PLANCK2024

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

José Rebelo Rocha

CFTP/IST, U. Lisbon

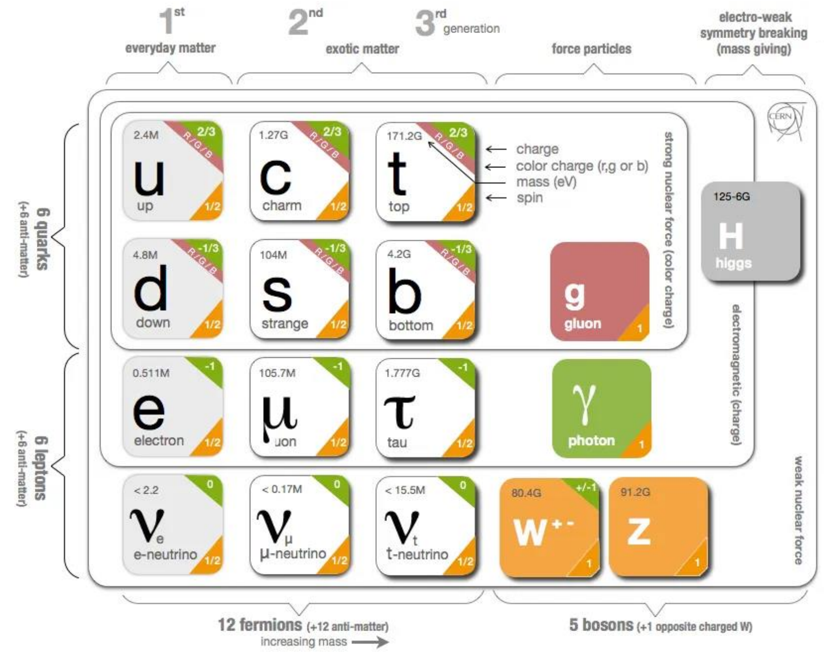
jose.r.rocha@tecnico.ulisboa.pt

In collaboration with: H. B. Câmara, F. R. Joaquim and R. G. Felipe

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

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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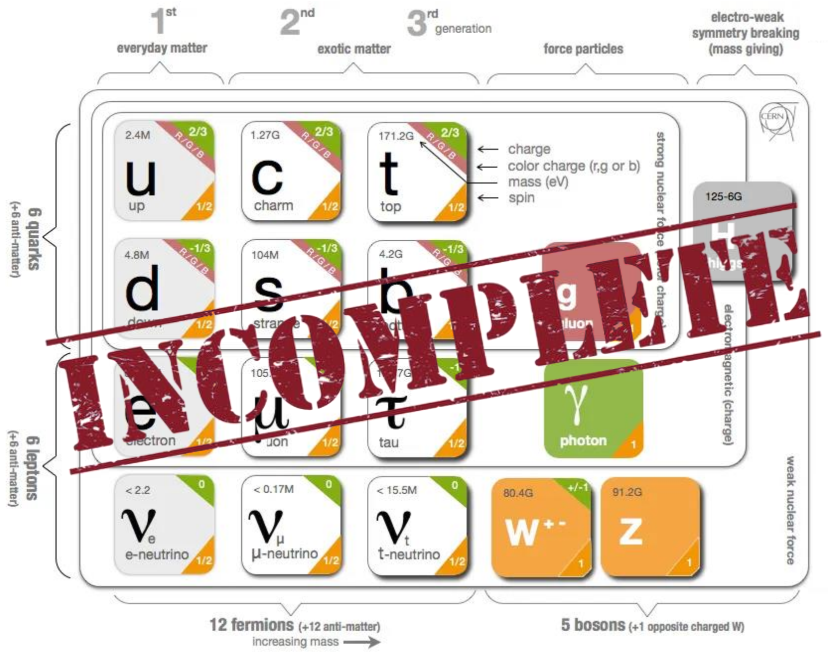
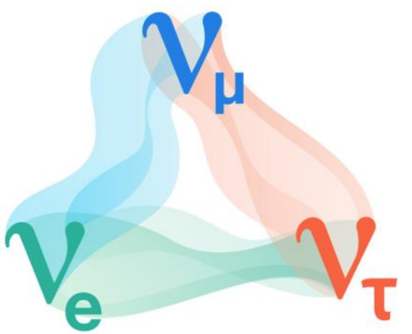
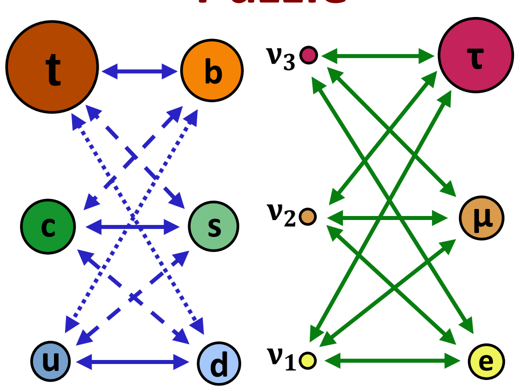


Neutrino Oscillations



Flavour Puzzle



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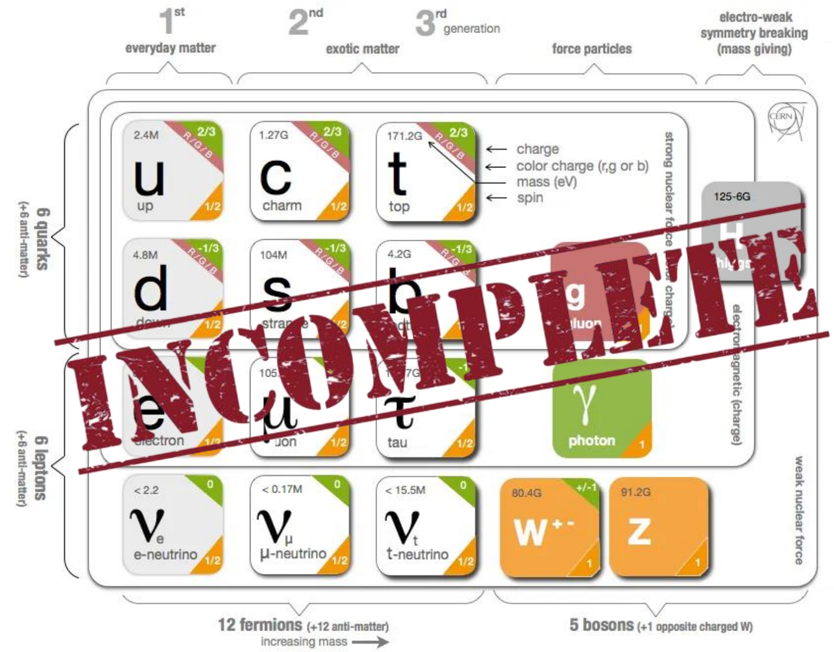

