Università degli Studi di Padova

INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

Neutrino Phenomenology from Flavour Deconstruction

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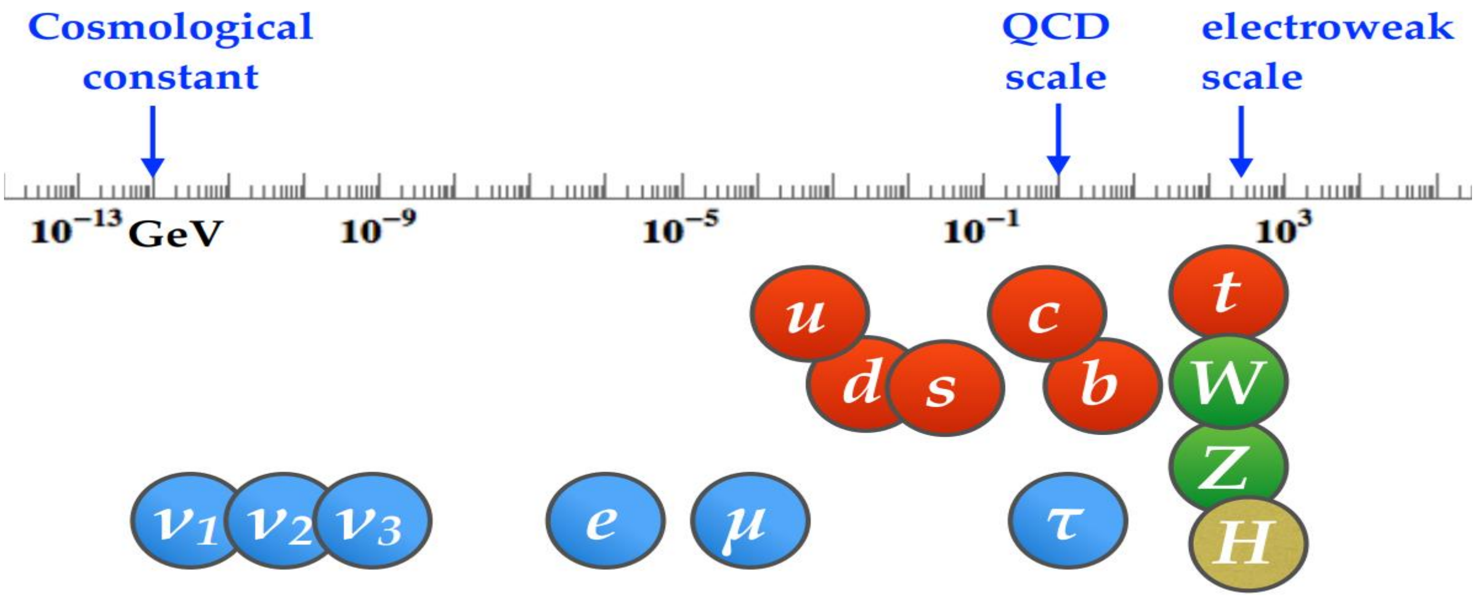
In collaboration with Gino Isidori, Paride Paradisi and Nudžeim Selimović

The Flavour Puzzle

Why are the SM-fermion masses so different?



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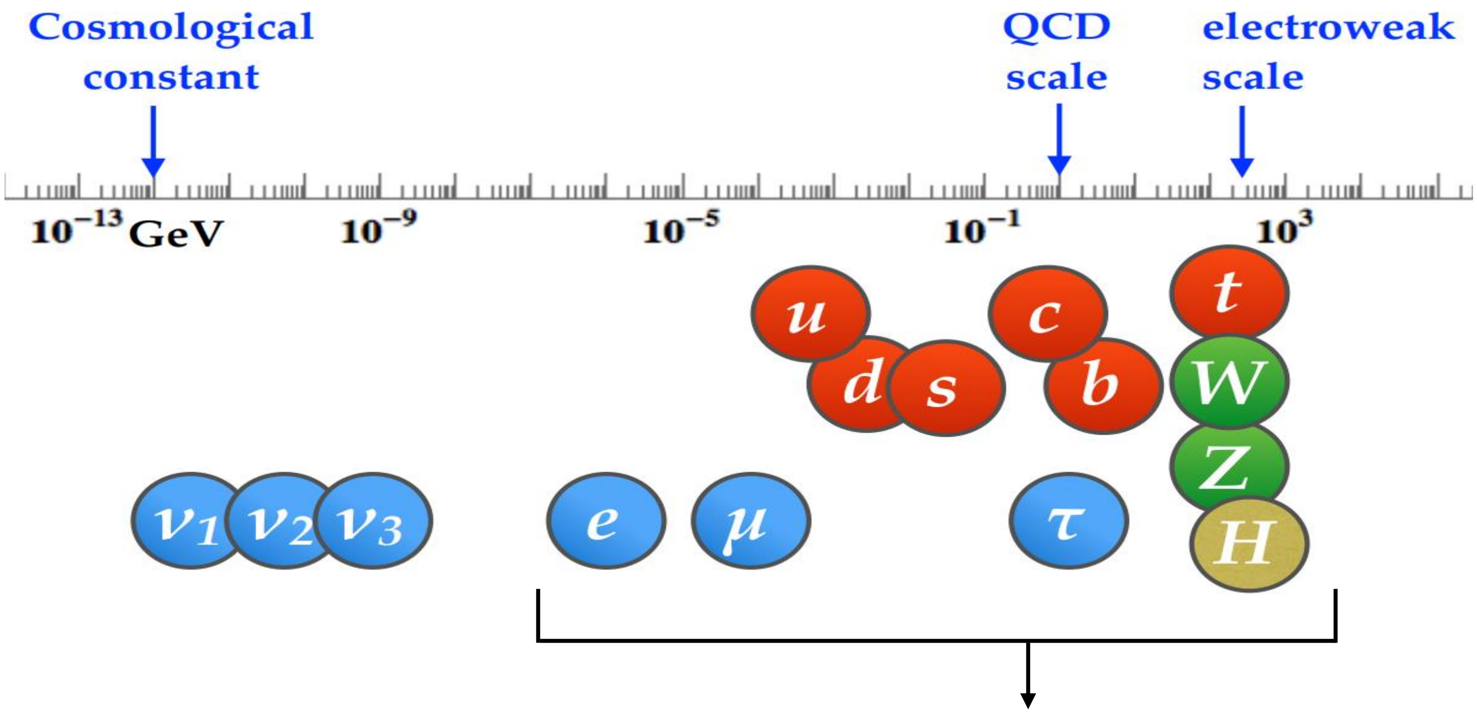
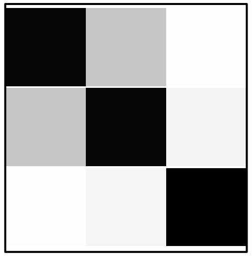


Very hierarchical masses

$V_{\mathrm{CKM}} \sim$ 

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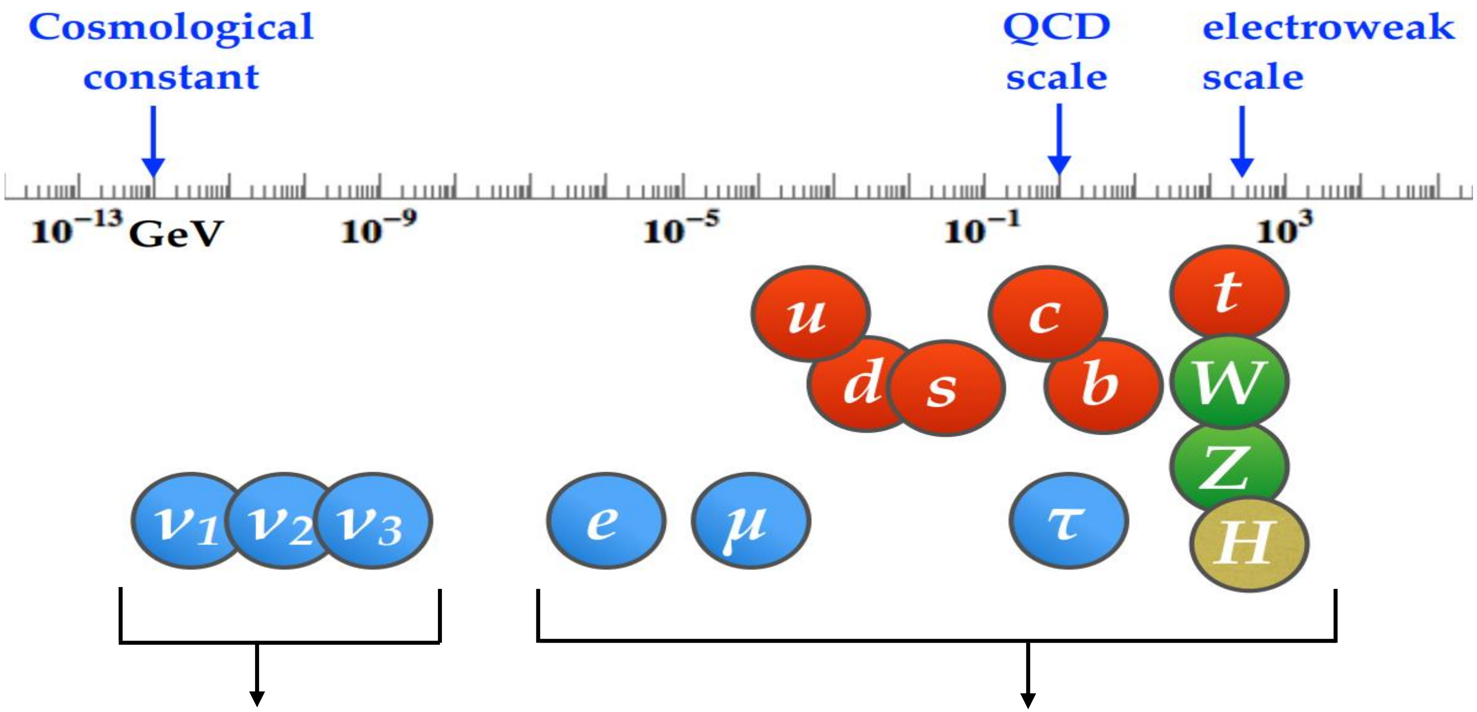
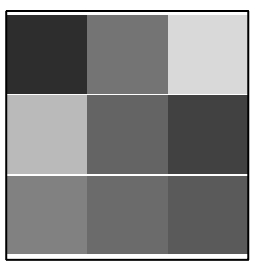
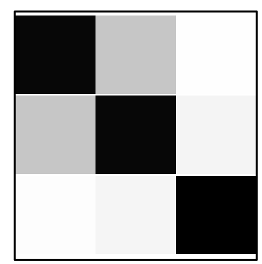


