Low Energy Signatures of the TeV Scale See-saw mechanism

Alejandro Ibarra

Technische Universität München

In collaboration with Emiliano Molinaro and Serguey Petcov
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Introduction

One of the most minimal extensions of the Standard Model consists on introducing right-handed neutrinos:

$$-\mathcal{L}_\nu = \overline{\nu_L} M_D \nu_R + \frac{1}{2}\overline{\nu_R^C} M_M \nu_R + \text{h.c.}$$

$$\Downarrow \quad M_M \gg M_D$$

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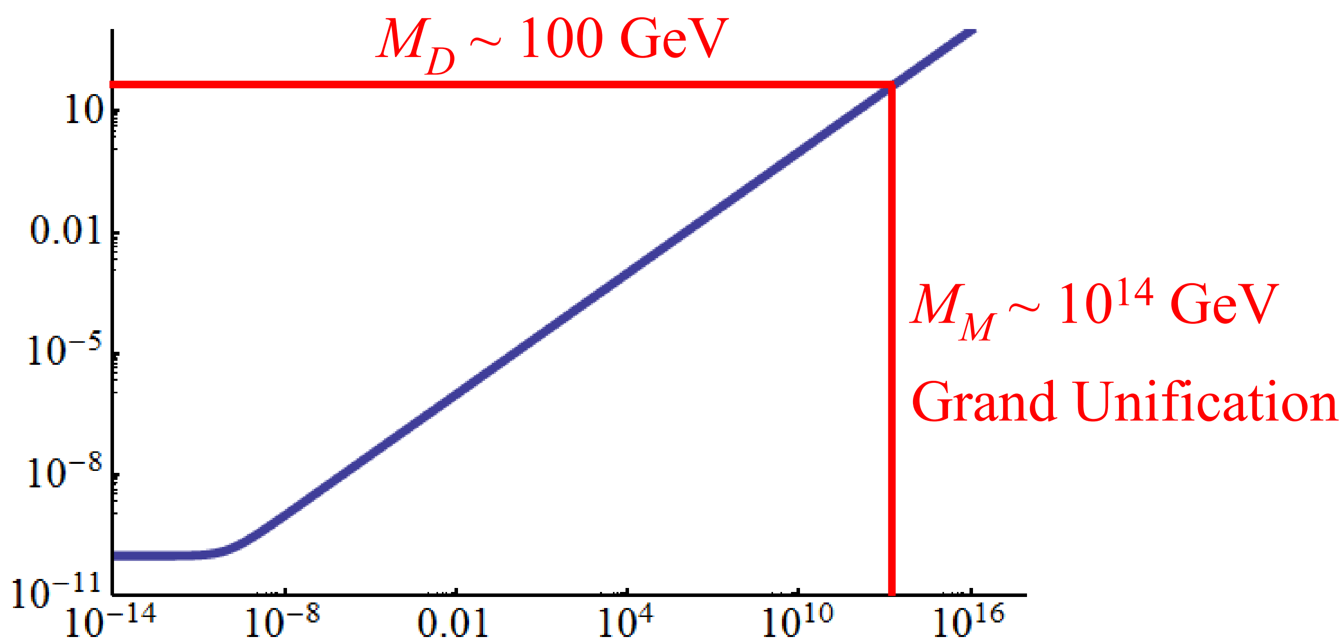

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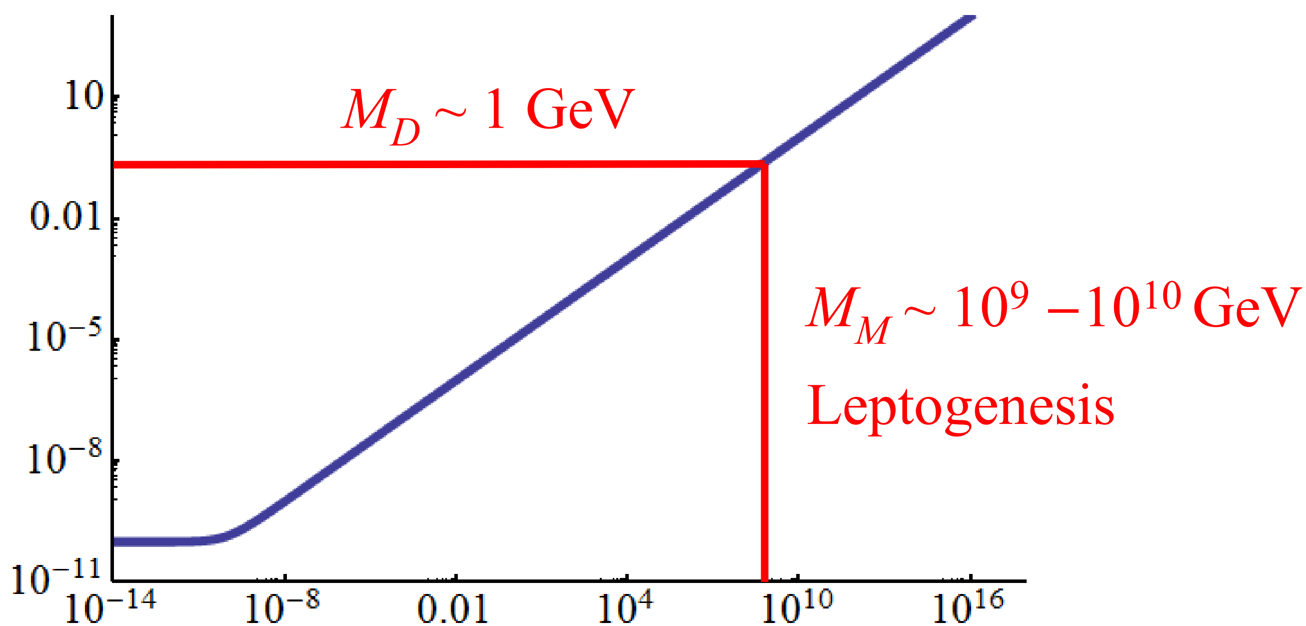

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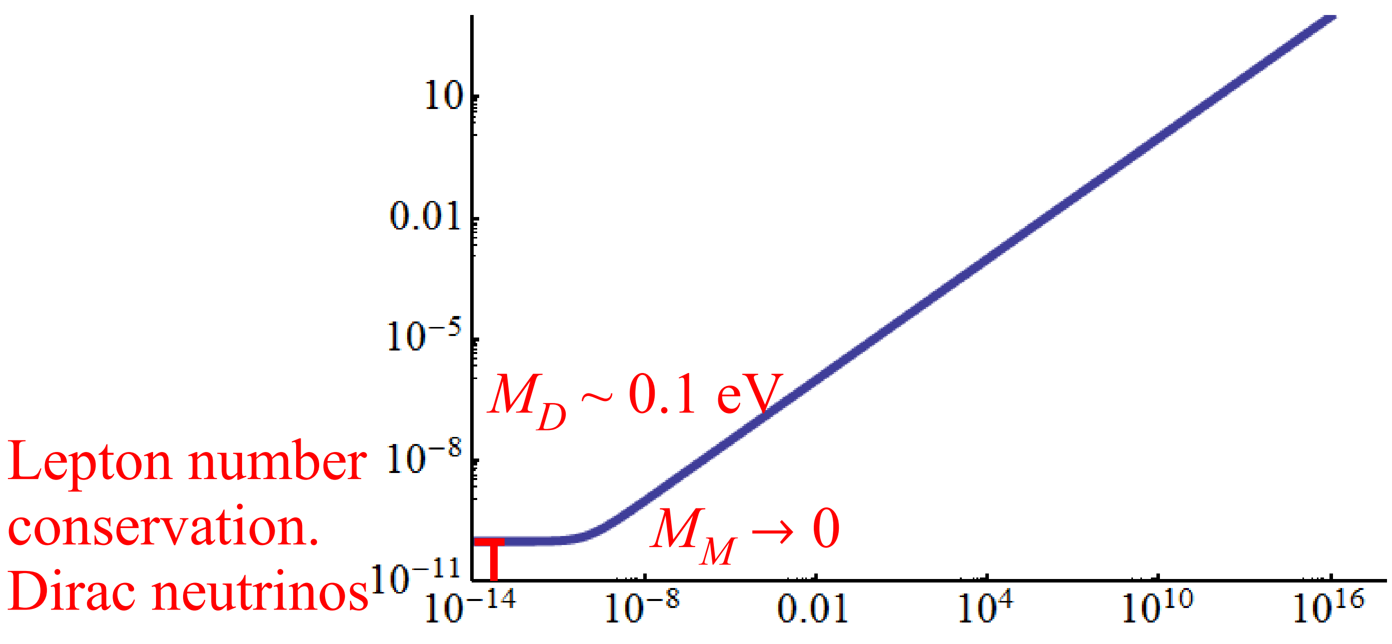

