Low Energy Signatures of TeV Scale

See-Saw Mechanism

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NEUTRINO MASSES AND MIXING

experiments on solar, atmospheric, accelerator and reactor neutrinos:

FLAVOUR NEUTRINO OSCILLATIONS

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

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

$U_{\mathrm{PMNS}} =$

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

physics beyond the Standard Model

Parameter	best-fit ($\pm 1\sigma$)	3σ
$\Delta m^2_{\odot}$ $[10^{-5}$ eV$^2]$	$7.58^{+0.22}_{-0.26}$	6.99 - 8.18
$\lvert\Delta m^2_A\rvert$ $[10^{-3}$ eV$^2]$	$2.35^{+0.12}_{-0.09}$	2.06 - 2.67
$\sin^2\theta_{12}$	$0.306^{+0.018}_{-0.015}$	0.265 - 0.364
$\sin^2\theta_{23}$	$0.42^{+0.08}_{-0.03}$	0.34 - 0.64
$\sin^2\theta_{13}$	$0.025^{+0.007}_{-0.007}$	0.005 - 0.050
$\sin^2\theta_{13}$	0.0236 ± 0.0042	0.010 - 0.036

Daya Bay

Fogli et al.

NEUTRINO MASSES 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":

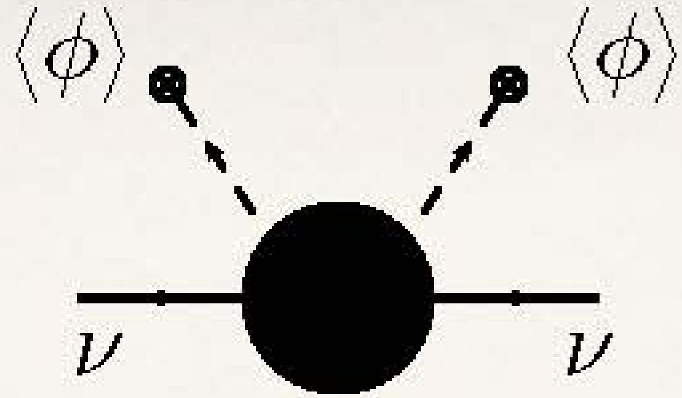
$$m_{1,2,3} < 1 \text{ eV and } m_1 \neq m_2 \neq m_3$$

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

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

- 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 ?*

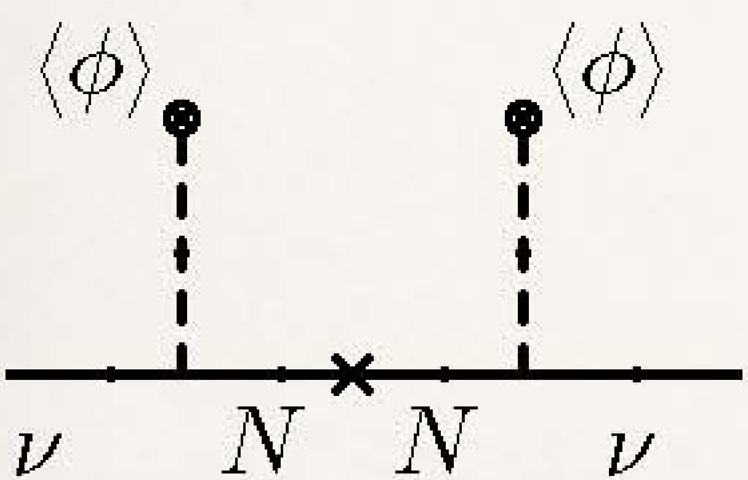


A Majorana mass term for $\nu_{\ell L}(x)$ can arise after EWSB from the (unique) d=5 operator:

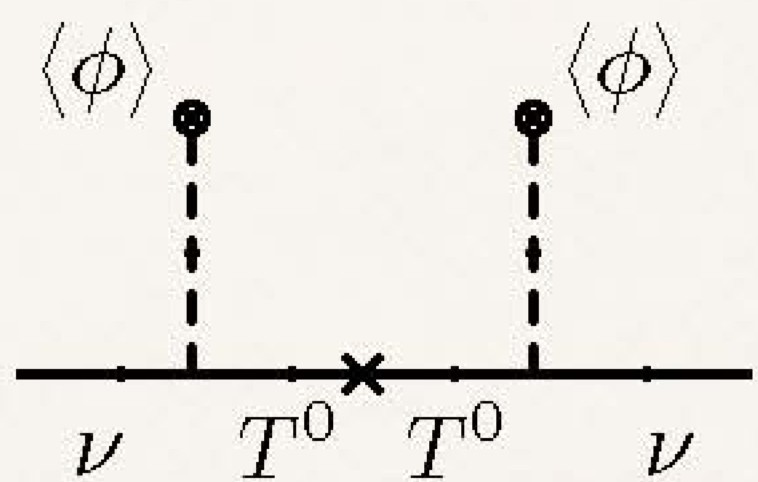
$$\frac{c_{\ell\ell'}}{\Lambda}\left(\overline{\psi^c_{\ell L}}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\psi_{\ell' L}\right) + \text{H.c.}$$

Weinberg, PRD 22 (1980) 1694

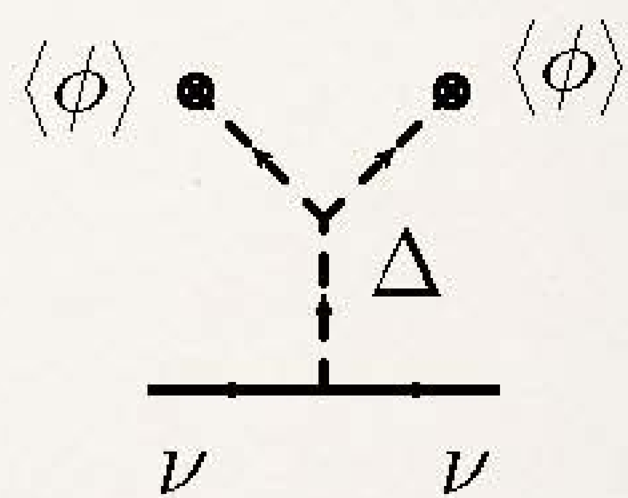
$$\psi_{\ell L}(x) = (\nu_{\ell L}(x), \ell_L(x)), \qquad \tilde{\phi}(x) = i\tau_2\phi(x)$$



type I



type III



type II

TYPE I SEESAW MECHANISM

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

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

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 $E \sim M_Z$:

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

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???*

RH NEUTRINOS AT COLLIDERS ?

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

naively for $M = 1$ TeV $\curvearrowright m_D \approx 10^{-4}$ 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 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 TeV scale consistent with light neutrino masses and sizeable Yukawa couplings ?

TeV 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

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

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

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

TeV 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:

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

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

Casas, Ibarra, 2001

adjust O to generate large m_D

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

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

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

exponentially enhanced!
fixed flavour structure!

TeV RH Neutrinos and Large Yukawa Couplings

sizeable couplings of RH neutrinos to Standard Model leptons

Lagrangian mass terms:

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

ν_L and ν_R are interaction eigenstates: $M = V^* \hat{M} V^\dagger, \quad \hat{M} \equiv \text{diag}(M_1, M_2)$

heavy Majorana mass eigenstates

$$\mathcal{L}^{\text{mass}}_\nu = -\frac{1}{2}\,\overline{\nu^C_{aR}}\,(m_\nu)_{ab}\,\nu_{bL} + \frac{1}{2}\,\hat{M}\,\overline{N^C_i}\,N_i + \text{h.c.}$$

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

diagonalization:

$$m_\nu \equiv U^*\,\text{diag}(m_1, m_2, m_3)\,U^\dagger \qquad M_N \simeq V^*\,\text{diag}(M_1, M_2)\,V^\dagger$$

TeV RH Neutrinos and Large Yukawa Couplings

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light neutrino interactions

non-unitarity effects

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

$$\mathcal{L}^\nu_{NC} = -\frac{g}{2c_w}\,\overline{\chi_{iL}}\,\gamma_\alpha\,\left(U^\dagger(1-(RV)(RV)^\dagger)U\right)_{ij}\,\chi_{jL}\,Z^\alpha$$

$R^* \simeq m_D\,M^{-1}$ provides the mixing between the interactions eigenstates ν_L and ν_R

Low energy effects are parametrized by (RV)

TeV RH Neutrinos and Large Yukawa Couplings

sizeable couplings of RH neutrinos to Standard Model leptons

Lagrangian mass terms:

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

ν_L and ν_R are interaction eigenstates: $M = V^* \hat{M} V^\dagger, \quad \hat{M} \equiv \text{diag}(M_1, M_2)$

heavy neutrino interactions

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

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

Low energy effects are parametrized by (RV)

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

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

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

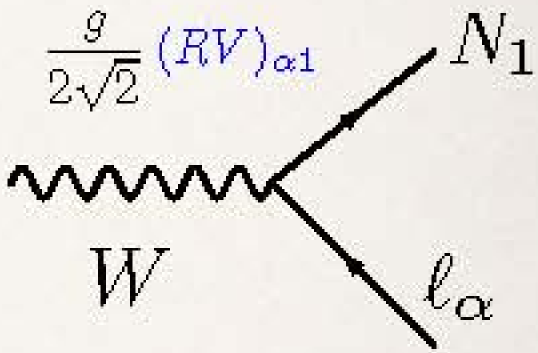
TeV RH Neutrinos and Large Yukawa Couplings

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

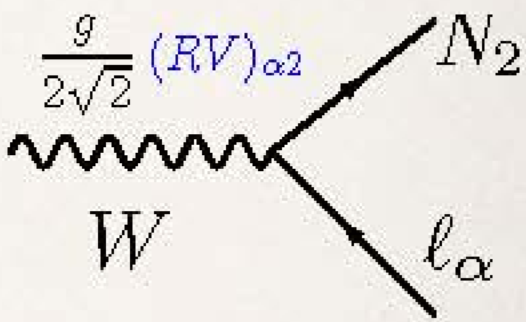
- maximum Yukawa coupling: y
- RH neutrino masses: M_1 and M_2
- a phase: ω

NH:

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



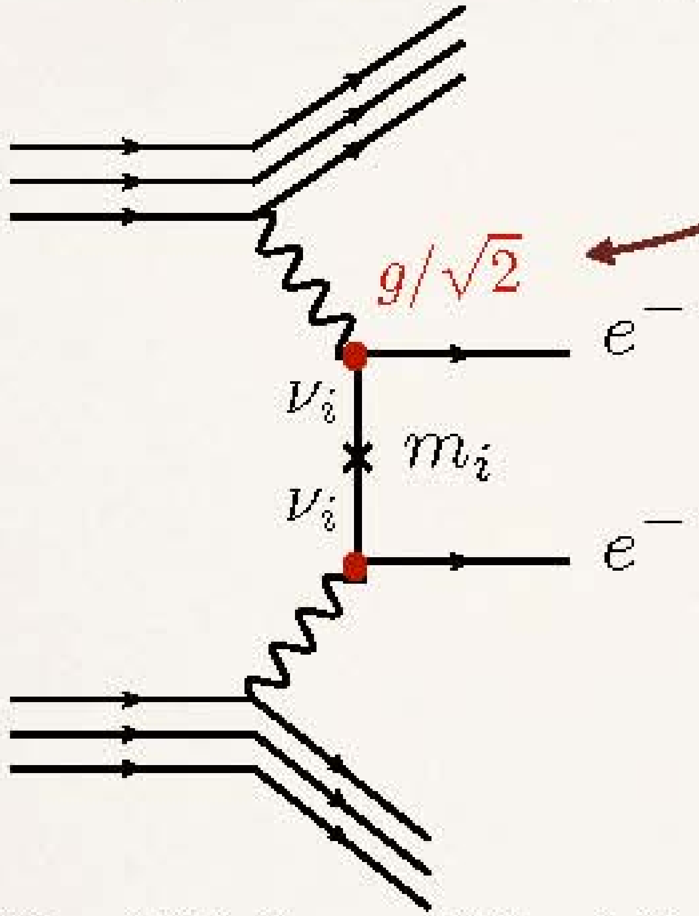
$$(RV)_{\alpha 2} = \mp i\, e^{i\omega} y v \sqrt{\frac{M_1}{M_2+M_1}} \sqrt{\frac{m_3}{m_2+m_3}} \left(U_{\alpha 3} + i\sqrt{m_2/m_3}\, U_{\alpha 2}\right)$$



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

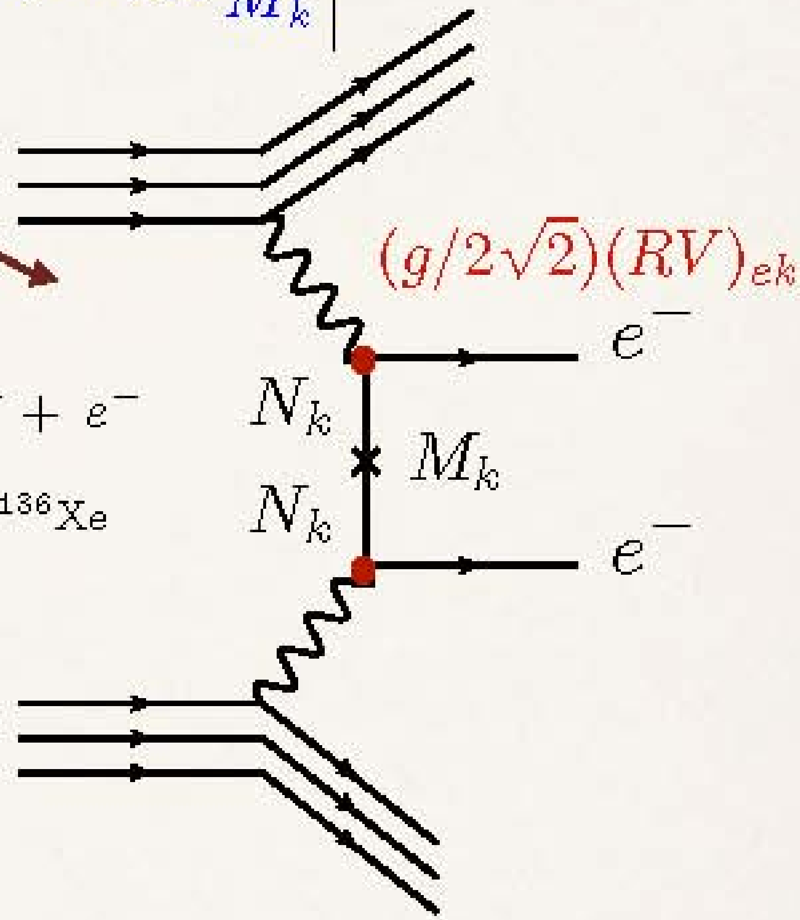
Constraints from neutrinoless double beta decay

