Extended Scalar Sectors From All Angles

CERN, France/Swiss, 21-25 October, 2024

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

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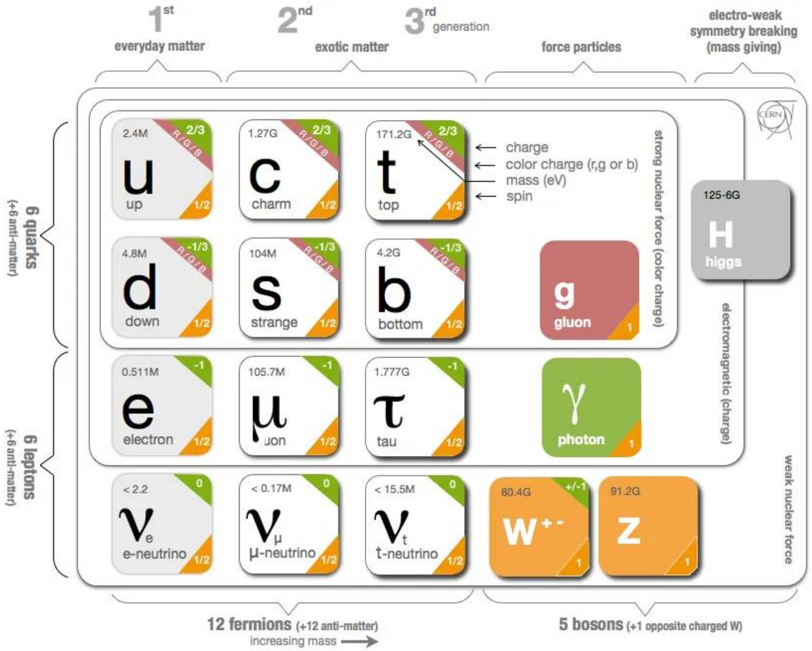
Introduction

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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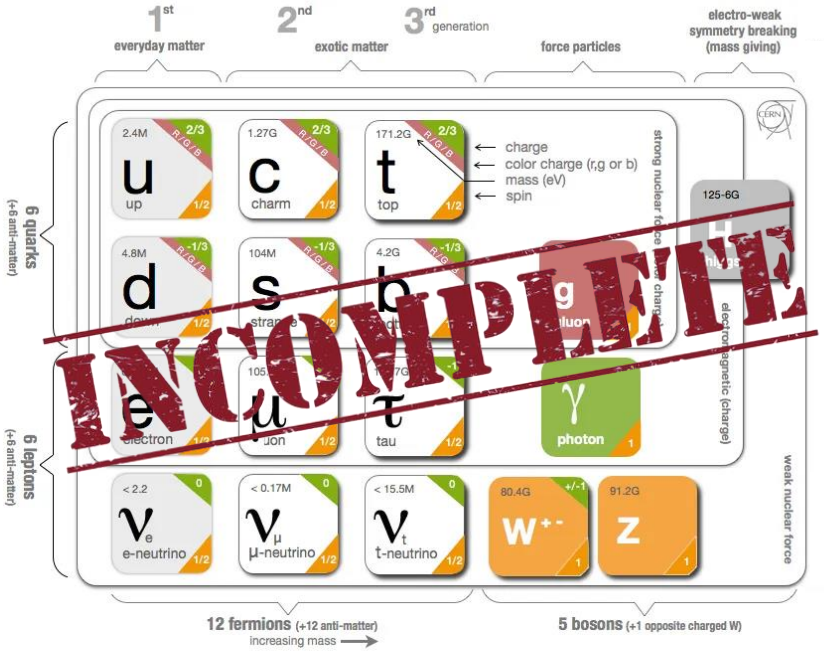
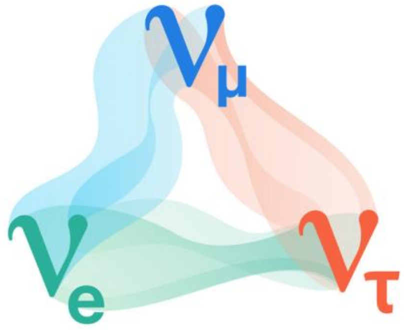
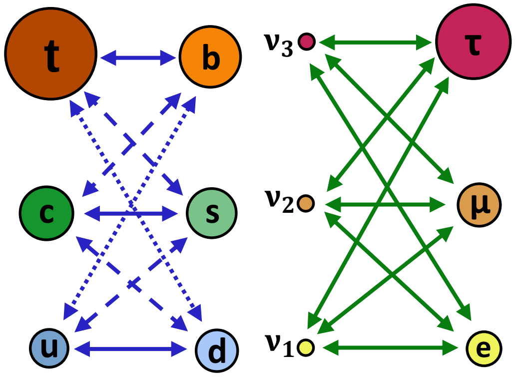


Neutrino Oscillations



Flavour Puzzle



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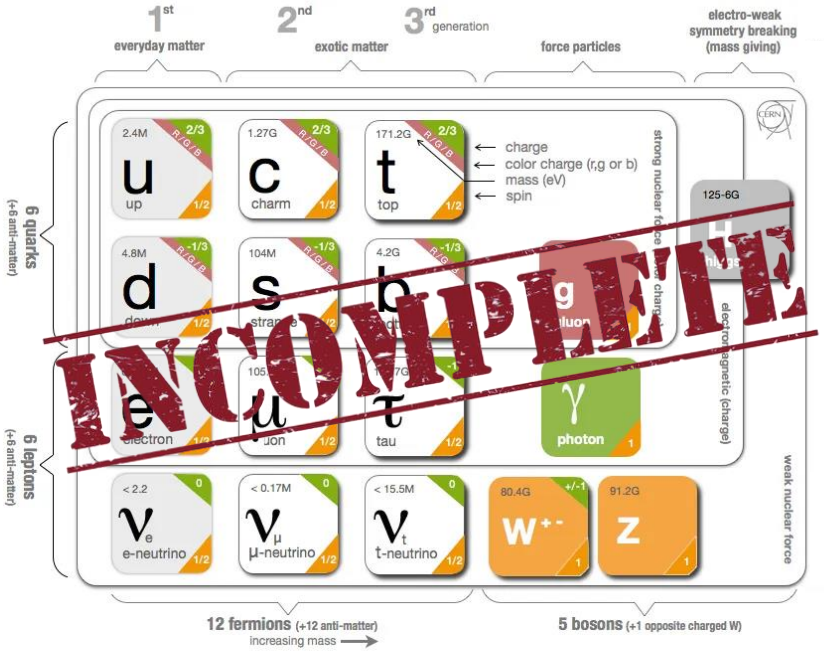

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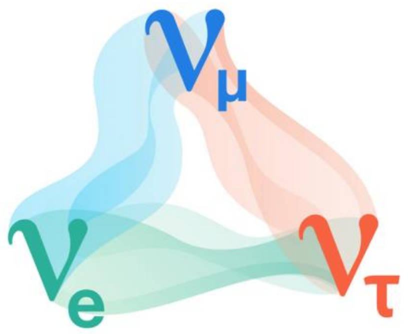

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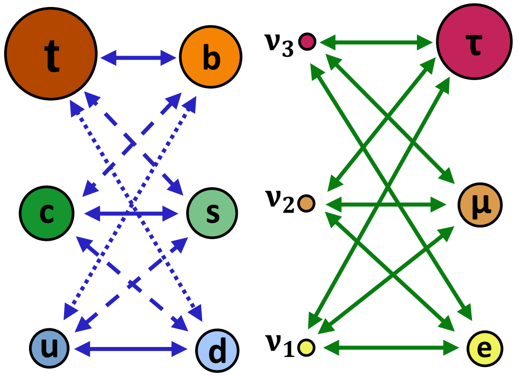

