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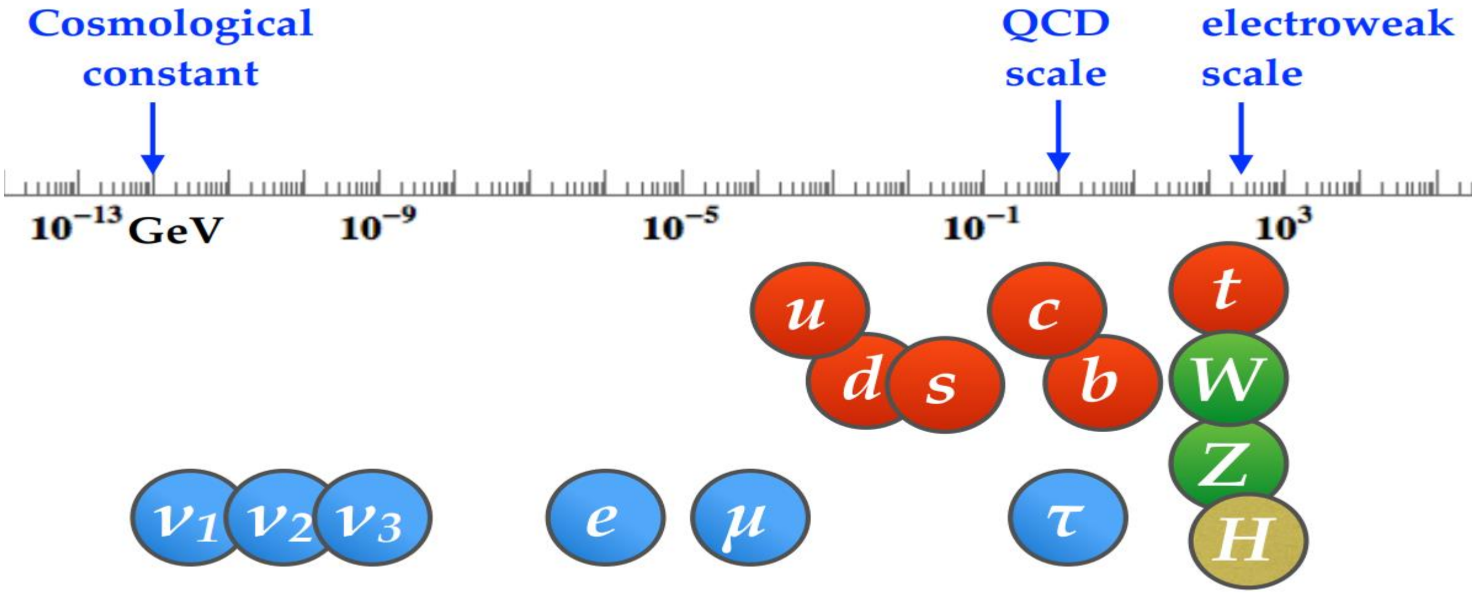
Neutrino Phenomenology from Flavour Deconstruction

Andrea Sainaghi

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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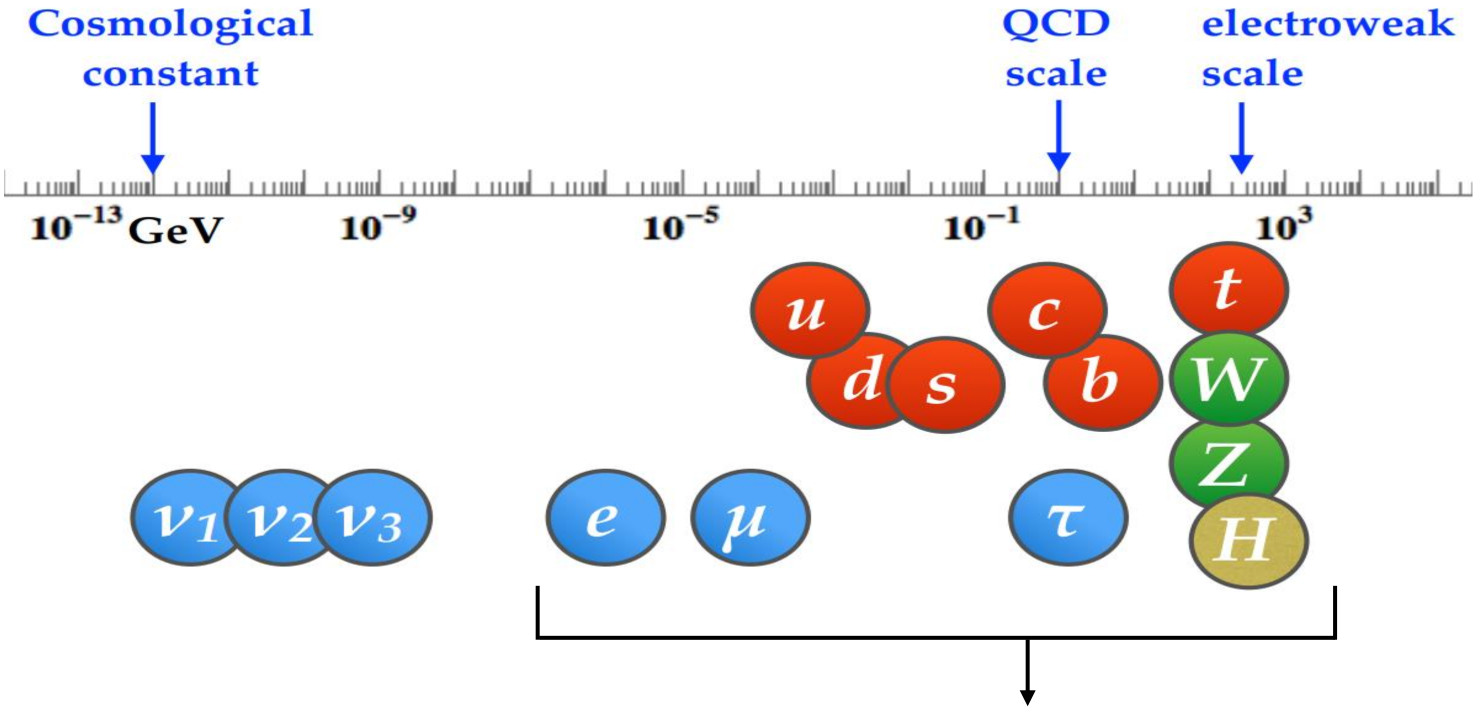
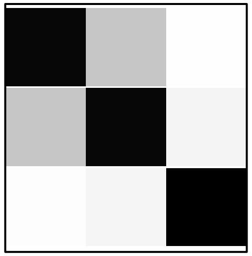


