ISAPP 2024: Particle Candidates for Dark Matter

Padua, Italy, June 25 – July 4, 2024

Minimal U(1) two-Higgs-doublet models for quark and lepton flavour

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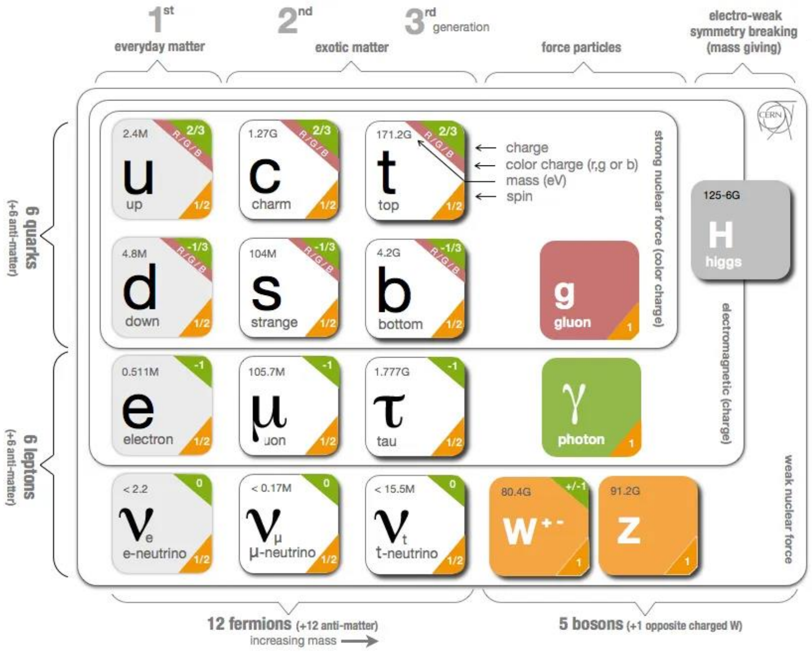
arXiv: **2406.03331** [hep-ph]

Introduction

The **Standard Model** of Particle Physics:

- ✓ Quark mixing is encoded in the CKM matrix;
- ✓ This flavour structure is the only known source of CP violation;
- ✓ The CKM parameters have been determined with extreme precision.



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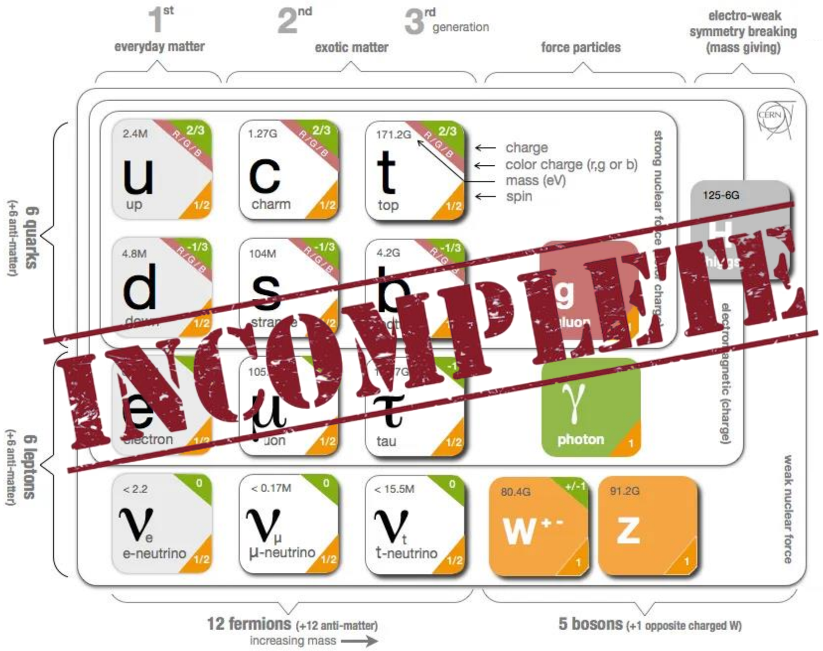
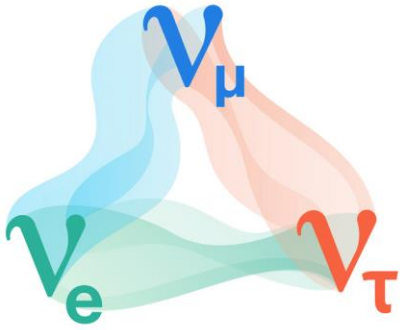
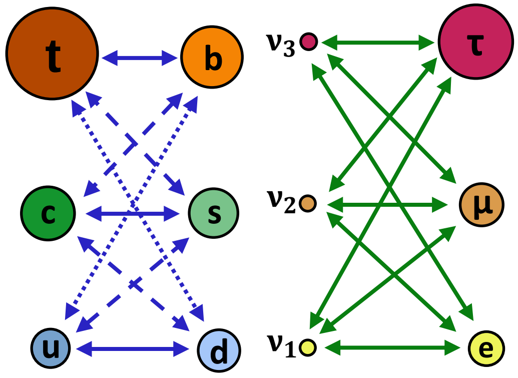


Neutrino Oscillations



Flavour Puzzle



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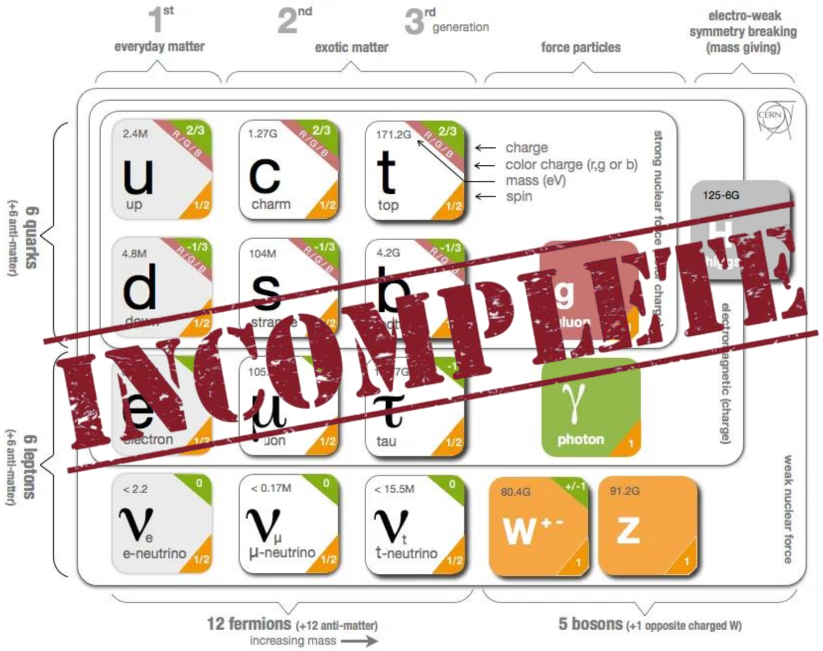

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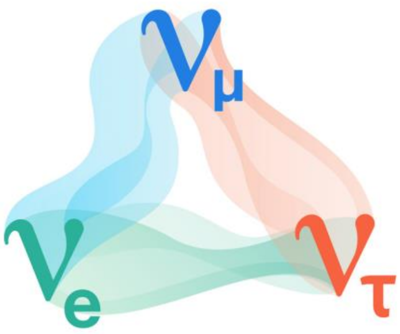

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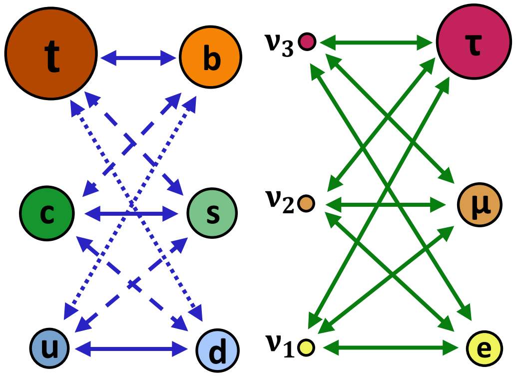

The SM must be extended!

