

Neutrino Oscillation Workshop

*Conca Specchiulla (Otranto, Italy)
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Minimal Flavor Violating extensions of the seesaw

(Type-I seesaw with 3 RH neutrinos)

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Based mainly on:

- R. Alonso, G. Isidori, L. Merlo, L. A. Muñoz, EN JHEP06(2011)037 [arXiv:1103.5461]
- V. Cirigliano, B. Grinstein, G. Isidori, M. B. Wise, NPB728(2005) [hep-ph/0507001]
- EN, NPB (Pr. S.) 2257(2012)236 [arXiv:1112.4418]

Why Charged Lepton Flavor Violation (cLFV)?

- ν -oscillations indisputably signal LFV in the neutral sector.
 - In extensions of the SM that can account for ν -oscillations it is natural to expect also cLFV.
 - However, in the simplest extensions (Dirac ν , SM+seesaw) cLFV remains unobservable (below the $\mathcal{O}(10^{-50})$ level).
 - Dirac ν : no new scale. Seesaw: large new scale $\Lambda_{\cancel{L}} \sim \Lambda_{\text{GUT}}$
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However, according to an old theoretical prejudice:

There is New Physics around the TeV scale

since NP is needed to cure the SM naturalness problem.

The flavor problem

If NP has a generic flavor structure, then FCNC constraints require $\Lambda_{\text{NP}} > \mathcal{O}(10^5) \text{ TeV} (\gg \Lambda_{EW})$

Possible ways out (apart from accepting $\Lambda_{\text{NP}} \gtrsim \mathcal{O}(10^5) \text{ TeV}$)

NP is Flavor Blind However, complete *blindness* is difficult to realize, it is theoretically unmotivated, (is boring), etc.

TeV-NP should (*approximately*) conserve B , $B-L$, CP (SM).
No reason for conserving *flavor*, that is not a SM symmetry.

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NP Violates Flavor Minimally The only sources of flavor violation are the SM Yukawa couplings

Ansatz: TeV-scale NP violates flavor “as much” as the SM does

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G. D’Ambrosio, G.F. Giudice, G. Isidori, A. Strumia, Nucl. Phys. B 645 (2002) 155, hep-ph/0207036.

V. Cirigliano, B. Grinstein, G. Isidori, M.B. Wise, Nucl. Phys. B 728 (2005) 121, hep-ph/0507001.

V. Cirigliano, B. Grinstein, Nucl. Phys. B 752, 18 (2006), [hep-ph/0601111].

B. Grinstein, V. Cirigliano, G. Isidori, M. B. Wise, Nucl. Phys. B 763, 35 (2007), [hep-ph/0608123].

S. Davidson, F. Palorini, Phys.Lett. B 642 (2006) 72, hep-ph/0607329.

...

MFV in the Quark Sector

[G D'Ambrosio et al., NPB 645 (2002) 155, hep-ph/0207036]

Gauge invariant kinetic terms

vs.

Yukawa interactions

$$\underbrace{\bar{Q}_i \not{D}_Q Q_i + \bar{u}_i \not{D}_u u_i + \bar{d}_i \not{D}_d d_i}_{U(3)_Q \times U(3)_u \times U(3)_d = \mathcal{G}_F \times U(1)_B \times U(1)_u \times U(1)_d} + \underbrace{\bar{Q}_i Y_u^{ij} u_j H + \bar{Q}_i Y_d^{ij} d_j \tilde{H}}_{\cancel{\mathcal{G}}_F, \quad \cancel{U(1)}_u, \quad \cancel{U(1)}_d \quad U(1)_B}$$

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To construct the MFV NP Operators $\Rightarrow$ Spurion Technique:

- Introduce Yukawa *formal* transformations $Y_{u,d} \rightarrow V_Q Y_{u,d} V_{u,d}^\dagger$
- Require formal invariance under the flavor group $\mathcal{G}_F$.

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NP Opts.: Dipole Contact Suppressed by Y_d

$$\frac{1}{\Lambda_{NP}^2} \times \quad \bar{Q} \sigma_{\mu\nu} Y_u Y_u^\dagger Q \cdot (F^{\mu\nu}); \quad \bar{Q} Y_u Y_u^\dagger Q \cdot (\bar{Q} Q); \quad \bar{d} Y_d^\dagger Y_u Y_u^\dagger Q \cdot (\bar{Q} Q)$$

MFV in the Lepton Sector

[V. Cirigliano et al. NPB 728 (2005) 121; V. Cirigliano and B. Grinstein, NPB752, 18 (2006)]

[R. Alonso, G. Isidori, L. Merlo, L. A. Munoz, EN, JHEP 1106, 037 (2011).