Very hierarchical masses

$V_{\rm CKM} \sim$



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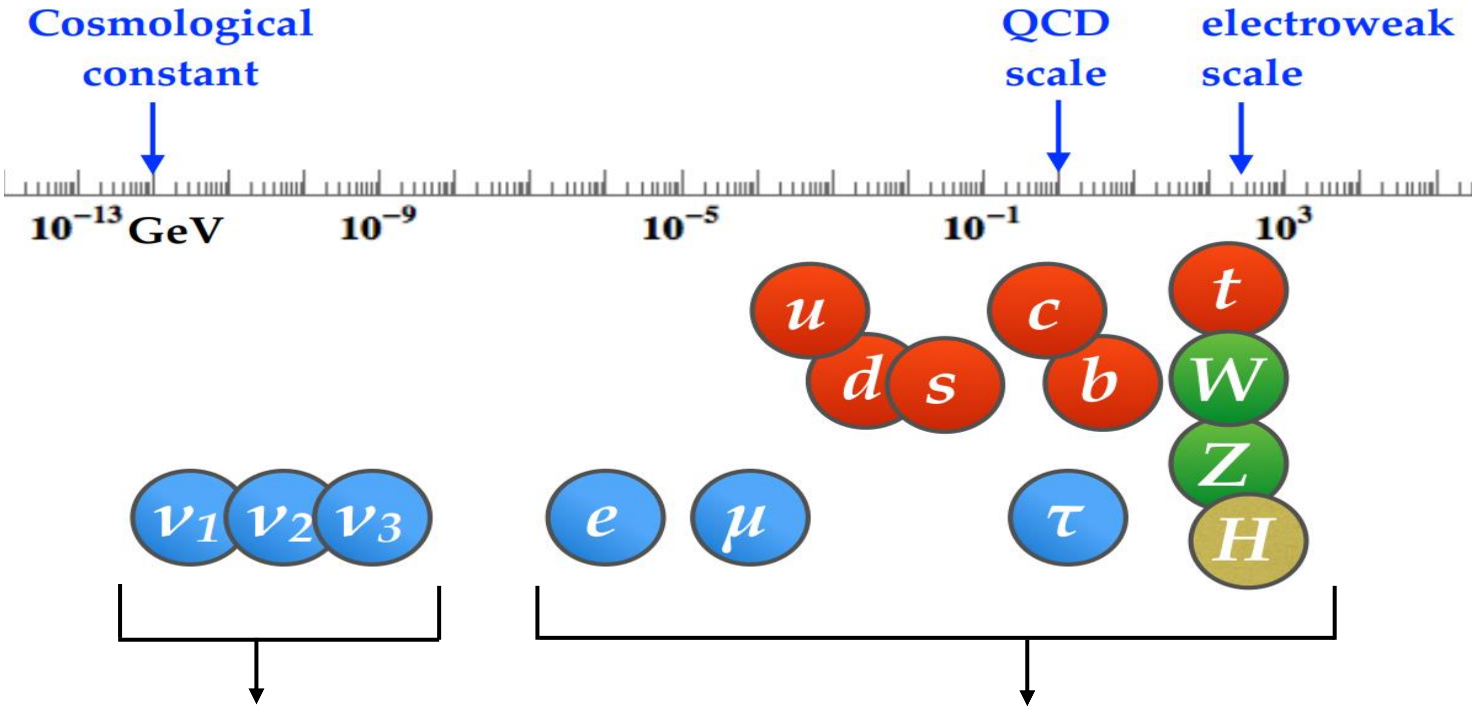
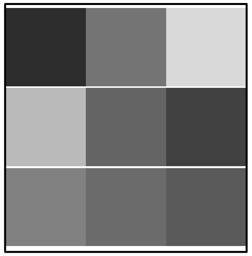


Almost anarchic

Very hierarchical masses

$U_{\text{PMNS}} \sim$



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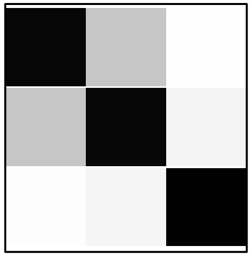
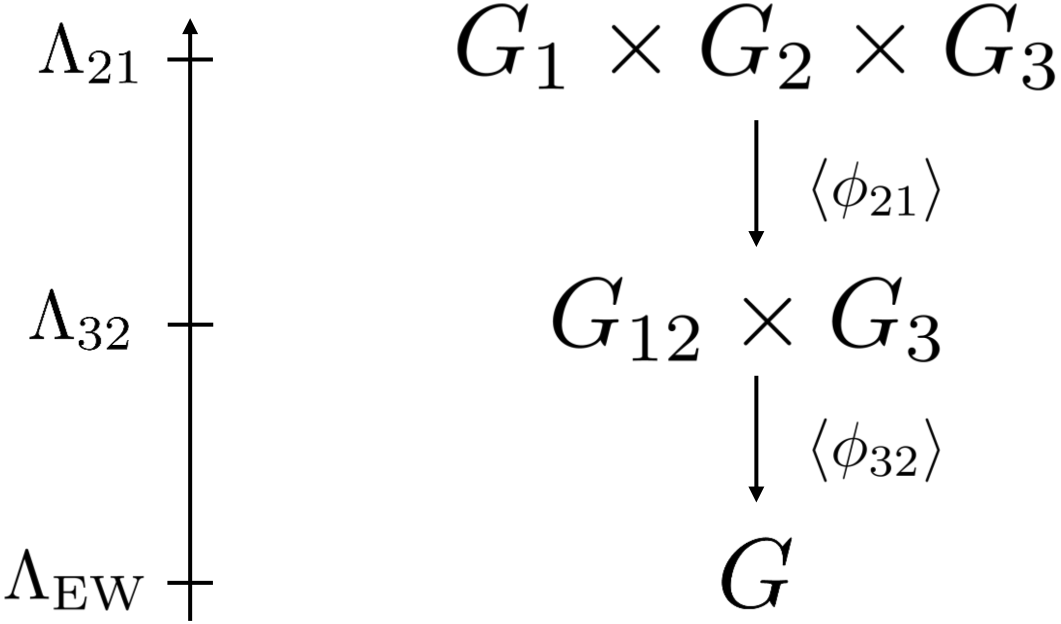