→ **The SM must be extended!**

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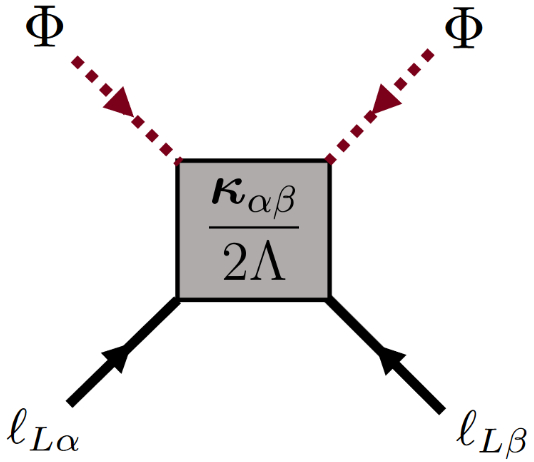
The lowest $d > 4$ operator is **unique (Weinberg Operator)**

(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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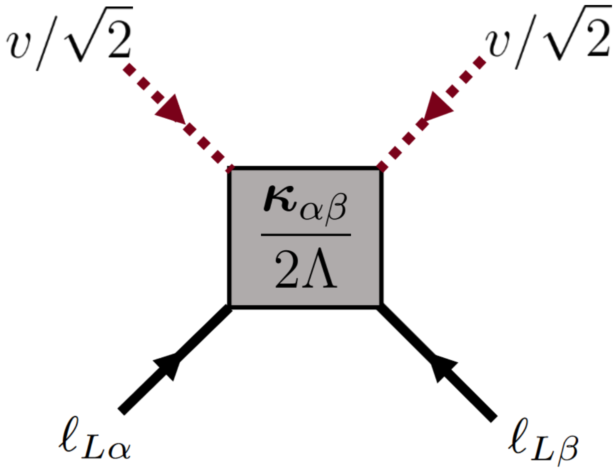
EWSB

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



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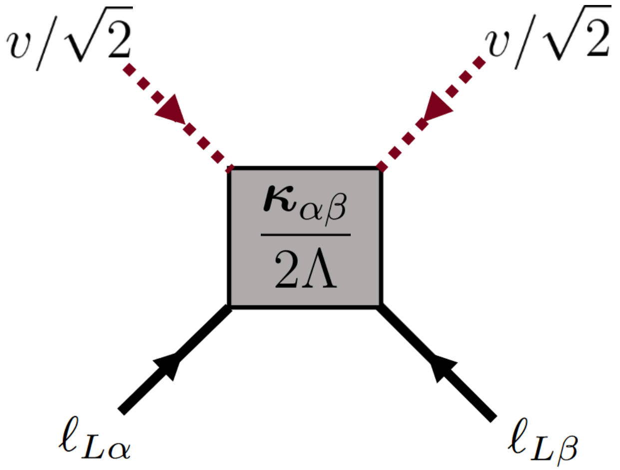


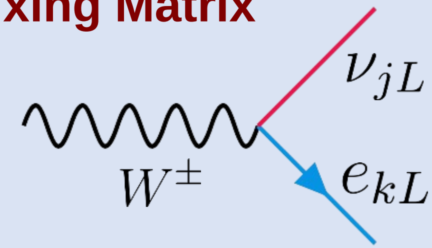
Majorana Mass Eigenstates

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

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

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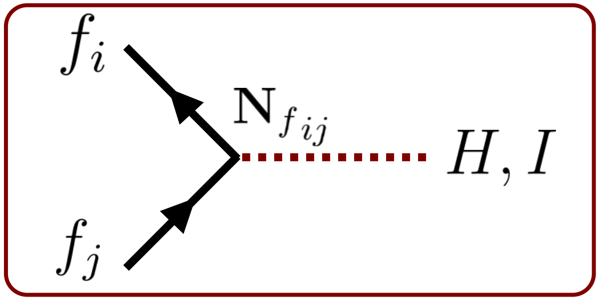
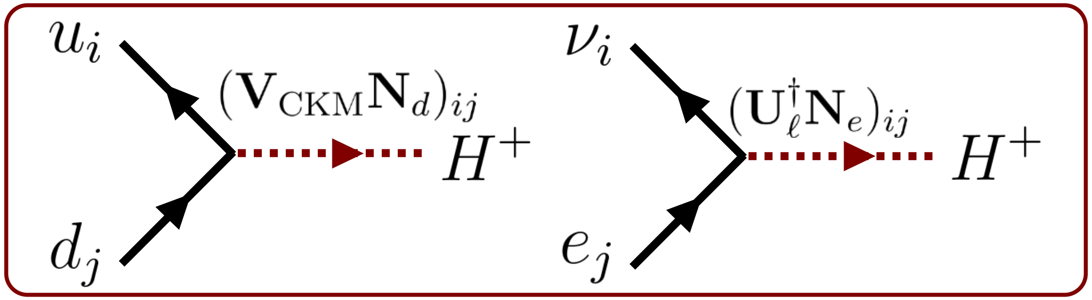
Expanding the **Yukawa Lagrangian** in the **mass eigenstates**:

FCNC



FCCC

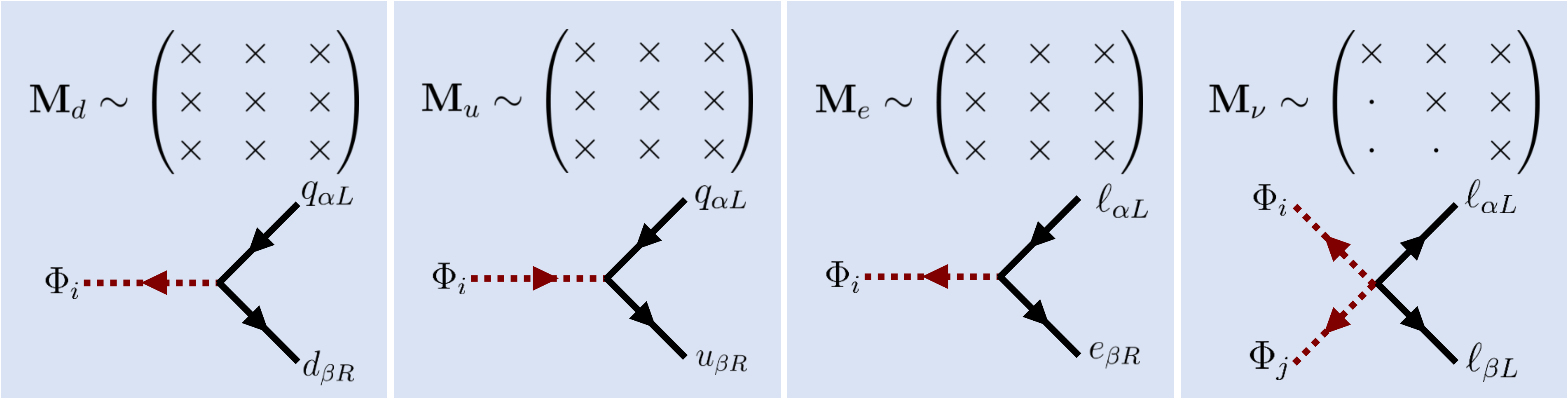


Abelian flavour symmetries

GOAL

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

Introduce flavour charges



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

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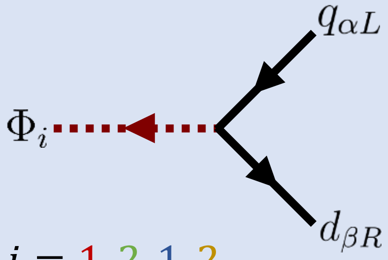