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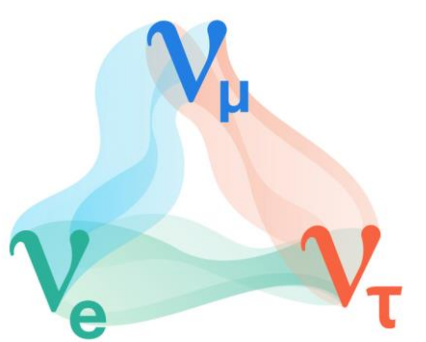

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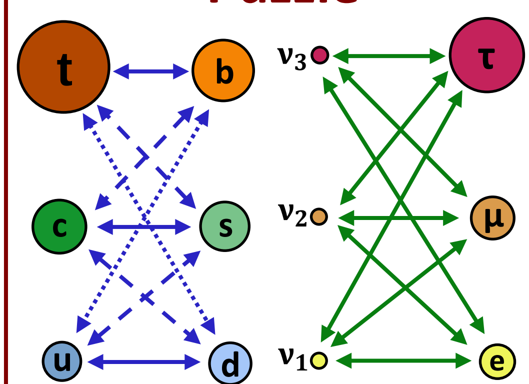

→ **The SM must be extended!**

EFFECTIVE THEORY with SM fields

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

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

(Weinberg,1979)

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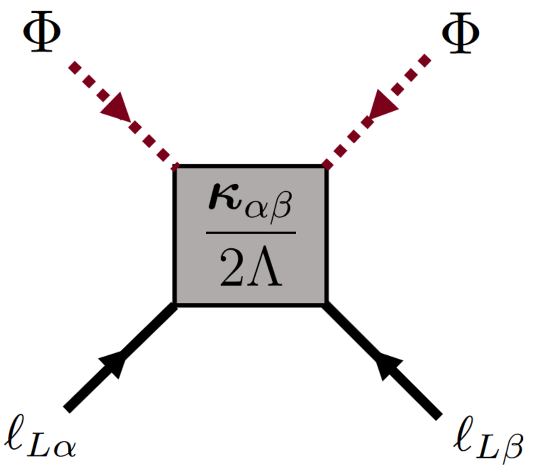

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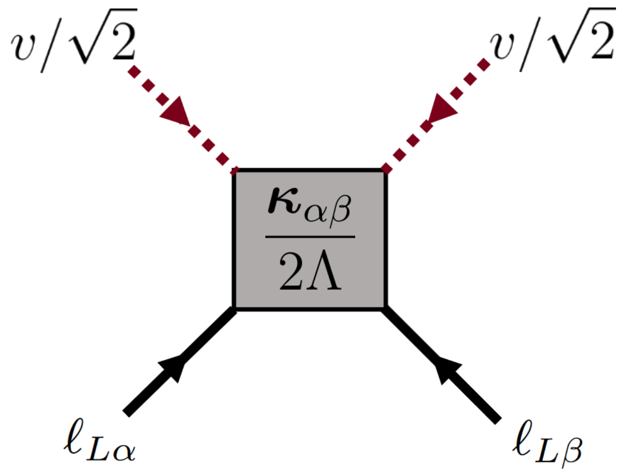
EWSB ↓

$$\mathcal{L}_{\text{m}}^{\text{Majorana}} = -\frac{1}{2}\mathbf{M}_{\nu\alpha\beta}\overline{\nu^C_{\alpha_L}}\nu_{\beta_L} + \text{ H.c.}$$



Neutrino masses and mixing

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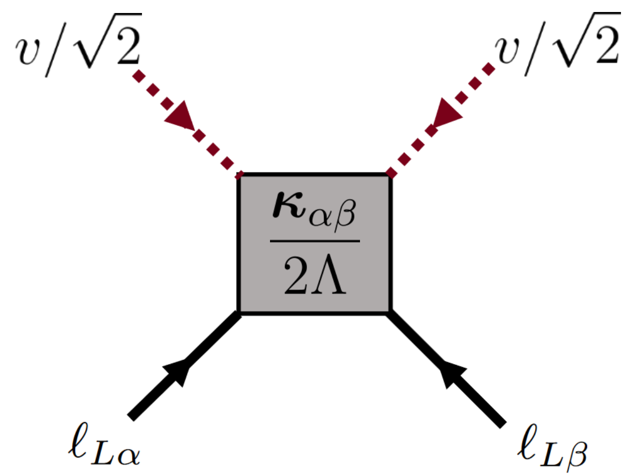


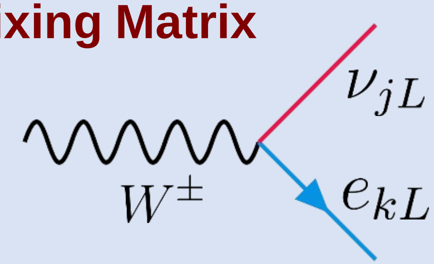
Majorana Mass Eigenstates

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

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

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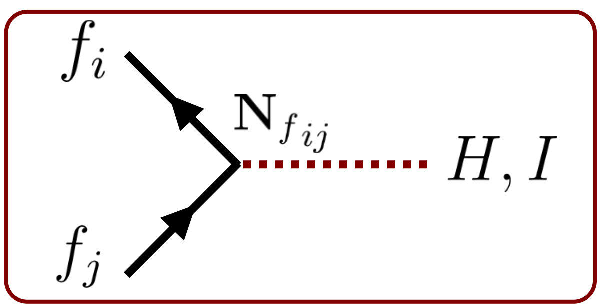
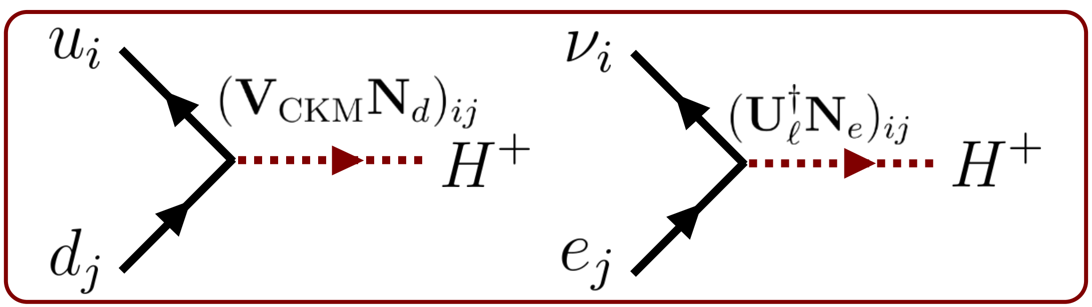
Expanding the **Yukawa Lagrangian** in the **mass eigenstates**:

FCNC



FCCC



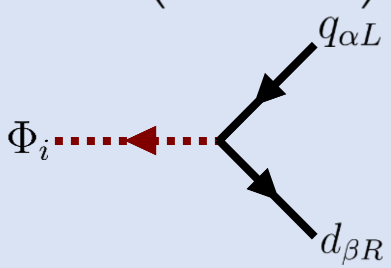
Abelian flavour symmetries

GOAL

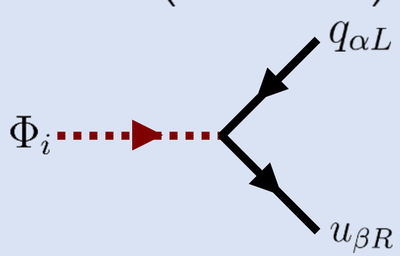
Reduce the number of free parameters in the mass matrices and make the **theory more predictive**

↓ **Introduce flavour charges**

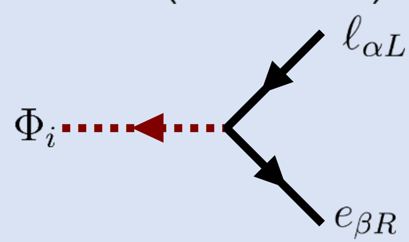
$$\mathbf{M}_d \sim \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$



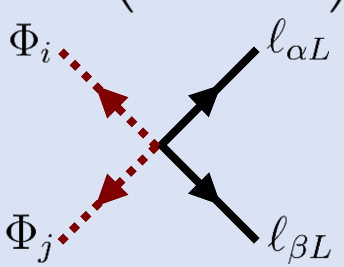
$$\mathbf{M}_u \sim \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$



$$\mathbf{M}_e \sim \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$



$$\mathbf{M}_\nu \sim \begin{pmatrix} \times & \times & \times \\ \cdot & \times & \times \\ \cdot & \cdot & \times \end{pmatrix}$$



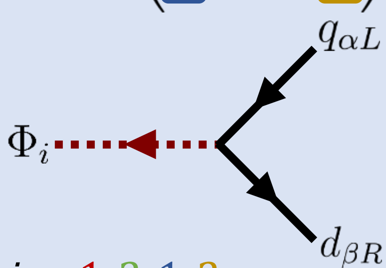
Abelian flavour symmetries

GOAL

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

Introduce flavour charges

$$\mathbf{M}_d \sim \begin{pmatrix} 0 & 0 & \boxtimes \\ 0 & \boxtimes & 0 \\ \boxtimes & 0 & \boxtimes \end{pmatrix}$$



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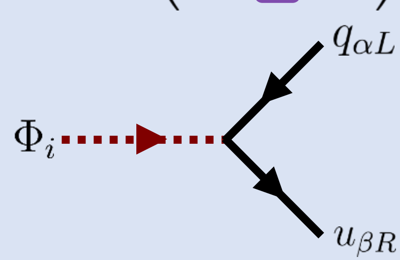

$i = 2, 1, 1, 2, 1$
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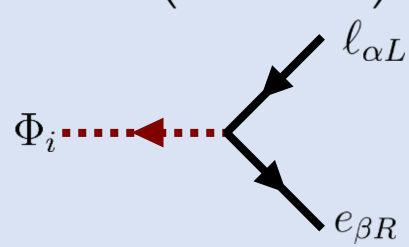
$$\mathbf{M}_e \sim \begin{pmatrix} 0 & 0 & \boxtimes \\ 0 & \boxtimes & 0 \\ \boxtimes & 0 & \boxtimes \end{pmatrix}$$



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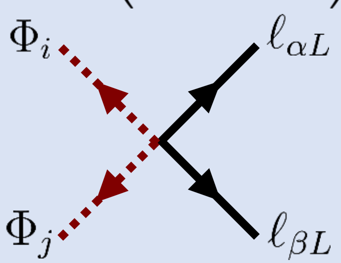

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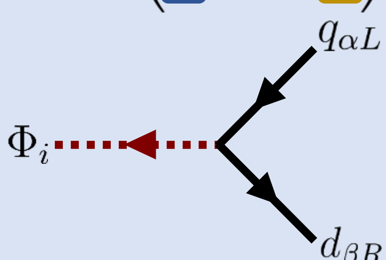

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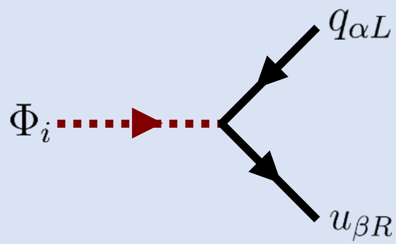

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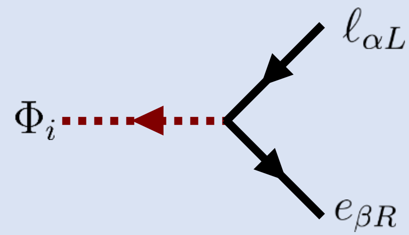

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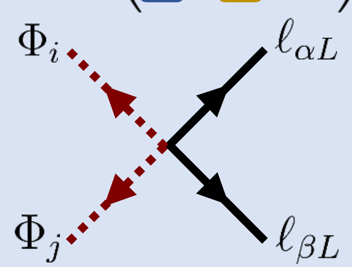

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Example:

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

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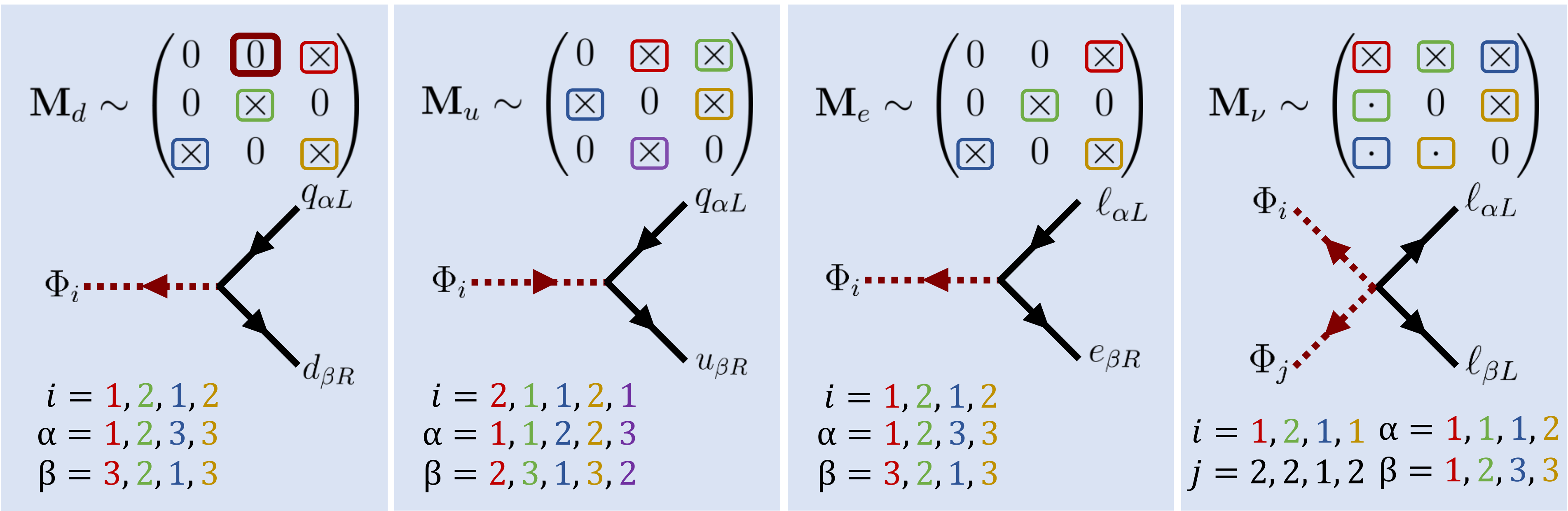

Example:

$$\Phi_{1,2} \to q_{1L} + d_{2R}$$ (struck through)

→

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

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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
$\Delta m^2_{21}\ (\times 10^{-5}\text{ eV}^2)$	$7.50^{+0.22}_{-0.20}$
$\lvert\Delta m^2_{31}\rvert\ (\times 10^{-3}\text{ eV}^2)$ [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
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$\theta^\ell_{23}(^\circ)$[IO]	$49.46^{+0.60}_{-0.97}$
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Maximally-restrictive textures from U(1) symmetries

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Equivalence classes with the maximum number of zeros

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Solve system of equations for the field charges

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Add nonzero entry (back to: Solve system of equations for the field charges)

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$\theta^q_{12}(^\circ)$	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
$\Delta m^2_{21}\ (\times 10^{-5}\ \text{eV}^2)$	$7.50^{+0.22}_{-0.20}$
$\lvert\Delta m^2_{31}\rvert\ (\times 10^{-3}\ \text{eV}^2)$ [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

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

$\mathbb{Z}_5$

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

$\mathbb{Z}_4$

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

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

Maximally restrictive mass matrices

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Leptons

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Maximally-restrictive textures from U(1) symmetries

Minimal flavour patterns for **quarks**:

- Four different models;
- There is a total of ten independent parameters, **matching** the number of observables;

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Minimal flavour patterns for **leptons**:

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Minimal flavour patterns for **leptons**:

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Predictions

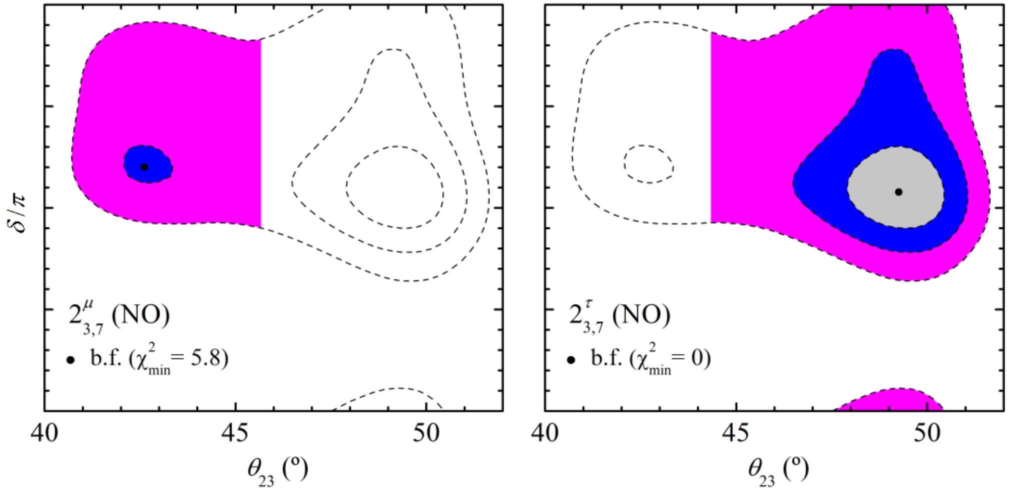
NO: $m_2 = \sqrt{m_1^2 + \Delta m_{21}^2}, \quad m_3 = \sqrt{m_1^2 + \Delta m_{31}^2}$

IO: $m_1 = \sqrt{m_3^2 + |\Delta m_{31}^2|}, \quad m_2 = \sqrt{m_3^2 + \Delta m_{21}^2 + |\Delta m_{31}^2|}$

$$m_{\beta\beta} = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{-i\alpha_{21}} + s_{13}^2 m_3 e^{-i\alpha_{31}} \right|$$