Almost anarchic

Very hierarchical masses

$U_{\mathrm{PMNS}} \sim$ 

$V_{\mathrm{CKM}} \sim$ 

The Flavour Puzzle

Flavour deconstruction refers to a framework wherein the SM gauge group G is extended in the UV to G^3, one for each fermion generation

$$\begin{tikzcd}
\Lambda_{21} & G_1 \times G_2 \times G_3 \arrow[d, "\langle \phi_{21} \rangle"] \\
\Lambda_{32} & G_{12} \times G_3 \arrow[d, "\langle \phi_{32} \rangle"] \\
\Lambda_{\mathrm{EW}} & G
\end{tikzcd}$$

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 & & \downarrow \langle \phi_{32} \rangle \\
\Lambda_{\mathrm{EW}} & & G
\end{array}
$$

The hierarchies in the charged fermion masses are reproduced as long as

$$\langle \phi_{32} \rangle / \Lambda_{32} \ll 1 \qquad \langle \phi_{21} \rangle / \Lambda_{21} \ll 1$$

However, it fails in explaining the anarchic neutrino sector

Theory Setup

Recently, [Greljo, Isidori, 2024] showed how to generate neutrino masses in a given flavour-deconstructed model using an Inverse Seesaw mechanism

$$-\mathcal{L} \supset \bar{\ell}_i Y_\nu^{ij} \tilde{H} \nu_j + \bar{s}_i M_R^{ij} \nu_j + \frac{1}{2} \bar{s}_i \mu^{ij} s_j^c + \text{h.c.}$$

Y_ν, M_R, μ are 3x3 matrices with $M_R \gg v Y_\nu \gg \mu$ $\quad v \equiv \langle H \rangle$

$$Y_\nu \sim \begin{pmatrix} \varepsilon_1 \varepsilon_2 & & \\ & \varepsilon_1 & \\ & & 1 \end{pmatrix} \qquad M_R \sim \Lambda \begin{pmatrix} \eta_1 \eta_2 & \eta_1 & 1 \\ \eta_1 \eta_2 & \eta_1 & 1 \\ \eta_1 \eta_2 & \eta_1 & 1 \end{pmatrix}$$

$\mu \longrightarrow$ Anarchic

$\Lambda \equiv \langle \chi \rangle$, where χ is a scalar which is charged under the flavour gauge sector G_3

The flavour non-universal gauge group ensures the hierarchies $\varepsilon_{2,1}, \eta_{2,1} \ll 1$

Mass Spectrum

Below the EW scale we have as mass eigenstates:

- 3 light active neutrinos with Majorana masses ν_L^i

$$m_\nu \approx A\mu A^T$$

- 3 heavy neutral leptons (HNLs) with hierarchical and (almost) Dirac masses n^i

$$M_n \approx \begin{pmatrix} 0 & M_R \\ M_R^T & \mu \end{pmatrix}$$

The anarchy in the active neutrino mass matrix is guaranteed since there is a (even partial) cancellation in the hierarchies as

$$A \equiv vY_\nu M_R^{-1} \sim \frac{v}{\Lambda} \begin{pmatrix} \Delta_1\Delta_2 & \Delta_1\Delta_2 & \Delta_1\Delta_2 \\ \Delta_1 & \Delta_1 & \Delta_1 \\ 1 & 1 & 1 \end{pmatrix} \qquad \Delta_i \equiv \frac{\varepsilon_i}{\eta_i}$$

SM Interactions

The HNLs interact weakly with the SM

$$\mathcal{L} \supset \frac{g}{\sqrt{2}}\bar{e}_L \not{W}^- U \nu_L + \frac{g}{\sqrt{2}}\bar{e}_L \not{W}^- V n_L + \mathrm{h.c.} + \mathcal{L}_Z$$

We exploit the following parameterization for the mixing matrices

$$U = \mathcal{N}\left(1 - \frac{1}{2}WW^\dagger\right) \quad V = \mathcal{N}W \quad W = \mathcal{U}^\dagger \hat{A} U_S^\dagger$$

Where $\mathcal{N}$ is the PMNS matrix of the SM and $\mathcal{U}$, U_S are 3x3 unitary matrices while $\hat{A} = \frac{y_\nu v}{\Lambda}\mathrm{diag}(\Delta_1\Delta_2, \Delta_1, 1)$

Parameters

There are 12 parameters relevant for the phenomenology:

$\Lambda \longrightarrow$ New-Physics (NP) scale

$\searrow$ Hopefully around few TeV

Parameters

There are 12 parameters relevant for the phenomenology:

y_ν

It represents the overall scale of the Yukawa matrix Y_ν

Expected to be $\mathcal{O}(1)$

$\varepsilon_1 \; , \; \varepsilon_2$

They represent the hierarchies in the Yukawa matrix Y_ν

Benchmark value

$m_e/m_\mu \approx 0.005$

Benchmark value

$m_\mu/m_\tau \approx 0.06$

Parameters

There are 12 parameters relevant for the phenomenology:

$$\alpha_1\ ,\ \alpha_2\ ,\ \alpha_3$$

Three angles that parameterize the 3x3 unitary matrix $\mathcal{U}$

If the leptonic Yukawa matrices are diagonalized on the left by matrices close to the identity, then

$\alpha_i \approx \theta_i$ (θ_i are the PMNS mixing angles)

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \bar{e}_L \not{W}^- U \nu_L + \frac{g}{\sqrt{2}} \bar{e}_L \not{W}^- V n_L + \text{h.c.} + \mathcal{L}_Z$$

α_i here

$$U = \mathcal{N}\left(1 - \frac{1}{2} W W^\dagger\right) \qquad V = \mathcal{N} W \qquad W = \mathcal{U}^\dagger \hat{A} U_S^\dagger$$

Parameters

There are 12 parameters relevant for the phenomenology:

$$\beta_1\ ,\ \beta_2\ ,\ \beta_3$$

Three angles that parameterize the 3x3 unitary matrix U_S

In principle, they can range in

$$[0, 2\pi]$$

They are related to the singlets of the Inverse Seesaw only, so there is no way to constrain them

---

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \bar{e}_L \not{W}^- U \nu_L + \frac{g}{\sqrt{2}} \bar{e}_L \not{W}^- V n_L + \text{h.c.} + \mathcal{L}_Z$$

β_i here

$$U = \mathcal{N}\left(1 - \frac{1}{2} W W^\dagger\right) \qquad V = \mathcal{N} W \qquad W = \mathcal{U}^\dagger \hat{A} U_S^\dagger$$

Parameters

There are 12 parameters relevant for the phenomenology:

$$\Delta_1 \,,\ \Delta_2$$

They effectively represent the hierarchies in the Heavy mass matrix M_R

$$\left[\ \text{Traded for } \eta_1 \,,\ \eta_2 \ \longrightarrow\ \Delta_i \equiv \frac{\varepsilon_i}{\eta_i}\ \right]$$

If they departure too much from 1, the model fails in reproducing the PMNS matrix as μ is assumed anarchic

$$\mu = W^{-1}\hat{m}_\nu (W^{-1})^T$$

Expected to be anarchic

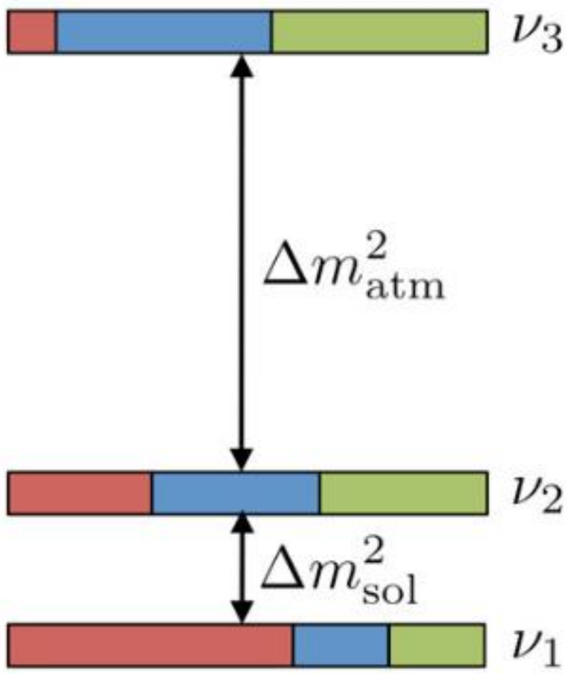
Δ_i here

Range?

