Classification of Modular UV Completions via cLFV observables

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with
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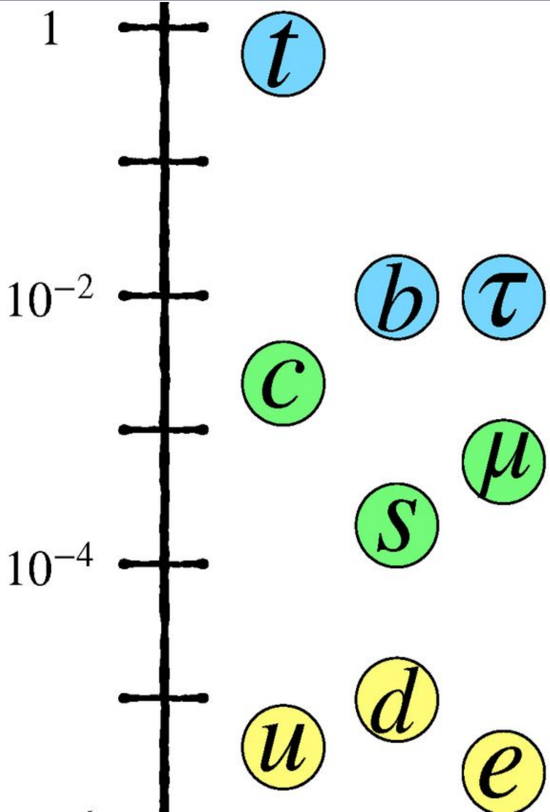
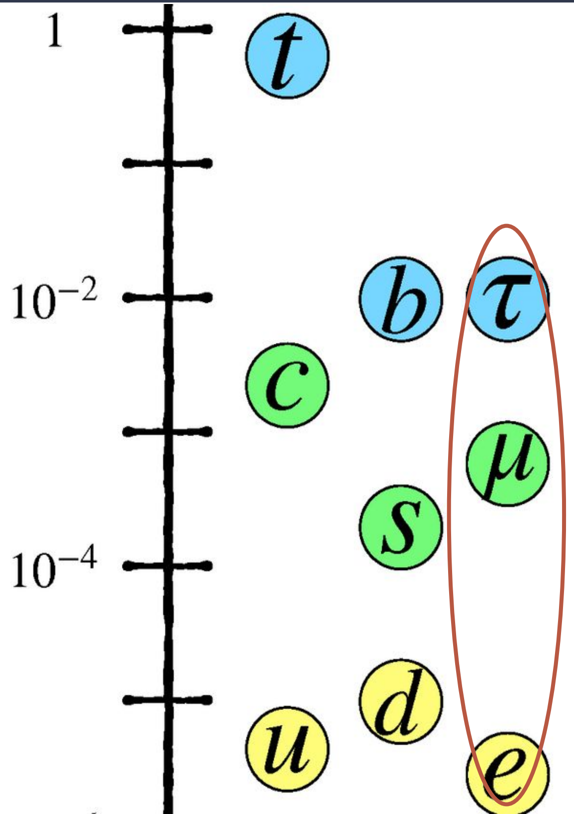
cLFV searches with Mu2e -LFN Workshop 2025

Introduction



- Flavor Puzzle: Three generations with no apparent explanation
- SM is flavor blind except for the yukawa sector
- Different UV explanations to reproduce the Yukawa matrix

Introduction



- Flavor Puzzle: Three generations with no apparent explanation
- SM is flavor blind except for the yukawa sector
- Different UV explanations to reproduce the Yukawa matrix
- This talk: just the leptonic sector

Effective Field Theories

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Our best tool to parameterize extensions beyond the SM

- Model-independent agnostic framework
- Systematically capture low-energy effects of UV physics
- Constrain UV physics through deviations in our experimental measurements

Wilson Coefficient

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d\geq 5} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Flavor structure in SMEFT

Dimension 6: [Grzadkowski, Iskrzynski, Misiak, Rosiek]

- Single generation: 59 parameters
- Three generations: 2499 parameters

Proliferation arises from flavor: What if we assume flavor? [Greljo, Palavrić, Thomsen]

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector															
		MFV_L		$\mathrm{U}(3)_V$		$\mathrm{U}(2)^2\times\mathrm{U}(1)^2$		$\mathrm{U}(2)^2$		$\mathrm{U}(2)_V$		$\mathrm{U}(1)^6$		$\mathrm{U}(1)^3$		No symm.	
Quark sector	MFV_Q	41	6	45	9	59	6	62	9	67	13	81	6	93	18	207	132
	$\mathrm{U}(2)^2\times\mathrm{U}(3)_d$	72	10	78	15	95	10	100	15	107	21	122	10	140	28	281	169
	$\mathrm{U}(2)^3\times\mathrm{U}(1)_{d_3}$	86	10	92	15	111	10	116	12	123	21	140	10	158	28	305	175
	$\mathrm{U}(2)^3$	93	17	100	23	118	17	124	23	132	30	147	17	168	38	321	191
	No symmetry	703	570	734	600	756	591	786	621	818	652	813	612	906	705	1350	1149