$i = 1, 2, 1, 2$
$\alpha = 1, 2, 3, 3$
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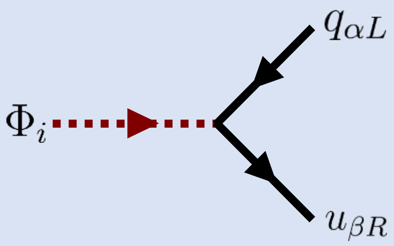

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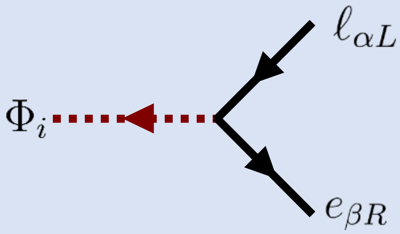

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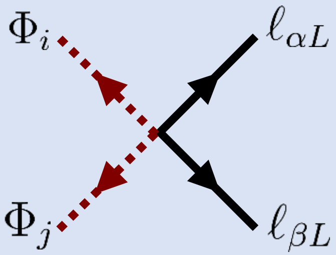

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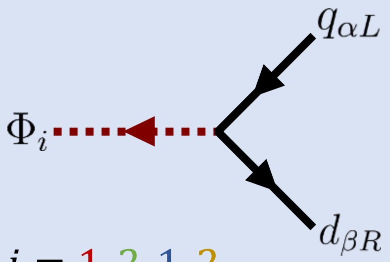

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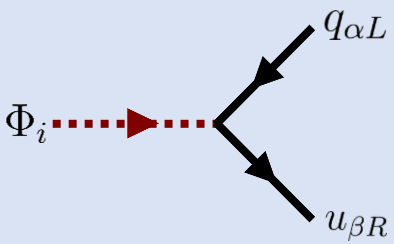

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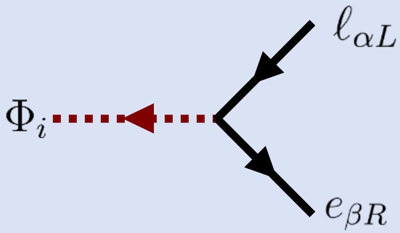

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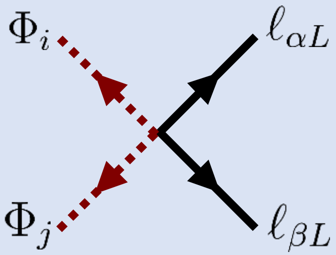

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Example:

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

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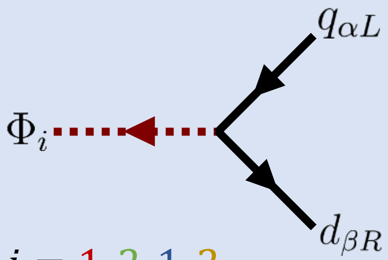

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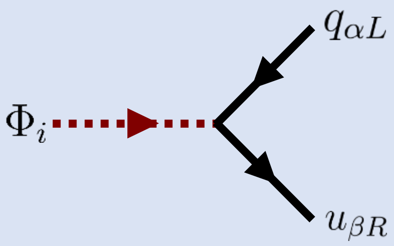

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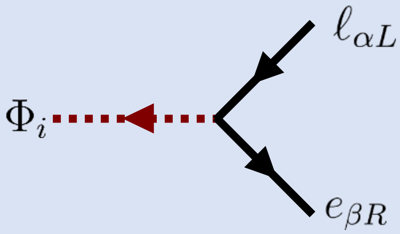

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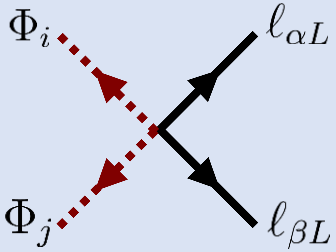

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Example:

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

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

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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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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

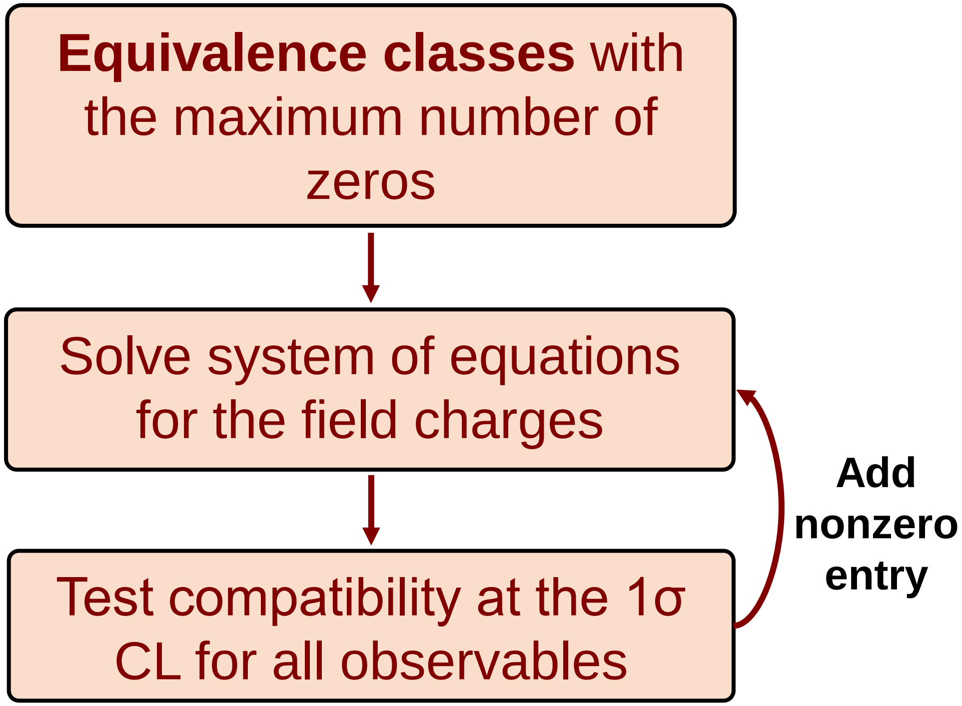
Parameter	Best fit $\pm 1\sigma$
$m_d(\times \text{ MeV})$	$4.67^{+0.48}_{-0.17}$
$m_s(\times \text{ MeV})$	$93.4^{+8.6}_{-3.4}$
$m_b(\times \text{ GeV})$	$4.18^{+0.03}_{-0.02}$
$m_u(\times \text{ MeV})$	$2.16^{+0.49}_{-0.26}$
$m_c(\times \text{ GeV})$	1.27 ± 0.02
$m_t(\times \text{ GeV})$	172.69 ± 0.30
$\theta^q_{12}(^\circ)$	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
$\theta^\ell_{23}(^\circ)$[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

