, Underwood, 2005
de Gouvea, 2007
Kersten, Smirnov, 2007
...

RH neutrinos and large Yukawa couplings

Sizable couplings of RH neutrinos to Standard Model leptons

Lagrangian mass terms:

$$\mathcal{L}_\nu \;=\; -\,\overline{\nu_{\ell L}}\,(m_D)^*_{\ell a}\,\nu_{aR} - \frac{1}{2}\,\overline{\nu^C_{aL}}\,(M)^*_{ab}\,\nu_{bR} \;+\; \text{h.c.}$$

$$M = V^*\hat{M}V^\dagger,\; \hat{M} \equiv \text{diag}(M_1, M_2),\; R^* \simeq m_D M^{-1}$$

Heavy Majorana Neutrino Interactions

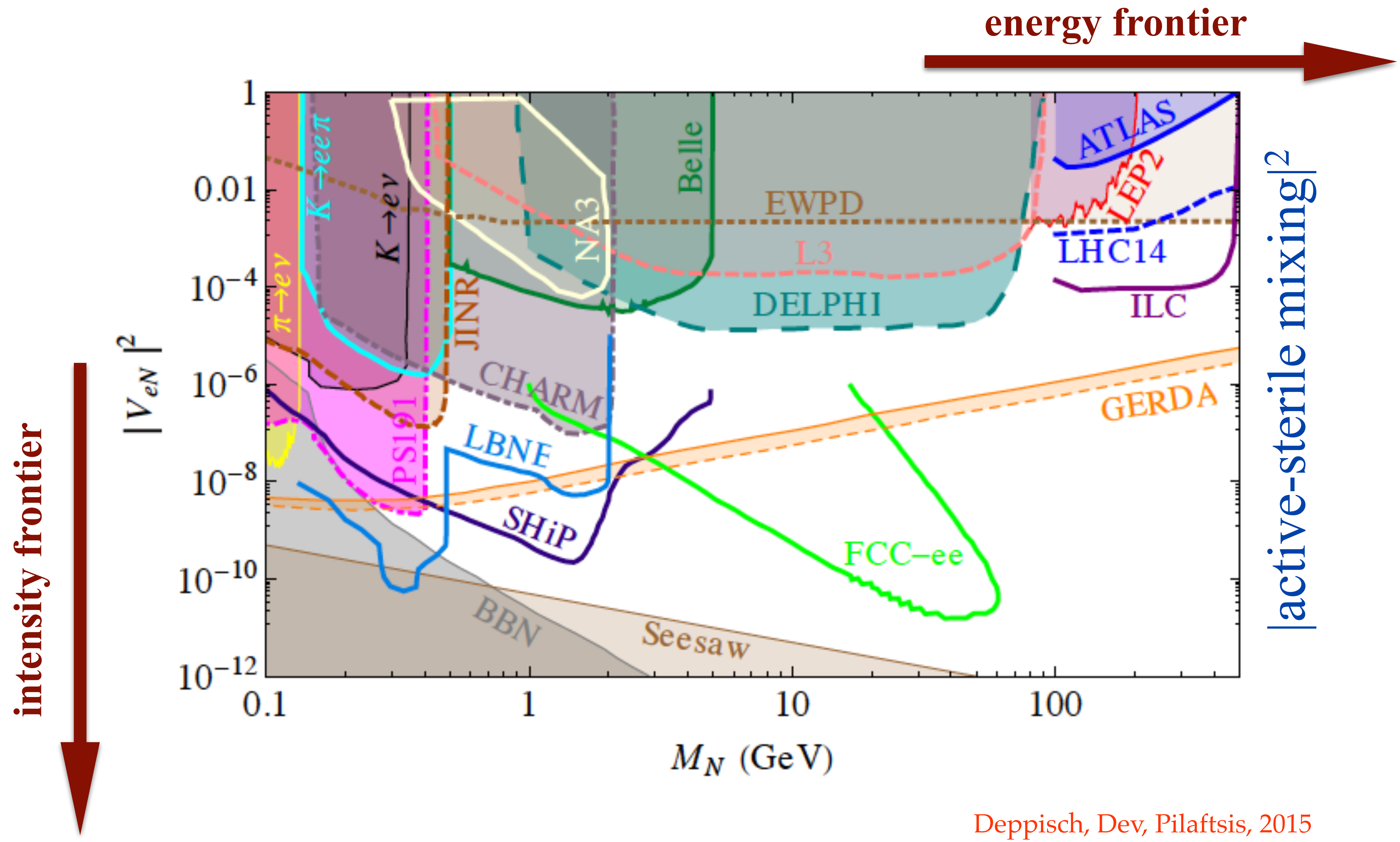
$$\mathcal{L}^N_{CC} \;=\; -\,\frac{g}{2\sqrt{2}}\,\bar{\ell}\,\gamma_\alpha\,(RV)_{\ell k}(1-\gamma_5)\,N_k\,W^\alpha \;+\; \text{h.c.}$$

$$\mathcal{L}^N_{NC} \;=\; -\frac{g}{4c_w}\,\overline{\nu_{\ell L}}\,\gamma_\alpha\,(RV)_{\ell k}\,(1-\gamma_5)\,N_k\,Z^\alpha \;+\; \text{h.c.}$$

$$\mathcal{L}^N_{H} \;=\; -\frac{gM_k}{4\,M_W}\,\overline{\nu_{\ell L}}\,(RV)_{\ell k}\,(1+\gamma_5)\,N_k\,h \;+\; \text{h.c.}$$

Low energy effects are parametrized by (RV)

Constraints on low scale seesaw scenarios



Deppisch, Dev, Pilaftsis, 2015

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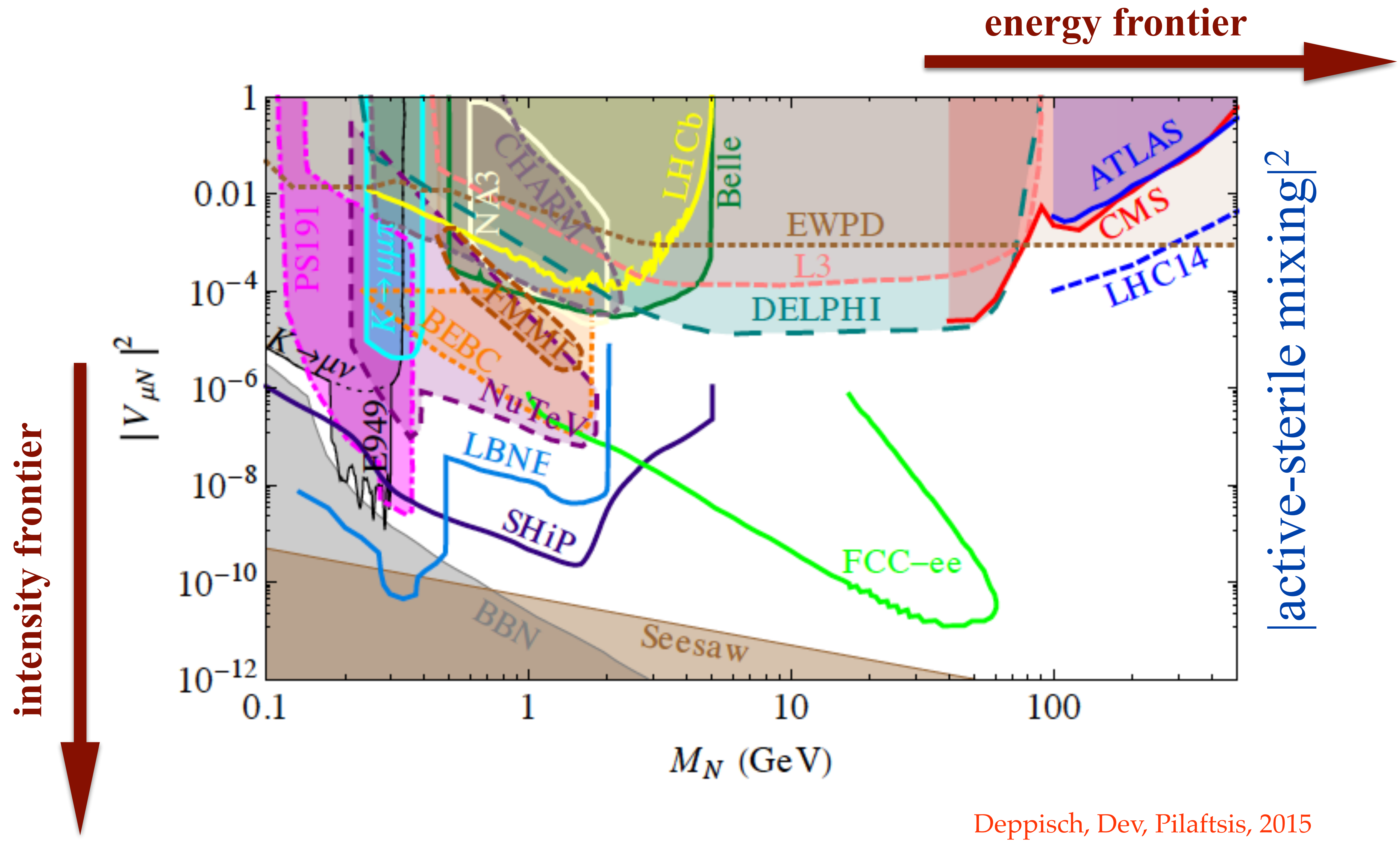


Deppisch, Dev, Pilaftsis, 2015

RH neutrinos and large Yukawa couplings

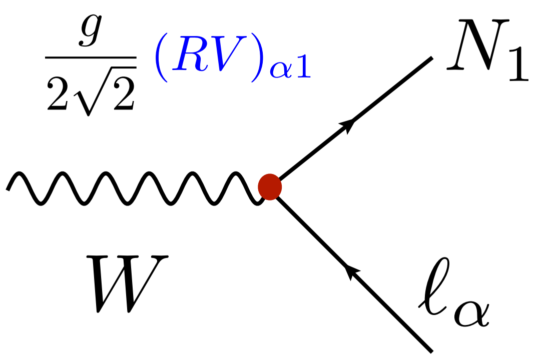
the flavour structure of the neutrino Yukawa couplings is fixed by neutrino oscillation data and *RV* can be calculated in terms of few parameters:

- maximum Yukawa coupling: y
- RH neutrino masses: M_1 and M_2
- a phase: ω

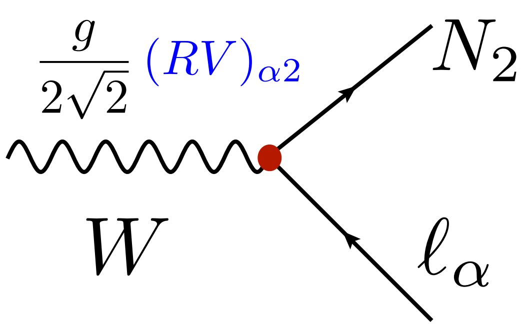
$$U \equiv U_{\rm PMNS}$$

NH:

$$(RV)_{\alpha 1} = -e^{i\,\omega} y\, v \sqrt{\frac{M_2}{M_2+M_1}} \sqrt{\frac{m_3}{m_2+m_3}} \left(U_{\alpha 3} + i\sqrt{m_2/m_3}\, U_{\alpha 2}\right)$$



$$(RV)_{\alpha 2} = \mp i\, e^{i\,\omega} y\, v \sqrt{\frac{M_1}{M_2+M_1}} \sqrt{\frac{m_3}{m_2+m_3}} \left(U_{\alpha 3} + i\sqrt{m_2/m_3}\, U_{\alpha 2}\right)$$

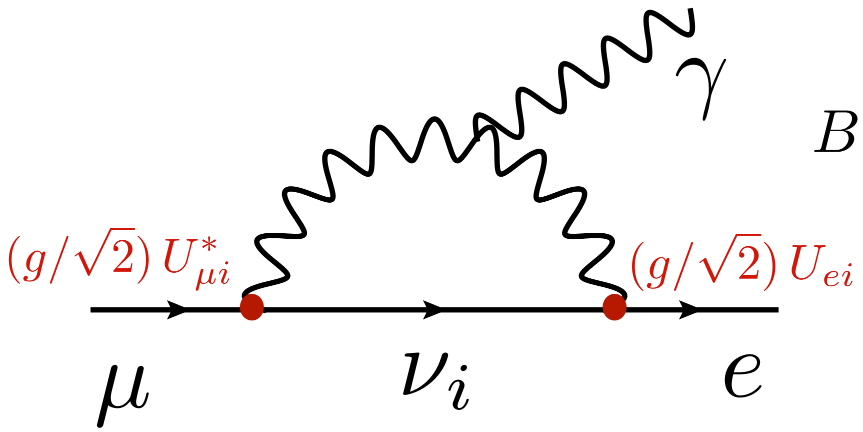


pseudo-Dirac heavy neutrino state $M_1 \sim M_2$

$$(RV)_{\alpha 2} = \pm i\,(RV)_{\alpha 1} \sqrt{\frac{M_1}{M_2}}$$

Charged lepton flavour violation

Standard contribution

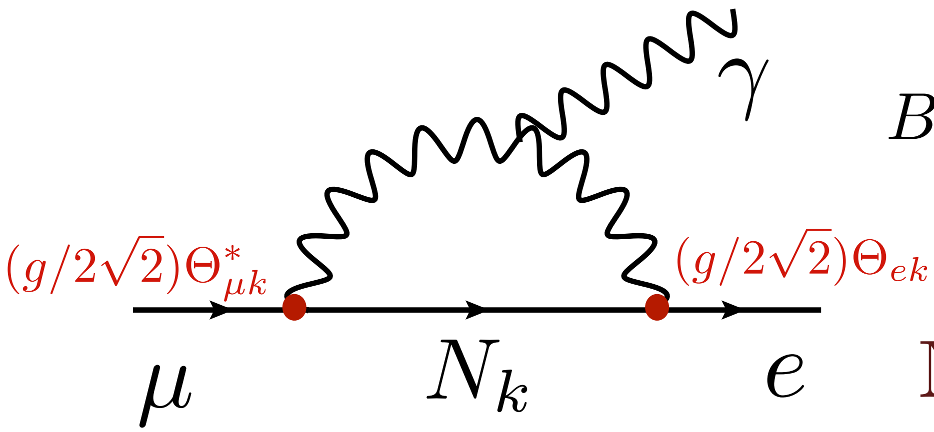


Petcov, '77
Marciano, Sanda, '77

$$BR(\mu \to e + \gamma) = \frac{3\alpha_{\rm em}}{32\pi} \left| \frac{\Delta m^2_{\rm sol}}{M_W^2} U_{e2} U^*_{\mu 2} + \frac{\Delta m^2_{\rm atm}}{M_W^2} U_{e3} U^*_{\mu 3} \right|^2 < 10^{-54}$$

Sizeable couplings, but strong GIM suppression, $\Delta m^2 / M_W^2$

New contribution



$$BR(\mu \to e + \gamma) = \frac{3\alpha_{\rm em}}{8\pi} \left|\Theta^*_{\mu 1} \Theta_{e1}\right|^2 \left|G(M_1^2/M_W^2) - G(0)\right|^2$$

No GIM suppression, observable effects!

$$\Theta = RV$$

Charged lepton flavour violation

Present experimental bound:

$$\mathrm{BR}\left(\mu^+ \to e^+\gamma\right) < 4.2 \times 10^{-13}$$ **MEG @ PSI**