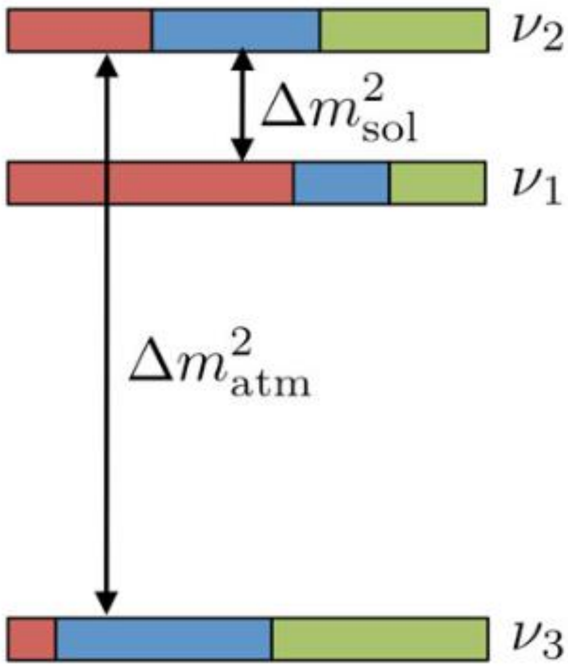
Neutrino Masses

The absolute scale of SM neutrino masses is still unknown

Normal Hierarchy (NH):



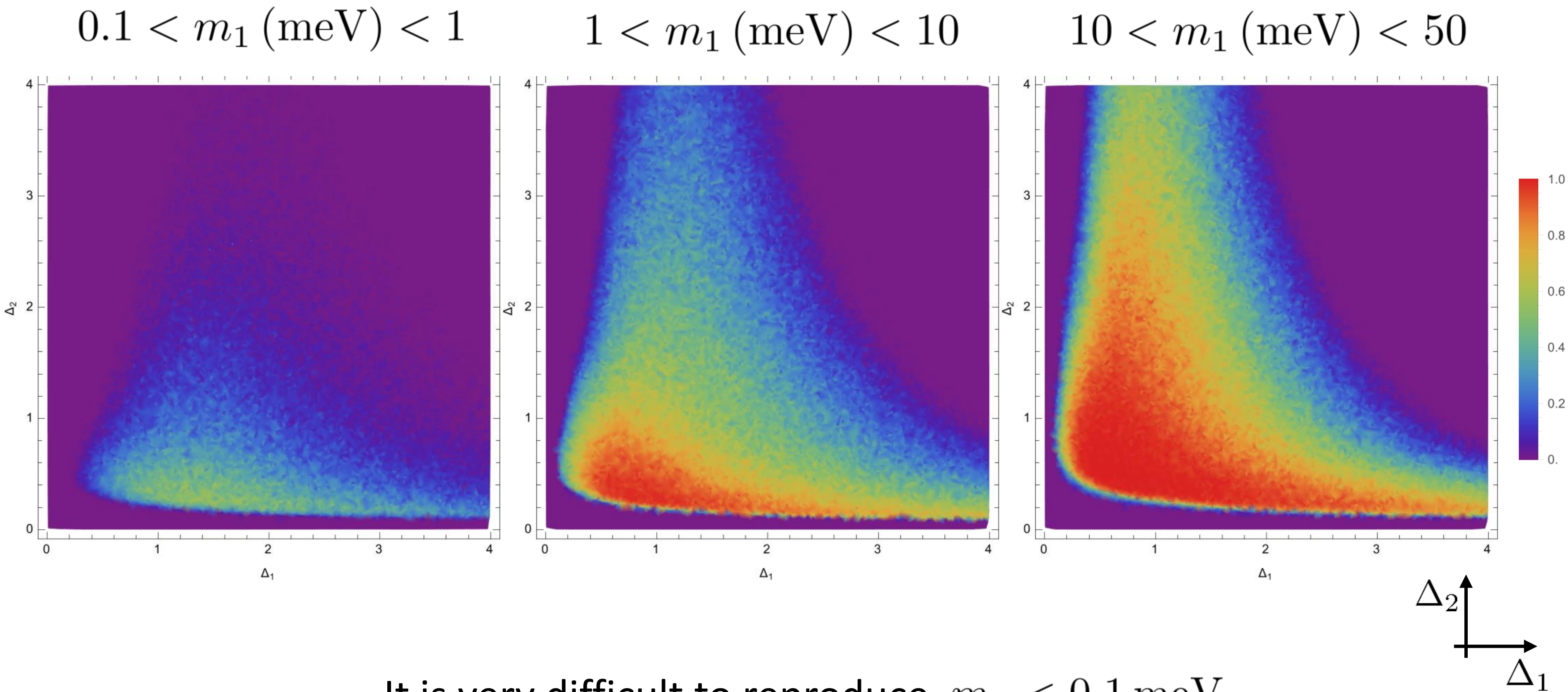
Inverted Hierarchy (IH):



$$\Delta m^2_{\rm atm} = 2.56 \cdot 10^{-3}\,{\rm eV}^2 \qquad \Delta m^2_{\rm sol} = 7.36 \cdot 10^{-5}\,{\rm eV}^2$$

Range of Δ

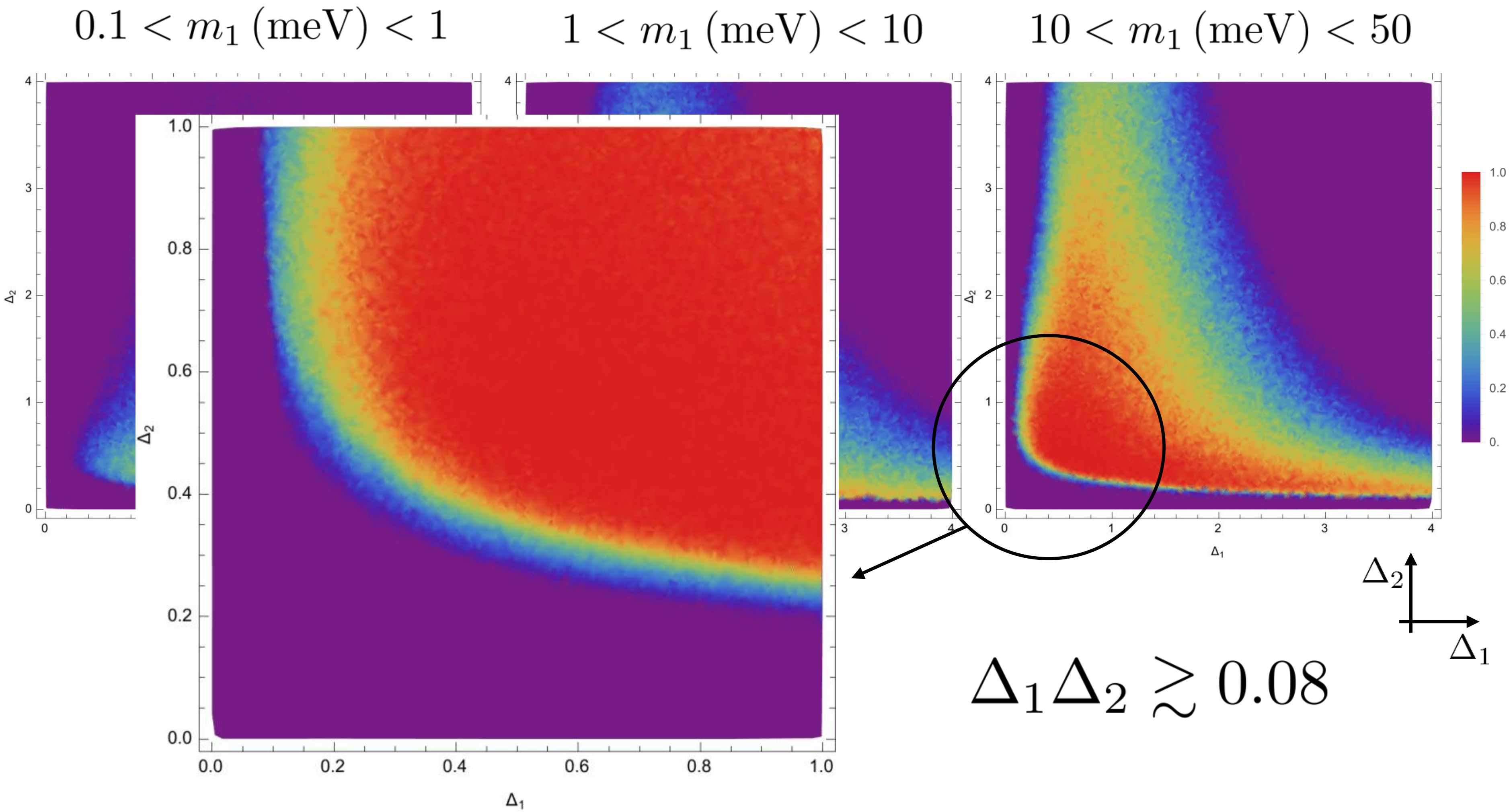
Normal Hierarchy:



It is very difficult to reproduce $m_1 < 0.1\,\mathrm{meV}$

Range of Δ

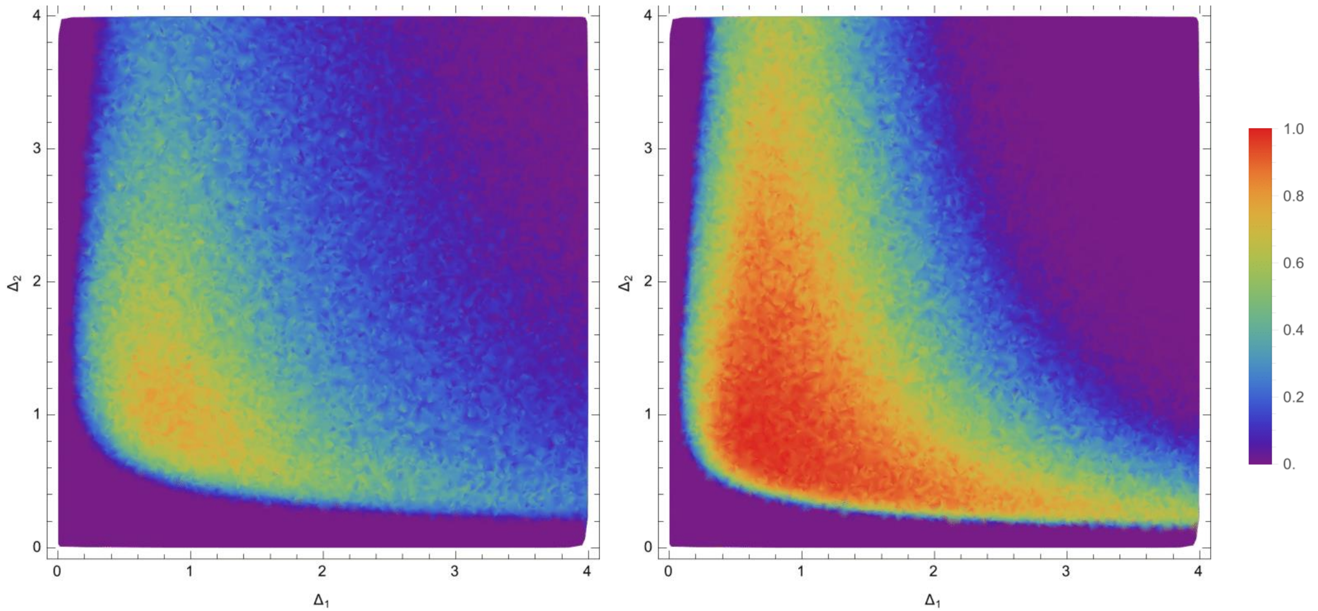
Normal Hierarchy:

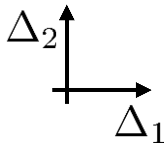


Range of Δ

Inverted Hierarchy:

$1 < m_3\,(\mathrm{meV}) < 10$ $\qquad$ $10 < m_3\,(\mathrm{meV}) < 50$





It is very difficult to reproduce $m_3 < 1\,\mathrm{meV}$

Range of Δ

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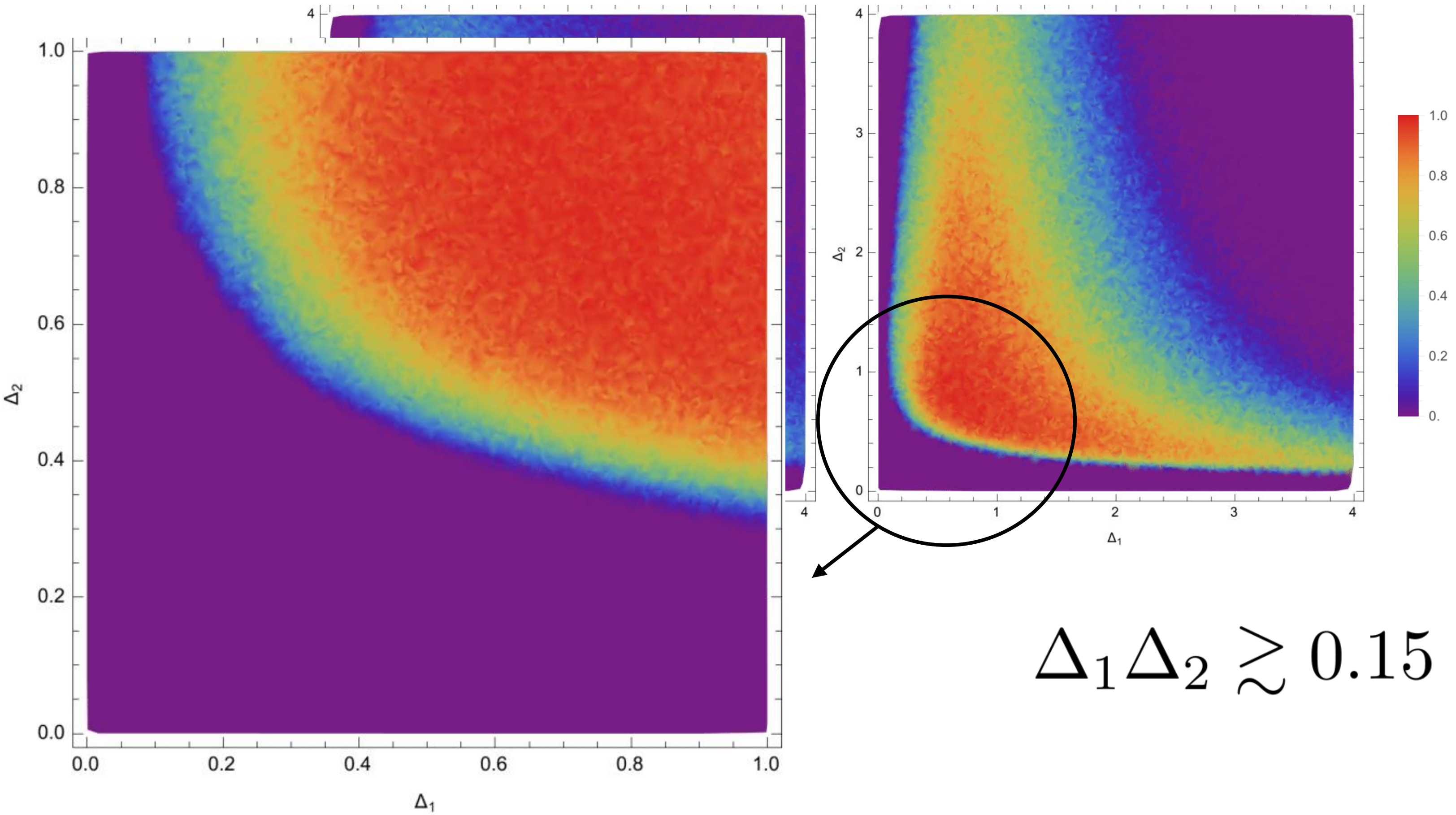
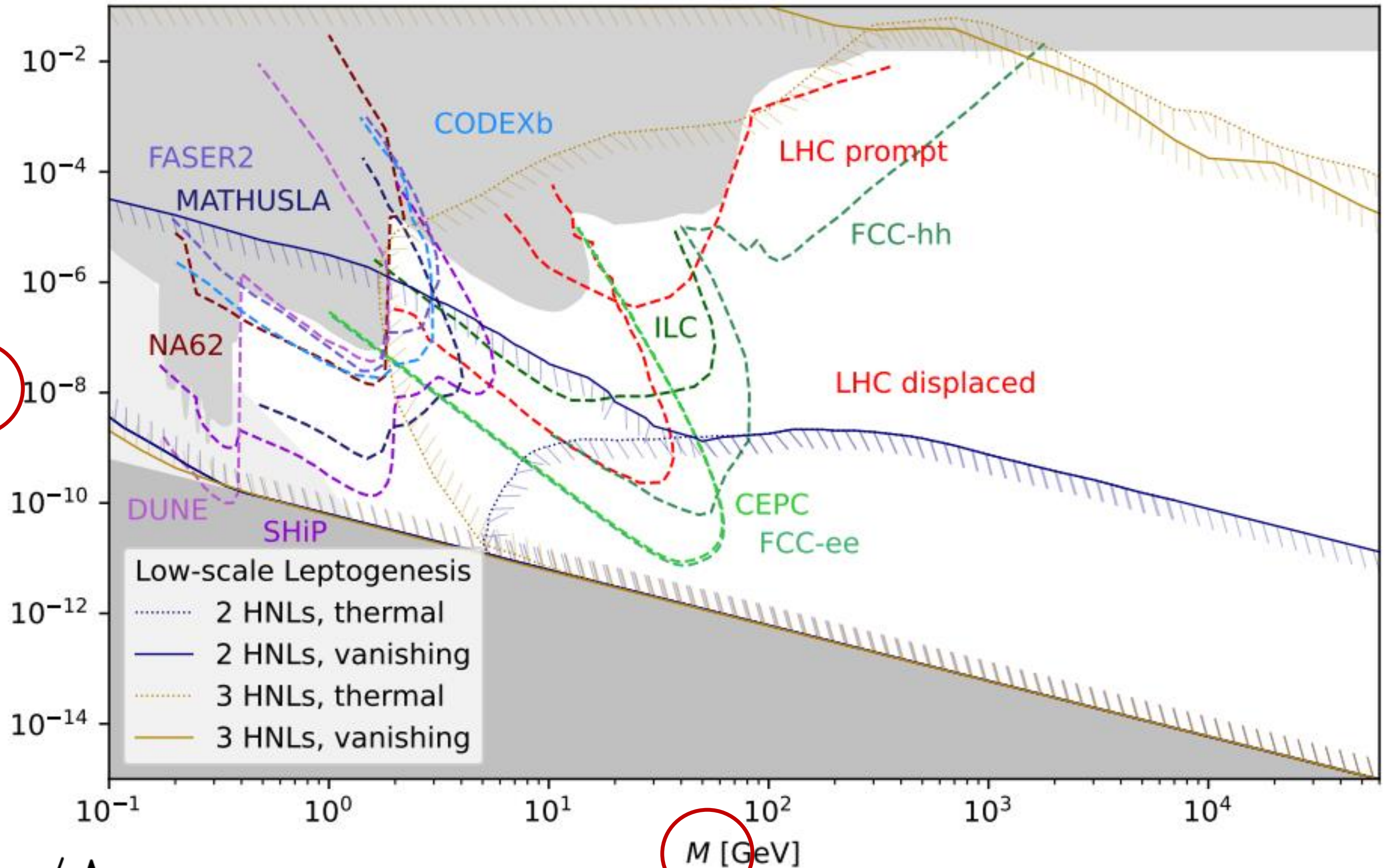


$$\Delta_1\Delta_2 \gtrsim 0.15$$

Δ_2 Δ_1

Direct Searches

The HNLs have hierarchical masses and interact with the charged leptons



[Abdullahi et al, 2022]