Granada Dictionary

[de Blas, Criado, Pérez-Victoria, Santiago]

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- All possible renormalizable heavy extensions in the leptonic sector

- Their matching to the SMEFT is automatized at tree-level and one-loop

UV Field	$-\mathcal{L}_{\mathrm{UV}}^{(4)} \supset$
$\mathcal{S}_1 \sim (\mathbf{1},\mathbf{1})_1$	$[y_{\mathcal{S}_1}]_{rij} \mathcal{S}_{1r}^\dagger \bar{\ell}_i i\sigma_2 \ell_j^c$
$\mathcal{S}_2 \sim (\mathbf{1},\mathbf{1})_2$	$[y_{\mathcal{S}_2}]_{rij} \mathcal{S}_{2r}^\dagger \bar{e}_i e_j^c$
$\varphi \sim (\mathbf{1},\mathbf{2})_{\frac{1}{2}}$	$[y_\varphi]_{rij} \varphi_r \bar{\ell}_i e_j$
$\Xi_1 \sim (\mathbf{1},\mathbf{3})_1$	$[y_{\Xi_1}]_{rij} \Xi_{1r}^{a\dagger} \bar{\ell}_i \sigma^a i\sigma_2 \ell_j^c$
$N \sim (\mathbf{1},\mathbf{1})_0$	$[\lambda_N]_{ri} \bar{N}_{R,r} \tilde{\phi}^\dagger \ell_i$
$E \sim (\mathbf{1},\mathbf{1})_{-1}$	$[\lambda_E]_{ri} \bar{E}_{R,r} \phi^\dagger \ell_i$
$\Delta_1 \sim (\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$[\lambda_{\Delta_1}]_{ri} \bar{\Delta}_{1L,r} \phi e_i$
$\Delta_3 \sim (\mathbf{1},\mathbf{2})_{-\frac{3}{2}}$	$[\lambda_{\Delta_3}]_{ri} \bar{\Delta}_{3L,r} \tilde{\phi} e_i$
$\Sigma \sim (\mathbf{1},\mathbf{3})_0$	$\frac{1}{2}[\lambda_\Sigma]_{ri} \bar{\Sigma}_{R,r}^a \tilde{\phi}^\dagger \sigma^a \ell_i$
$\Sigma_1 \sim (\mathbf{1},\mathbf{3})_{-1}$	$\frac{1}{2}[\lambda_{\Sigma_1}]_{ri} \bar{\Sigma}_{1R,r}^a \phi^\dagger \sigma^a \ell_i$
$\mathcal{B} \sim (\mathbf{1},\mathbf{1})_0$	$[g_{\mathcal{B}}^\ell]_{rij} \mathcal{B}_r^\mu \bar{\ell}_i \gamma_\mu \ell_j + [g_{\mathcal{B}}^e]_{rij} \mathcal{B}_r^\mu \bar{e}_i \gamma_\mu e_j$
$\mathcal{W} \sim (\mathbf{1},\mathbf{3})_0$	$\frac{1}{2}[g_{\mathcal{W}}^\ell]_{rij} \mathcal{W}_r^{\mu a} \bar{\ell}_i \sigma^a \gamma_\mu \ell_j$
$\mathcal{L}_3 \sim (\mathbf{1},\mathbf{2})_{-\frac{3}{2}}$	$[g_{\mathcal{L}_3}]_{rij} \mathcal{L}_{3r}^{\mu\dagger} \bar{e}_i^c \gamma_\mu \ell_j$

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- All possible renormalizable heavy extensions in the leptonic sector
- Their matching to the SMEFT is automatized at tree-level and one-loop
- SMEFT directions: Classification with a flavor assumption

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Discrete Symmetries

Broken flavor symmetry: A_4 [Ferreira, Morisi, Peinado, Holthausen,...]

- The leptonic sector can be very well accommodated in

$$\ell \equiv (\ell_1, \ell_2, \ell_3)^\intercal \sim \mathbf{3},$$

$$(e_1, e_2, e_3) \sim (\mathbf{1}, \mathbf{1}', \mathbf{1}'')$$

- Yukawa interactions can be very well reproduced

Tensor Decomposition

$$\mathbf{1} \otimes \mathbf{1} = \mathbf{1}, \qquad \mathbf{1}'' \otimes \mathbf{1}'' = \mathbf{1}',$$

$$\mathbf{1}' \otimes \mathbf{1}' = \mathbf{1}'', \qquad \mathbf{1}' \otimes \mathbf{1}'' = \mathbf{1}.$$

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{1}' \oplus \mathbf{1}'' \oplus \mathbf{3}_S \oplus \mathbf{3}_A$$

Modular Symmetries

[Feruglio, Criado , Asaka, Yoshida,...]