$$\begin{array}{ccc}
 \boxed{\text{SM:}} & \underbrace{\bar{\ell}_i \not{D}_\ell \ell_i + \bar{e}_i \not{D}_e e_i}_{U(3)_\ell \times U(3)_e = \mathcal{G}_F^{SM} \times U(1)_\ell \times U(1)_e} & + \underbrace{\bar{\ell}_i Y_e^{ij} e_j H}_{U(1)_e \times U(1)_\mu \times U(1)_\tau} \\
 & \Rightarrow &
 \end{array}$$

The SM Lepton sector is incomplete $\left[\begin{array}{l} \text{no } \nu\text{-masses} \\ \text{no } \nu\text{-oscillat.} \end{array} \right]$. A choice for a specific SM extension must be made:

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$$\underbrace{\bar{\ell} \not{D}_\ell \ell + \bar{e} \not{D}_e e + \overbrace{\bar{N} \not{D} N}^{\text{Kinetic}}}_{U(3)_{\ell,e}^2 \times U(3)_N = \mathcal{G}_F \times U(1)_L \times U(1)_{e,N}^2} + \underbrace{\bar{\ell}_i Y_e^{ij} e_j H + \overbrace{\bar{\ell}_i Y_\nu^{ij} N_j \tilde{H}}^{\text{Yukawa}}}_{\cancel{\mathcal{G}_F}, \cancel{U(1)_{e,N}^2}} + \frac{1}{2} \underbrace{\mu_L \bar{N}_i^c \overbrace{Y_M^{ij}}^{\text{Majorana}} N_j}_{\cancel{U(1)_L} \cancel{U(1)_N^2}}$$

Role of $U(1)_{e,N}^2$ see: R. Alonso et al., JHEP 1106 037 (2011); D. Aristizabal et al., JHEP 1207 135 (2012).

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3 spurions $Y_e, Y_\nu, Y_M \Rightarrow$ The leading MLFV effective terms:

$$\Delta_8^{(1)} = Y_\nu Y_\nu^\dagger, \quad \Delta_6 = Y_\nu Y_M^\dagger Y_\nu^T, \quad \Delta_8^{(2)} = Y_\nu Y_M^\dagger Y_M Y_\nu^\dagger, \quad Y_e \Delta, \quad \dots$$

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Predictivity: Y_ν, Y_M (18) $\Leftrightarrow m_\nu, U_{\text{PMNS}}$ (9)

Two ansatzs can match No. LFV paramts to No. observables:

$$1) Y_M \propto I_{3 \times 3}$$

Reduced symmetry: $SU(3)_N \rightarrow SO(3)_N \times CP$

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2) $Y_\nu \propto \mathcal{U}_Y$ (Unitary)

Symmetry: $SU(3)_N \times SU(3)_\ell \rightarrow SU(3)_{N+\ell}$

[R. Alonso, G. Isidori, L. Merlo, L. A. Munoz, EN, JHEP 1106, 037 (2011)]

$$\Delta_6 = \frac{v^2}{\mu_L} U \frac{1}{\mathbf{m}_\nu} U^T; \quad \Delta_8^{(2)} = \Delta_6 \cdot \Delta_6^\dagger = \frac{v^4}{\mu_L^2} U \frac{1}{\mathbf{m}_\nu^2} U^\dagger \quad \Delta_8^{(1)} = I_{3 \times 3}$$

- This second scenario (2) allows for $\mathcal{CP}$.
- Non-Abelian symmetries ($\Rightarrow$ TBM) imply $Y_\nu^0 \propto \mathcal{U}_Y$ at LO.

[E. Bertuzzo, P. Di Bari, F. Feruglio, EN, JHEP 0911:036, (2009)]

MLFV Operators: $\ell \rightarrow \ell' \gamma$; $\mu + A \rightarrow e + A$; $\ell \rightarrow 3\ell'$

$\ell \rightarrow \ell' \gamma$ ($\mu \rightarrow e$; $\ell \rightarrow 3\ell'$) (On-shell photonic operators only)

$$O_{RL}^{(1)} = g' H^\dagger \bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta \ell_L \cdot B_{\mu\nu}$$

$$O_{RL}^{(2)} = g H^\dagger \bar{e}_R \sigma^{\mu\nu} \tau^a \lambda_e \Delta \ell_L \cdot W_{\mu\nu}^a$$

$$B(\mu \rightarrow eee) \simeq \frac{1}{160} B(\mu \rightarrow e\gamma)$$

$$\frac{\Gamma(\mu Ti \rightarrow e Ti)}{\Gamma(\mu Ti \rightarrow \text{capt})} \simeq \frac{1}{240} B(\mu \rightarrow e\gamma)$$