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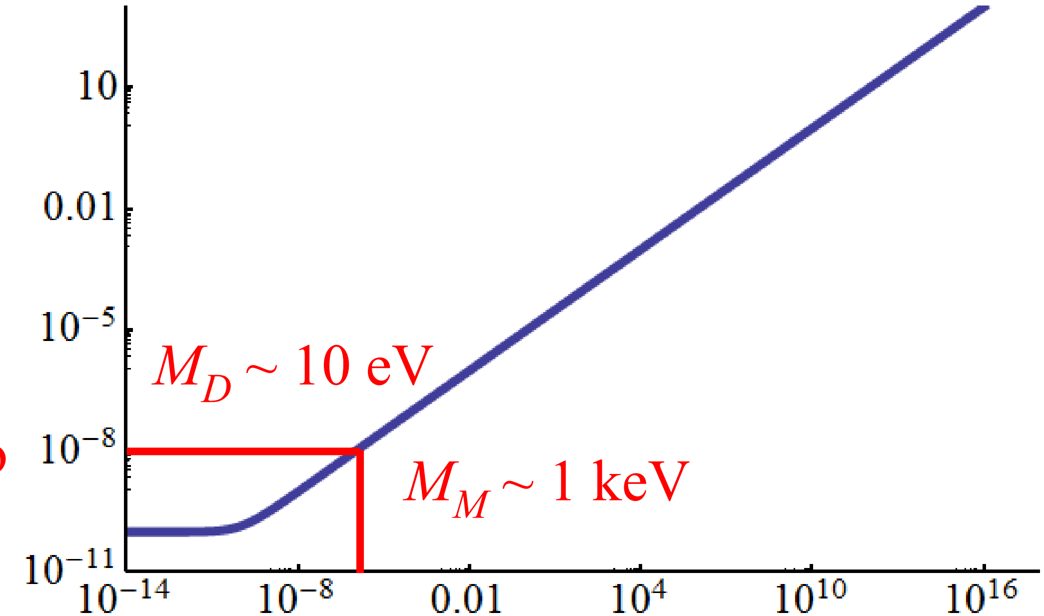
Sterile neutrino dark matter



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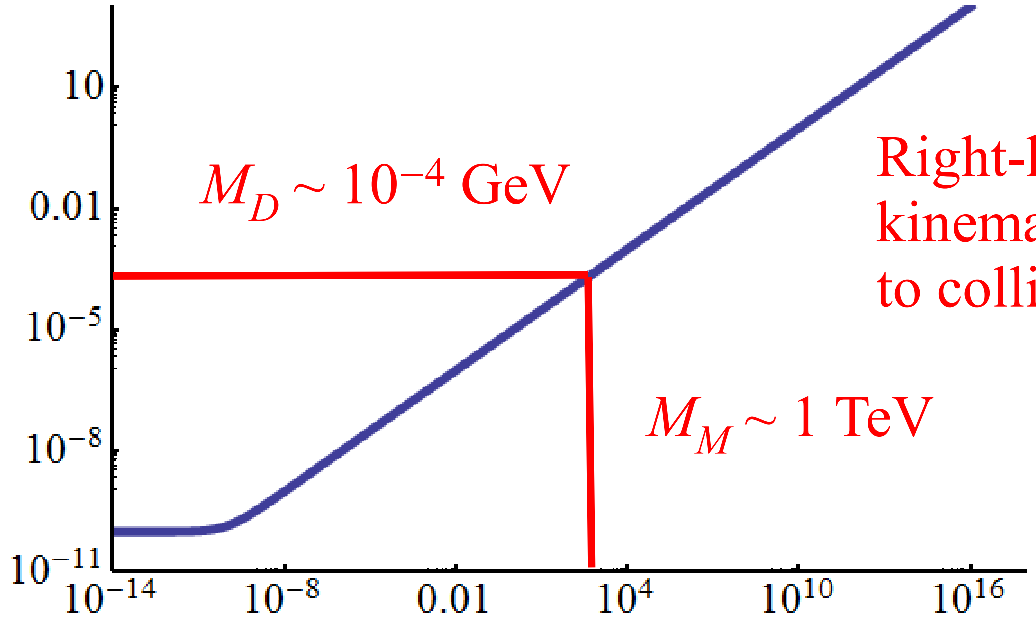

Right-handed neutrinos kinematically accessible to collider experiments

Right handed neutrinos at colliders???

Naively, for $M_M = 1$ TeV $\hookrightarrow m_D \approx 10^{-4}$ GeV $\Rightarrow$ yukawa coupling $\approx 10^{-6}$.

- Low energy effects very suppressed
- Production cross section at colliders tiny (except when the right-handed neutrino has additional interactions, e.g. $U(1)_{B-L}$)

Conversely, low energy signatures of RH neutrinos require large Yukawa couplings. However, naively

$$Y_\nu = 0.1 \ , \quad M_M = 1 \text{ TeV} \Rightarrow (\mathcal{M}_\nu)_{ij} \approx 0.1 \text{ GeV}$$

Nine orders of magnitude larger than the measured value!

No-go for testing the TeV scale see-saw model?

Scenarios with TeV RH neutrinos and large Yukawa couplings

There is a continuous family of neutrino Dirac masses which are compatible with the observed neutrino data.

Assume for simplicity two RH neutrinos. In the basis where the charged lepton Yukawa coupling and the RH neutrino mass matrix is diagonal,

Low energy, "measurable" — High energy, free parameters

$$M_D = \underbrace{i U^*_{\text{lep}} \sqrt{D_m}}_{\text{Low energy, "measurable"}} \, \underbrace{\Omega \sqrt{D_M}}_{\text{High energy, free parameters}}$$

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

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

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Assume for simplicity two RH neutrinos. In the basis where the charged lepton Yukawa coupling and the RH neutrino mass matrix is diagonal,

$\mathcal{O}(0.1)$ $\sqrt{\mathcal{O}(10^{-10})\ \mathrm{GeV}}$

$$M_D = i U^*_{\mathrm{lep}} \sqrt{D_m}\, \Omega \sqrt{D_M}$$

Adjust Ω to generate a large M_D.
e.g. $M_D \approx 10$ GeV $\Rightarrow |\Omega| \approx 10^6$.

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

Decompose $\hat{\theta} = \omega - i\xi$

For NH, $\Omega \equiv \begin{pmatrix} 0 & 0 \\ \cos\hat{\theta} & \pm\sin\hat{\theta} \\ -\sin\hat{\theta} & \pm\cos\hat{\theta} \end{pmatrix} \xrightarrow{\xi \gg 1} \Omega \approx \frac{e^{i\omega} e^{\xi}}{2} \begin{pmatrix} 0 & 0 \\ 1 & \mp i \\ i & \pm 1 \end{pmatrix}$

Exponentially enhanced!
No ambiguity in the extra flavour structure!!!

Family of Dirac neutrino mass matrices in the TeV see-saw model which lead to potentially observable signatures:

Normal hierarchy

$$m_D \approx -\frac{e^{i\omega}e^{\xi}}{2}\sqrt{M_2 m_3}\begin{pmatrix} \sqrt{\frac{M_1}{M_2}}\left(U_{e3} - i\sqrt{\frac{m_2}{m_3}}U_{e2}\right) & \mp i\left(U_{e3} - i\sqrt{\frac{m_2}{m_3}}U_{e2}\right) \\ \sqrt{\frac{M_1}{M_2}}\left(U_{\mu 3} - i\sqrt{\frac{m_2}{m_3}}U_{\mu 2}\right) & \mp i\left(U_{\mu 3} - i\sqrt{\frac{m_2}{m_3}}U_{\mu 2}\right) \\ \sqrt{\frac{M_1}{M_2}}\left(U_{\tau 3} - i\sqrt{\frac{m_2}{m_3}}U_{\tau 2}\right) & \mp i\left(U_{\tau 3} - i\sqrt{\frac{m_2}{m_3}}U_{\tau 2}\right) \end{pmatrix}$$

Inverted hierarchy

$$m_{2,3} \to m_{1,2}$$

$$U_{\alpha 2,\alpha 3} \to U_{\alpha 1,\alpha 2} \ (\alpha = e, \mu, \tau)$$

Fairly predictive

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Normal hierarchy

$$m_D \approx -e^{i\omega} y v \sqrt{\frac{M_2}{(M_1+M_2)}\frac{m_3}{m_2+m_3}} \begin{pmatrix} \sqrt{\frac{M_1}{M_2}}(U_{e3} - i\sqrt{\frac{m_2}{m_3}}U_{e2}) & \mp i(U_{e3} - i\sqrt{\frac{m_2}{m_3}}U_{e2}) \\ \sqrt{\frac{M_1}{M_2}}(U_{\mu 3} - i\sqrt{\frac{m_2}{m_3}}U_{\mu 2}) & \mp i(U_{\mu 3} - i\sqrt{\frac{m_2}{m_3}}U_{\mu 2}) \\ \sqrt{\frac{M_1}{M_2}}(U_{\tau 3} - i\sqrt{\frac{m_2}{m_3}}U_{\tau 2}) & \mp i(U_{\tau 3} - i\sqrt{\frac{m_2}{m_3}}U_{\tau 2}) \end{pmatrix}$$

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A closer look at the Lagrangian of the TeV see-saw model

$$-\mathcal{L}_\nu = \overline{\nu_L} M_D \nu_R + \frac{1}{2}\overline{\nu_R^C} M_M \nu_R + \frac{g}{\sqrt{2}}\bar{\ell}\gamma_\alpha \nu_L W^\alpha + \frac{g}{\sqrt{2}c_W}\overline{\nu_L}\gamma_\alpha \nu_L Z^\alpha + \text{h.c.}$$

ν_L and ν_R are interaction eigenstates, $M_M = V^* D_M V^\dagger$

The Lagrangian in terms of the mass eigenstates ν_i and N_i contains several terms:

Mass terms

$$\mathcal{L}^\nu_{\text{mass}} = \frac{1}{2}\overline{\nu_i^C} \mathcal{M}_{\nu ij} \nu_j + \frac{1}{2}\overline{N_i^C} M_{Nij} N_{Rj} + \text{h.c.}$$

$$\mathcal{M}_\nu \simeq -M_D M_M^{-1} M_D^T \qquad M_N \simeq M_M$$

Diagonalisation:

$$\mathcal{M}_\nu \equiv U^* D_m U^\dagger \qquad M_N \simeq V^* D_M V^\dagger$$

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Light neutrino interactions

U_{lep} non-unitary

$$\mathcal{L}^\nu_{CC} = -\frac{g}{\sqrt{2}}\,\bar{\ell}\,\gamma_\alpha \left[\left(1 - \frac{1}{2}(RV)(RV)^\dagger\right) U\right]_{\ell i} \nu_i W^\alpha \; + \; \text{h.c.}$$

$$\mathcal{L}^\nu_{NC} = -\frac{g}{2c_w}\overline{\nu_i}\,\gamma_\alpha \left[U^\dagger \left(1 - (RV)(RV)^\dagger\right) U\right]_{ij} \nu_j Z^\alpha + \text{h.c.}$$