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Breaking of A4 dynamically controlled by VEV of a modulus field that transforms under the modulus group

$$\tau \to \gamma\tau = \frac{a\tau + b}{c\tau + d}$$

- Fields are modular forms

$$f(\tau) \to (c\tau + d)^k U f(\tau), \qquad U \in \Gamma_3$$

$$k_\ell = 2$$
$$k_e = 0$$

- Yukawa couplings too...

$$\begin{bmatrix} Y_1(\tau) \\ Y_2(\tau) \\ Y_3(\tau) \end{bmatrix} = \begin{bmatrix} 1 + 12q + 36q^2 + 12q^3 + \ldots \\ -6q^{1/3}(1 + 7q + 8q^2 + \ldots) \\ -18q^{2/3}(1 + 2q + 5q^2 + \cdots) \end{bmatrix}, \quad q = e^{2i\pi\tau}$$

[Kobayashi, Otsuka, Tanimoto, Yamamoto]

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[Feruglio, Criado , Asaka, Yoshida,...]

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$$\tau \to \gamma\tau = \frac{a\tau + b}{c\tau + d}$$

Yukawa couplings explained just with one parameter: τ

- Fields are modular forms

$$f(\tau) \to (c\tau + d)^k U f(\tau), \qquad U \in \Gamma_3$$

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[Kobayashi, Otsuka, Tanimoto, Yamamoto]

UV Classification $\mathcal{S}_1 \sim (\mathbf{1}, 4)$

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- Consider the UV interaction

$$[y_{\mathcal{S}_1}]_{rij} \mathcal{S}_{1r}^{\dagger} \bar{\ell}_i i\sigma_2 \ell_j^c$$

- Extract the flavor tensor

$$[y_{\mathcal{S}_1}]_{rij} = \frac{y_{\mathcal{S}_1}^{(1)}}{2} \Big[\delta_{r1}(\delta_{i2}\delta_{j3} - \delta_{i3}\delta_{j2}) + \delta_{r2}(\delta_{i3}\delta_{j1} - \delta_{i1}\delta_{j3}) + \delta_{r3}(\delta_{i1}\delta_{j2} - \delta_{i2}\delta_{j1}) \Big],$$

- Perform the matching to the SMEFT

$$\frac{1}{M_{\mathcal{S}_1}^2} [y_{\mathcal{S}_1}]_{rjl}^* [y_{\mathcal{S}_1}]_{rik} [\mathcal{O}_{\ell\ell}]_{ijkl}$$

- Compute the experimental bounds

$$y_{\mathcal{S}_1} \sim 1$$

Observables

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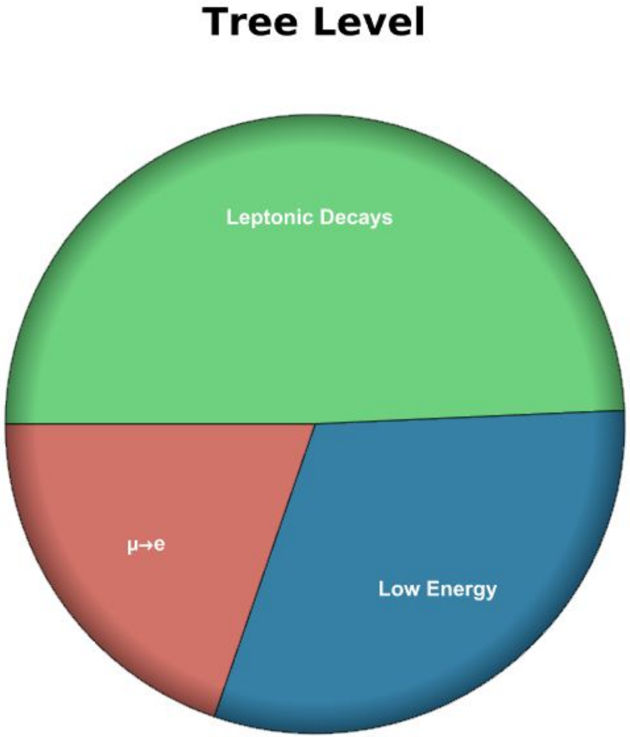
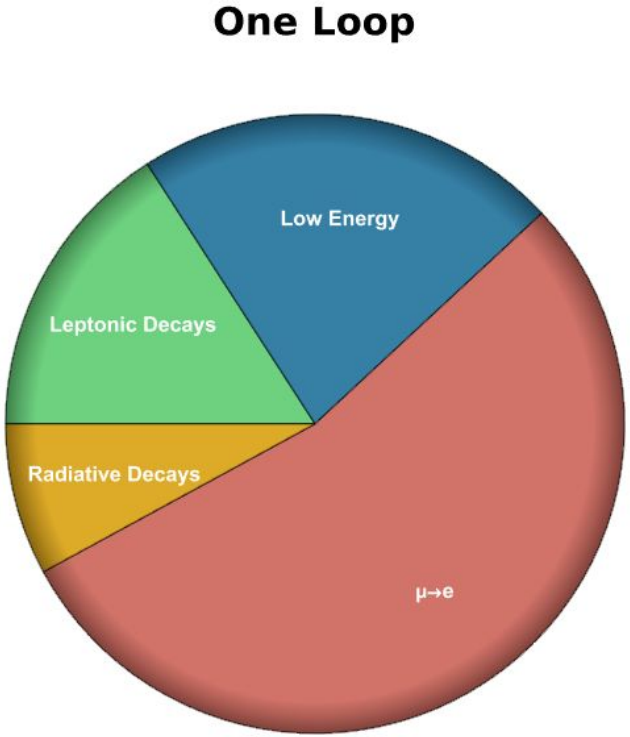
Low Energy observables: Global Fit [Falkowski et al.]