Neutrino masses and mixing

EFFECTIVE THEORY with SM fields

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \ldots, \quad \delta\mathcal{L}^{D=d} \equiv \sum_k \frac{\mathcal{O}_k^{(d)}}{\Lambda^{d-4}}$$

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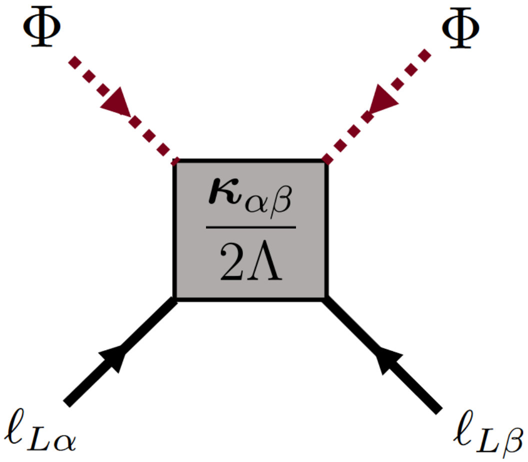
The lowest $d > 4$ operator is **unique (Weinberg Operator)**

(Weinberg,1979)

$$\delta\mathcal{L}^{d=5} = \frac{1}{2\Lambda}\boldsymbol{\kappa}_{\alpha\beta}\left(\overline{\ell^C_{\alpha_L}}\widetilde{\Phi}^*\right)\left(\widetilde{\Phi}^\dagger \ell_{\beta_L}\right) + \text{ H.c.}$$



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EWSB

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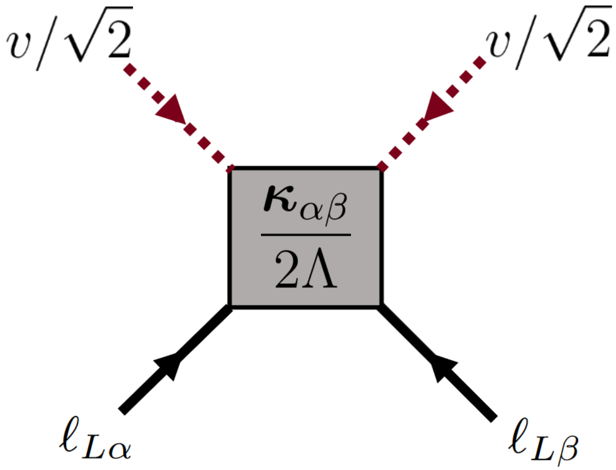

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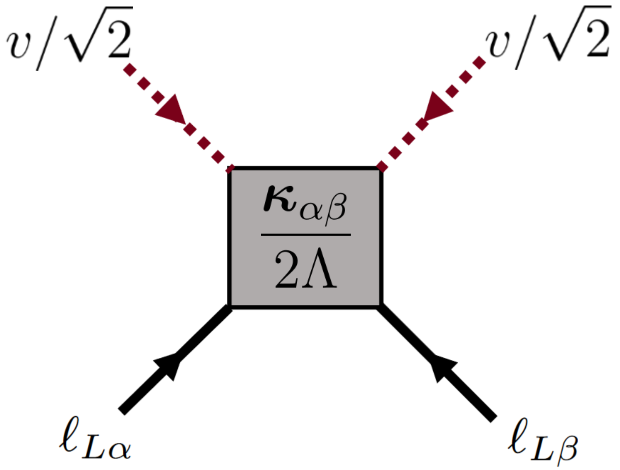


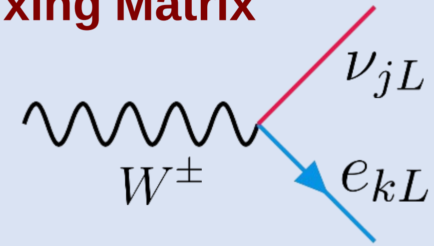
Majorana Mass Eigenstates

$$\nu_{\alpha_L} \rightarrow (\mathbf{U}_L^\nu)_{\alpha j}\nu_{j_L}$$

$$\mathbf{U}_L^{\nu T}\mathbf{M}_\nu\mathbf{U}_L^\nu = \text{diag}(m_1, m_2, m_3)$$

Lepton Mixing Matrix

$$\mathbf{U}_\ell = \mathbf{U}_L^{e\dagger}\mathbf{U}_L^\nu$$



Softly-broken U(1)-symmetric 2HDM

The **SM does not allow** for the implementation of **Abelian flavour symmetries**

→

(Branco, et al., 2012) **2HDM**

$$\Phi_{1,2} = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+_{1,2} \\ v_{1,2} + \rho_{1,2} + i\eta_{1,2} \end{pmatrix}$$

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Imposing a **global U(1) symmetry (softly broken)** the scalar potential reads:

$$\begin{aligned} V = {} & \mu_{11}^2 \left(\Phi_1^\dagger \Phi_1\right) + \mu_{22}^2 \left(\Phi_2^\dagger \Phi_2\right) + \mu_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) \\ & + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2\right)^2 \\ & + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right) \left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right) \left(\Phi_2^\dagger \Phi_1\right) \end{aligned}$$

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Mass Eigenstates

m_h m_I

m_H $m_{H^\pm}$

Alignment Limit

$\beta - \alpha = \pi/2$

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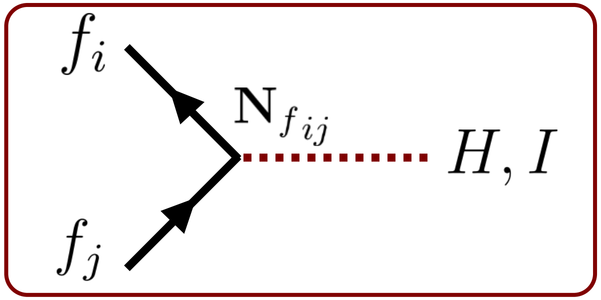
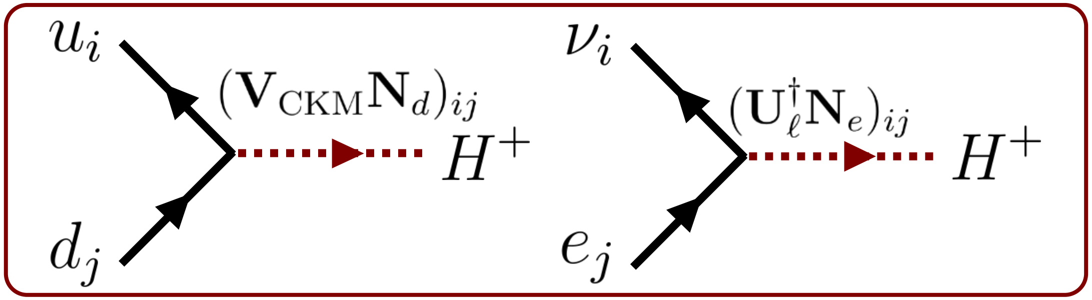
Expanding the **Yukawa Lagrangian** in the **mass eigenstates**:

FCNC



FCCC

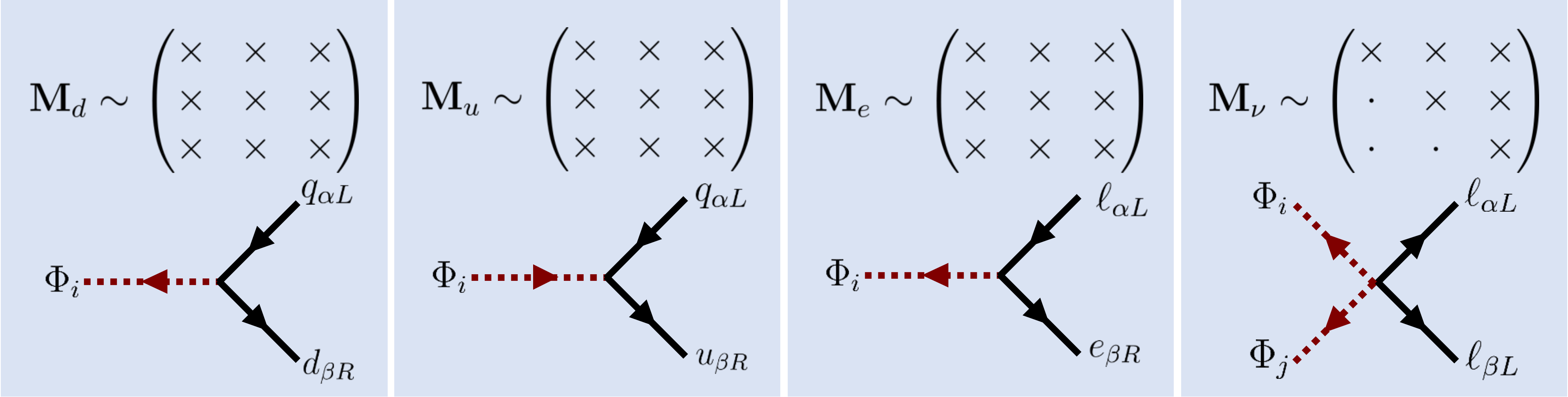


Abelian flavour symmetries

GOAL

Reduce the number of free parameters in the mass matrices and make the **theory more predictive**

Introduce flavour charges



$$\mathrm{M}_d \sim \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix} \qquad \mathrm{M}_u \sim \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix} \qquad \mathrm{M}_e \sim \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix} \qquad \mathrm{M}_\nu \sim \begin{pmatrix} \times & \times & \times \\ \cdot & \times & \times \\ \cdot & \cdot & \times \end{pmatrix}$$

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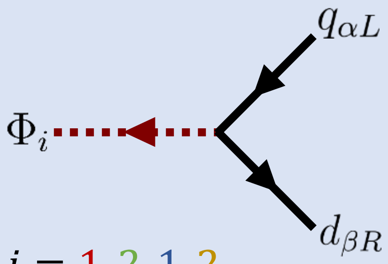

$i = 1, 2, 1, 2$
$\alpha = 1, 2, 3, 3$
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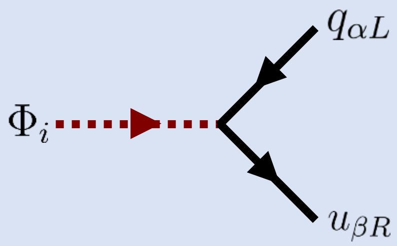

$i = 2, 1, 1, 2, 1$
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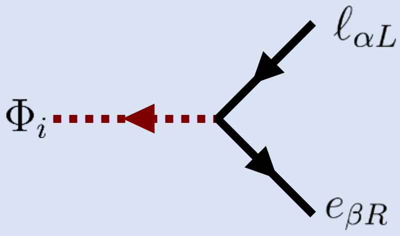

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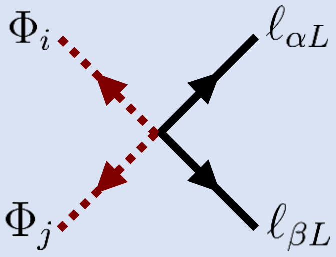

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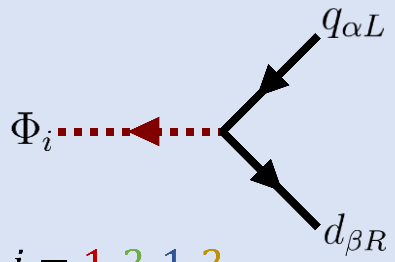

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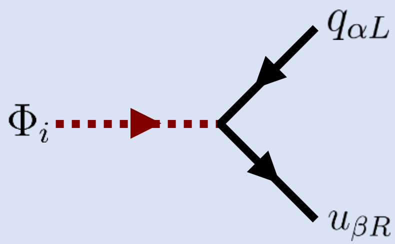

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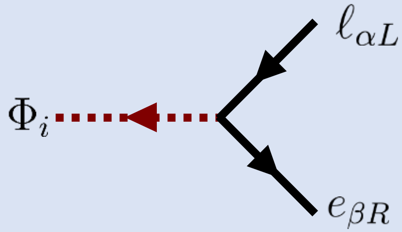

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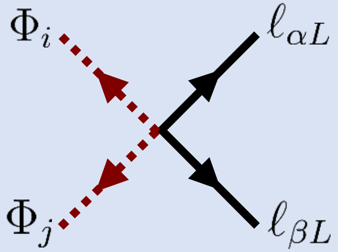

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Example:

$$\Phi_{1,2} \to q_{1L} + d_{2R}$$

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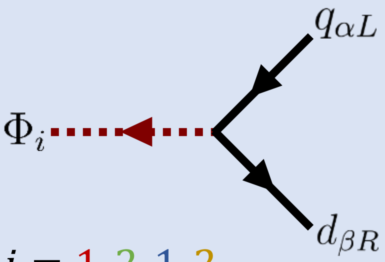

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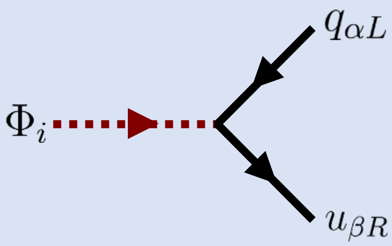

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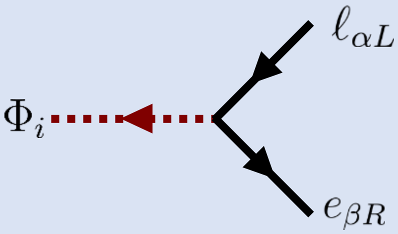

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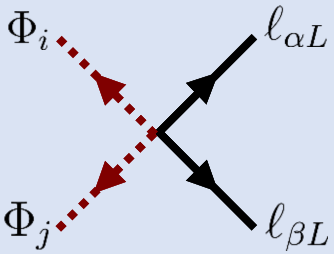

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Example:

$$\Phi_{1,2} \cancel{\rightarrow q_{1L} + d_{2R}} \longrightarrow$$

Flavour charge is not conserved

$$Q_{\Phi_{1,2}} - Q_{q_{1L}} + Q_{d_{2R}} \neq 0$$

Maximally-restrictive textures from U(1) symmetries

Procedure

Equivalence classes with the maximum number of zeros

Maximally-restrictive textures from U(1) symmetries

Procedure

Equivalence classes with the maximum number of zeros

↓

Solve system of equations for the field charges

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Procedure

Equivalence classes with the maximum number of zeros

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Solve system of equations for the field charges

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Test compatibility at the 1σ CL for all observables