Effective Majorana mass $\quad |\langle m \rangle| \cong \left| \sum_{i=1}^{3} U_{ei}^2 m_i - \sum_{k=1}^{2} f(A)\,(RV)_{ek}^2 \frac{M_a^2}{M_k} \right|$



$(A, Z) \Longrightarrow (A, Z+2) + e^- + e^-$

^{48}Ca, ^{76}Ge, ^{82}Se, ^{124}St, ^{130}Te, ^{136}Xe



$M_a \approx 0.9\,\mathrm{GeV}\,, \qquad f(A) \approx 0.05 - 0.1$

the contribution from RH neutrinos is dominant for sizeable Yukawa couplings:

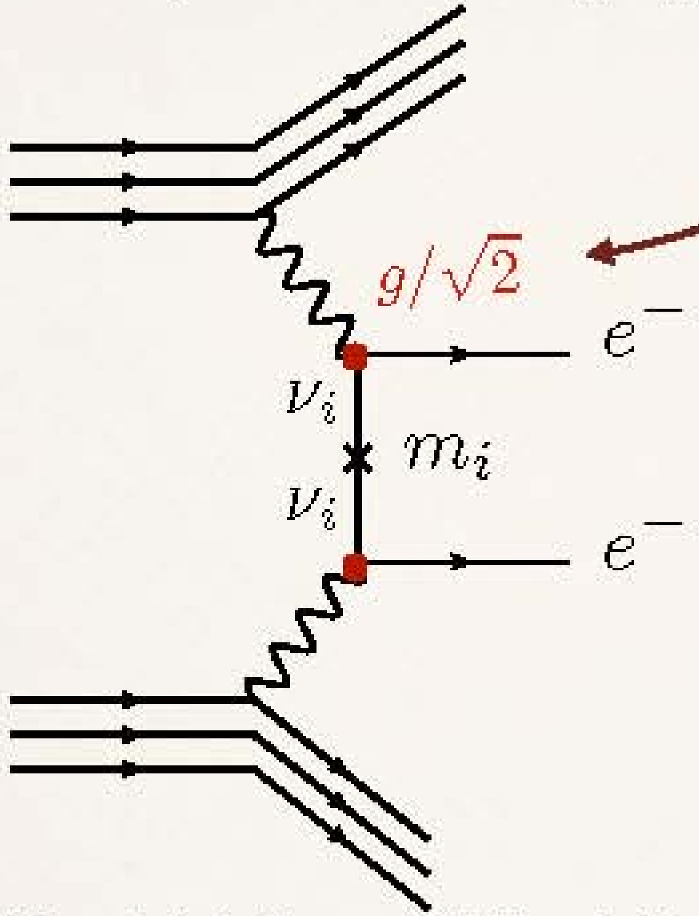
$$|\langle m \rangle| \approx 10\,\mathrm{eV} \left(\frac{M_2 - M_1}{M_1}\right) \left(\frac{|(RV)_{e2}|}{10^{-2}}\right)^2 \left(\frac{M_2}{1000\,\mathrm{GeV}}\right)$$

$$|\langle m \rangle| \lesssim 0.2\,\mathrm{eV} \quad \Longrightarrow \quad \left(\frac{M_2 - M_1}{M_1}\right) \lesssim 10^{-2}$$

RH neutrinos must be quasi-degenerate

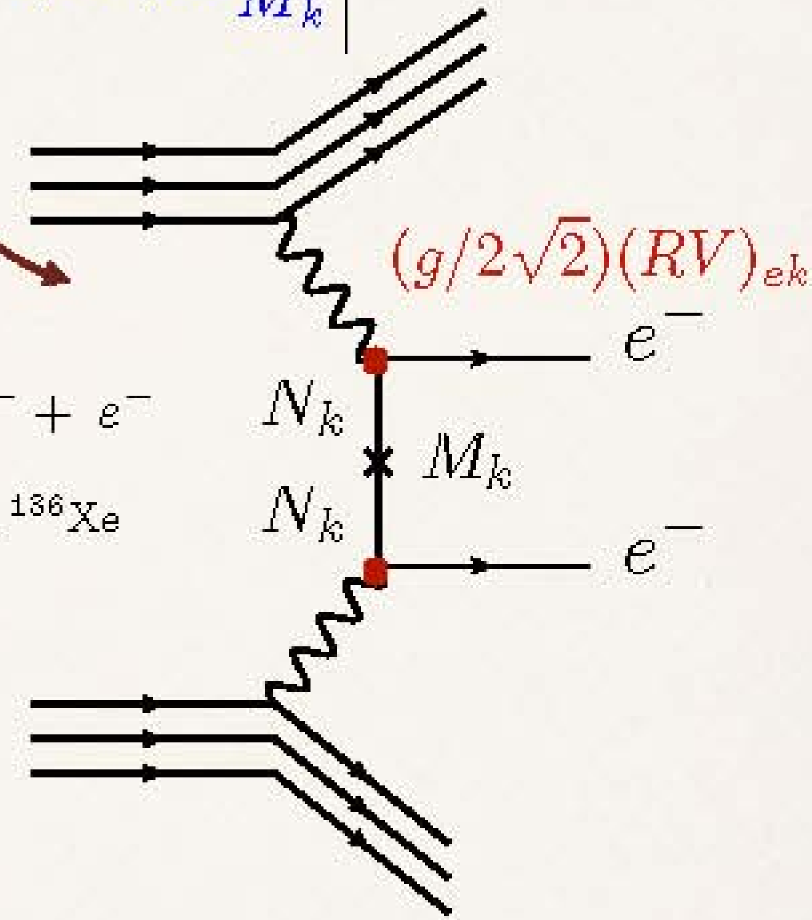
Constraints from neutrinoless double beta decay

Effective Majorana mass $|\langle m\rangle| \cong \left|\sum_{i=1}^{3} U_{ei}^2 m_i - \sum_{k=1}^{2} f(A)\,(RV)_{ek}^2\,\frac{M_a^2}{M_k}\right|$



$$(A,Z) \Longrightarrow (A,Z+2) + e^- + e^-$$

^{48}Ca, ^{76}Ge, ^{82}Se, ^{124}St, ^{130}Te, ^{136}Xe



$M_a \approx 0.9\,\mathrm{GeV}\,, \qquad f(A) \approx 0.05 - 0.1$

cross-section of same sign di-muon production at LHC suppressed!

$$A(p\,p\;\rightarrow\;\mu^-\;\mu^-\;2\,\mathrm{jets}) \;\propto\; |(RV)_{\mu 2}|^2\,\frac{M_1 M_2}{M_1+M_2}\,\frac{M_2^2 - M_1^2 - i(\Gamma_2 M_2 - \Gamma_1 M_1)}{(p^2 - M_2^2 + i\Gamma_2 M_2)(p^2 - M_1^2 + i\Gamma_1 M_1)}$$
$$\propto\;\left(\frac{M_2 - M_1}{M_1}\right)$$

the Majorana nature of RH neutrinos with "large" couplings cannot be tested at colliders !

Ibarra, EM, Petcov, 2010

TeV RH Neutrinos and Large Yukawa Couplings

more in detail...

$$y^2 v^2 \simeq 2 M_1^2 \left(|(RV)_{e1}|^2 + |(RV)_{\mu 1}|^2 + |(RV)_{\tau 1}|^2 \right)$$

imposing perturbative unitarity:

$$\Gamma_{N_i} \simeq \frac{g^2}{16\pi M_W^2} M_i^3 \sum_\ell |(RV)_{\ell i}|^2 = \frac{g^2}{32\pi} \frac{M_i v^2}{M_W^2} y^2$$

$$\Gamma_{N_i}/M_i < 1/2 \quad \Longrightarrow \quad y < 4$$

naively for $M_2 > M_1 \gtrsim 100$ GeV: $|(m_\nu)_{\ell\ell'}| \simeq \sum_k |(RV)^*_{\ell k}\, M_k\, (RV)^\dagger_{k\ell'}| \lesssim 1$ eV

$$|(RV)_{\ell k}| \lesssim 3 \times 10^{-6} \left(\frac{100 \text{ GeV}}{M} \right)^{1/2}$$

By definition TeV scale see-saw scenarios with large Yukawa coupling y correspond to $|(RV)_{\ell k}| \gg 10^{-6}$

top - down approach

Consider the case of 3 RH neutrinos:

$$m_D = \begin{pmatrix} 0 & 0 & m^D_{e3} \\ 0 & 0 & m^D_{\mu 3} \\ 0 & 0 & m^D_{\tau 3} \end{pmatrix} \qquad M_N = \begin{pmatrix} M_{11} & 0 & 0 \\ 0 & 0 & M_{23} \\ 0 & M_{23} & 0 \end{pmatrix}$$

conserved lepton charge: $L' = L_e + L_\mu + L_\tau + L_3 - L_2,\ L_a(\nu_{Rb}) = -\delta_{ab}\ (a, b = 1, 2)$

mass spectrum: 1 Majorana fermion of mass M_{11}, 1 Dirac fermion of mass M_{23} and 3 massless neutrinos

$m_\nu = 0$ independently of the size of m_D and M_N

top - down approach

Consider the case of 3 RH neutrinos:

$$m_D = \begin{pmatrix} 0 & 0 & m^D_{e3} \\ 0 & 0 & m^D_{\mu 3} \\ 0 & 0 & m^D_{\tau 3} \end{pmatrix} \qquad M_N = \begin{pmatrix} M_{11} & 0 & 0 \\ 0 & 0 & M_{23} \\ 0 & M_{23} & 0 \end{pmatrix}$$

For an arbitrary number of RH neutrinos:

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

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

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

Leung, Petcov, 1983; Weyler, Wolfenstein, 1983

top - down approach

Consider the case of 3 RH neutrinos:

$$m_D = \begin{pmatrix} 0 & 0 & m^D_{e3} \\ 0 & 0 & m^D_{\mu 3} \\ 0 & 0 & m^D_{\tau 3} \end{pmatrix} \qquad M_N = \begin{pmatrix} M_{11} & 0 & 0 \\ 0 & \mu & M_{23} \\ 0 & M_{23} & 0 \end{pmatrix}$$

μ is a small lepton number violating term

↓

2 quasi-degenerate Majorana neutrinos N_2 and N_3 with $|M_3 - M_2| = \mu$

pseudo-Dirac neutrino

tiny contribution to light neutrino mass matrix:

$$(m_\nu)_{\ell\ell'} \approx \mu \frac{m^D_{\ell 3} m^D_{\ell' 3}}{M^2_{23}}$$

light Majorana neutrino masses can be generated while keeping sizeable m_D and $M_N \sim 1$ TeV

Constraints from EW precision observables

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

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

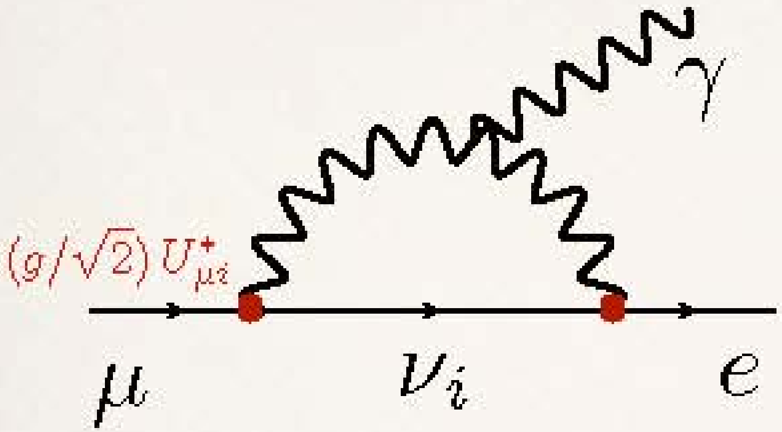
$$|(RV)(RV)^\dagger| < \begin{pmatrix} 4.0\times 10^{-3} & 1.2\times 10^{-4} & 3.2\times 10^{-3} \\ 1.2\times 10^{-4} & 1.6\times 10^{-3} & 2.0\times 10^{-3} \\ 3.2\times 10^{-3} & 2.0\times 10^{-3} & 5.2\times 10^{-3} \end{pmatrix}$$

$$y^2\, v^2 \simeq 2\, M_1^2 \left(|(RV)_{e1}|^2 + |(RV)_{\mu 1}|^2 + |(RV)_{\tau 1}|^2\right)$$

$$y \lesssim 0.06 \left(\frac{M_1}{100\,\mathrm{GeV}}\right)$$

Constraints from LFV observables: $\mu \to e + \gamma$

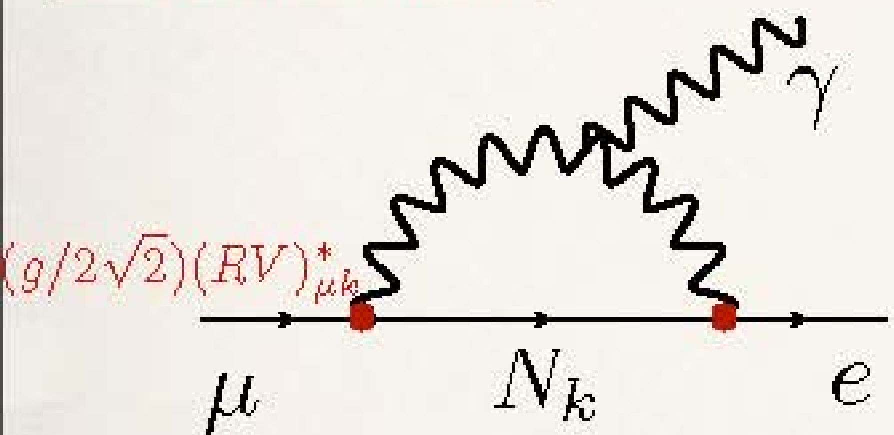
Standard contribution



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

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

New contribution



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

No GIM suppression, observable effects!