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$$O_{LL}^{(3)} = \bar{\ell}_L \gamma^\mu \Delta \ell_L \cdot (\bar{Q}_L \gamma_\mu Q_L)$$

$$O_{LL}^{(4d)} = \bar{\ell}_L \gamma^\mu \Delta \ell_L \cdot (\bar{d}_R \gamma_\mu d_R)$$

$$O_{LL}^{(4u)} = \bar{\ell}_L \gamma^\mu \Delta \ell_L \cdot (\bar{u}_R \gamma_\mu u_R)$$

$$O_{LL}^{(5)} = \bar{\ell}_L \gamma^\mu \tau^a \Delta \ell_L \cdot (\bar{Q}_L \gamma_\mu \tau^a Q_L)$$

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$\ell \rightarrow \ell' \ell'' \ell'''$ (4-leptons contact, LO)

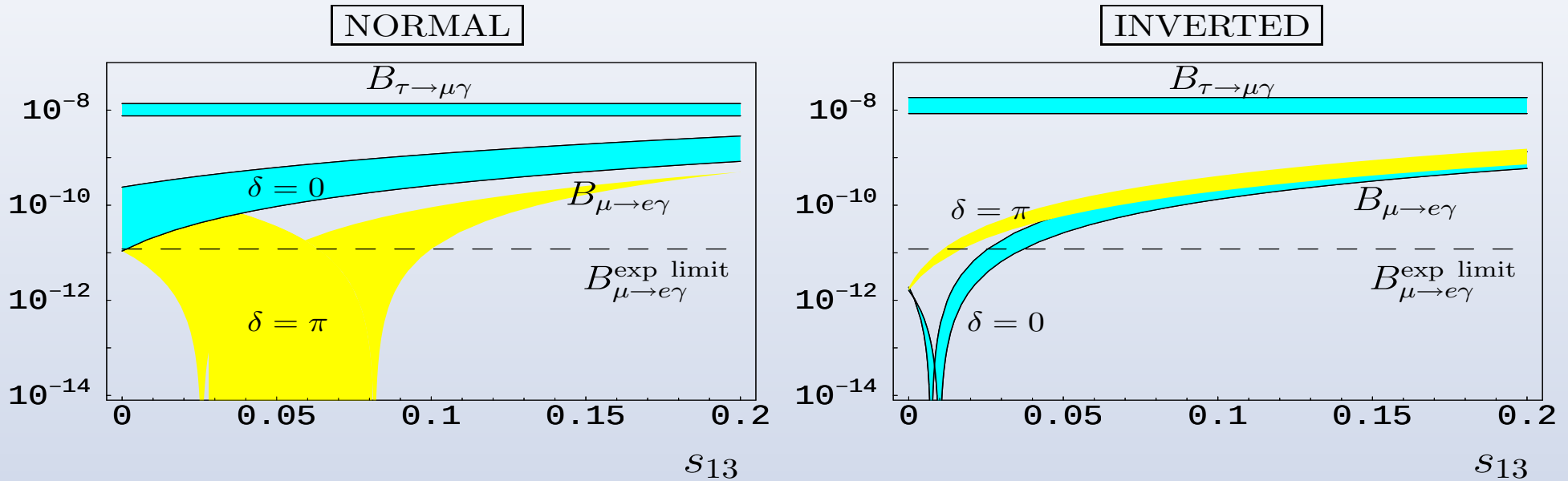
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MLFV Predictions: $\ell \rightarrow \ell' \gamma$; $\mu + A \rightarrow e + A$; $\ell \rightarrow 3\ell'$