The Flavour Puzzle

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



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

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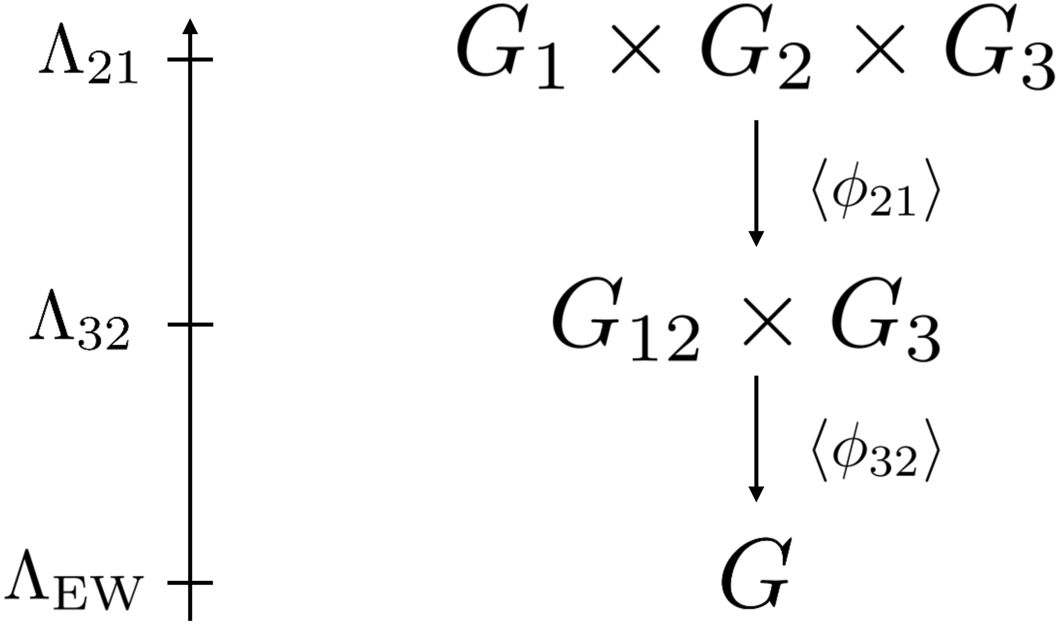

$$\begin{tikzcd}
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G
\end{tikzcd}$$

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

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

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

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

μ ⟶ 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 $\varepsilon_{2,1}, \eta_{2,1} \ll 1$

Theory Setup

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

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

SM Interactions

The HNLs interact weakly with the SM

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \bar{e}_L \cancel{W}^- U \nu_L + \frac{g}{\sqrt{2}} \bar{e}_L \cancel{W}^- V n_L + \mathrm{h.c.} + \mathcal{L}_Z$$

We exploit the following parameterization for the mixing matrices

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

Where $\mathcal{N}$ is the PMNS matrix of the SM and $\mathcal{U}$, U_S are 3x3 unitary matrices

while $\hat{A} = \frac{v}{\Lambda} \mathrm{diag}(\Delta_1 \Delta_2, \Delta_1, 1)$

Parameters

There are 11 parameters relevant for the phenomenology:

Λ → New-Physics (NP) scale

→ Hopefully around few TeV

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$\varepsilon_1 \;,\; \varepsilon_2$ → 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 11 parameters relevant for the phenomenology:

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

They effectively represent the hierarchies in the Heavy mass matrix M_R (traded for $\eta_1 \; , \; \eta_2$)

They enter in m_ν, so, if they departure too much from 1, the model fails in reproducing the PMNS matrix as μ is assumed anarchic

Normal Ordering:
$m_1 < m_2 < m_3$

$$0.25 \lesssim \Delta_1 \lesssim 0.6 \qquad 0.15 \lesssim \Delta_2 < 1$$

Inverted Ordering:
$m_3 < m_1 \lesssim m_2$

$$1 < \Delta_1 \lesssim 4 \qquad \Delta_2 \approx 1$$

Parameters

There are 11 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)

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

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 11 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

---

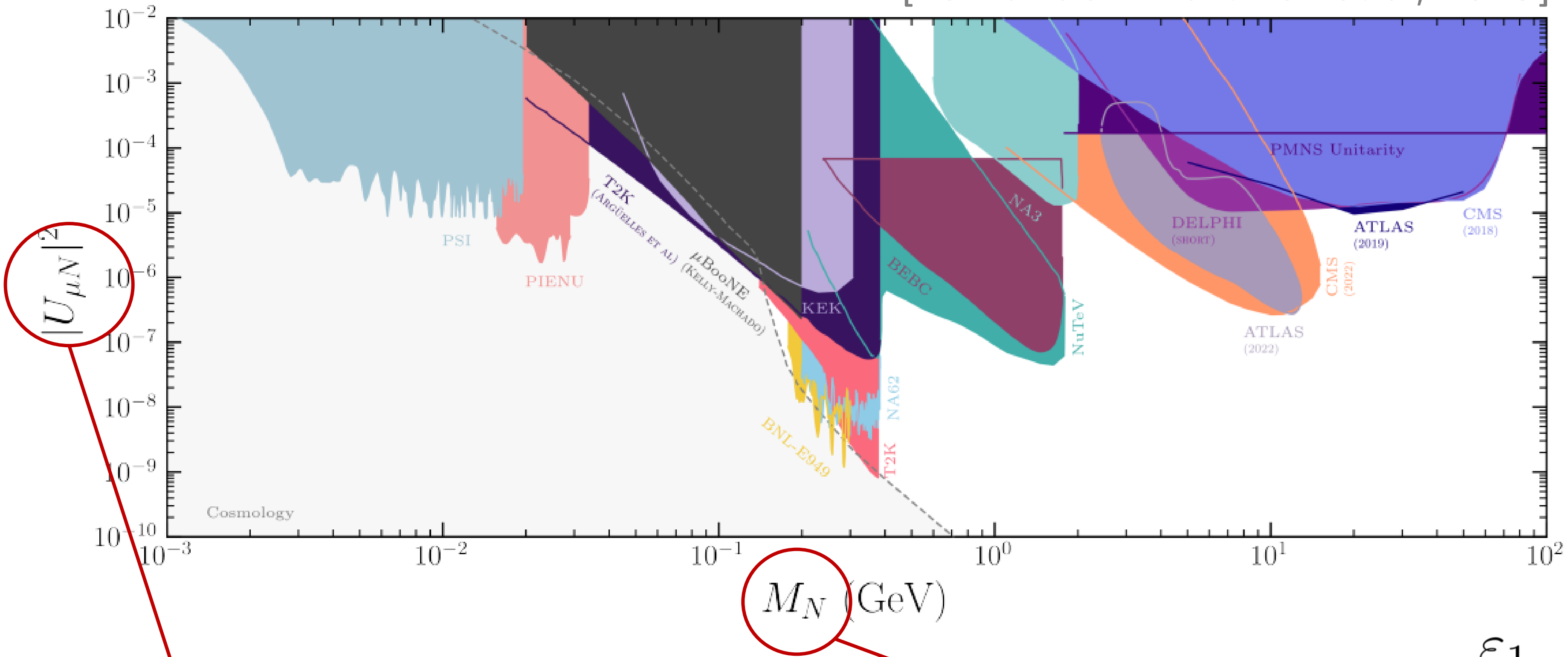
$$\mathcal{L} \supset \frac{g}{\sqrt{2}}\bar{e}_L \not{W}^- U \nu_L + \frac{g}{\sqrt{2}}\bar{e}_L \not{W}^- V n_L + \text{h.c.} + \mathcal{L}_Z$$

β_i here

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

Direct Searches

[Fernández-Martínez et al, 2023]