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Add nonzero entry

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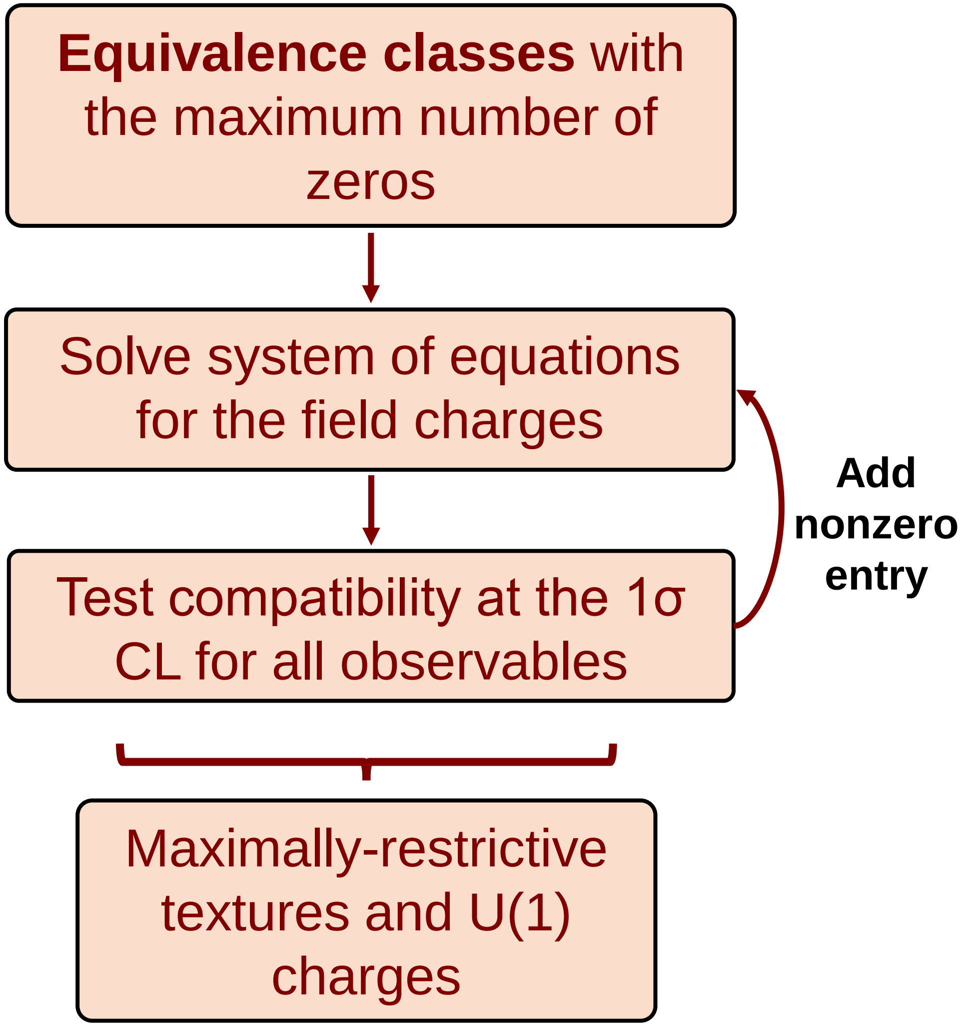
$\theta^q_{12}(^\circ)$	13.04 ± 0.05
$\theta^q_{23}(^\circ)$	2.38 ± 0.06
$\theta^q_{13}(^\circ)$	0.201 ± 0.011
$\delta^q(^\circ)$	68.75 ± 4.5

Leptons

Parameter	Best Fit $\pm 1\sigma$
$m_e(\times\ \mathrm{keV})$	$510.99895000 \pm 0.00000015$
$m_\mu(\times\ \mathrm{MeV})$	$105.6583755 \pm 0.0000023$
$m_\tau(\times\ \mathrm{GeV})$	1.77686 ± 0.00012
$\Delta m^2_{21}\ (\times 10^{-5}\ \mathrm{eV}^2)$	$7.50^{+0.22}_{-0.20}$
$\lvert\Delta m^2_{31}\rvert\ (\times 10^{-3}\ \mathrm{eV}^2)$ [NO]	$2.55^{+0.02}_{-0.03}$
$\lvert\Delta m^2_{31}\rvert\ (\times 10^{-3}\ \mathrm{eV}^2)$ [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 $\pm1\sigma$
$m_d(\times\text{ MeV})$	$4.67^{+0.48}_{-0.17}$
$m_s(\times\text{ MeV})$	$93.4^{+8.6}_{-3.4}$
$m_b(\times\text{ GeV})$	$4.18^{+0.03}_{-0.02}$
$m_u(\times\text{ MeV})$	$2.16^{+0.49}_{-0.26}$
$m_c(\times\text{ GeV})$	1.27 ± 0.02
$m_t(\times\text{ GeV})$	172.69 ± 0.30
$\theta^q_{12}(^\circ)$	13.04 ± 0.05
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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

$\mathbb{Z}_5$

$(\mathbf{M}_e,\mathbf{M}_\nu)$	$(\delta_1,\delta_2,\delta_3)$	$(\epsilon_1,\epsilon_2,\epsilon_3)$
$(5^e_1, 2^\nu_3)$	$(-1,-3,1)$	$(1,-5,-1)$
$(5^e_1, 2^\nu_7)$	$(-1,-2,0)$	$(0,-3,-1)$
$(5^e_1, 2^\nu_{10})$	$(0,-1,1)$	$(1,-2,0)$

$\mathbb{Z}_4$

$(\mathbf{M}_d,\mathbf{M}_u)$	$(\alpha_1,\alpha_2,\alpha_3)$	$(\beta_1,\beta_2,\beta_3)$	$(\gamma_1,\gamma_2,\gamma_3)$
$(4^d_3, \mathbf{P}_{12}5^u_1\mathbf{P}_{23})$	$(0,1,2)$	$(2,1,0)$	$(3,2,0)$
$(4^d_3, \mathbf{P}_{123}5^u_1\mathbf{P}_{12})$	$(0,1,2)$	$(2,1,0)$	$(3,0,1)$
$(5^d_1, \mathbf{P}_{12}4^u_3)$	$(0,-1,1)$	$(1,-2,0)$	$(2,1,0)$
$(5^d_1, \mathbf{P}_{321}4^u_3\mathbf{P}_{23})$	$(0,-1,1)$	$(1,-2,0)$	$(-1,1,0)$

“Decoupled” entry in the matrices of type “5” lead to zeros in the N$_k$ matrices

Maximally restrictive mass matrices

Quarks

$$4^d_3 \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & 0 \end{pmatrix}$$

$$5^d_1 \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}$$

$$\mathbf{P}_{12}5^u_1\mathbf{P}_{23} \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \bullet & 0 \\ \times & \times & 0 \end{pmatrix}$$

$$\mathbf{P}_{123}5^u_1\mathbf{P}_{12} \sim \begin{pmatrix} 0 & \times & \bullet \\ 0 & 0 & \times \\ \times & 0 & 0 \end{pmatrix}$$

$$\mathbf{P}_{12}4^u_3 \sim \begin{pmatrix} 0 & \bullet & \times \\ 0 & 0 & \times \\ \times & \times & 0 \end{pmatrix}$$

$$\mathbf{P}_{321}4^u_3\mathbf{P}_{23} \sim \begin{pmatrix} 0 & \bullet & \times \\ \times & 0 & \times \\ 0 & \times & 0 \end{pmatrix}$$

Leptons

$$5^e_1 \sim \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}$$

$$2^\nu_3 \sim \begin{pmatrix} \times & \times & \bullet \\ \cdot & 0 & \bullet \\ \cdot & \cdot & 0 \end{pmatrix}$$

$$2^\nu_7 \sim \begin{pmatrix} \times & 0 & \bullet \\ \cdot & 0 & \times \\ \cdot & \cdot & \bullet \end{pmatrix}$$

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

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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- ✓ Three different models;
- ✓ There are ten parameters, **two less** than the number of lepton observables;

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Minimal flavour patterns for **leptons**:

- ✓ Three different models;
- ✓ There are ten parameters, **two less** than the number of lepton observables;