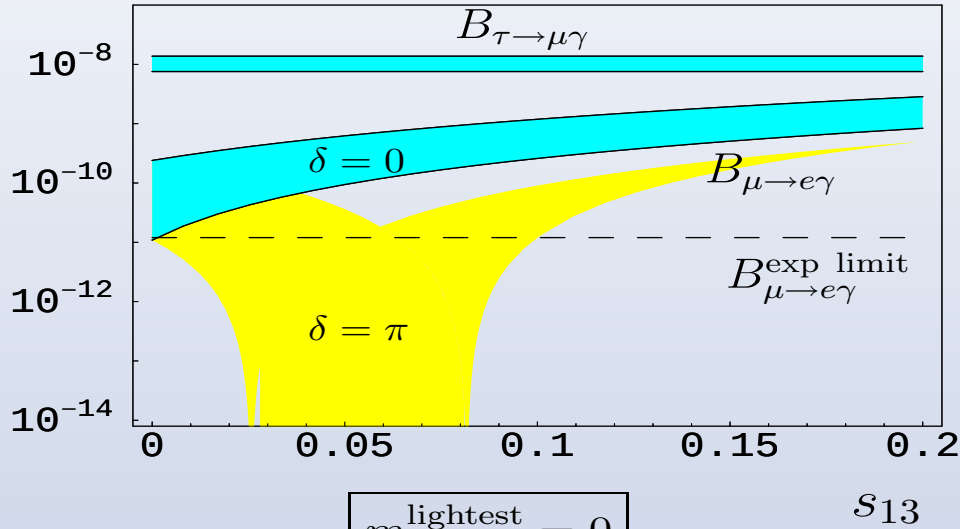
Case 1. $B_{\tau \rightarrow \mu \gamma}$ and $B_{\mu \rightarrow e \gamma}$ for $v\mu_L/\Lambda_{NP}^2 = 5 \times 10^7$ as a function of s_{13} .



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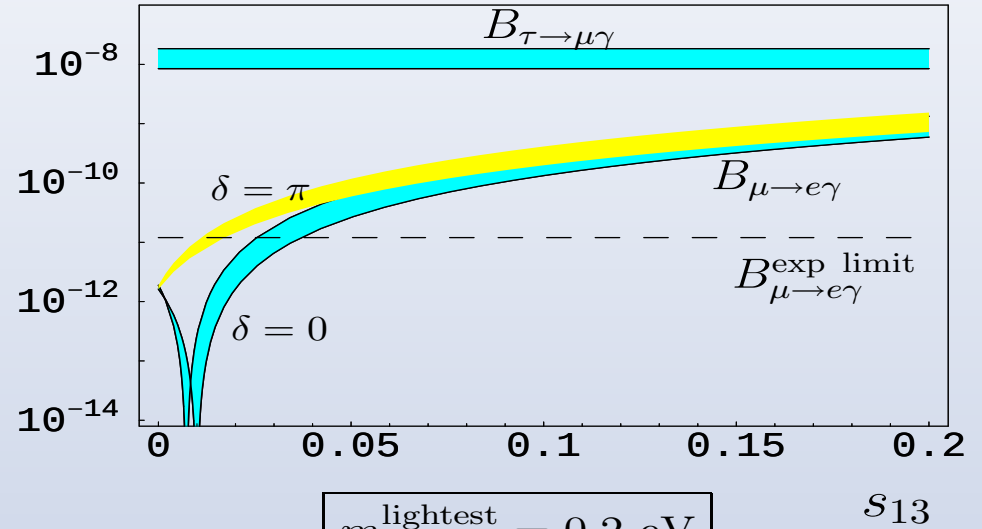
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NORMAL