Present upper limit on the BR given by MEG experiment:

$$BR(\mu \to e + \gamma) < 2.4 \times 10^{-11} \implies |(RV)^*_{\mu 1}(RV)_{e1}| < \begin{cases} 0.4 \times 10^{-3} \text{ for } M_1 = 100 \text{ GeV} \\ 1.5 \times 10^{-4} \text{ for } M_1 = 1000 \text{ GeV} \end{cases}$$

Constraints on the parameters of the full Lagrangian

Ibarra, EM, Petcov, 2011

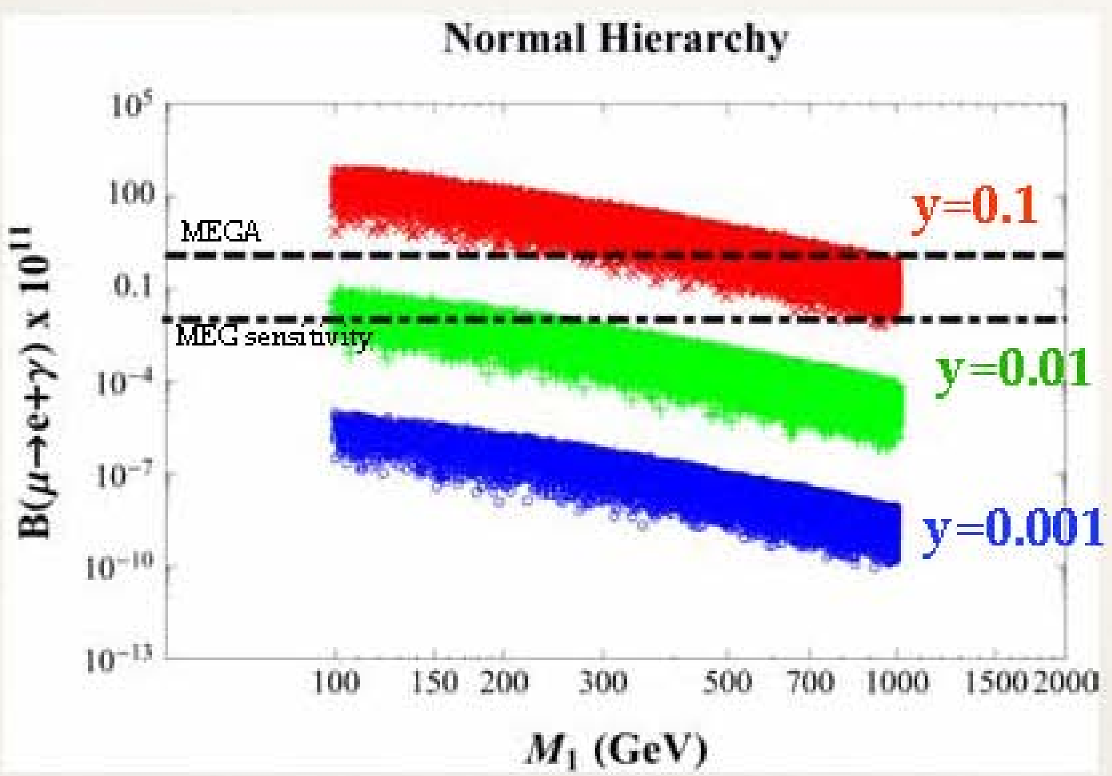
If the neutrino Yukawa couplings are large enough to have observable effects, RV basically depends on neutrino Yukawa eigenvalue and the RH neutrino mass scale. The rate of $\mu \to e + \gamma$ depends on very few unknown parameters

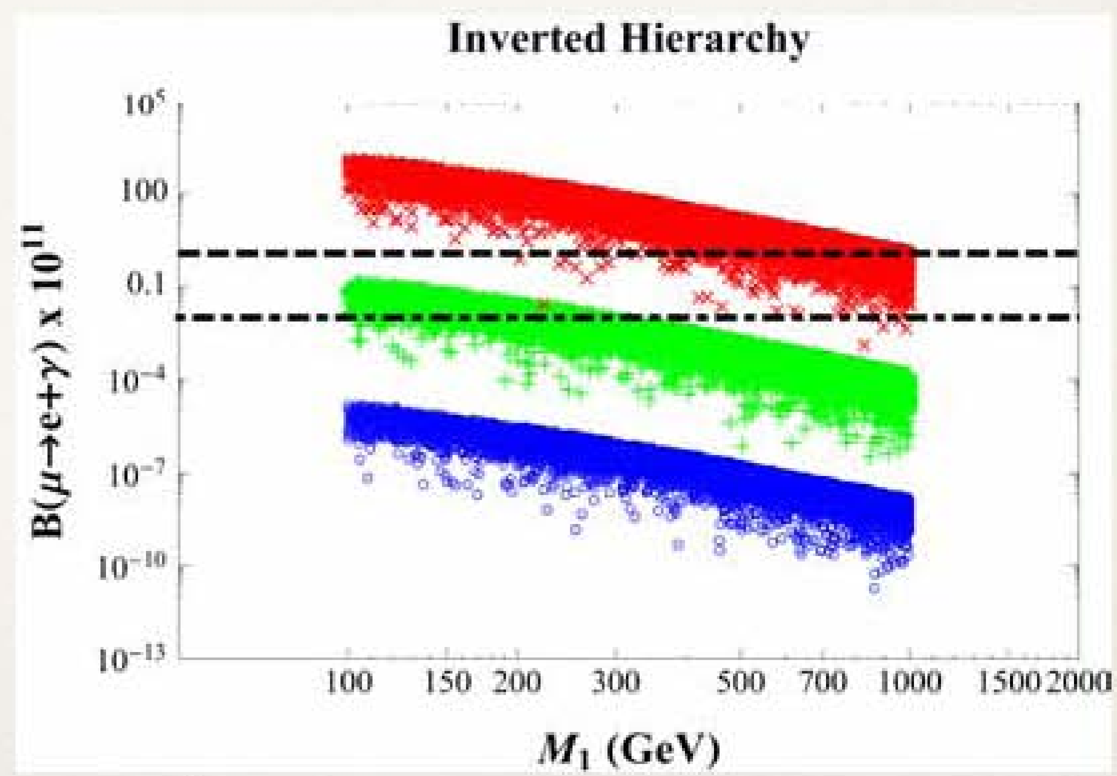
$$\text{NH}: \quad B(\mu \to e + \gamma) \cong$$

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

$$\text{IH}: \quad B(\mu \to e + \gamma) \cong$$

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





Constraints on the parameters of the full Lagrangian

From the projected sensitivity of the MEG experiment, $\mathrm{BR}(\mu \to \mathrm{e} + \gamma) \simeq 10^{-13}$, the neutrino Yukawa coupling y is constrained:

$$y \lesssim 0.035 \;\; (0.21) \;\; \text{for NH with } M_1 = 100\,\text{GeV}\,(1000\,\text{GeV}) \text{ and } \sin\theta_{13} = 0.13$$
$$y \lesssim 0.025 \;\; (0.15) \;\; \text{for IH with } M_1 = 100\,\text{GeV}\,(1000\,\text{GeV}) \text{ and } \sin\theta_{13} = 0.13$$

rate of $\mu \to \mathbf{e} + \gamma$ can be highly suppressed in the case of IH spectrum:

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

in the standard parametrisation of PMNS matrix

$$\min\left(|U_{\mu 2} + iU_{\mu 1}|^2\right) = c_{23}^2 \frac{\left(\cos\delta\cos\frac{\alpha_{21}}{2} + \cos 2\theta_{12}\sin\delta\sin\frac{\alpha_{21}}{2}\right)^2}{1 + 2c_{12}\,s_{12}\,\sin\frac{\alpha_{21}}{2}}$$

$$\sin\theta_{13} = \frac{c_{23}}{s_{23}} \frac{\cos 2\theta_{12}\cos\delta\sin\frac{\alpha_{21}}{2} - \cos\frac{\alpha_{21}}{2}\sin\delta}{1 + 2c_{12}\,s_{12}\,\sin\frac{\alpha_{21}}{2}}$$

to be compared with Daya Bay measurement: $\sin^2\theta_{13} = 0.0236 \pm 0.0042$

Constraints on the parameters of the full Lagrangian

From the projected sensitivity of the MEG experiment, $BR(\mu \to e + \gamma) \simeq 10^{-13}$, the neutrino Yukawa coupling y is constrained:

$$y \lesssim 0.035\ (0.21)\ \text{for NH with}\ M_1 = 100\,\text{GeV}\ (1000\,\text{GeV})\ \text{and}\ \sin\theta_{13} = 0.13$$
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$$\text{IH}: \quad B(\mu \to e + \gamma) \cong$$
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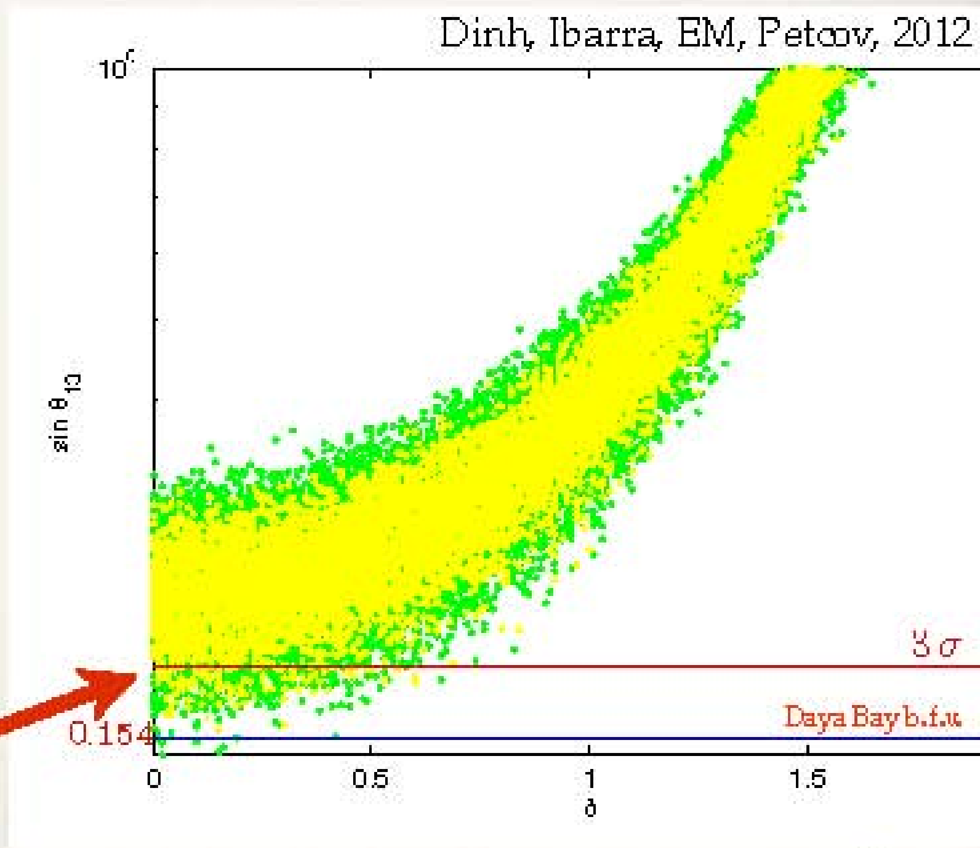
suppressed branching ratio for

<u>CP conserving scenario:</u> $\delta \cong 0\,, \qquad \alpha_{21} \cong \pi$

$\sin\theta_{13} \gtrsim 0.13$ **compatible with Daya Bay measurement!**

<u>CP violating scenario:</u> $\tan\delta \cong -\tan(\alpha_{21}/2)/\cos 2\theta_{12}$

$$\sin\theta_{13} = \frac{c_{23}}{s_{23}}\,\frac{\sqrt{1+\tan^2\delta}\,\cos 2\theta_{12}}{\sqrt{1+\cos^2 2\theta_{12}\,\tan^2\delta} + 2c_{12}\,s_{12}\,\text{sgn}(\cos\delta)}$$