Present experimental bound:

$$\mathrm{BR}(\mu^+ \to e^+e^-e^+) < 1.0 \times 10^{-12}$$ **SINDRUM @ PSI**

Projected bounds:

$$\mathrm{BR}(\mu^+ \to e^+e^-e^+) < 10^{-15}$$ **MuSIC facility @ Osaka University**

Present experimental bound:

$$\mathrm{CR}(\mu\mathrm{Ti} \to e\mathrm{Ti}) \; < \; 4.3 \times 10^{-12}$$ **SINDRUM II @ PSI**

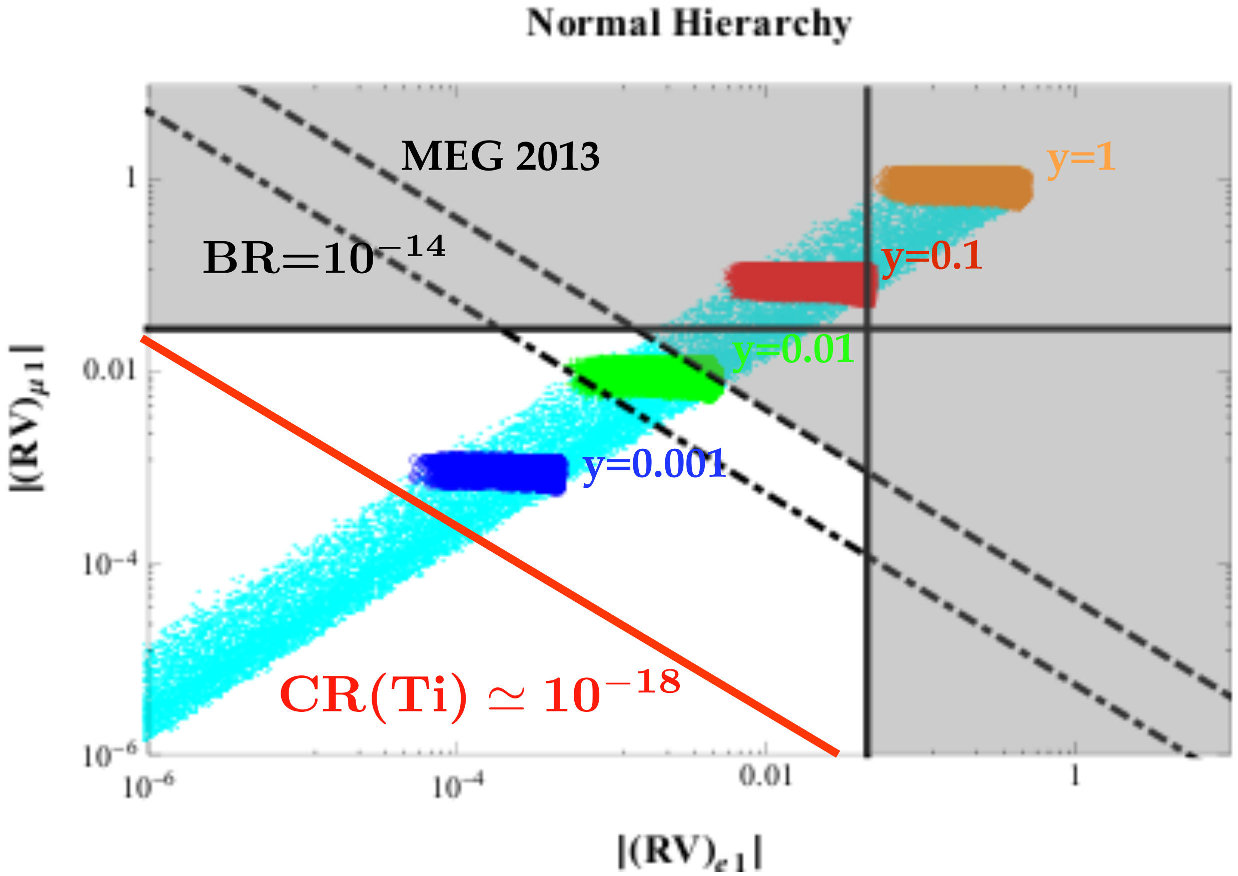
Projected bounds:

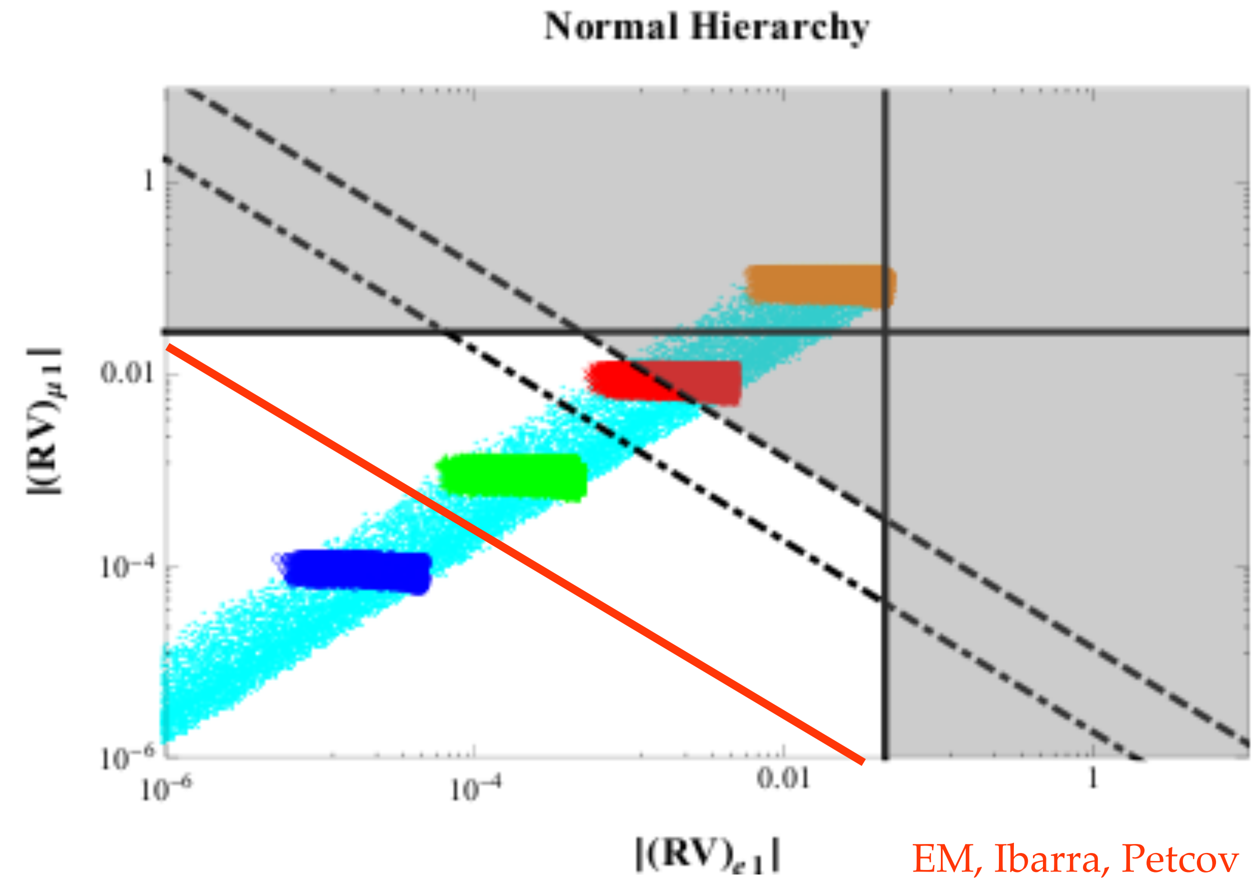
$$\mathrm{CR}(\mu\mathrm{Ti} \to e\mathrm{Ti}) \; \approx \; 10^{-18}$$ **PRISM/PRIME @ KEK, Project-X @ Fermilab**

$$\mathrm{CR}(\mu\mathrm{Al} \to e\mathrm{Al}) \; \approx \; 10^{-16}$$ **COMET @ KEK, Mu2e @ Fermilab**

Charged lepton flavour violation

$\mathbf{M_1} = \mathbf{100}\ \mathrm{GeV}$ $\mathbf{M_1} = \mathbf{1000}\ \mathrm{GeV}$





EM, Ibarra, Petcov
Dinh, EM, Ibarra, Petcov

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flavour structure fixed by neutrino oscillation parameters and $(RV)_{\ell k} \propto y\,v/M_k$

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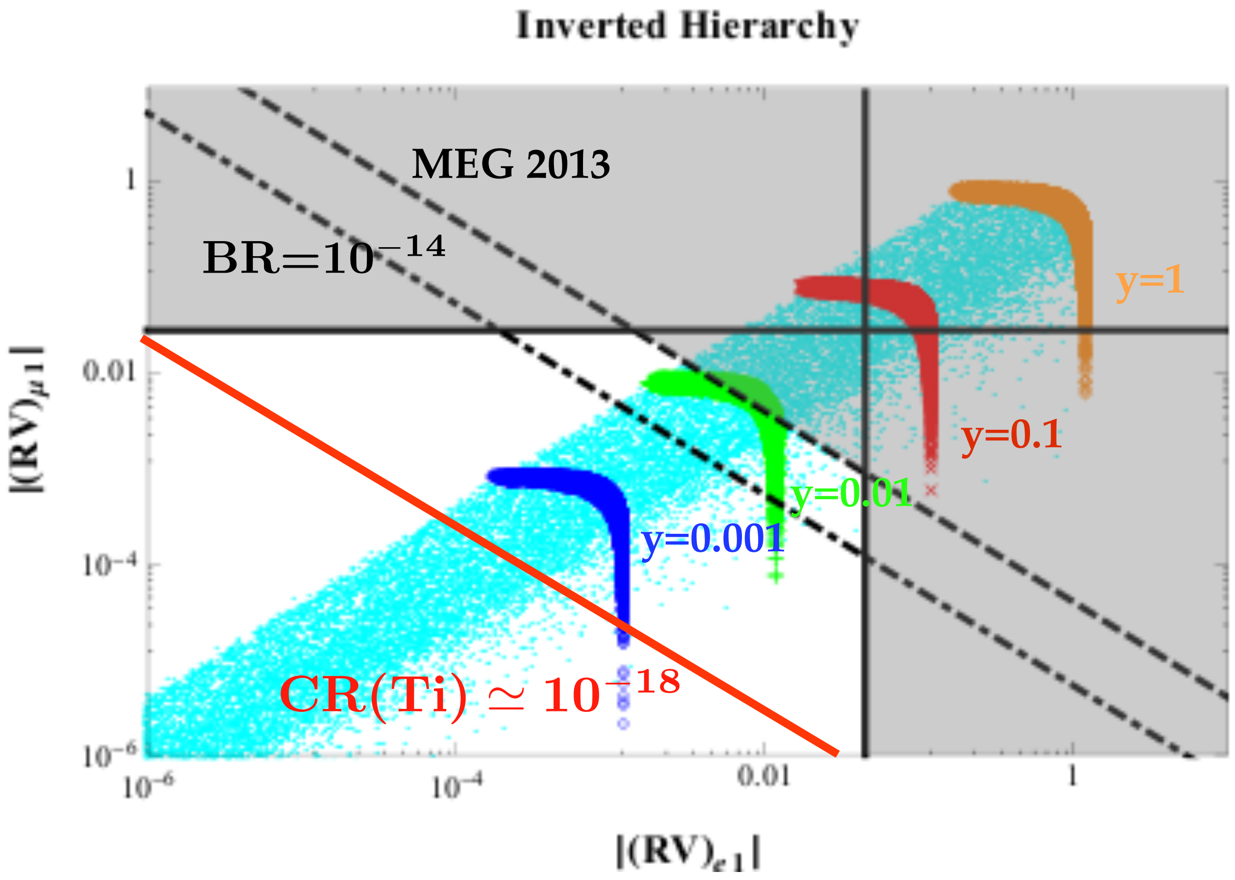