Flavor Violating

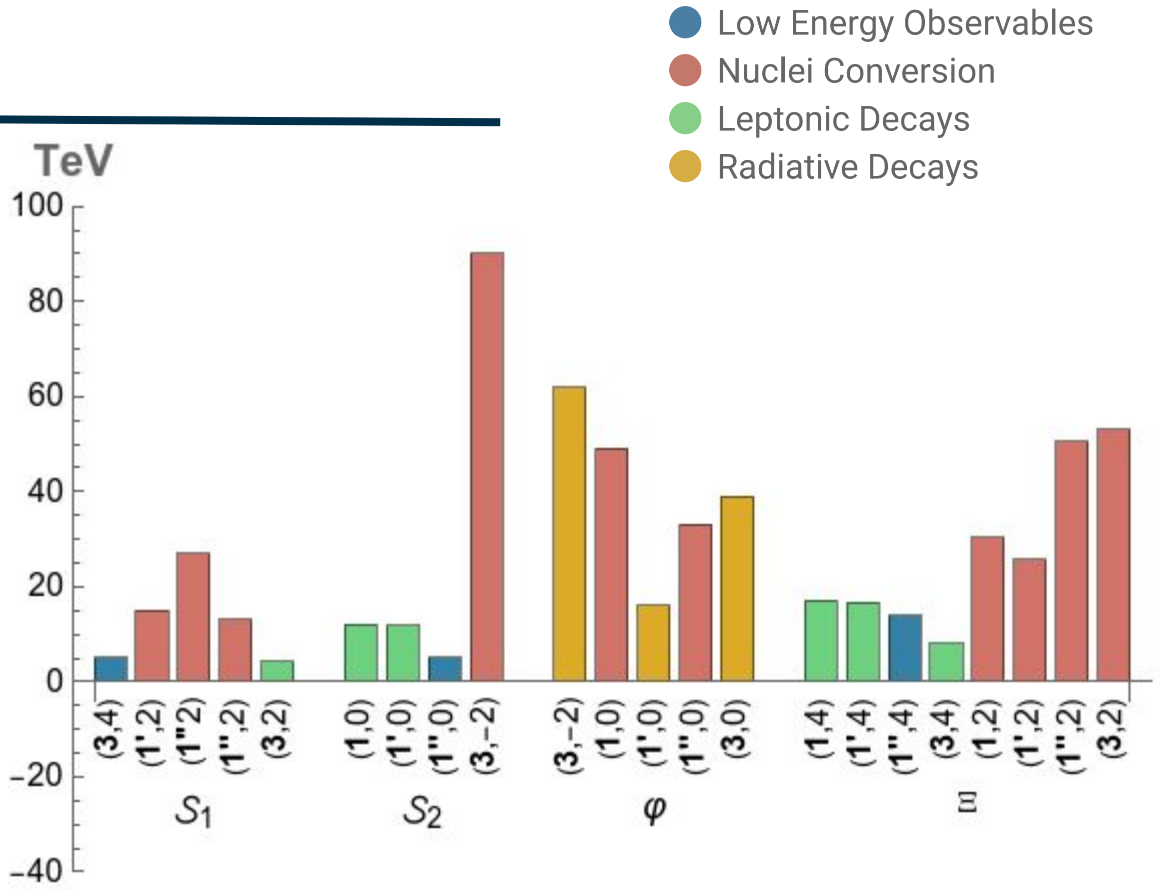
- Radiative Decays [MEG, BaBar, Belle] $\mathrm{BR}(\mu \to e, \gamma)$
- 3 body leptonic decays [SINDRUM, Belle, Mu3e] $\mathrm{BR}(\ell_i \to \ell_j \ell_k \ell_l)$
- Muon-to-electron conversion [SINDRUM, Mu2e] $CR(\mu \to e, \mathrm{N})$