Predictions

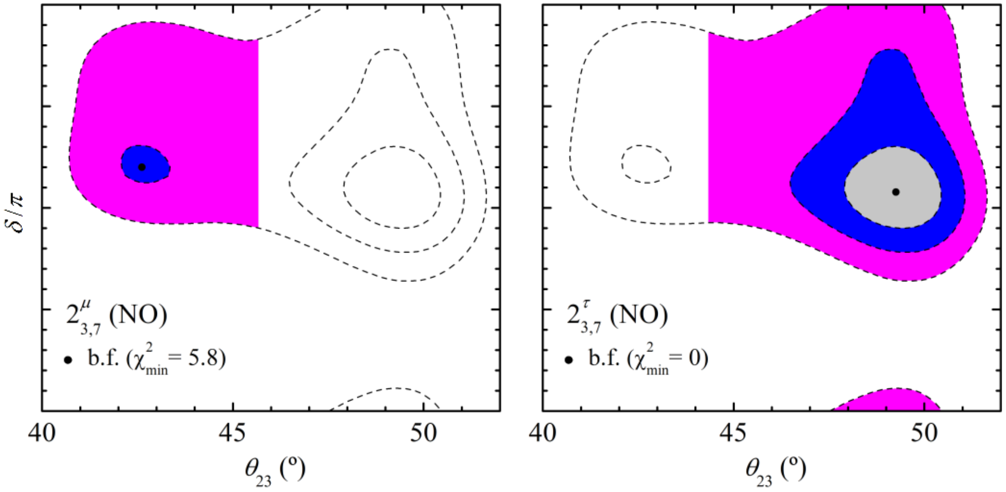
NO: $m_2 = \sqrt{m_1^2 + \Delta m_{21}^2}, \quad m_3 = \sqrt{m_1^2 + \Delta m_{31}^2}$

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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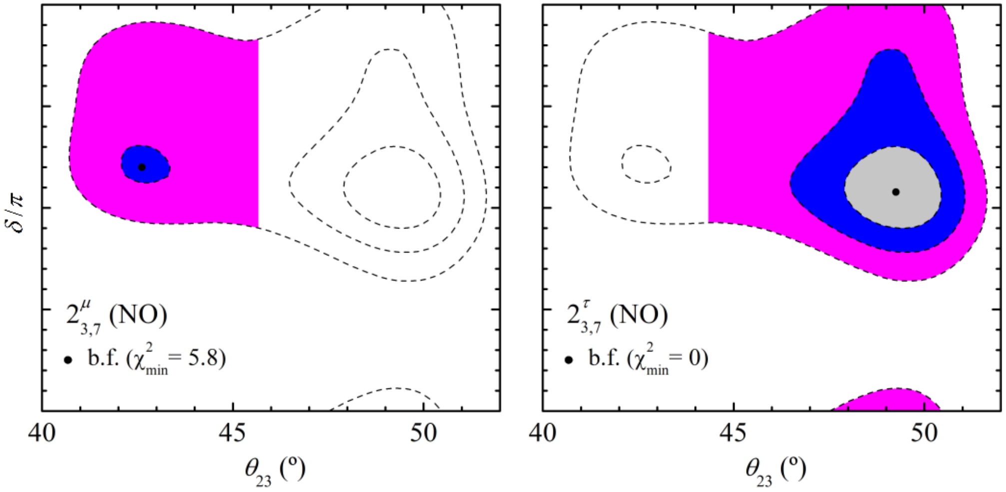
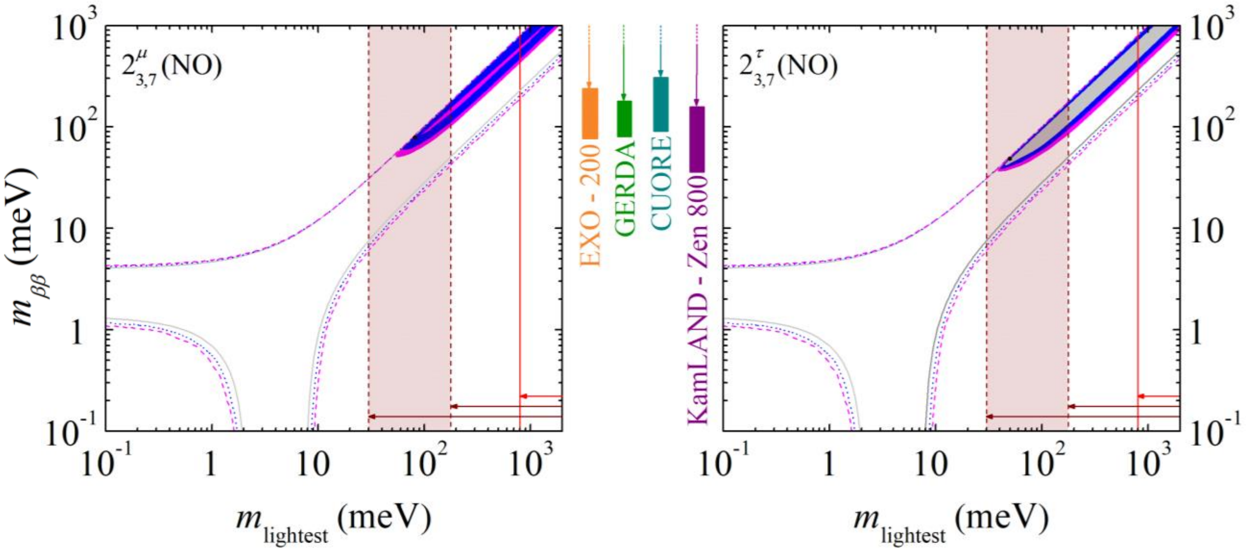


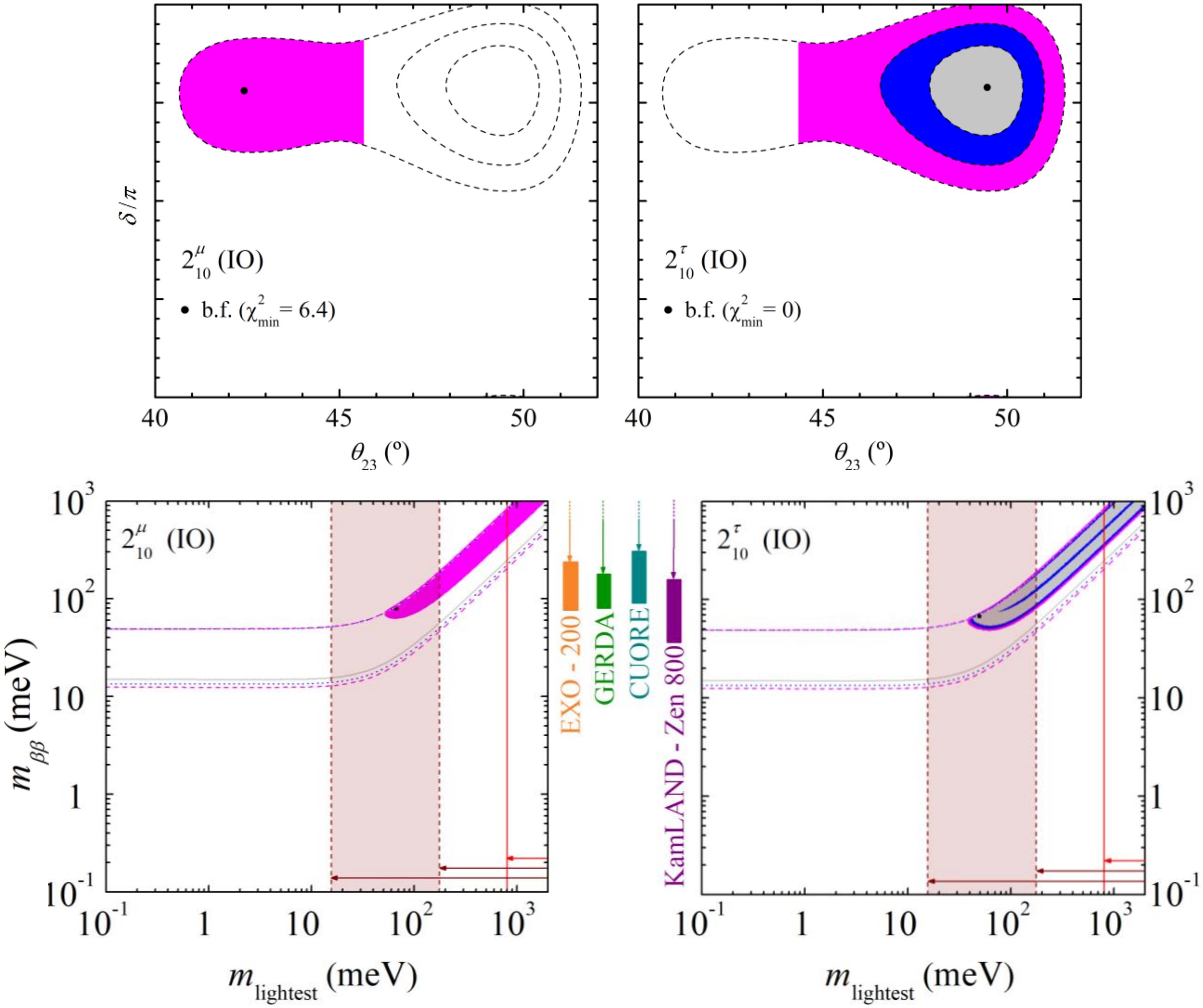
For NO, $2^{\mu}_{3,7}$ and $2^{\tau}_{3,7}$ select the **first** and **second octant** for the atmospheric mixing angle θ_{23}, respectively