$R^* \simeq M_D M_M^{-1}$ being a matrix which "connects" the heavy neutrino sector with the light neutrino sector

Low energy effects parametrised by (RV)

A closer look at the Lagrangian of the TeV see-saw model

$$-\mathcal{L}_\nu = \overline{\nu_L} M_D \nu_R + \frac{1}{2}\overline{\nu_R^C} M_M \nu_R + \frac{g}{\sqrt{2}}\bar{\ell}\gamma_\alpha \nu_L W^\alpha + \frac{g}{\sqrt{2}c_W}\overline{\nu_L}\gamma_\alpha \nu_L Z^\alpha + \text{h.c.}$$

ν_L and ν_R are interaction eigenstates, $M_M = V^* D_M V^\dagger$

The Lagrangian in terms of the mass eigenstates ν_i and N_i contains several terms:

Heavy neutrino interactions

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

$$\mathcal{L}_{NC}^N = -\frac{g}{2c_w}\,\overline{\nu_{\ell L}}\,\gamma_\alpha\,(RV)_{\ell i}\,N_i\,Z^\alpha \;+\; \text{h.c.}$$

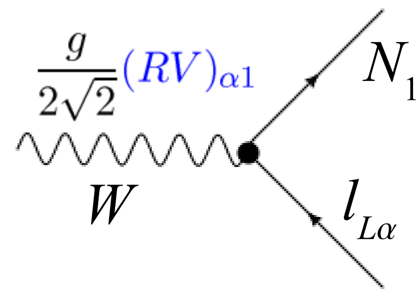
Low energy effects parametrised by (RV)

In scenarios with observable signatures, M_D must be sizable.
(RV) can be calculated in terms of a few parameters:

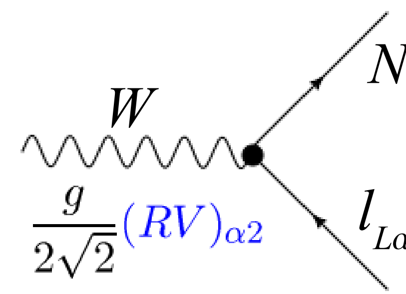
- y, the Yukawa coupling.
- M_1, M_2 the right-handed neutrino masses.
- A phase, ω.

Normal hierarchy

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



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



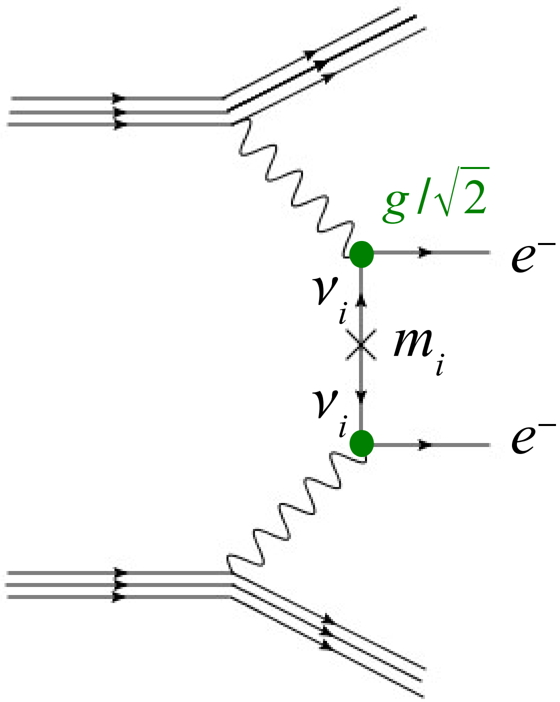
Which satisfy

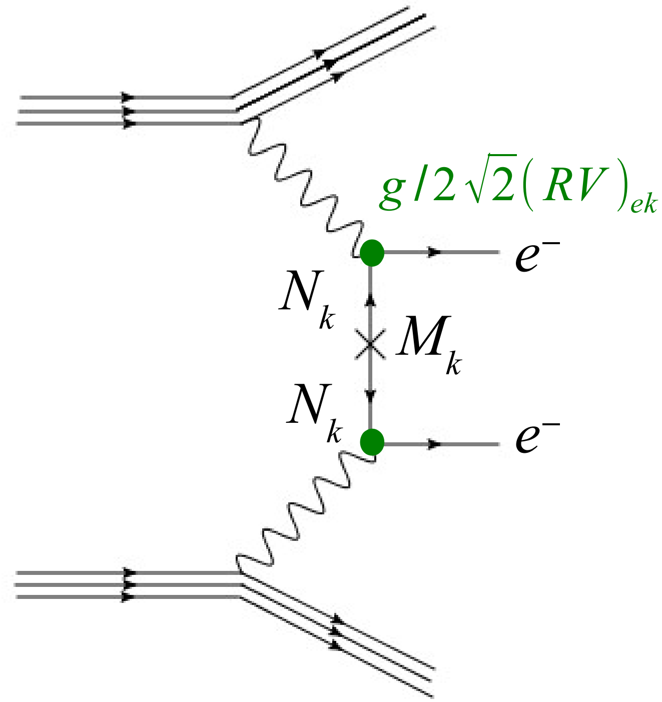
$$(RV)_{\alpha 2} = \pm i \sqrt{\frac{M_1}{M_2}} (RV)_{\alpha 1}$$

Fairly constrained scenario

Neutrinoless double beta decay

$$|(m_\nu)_{ee}| \simeq \left|\sum_i (U_{\text{lep}})^2_{ei} m_i - \sum_k F(A, M_k)(RV)^2_{ek} M_k\right|$$





$$|(m_\nu)_{ee}| \approx 10 \text{ eV} \left(\frac{M_2 - M_1}{M_1}\right) \left(\frac{|(RV)_{e2}|}{10^{-2}}\right)^2 \left(\frac{M_2}{10^3 \text{ GeV}}\right)$$

$$|(m_\nu)_{ee}| \lesssim 0.2 \text{ eV} \Rightarrow \left(\frac{M_2 - M_1}{M_1}\right) \lesssim 10^{-2}$$

The right-handed neutrinos *must* be quasi-degenerate

The top down approach

Shaposhnikov;
Kersten, Smirnov;
Raidal, Strumia, Turzynski;
Gavela, Hambye, Hernandez, Hernandez

Consider a scenario with exact lepton number conservation

$$M_D = \begin{pmatrix} m_{e1} & 0 \\ m_{\mu 1} & 0 \\ m_{\tau 1} & 0 \end{pmatrix} \quad M_M = \begin{pmatrix} 0 & M_{12} \\ M_{12} & 0 \end{pmatrix} \Rightarrow M_2 - M_1 = 0$$

The dimension 5 effective operator (which violates lepton number) exactly vanishes, regardless of the size of M_D, M_M.

Introduce now a small lepton number violating term

$$M_D = \begin{pmatrix} m_{e1} & 0 \\ m_{\mu 1} & 0 \\ m_{\tau 1} & 0 \end{pmatrix} \quad M_M = \begin{pmatrix} 0 & M_{12} \\ M_{12} & \mu \end{pmatrix} \Rightarrow M_2 - M_1 = \mu$$

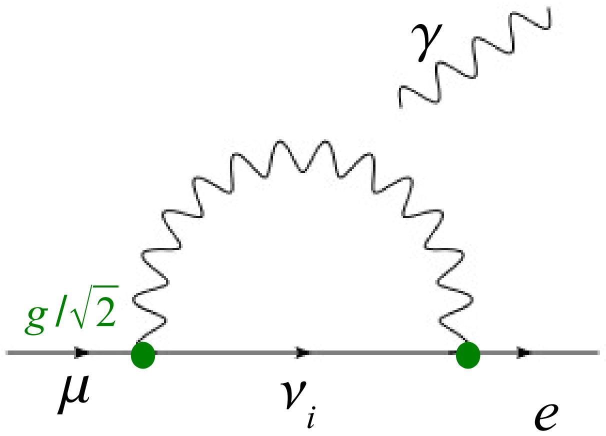
$$\Downarrow$$

$$m \sim \mu \frac{m_{\alpha 1}^2}{M_{12}^2}$$

Light Majorana neutrino masses can be generated while keeping M_D sizable and $M_{1,2} \sim 1$ TeV

Lepton flavour violation

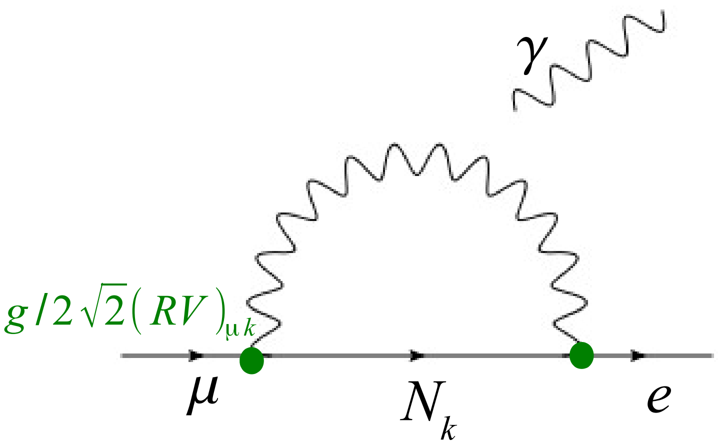
Standard contribution



$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\frac{\Delta m^2_{\rm sol}}{M_W^2}U^*_{i2}U_{j2} + \frac{\Delta m^2_{\rm atm}}{M_W^2}U^*_{i3}U_{j3}\right|^2$$