Experimental Data

Quarks

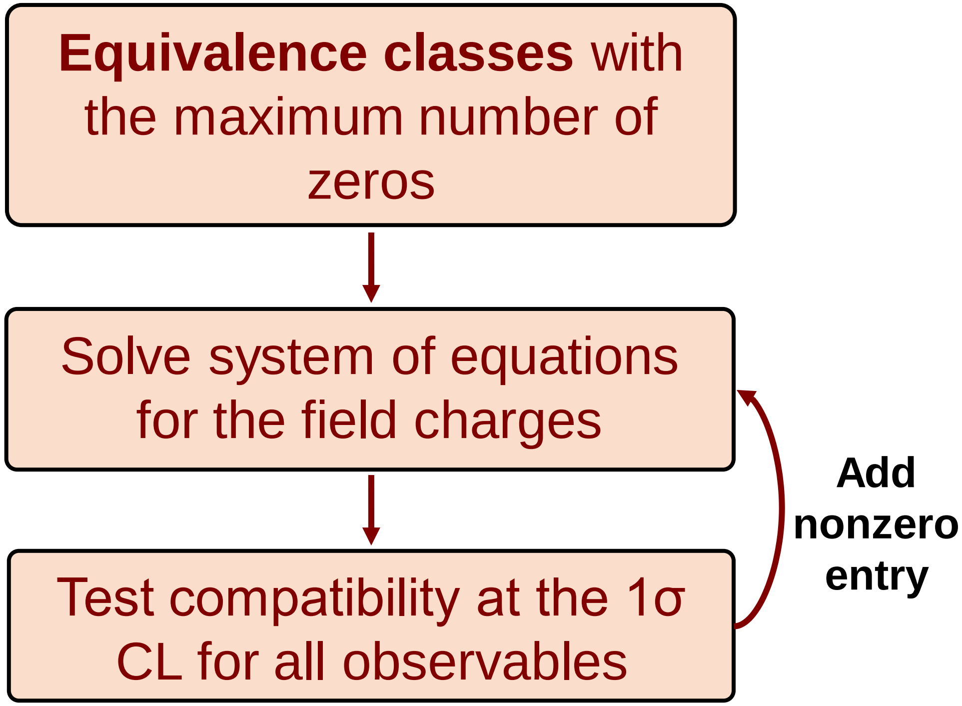
Parameter	Best fit $\pm 1\sigma$
$m_d(\times \text{ MeV})$	$4.67^{+0.48}_{-0.17}$
$m_s(\times \text{ MeV})$	$93.4^{+8.6}_{-3.4}$
$m_b(\times \text{ GeV})$	$4.18^{+0.03}_{-0.02}$
$m_u(\times \text{ MeV})$	$2.16^{+0.49}_{-0.26}$
$m_c(\times \text{ GeV})$	1.27 ± 0.02
$m_t(\times \text{ GeV})$	172.69 ± 0.30
$\theta^q_{12}(^\circ)$	13.04 ± 0.05
$\theta^q_{23}(^\circ)$	2.38 ± 0.06
$\theta^q_{13}(^\circ)$	0.201 ± 0.011
$\delta^q(^\circ)$	68.75 ± 4.5

Leptons

Parameter	Best Fit $\pm 1\sigma$
$m_e(\times \text{ keV})$	$510.99895000 \pm 0.00000015$
$m_\mu(\times \text{ MeV})$	$105.6583755 \pm 0.0000023$
$m_\tau(\times \text{ GeV})$	1.77686 ± 0.00012
Δm^2_{21} $(\times 10^{-5}\text{ eV}^2)$	$7.50^{+0.22}_{-0.20}$
$\lvert\Delta m^2_{31}\rvert$ $(\times 10^{-3}\text{ eV}^2)$ [NO]	$2.55^{+0.02}_{-0.03}$
$\lvert\Delta m^2_{31}\rvert$ $(\times 10^{-3}\text{ eV}^2)$ [IO]	$2.45^{+0.02}_{-0.03}$
$\theta^\ell_{12}(^\circ)$	34.3 ± 1.0
$\theta^\ell_{23}(^\circ)$[NO]	49.26 ± 0.79
$\theta^\ell_{23}(^\circ)$[IO]	$49.46^{+0.60}_{-0.97}$
$\theta^\ell_{13}(^\circ)$[NO]	$8.53^{+0.13}_{-0.12}$
$\theta^\ell_{13}(^\circ)$[IO]	$8.58^{+0.12}_{-0.14}$
$\delta^\ell(^\circ)$[NO]	194^{+24}_{-22}
$\delta^\ell(^\circ)$[IO]	284^{+26}_{-28}

Maximally-restrictive textures from U(1) symmetries

Procedure



Equivalence classes with the maximum number of zeros

Solve system of equations for the field charges

Test compatibility at the 1σ CL for all observables

Add nonzero entry

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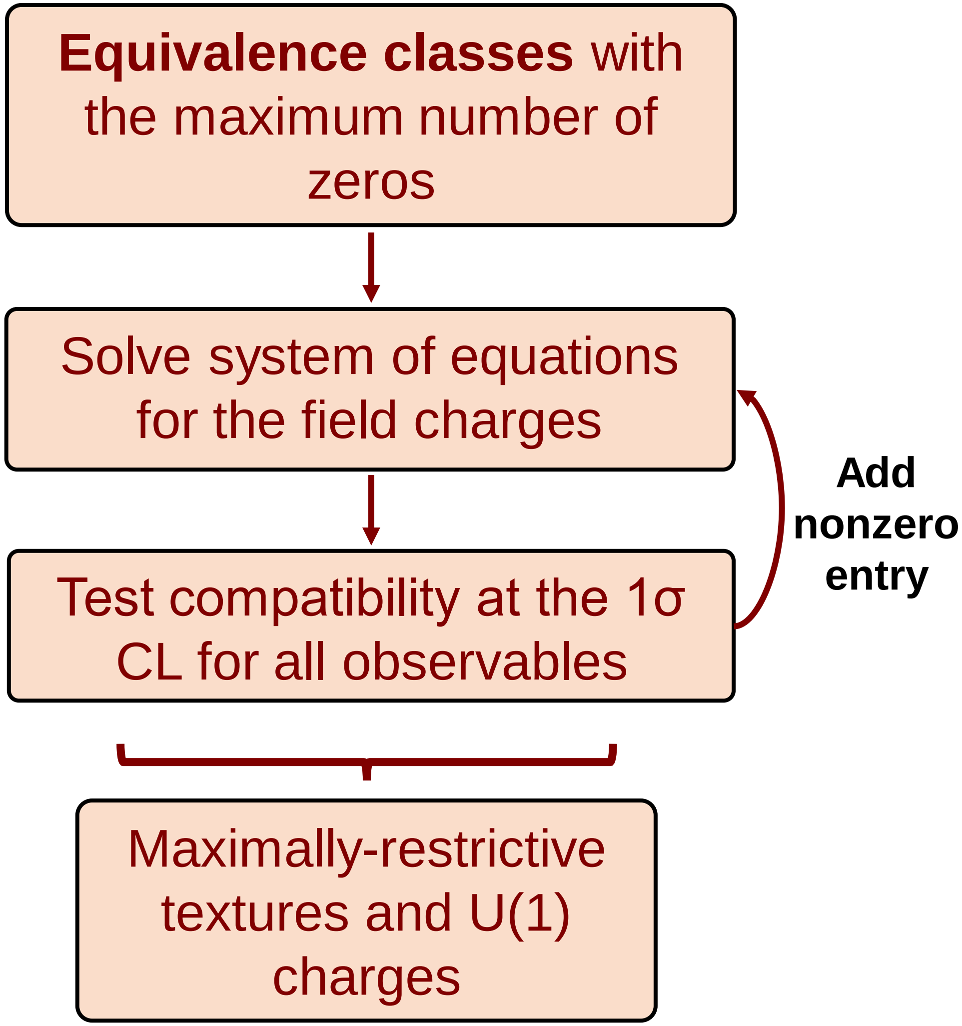
$\delta^q(^\circ)$	68.75 ± 4.5