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

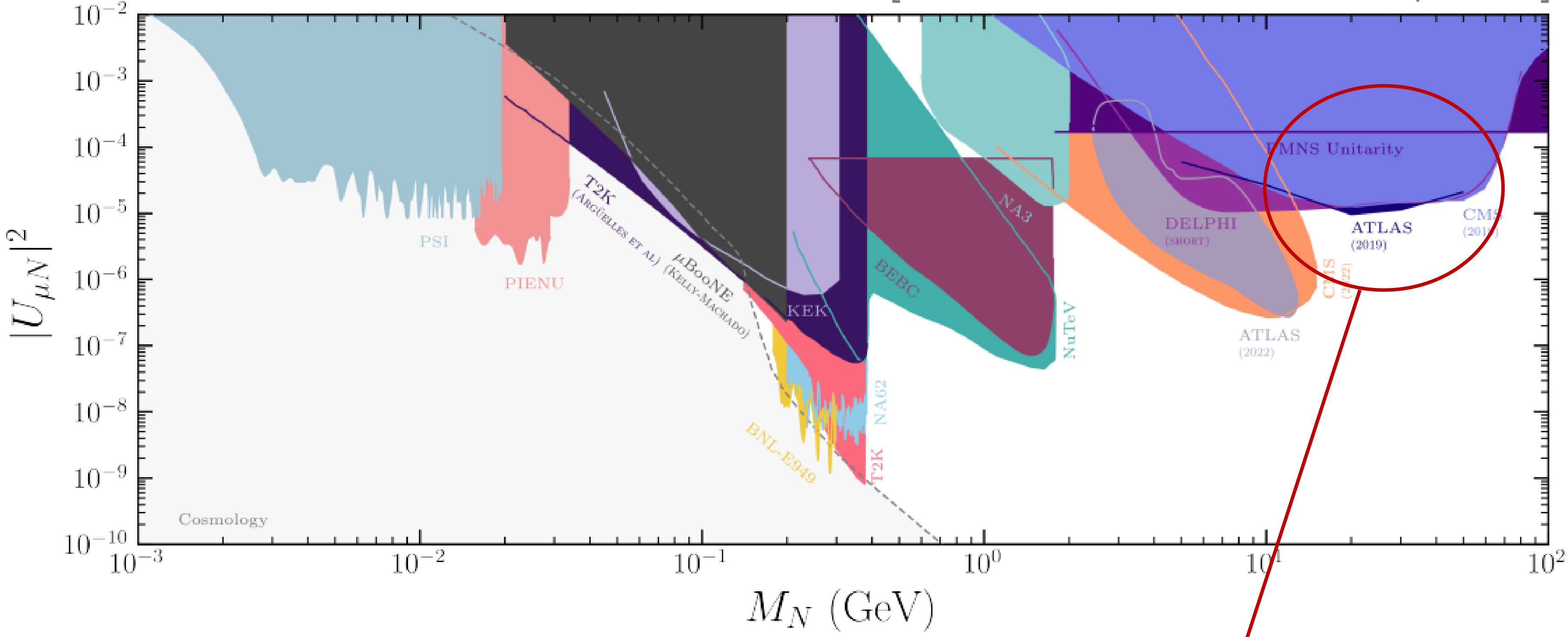
$$M_1 = \Lambda \frac{\varepsilon_1}{\Delta_1} \frac{\varepsilon_2}{\Delta_2}$$

The HNLs have hierarchical masses and interact with the charged leptons

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

Direct Searches

[Fernández-Martínez et al, 2023]

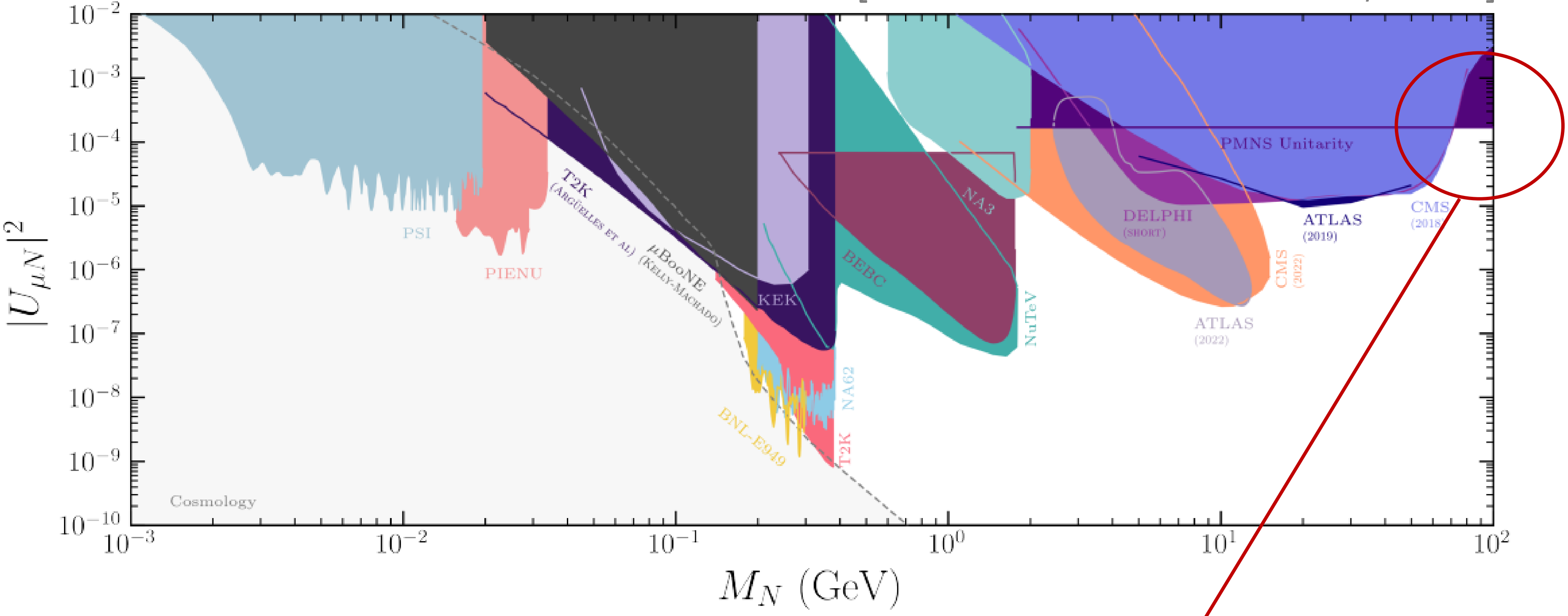


If the lightest HNL is lighter than Z and W bosons,
it can be produced on-shell at colliders

$M_1 < M_{W,Z}$ imposes $\Lambda \gtrsim 25\,\text{TeV}$

Direct Searches

[Fernández-Martínez et al, 2023]



Otherwise, for $M_1 > M_{W,Z}$

$$\Lambda \gtrsim 20 \left(\frac{\Delta_1 \Delta_2}{0.07}\right) \left(\frac{m_\mu / m_\tau}{\varepsilon_1}\right) \left(\frac{m_e / m_\mu}{\varepsilon_2}\right) \text{TeV}$$