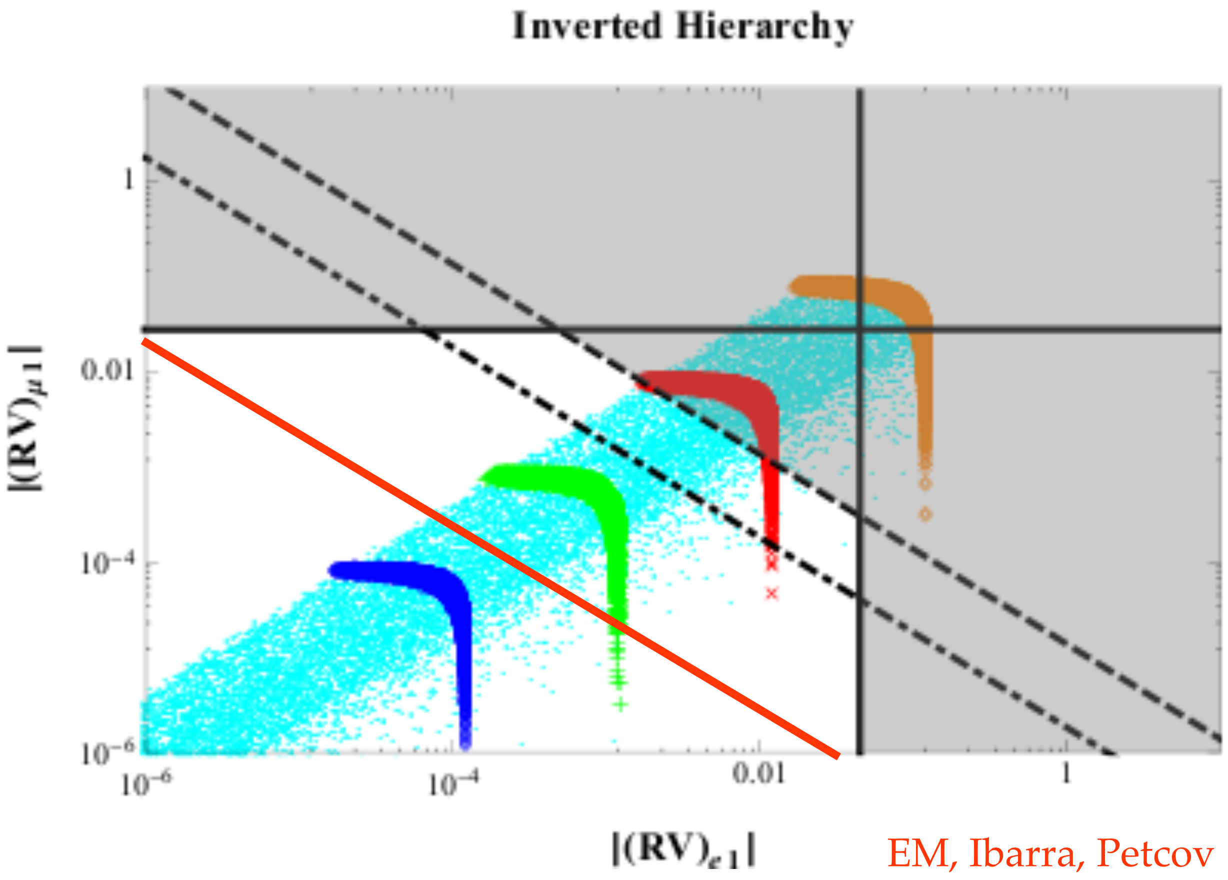

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Dinh, EM, Ibarra, Petcov

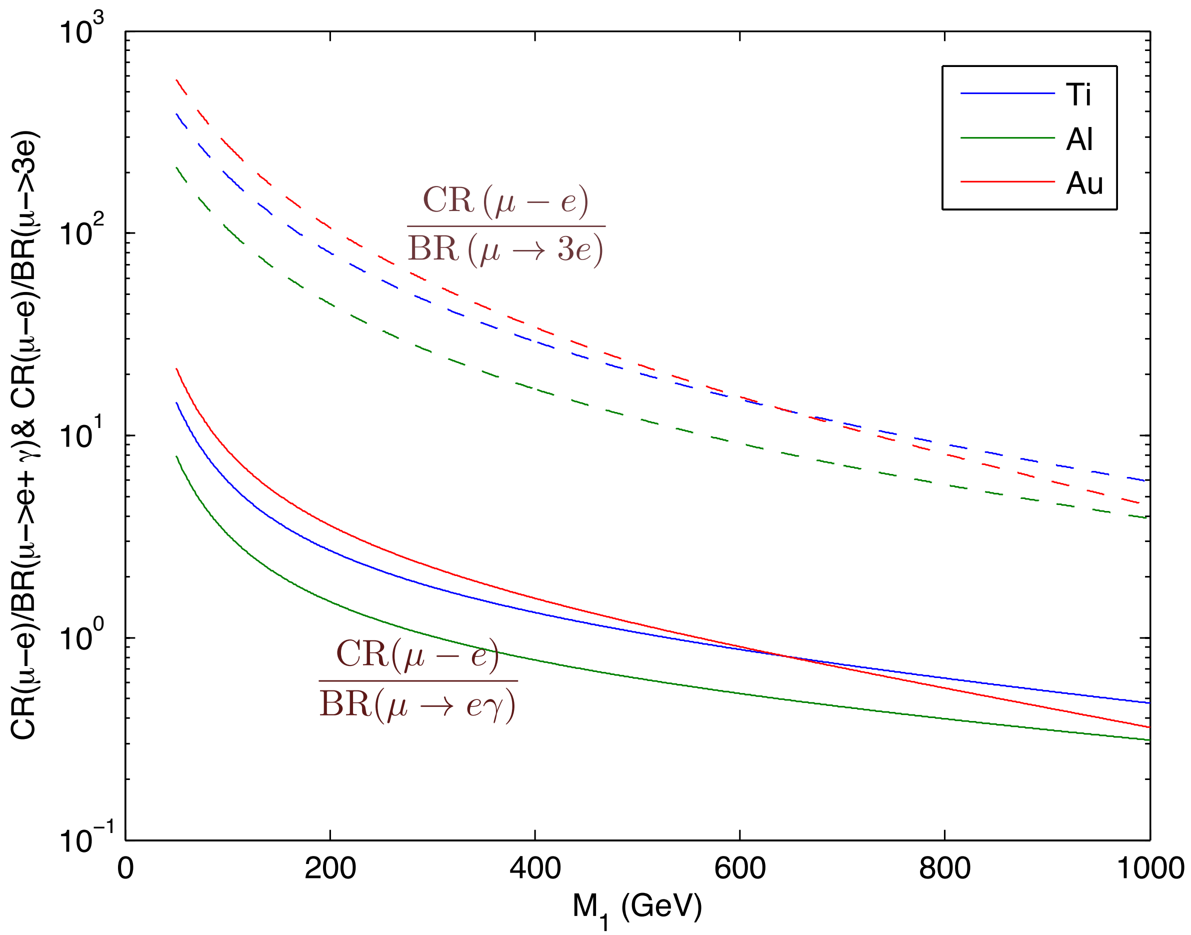
$$\mathcal{L}^N_{CC} \;=\; -\frac{g}{2\sqrt{2}}\,\bar{\ell}\,\gamma_\alpha\,(RV)_{\ell k}(1-\gamma_5)\,N_k\,W^\alpha \;+\; \text{h.c.},$$

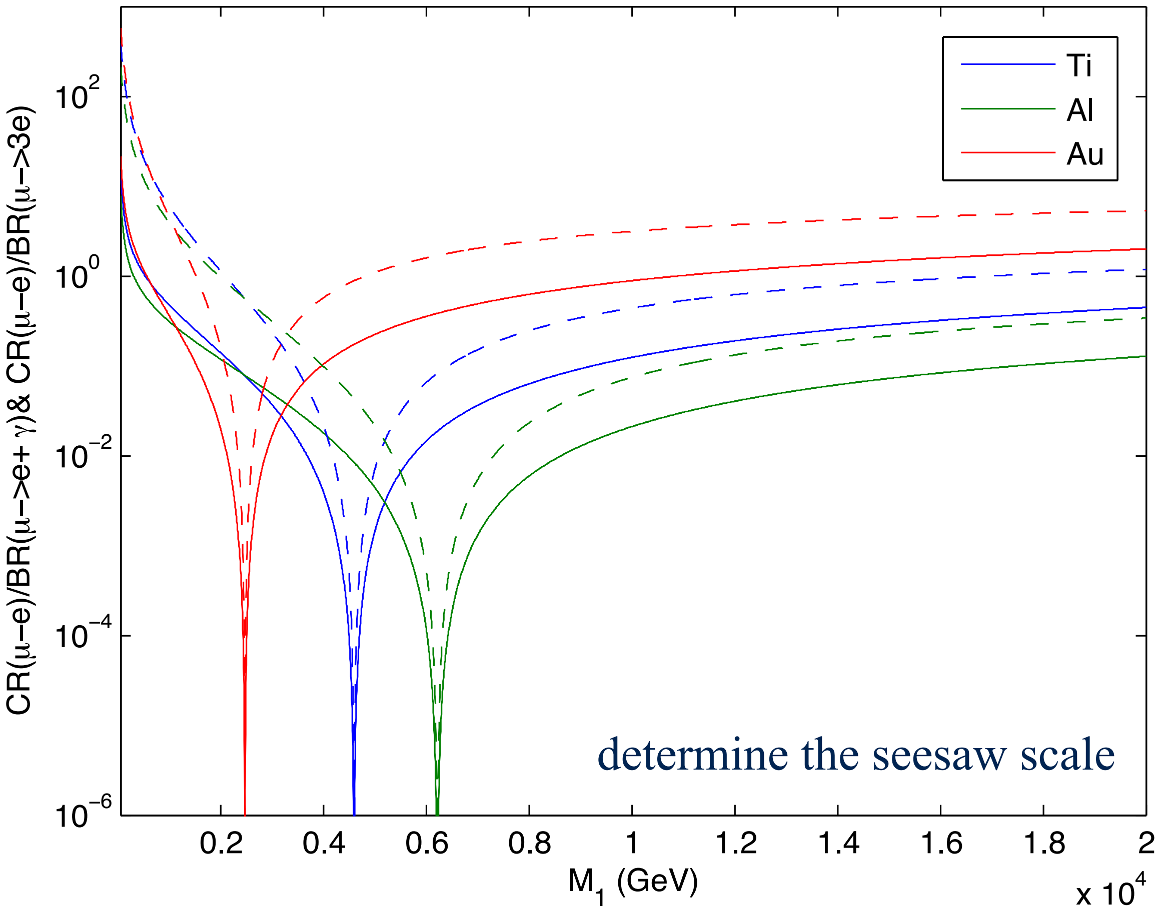
$$\mathcal{L}^N_{NC} \;=\; -\frac{g}{4c_w}\,\overline{\nu_{\ell L}}\,\gamma_\alpha\,(RV)_{\ell k}\,(1-\gamma_5)\,N_k\,Z^\alpha \;+\; \text{h.c.}$$

flavour structure fixed by neutrino oscillation parameters and $(RV)_{\ell k} \propto y\,v/M_k$

Charged lepton flavour violation

Muon conversion to electron in nuclei





$$\frac{\text{CR}(\mu\,\text{Ti}-e\,\text{Ti})}{\text{BR}(\mu\to e\gamma)} \gtrsim 6\ (0.5) \quad \text{for } M_1 = 100\ (1000)\ \text{GeV}$$

Dinh, Ibarra, EM, Petcov, 2012
see also Alonso, Dhen, Gavela, Hambye, 2012

$$\frac{\text{BR}(\mu\to 3e)}{\text{BR}(\mu\to e\gamma)} \gtrsim 0.03 \quad \text{for } M_1 \geq 100\ \text{GeV}$$

conversion ratio highly affected by ***M_1*!**

Thermal leptogenesis

Boltzmann equations for the evolution of *B-L* asymmetry

$$\frac{dY_{N_1}}{dz} = -\frac{z}{sH(M_1)}\left(\gamma_D + \gamma_{S,\,\Delta L=1}\right)\left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1\right)$$

$$\frac{dY_{\Delta(B-L)}}{dz} = -\frac{z}{sH(M_1)}\left[\epsilon_1\left(\gamma_D + \gamma_{S,\,\Delta L=1}\right)\left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1\right) - \left(\frac{\gamma_D}{2} + \gamma_{W,\,\Delta L=1}\right)\frac{Y_{\Delta(B-L)}}{Y_L^{\rm eq}}\right]$$

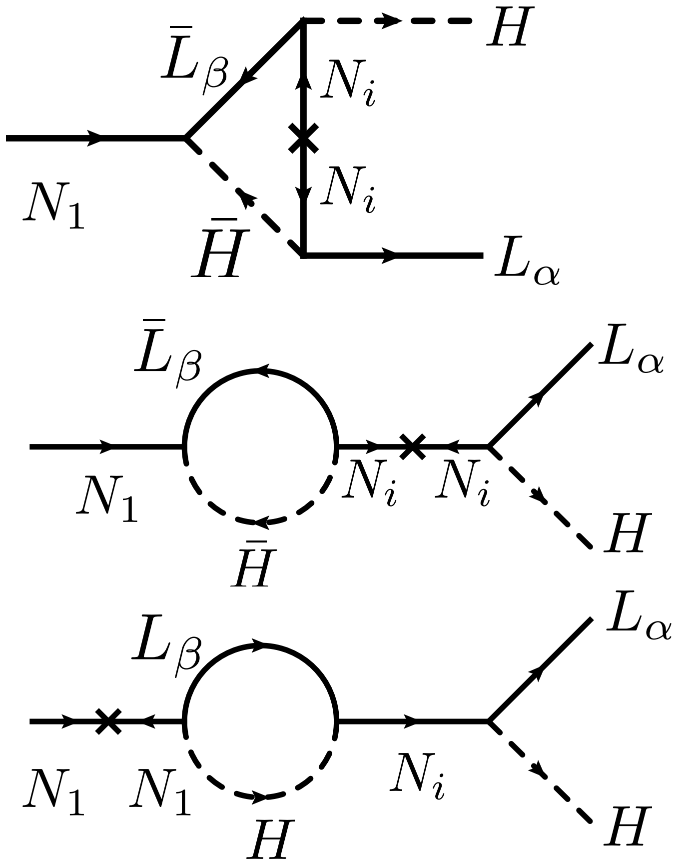
$$M_1 \ll M_{2,3}$$

N_1

CP violation in decays

ΔL ⟷ sphalerons ⟷ ΔB

lepton asymmetry — baryon asymmetry



$$Y_{\Delta B} \equiv \frac{n_B - n_{\bar{B}}}{s} \simeq C\, Y_{N_1}^{eq}\, \epsilon_1\, \eta_{\rm eff} \approx 10^{-11} \qquad Y_{N_1}^{eq} \approx 4\times 10^{-3}$$

$\eta_{\rm eff}$ → ≈ 0.01, efficiency factor

ϵ_1 → $\approx 10^{-6}$, CP asymmetry

$$Y_{\Delta B}^{\rm CMB} \equiv (8.79 \pm 0.44)\times 10^{-11}$$

Thermal leptogenesis

Davidson-Ibarra bound:

$$|\epsilon_1| \leq \epsilon^{\rm DI} = \frac{3}{16\,\pi}\frac{M_1}{v^2}\frac{\Delta m^2_{\rm atm}}{m_{\nu_1}+m_{\nu_3}}$$

$$M_1 \gtrsim \frac{2.5\times 10^8}{\eta_1^{\rm eff}}\left(\frac{m_{\nu_1}+m_{\nu_3}}{0.1\ {\rm eV}}\right)\ {\rm GeV}$$

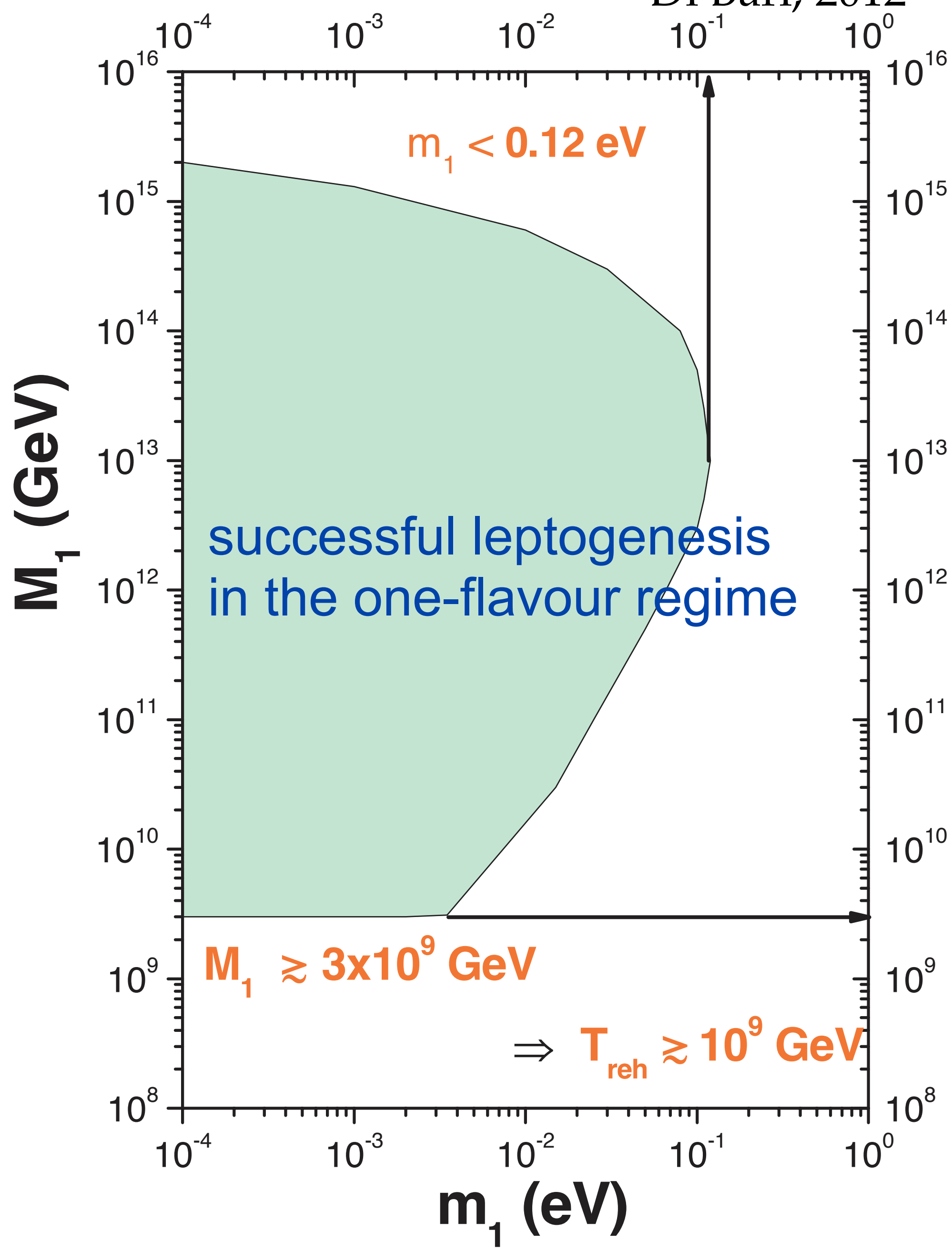
light neutrino mass window compatible with successful thermal leptogenesis:

$$10^{-3}\,{\rm eV} \lesssim m_i \lesssim 0.1\,{\rm eV}$$

these bounds slightly change if flavour dynamics is taken into account ($T \lesssim 10^{12}$ GeV)

Barbieri, Creminelli, Strumia, Tetradis, 2000
Abada et al., 2006
Nardi, Nir, Roulet, Racker, 2006;
Blanchet, Di Bari, 2008; Aristizabal Sierra et al., 2009
Antusch, Blanchet, Blennow, Fernandez-Martinez, 2009
Racker, Pena, Rius, 2012, ...