Sizable couplings, but strong GIM suppression $\Delta m^2/M_W{}^2$

New contribution



$$B(\mu \to e\gamma) = \frac{3\alpha}{8\pi}\left|(RV)_{\mu 1}(RV)_{e1}\right|^2\left|G\left(\frac{M_1^2}{M_W^2}\right) - G(0)\right|^2$$

No GIM suppression. Couplings should be suppressed to yield rates within the experimental bounds

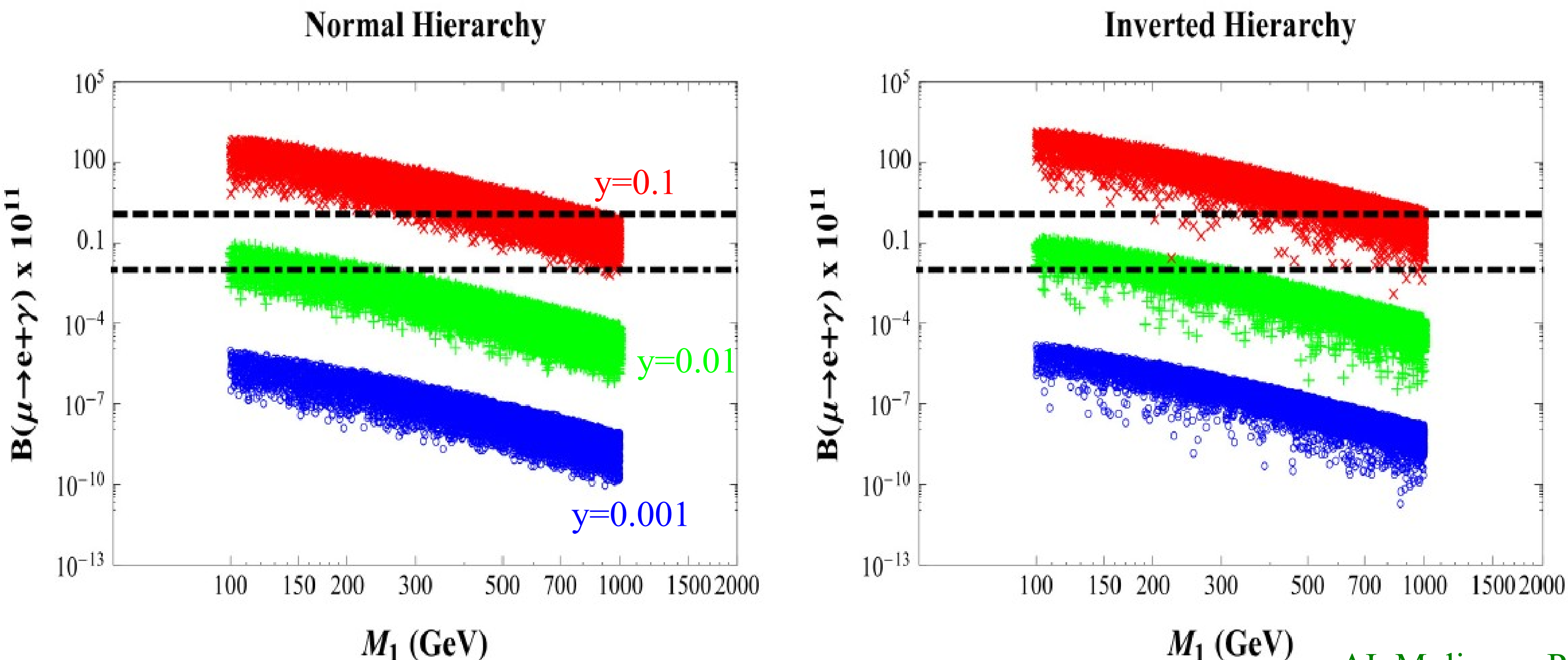
$$B(\mu \to e\gamma) \leq 1.2\times 10^{-11} \;\Rightarrow |(RV)_{\mu_1}(RV)_{e_1}| < \begin{cases} 1.8\times 10^{-4} & \text{for } M_1 = 100 \text{ GeV} \\ 0.6\times 10^{-4} & \text{for } M_1 = 1000 \text{ GeV} \end{cases}$$

Constraints on the parameters of the full Lagrangian

If the couplings is large enough to have observable effects, (RV) depend basically on the neutrino Yukawa eigenvalue and the right-handed neutrino mass scale. The rate of $\mu \to e\,\gamma$ depends on very few unknown parameters:

NH $$B(\mu \to e+\gamma) \cong \frac{3\alpha_{\rm em}}{32\pi}\left(\frac{y^2 v^2}{M_1^2}\frac{m_3}{m_2+m_3}\right)^2 \left|U_{\mu 3} + i\sqrt{\frac{m_2}{m_3}}U_{\mu 2}\right|^2 \left|U_{e3} + i\sqrt{\frac{m_2}{m_3}}U_{e2}\right|^2 \left[G\left(\frac{M_1^2}{M_W^2}\right) - G(0)\right]^2$$

IH $$B(\mu \to e+\gamma) \cong \frac{3\alpha_{\rm em}}{32\pi}\left(\frac{y^2 v^2}{M_1^2}\frac{1}{2}\right)^2 |U_{\mu 2} + iU_{\mu 1}|^2 \, |U_{e2} + iU_{e1}|^2 \left[G\left(\frac{M_1^2}{M_W^2}\right) - G(0)\right]^2$$



AI, Molinaro, Petcov

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- Upper bounds on the Yukawa coupling:

$$y \lesssim 0.036\ (0.21)\ \text{ for NH with } M_1 = 100\,\text{GeV}\ (1000\,\text{GeV}) \text{ and } \sin\theta_{13} = 0\,,$$
$$y \lesssim 0.031\ (0.18)\ \text{ for IH with } M_1 = 100\,\text{GeV}\ (1000\,\text{GeV}) \text{ and } \sin\theta_{13} = 0\,,$$
$$y \lesssim 0.094\ (0.54)\ \text{ for NH with } M_1 = 100\,\text{GeV}\ (1000\,\text{GeV}) \text{ and } \sin\theta_{13} = 0.2\,,$$
$$y \lesssim 0.16\ (0.90)\ \text{ for IH with } M_1 = 100\,\text{GeV}\ (1000\,\text{GeV}) \text{ and } \sin\theta_{13} = 0.2\,.$$

For large θ_{13}, certain choices of the Majorana phases lead to cancellations among terms, thus lowering the rate of $\mu \to e\gamma$.

Electroweak precision observables

- Invisible decay width of Z
- $W^{\pm}$ decays
- Universality tests of EW interactions
- ...

Langacker, London;
Nardi, Roulet, Tommasini;
del Aguila, de Blas, Perez-Victoria;
Antusch, Baumann, Fernandez-Martinez;
...

$$\left|\frac{1}{2}(RV)(RV)^{\dagger}\right| < \begin{pmatrix} 2.0\times10^{-3} & 0.6\times10^{-4} & 1.6\times10^{-3} \\ 0.6\times10^{-4} & 0.8\times10^{-3} & 1.0\times10^{-3} \\ 1.6\times10^{-3} & 1.0\times10^{-3} & 2.6\times10^{-3} \end{pmatrix}$$

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$$|(RV)_{e1}|^2 \lesssim 2 \times 10^{-3},$$
$$|(RV)_{\mu 1}|^2 \lesssim 0.8 \times 10^{-3},$$
$$|(RV)_{\tau 1}|^2 \lesssim 2.6 \times 10^{-3}.$$

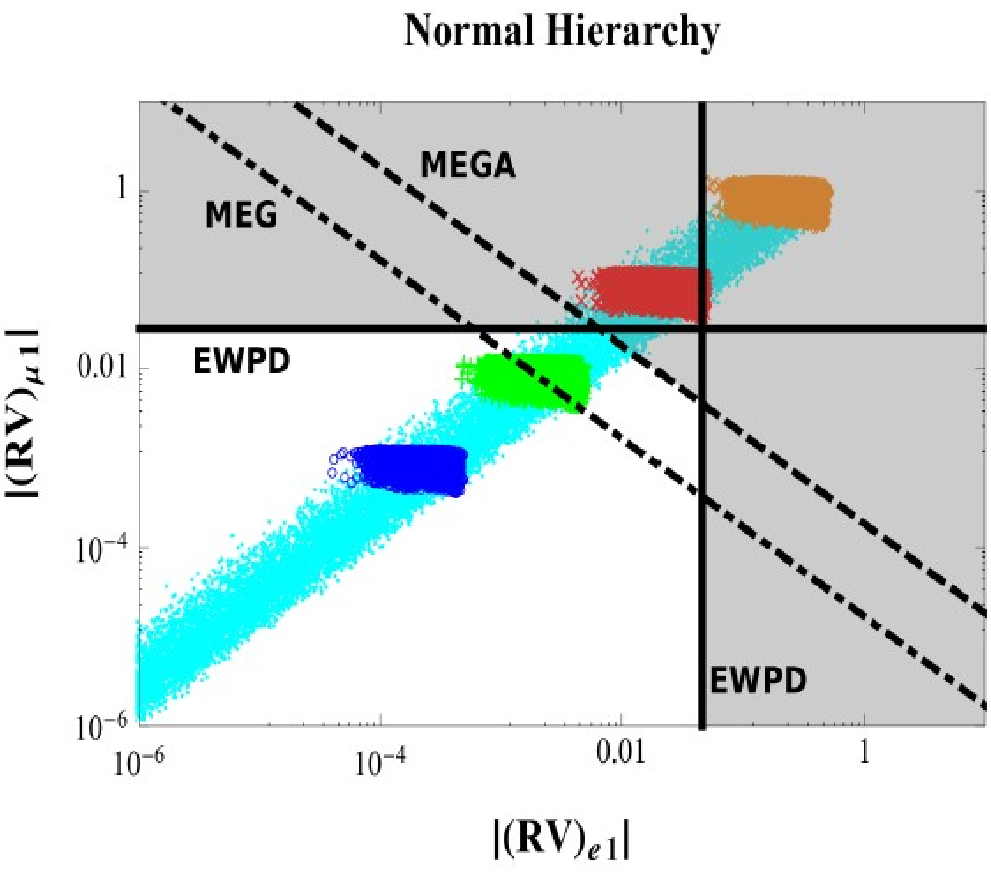
NH $$|(RV)_{\alpha 1}|^2 \simeq \frac{1}{2}\frac{y^2 v^2}{M_1^2}\frac{m_3}{m_2+m_3}\left|U_{\alpha 3} + i\sqrt{\frac{m_2}{m_3}}U_{\alpha 2}\right|^2$$