PMNS non-Unitarity

As we add new neutrino states, the PMNS matrix is not unitary anymore

$$\eta \equiv |\mathbb{I} - UU^\dagger| \sim \left(\frac{v}{\Lambda}\right)^2 \begin{pmatrix} \Delta_1^2\Delta_2^2 & \Delta_1^2\Delta_2 & \Delta_1\Delta_2 \\ \Delta_1^2\Delta_2 & \Delta_1^2 & \Delta_1 \\ \Delta_1\Delta_2 & \Delta_1 & 1 \end{pmatrix}$$

The current updated bounds are [Antusch, Fischer, 2014]

$$\eta < \begin{pmatrix} 2.1\cdot 10^{-3} & 1.0\cdot 10^{-5} & 2.1\cdot 10^{-3} \\ 1.0\cdot 10^{-5} & 4.0\cdot 10^{-4} & 8.0\cdot 10^{-4} \\ 2.1\cdot 10^{-3} & 8.0\cdot 10^{-4} & 5.3\cdot 10^{-3} \end{pmatrix}$$

Normal Ordering: η_{33} imposes $\Lambda \gtrsim 2.5\,\mathrm{TeV}$

Inverted Ordering: η_{11} imposes $\Lambda \gtrsim 4\Delta_1\,\mathrm{TeV}$

LFV Processes

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

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

$$\begin{aligned}\delta_\nu &= \sum_k V_{ek}V^*_{\mu k}\, G_\gamma\left(\frac{M_k^2}{M_W^2}\right)\\ &\approx \frac{v^2}{\Lambda^2}\Delta_1^2\Delta_2 \sum_k \underbrace{(U_S)_{ek}(U_S^*)_{\mu k}}_{\beta_i \text{ inside here}}\, G_\gamma\left(\frac{M_k^2}{M_W^2}\right)\end{aligned}$$

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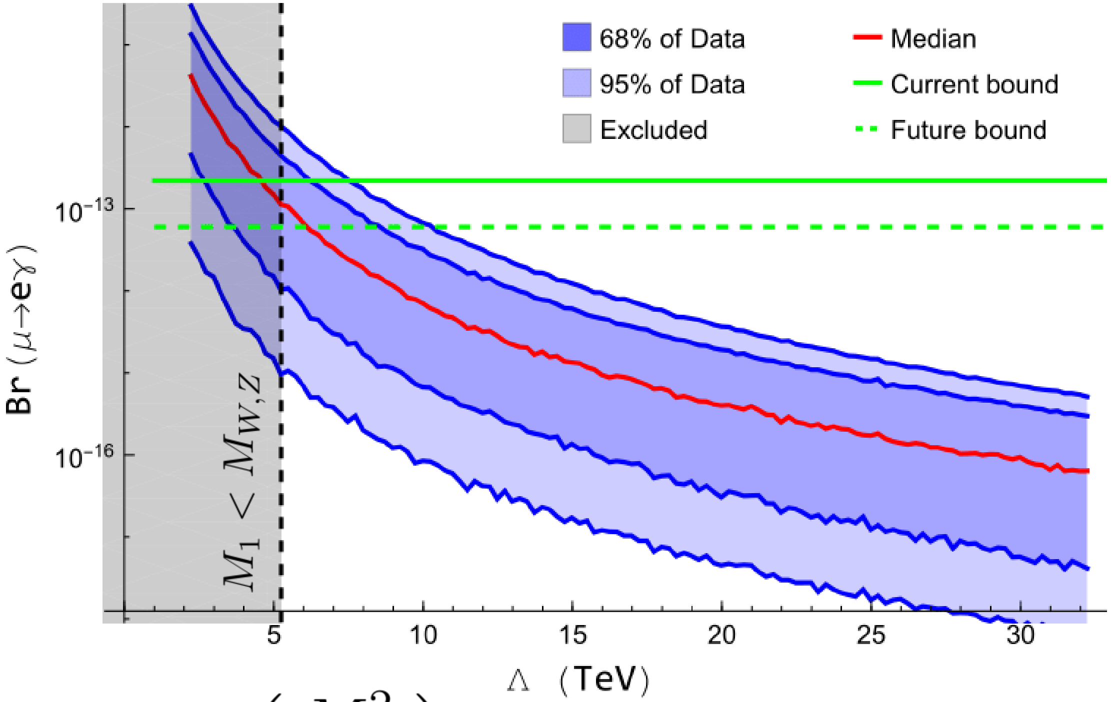
β_i inside here

Normal Ordering allows for Λ to be around few TeV



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

$$\Delta_1 = 0.35 \quad \Delta_2 = 0.2$$
$$\varepsilon_1 = 0.06 \quad \varepsilon_2 = 0.02$$
$$\alpha_i \in [\theta_i - 0.1, \theta_i + 0.1]$$
$$\beta_i \in [0, 2\pi]$$

LFV Processes

Correlation plots between the main LFV processes

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

$$\mathrm{Br}(\mu\,\mathrm{Al} \to e\,\mathrm{Al})$$

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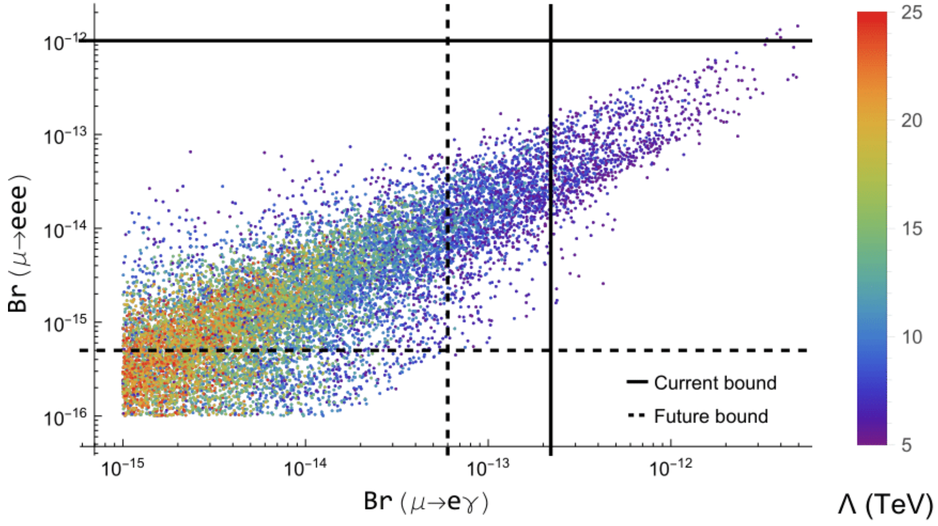