Radiative Corrections



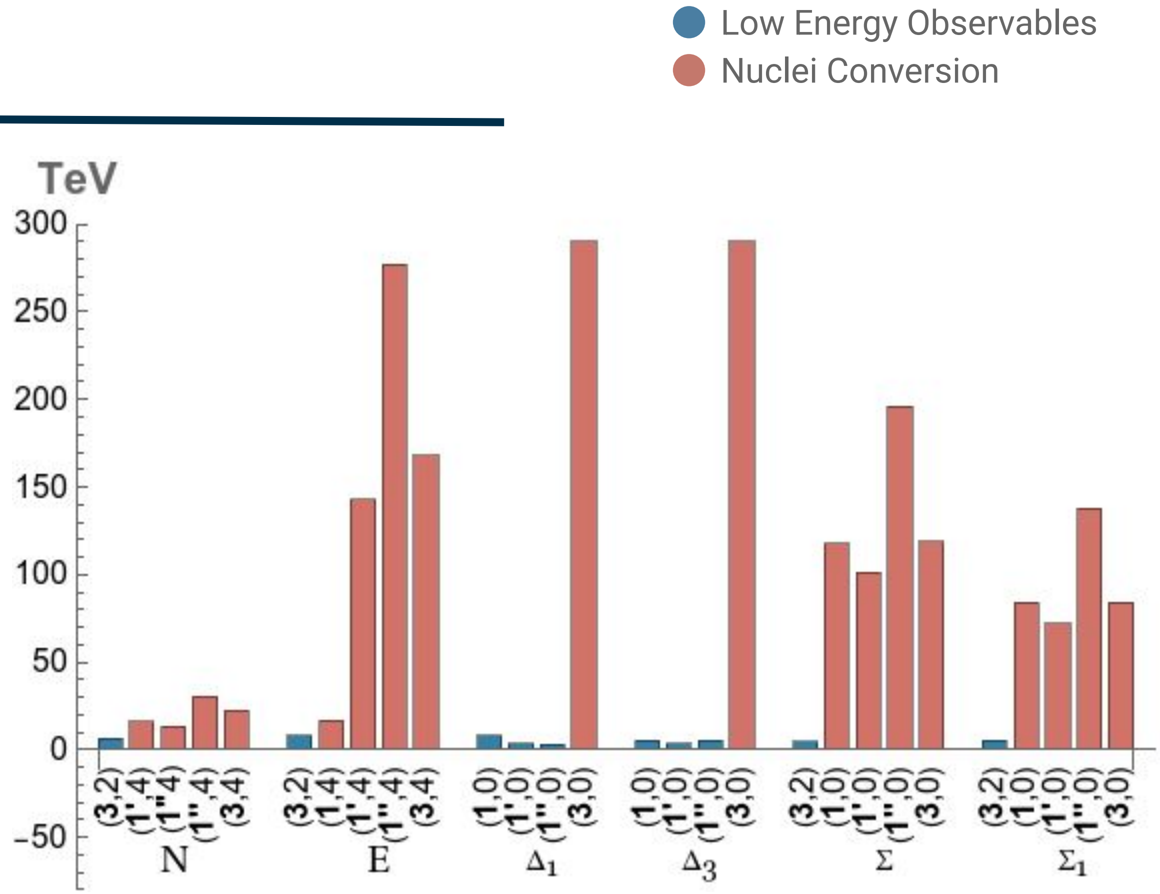


Scalars



Low Energy Observables
Nuclei Conversion
Leptonic Decays
Radiative Decays
TeV
100
80
60
40
20
0
−20
−40
(3,4)
(1',2)
(1'',2)
(1''',2)
(3,2)
(1,0)
(1',0)
(1'',0)
(3,−2)
(3,−2)
(1,0)
(1',0)
(1'',0)
(3,0)
(1,4)
(1',4)
(1'',4)
(3,4)
(1,2)
(1',2)
(1'',2)
(3,2)
S_1
S_2
φ
Ξ