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 $m_{lightest}$



Lepton sector predictions - IO

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



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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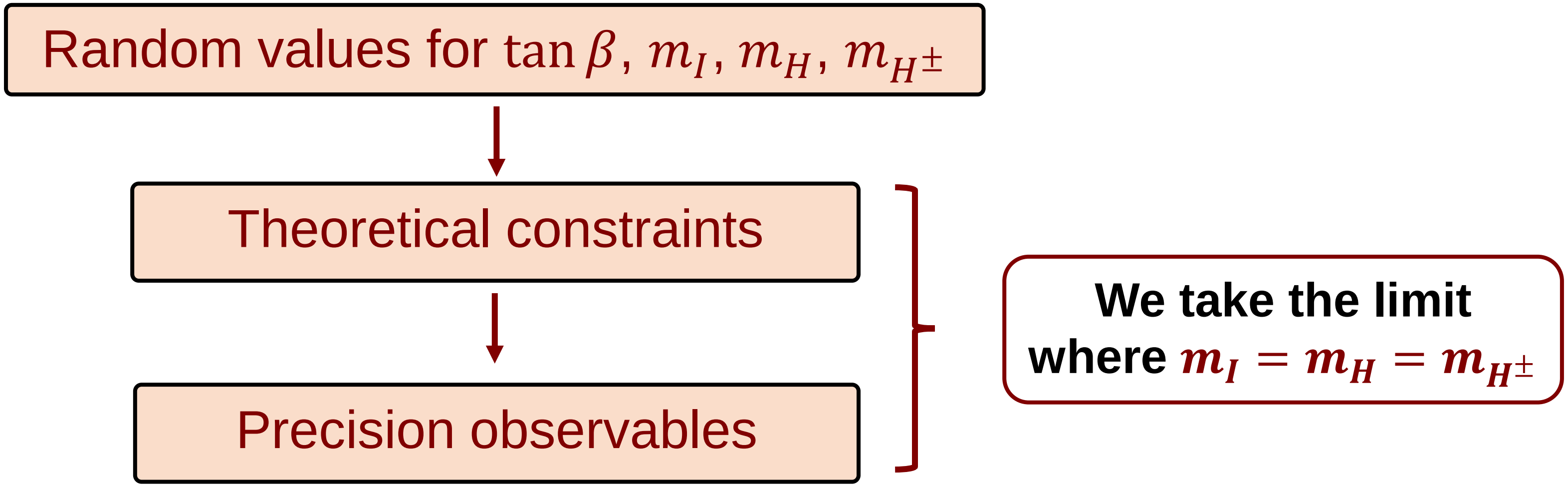

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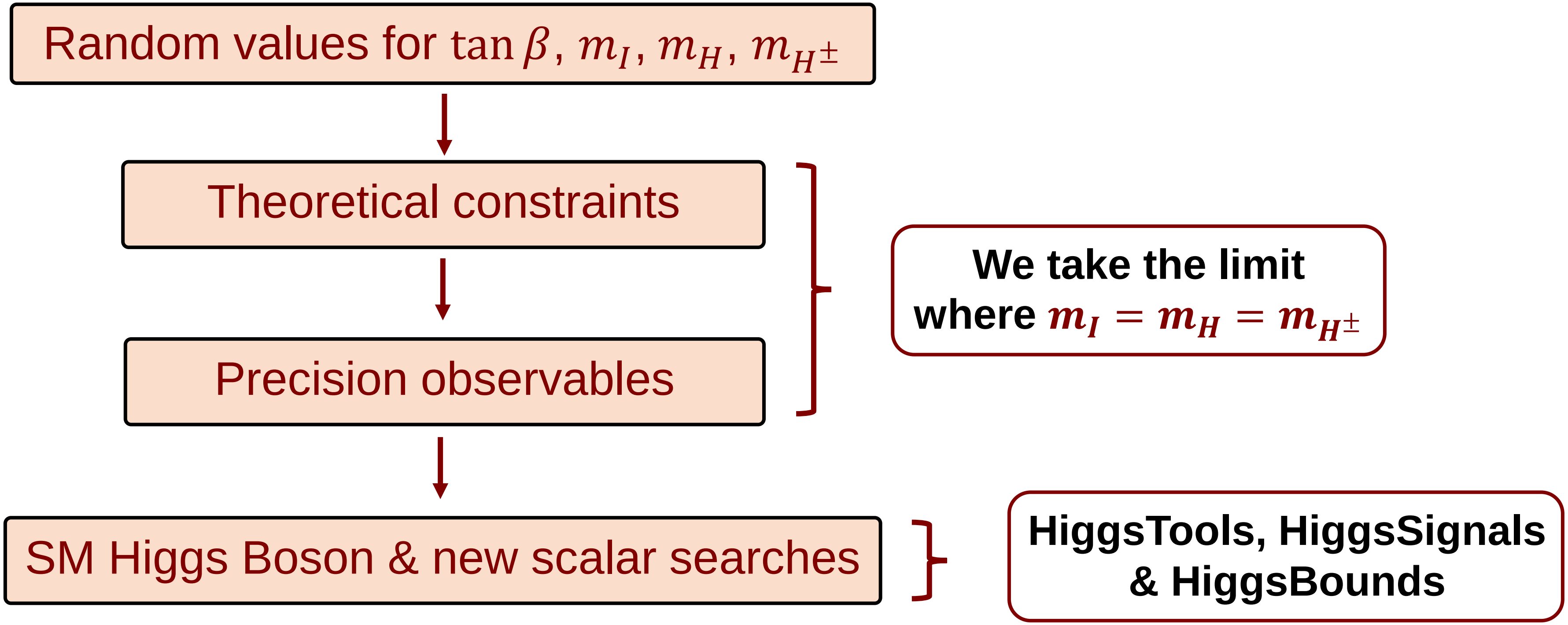