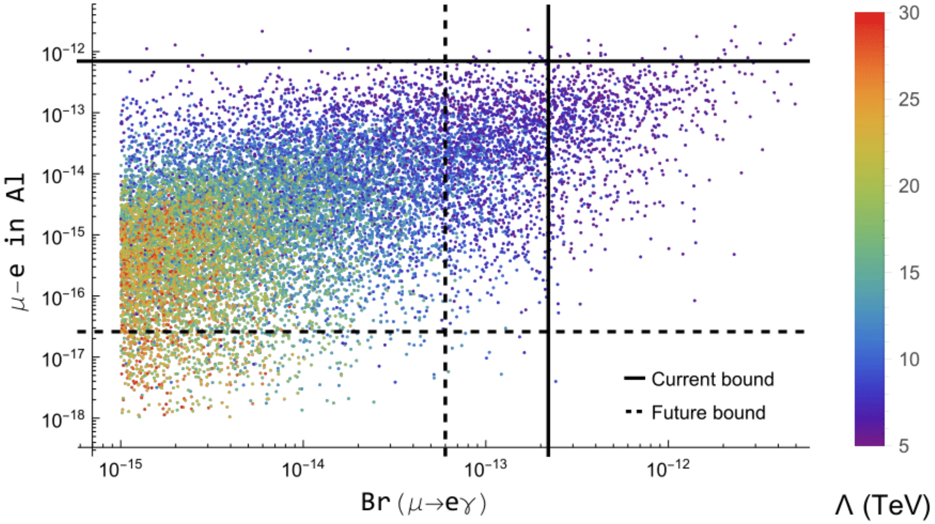

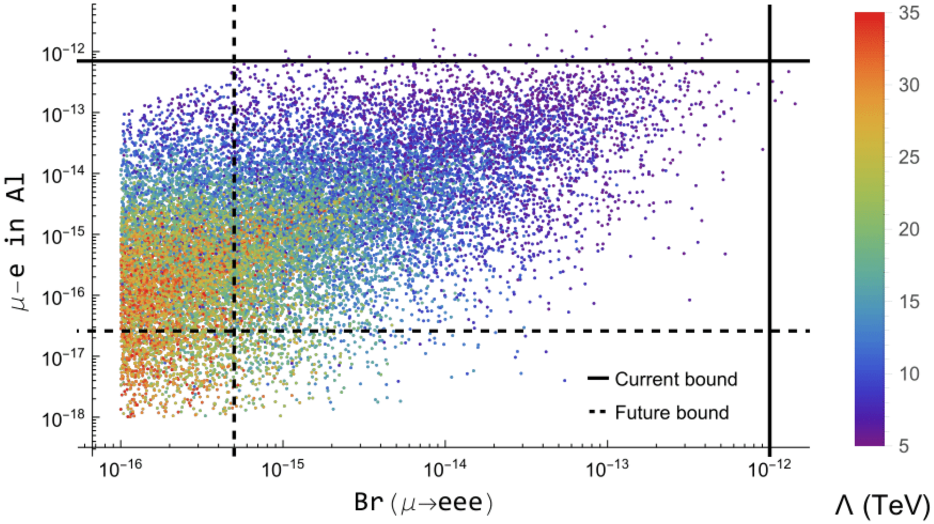

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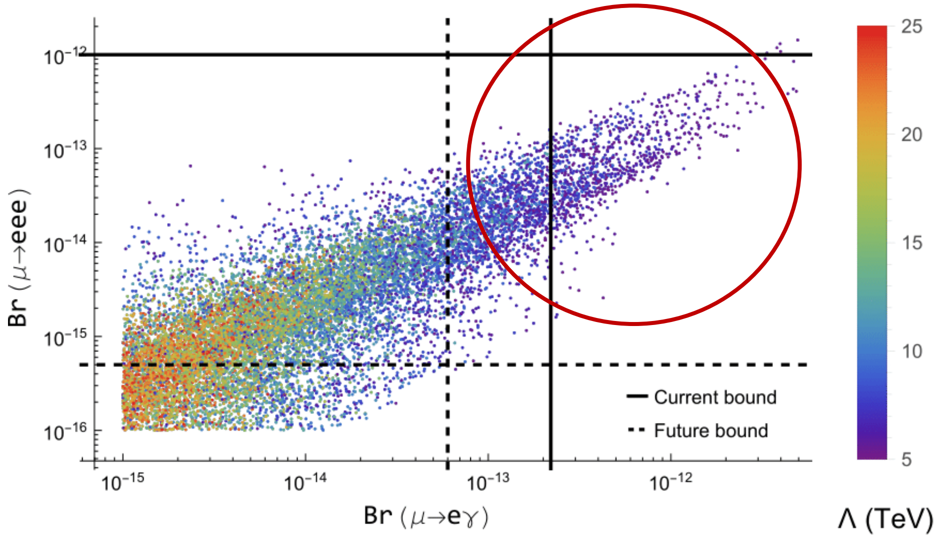