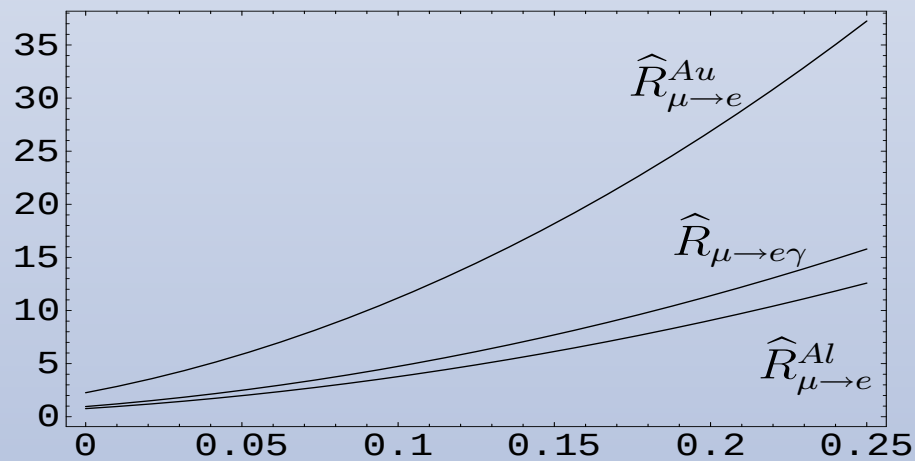


$m_{\nu}^{\text{lightest}} = 0$

INVERTED

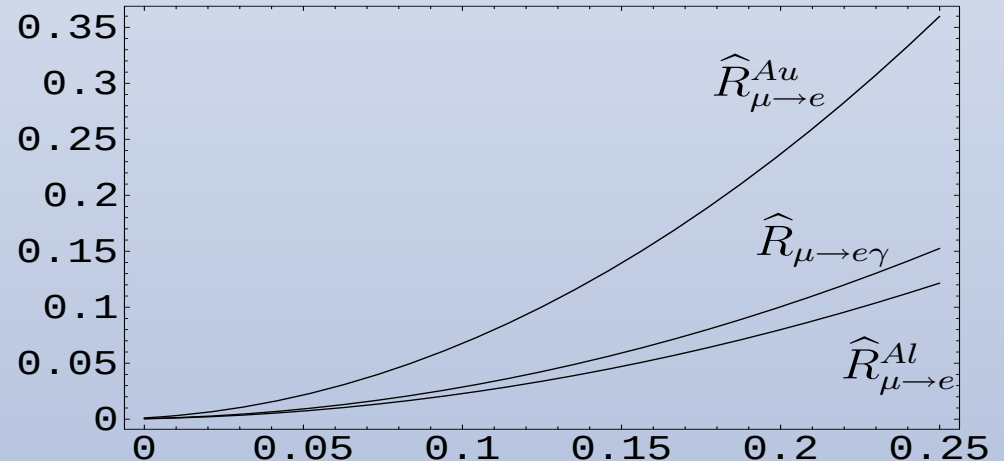


$m_{\nu}^{\text{lightest}} = 0.2 \text{ eV}$



Vertical units $\times \sim 2 \cdot 10^{-12}$ ($\delta = 0$)

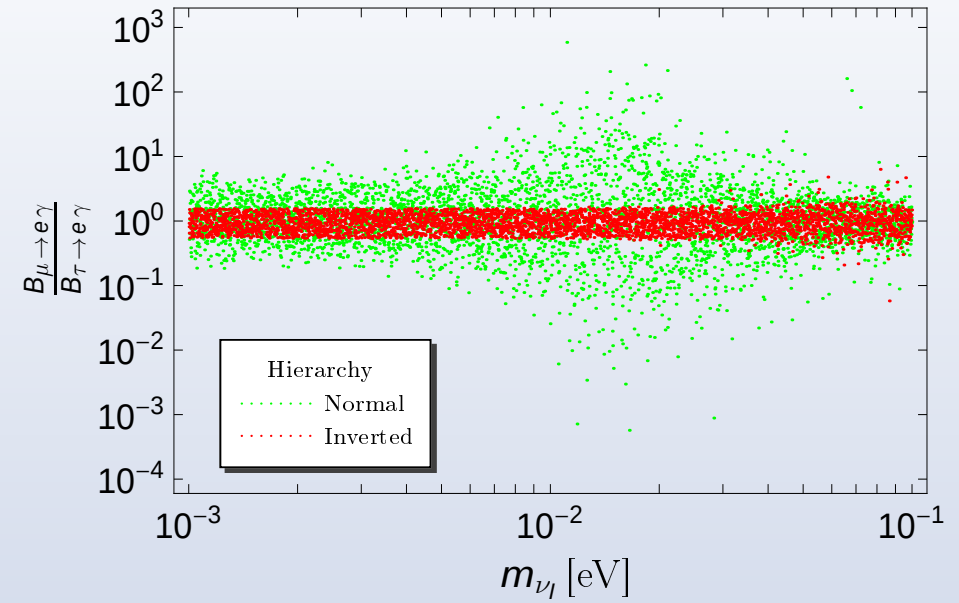
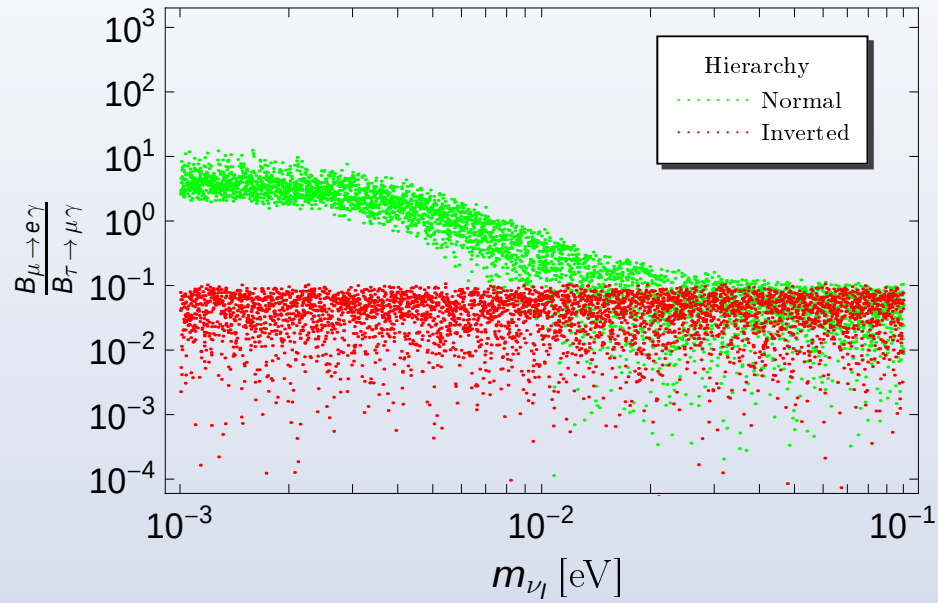
s_{13}