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Theoretical constraints

Precision observables

SM Higgs Boson & new scalar searches

We take the limit where $m_I = m_H = m_{H^\pm}$

HiggsTools, HiggsSignals & HiggsBounds

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↓

Theoretical constraints

↓

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Charged lepton-flavour violation processes

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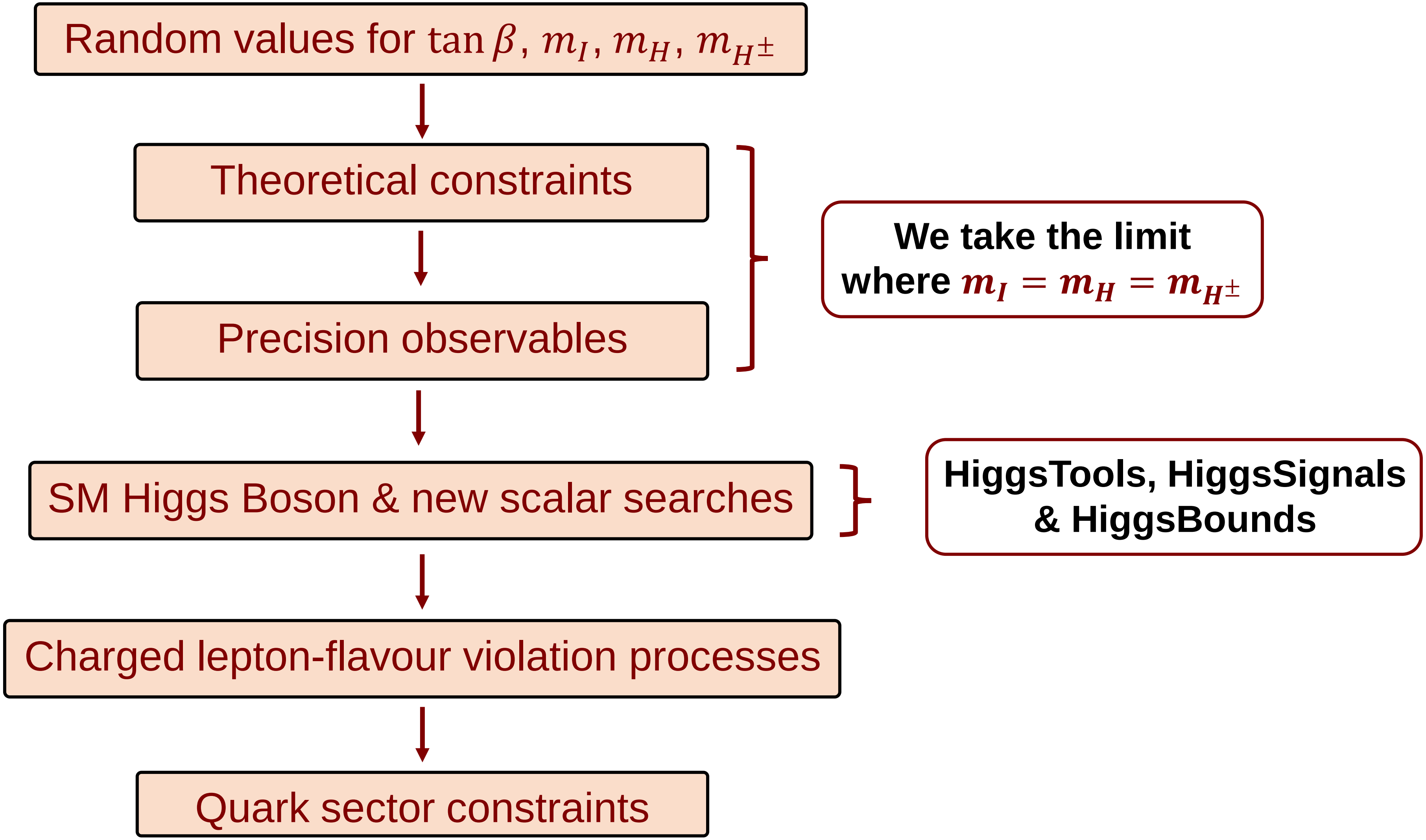

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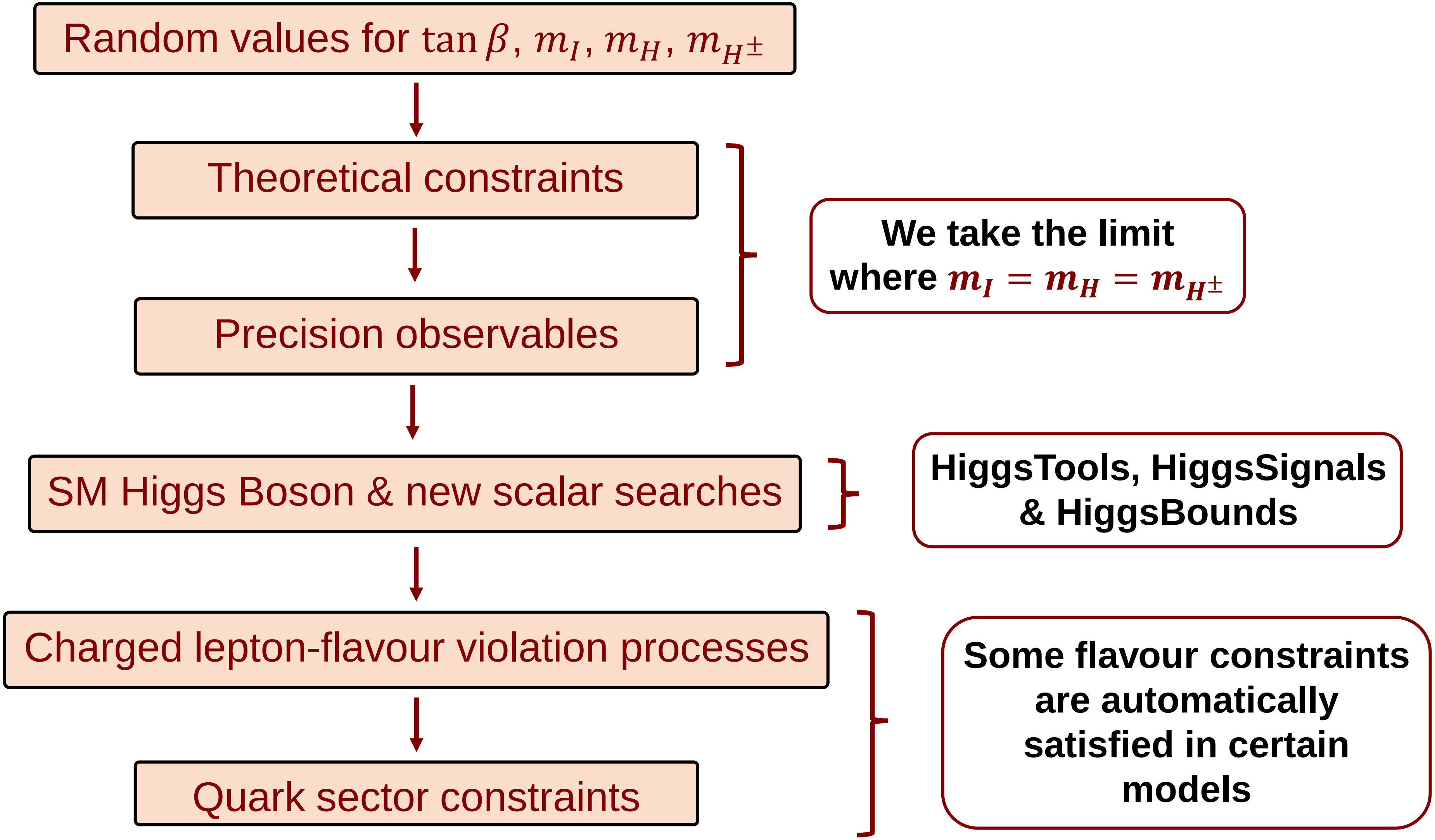