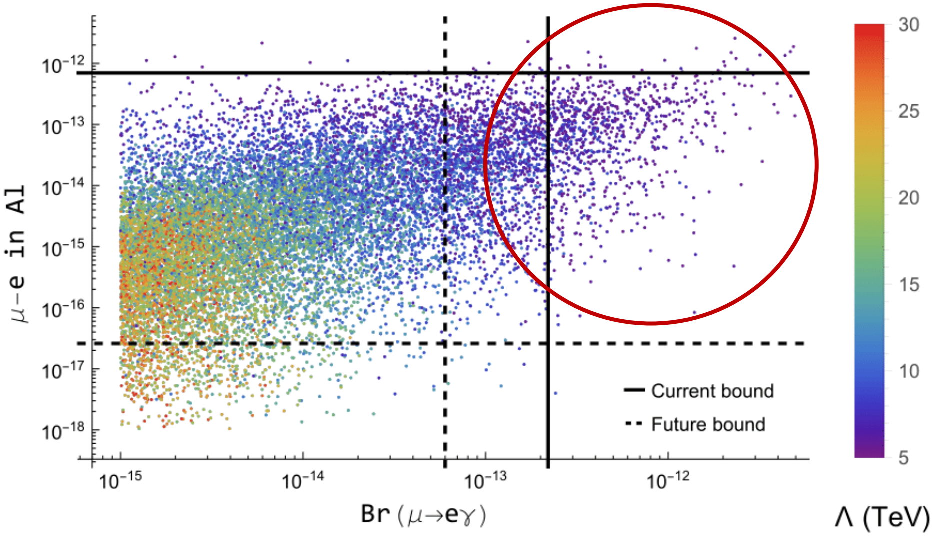

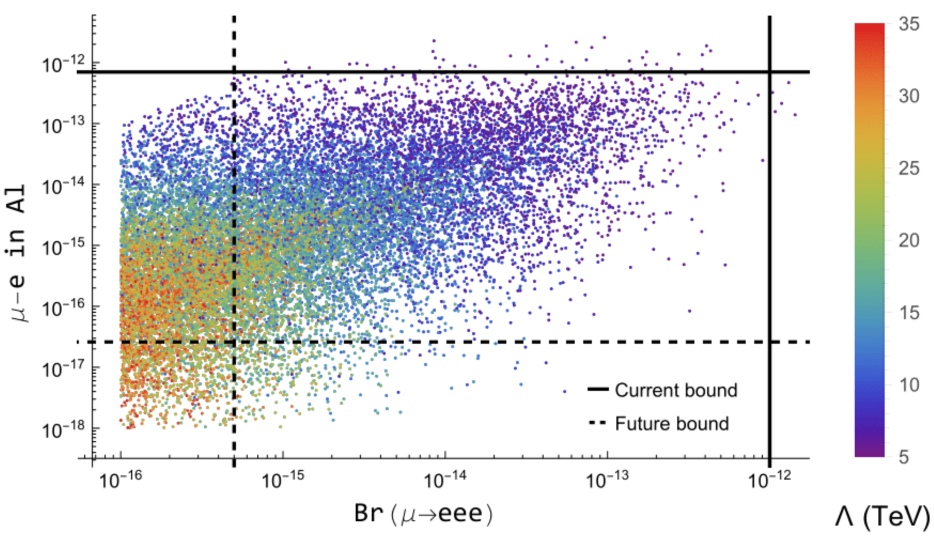

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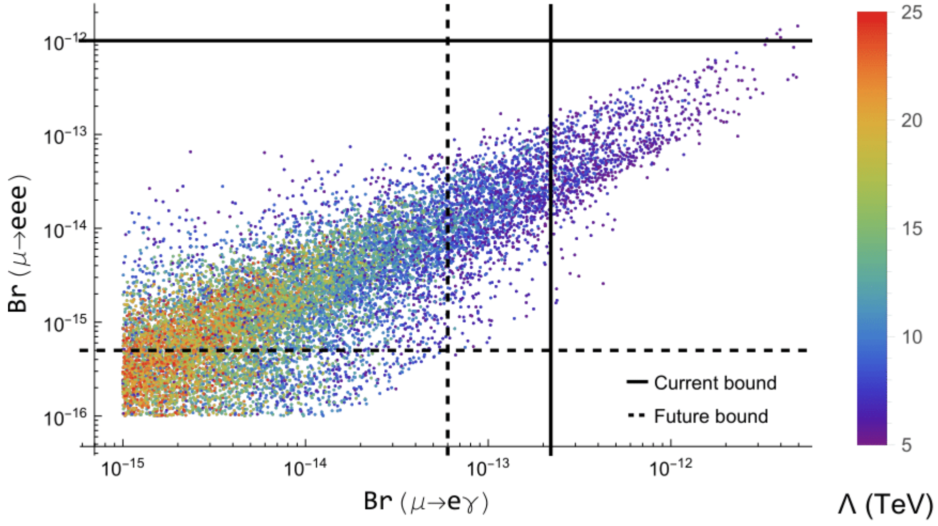

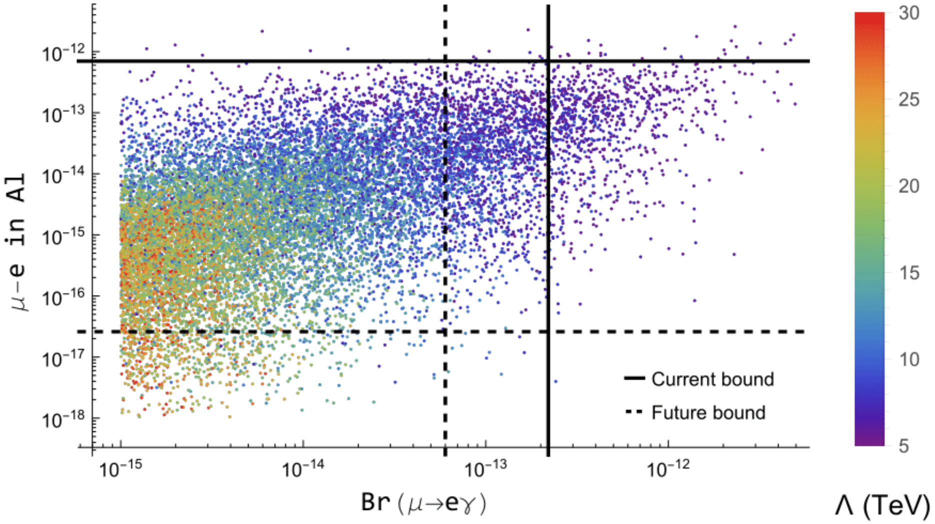

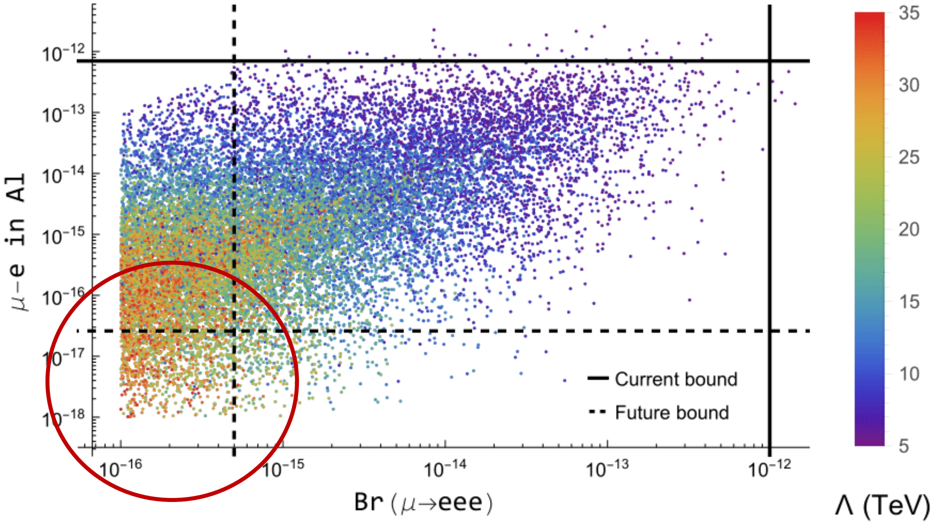

LFV from Gauge and Yukawa Sectors

Flavour-deconstructed models predict LFV processes even without including neutrinos

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

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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' ⟶ 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_α → Heavy NP fermions

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

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$$+ \left[\sum_{\alpha=\text{heavy}} Y'_{\alpha i} \overline{E}_\alpha \phi_{32} e_2 + \sum_{\alpha=\text{heavy}} M_\alpha \overline{E}_\alpha E_\alpha + 1^{\text{st}} \text{ generation} \right]$$