IH $$|(RV)_{\alpha 1}|^2 \simeq \frac{1}{4}\frac{y^2 v^2}{M_1^2}|U_{\alpha 2} + iU_{\alpha 1}|^2$$

$y \lesssim 0.047\ (0.47)$ for NH with $M_1 = 100\,\mathrm{GeV}\ (1000\,\mathrm{GeV})$ and $\sin\theta_{13} = 0$,
$y \lesssim 0.046\ (0.46)$ for IH with $M_1 = 100\,\mathrm{GeV}\ (1000\,\mathrm{GeV})$ and $\sin\theta_{13} = 0$,
$y \lesssim 0.049\ (0.49)$ for NH with $M_1 = 100\,\mathrm{GeV}\ (1000\,\mathrm{GeV})$ and $\sin\theta_{13} = 0.2$,
$y \lesssim 0.053\ (0.53)$ for IH with $M_1 = 100\,\mathrm{GeV}\ (1000\,\mathrm{GeV})$ and $\sin\theta_{13} = 0.2$.

Comparison of the constraints

M_1=100 GeV



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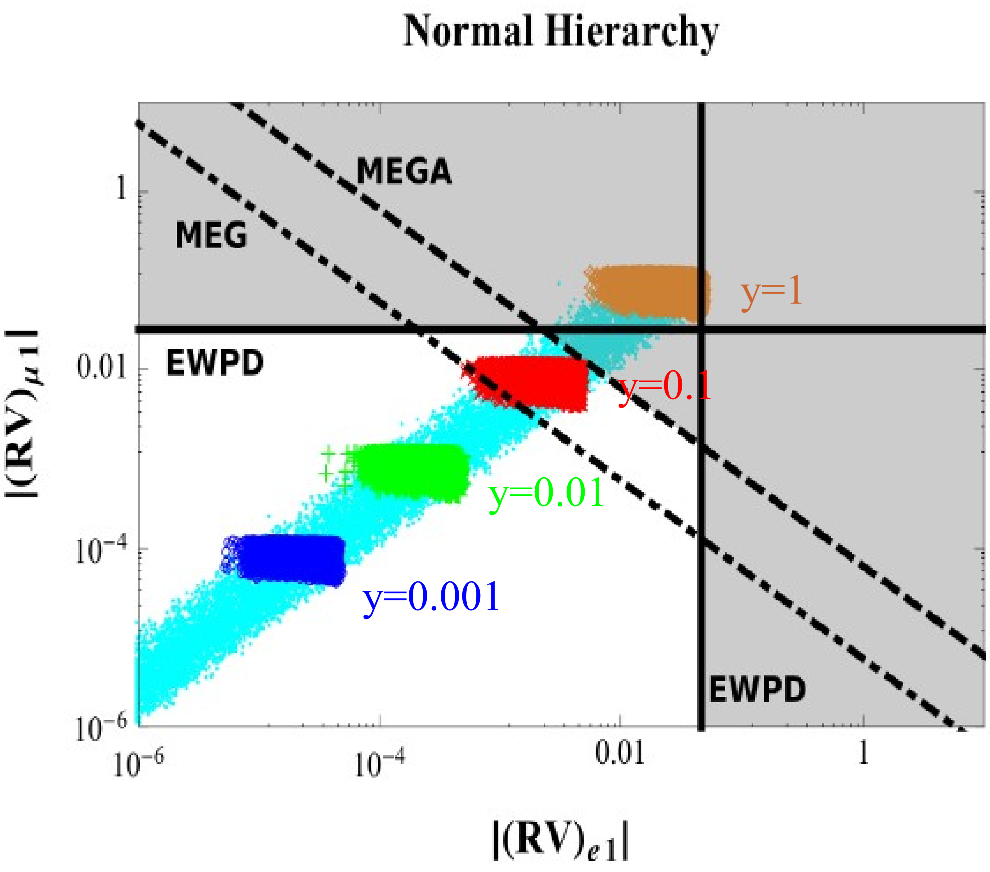

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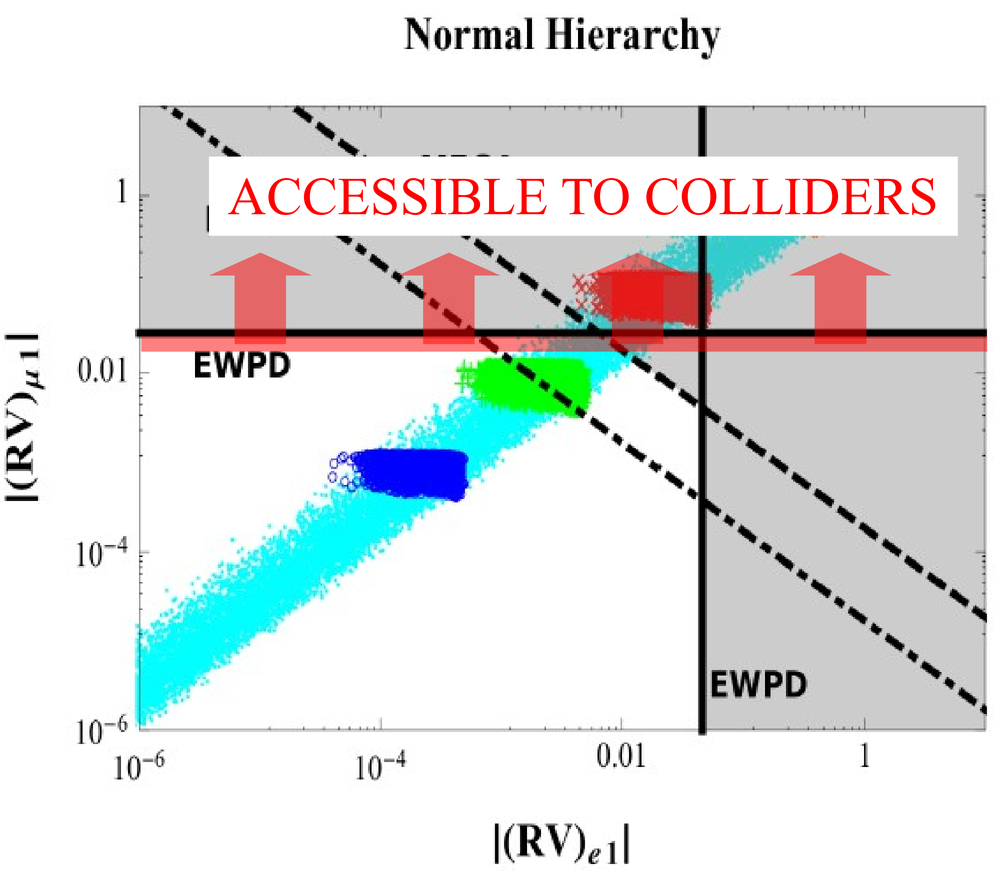
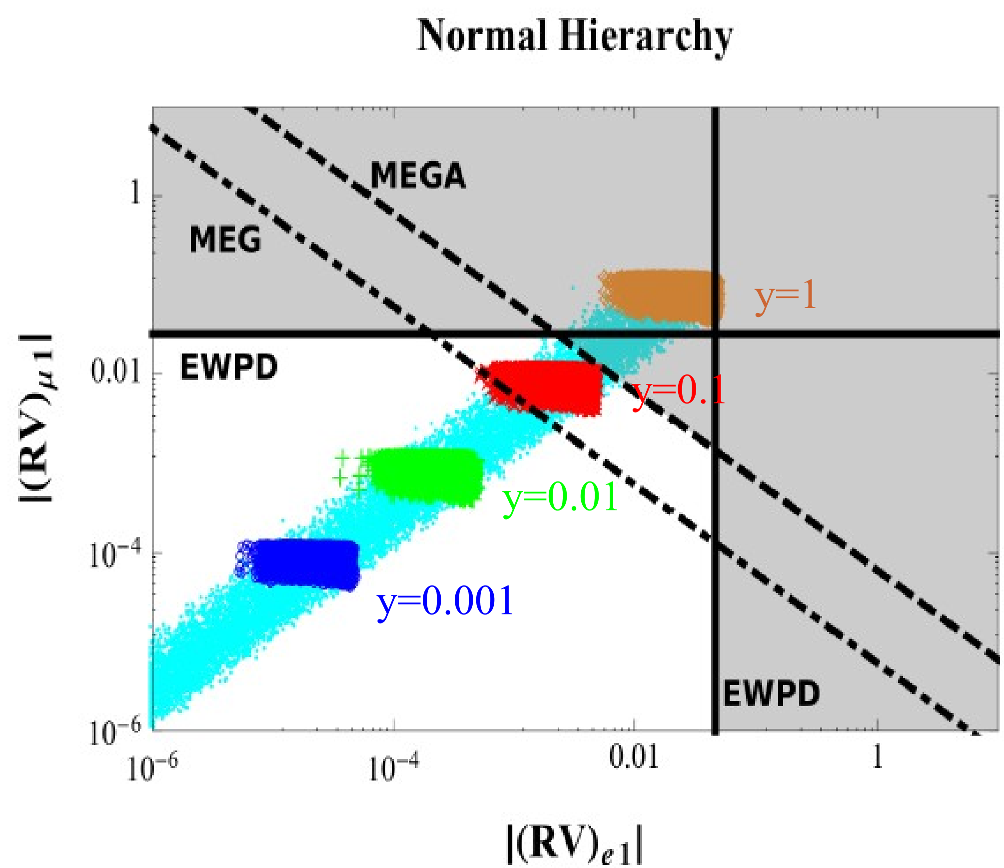