Leptons

Parameter	Best Fit ±1σ
$m_e(\times \text{ keV})$	$510.99895000 \pm 0.00000015$
$m_\mu(\times \text{ MeV})$	$105.6583755 \pm 0.0000023$
$m_\tau(\times \text{ GeV})$	1.77686 ± 0.00012
$\Delta m^2_{21}\ (\times 10^{-5}\text{ eV}^2)$	$7.50^{+0.22}_{-0.20}$
$\lvert\Delta m^2_{31}\rvert\ (\times 10^{-3}\text{ eV}^2)$ [NO]	$2.55^{+0.02}_{-0.03}$
$\lvert\Delta m^2_{31}\rvert\ (\times 10^{-3}\text{ eV}^2)$ [IO]	$2.45^{+0.02}_{-0.03}$
$\theta^\ell_{12}(^\circ)$	34.3 ± 1.0
$\theta^\ell_{23}(^\circ)$[NO]	49.26 ± 0.79
$\theta^\ell_{23}(^\circ)$[IO]	$49.46^{+0.60}_{-0.97}$
$\theta^\ell_{13}(^\circ)$[NO]	$8.53^{+0.13}_{-0.12}$
$\theta^\ell_{13}(^\circ)$[IO]	$8.58^{+0.12}_{-0.14}$
$\delta^\ell(^\circ)$[NO]	194^{+24}_{-22}
$\delta^\ell(^\circ)$[IO]	284^{+26}_{-28}

Maximally-restrictive textures from U(1) symmetries

Procedure



Equivalence classes with the maximum number of zeros

Solve system of equations for the field charges

Test compatibility at the 1σ CL for all observables

Add nonzero entry

Maximally-restrictive textures and U(1) charges

Experimental Data

Quarks

Parameter	Best fit $\pm 1\sigma$
$m_d(\times\ \mathrm{MeV})$	$4.67^{+0.48}_{-0.17}$
$m_s(\times\ \mathrm{MeV})$	$93.4^{+8.6}_{-3.4}$
$m_b(\times\ \mathrm{GeV})$	$4.18^{+0.03}_{-0.02}$
$m_u(\times\ \mathrm{MeV})$	$2.16^{+0.49}_{-0.26}$
$m_c(\times\ \mathrm{GeV})$	1.27 ± 0.02
$m_t(\times\ \mathrm{GeV})$	172.69 ± 0.30
$\theta^q_{12}(^\circ)$	13.04 ± 0.05
$\theta^q_{23}(^\circ)$	2.38 ± 0.06
$\theta^q_{13}(^\circ)$	0.201 ± 0.011
$\delta^q(^\circ)$	68.75 ± 4.5

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Maximally-restrictive textures from U(1) symmetries

U(1) charges

$\mathbb{Z}_5$

$(\mathbf{M}_e,\mathbf{M}_\nu)$	$(\delta_1,\delta_2,\delta_3)$	$(\epsilon_1,\epsilon_2,\epsilon_3)$
$(5_1^e, 2_3^\nu)$	$(-1,-3,1)$	$(1,-5,-1)$
$(5_1^e, 2_7^\nu)$	$(-1,-2,0)$	$(0,-3,-1)$
$(5_1^e, 2_{10}^\nu)$	$(0,-1,1)$	$(1,-2,0)$

$\mathbb{Z}_4$

$(\mathbf{M}_d,\mathbf{M}_u)$	$(\alpha_1,\alpha_2,\alpha_3)$	$(\beta_1,\beta_2,\beta_3)$	$(\gamma_1,\gamma_2,\gamma_3)$
$(4_3^d, \mathbf{P}_{12}5_1^u\mathbf{P}_{23})$	$(0,1,2)$	$(2,1,0)$	$(3,2,0)$
$(4_3^d, \mathbf{P}_{123}5_1^u\mathbf{P}_{12})$	$(0,1,2)$	$(2,1,0)$	$(3,0,1)$
$(5_1^d, \mathbf{P}_{12}4_3^u)$	$(0,-1,1)$	$(1,-2,0)$	$(2,1,0)$
$(5_1^d, \mathbf{P}_{321}4_3^u\mathbf{P}_{23})$	$(0,-1,1)$	$(1,-2,0)$	$(-1,1,0)$

Maximally restrictive mass matrices

Quarks

$$4_3^d \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix}$$

$$5_1^d \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}$$

$$\mathbf{P}_{12}5_1^u\mathbf{P}_{23} \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \bullet & 0 \\ \times & \times & 0 \end{pmatrix}$$

$$\mathbf{P}_{123}5_1^u\mathbf{P}_{12} \sim \begin{pmatrix} 0 & \times & \bullet \\ 0 & 0 & \times \\ \times & 0 & 0 \end{pmatrix}$$

$$\mathbf{P}_{12}4_3^u \sim \begin{pmatrix} 0 & \bullet & \times \\ 0 & 0 & \times \\ \times & \times & 0 \end{pmatrix}$$

$$\mathbf{P}_{321}4_3^u\mathbf{P}_{23} \sim \begin{pmatrix} 0 & \bullet & \times \\ \times & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

Leptons

$$5_1^e \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}$$

$$2_3^\nu \sim \begin{pmatrix} \times & \times & \bullet \\ \cdot & 0 & \bullet \\ \cdot & \cdot & 0 \end{pmatrix}$$

$$2_7^\nu \sim \begin{pmatrix} \times & 0 & \bullet \\ \cdot & 0 & \times \\ \cdot & \cdot & \bullet \end{pmatrix}$$

$$2_{10}^\nu \sim \begin{pmatrix} \times & \bullet & 0 \\ \cdot & \times & \bullet \\ \cdot & \cdot & 0 \end{pmatrix}$$

Maximally-restrictive textures from U(1) symmetries

U(1) charges

$\mathbb{Z}_5$

$(\mathbf{M}_e,\mathbf{M}_\nu)$	$(\delta_1,\delta_2,\delta_3)$	$(\epsilon_1,\epsilon_2,\epsilon_3)$
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$(5_1^e,2_7^\nu)$	$(-1,-2,0)$	$(0,-3,-1)$
$(5_1^e,2_{10}^\nu)$	$(0,-1,1)$	$(1,-2,0)$

$\mathbb{Z}_4$

$(\mathbf{M}_d,\mathbf{M}_u)$	$(\alpha_1,\alpha_2,\alpha_3)$	$(\beta_1,\beta_2,\beta_3)$	$(\gamma_1,\gamma_2,\gamma_3)$
$(4_3^d,\mathbf{P}_{12}5_1^u\mathbf{P}_{23})$	$(0,1,2)$	$(2,1,0)$	$(3,2,0)$
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$(5_1^d,\mathbf{P}_{12}4_3^u)$	$(0,-1,1)$	$(1,-2,0)$	$(2,1,0)$
$(5_1^d,\mathbf{P}_{321}4_3^u\mathbf{P}_{23})$	$(0,-1,1)$	$(1,-2,0)$	$(-1,1,0)$

“Decoupled” entry in the matrices of type “5” lead to zeros in the N_k matrices

Maximally restrictive mass matrices

Quarks

$$4_3^d \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix}$$

$$5_1^d \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}$$

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$$\mathbf{P}_{123}5_1^u\mathbf{P}_{12} \sim \begin{pmatrix} 0 & \times & \bullet \\ 0 & 0 & \times \\ \times & 0 & 0 \end{pmatrix}$$

$$\mathbf{P}_{12}4_3^u \sim \begin{pmatrix} 0 & \bullet & \times \\ 0 & 0 & \times \\ \times & \times & 0 \end{pmatrix}$$

$$\mathbf{P}_{321}4_3^u\mathbf{P}_{23} \sim \begin{pmatrix} 0 & \bullet & \times \\ \times & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