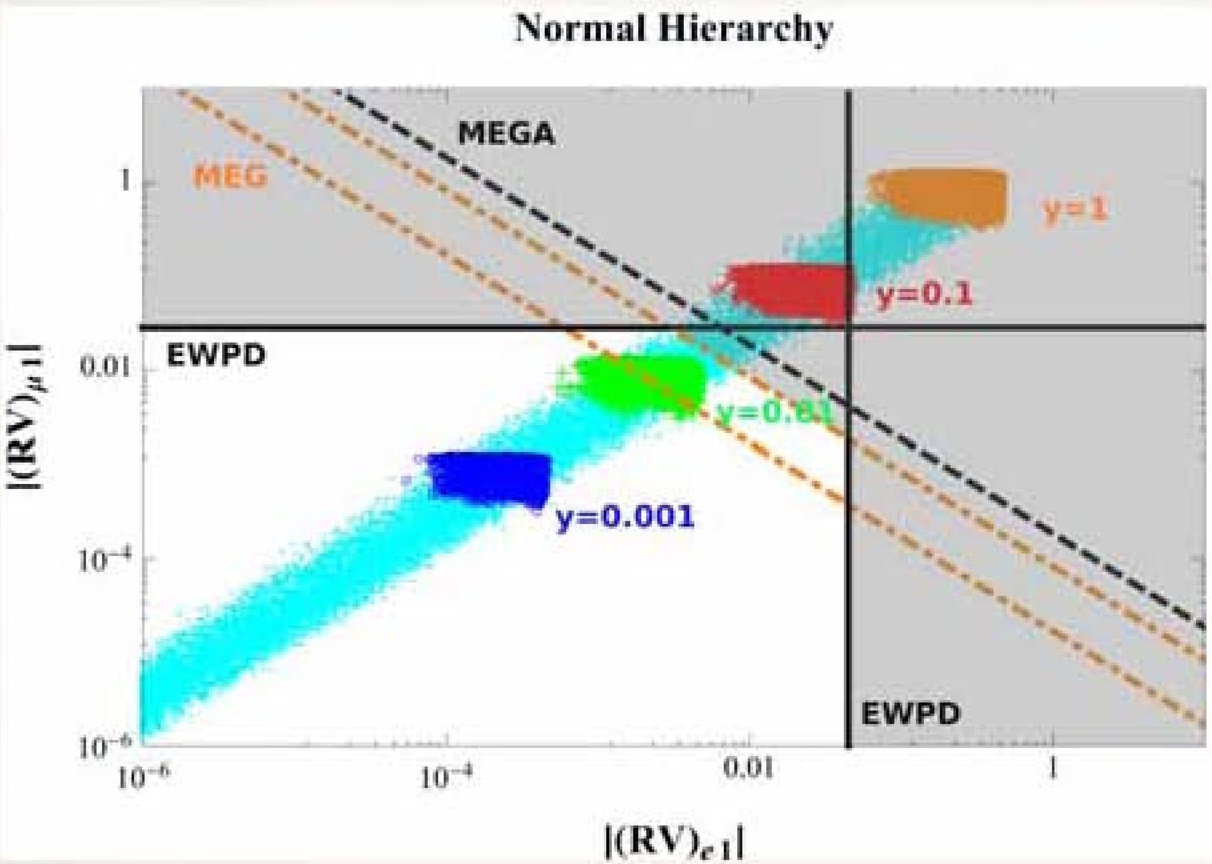


$0 \simeq \delta \simeq 0.7$

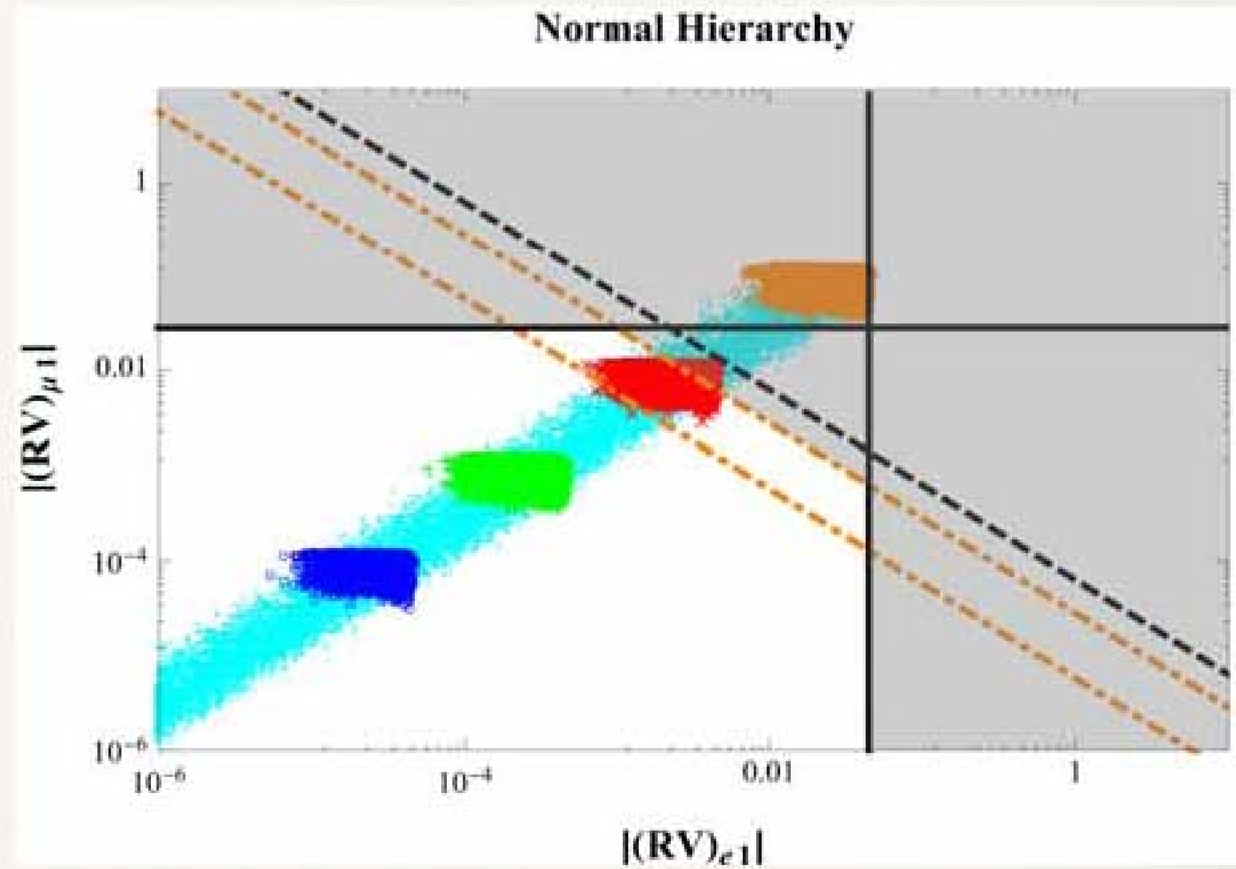
Putting together all the constraints:

Ibarra, EM, Petcov, 2011
Dinh, Ibarra, EM, Petcov, 2012

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



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



Discovery channel at LHC with L~13 fb^{-1} and M_1 = 100 GeV:

$$q\bar{q}' \to \mu^+ N_{PD} \to \mu^+\mu^- W^+ \to \mu^+\mu^-\mu^+\nu_\mu \,.$$

del Aguila, Aguilar-Saavedra, 2009

Taking $|(RV)_{\mu 1}| \gtrsim 0.04$

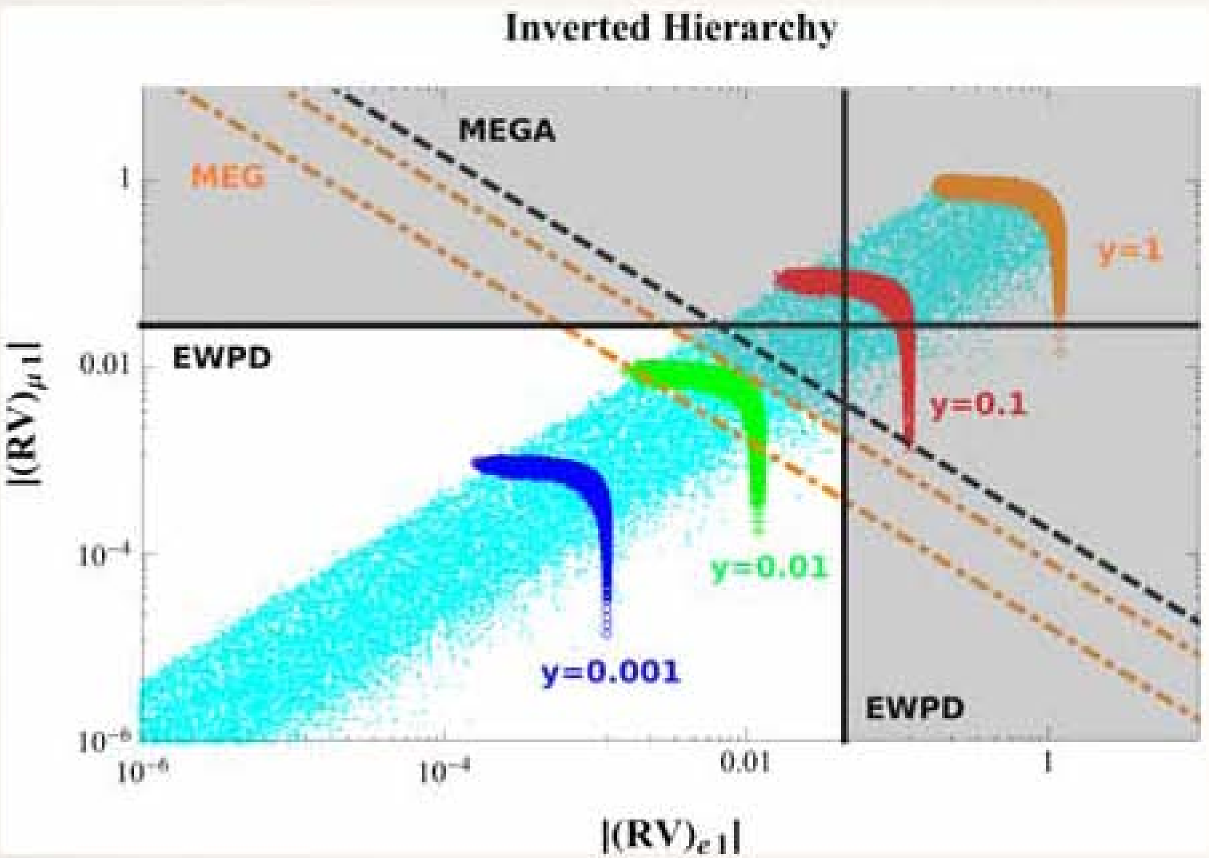
$y \gtrsim 0.04$ for NH with $M_1 = 100\,\mathrm{GeV}$
$y \gtrsim 0.05$ for IH with $M_1 = 100\,\mathrm{GeV}$

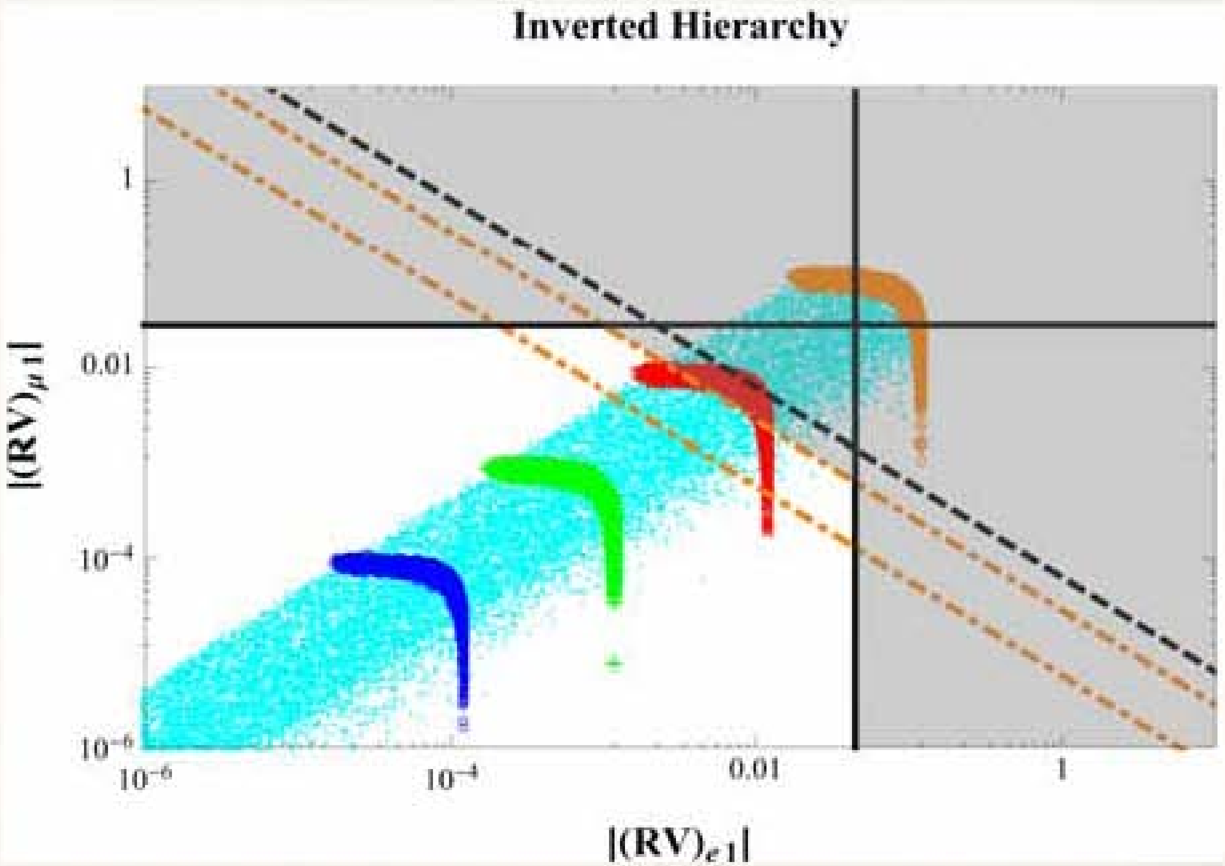
no production and detection at LHC due to LFV bound!

Putting together all the constraints:

Ibarra, EM, Petcov, 2011
Dinh, Ibarra, EM, Petcov, 2012

$M_1 = 100$ GeV $M_1 = 1000$ GeV





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no production and detection at LHC due to LFV bound!

Constraints from LFV observables: $\mu - e$ conversion in nuclei

Dinh, Ibarra, EM, Petcov, 2012

Present experimental bound:

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

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**

In type I see-saw scenarios at EW scale with sizeable Yukawa couplings:

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

depends on very few parameters!

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

Hisano, Moroi, Tobe, Yamaguchi, Yanagida, 1995
Hisano, Moroi, Tobe, Yamaguchi, 1996
Buras,Duling,Feldmann,Heildsiek,Promberger, 2010

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In type I see-saw scenarios at EW scale with sizeable Yukawa couplings:

- very small values of the couplings may be probed, e.g. from $\mathrm{CR}(\mu\mathrm{Ti} \to e\mathrm{Ti}) \approx 10^{-18}$

$$\left|(RV)^*_{\mu 1}(RV)_{e1}\right| \lesssim 2.6 \times 10^{-8}\ (0.14 \times 10^{-8}) \quad \text{for} \quad M_1 \approx 100\ (1000) \quad \mathrm{GeV}$$

- interplay between different LFV observables:

$$\frac{\mathrm{CR}(\mu\,\mathrm{Ti} \to e\,\mathrm{Ti})}{\mathrm{BR}(\mu \to e\gamma)} \approx 4.2\ (174) \quad \text{for} \quad M_1 \approx 100\ (1000) \quad \mathrm{GeV}$$

only one unknown parameter: the RH neutrino mass!