Di Bari, 2012



or in the case of resonant enhancement of the CP asymmetry

Pilaftsis, Underwood, 2004; Pilaftsis, 2005; Deppisch, Pilaftsis, 2012;
Dev, Millington, Pilaftsis, Teresi, 2014

Thermal leptogenesis

From the experimental side, a direct test of thermal leptogenesis is excluded *(we would need to produce the heavy Majorana neutrinos and measure the CP asymmetry in their decays)*

However, we may have further indirect confirmation that thermal leptogenesis is the correct mechanism for the generation of the BAU if we will answer the following questions:

1. Are light active neutrinos Majorana fermions? $0\nu\beta\beta$-decay experiments may reveal the Majorana nature of neutrinos (first Sakharov condition, *L*, is fulfilled)

2. Is there CP violation in the lepton sector? SuperBeam facilities, T2HK and NOνA experiments,..., can probe *Dirac CP violation* (second Sakharov condition can be easily satisfied for successful leptogenesis)

3. Why should the reheating temperature be as large as the temperature favoured by leptogenesis?

Baryogenesis through neutrino oscillations

Akhmedov, Rubakov, Smirnov, 1998

Let's consider the Standard Model extended with **3** EW singlet RH (sterile) neutrinos N_k with masses below the EW scale: **Neutrino Minimal Standard Model** (νMSM)

Asaka, Shaposhnikov, 2005

Now deviation from thermal equilibrium is realized during the production rather than the freeze-out and decay of RH neutrinos

Neutrino Yukawa interactions generate lepton asymmetries, $\mu_\alpha \neq 0$, during production, oscillations, freeze-out and decays of N_k, when all Sakharov conditions are fulfilled: *opposite sign asymmetries are created in the sterile and active flavours*

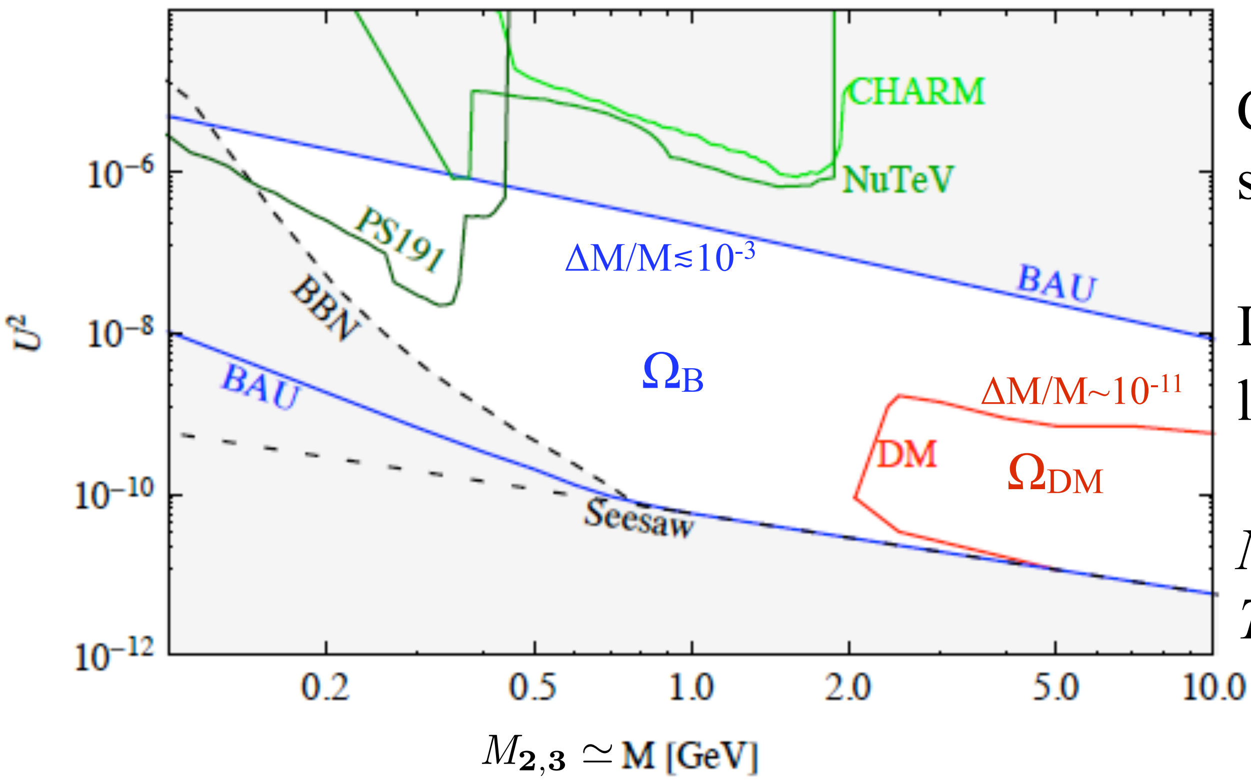
The lightest sterile neutrino $\boldsymbol{N_1}$ can be a viable dark matter candidate if its mass and mixing are constrained to 1 keV$\lesssim \boldsymbol{M_1} \lesssim$ 50 keV and $10^{-13} \lesssim \sin^2(2\theta_1) \lesssim 10^{-7}$

Laine, Shaposhnikov, 2008

The decay of $\boldsymbol{N_1}$ leaves a distinct X-ray line of energy $\boldsymbol{M_1}/2$ that can be searched for with X-ray satellites

No additional new physics is necessary to explain neutrino masses, baryogenesis and dark matter

Canetti, Drewes, Shaposhnikov, 2012



Baryon asymmetry produced during $\boldsymbol{N_{2,3}}$ oscillations;
$\boldsymbol{N_{2,3}}$ thermalize at $T \lesssim T_{EW} \sim 135$ GeV, with $\boldsymbol{\lambda_{23}} \sim 10^{-7}$-$10^{-6}$

CP violation in the sterile sector may be measurable in LNV semihadrodic decays of K,D,D_s,B,B_s (Cvetic,Kim,Zamora-Saa, 2014)

If $N_{2,3}$ freeze-out and decays happen at T~few GeV, large lepton flavour asymmetries are possible, $|\mu_\alpha| \gtrsim 8 \times 10^{-6}$

N_1~few keV dark matter production is resonantly amplified at T~100 MeV (Shi-Fuller mechanism) and $M_{2,3} \gtrsim 2$ GeV

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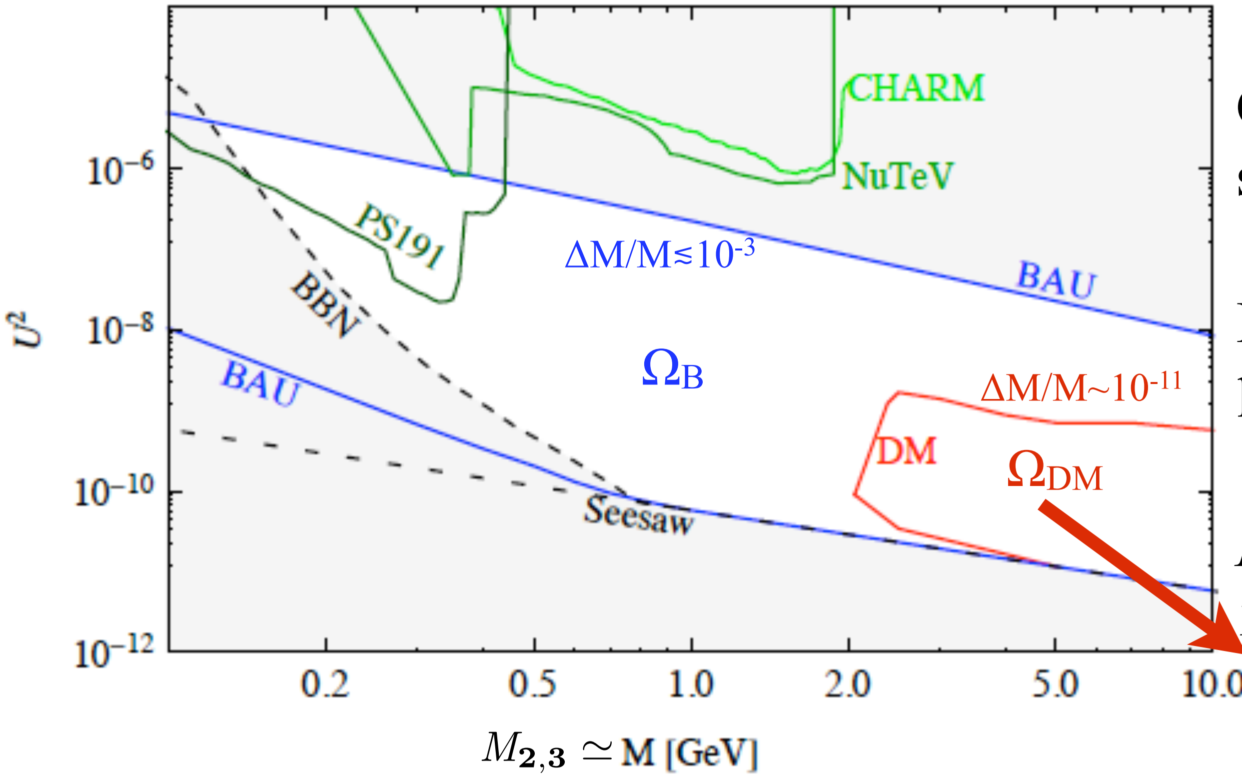
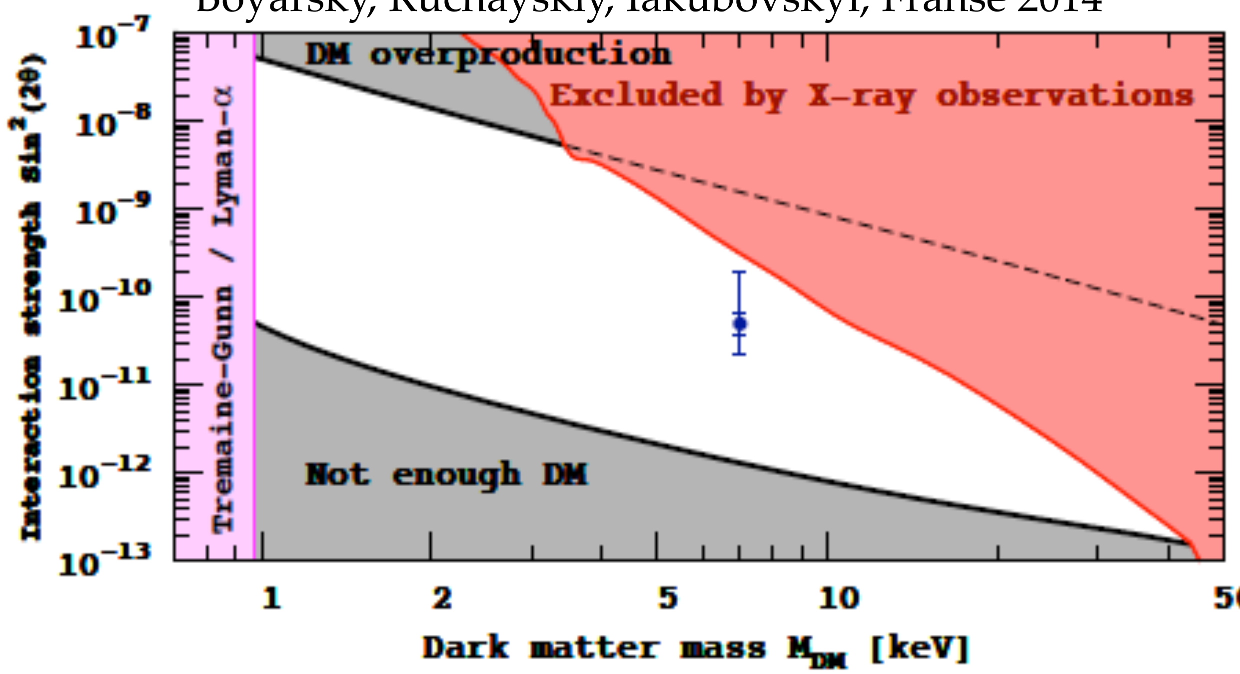
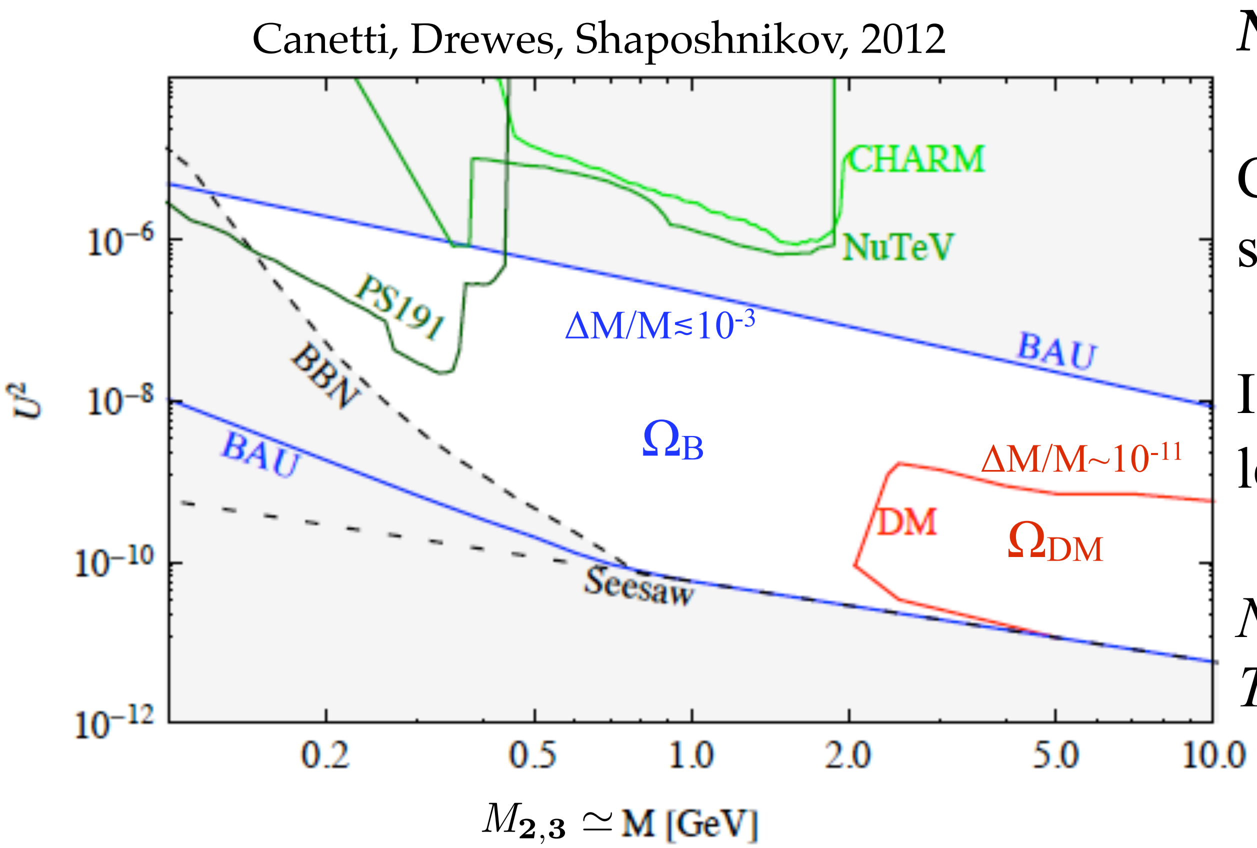