Leptons

$$5_1^e \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}$$

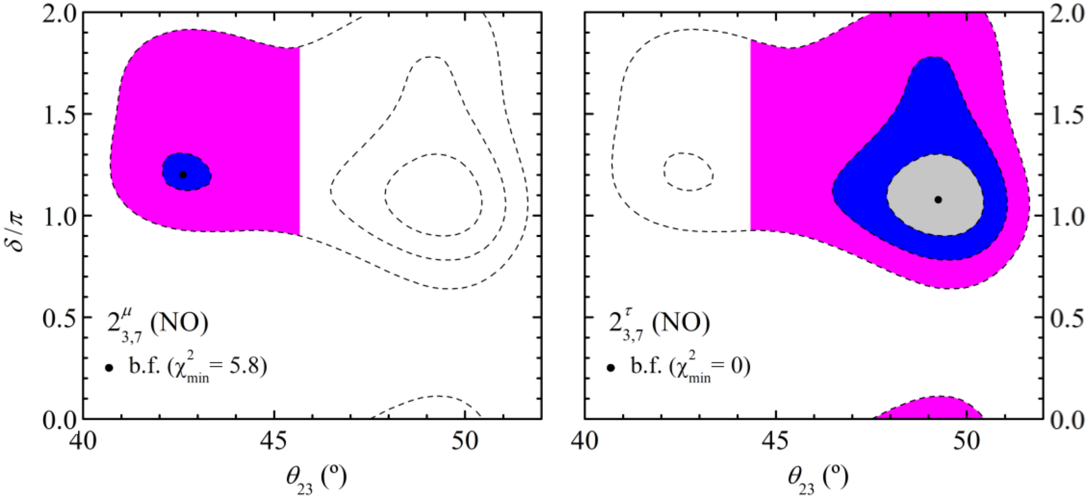
$$2_3^\nu \sim \begin{pmatrix} \times & \times & \bullet \\ \cdot & 0 & \bullet \\ \cdot & \cdot & 0 \end{pmatrix}$$

$$2_7^\nu \sim \begin{pmatrix} \times & 0 & \bullet \\ \cdot & 0 & \times \\ \cdot & \cdot & \bullet \end{pmatrix}$$

$$2_{10}^\nu \sim \begin{pmatrix} \times & \bullet & 0 \\ \cdot & \times & \bullet \\ \cdot & \cdot & 0 \end{pmatrix}$$

Lepton sector predictions - NO

The symmetry-constrained lepton models provide **predictions** for the **neutrino sector**, for example:



For NO, $2^{\mu}_{3,7}$ and $2^{\tau}_{3,7}$ select the **first** and **second octant** for the atmospheric mixing angle θ_{23}, respectively

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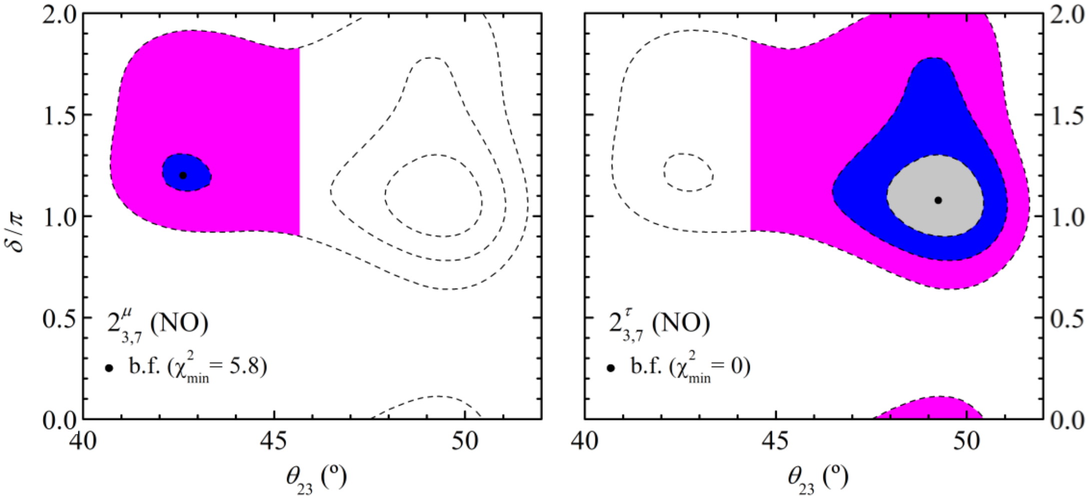
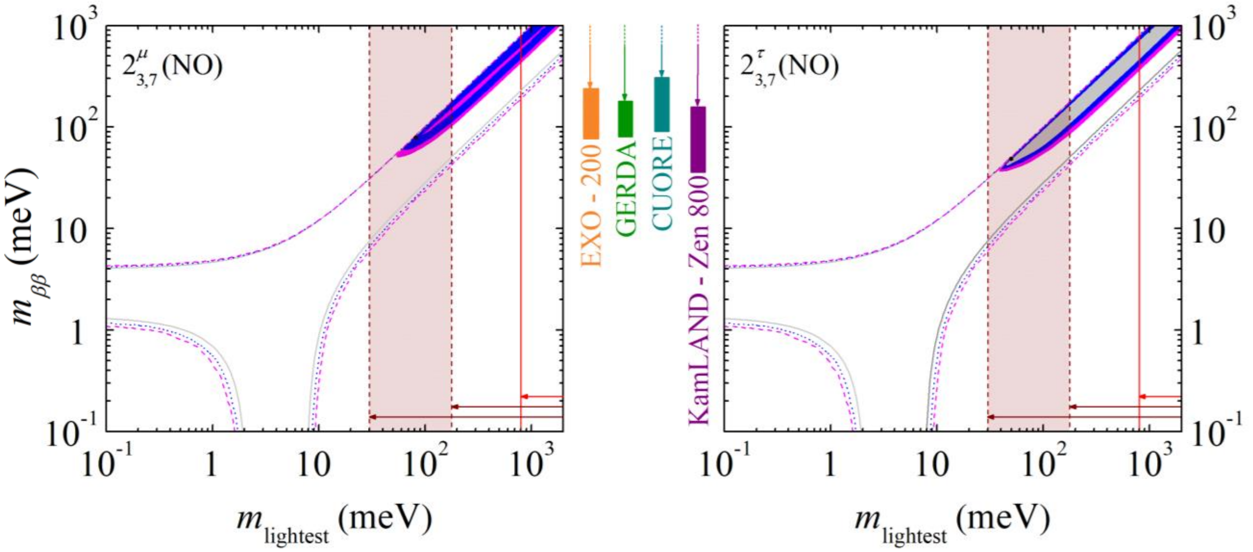
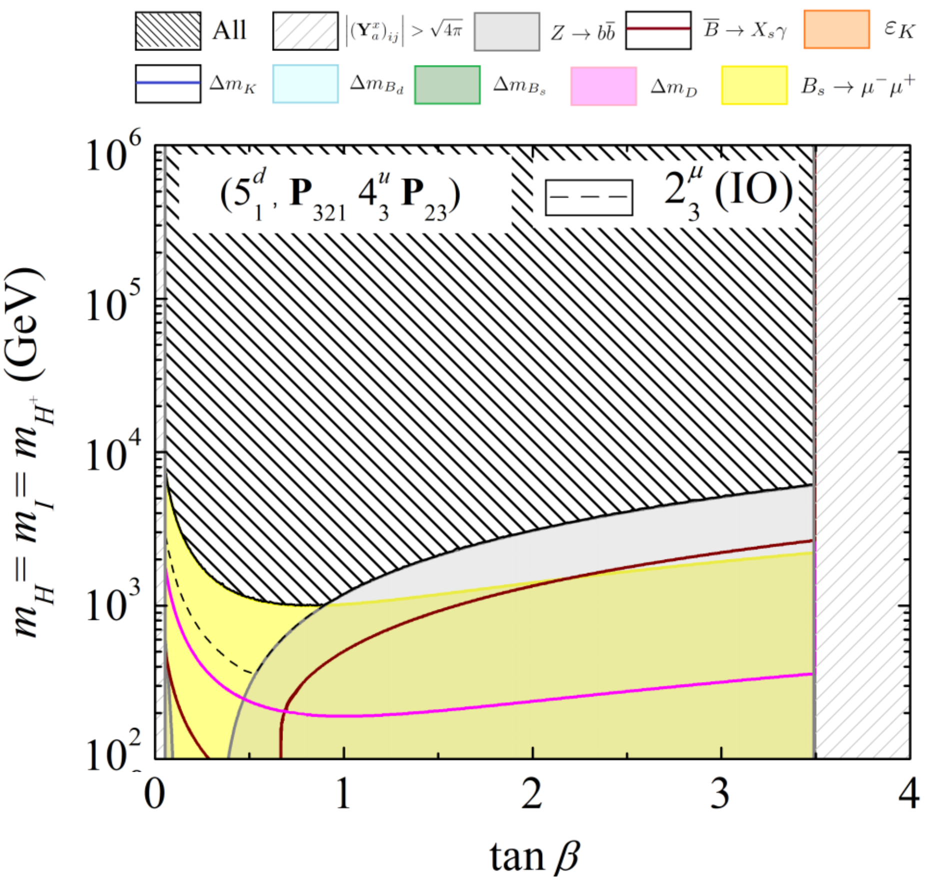