Constraints from LFV observables: $\mu - e$ conversion in nuclei

Dinh, Ibarra, EM, Petcov, 2012

Present experimental bound:

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

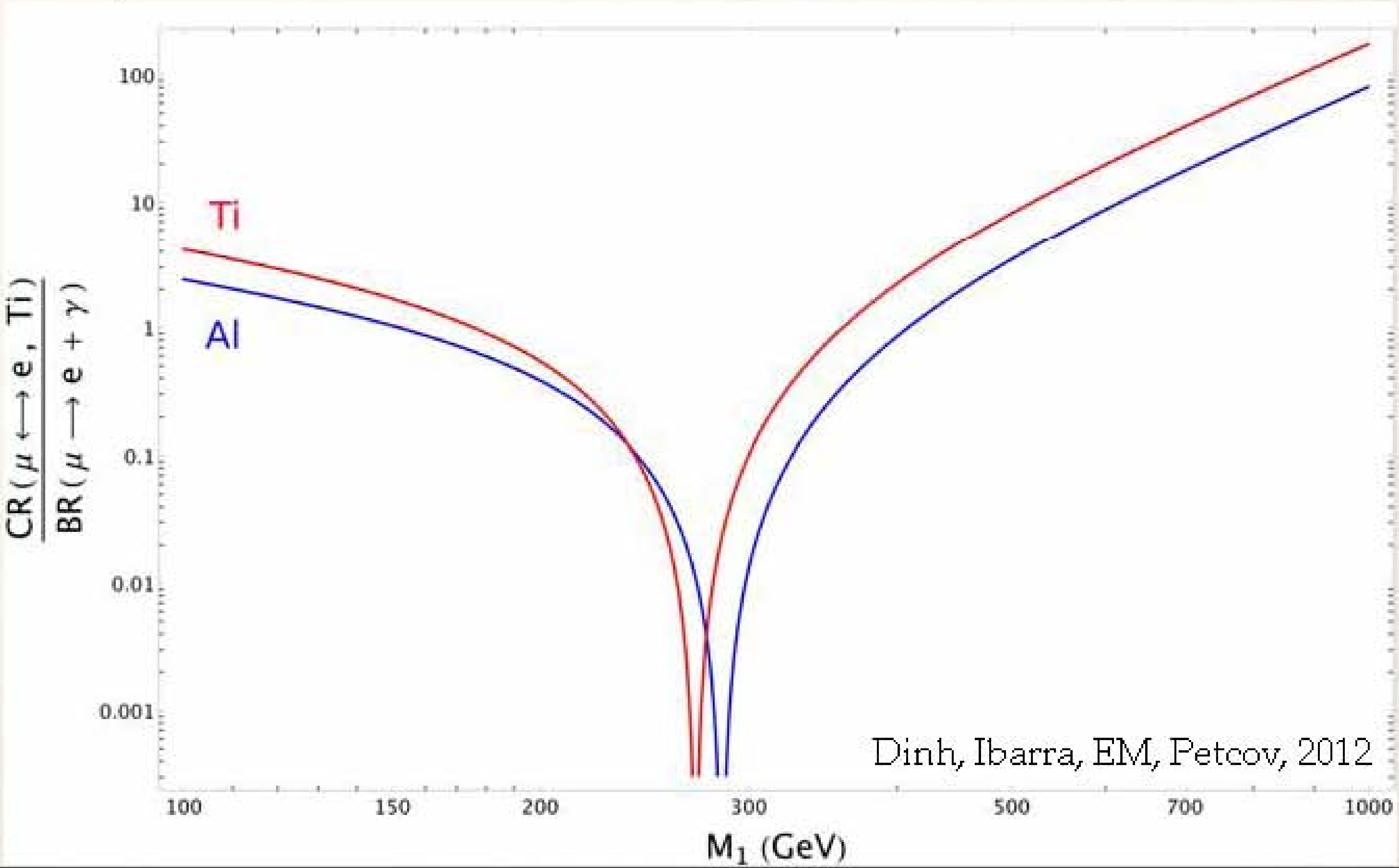
Projected bounds:

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

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

ratio highly affected

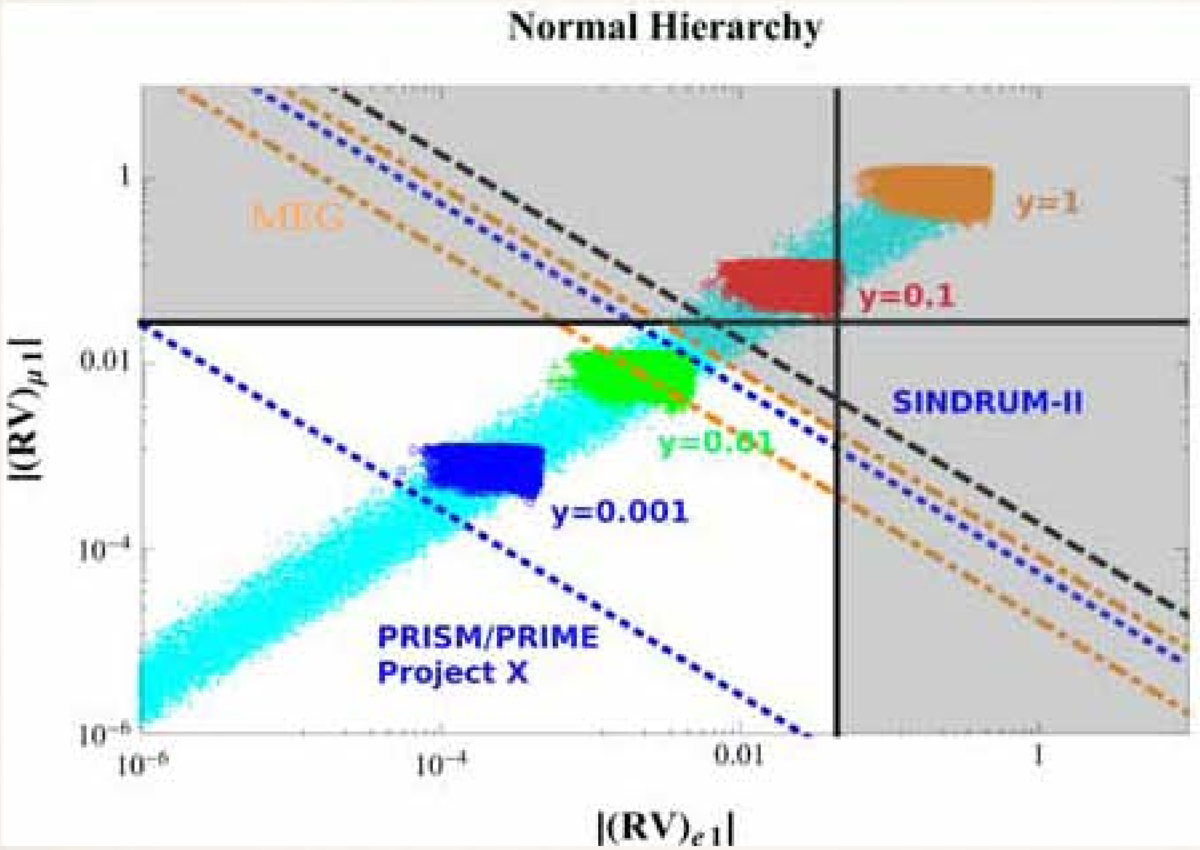
by the value of M_1!

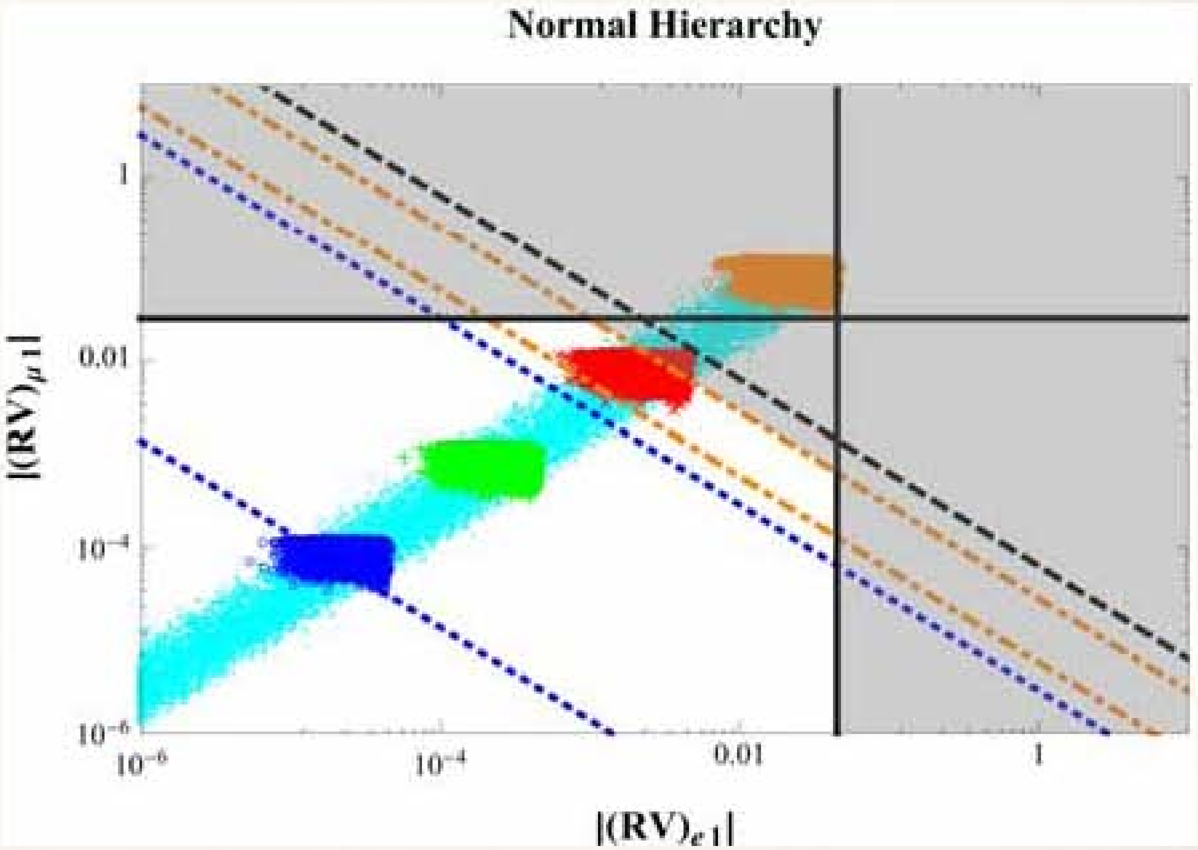


Putting together all the constraints:

Dinh, Ibarra, EM, Petcov, 2012

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





possibility to probe values of $y \lesssim 0.001$

Constraints from LFV observables: $\mu^+ \to e^+ + e^- + e^+$

Dinh, Ibarra, EM, Petcov, 2012

Present experimental bound:

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

Projected bounds:

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

Branching ratio sensitive to the neutrino Yukawa coupling and the RH neutrino mass:

$$\mathrm{BR}(\mu \to 3e) \;=\; \frac{4\,\alpha_{\rm em}^2}{\pi^2} \left|(RV)^*_{\mu 1}(RV)_{e1}\right|^2 \left|C_{\mu 3e}(M_1^2/M_W^2)\right|^2$$

flavour structure fixed by neutrino oscillation data

contributions from $\gamma-$penguin and box type diagrams
Hisano et al., 1996; Buras et al., 2010

From the current experimental bound:

$$\left|(RV)^*_{\mu 1}(RV)_{e1}\right| \lesssim 2.1 \times 10^{-4}\ (5.3 \times 10^{-6}) \quad \text{for} \quad M_1 = 100\ (1000) \quad \text{GeV}$$

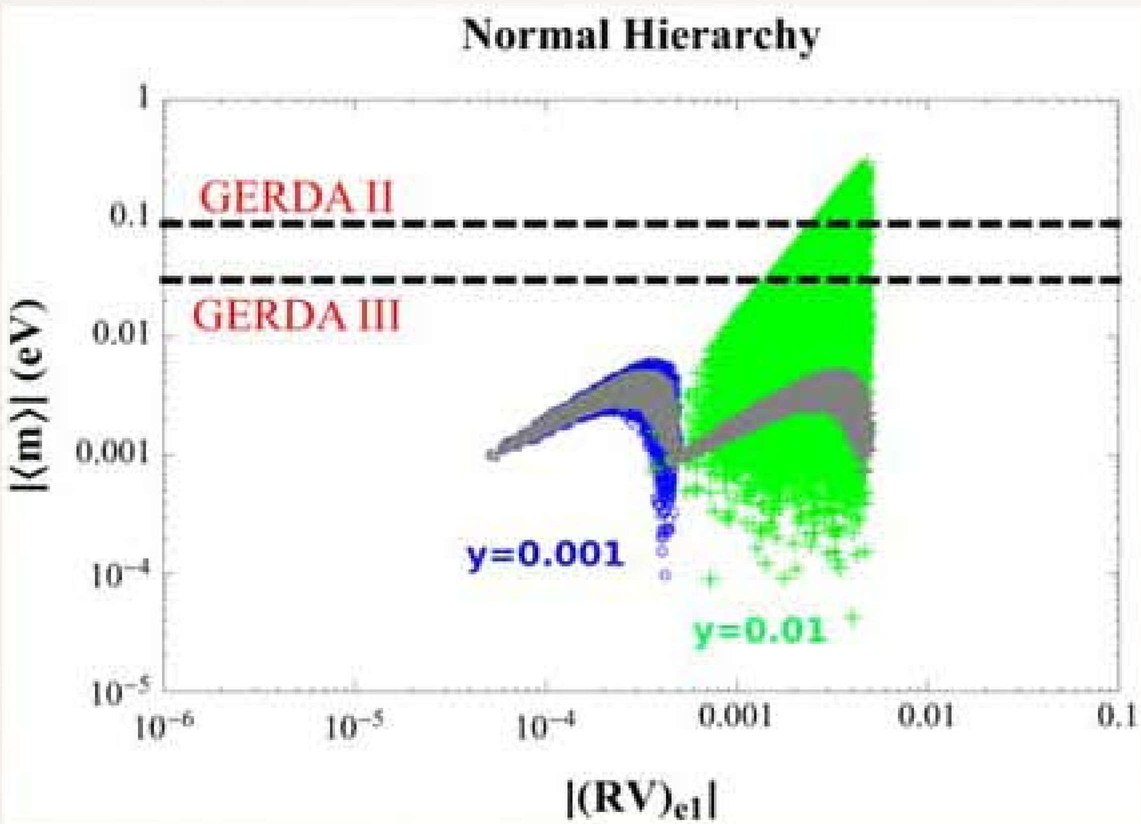
less stringent than $\mu - e$ conversion in Ti