$V_{\ell N} \sim v/\Lambda$

$$M_1 = \Lambda \frac{\varepsilon_1}{\Delta_1}\frac{\varepsilon_2}{\Delta_2} \qquad M_2 = \Lambda \frac{\varepsilon_1}{\Delta_1} \qquad M_3 = \Lambda$$

Direct Searches

If the lightest HNL is lighter than Z and W bosons, it can be produced on-shell at colliders

$$M_1 < M_{W,Z}$$

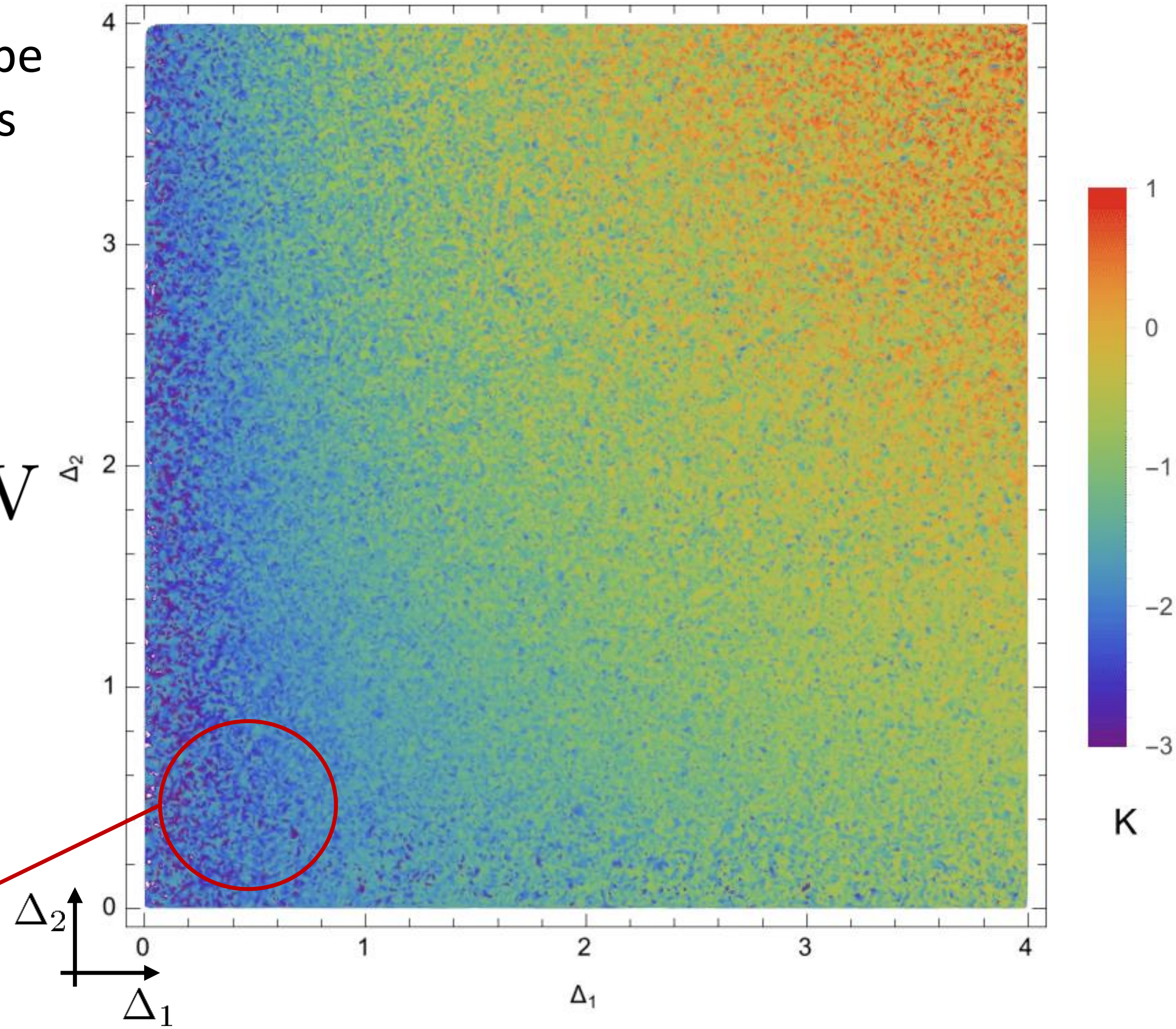
$$\Downarrow$$

$$\Lambda \gtrsim y_\nu 10^{(K+5)/2}\,\mathrm{TeV}$$

From the current bound on

$$|V_{\ell N}|^2 < 10^{-5}$$

$$\Lambda \gtrsim 20\,\mathrm{TeV}$$



Direct Searches

$$M_1 < M_{W,Z} \quad \longrightarrow \quad \Lambda \gtrsim 20\,\mathrm{TeV}$$

Otherwise, by imposing $M_1 > M_{W,Z}$

$$\Big\downarrow$$

$$\Lambda \gtrsim 40 \left(\frac{\Delta_1\Delta_2}{0.13}\right)\left(\frac{m_\mu/m_\tau}{\varepsilon_1}\right)\left(\frac{m_e/m_\mu}{\varepsilon_2}\right)\,\mathrm{TeV}$$

Compatible with NP at TeV scale!

$$\Lambda \gtrsim \text{few TeV}$$

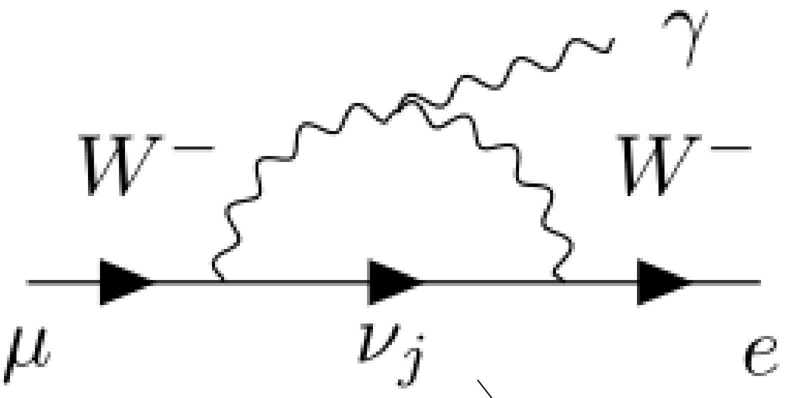
Recall that

NH: $\Delta_1\Delta_2 \gtrsim 0.08$

IH: $\Delta_1\Delta_2 \gtrsim 0.15$

LFV Processes

Currently, $\mu \to e\gamma$ is the most constraining LFV process



Both light and heavy states

$$\mathrm{Br}(\mu \to e\gamma) = \frac{3\alpha}{2\pi}|\delta_\nu|^2$$

$$\delta_\nu = \sum_k V_{ek} V^*_{\mu k}\, G_\gamma\left(\frac{M_k^2}{M_W^2}\right)$$

$$\approx \frac{v^2}{\Lambda^2}\Delta_1^2\Delta_2 \sum_k (U_S)_{ek}(U_S^*)_{\mu k}\, G_\gamma\left(\frac{M_k^2}{M_W^2}\right)$$

β_i inside here

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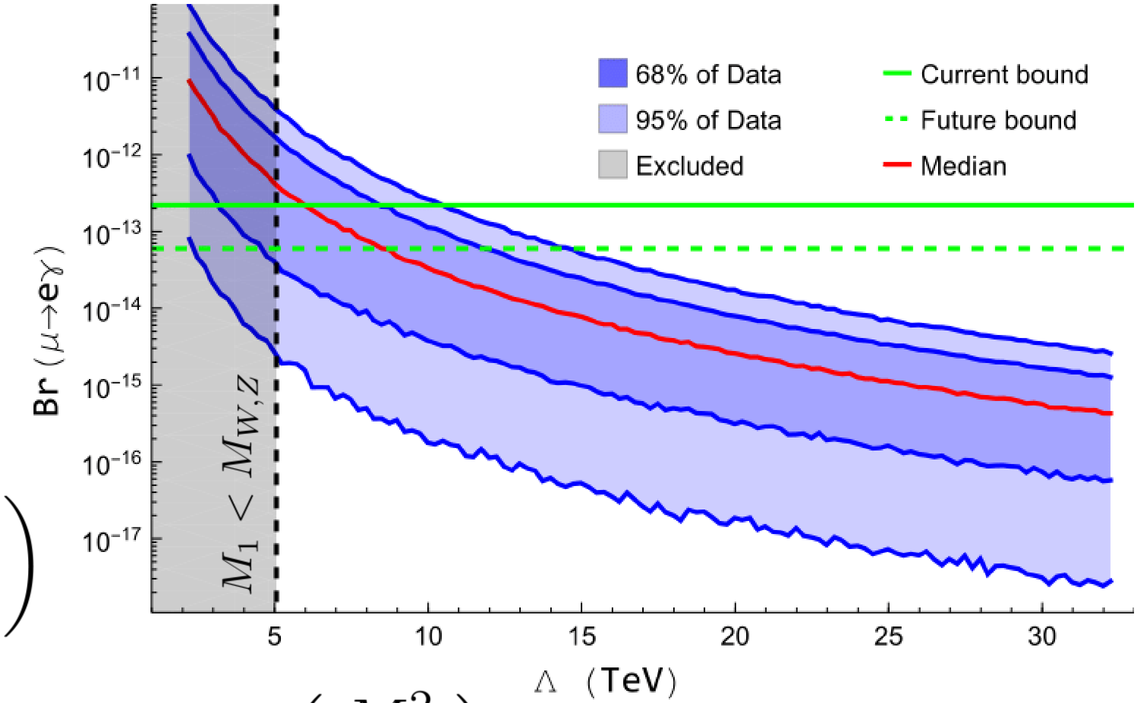
Normal Hierarchy allows for Λ to be around few TeV