Fermions



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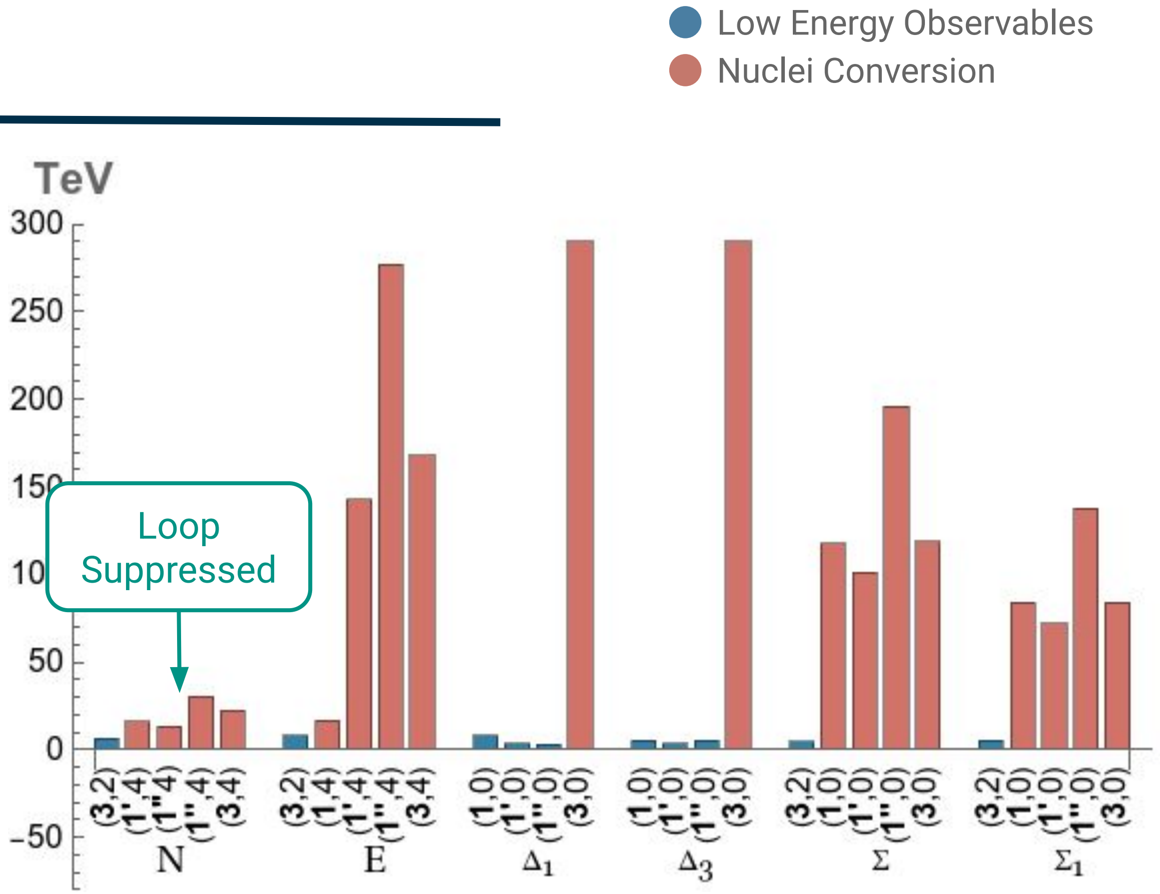
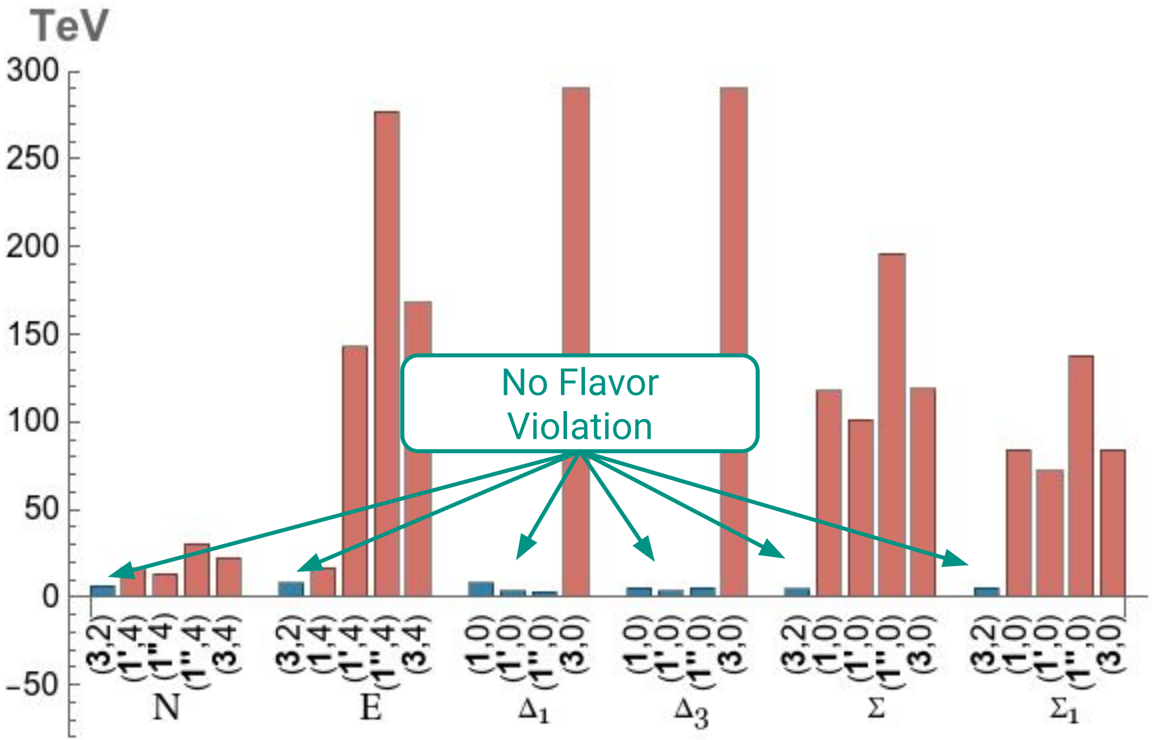
Fermions