M_1=1000 GeV



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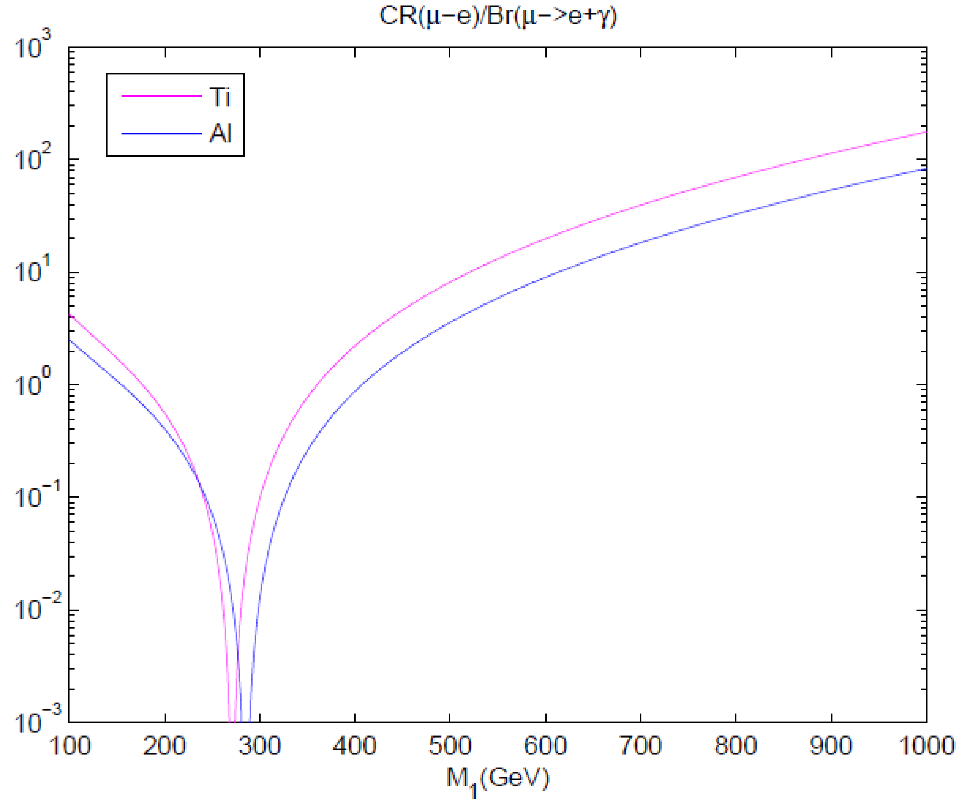
The role of mu-e conversion in nuclei

Present bounds:

$$\mathrm{B}(\mu \to e\gamma) \leq 2.4 \times 10^{-12} \text{ (MEG)}$$
$$R(\mu\,\mathrm{Ti} \to e\,\mathrm{Ti}) \leq 7 \times 10^{-13} \text{ (SINDRUM-II)}$$

Projected bounds:

$$\mathrm{B}(\mu \to e\gamma) \lesssim 10^{-13} \text{ (MEG)}$$
$$R(\mu\,\mathrm{Al} \to e\,\mathrm{Al}) \lesssim 10^{-16} \text{ (COMET, Mu2e)}$$
$$R(\mu\,\mathrm{Ti} \to e\,\mathrm{Ti}) \lesssim 10^{-18} \text{ (PRISM/PRIME, Project X)}$$



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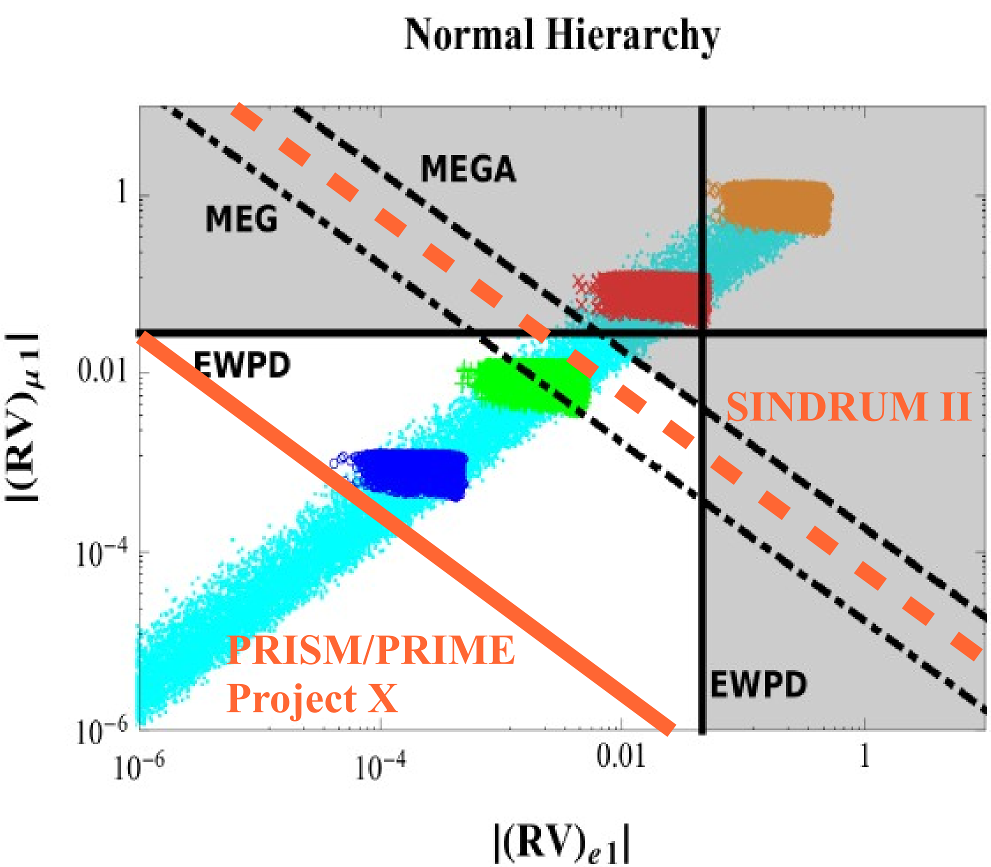
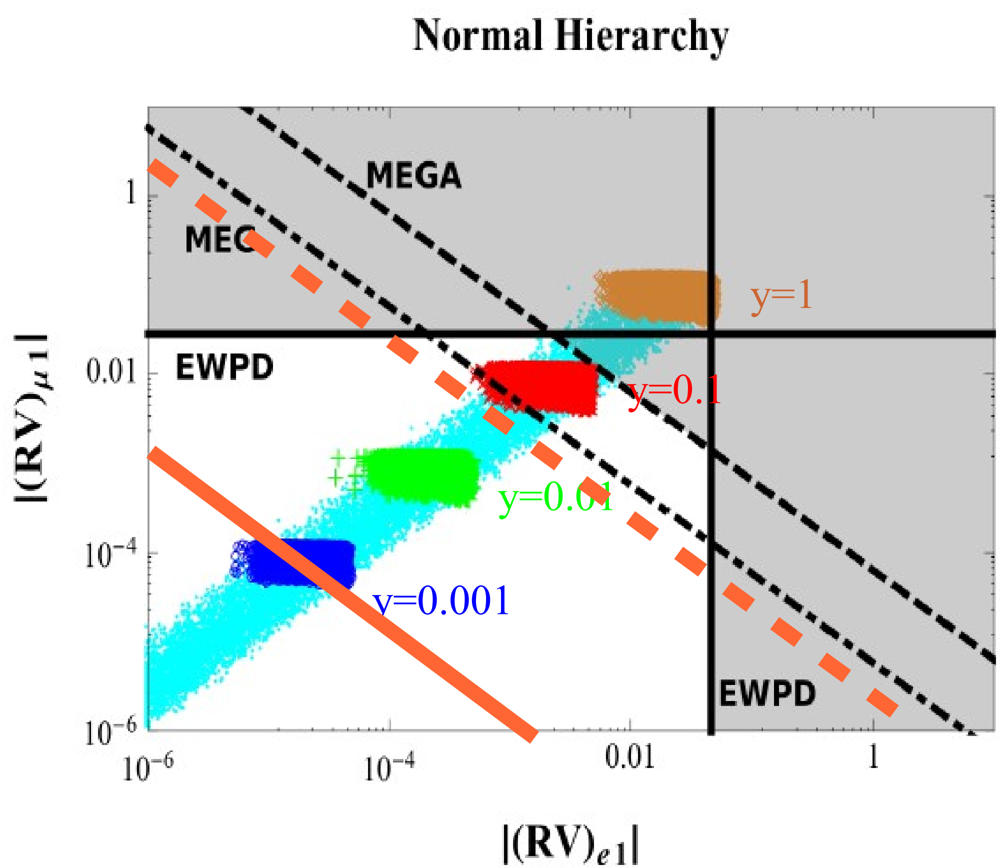
Preliminary