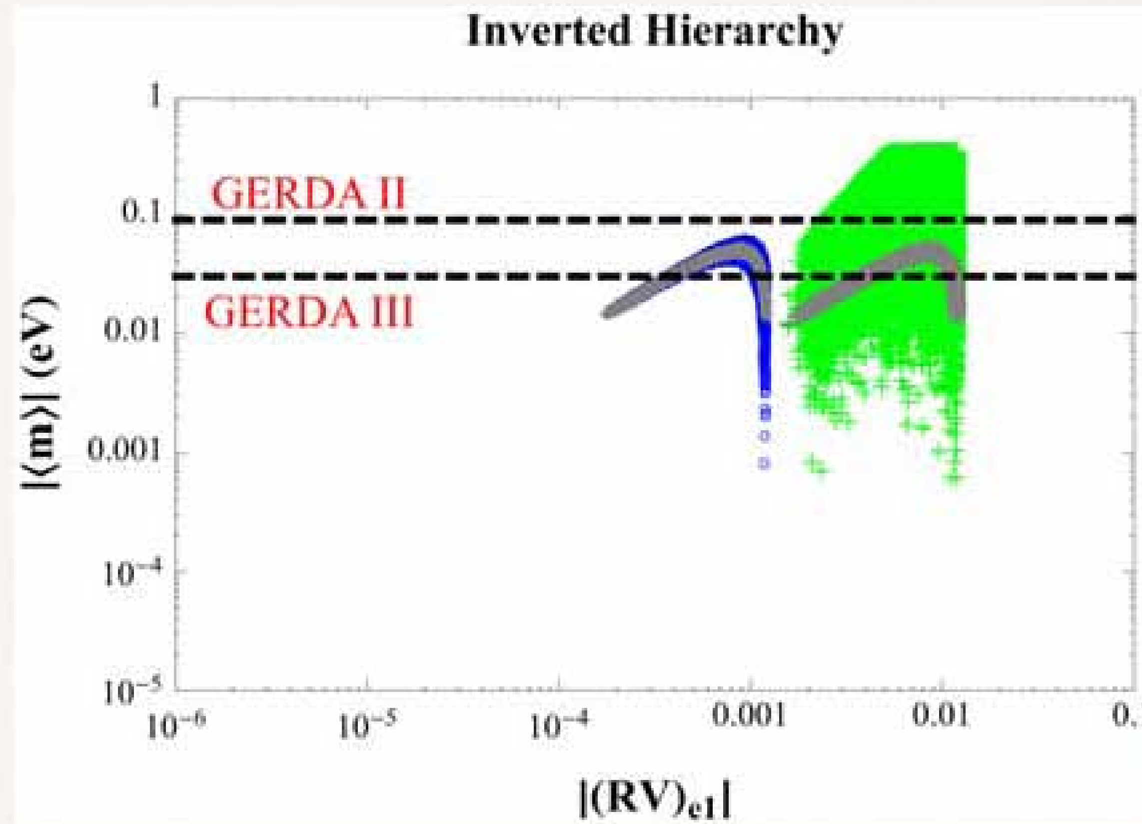
$$\frac{\mathrm{BR}(\mu \to 3e)}{\mathrm{BR}(\mu \to e\gamma)} \gtrsim 0.067 \quad \text{for } M_1 \geq 100\ \text{GeV}$$ **lower bound on the ratio**

Future constraints from neutrinoless double beta decay:

$$(A, Z) \Longrightarrow (A, Z+2) + e^- + e^-$$

^{48}Ca, ^{76}Ge, ^{82}Se, ^{124}St, ^{130}Te, ^{136}Xe



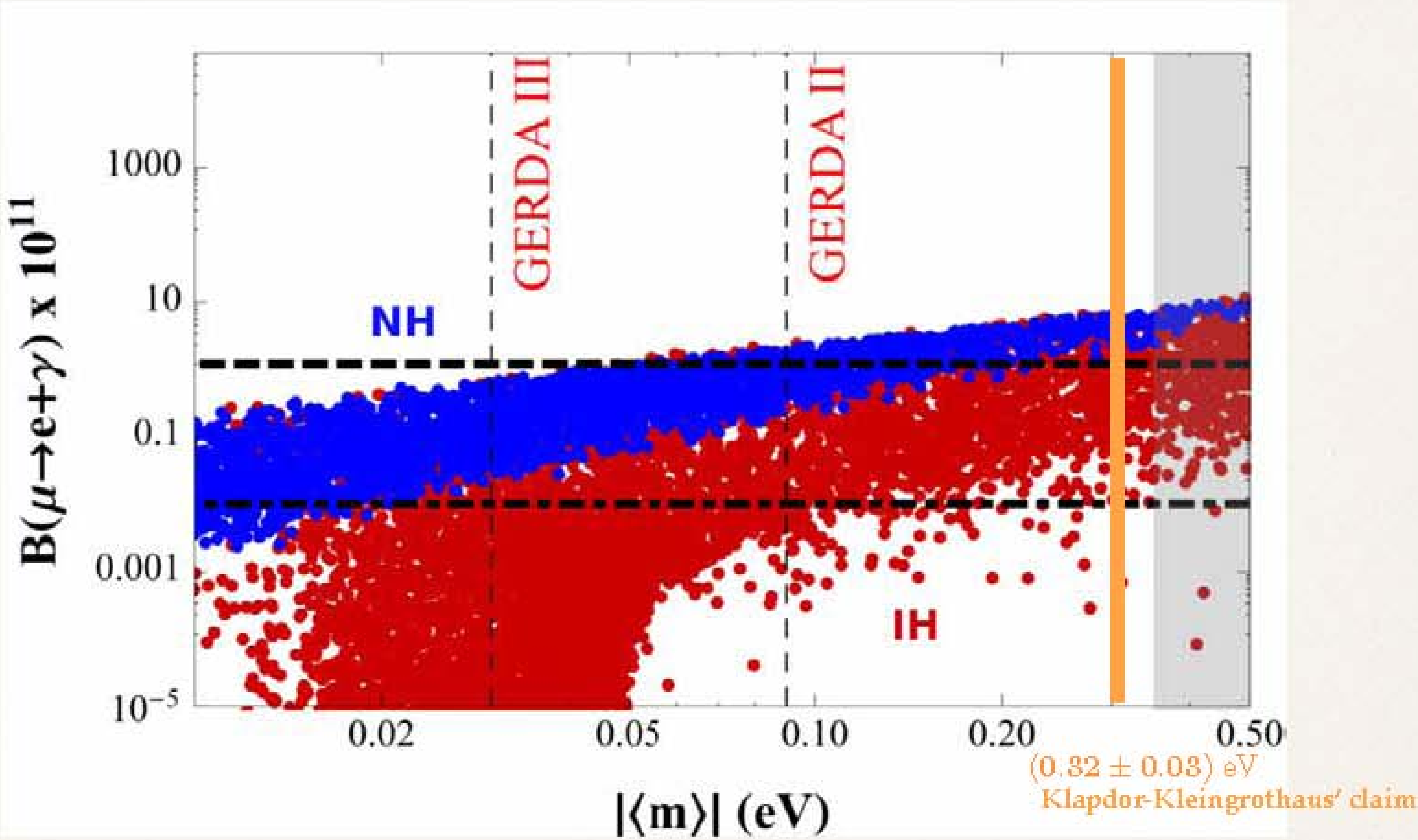


$$M_1 = 100 \text{ GeV}$$

$$|\langle m \rangle| \cong \left| \sum_{i=1}^{3} U_{ei}^2 m_i - \sum_{k=1}^{2} f(A) (RV)_{ek}^2 \frac{M_a^2}{M_k} \right|$$

Ibarra, EM, Petcov, 2011

Interplay between different low energy observables:



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

Ibarra, EM, Petcov, 2011

Summary about type I see-saw scenarios:

A minimal extension of the Standard Model, which aims to explain the mechanism of generation of neutrino masses and mixing, consists in adding RH neutrinos. The RH neutrino mass introduces a new scale in the theory.

The TeV scale see-saw model may 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 $0\nu\beta\beta$-decay

1. RH neutrino must be almost degenerate in mass
2. $y \lesssim 0.03\ (0.1)$ for $M_1 = 100\,\mathrm{GeV}\ (1000\,\mathrm{GeV})$ and $\sin\theta_{13} = 0.13$
3. values of $y \gtrsim$ few $\times\ 10^{-4}$ can be probed with $\mu - e$ conversion in Ti

TYPE II SEESAW MECHANISM
(Higgs Triplet Models)

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:

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

Lepton number soft-breaking parameter

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

Generation of active neutrino masses

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 <u>in the limit $\mu_\Delta \to 0$: massless neutrinos</u>

Generation of active neutrino masses

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:

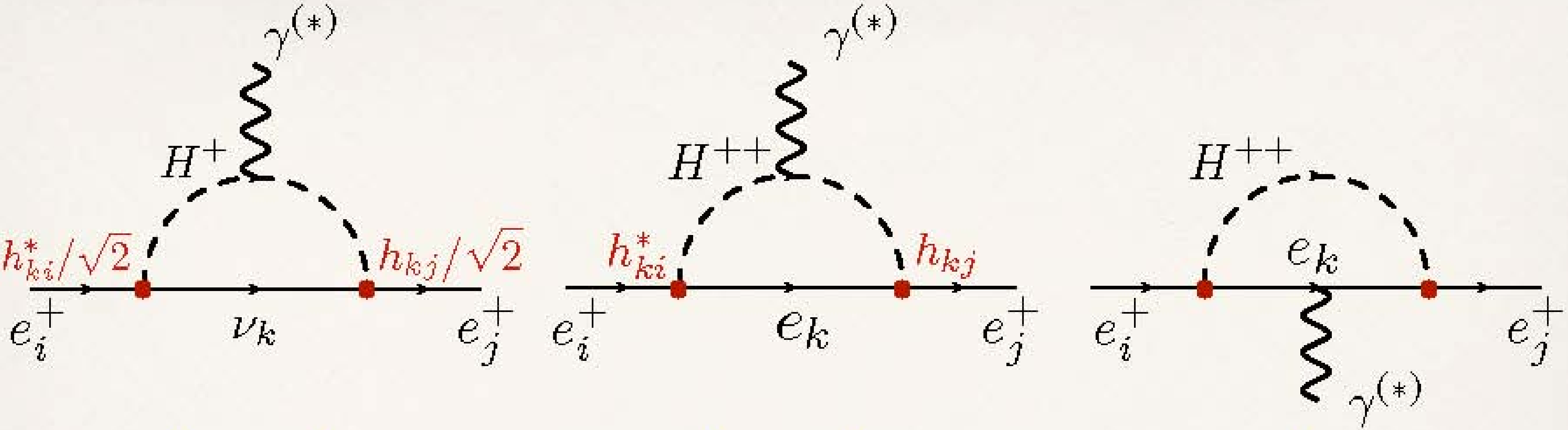
$$\underbrace{H^{\pm\pm}}_{\text{only triplet}},\ \underbrace{H^{\pm},\ H^0,\ A^0}_{\text{mainly triplet}},\ \underbrace{h^0}_{\text{mainly doublet}}$$

Possible hierarchies:

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

Lepton Flavour Violation

Dinh, Ibarra, EM, Petcov, 2012



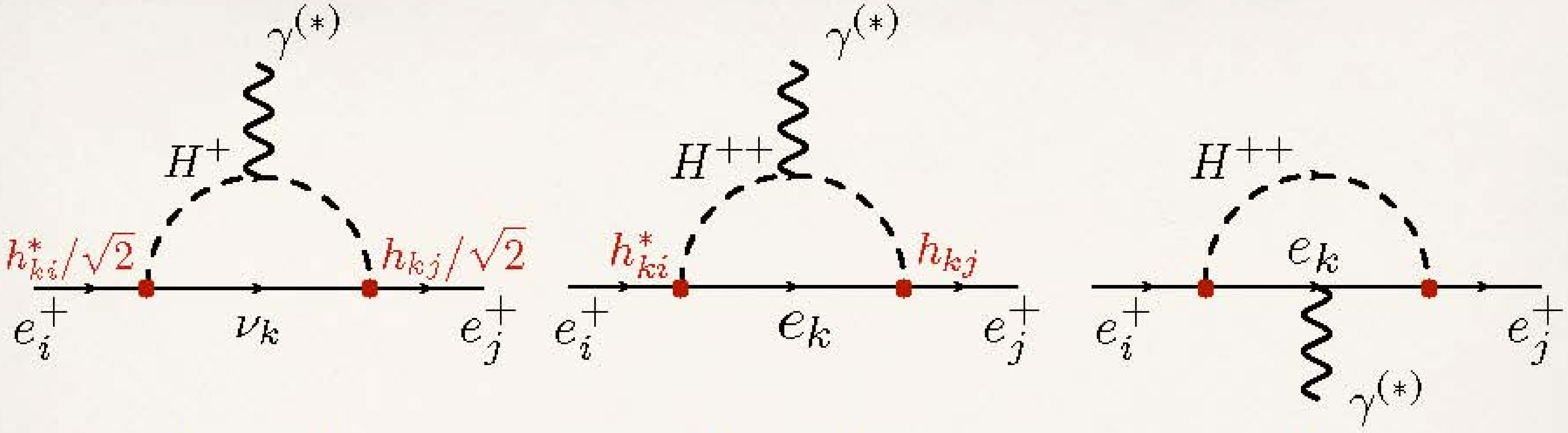
$A_R\ ,\ A_L$ $\qquad$ $A_R\ ,\ A_L$ $\qquad$ A_L

Effective low energy LFV Lagrangian:

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

Lepton Flavour Violation

Dinh, Ibarra, EM, Petcov, 2012



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

Effective low energy LFV Lagrangian:

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

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

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

Constraints from LFV observables: $\mu \to \mathrm{e} + \gamma$

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

- **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:**

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

exact relation

independent of the Majorana phases

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

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

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

Constraints from LFV observables: $\mu \to e + \gamma$

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

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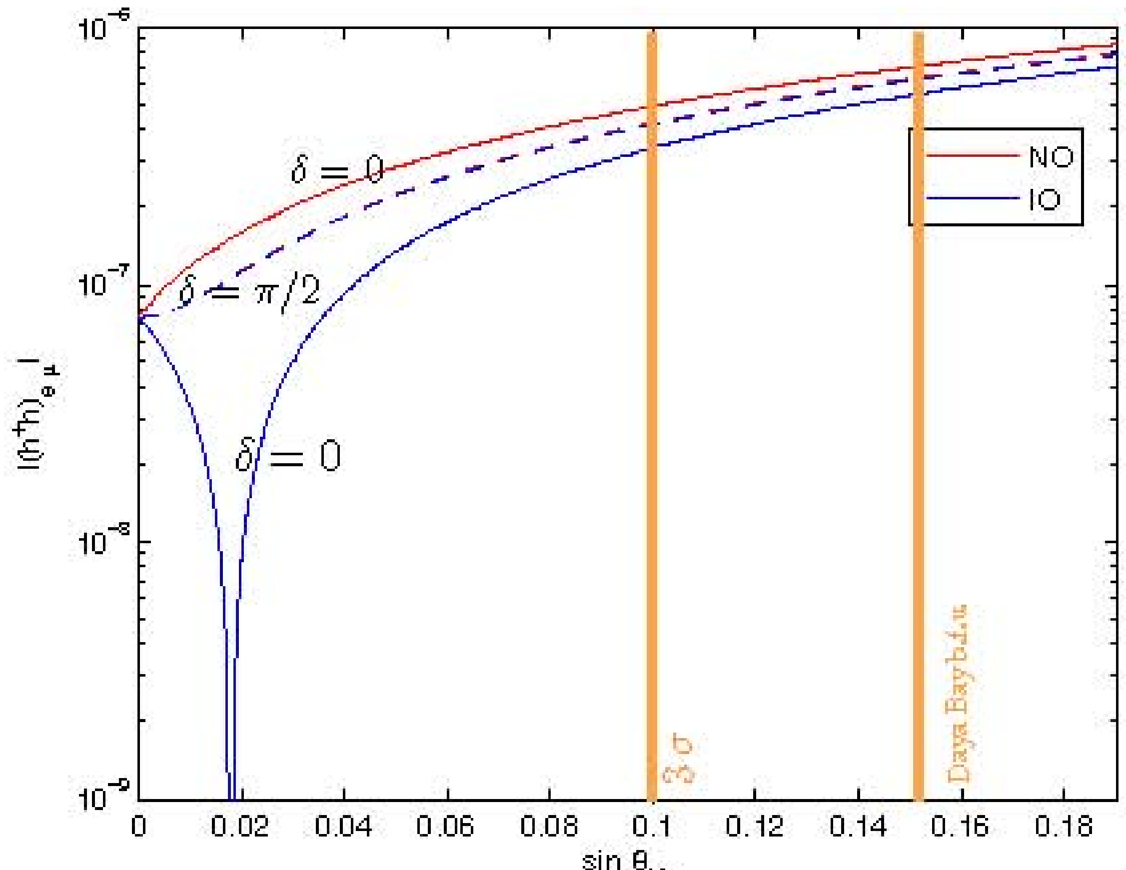
$$\left|(h^\dagger h)_{e\mu}\right| \;<\; 5.8\times 10^{-6}\left(\frac{M_\Delta}{100\,\mathrm{GeV}}\right)^2$$

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



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

Constraints from LFV observables: $\mu - \mathrm{e}$ conversion in nuclei

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

Constraints from LFV observables: $\mu - e$ conversion in nuclei

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

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:

Constraints from LFV observables: $\mu - e$ conversion in nuclei

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$$\left. + \frac{1}{m_{H^{++}}^2}\sum_{l=e,\mu,\tau} h^\dagger_{e\ell}\, f\left(\frac{m_\mu^2}{m_{H^{++}}^2},\frac{m_\ell^2}{m_{H^{++}}^2}\right) h_{\ell\mu}\right|^2$$

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:

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

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

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

From current experimental upper limit in Ti

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

Constraints from LFV observables: $\mu - e$ conversion in nuclei

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

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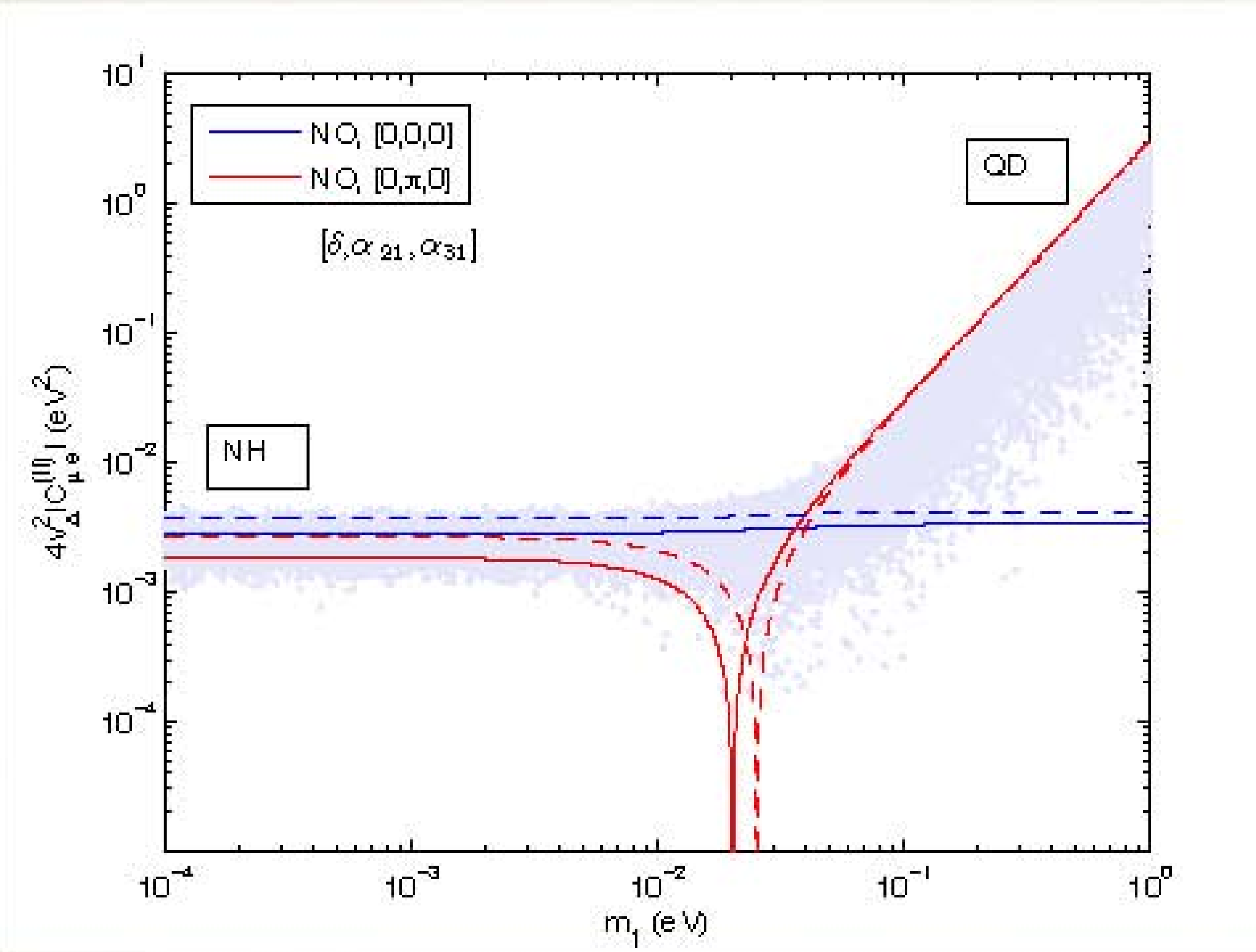
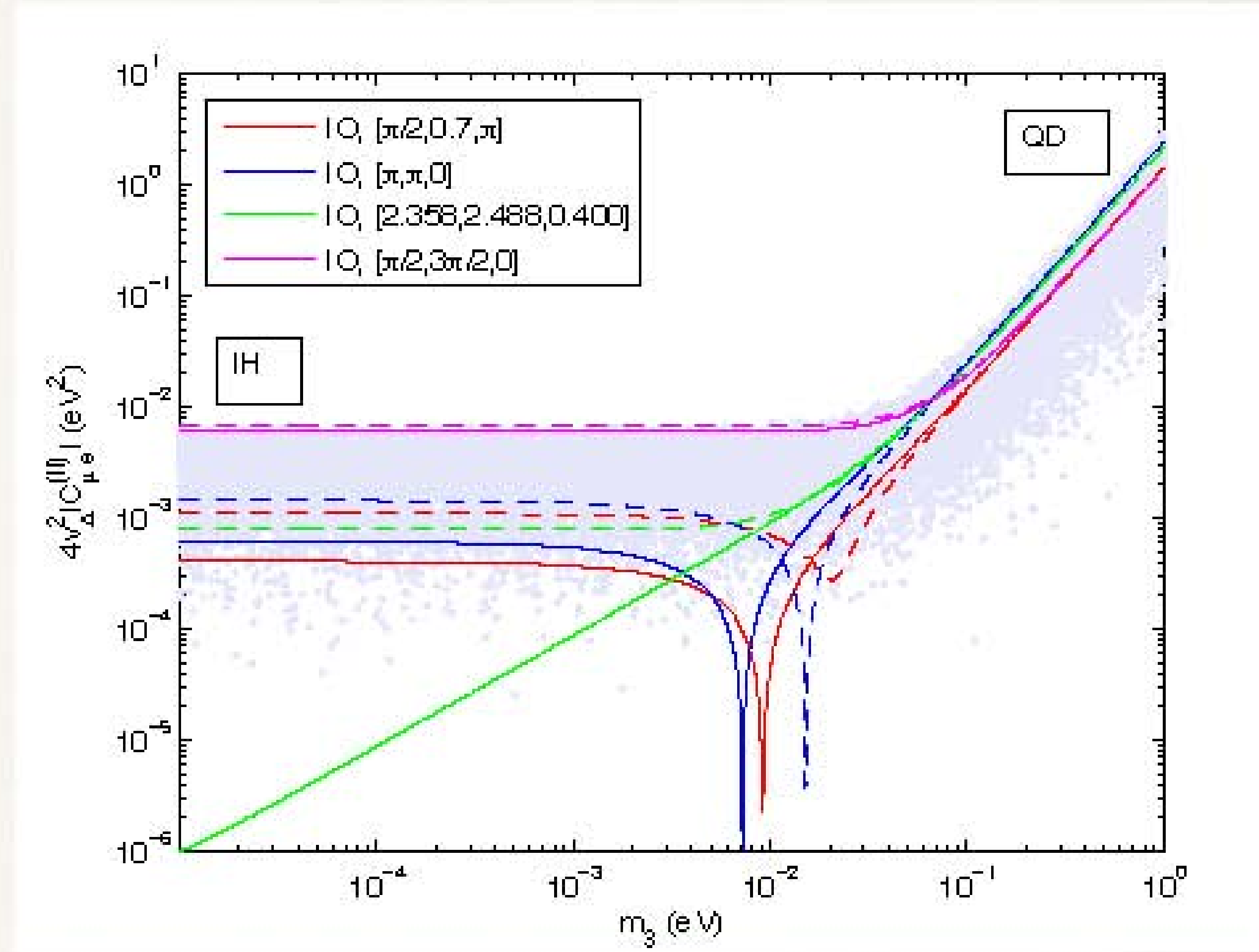
An experiment sensitive to CR ~ 10^{-18} will be able to probe values

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

Putting together all the constraints:





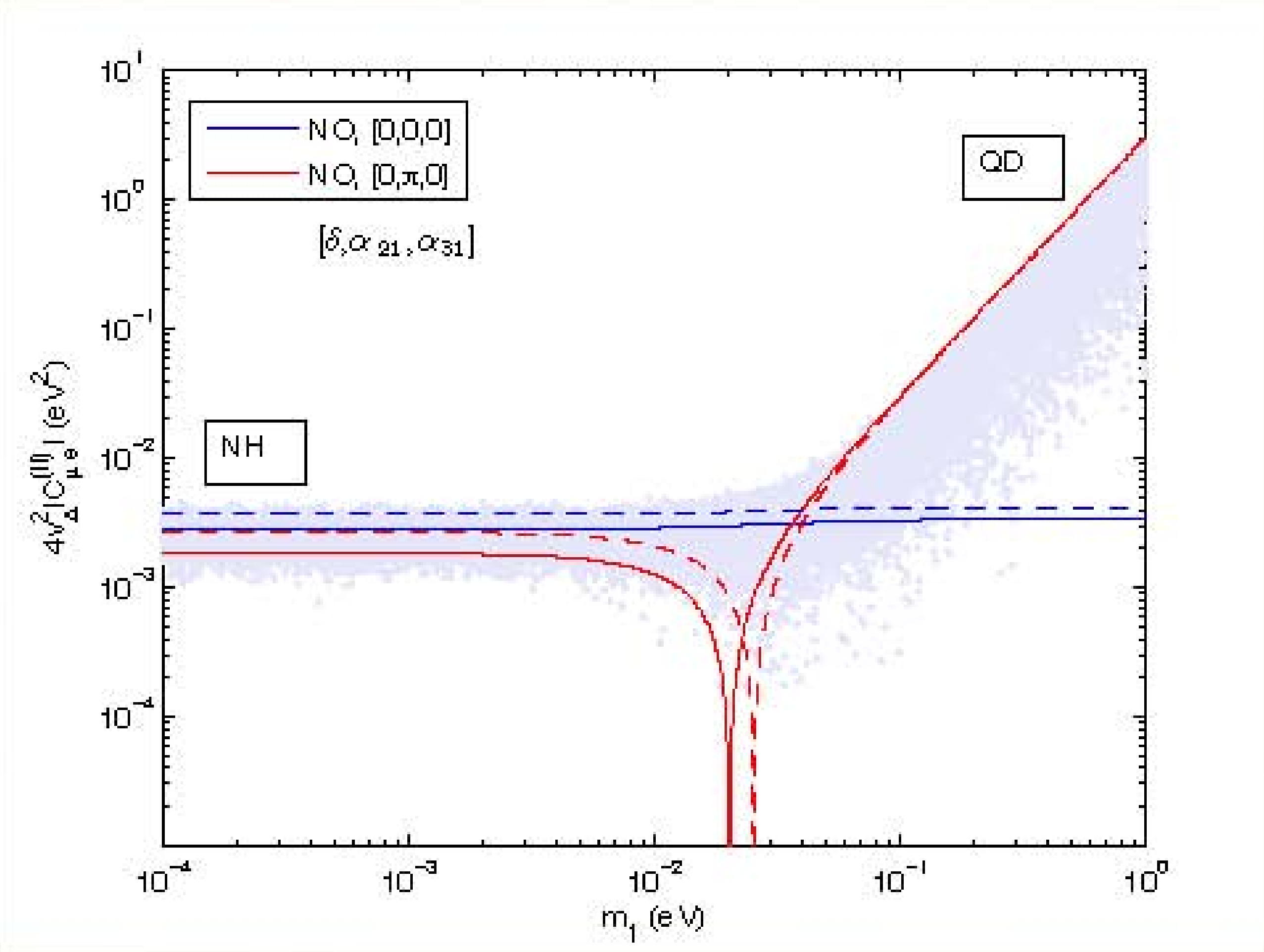
$$M_\Delta = (100 - 1000)\ \mathrm{GeV}$$