Plot of $\mathrm{Br}(\mu \to e\gamma)$ with

$\Delta_1 = 0.45 \quad \Delta_2 = 0.3$

$\varepsilon_1 = 0.06 \quad \varepsilon_2 = 0.04$

$y_\nu = 1$

LFV Processes

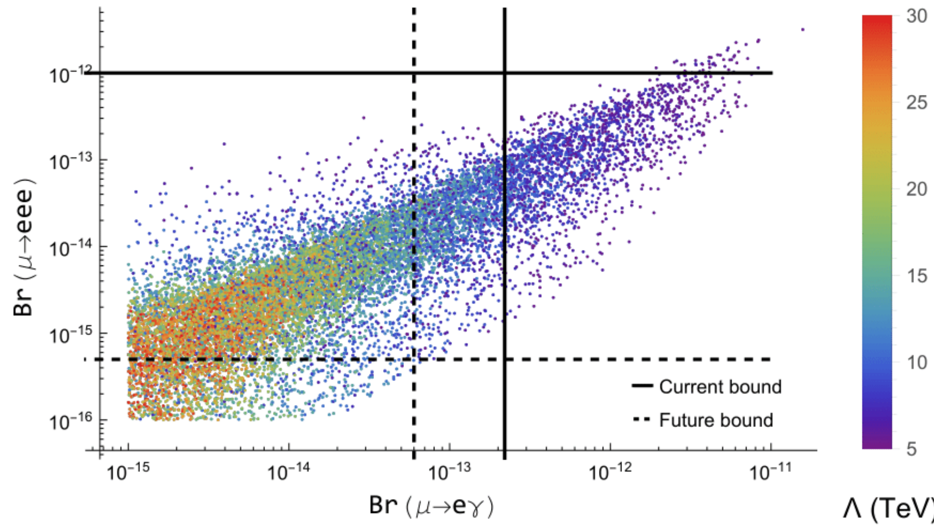
Correlation plots between the main LFV processes

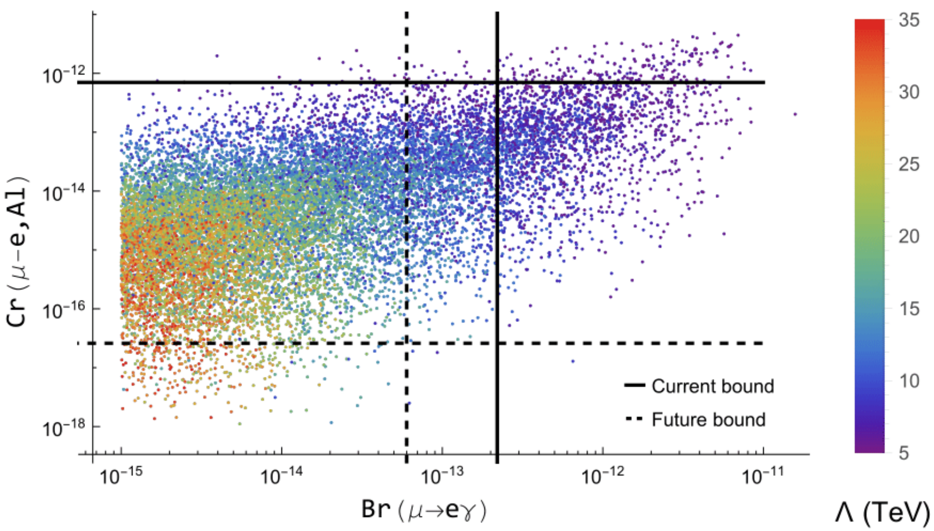
$$\mathrm{Br}(\mu \to e\gamma) \quad \mathrm{Br}(\mu \to eee)$$

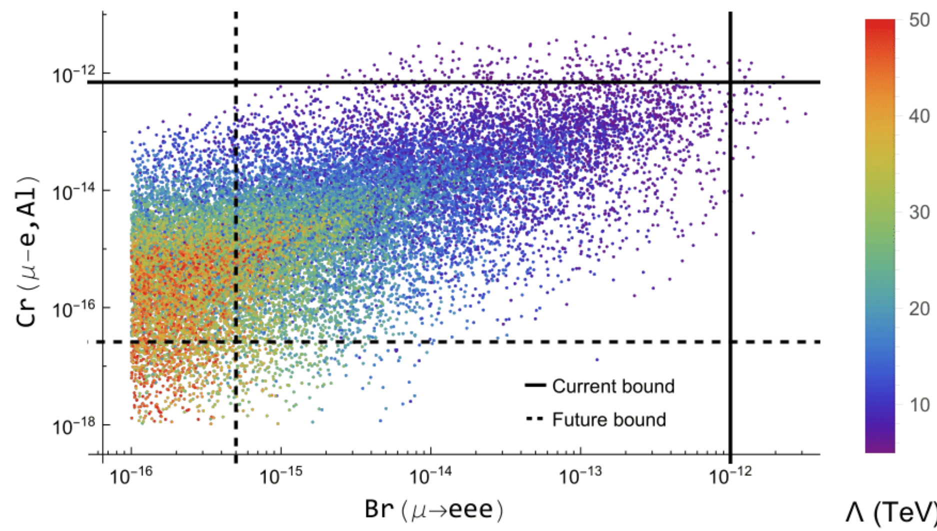
$$\mathrm{Cr}(\mu - e, \mathrm{Al})$$

$$\Delta_1 = 0.5 \quad \Delta_2 = 0.5$$

$$\varepsilon_1 = 0.06 \quad \varepsilon_2 = 0.02 \quad y_\nu = 1$$







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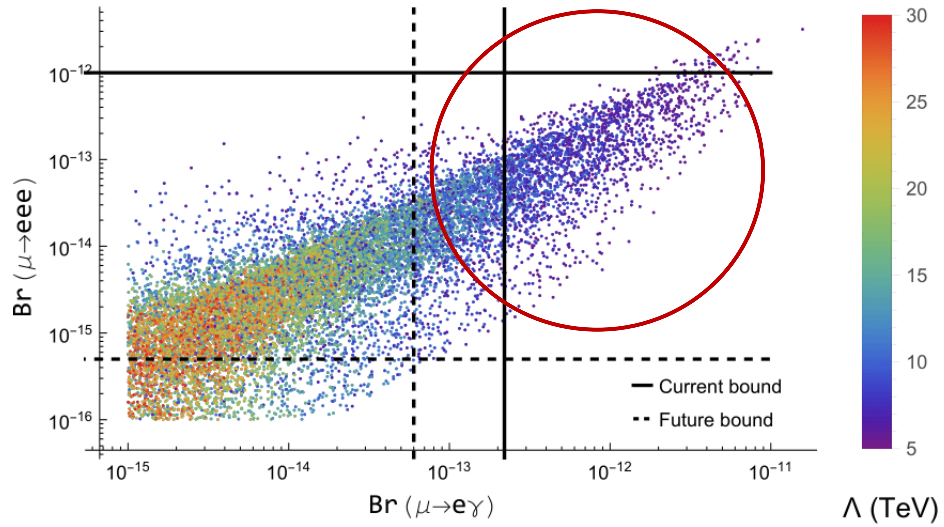