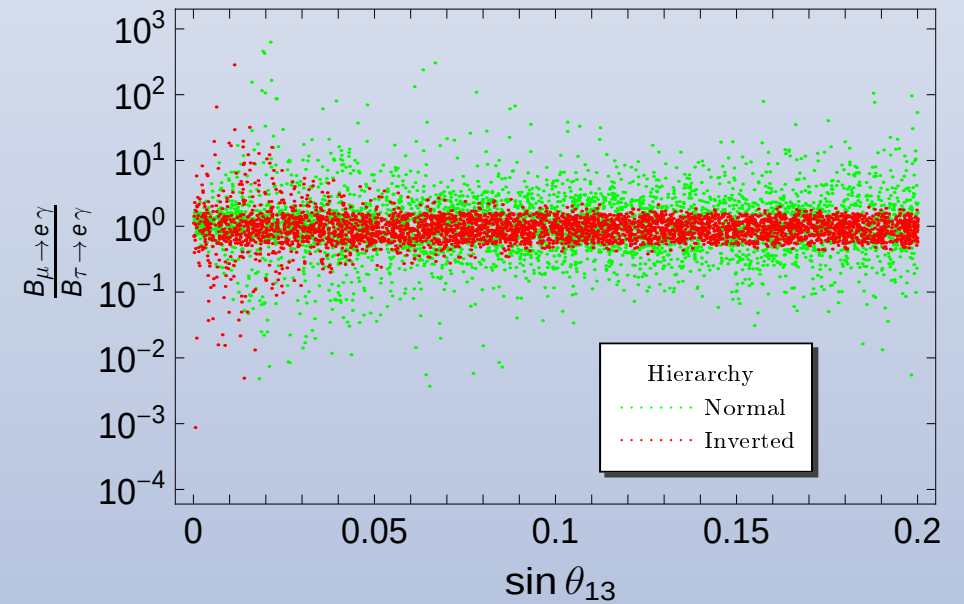
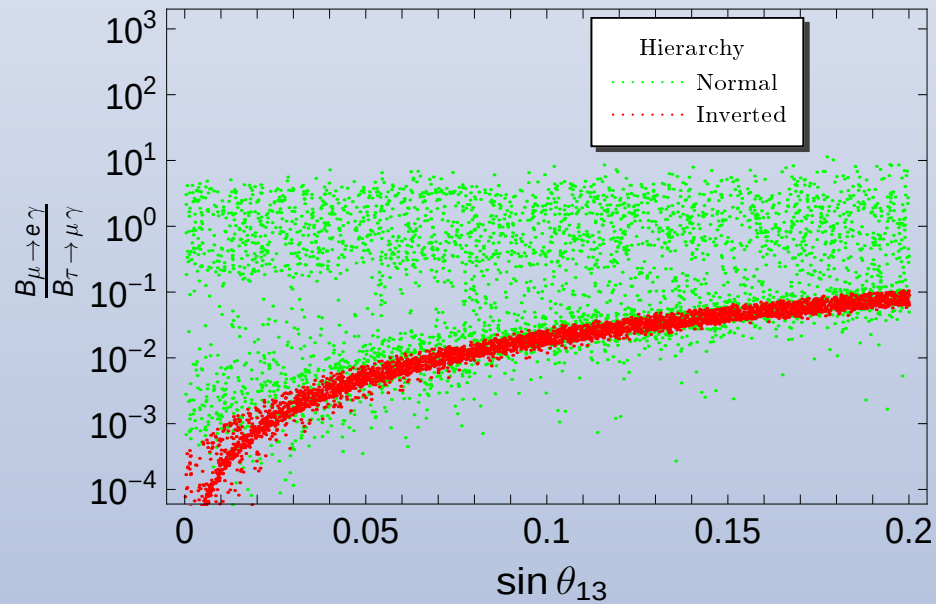
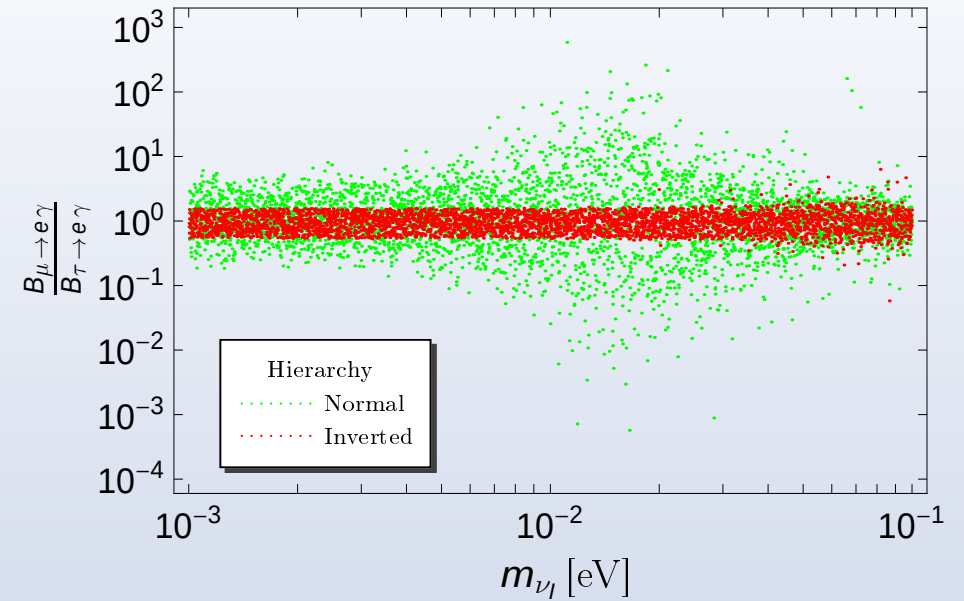