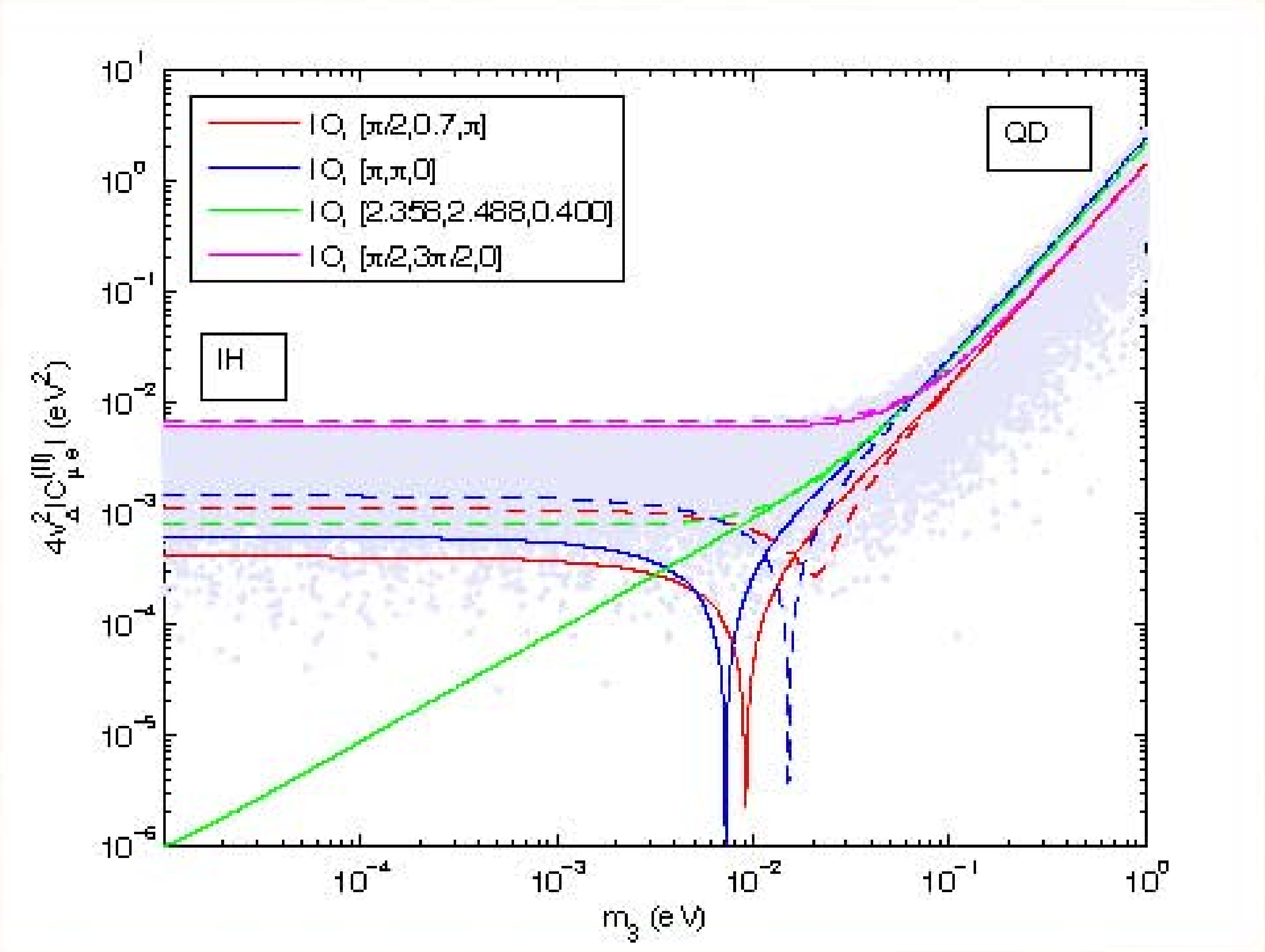
no strong suppression in the limit $m^2_{H^{++}} \gg m^2_{H^+} > (100\ \mathrm{GeV})^2$

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

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

Putting together all the constraints:





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

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

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

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

Constraints from LFV observables: $\mu^+ \to e^+ + e^- + e^+$

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

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

fixed flavour structure !

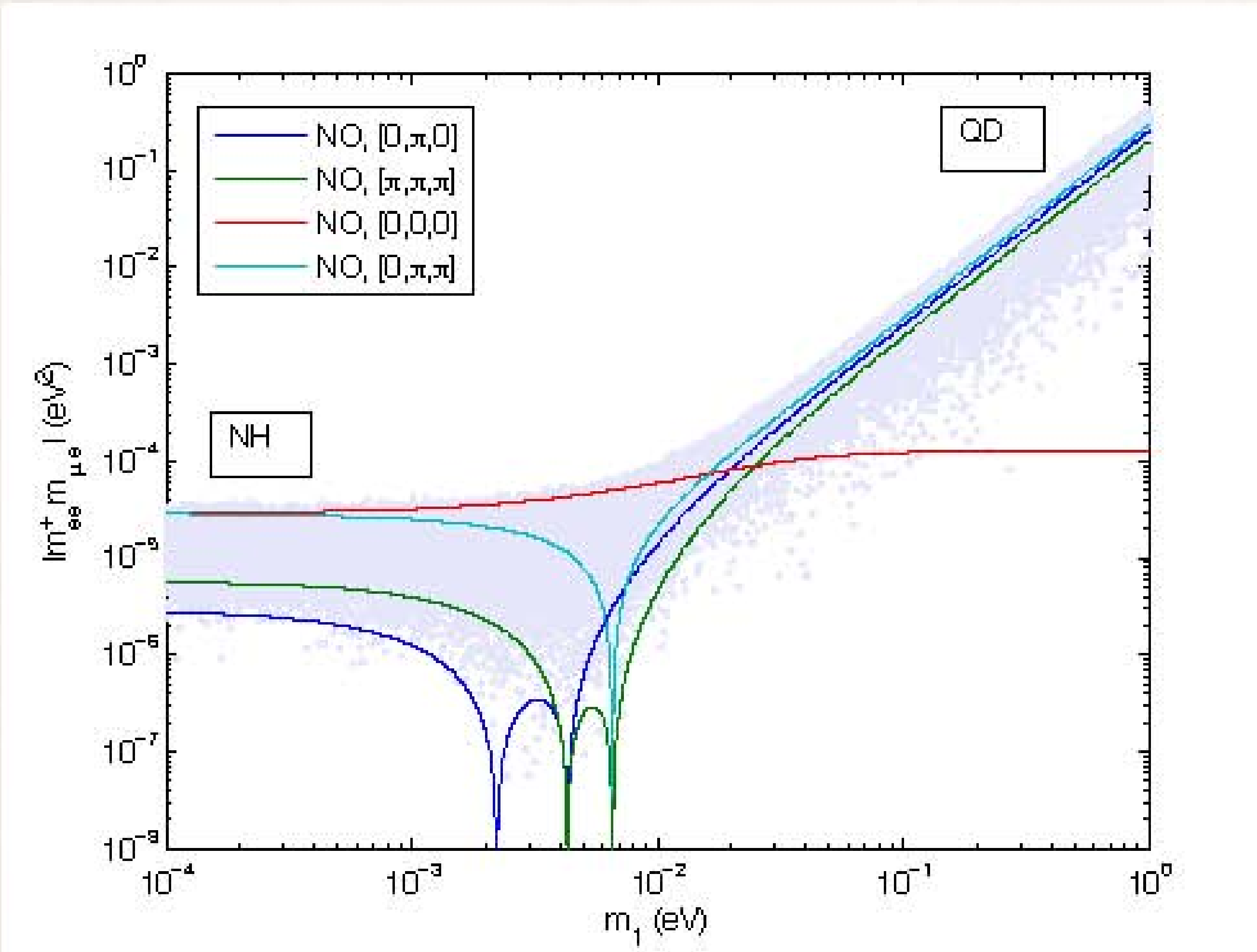
For $M_{H^{\pm\pm}} = (100 - 1000)$ GeV and $v_\triangle \ll 1$ MeV:

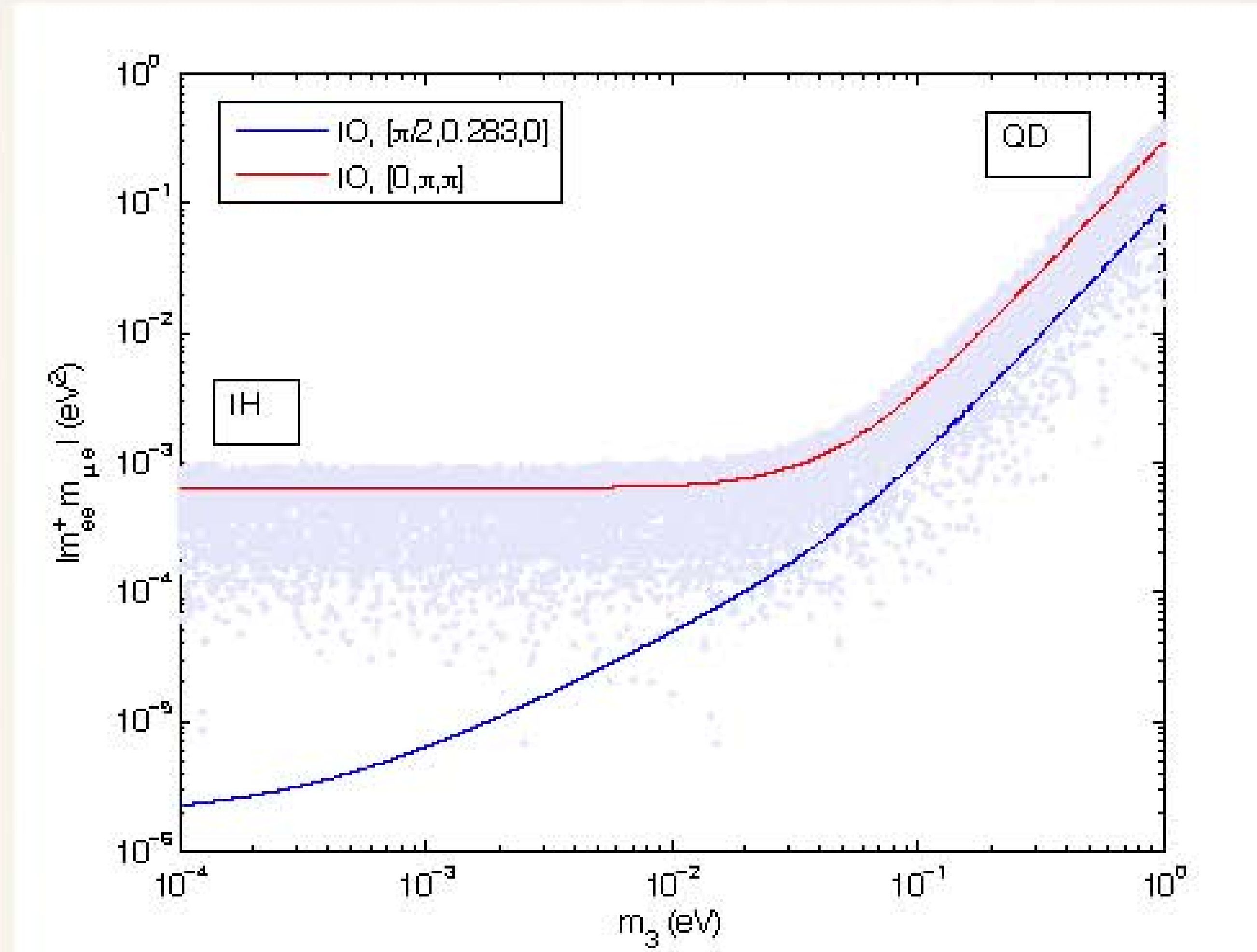
$$|(m_\nu)_{ee}| = \left|\sum_{j=1}^{3} m_j U^2_{ej}\right| \cong |\langle m \rangle|$$

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

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

Putting together all the constraints:





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

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

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

observable effects!

Summary about type II see-saw (Higgs triplet) scenarios:

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:

- $BR(\mu \to e\gamma)$ does not depend on the Majorana CPV phases and on $\min(m_j)$
- $BR(\mu \to 3e)$ and $CR(\mu\mathcal{N} \to e\mathcal{N})$ 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