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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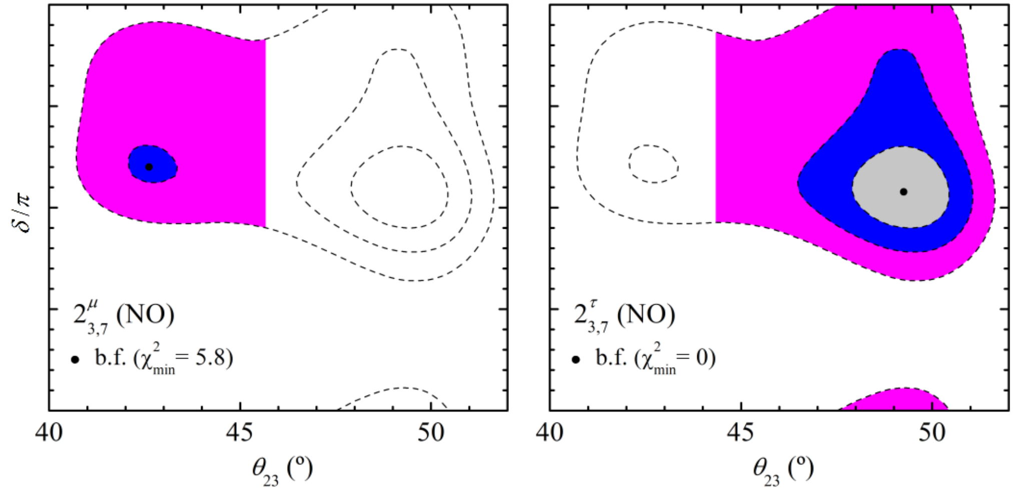
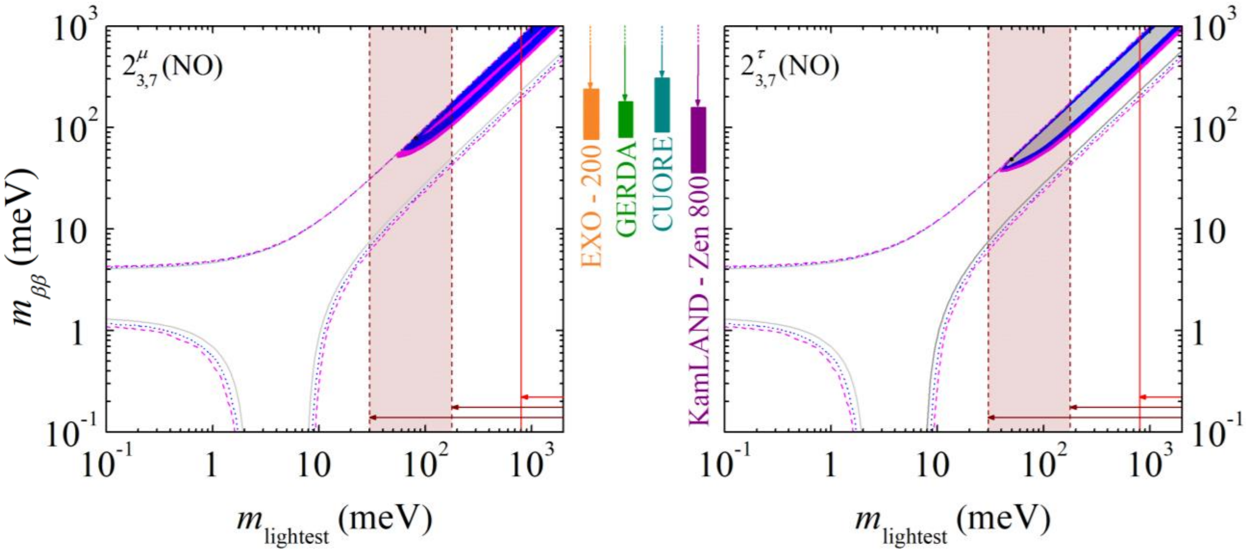
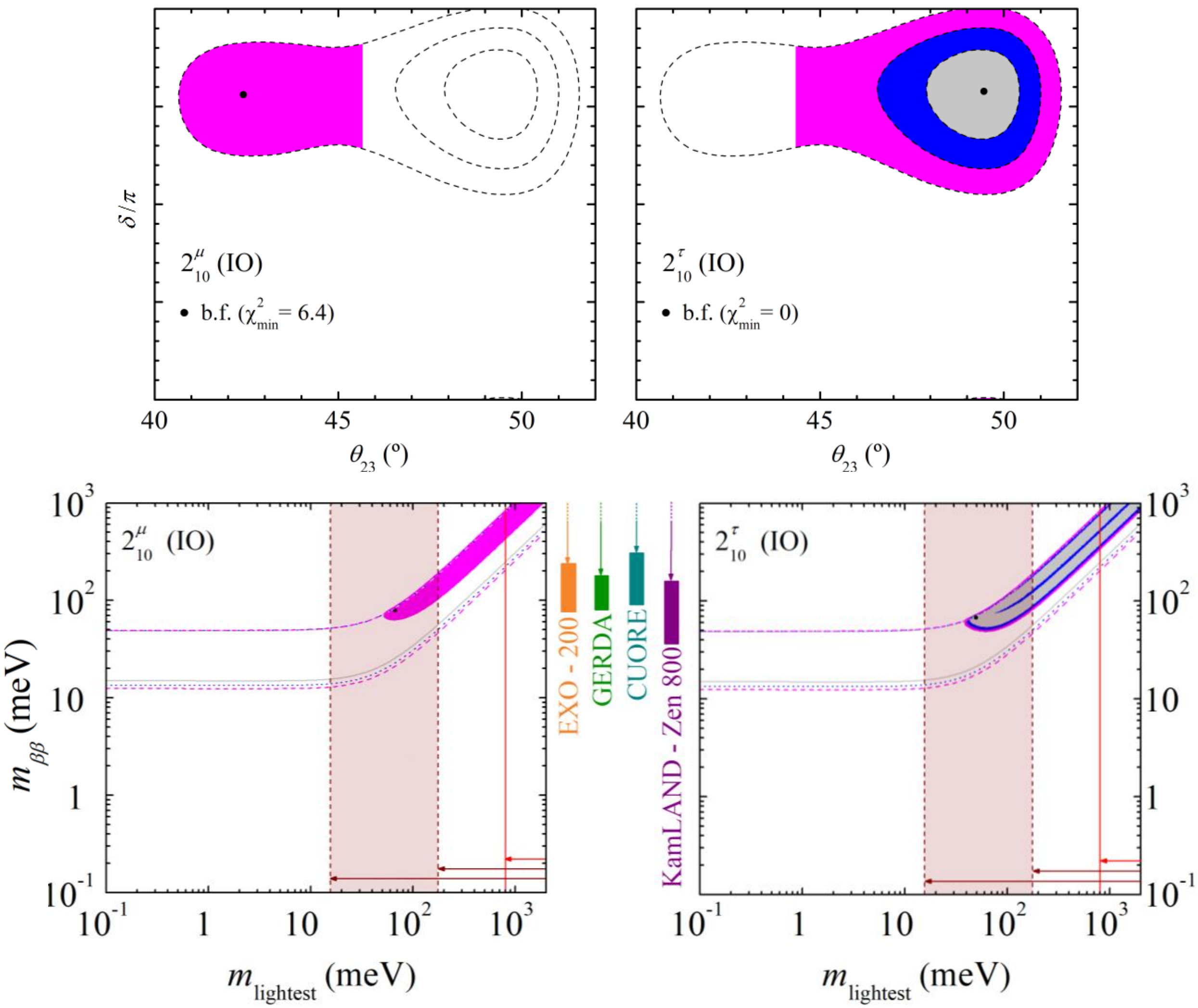


For NO, $2^{\mu}_{3,7}$ and $2^{\tau}_{3,7}$ select the **first** and **second octant** for the atmospheric mixing angle θ_{23}, respectively

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 $m_{lightest}$



There are models that behave similarly for **inverted ordering** (IO), namely 2^{μ}_{10} and 2^{τ}_{10}



Numerical procedure and phenomenological analysis

For the numerical analysis of the phenomenology of maximally-restrictive matrices, a private *Python* code was developed, which works as follows:

Random values for $\tan\beta$, m_I, m_H, $m_{H^\pm}$

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Theoretical constraints

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Precision observables

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SM Higgs Boson & new scalar searches

→ **HiggsTools, HiggsSignals & HiggsBounds**

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Quark sector constraints

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}

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Some flavour constraints are automatically satisfied in certain models

Numerical procedure and phenomenological analysis

The mass matrices labelled ”5” exhibit an isolated non-zero entry in a given row and column, which coincides with the mass of a fermion translating into:

$$5^{d,u,e} : \mathbf{N}_{d,u,e} \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}, \; 5^{s,c,\mu} : \mathbf{N}_{s,c,\mu} \sim \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}, \; 5^{b,t,\tau} : \mathbf{N}_{b,t,\tau} \sim \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

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To directly observe the effect of flavour symmetries, consider the NP contribution to the matrix element that contributes to the $\overline{K}_0 \to K_0$ transition:

$$M_{21}^{\mathrm{NP}} = \frac{f_k^2 m_K}{96 v^2} \Bigg\{ \left[(\mathbf{N}_d^*)_{ds}^2 + (\mathbf{N}_d)_{sd}^2 \right] \frac{10 m_k^2}{(m_s + m_d)^2} \left(\frac{1}{m_I^2} - \frac{c_{\beta-\alpha}^2}{m_h^2} - \frac{s_{\beta-\alpha}^2}{m_H^2} \right) + 4 (\mathbf{N}_d^*)_{ds} (\mathbf{N}_d)_{sd} \left[1 + \frac{6 m_K^2}{(m_s + m_d)^2} \left(\frac{1}{m_I^2} + \frac{c_{\beta-\alpha}^2}{m_h^2} + \frac{s_{\beta-\alpha}^2}{m_H^2} \right) \right] \Bigg\}$$

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↓

$$\Delta m_K^{\rm NP}=2|M_{21}^{\rm NP}|=0 \qquad \varepsilon_K=\varepsilon_K^{\rm SM}-\frac{{\rm Im}(M_{21}^{\rm NP}\lambda_u^{*2})}{\sqrt{2}\Delta m_K|\lambda_u|^2}$$

The two constraints associated with K^0 are **inherently satisfied** for d or s decoupled

Yukawa perturbativity bounds

$$\tan^2\beta \leq \frac{2\pi v^2}{|\,(\mathbf{M}_1^x)_{ij}\,|^2} - 1, \quad \tan^2\beta \geq 1/\left(\frac{2\pi v^2}{|\,(\mathbf{M}_2^x)_{ij}\,|^2} - 1\right)$$

Thus, $\tan\beta$ finds its upper and lower bounds determined by the maximum value of $|(\mathbf{M}_1^x)_{ij}|$ and $|(\mathbf{M}_2^x)_{ij}|$.

Numerical procedure and phenomenological analysis

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Lepton sector constraints

We only consider the lepton model $(5_1^e, 2_3^\nu)_{\mathrm{NO}}$, as the conclusions do not differ with a more detailed analysis.

The only exception is for the $(5_1^d, \mathbf{P}_{123} 4_3^u \mathbf{P}_{12})$ model.

Numerical procedure and phenomenological analysis

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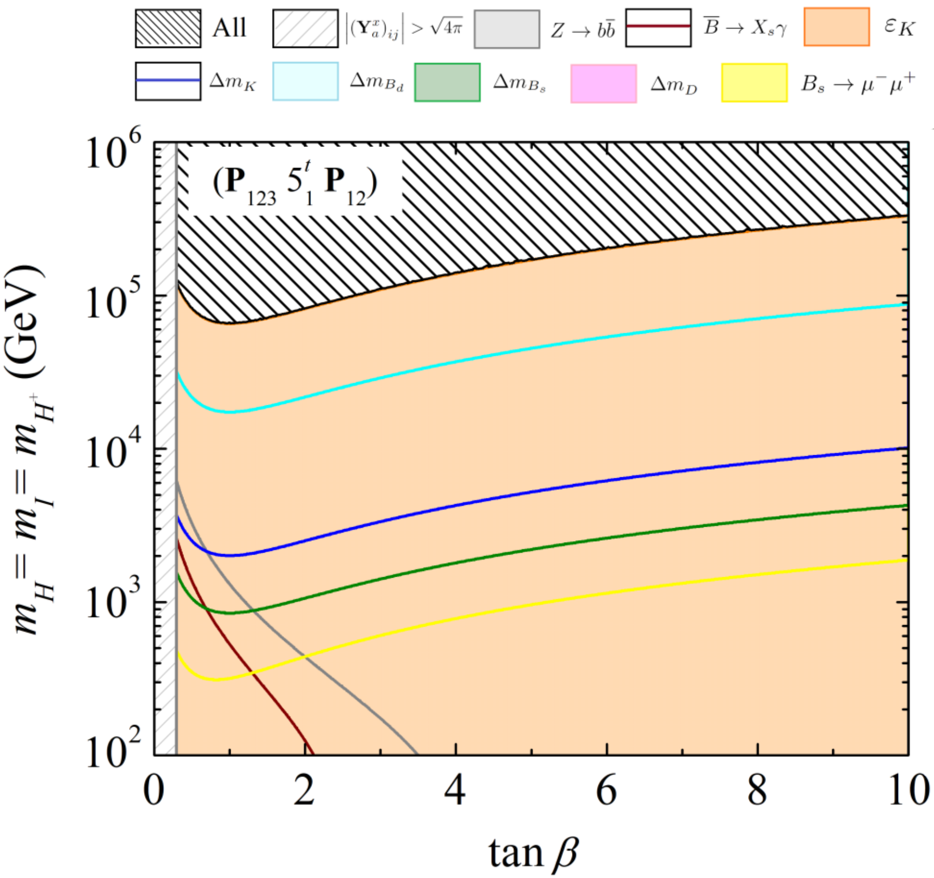
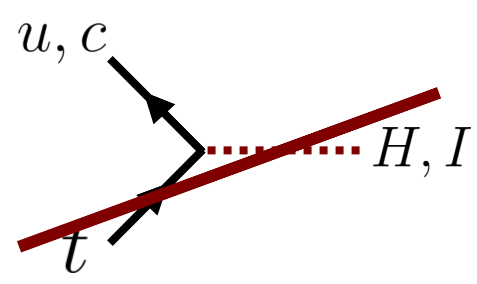
Most restrictive constraints

Only some constraints shape the allowed region $(\tan\beta, \{m_H = m_I = m_{H^\pm}\})$, which we refer to as the **most restrictive constraints**.