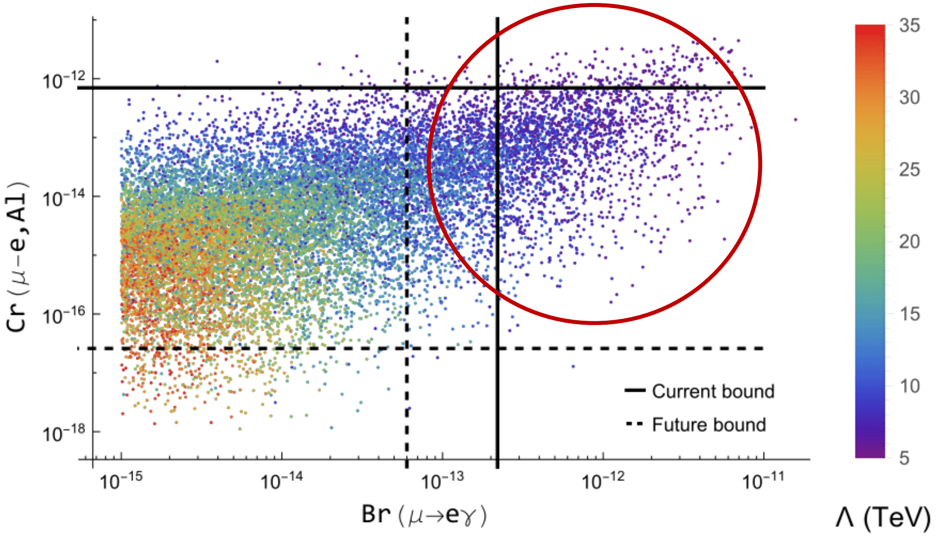

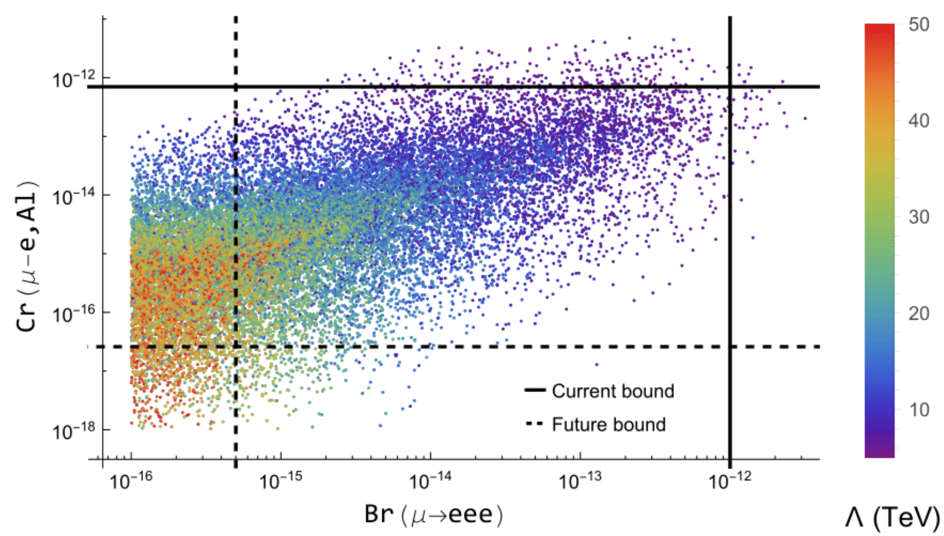

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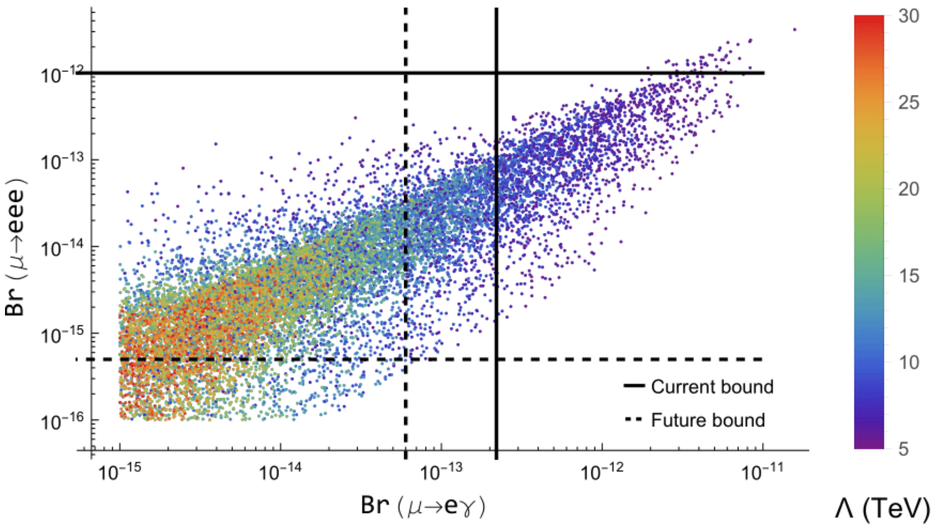

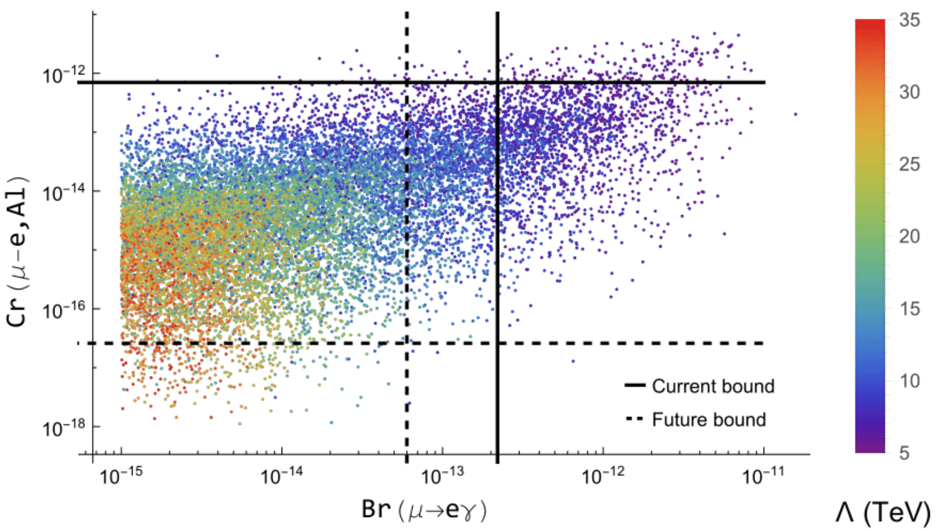

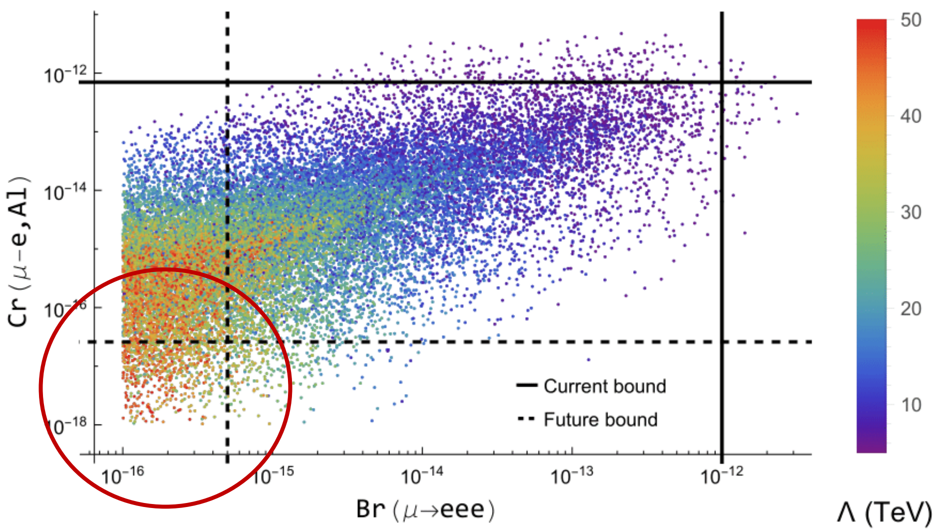

LFV from Gauge and Yukawa Sectors

Flavour-deconstructed models predict LFV processes even without including neutrinos

$$\mathcal{L} \supset |D_\mu H|^2 + Z'_\mu J^\mu_{Z'} + \frac{1}{2} M^2_{Z'} Z'_\mu Z'^\mu + \mathcal{L}_Y$$

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$$J^\mu_{Z'} = g_{\mathrm{NP}} \sum_\psi \overline{\psi} \gamma^\mu \psi Q_{Z'}(\psi)$$

$$D_\mu H \supset \partial_\mu H - \frac{ig}{c_W}(T_3 - s_W^2 Q) Z_\mu H - i g_{\mathrm{NP}} Q_{Z'}(H) Z'_\mu H$$

Z' $\longrightarrow$ It is a neutral heavy gauge boson that couples non-universally with all the fermions in the theory

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$$\mathcal{L}_Y \sim y_{33} \bar{\ell}_3 H e_3 + \sum_{j=1,2} \sum_{\alpha=\text{heavy}} Y_{j\alpha} \bar{\ell}_j H E_\alpha + \left[\sum_{\alpha=\text{heavy}} Y'_{\alpha i} \overline{E}_\alpha \phi_{32} e_2 + \sum_{\alpha=\text{heavy}} M_\alpha \overline{E}_\alpha E_\alpha + 1^{\text{st}} \text{ generation} \right]$$

$E_\alpha \longrightarrow$ Heavy NP fermions

$$\Lambda_{32} \sim M_\alpha$$

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It generates a mass-mixing matrix between light and heavy fermions

$$U_{\text{mix}} = \begin{pmatrix} \mathbb{I} - \frac{1}{2}\mathcal{E}^\dagger \mathcal{E} & \mathcal{E}^\dagger \\ -\mathcal{E} & \mathbb{I} - \frac{1}{2}\mathcal{E}\mathcal{E}^\dagger \end{pmatrix}$$