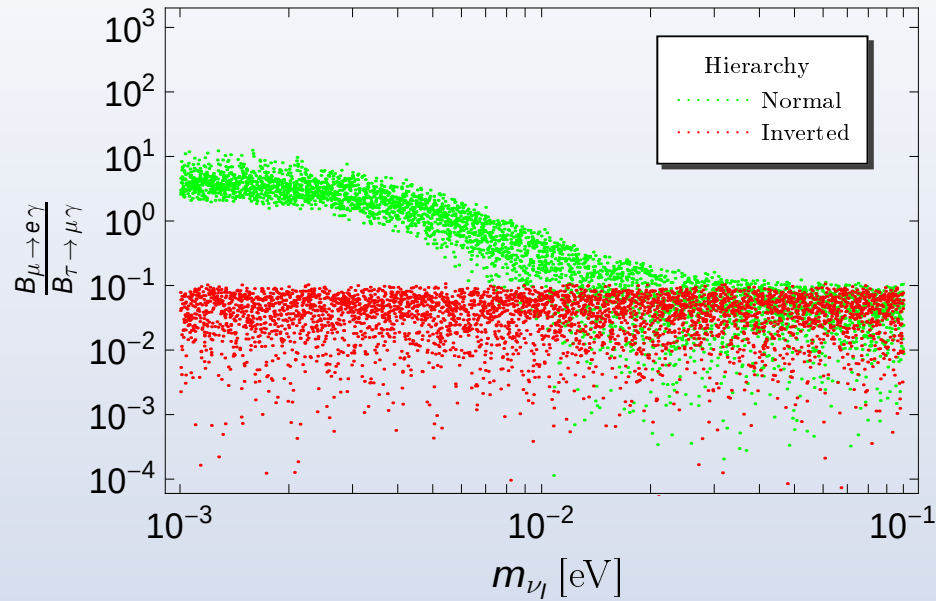
(Ti $4 \cdot 10^{-12}$; Au $7 \cdot 10^{-13}$)