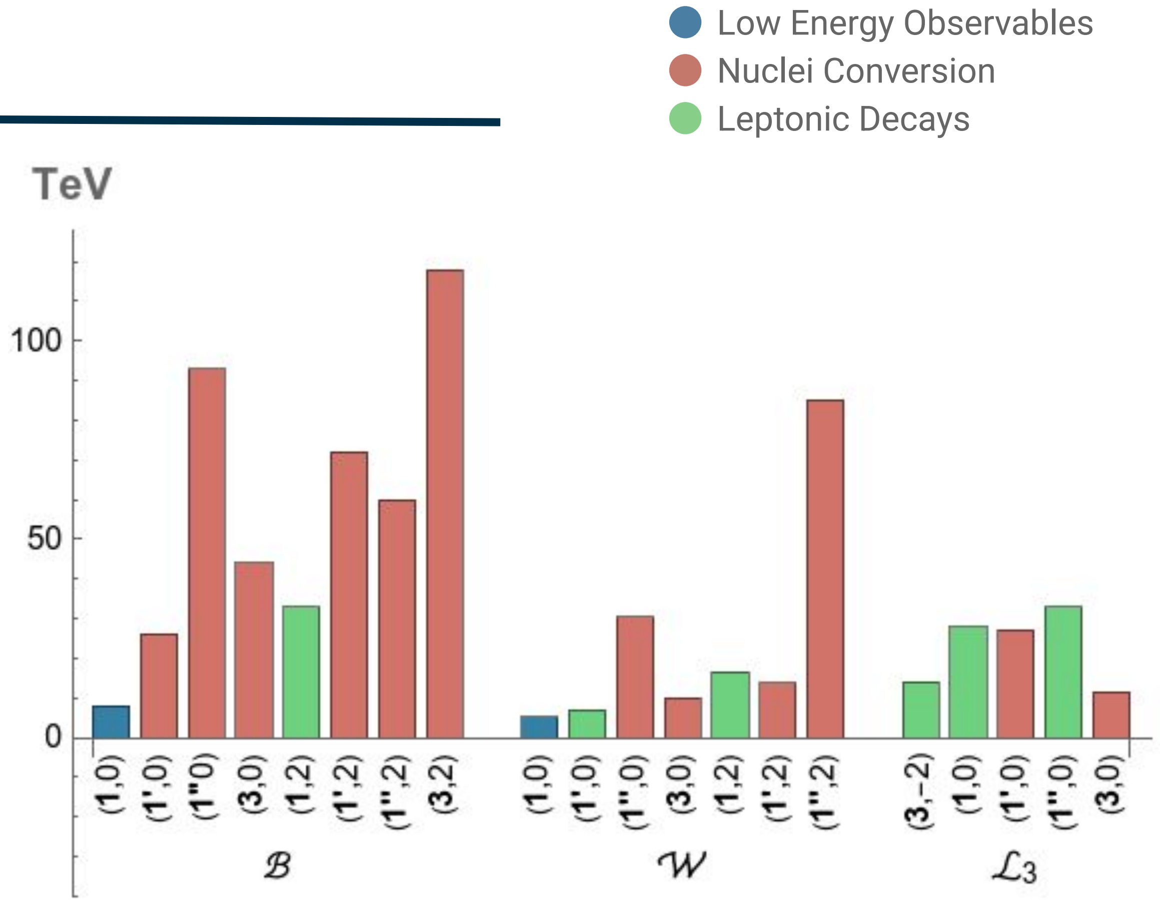
Low Energy Observables
Nuclei Conversion
TeV
300
250
200
150
100
50
0
-50
Loop Suppressed
N
E
Δ_1
Δ_3
Σ
Σ_1