Detection of an unidentified spectral line at ~3.5 keV
(Boyarsky et al., Bulbul et al. 2014; also Jeltema and Profumo 2014)

Boyarsky, Ruchayskiy, Iakubovskyi, Franse 2014



The signal can be explained by decaying sterile neutrino DM with $M_1 \sim 7$ keV and $\sin^2(2\theta_1) \sim 5\text{x}10^{-11}$



Baryon asymmetry produced during $N_{2,3}$ oscillations; $N_{2,3}$ thermalize at $T \lesssim T_{EW}$~135 GeV, with λ_{23}~10^{-7}-10^{-6}

CP violation in the sterile sector may be measurable in LNV semihadrodic decays of K,D,D_s,B,B_s (Cvetic,Kim,Zamora-Saa, 2014)

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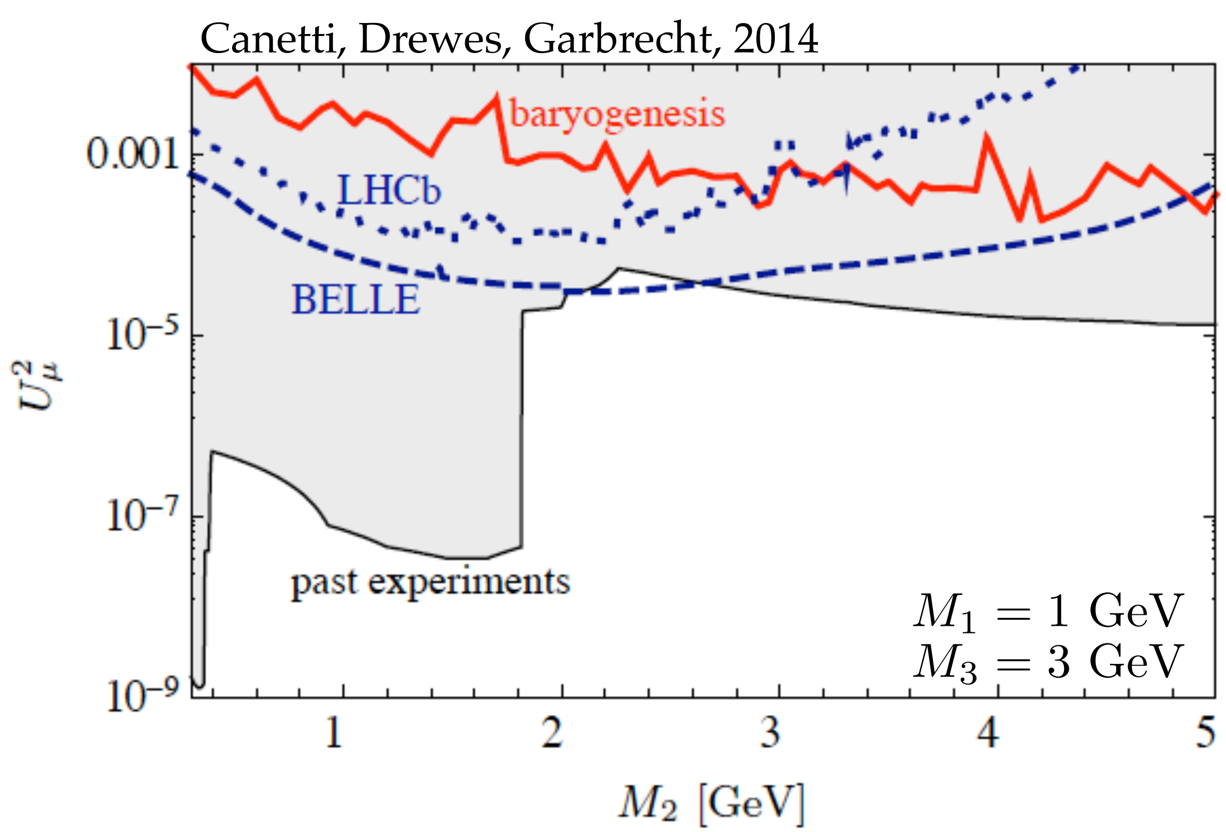


No dark matter, but all the 3 RH neutrinos contribute to neutrino masses and the generation of the asymmetry at $T \gtrsim T_{EW}$; additional sources of CP violation

Enhancement factor for the *flavour asymmetries* at T~10^5 GeV, without mass degeneracy

$\Gamma_{\mu,\tau}/H \gtrsim 1$ and $\Gamma_e/H < 1$ at $T \gtrsim T_{EW}$

$$\frac{q_B}{s} \simeq -\frac{28}{79}\frac{q_e}{s}\frac{3}{7}e^{-\Gamma_e/H}.$$

New states can be found at LHCb and BELLE II

Proposal for a fixed target experiment SHIP at CERN SPS with a sensitivity $U_\mu^2 \gtrsim 10^{-9}$ (Bonivento et al., 2013)

Summary and outlook

We have convincingly observed neutrino oscillations in atmospheric, solar, reactor, and accelerator neutrinos, and accurately measured many of the parameters

Neutrinos point the way to New Physics beyond the Standard Model

Information still missing:

1. **Absolute neutrino mass scale**
2. **Neutrino mass hierarchy**
3. **The nature of neutrinos - Dirac or Majorana**
4. **CP violation in neutrino oscillation**
5. **The octant of the atmospheric mixing angle**
6. **Possible sterile neutrinos**
7. **…**

Summary and outlook

A minimal extension of the Standard Model, which provides a mechanism for the generation of neutrino masses and mixing, consists of adding singlet RH neutrinos

The RH neutrino mass introduces a new scale in the theory, which can be of the same order as or smaller than the EW symmetry breaking scale

- It is possible to probe the mechanism of neutrino mass generation with experiments at the energy and intensity frontiers

- Baryon asymmetry can originate *only* from New Physics in the lepton sector: leptogenesis mechanism

- Baryogenesis can be achieved from CP violating oscillations of (sterile) RH neutrinos with **masses in the GeV range**. *Theory possibly testable in laboratory experiments:*

  Any experiment that improves the present bounds has the potential to discover GeV RH neutrinos responsible for baryogenesis and neutrino masses

- Low scale seesaw scenarios can also predict production of keV sterile neutrino dark matter in the early Universe (*a smoking signature is monochromatic X-ray line*)

BACKUP SLIDES

RH neutrinos and large Yukawa couplings

There is a continuous family of Dirac masses compatible with neutrino data

Consider for simplicity the case of 2 RH neutrinos in the basis where charged lepton Yukawa and RH neutrino mass matrices are diagonal:

$$m_D = i \overbrace{U^*_{PMNS}\sqrt{\hat{m}}}^{\text{low energy ``measurable''}} \overbrace{O\sqrt{\hat{M}}}^{\text{high energy free parameters}}$$

Casas, Ibarra, 2001

$$O \equiv \begin{pmatrix} 0 & 0 \\ \cos\hat{\theta} & \pm\sin\hat{\theta} \\ -\sin\hat{\theta} & \pm\cos\hat{\theta} \end{pmatrix} \quad \text{for normal hierarchy}$$

$$O \equiv \begin{pmatrix} \cos\hat{\theta} & \pm\sin\hat{\theta} \\ -\sin\hat{\theta} & \pm\cos\hat{\theta} \\ 0 & 0 \end{pmatrix} \quad \text{for inverted hierarchy}$$

$$\hat{\theta} \equiv \omega - i\xi$$

RH neutrinos and large Yukawa couplings

There is a continuous family of Dirac masses compatible with neutrino data

Consider for simplicity the case of 2 RH neutrinos in the basis where charged lepton Yukawa and RH neutrino mass matrices are diagonal:

$$m_D = i\, U^*_{PMNS} \sqrt{\hat{m}}\, O \sqrt{\hat{M}}$$

U^*_{PMNS}: $\mathcal{O}(0.1)$

$\sqrt{\hat{m}}$: $\sqrt{\mathcal{O}(10^{-10})\ \mathrm{GeV}}$

$\sqrt{\hat{M}}$: $\sqrt{\mathcal{O}(10^{3})\ \mathrm{GeV}}$

Casas, Ibarra, 2001

adjust O to generate large m_D

e.g. $m_D \approx 10$ GeV $\Rightarrow$ $|O| \approx 10^6$

$$O \equiv \begin{pmatrix} 0 & 0 \\ \cos\hat{\theta} & \pm\sin\hat{\theta} \\ -\sin\hat{\theta} & \pm\cos\hat{\theta} \end{pmatrix} \xrightarrow[\xi \gg 1]{\hat{\theta} \equiv \omega - i\xi} \frac{e^{i\omega} e^{\xi}}{2} \begin{pmatrix} 0 & 0 \\ 1 & \mp i \\ i & \pm 1 \end{pmatrix}$$

exponentially enhanced!
fixed flavour structure!

RH neutrinos and large Yukawa couplings

the flavour structure of the neutrino Yukawa couplings is determined by neutrino oscillation parameters:

NH: $$RV \approx -\frac{e^{-i\,\omega}e^{\xi}}{2}\sqrt{\frac{m_3}{|M_1|}}\begin{pmatrix} \left(U_{e3}+i\sqrt{m_2/m_3}\,U_{e2}\right) & \pm i\left(U_{e3}+i\sqrt{m_2/m_3}\,U_{e2}\right)/\sqrt{M_2/M_1} \\ \left(U_{\mu3}+i\sqrt{m_2/m_3}\,U_{\mu2}\right) & \pm i\left(U_{\mu3}+i\sqrt{m_2/m_3}\,U_{\mu2}\right)/\sqrt{M_2/M_1} \\ \left(U_{\tau3}+i\sqrt{m_2/m_3}\,U_{\tau2}\right) & \pm i\left(U_{\tau3}+i\sqrt{m_2/m_3}\,U_{\tau2}\right)/\sqrt{M_2/M_1} \end{pmatrix}$$

Shaposhnikov, 2007
Raidal,Strumia,Turzynski, 2007
Kersten,Smirnov, 2009
Gavela,Hambye,Hernandez,Hernandez, 2009
Ibarra, EM, Petcov, 2010

IH: $$m_{2,3} \to m_{1,2}$$
$$U_{\alpha2,\alpha3} \to U_{\alpha1,\alpha2}\,(\alpha = e,\mu,\tau)$$

It is convenient to parametrize the size of the couplings in terms of the highest neutrino Yukawa eigenvalue:

$$y^2v^2 \equiv \max\left\{\text{eig}\left(m_D m_D^\dagger\right)\right\} = \max\left\{\text{eig}\left(\sqrt{\hat{m}}O\hat{M}O^\dagger\sqrt{m}\right)\right\} = \frac{1}{4}e^{2\,\xi}(m_2+m_3)(M_1+M_2)$$

Generalized lepton charge

$$\mathcal{L}_\nu \;=\; -\,\overline{\nu_{\ell L}}\,(m_D)_{\ell a}\,\nu_{aR} - \frac{1}{2}\,\overline{\nu^c_{aL}}\,(M_R)_{ab}\,\nu_{bR} \;+\; \text{h.c.}$$

For an arbitrary number of RH neutrino fields ν_{aR}:

$$L' \;=\; \sum_{k=e,\mu,\tau,\ldots} (-1)^{n_k}\, a_k\, L_k, \;\; n_k = 0,1, \;\; a_k = 0,1, \;\; L_k \neq 0$$

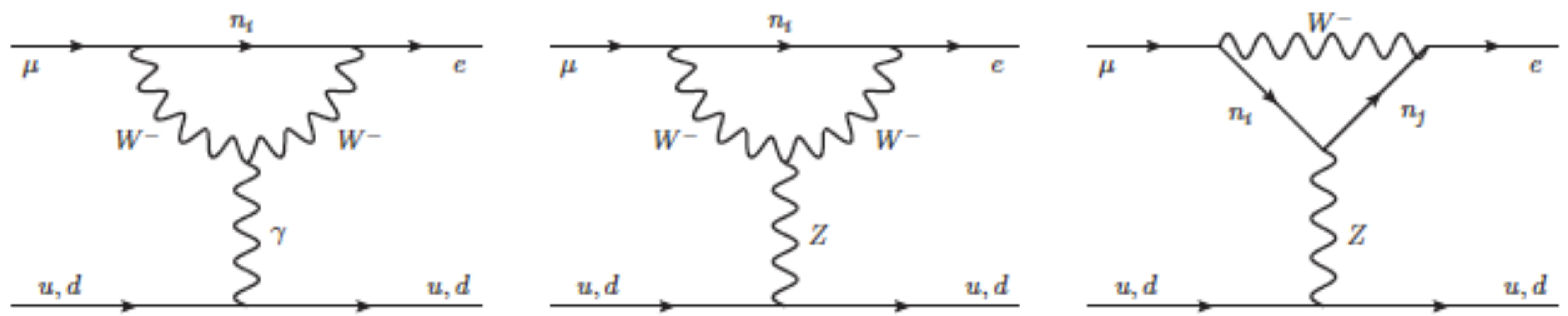
massive Dirac fermions : $\min(n_+(L'), n_-(L'))$

massless fermions : $|n_+(L') - n_-(L')|$

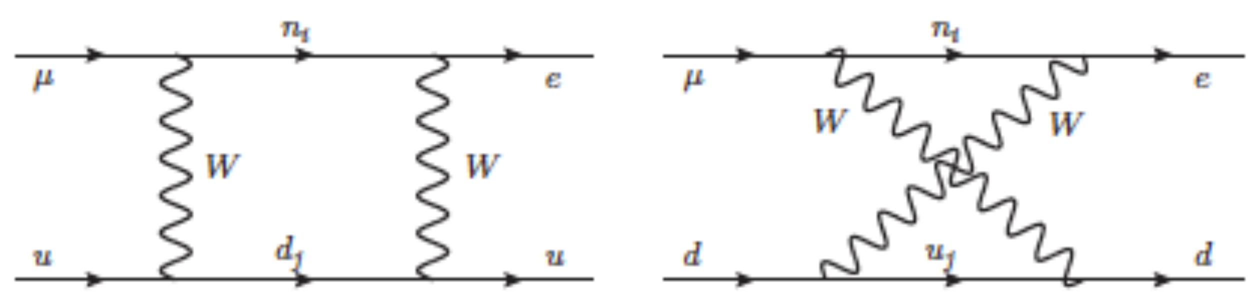
Bilenky, Pontecorvo, 1981; Wolfenstein, 1981
Leung, Petcov, 1983; Wyler, Wolfenstein, 1983