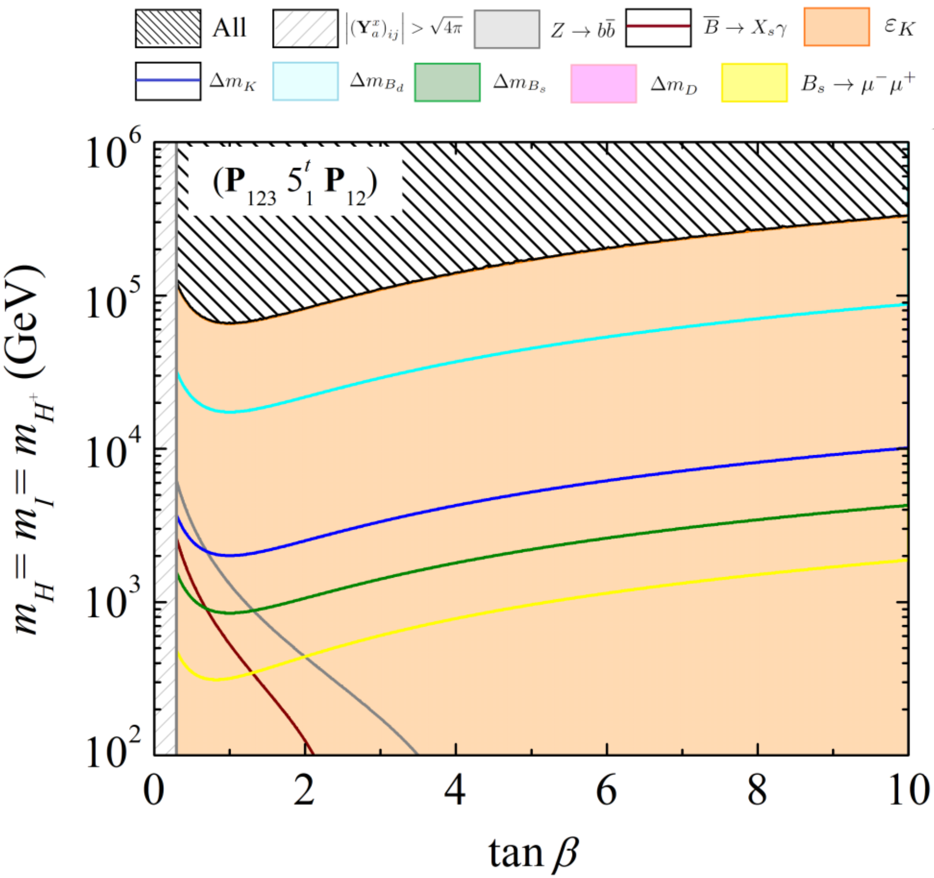
Numerical procedure and phenomenological analysis



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



Numerical procedure and phenomenological analysis



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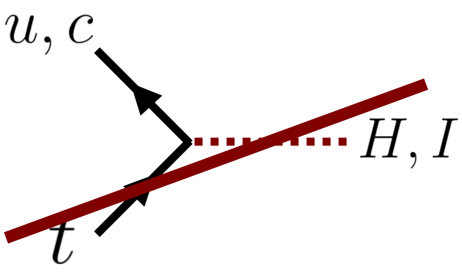
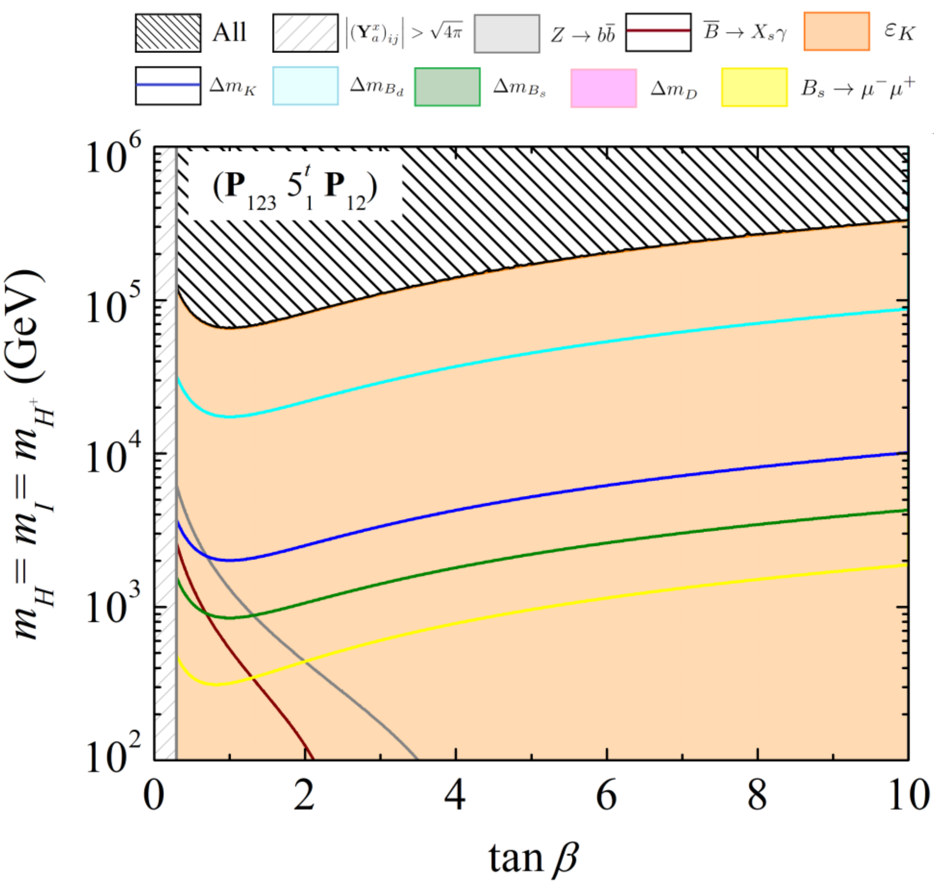


None of the most restrictive constraints are automatically satisfied.