Comparison of the constraints

M_1=100 GeV



M_1=1000 GeV



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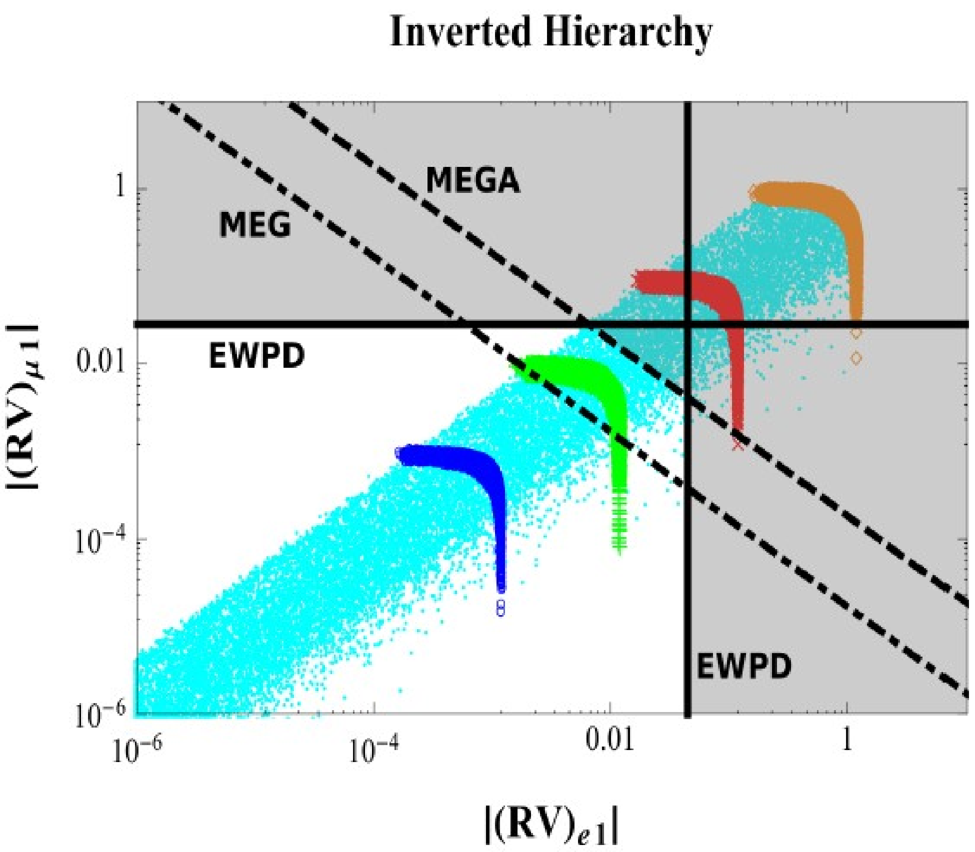
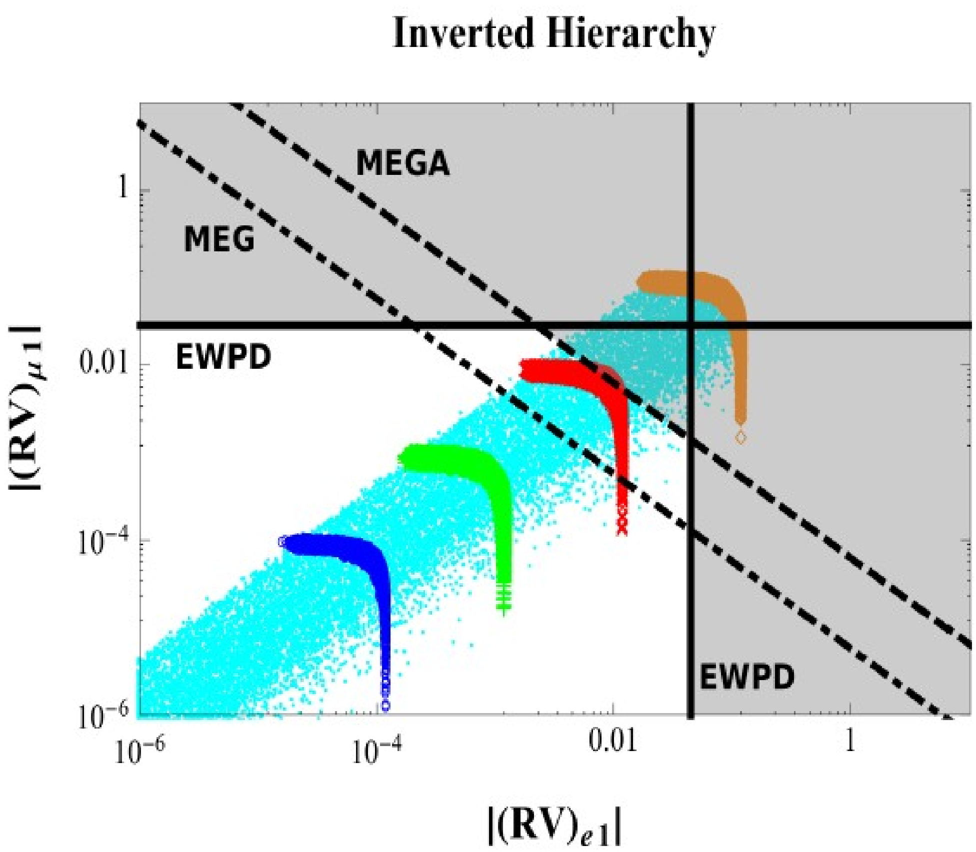
Preliminary

Comparison of the constraints

M_1=100 GeV



M_1=1000 GeV



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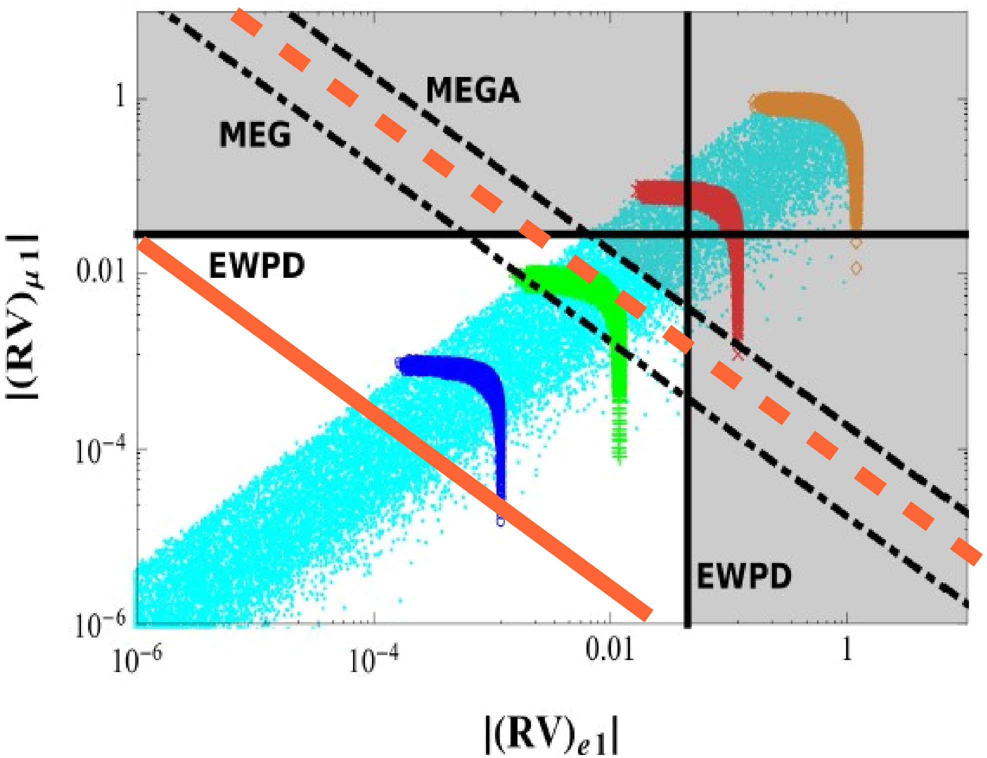
Comparison of the constraints