L' softly broken $\Longrightarrow$ $|n_+(L') - n_-(L')|$ Majorana neutrinos with tiny masses and $\min(n_+(L'), n_-(L'))$ massive pseudo-Dirac fermions, corresponding to pairs of Majorana fermions almost degenerate in mass

Muon to electron conversion in type I seesaw



(a) Photon Penguin Diagram (b) Z Penguin Diagram (c) Z Penguin Diagram



(d) Box Diagram (e) Box Diagram

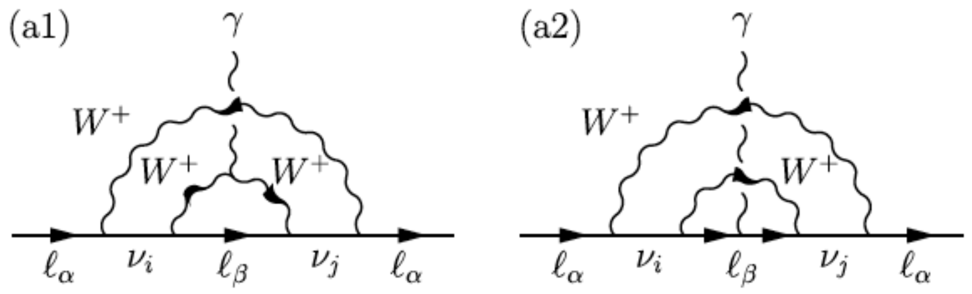
$$\mathrm{CR}(\mu\,\mathcal{N} \to e\,\mathcal{N}) \equiv \frac{\Gamma(\mu\,\mathcal{N} \to e\,\mathcal{N})}{\Gamma_{\rm capt}} = \frac{\alpha_{\rm em}^5}{2\,\pi^4}\,\frac{Z_{eff}^4}{Z}\,\left|F(-m_\mu^2)\right|^2\,\frac{G_F^2 m_\mu^5}{\Gamma_{\rm capt}}\,\left|(RV)^*_{\mu 1}(RV)_{e1}\right|^2\,\left|\mathcal{C}_{\mu e}(M_1^2/M_W^2)\right|^2$$

depends on very few parameters!

contributions from $\gamma-$penguin, Z^0-penguin and box type diagrams

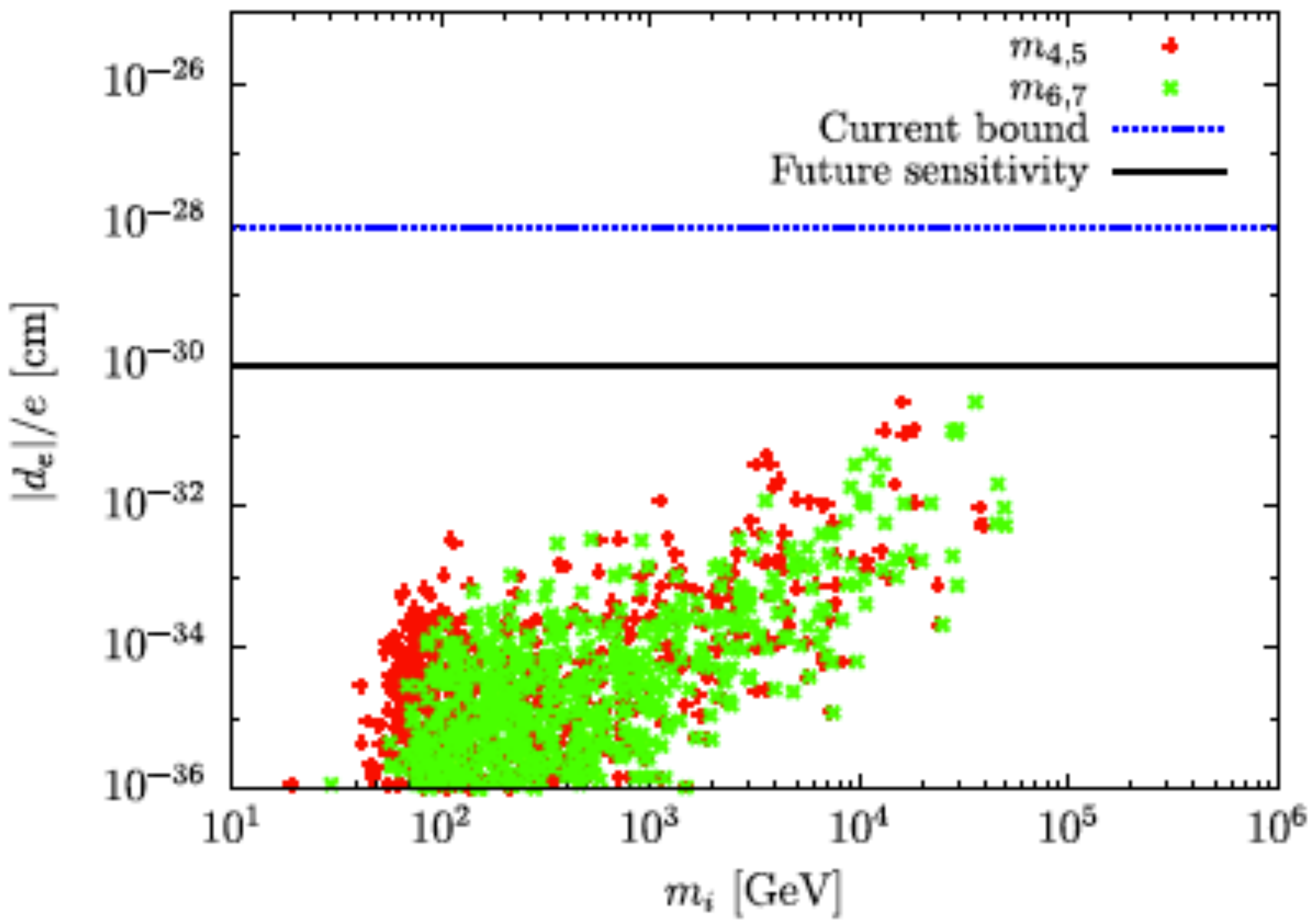
Alonso, Dhen, Gavela, Hambye, 2012
Hisano, Moroi, Tobe, Yamaguchi, Yanagida, 1995
Hisano, Moroi, Tobe, Yamaguchi, 1996

Constraints from Electric Dipole Moments



$$d_e \approx -\frac{g_2^4\, e\, m_e}{4(4\pi)^2 m_W^2} \sum_{\beta} \sum_{i,j} J^D_{ije\beta} I_D(x_i, x_j)$$

$$J^D_{ij\alpha\beta} \equiv \mathrm{Im}\left(U_{\alpha j} U^*_{\beta j} U_{\beta i} U^*_{\alpha i}\right)$$



Abada, Toma, 2016

Type II sessaw scenario

Consider a minimal extension of the Standard Model with at least one SU(2) triplet scalar representation:

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

see-saw Lagrangian:

$$\mathcal{L}^{\rm II}_{\rm seesaw} = -M^2_\Delta \, {\rm Tr}\left(\Delta^\dagger \Delta\right) - \left(h_{\ell\ell'} \, \overline{\psi^C}_{\ell L} \, i\tau_2 \, \Delta \, \psi_{\ell' L} + \mu_\Delta \, H^T \, i\tau_2 \, \Delta^\dagger \, H + {\rm h.c.}\right) + \ldots$$

Lepton number soft-breaking parameter

$$M_\Delta = (100 - 1000)~{\rm GeV}$$

Type II sessaw scenario

The light neutrino mass scale and mixing determined by $\langle \Delta^0 \rangle \equiv v_\Delta$ and the Yukawa coupling $h_{\ell\ell'} = h_{\ell'\ell}$:

$$(m_\nu)_{\ell\ell'} \simeq 2\, h_{\ell\ell'}\, v_\Delta$$

From EW precision observables: $\rho = \frac{1+2(v_\Delta/v)^2}{1+4(v_\Delta/v)^2} \simeq 1 \Rightarrow v_\Delta < 5\ \mathrm{GeV}$

Taking the Yukawa couplings sizeable in order to predict observable signatures of LFV and the see-saw scale in the TeV range, typically:

$$v_\Delta \cong (1-100)\ \mathrm{eV} \qquad \begin{cases} v_\Delta \approx \mu_\Delta & \text{for} \quad M_\Delta^2 \approx v^2 \\ v_\Delta \approx \mu_\Delta \frac{v^2}{M_\Delta^2} & \text{for} \quad M_\Delta^2 \gg v^2 \end{cases}$$

Lepton number is restored in the limit $\mu_\Delta \to 0$: massless neutrinos

Type II sessaw scenario

The matrix of Yukawa couplings is directly related to the PMNS matrix:

$$h_{\ell\ell'} \equiv \frac{1}{2\,v_\Delta}\left(U^*\,\mathrm{diag}(m_1, m_2, m_3)\,U^\dagger\right)_{\ell\ell'}$$

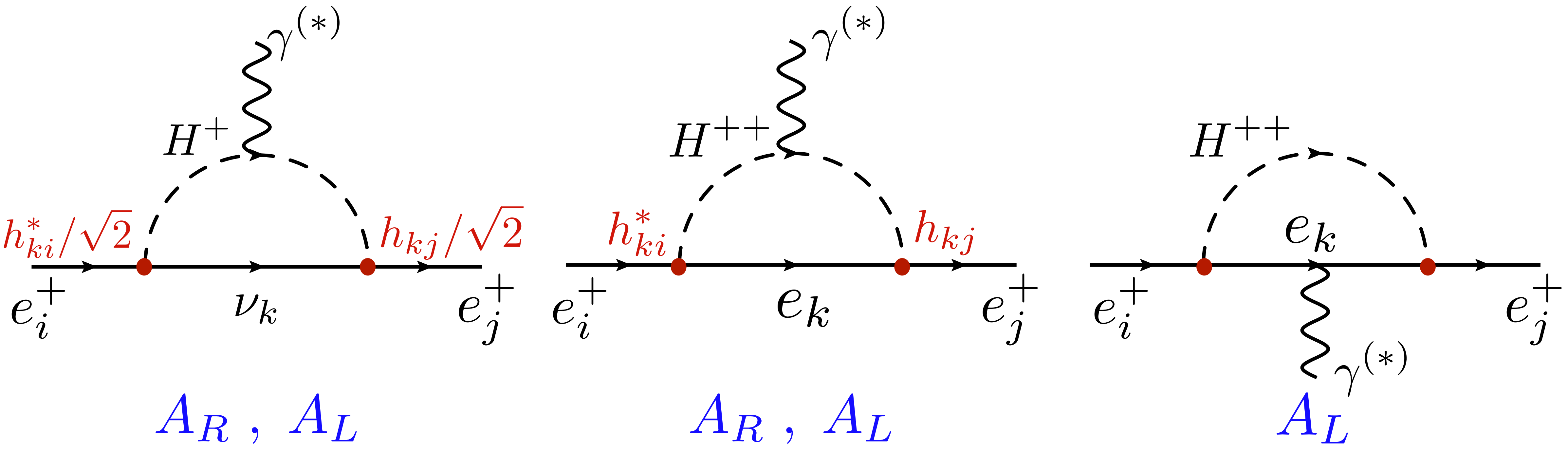
Scalar spectrum:

$$\underbrace{H^{\pm\pm}}_{\text{only triplet}},\ \underbrace{H^{\pm},\ H^0,\ A^0}_{\text{mainly triplet}},\ \underbrace{h^0}_{\text{mainly doublet}}$$

Possible hierarchies:

$$m_H^{++} > m_H^{+} > m_{H^0,A^0}$$
$$m_H^{++} < m_H^{+} < m_{H^0,A^0}$$

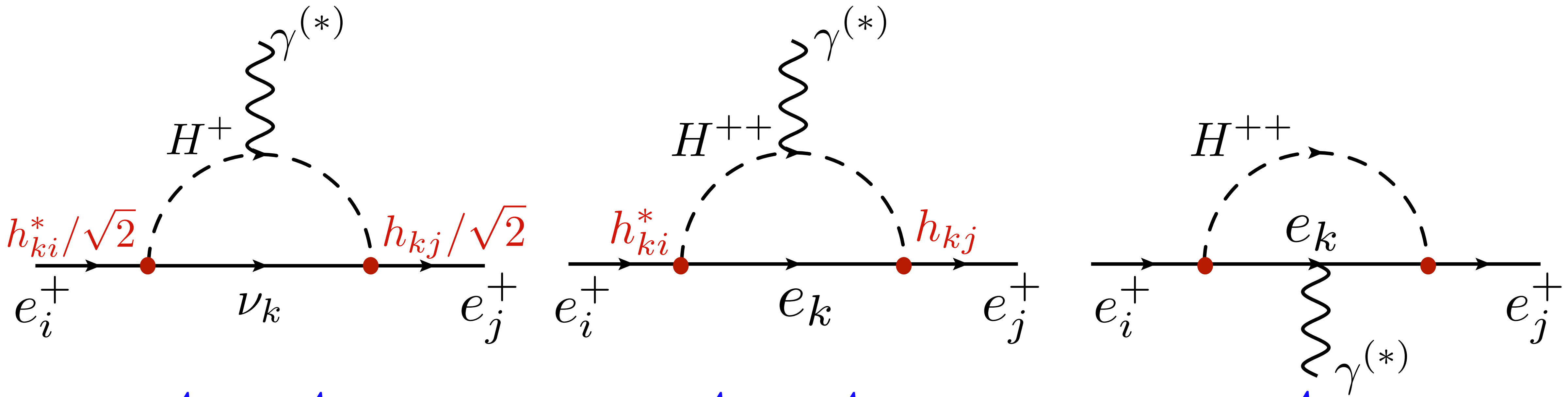
Type II sessaw scenario



Effective low energy LFV Lagrangian:

$$\mathcal{L}^{eff} = -4\,\frac{q_e\,G_F}{\sqrt{2}}\left(m_\mu\,A_R\,\overline{e}\,\sigma^{\alpha\beta}\,P_R\,\mu\,F_{\beta\alpha} + \text{h.c.}\right)$$
$$-\,\frac{q_e^2\,G_F}{\sqrt{2}}\left(A_L(-m_\mu^2)\,\overline{e}\,\gamma^\alpha\,P_L\,\mu\sum_{Q=u,d} q_Q\,\overline{Q}\,\gamma_\alpha\,Q + \text{h.c.}\right)$$