For NO, $2^{\mu}_{3,7}$ and $2^{\tau}_{3,7}$ select the **first** and **second octant** for the atmospheric mixing angle θ_{23}, respectively

The lower bounds on $m_{\beta\beta}$ are **within the sensitivity** of $0\nu\beta\beta$ decay experiments, while being simultaneously in **tension with cosmological** constraints on $m_{lightest}$

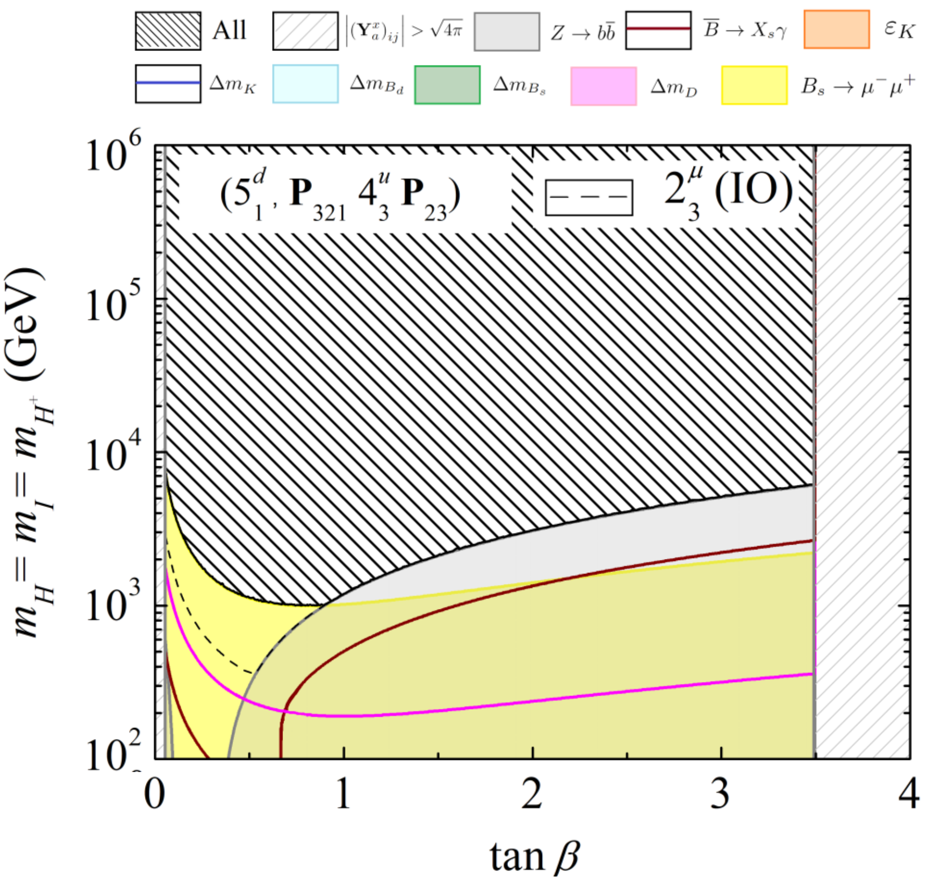


Numerical procedure and phenomenological analysis



$$\mathbf{N}_d \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

Numerical procedure and phenomenological analysis



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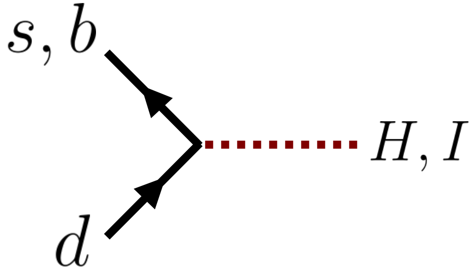

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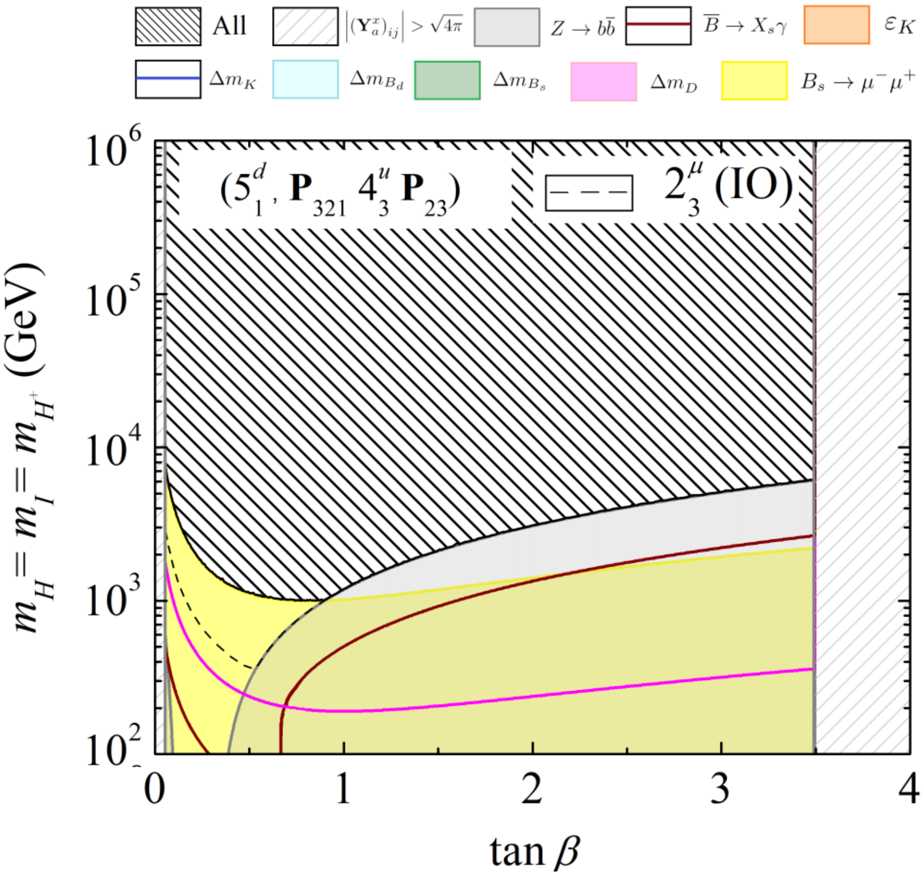