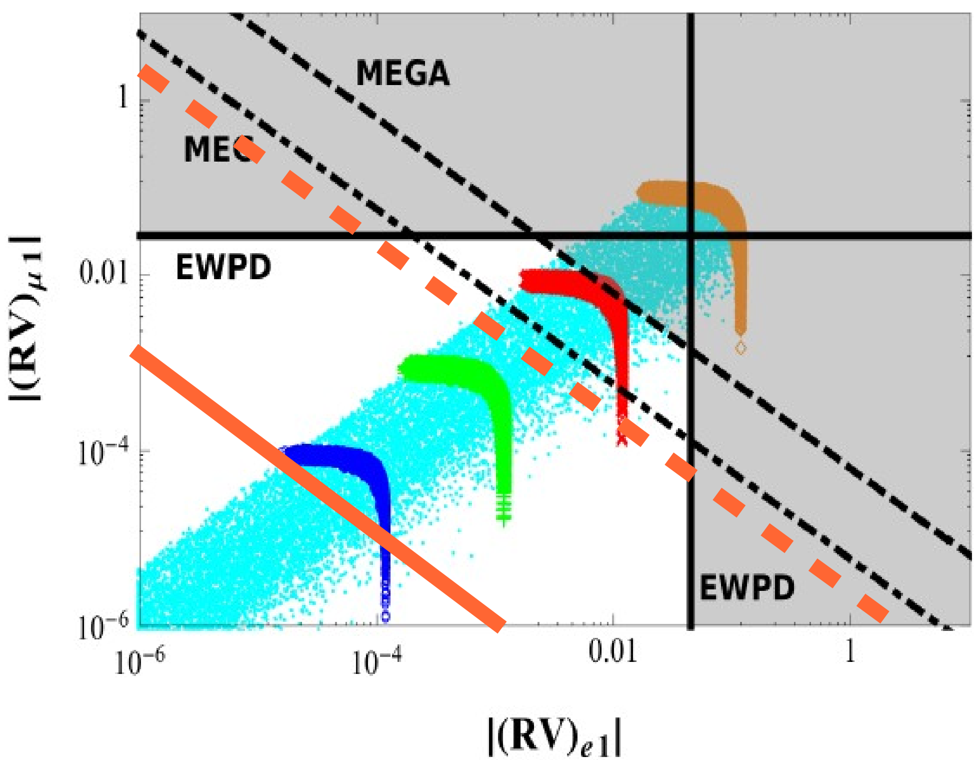
M_1=100 GeV

Inverted Hierarchy



M_1=1000 GeV

Inverted Hierarchy



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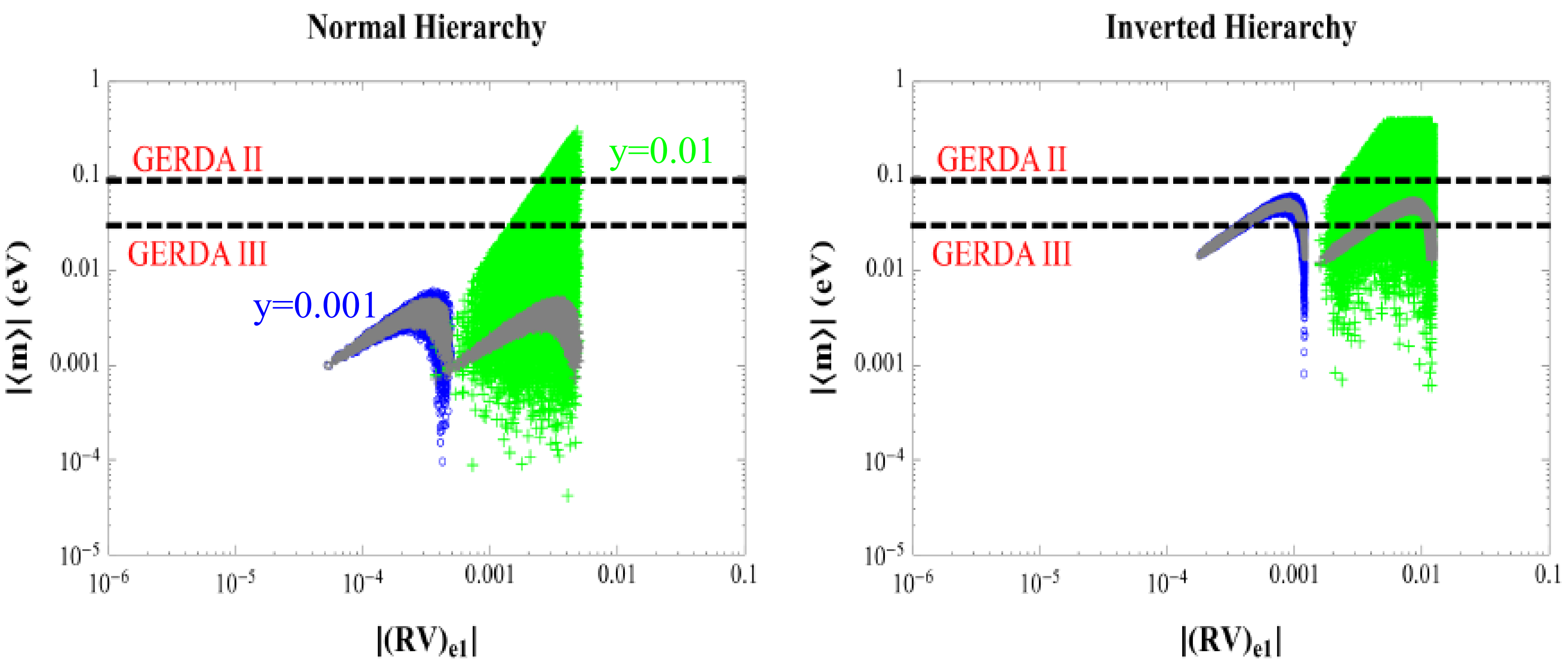
Future tests of the TeV scale see-saw model

Neutrinoless double beta decay

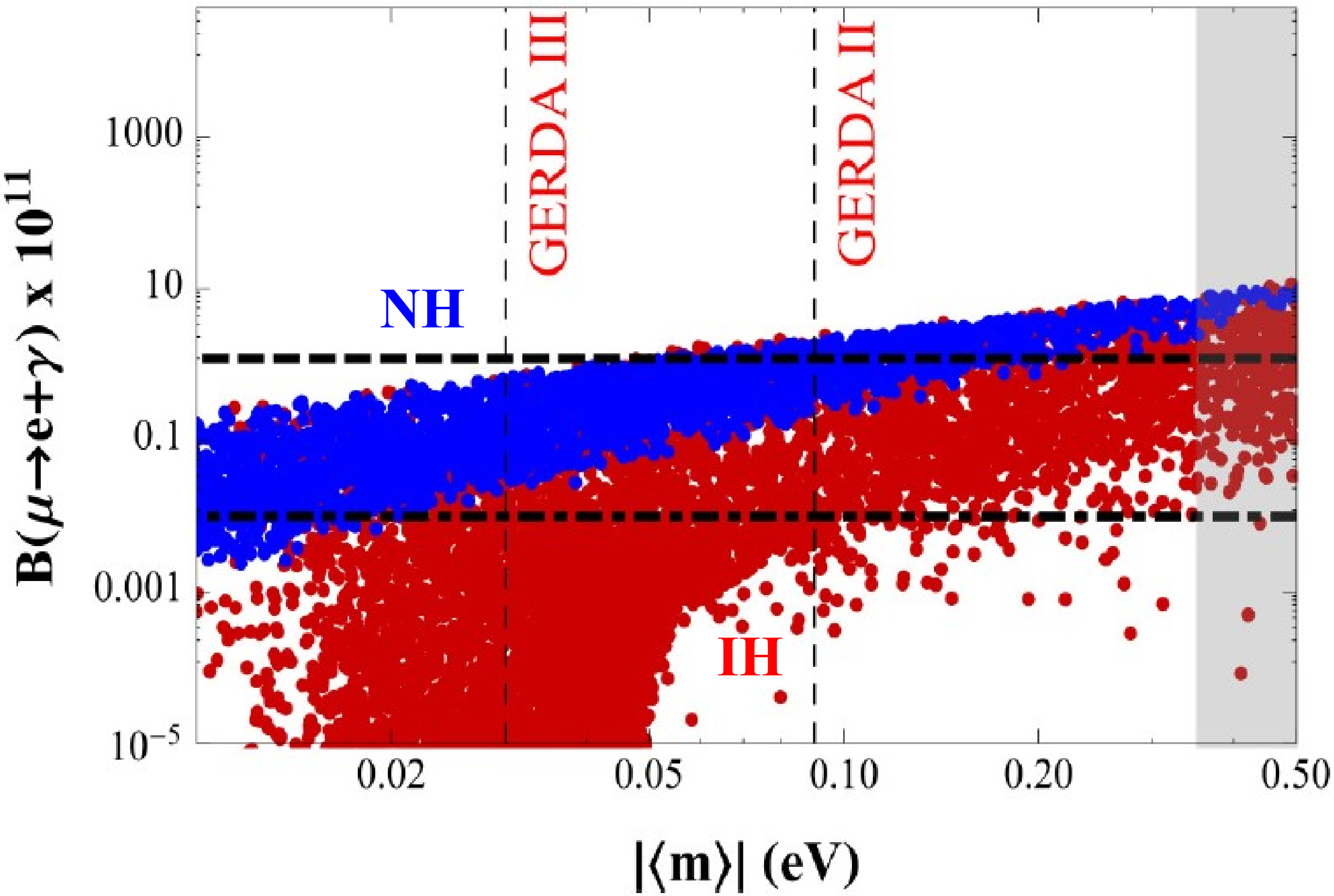
The new sources of lepton number violation and can greatly enhance the rate of neutrinoless double beta decay



M_1=100 GeV,

Future tests of the TeV scale see-saw model

Lepton flavour violation



M_1=100 GeV, $(M_2-M_1)/M_2=10^{-3}$.

Conclusions

A simple extension of the Standard Model consists on introducing right-handed neutrinos. The right-handed neutrino mass can lie anywhere between 0 and the Planck mass.

The TeV see-saw model could induce observable signatures in:

- Collider experiments,
- Electroweak precision observables,
- Lepton flavour violating processes,
- Neutrinoless double beta decay.

The most stringent constraints come from LFV and $\nu 0 2\beta$:

- Right-handed neutrino masses very degenerate,
- $y \lesssim 0.03$ (0.2) for M_1=100 (1000 GeV) and θ_{13}=0.