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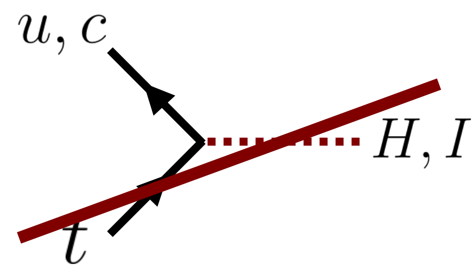

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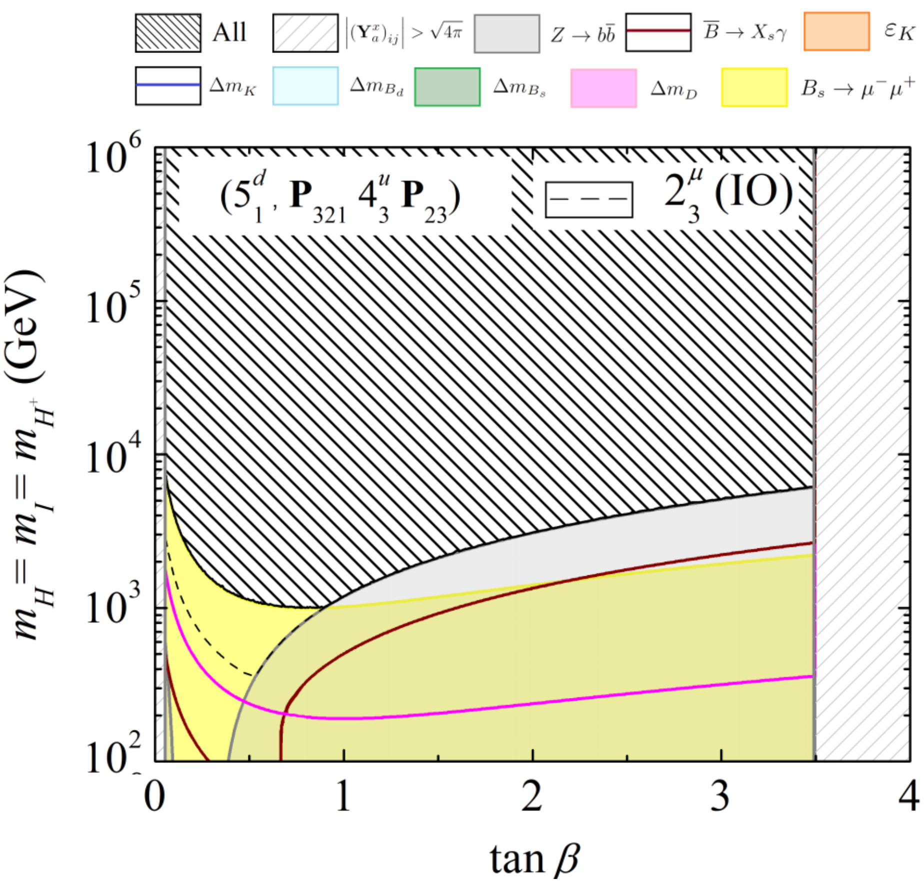
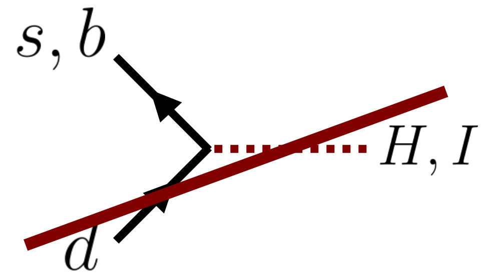
The decoupled state could be picked to satisfy some constraints, for example *d*

Observable	Constraint	Decoupled state
$\lvert\varepsilon_K\rvert$	$(2.228 \pm 0.011) \times 10^{-3}$	(u, d, s)
Δm_K^{NP}	$< 3.484 \times 10^{-15}$ GeV	(d, s)
Δm_{B_d}	$(3.334 \pm 0.013) \times 10^{-13}$ GeV	(d, b)
Δm_{B_s}	$(1.1693 \pm 0.0004) \times 10^{-11}$ GeV	(s, b)
Δm_D^{NP}	$< 6.56 \times 10^{-15}$ GeV	(u, c)

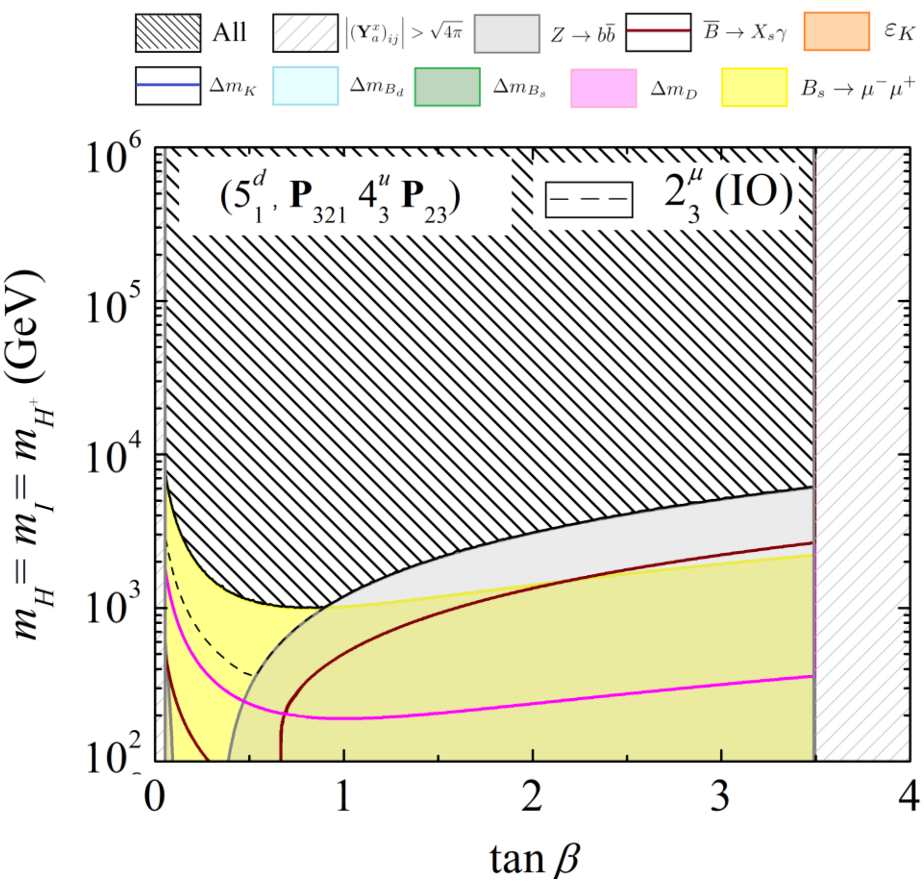
Numerical procedure and phenomenological analysis



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



- ✔ 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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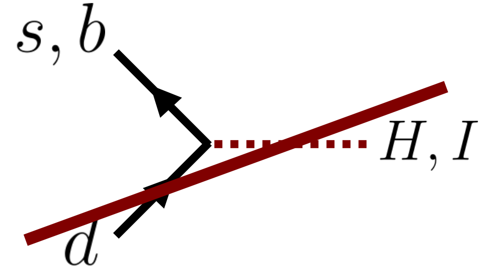

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This model highlights the effectiveness of Abelian flavour symmetries in aligning theoretical frameworks with highly constrained experimental observations.

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**;
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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 !