Type II sessaw scenario



A_R , A_L $\qquad$ A_R , A_L $\qquad$ A_L

Effective low energy LFV Lagrangian:

$$A_R = -\frac{1}{\sqrt{2}\,G_F}\frac{\left(h^\dagger h\right)_{e\mu}}{48\pi^2}\left[\frac{1}{8\,m^2_{H^+}}+\frac{1}{m^2_{H^{++}}}\right]$$

$$A_L(q^2) = -\frac{1}{\sqrt{2}\,G_F}\frac{h^*_{le}h_{l\mu}}{6\pi^2}\left[\frac{1}{12\,m^2_{H^+}}+\frac{1}{m^2_{H^{++}}}f\left(\frac{-q^2}{m^2_{H^{++}}},\frac{m_l^2}{m^2_{H^{++}}}\right)\right]$$

$$f(r,s_l) = \frac{4s_l}{r}+\log(s_l)+\left(1-\frac{2s_l}{r}\right)\sqrt{1+\frac{4s_l}{r}}\log\frac{\sqrt{r}+\sqrt{r+4s_l}}{\sqrt{r}-\sqrt{r+4s_l}}$$

Type II sessaw scenario

$$\mathrm{BR}(\mu \to e\gamma) \quad \cong \quad 384\,\pi^2\,(4\pi\,\alpha_{\rm em})|A_R|^2 \;=\; \frac{\alpha_{\rm em}}{192\,\pi}\,\frac{\left|\left(h^\dagger h\right)_{e\mu}\right|^2}{G_F^2}\,\left(\frac{1}{m_{H^+}^2}+\frac{8}{m_{H^{++}}^2}\right)^2$$

- **From present upper limit on the BR given by MEG:** $m_H^+ \simeq m_H^{++} \simeq M_\Delta$

$$\left|\left(h^\dagger h\right)_{e\mu}\right| \;<\; 5.8\times 10^{-6}\,\left(\frac{M_\Delta}{100\,\mathrm{GeV}}\right)^2$$

- **Flavour structure fixed by neutrino mixing parameters:**

$$\left|\left(h^\dagger h\right)_{e\mu}\right| = \frac{1}{4\,v_\Delta^2}\,\left|U_{e2}\,U_{2\mu}^\dagger\,\Delta m_{21}^2 + U_{e3}\,U_{3\mu}^\dagger\,\Delta m_{31}^2\right|$$

exact relation

independent of the Majorana phases

$$v_\Delta > 2.1\times 10^2\,\left|s_{13}\,s_{23}\,\Delta m_{31}^2\right|^{\frac{1}{2}}\,\left(\frac{100\,\mathrm{GeV}}{M_\Delta}\right) \cong 3.0\,\mathrm{eV}\,\left(\frac{100\,\mathrm{GeV}}{M_\Delta}\right)$$

$\mu \to e + \gamma$ may be detected if the charged scalars are in the TeV range

$$\mathrm{BR}(\mu \to e\gamma) \cong 2.7\times 10^{-10}\,\left(\frac{1\,\mathrm{eV}}{v_\Delta}\right)^4\,\left(\frac{100\,\mathrm{GeV}}{M_\Delta}\right)^4$$

Type II sessaw scenario

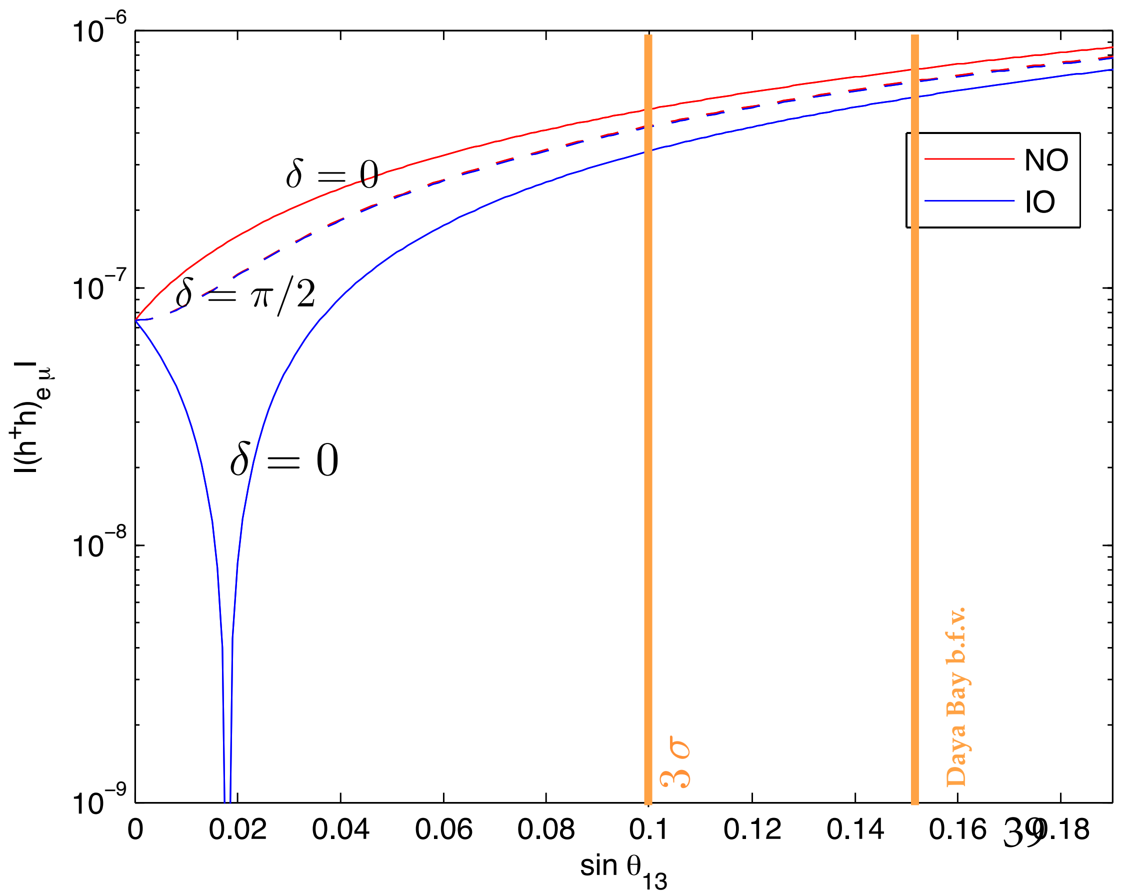
$$\mathrm{BR}(\mu \to e\gamma) \;\cong\; 384\,\pi^2\,(4\pi\,\alpha_{\rm em})|A_R|^2 = \frac{\alpha_{\rm em}}{192\,\pi}\,\frac{\left|(h^\dagger h)_{e\mu}\right|^2}{G_F^2}\left(\frac{1}{m_{H^+}^2}+\frac{8}{m_{H^{++}}^2}\right)^2$$

- **From present upper limit on the BR given by MEG:** $m_H^+ \simeq m_H^{++} \simeq M_\Delta$

$$\left|(h^\dagger h)_{e\mu}\right| < 5.8\times 10^{-6}\left(\frac{M_\Delta}{100\,\mathrm{GeV}}\right)^2$$

- **Flavour structure fixed by neutrino mixing parameters:**

The dependance of the BR on the neutrino mass spectrum and on the Dirac phase is negligible



Type II sessaw scenario

$$\mathrm{CR}(\mu\,\mathcal{N} \to e\,\mathcal{N}) \quad \cong \quad (4\pi\alpha_{\mathrm{em}})^2\,\frac{2\,G_F^2}{\Gamma_{\mathrm{capt}}}\,\left|A_R\,\frac{D}{\sqrt{4\pi\,\alpha_{\mathrm{em}}}} + (2\,q_u + q_d)\,A_L\,V^{(p)}\right|^2$$

Type II sessaw scenario

$$\mathrm{CR}(\mu\,\mathcal{N} \to e\,\mathcal{N}) \;\cong\; \frac{\alpha_{\rm em}^5}{36\,\pi^4}\,\frac{m_\mu^5}{\Gamma_{\rm capt}}\,Z_{eff}^4\,Z\,F^2(-m_\mu^2)\,\Bigg|\left(h^\dagger h\right)_{e\mu}\left[\frac{5}{24\,m_{H^+}^2}+\frac{1}{m_{H^{++}}^2}\right] + \frac{1}{m_{H^{++}}^2}\sum_{l=e,\mu,\tau} h^\dagger_{e\ell}\,f\left(\frac{m_\mu^2}{m_{H^{++}}^2},\frac{m_\ell^2}{m_{H^{++}}^2}\right)h_{\ell\mu}\Bigg|^2$$

The flavour structure is sensitive to the see-saw scale, to the CP violating phases of the PMNS matrix and to the type of neutrino mass spectrum:

Type II sessaw scenario

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The flavour structure is sensitive to the see-saw scale, to the CP violating phases of the PMNS matrix and to the type of neutrino mass spectrum:

Taking $m_H^+ \simeq m_H^{++} \simeq M_\Delta$

$$\mathrm{CR}(\mu\,\mathcal{N}\to e\,\mathcal{N}) \propto |C_{\mu e}^{(II)}|^2$$

$$C_{\mu e}^{(II)} \equiv \frac{1}{4\,v_\Delta^2}\left[\frac{29}{24}\left(m_\nu^\dagger\,m_\nu\right)_{e\mu} + \sum_{l=e,\mu,\tau}(m_\nu)_{e\ell}^\dagger\, f\left(\frac{m_\mu^2}{M_\Delta^2},\frac{m_\ell^2}{M_\Delta^2}\right)(m_\nu)_{\ell\mu}\right]$$

From current experimental upper limit in Ti

$$|C_{\mu e}^{(II)}| < 1.24\times 10^{-4}\left(\frac{M_\Delta}{100\ \mathrm{GeV}}\right)^2$$

Type II sessaw scenario

$$\mathrm{CR}(\mu\mathcal{N}\to e\mathcal{N}) \cong \frac{\alpha_{\rm em}^5}{36\,\pi^4}\,\frac{m_\mu^5}{\Gamma_{\rm capt}}\,Z_{eff}^4\,Z\,F^2(-m_\mu^2)\,\Bigg|\left(h^\dagger h\right)_{e\mu}\left[\frac{5}{24\,m_{H+}^2}+\frac{1}{m_{H++}^2}\right] + \frac{1}{m_{H++}^2}\sum_{l=e,\mu,\tau} h_{e\ell}^\dagger\, f\left(\frac{m_\mu^2}{m_{H++}^2},\frac{m_\ell^2}{m_{H++}^2}\right)\,h_{\ell\mu}\Bigg|^2$$

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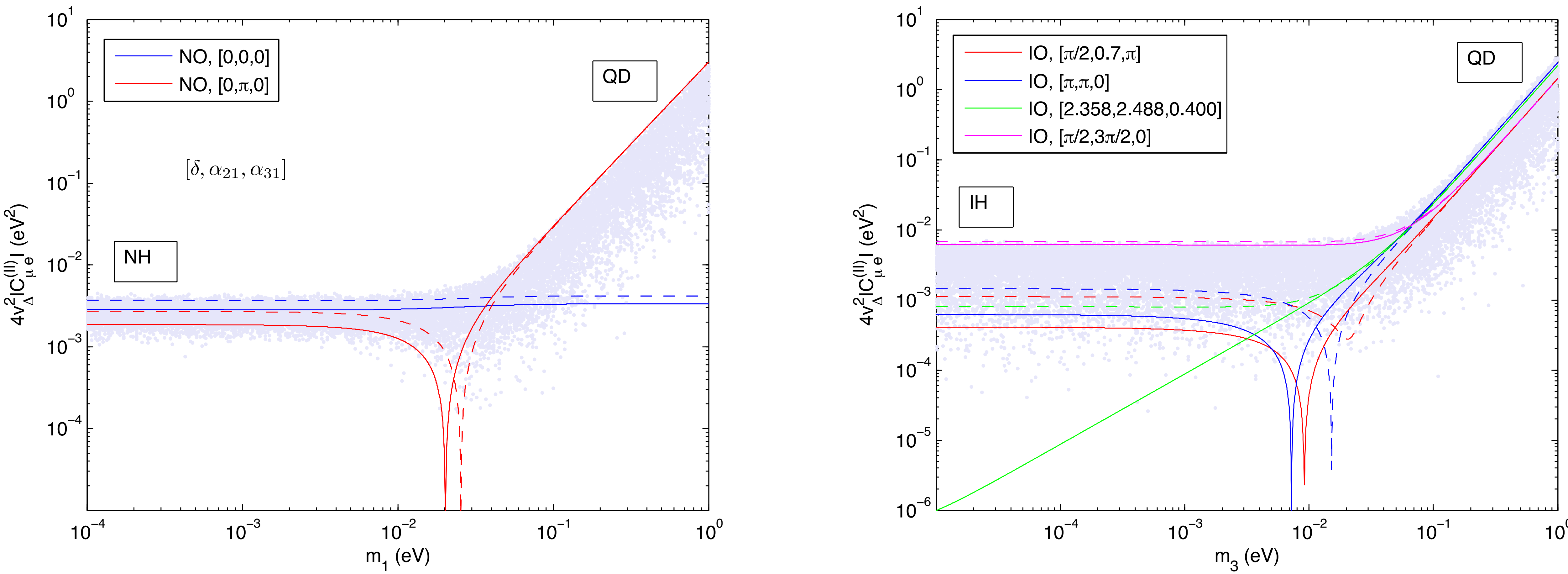
An experiment sensitive to CR ~ 10^{-18} will be able to probe values

$$|C_{\mu e}^{(II)}| > 5.8\times 10^{-8}\,\left(\frac{M_\Delta}{100\,\mathrm{GeV}}\right)^2$$

Type II sessaw scenario



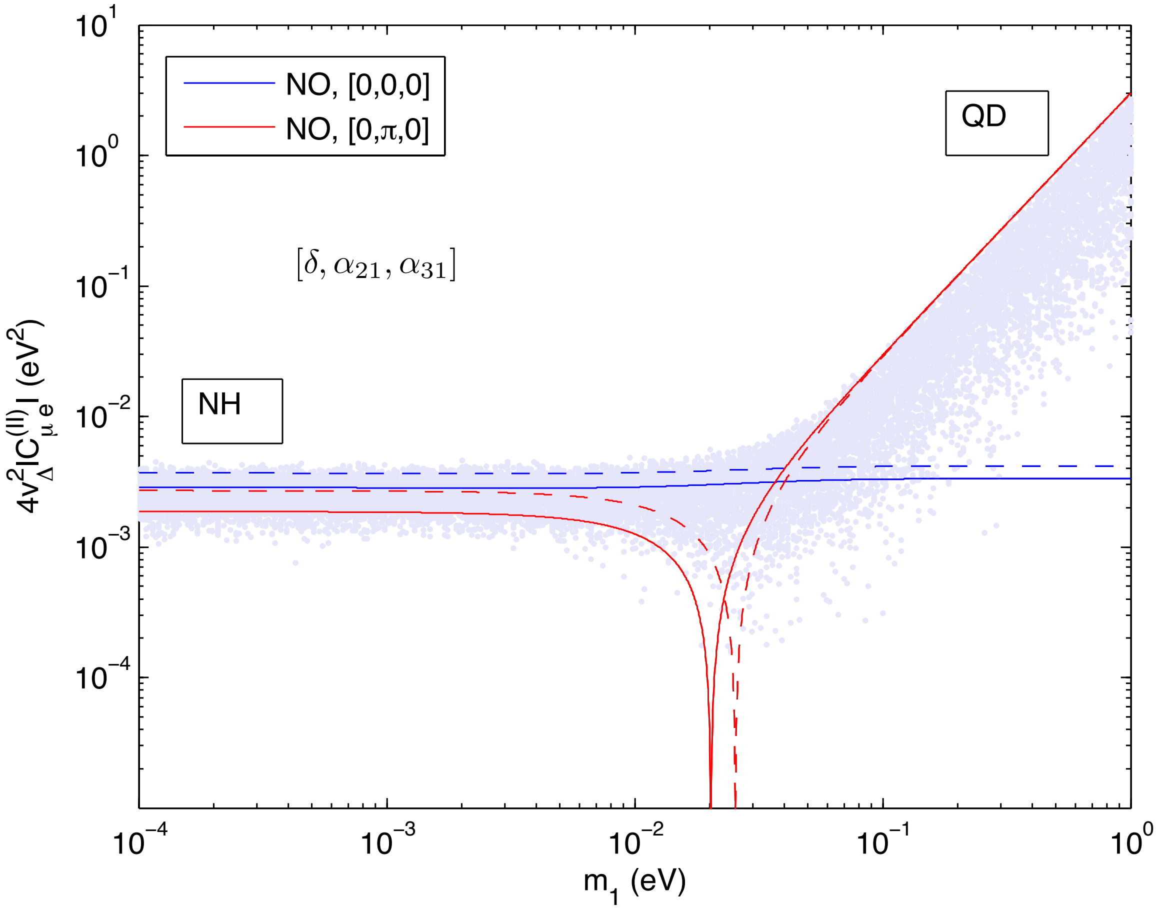
$$M_\Delta \ = \ (100 - 1000)\ \text{GeV}$$