s_{13}

MLFV Predictions (Case 2): $\frac{B_{\mu \rightarrow e \gamma}}{B_{\tau \rightarrow \mu \gamma}}; \frac{B_{\mu \rightarrow e \gamma}}{B_{\tau \rightarrow e \gamma}}$

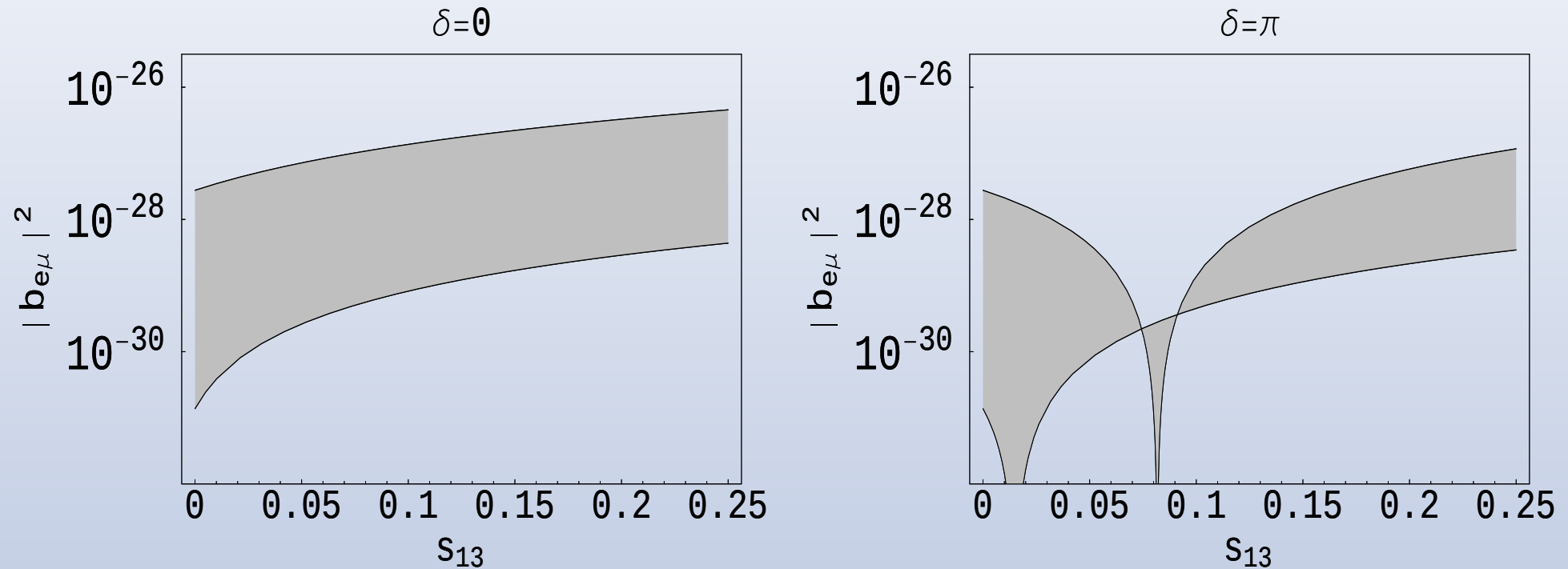


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MLFV Predictions (Case 1): $\frac{\Gamma_{\mu \rightarrow 3e}}{\Gamma_{\mu \rightarrow e\nu\bar{\nu}}}$

$$\frac{\Gamma_{\mu \rightarrow 3e}}{\Gamma_{\mu \rightarrow e\nu\bar{\nu}}} = (\text{Wilson Coeff.}) \times \left(\frac{v\mu_L}{\Lambda_{NP}^2} \right)^2 \times |b_{e\mu}|^2 \sim (10^{14} - 10^{16}) \times |b_{e\mu}|^2$$



$B_{\mu \rightarrow 3e}$ for normal neutrino mass hierarchy and $\delta = 0, \pi$.

Shaded band: $0 \leq m_{\nu}^{\min} \leq 0.2 \text{ eV}$ (Upper edge: $m_{\nu}^{\min} = 0$)

CONCLUSIONS

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- UV-MFV $\implies$ IR-MFV only if after sending spurions $\rightarrow 0$ the only fields that become massless are the SM fields.
- Even with MFV, exp. constraints on FCNC imply $\Lambda_{NP} > (\gg) 10 \text{ TeV}$.
(Is the original motivation for MFV matched ? Flavor is a real puzzle !)

CONCLUSIONS

- MFV is a **guess** about the behaviour of NP with respect to FV.
- MLFV is a **double guess**: a specific extension of the SM to account for $m_\nu \neq 0$ has to be assumed first.
- MLFV **does not necessarily imply** suppression of the LFV processes involving the lightest generations.
- This is because a theory that is **MFV in the UV** it can well be **non-MFV in the IR** (C.C.B.) .
- **UV-MFV $\implies$ IR-MFV** only if after sending **spurions $\rightarrow 0$** the only fields that become massless are the SM fields.
- Even with MFV, exp. constraints on FCNC imply $\Lambda_{NP} > (\gg) 10 \text{ TeV}$.
(Is the original motivation for MFV matched ? Flavor is a real puzzle !)
- As a general remark, the LFV processes $\ell \rightarrow \ell' \gamma$, μ -e conversion, $\ell \rightarrow 3\ell'$, are sensitive to different NP operators. They are all important since can provide **complementary informations**.