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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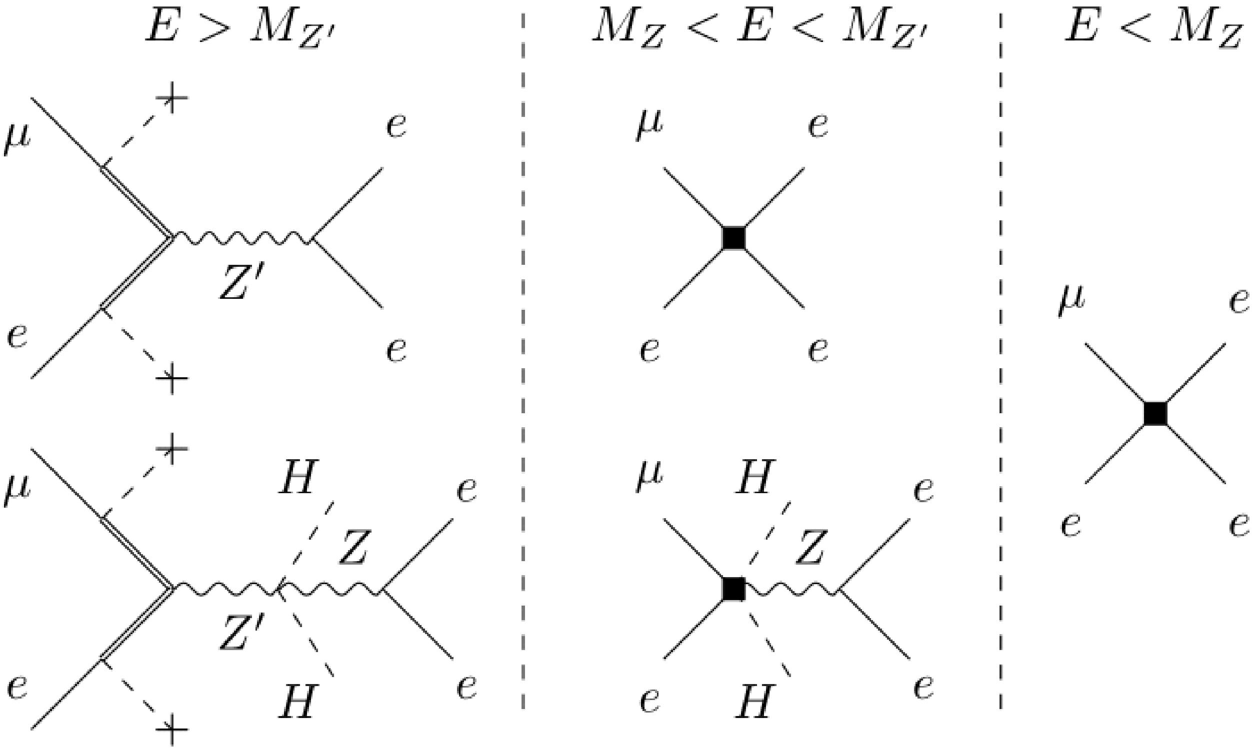

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$$\mathcal{L} \supset |D_\mu H|^2 + Z'_\mu J^\mu_{Z'} + \frac{1}{2} M_{Z'} Z'_\mu Z'^\mu + \mathcal{L}_Y$$

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

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

This range is only due to β_i

Mixing between third and light generations

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

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]

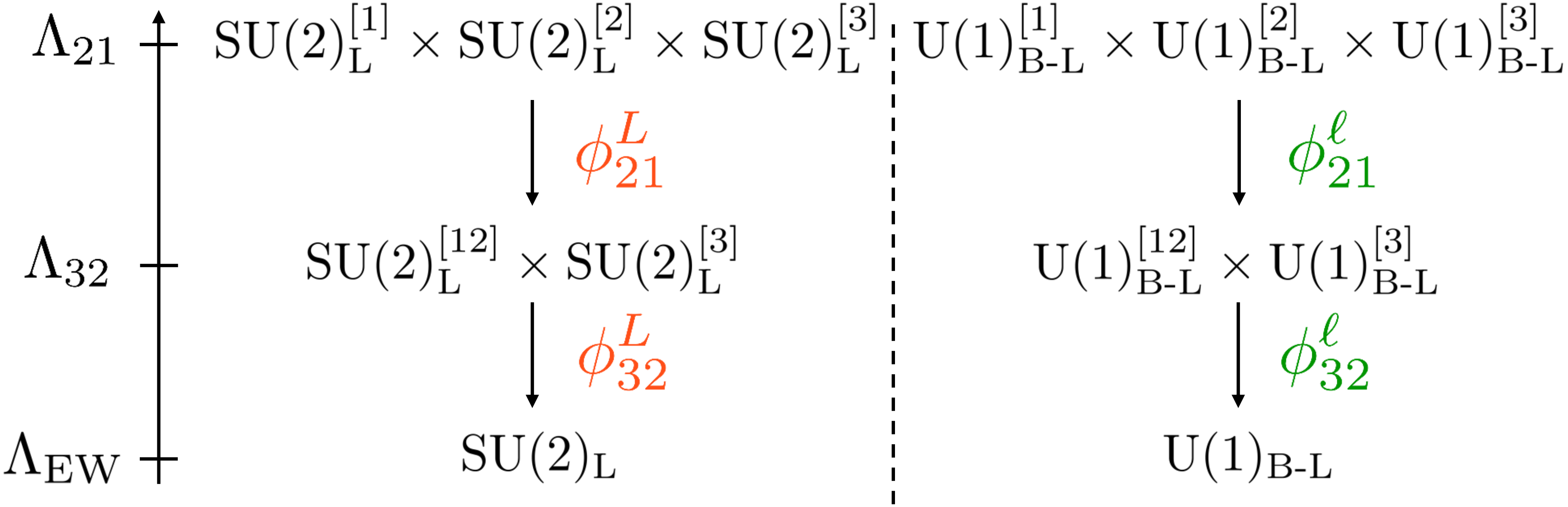
Explicit Model

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

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

Flavour-deconstructed

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



$$\begin{tikzcd}
\Lambda_{21} & \mathrm{SU}(2)_{\mathrm{L}}^{[1]} \times \mathrm{SU}(2)_{\mathrm{L}}^{[2]} \times \mathrm{SU}(2)_{\mathrm{L}}^{[3]} \arrow[d, "\phi_{21}^{L}"] & \mathrm{U}(1)_{\mathrm{B\text{-}L}}^{[1]} \times \mathrm{U}(1)_{\mathrm{B\text{-}L}}^{[2]} \times \mathrm{U}(1)_{\mathrm{B\text{-}L}}^{[3]} \arrow[d, "\phi_{21}^{\ell}"] \\
\Lambda_{32} \arrow[u] & \mathrm{SU}(2)_{\mathrm{L}}^{[12]} \times \mathrm{SU}(2)_{\mathrm{L}}^{[3]} \arrow[d, "\phi_{32}^{L}"] & \mathrm{U}(1)_{\mathrm{B\text{-}L}}^{[12]} \times \mathrm{U}(1)_{\mathrm{B\text{-}L}}^{[3]} \arrow[d, "\phi_{32}^{\ell}"] \\
\Lambda_{\mathrm{EW}} \arrow[u] & \mathrm{SU}(2)_{\mathrm{L}} & \mathrm{U}(1)_{\mathrm{B\text{-}L}}
\end{tikzcd}$$

Explicit Model

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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

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

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

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

Explicit Model

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

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

The Lagrangian leads to the following hierarchical matrices

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

$$\varepsilon_1 = \langle \phi^L_{32} \rangle / \Lambda_{32}$$

$$\varepsilon_2 = \langle \phi^L_{21} \rangle / \Lambda_{21}$$

$$\eta_1 = \langle \phi^\ell_{32} \rangle / \Lambda_{32}$$

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

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

Conclusions

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

- We have shown that Normal Ordering allows for the NP scale Λ to be lower with respect to Inverted Ordering
- 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