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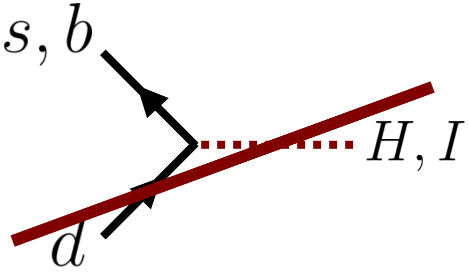

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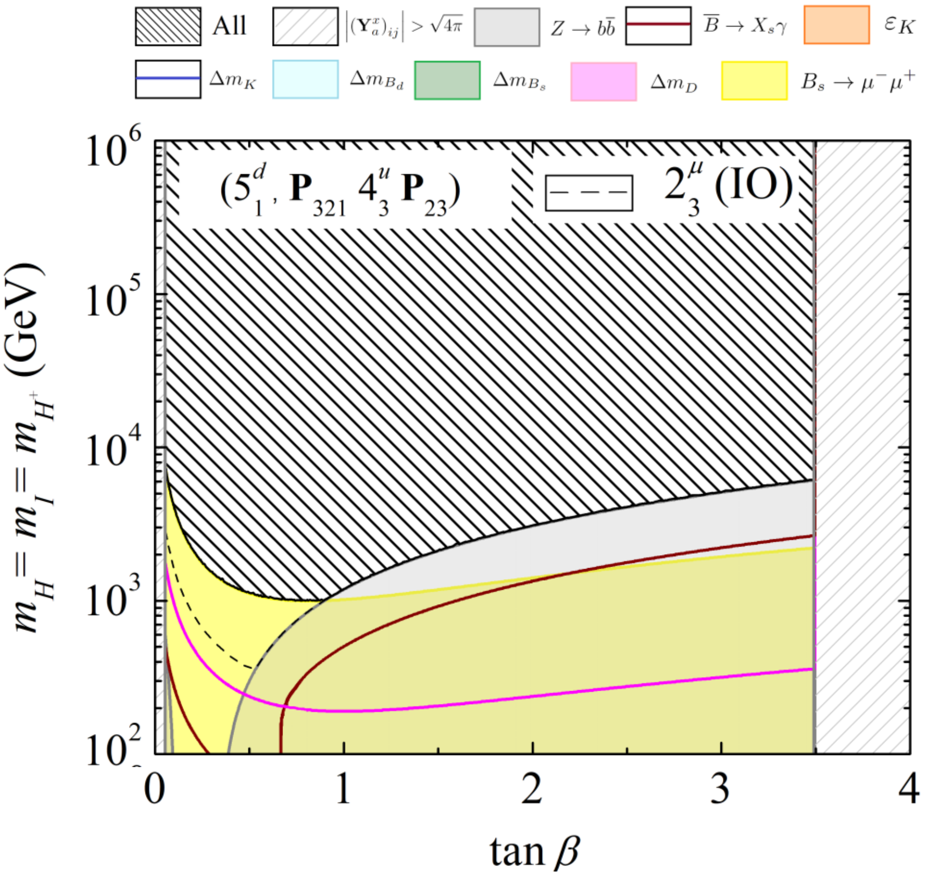

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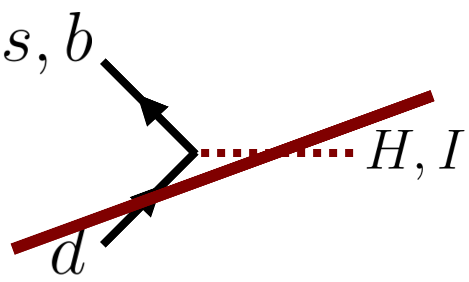

✓ K mesons: $K^0(d\bar{s})$: $\Delta m_K, \varepsilon_K$

✓ B mesons:
$B_d^0(d\bar{b})$: Δm_{B_d}, $\mathrm{Br}(B_d^0 \to \mu^+\mu^-)$

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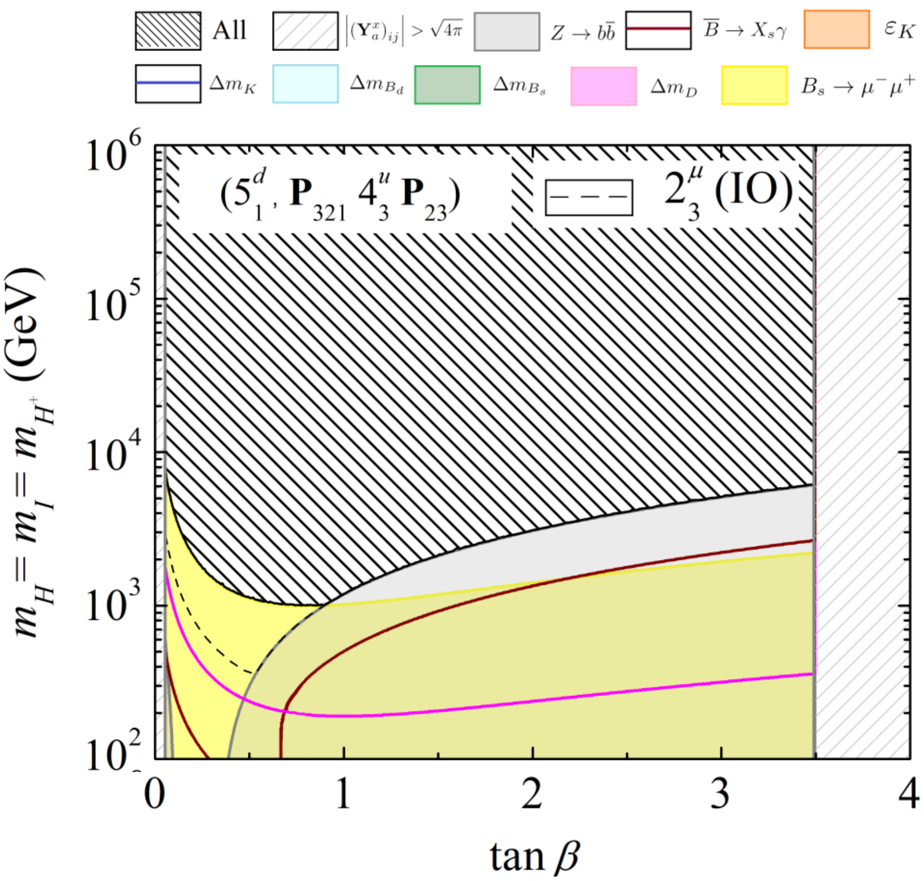

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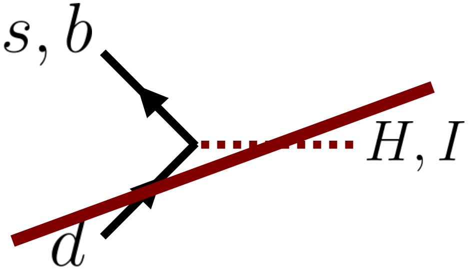

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This model highlights the effectiveness of Abelian flavour symmetries in aligning theoretical frameworks with highly constrained experimental observations.

Summary and outlook

Work done:

- ✓ Study of the theoretical framework of the **minimal U(1) 2HDM for flavour**;
- ✓ Identification of the **maximally-restrictive pairs of quark and lepton mass matrices** compatible with current masses, mixing and CP violation data;
- ✓ Lepton sector **predictions**;
- ✓ **Phenomenological study** (analytical and numerical) of the quark and charged lepton sectors.

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Abelian flavour symmetries in the 2HDM stand out as a simple approach in addressing the flavour puzzle, leading to minimal quark and lepton models that are predictive

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Thank you !