Fermions

- Low Energy Observables
- Nuclei Conversion



Vectors



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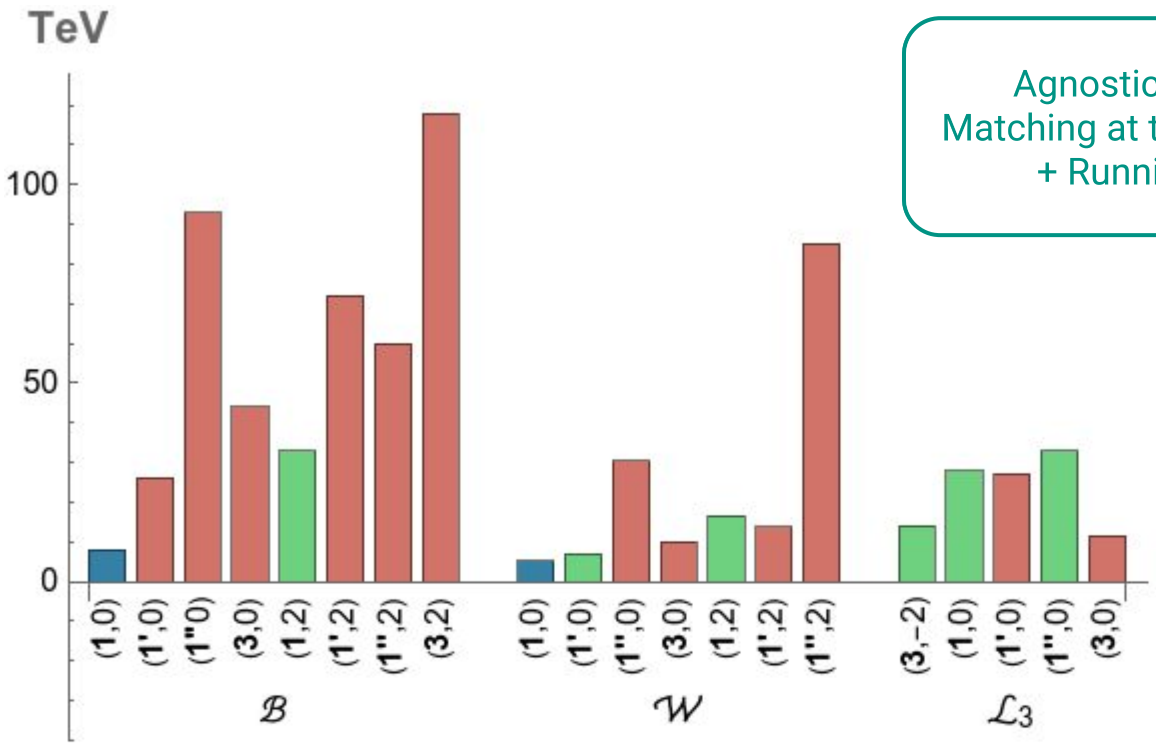
Vectors

- Low Energy Observables
- Nuclei Conversion
- Leptonic Decays

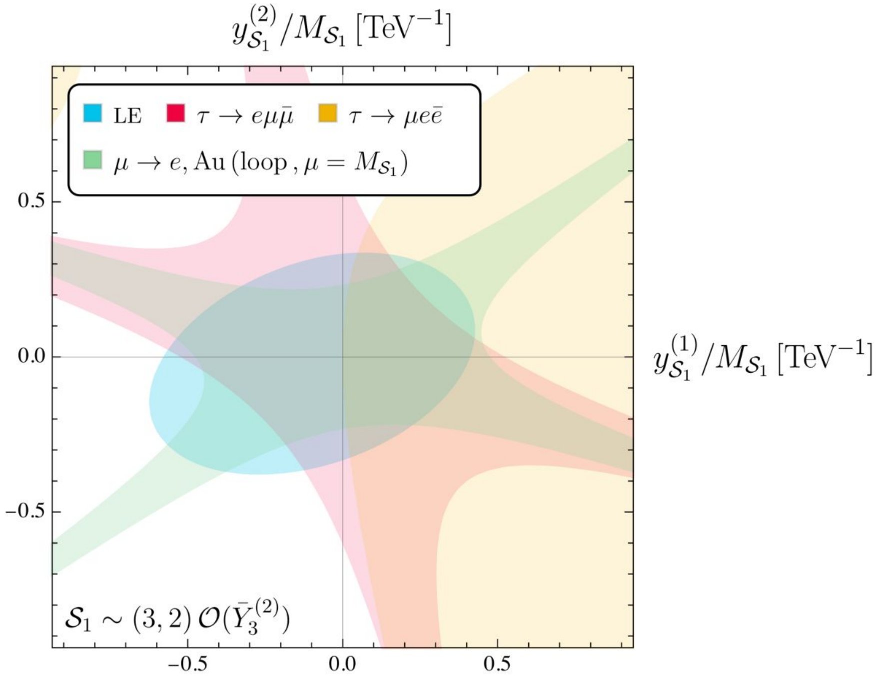


Agnostic UV:
Matching at tree-level
+ Running

Multi-Parameter

Flavor tensor with various different couplings

- Combined fit with correlations
- Projected two-dimensional likelihoods
- Blind lines



To take home

- Modular symmetries are a promising explanation for flavor
- UV modular physics is very constrained by cFLV
- Radiative correction are relevant
- $CR(\mu \to e, \mathrm{N})$ as the most relevant observable

Grazie mille!