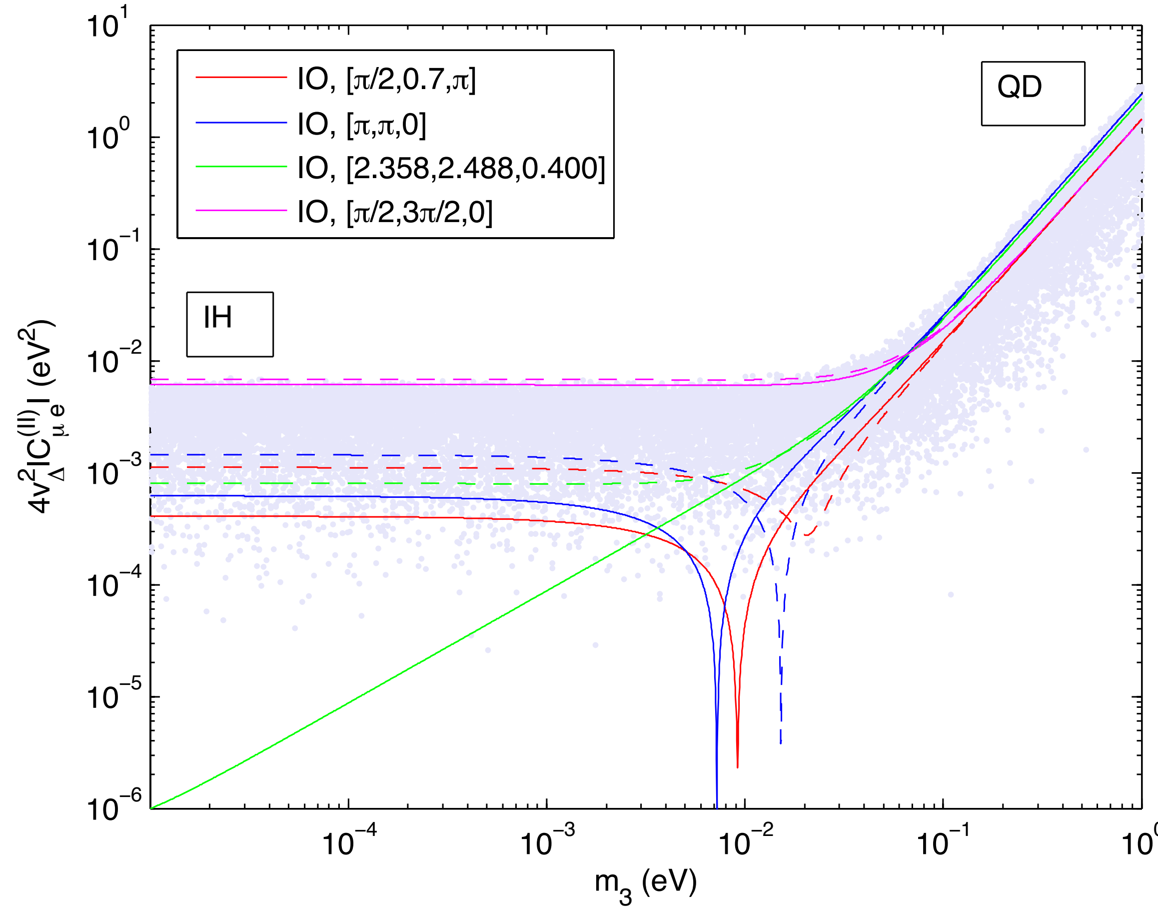
no strong suppression in the limit $m^2_{H^{++}} \gg m^2_{H^+} > (100\ \text{GeV})^2$

current bound: $|(h^\dagger h)_{e\mu}| < 6 \times 10^{-4} \left(\frac{m_{H^+}}{100\,\text{GeV}}\right)^2$

less stringent than $\mu \to e + \gamma$

Type II sessaw scenario





$$M_\Delta = (100 - 1000)\ \text{GeV}$$

no strong suppression in the limit $m^2_{H^{++}} \gg m^2_{H^+} > (100\ \text{GeV})^2$

future bound: $$|(h^\dagger h)_{e\mu}| < 3 \times 10^{-7} \left(\frac{m_{H^+}}{100\,\text{GeV}}\right)^2$$

more stringent than future $\mu \to e + \gamma$ constraint

Type II sessaw scenario

Tree-level contribution mediated by a TeV scale $H^{\pm\pm}$

$$\mathrm{BR}(\mu \to 3e) = \frac{1}{G_F^2}\frac{|(h^\dagger)_{ee}(h)_{\mu e}|^2}{m_{H^{++}}^4} = \frac{1}{G_F^2\, m_{H^{++}}^4}\frac{|(m_\nu)^*_{ee}\,(m_\nu)_{\mu e}|^2}{16\, v_\Delta^4}$$

fixed flavour structure !

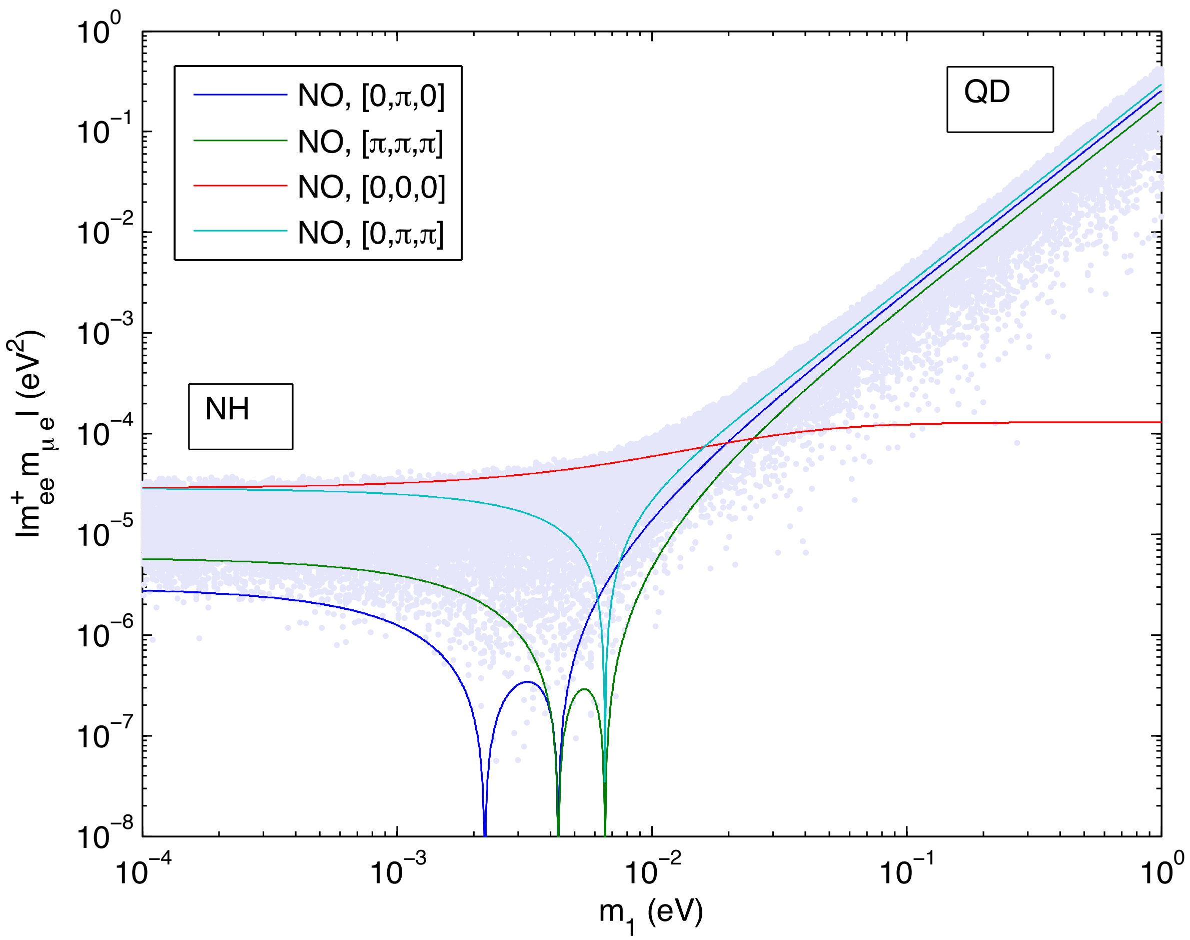
For $M_{H^{\pm\pm}} = (100 - 1000)$ GeV and $v_\Delta \ll 1$ MeV:

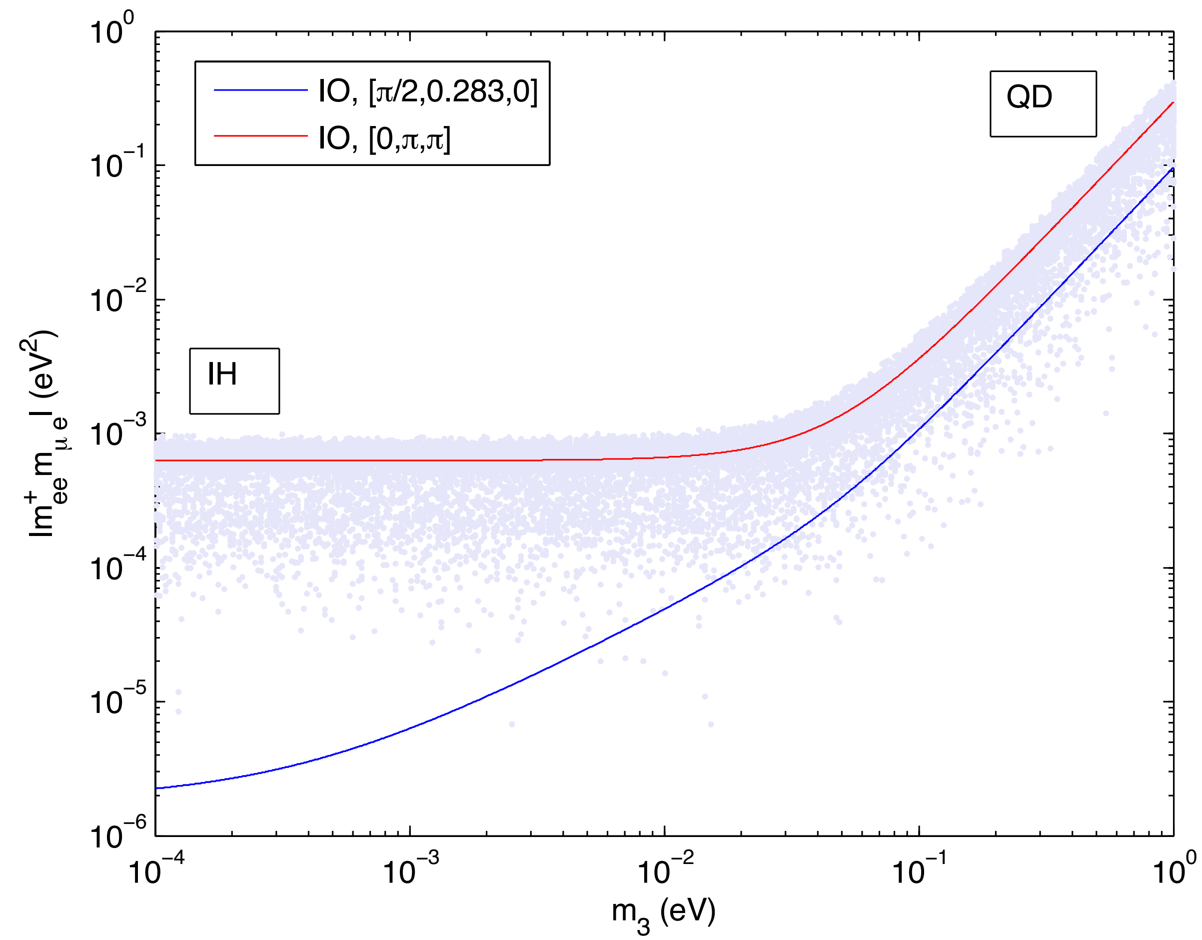
$$|(m_\nu)_{ee}| = \left|\sum_{j=1}^{3} m_j U_{ej}^2\right| \cong |\langle m\rangle|$$

standard contribution to the effective Majorana mass of $0\nu\beta\beta$-decay

the prediction for BR depends very strongly on the type of neutrino mass spectrum!

Type II sessaw scenario





$$M_{H^{++}} = (100 - 1000) \text{ GeV}$$

NH: $\text{BR}(\mu \to 3e) \lesssim 6 \times 10^{-9}(1 \text{ eV}/v_\Delta)^4(100 \text{ GeV}/m_{H^{++}})^4$

IH: $\text{BR}(\mu \to 3e) \lesssim 2.4 \times 10^{-6}(1 \text{ eV}/v_\Delta)^4(100 \text{ GeV}/m_{H^{++}})^4$

Type II sessaw scenario

Neutrino masses can be generated by tree-level exchange of $SU(2)_L$-triplet scalars coupled to Standard Model leptons (type II see-saw mechanism). It is possible to test Higgs triplet models at present and future collider facilities if the mass scale of the new scalars is in the TeV range.

Indirect tests are possible in ongoing and future experiments searching for LFV.

Main features:

- $\mathrm{BR}(\mu \to e\,\gamma)$ does not depend on the Majorana CPV phases and on $\min(m_j)$
- $\mathrm{BR}(\mu \to 3\,e)$ and $\mathrm{CR}(\mu\,\mathcal{N} \to e\,\mathcal{N})$ are strongly affected by both the type of neutrino mass spectrum and the Dirac and Majorana CPV phases
- All LFV observables can have values within the sensitivity of current and planned future experiments. The best constraints will be provided by $\mu - e$ conversion experiments