$$\mathcal{E} \sim \langle \phi_{32} \rangle / \Lambda_{32}$$

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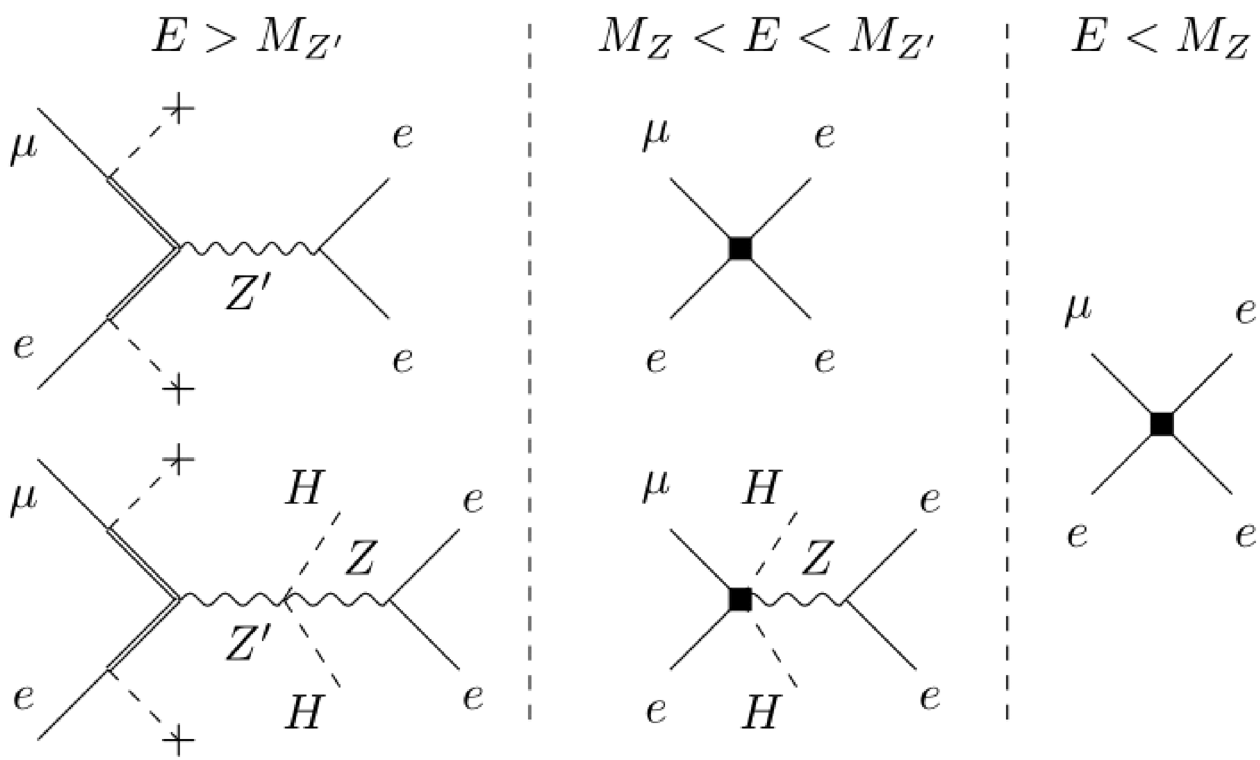

LFV from Gauge and Yukawa Sectors

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$$\mathcal{L} \supset |D_\mu H|^2 + Z'_\mu J^\mu_{Z'} + \frac{1}{2} M^2_{Z'} Z'_\mu Z'^\mu + \mathcal{L}_Y$$

$$\frac{\mathrm{Br}(\mu \to eee)|_{Z'}}{\mathrm{Br}(\mu \to eee)|_\nu} \approx (10^{-1} \div 10) \times \left(\frac{1}{y_\nu}\right)^4 \left(\frac{0.5^3}{\Delta_1^2 \Delta_2}\right)^2 \left(\frac{\varepsilon_e \varepsilon_\mu}{0.05^2}\right)^2 \left(\frac{\alpha_{\mathrm{NP}}}{\alpha}\right)^2 \left(\frac{\Lambda}{M_{Z'}}\right)^4$$

$$\frac{\mathrm{Cr}(\mu - e, Al)|_{Z'}}{\mathrm{Cr}(\mu - e, Al)|_\nu} \approx (10^{-1} \div 10) \times \left(\frac{1}{y_\nu}\right)^4 \left(\frac{0.5^3}{\Delta_1^2 \Delta_2}\right)^2 \left(\frac{\varepsilon_e \varepsilon_\mu}{0.05^2}\right)^2 \left(\frac{\alpha_{\mathrm{NP}}}{\alpha}\right)^2 \left(\frac{\Lambda}{M_{Z'}}\right)^4$$

This range is only due to β_i

Mixing between third and light generations

Neutrino sector could dominate for $\Lambda \lesssim M_{Z'}$

Explicit Model

This model-independent study can be easily matched to any given flavour-deconstructed model of interest

As example, we refer to Model B discussed in [Greljo, Isidori, 2024]

Explicit Model

This model-independent study can be easily matched to any given flavour-deconstructed model of interest

Gauge group: $\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)^3_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{R}} \times \mathrm{U}(1)^3_{\text{B-L}}$

Flavour-deconstructed

To break the symmetry down to the SM gauge group we need some scalar fields

$$
\begin{array}{c|c|c}
\Lambda_{21} & \mathrm{SU}(2)^{[1]}_{\mathrm{L}} \times \mathrm{SU}(2)^{[2]}_{\mathrm{L}} \times \mathrm{SU}(2)^{[3]}_{\mathrm{L}} & \mathrm{U}(1)^{[1]}_{\text{B-L}} \times \mathrm{U}(1)^{[2]}_{\text{B-L}} \times \mathrm{U}(1)^{[3]}_{\text{B-L}} \\
 & \downarrow \phi^{L}_{21} & \downarrow \phi^{\ell}_{21} \\
\Lambda_{32} & \mathrm{SU}(2)^{[12]}_{\mathrm{L}} \times \mathrm{SU}(2)^{[3]}_{\mathrm{L}} & \mathrm{U}(1)^{[12]}_{\text{B-L}} \times \mathrm{U}(1)^{[3]}_{\text{B-L}} \\
 & \downarrow \phi^{L}_{32} & \downarrow \phi^{\ell}_{32} \\
\Lambda_{\mathrm{EW}} & \mathrm{SU}(2)_{\mathrm{L}} & \mathrm{U}(1)_{\text{B-L}}
\end{array}
$$

Explicit Model

This model-independent study can be easily matched to any given flavour-deconstructed model of interest

Gauge group: $\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)^3_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{R}} \times \mathrm{U}(1)^3_{\mathrm{B\text{-}L}}$

The Lagrangian contains all the possible EFT operators allowed by the full symmetry

$$\left.\begin{aligned}\mathcal{L}_Y &= y_{33}\bar{\ell}_3\tilde{H}\nu_3 + \frac{c_{32}}{\Lambda_{32}}\bar{\ell}_3\tilde{H}\phi^{\ell}_{32}\nu_2 \\ &+ \frac{c_{23}}{\Lambda^2_{32}}\bar{\ell}_2\tilde{H}\phi^{L}_{32}\phi^{\ell}_{32}\nu_3 + \text{1-st generation}\end{aligned}\right] \rightarrow Y_\nu$$

$$\left.\mathcal{L}_R = \tilde{c}_{i3}\bar{s}_i\chi\nu_3 + \frac{\tilde{c}_{i2}}{\Lambda_{32}}\bar{s}_i\chi\phi^{\ell}_{32}\nu_2 + 1^{\text{st}} \text{ generation}\right] \rightarrow M_R$$

$$\langle\chi\rangle \sim \Lambda$$

Explicit Model

This model-independent study can be easily matched to any given flavour-deconstructed model of interest

Gauge group: $\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}}^{3} \times \mathrm{U}(1)_{\mathrm{R}} \times \mathrm{U}(1)_{\mathrm{B\text{-}L}}^{3}$

The Lagrangian leads to the following hierarchical matrices

$$Y_\nu \sim \begin{pmatrix} \varepsilon_1\varepsilon_2 & \varepsilon_1\varepsilon_2\eta_2 & \varepsilon_1\varepsilon_2\eta_1\eta_2 \\ \varepsilon_1\eta_2 & \varepsilon_1 & \varepsilon_1\eta_1 \\ \eta_1\eta_2 & \eta_1 & 1 \end{pmatrix} \qquad M_R \sim \Lambda \begin{pmatrix} \eta_1\eta_2 & \eta_1 & 1 \\ \eta_1\eta_2 & \eta_1 & 1 \\ \eta_1\eta_2 & \eta_1 & 1 \end{pmatrix}$$

$$\varepsilon_1 = \langle \phi_{32}^{L} \rangle / \Lambda_{32}$$

$$\varepsilon_2 = \langle \phi_{21}^{L} \rangle / \Lambda_{21}$$

$$\eta_1 = \langle \phi_{32}^{\ell} \rangle / \Lambda_{32}$$

$$\eta_2 = \langle \phi_{21}^{\ell} \rangle / \Lambda_{21}$$

Explicit Model

This model-independent study can be easily matched to any given flavour-deconstructed model of interest

Gauge group: $$\mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)^3_{\mathrm{L}} \times \mathrm{U}(1)_{\mathrm{R}} \times \mathrm{U}(1)^3_{\mathrm{B\text{-}L}}$$

The Lagrangian leads to the following hierarchical matrices

$$Y_\nu \sim \begin{pmatrix} \varepsilon_1\varepsilon_2 & \varepsilon_1\varepsilon_2\eta_2 & \varepsilon_1\varepsilon_2\eta_1\eta_2 \\ \varepsilon_1\eta_2 & \varepsilon_1 & \varepsilon_1\eta_1 \\ \eta_1\eta_2 & \eta_1 & 1 \end{pmatrix} \qquad M_R \sim \Lambda \begin{pmatrix} \eta_1\eta_2 & \eta_1 & 1 \\ \eta_1\eta_2 & \eta_1 & 1 \\ \eta_1\eta_2 & \eta_1 & 1 \end{pmatrix}$$

$$\varepsilon_1 = \langle \phi^L_{32} \rangle / \Lambda_{32}$$
$$\varepsilon_2 = \langle \phi^L_{21} \rangle / \Lambda_{21}$$
$$\eta_1 = \langle \phi^\ell_{32} \rangle / \Lambda_{32}$$
$$\eta_2 = \langle \phi^\ell_{21} \rangle / \Lambda_{21}$$

We have the freedom to require Normal Hierarchy $\Delta_1 \lesssim 1 \quad \Delta_2 \lesssim 1$

$$\Longrightarrow \quad \Lambda \gtrsim \text{few TeV}$$

Conclusions

In this work we have considered the leading phenomenological implications of neutrino anarchy in flavour deconstruction [Greljo, Isidori, 2024]

- We have computed which is the expected absolute neutrino mass scale predicted by any given flavour-deconstructed model
- We have shown that Normal Hierarchy allows for the NP scale Λ to be lower with respect to Inverted Hierarchy
- The contribution to LFV processes coming from the neutrino sector can be dominant over the Gauge and Yukawa sectors
- In some cases, the NP scale Λ can be as low as few TeV and can be probed by near future experiments, such as Mu3e and COMET