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Charged lepton-flavour violation processes

Quark sector constraints

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 $\overline{K}_0 \rightarrow K_0$ transition:

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

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Numerical procedure and phenomenological analysis

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$$+ 4 (\cancel{\mathbf{N}_d^*})_{ds} (\cancel{\mathbf{N}_d})_{sd} \left[1 + \frac{6 m_K^2}{(m_s + m_d)^2} \left(\frac{1}{m_I^2} + \frac{c^2_{\beta-\alpha}}{m_h^2} + \frac{s^2_{\beta-\alpha}}{m_H^2} \right) \right] \Bigg\}$$

↓

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

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

Numerical procedure and phenomenological analysis

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

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 $|(\mathbf{M}_2^x)_{ij}|$.

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.

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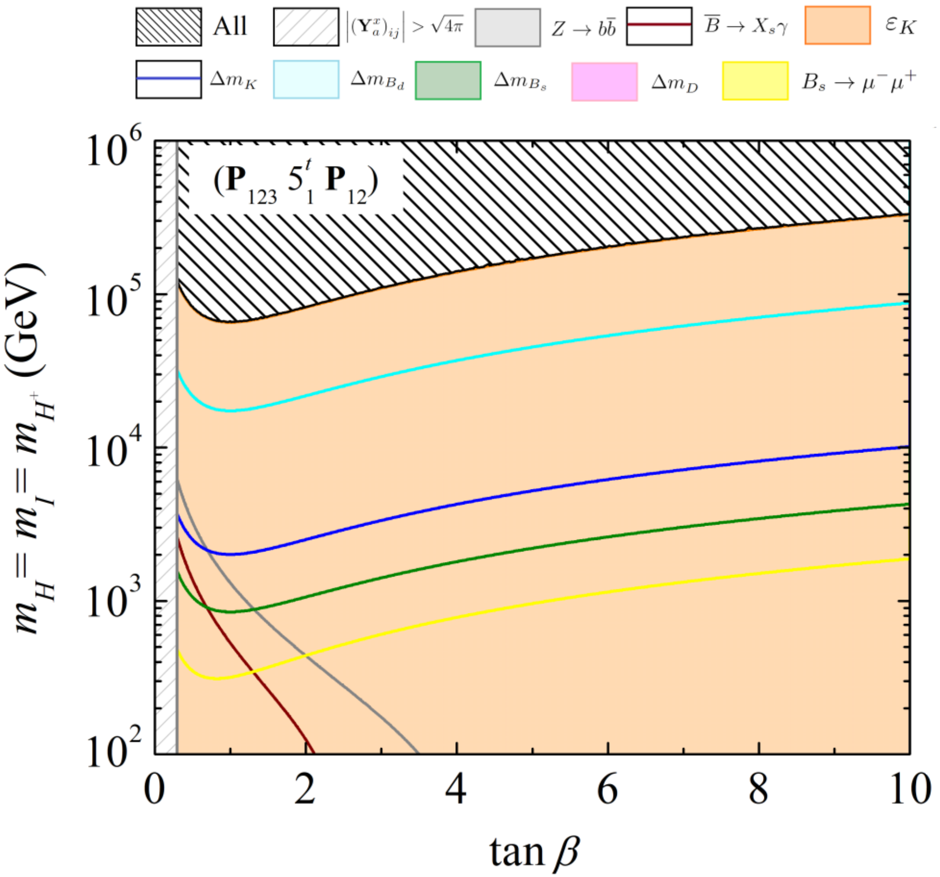
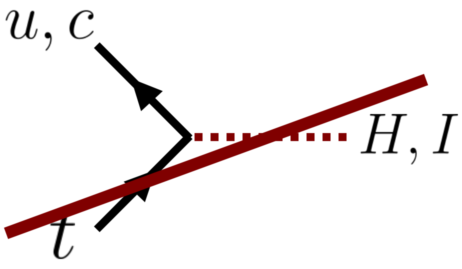
Most restrictive constraints

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



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



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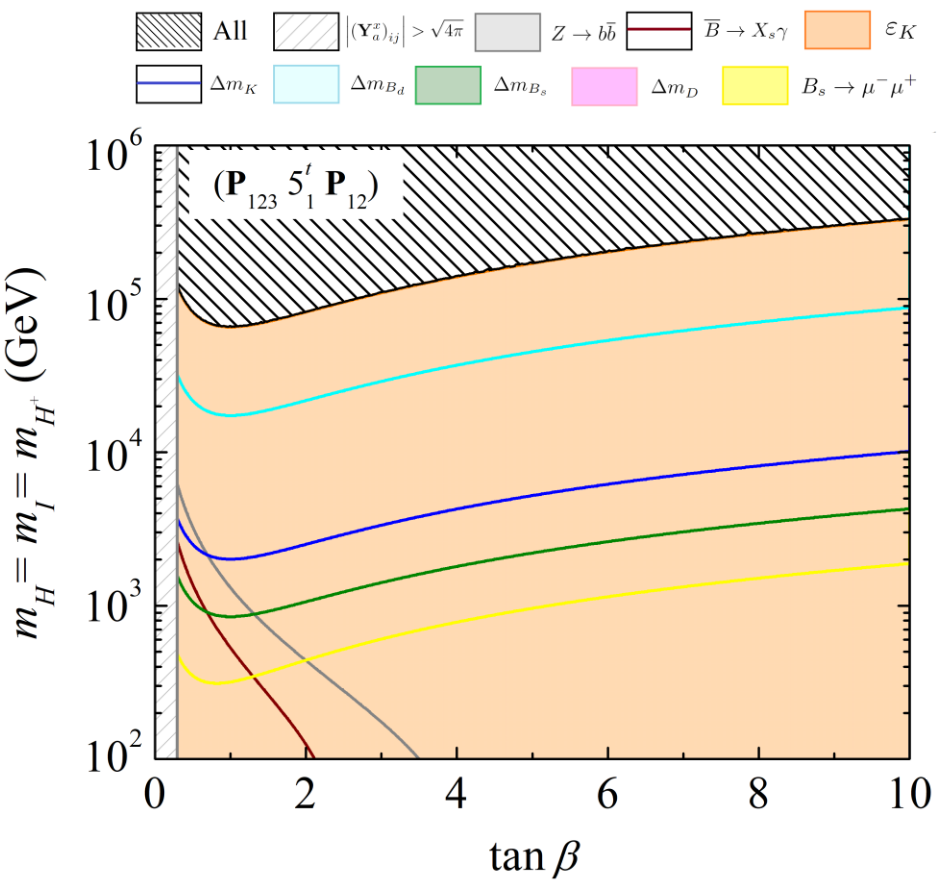

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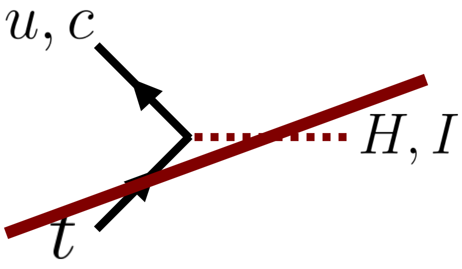

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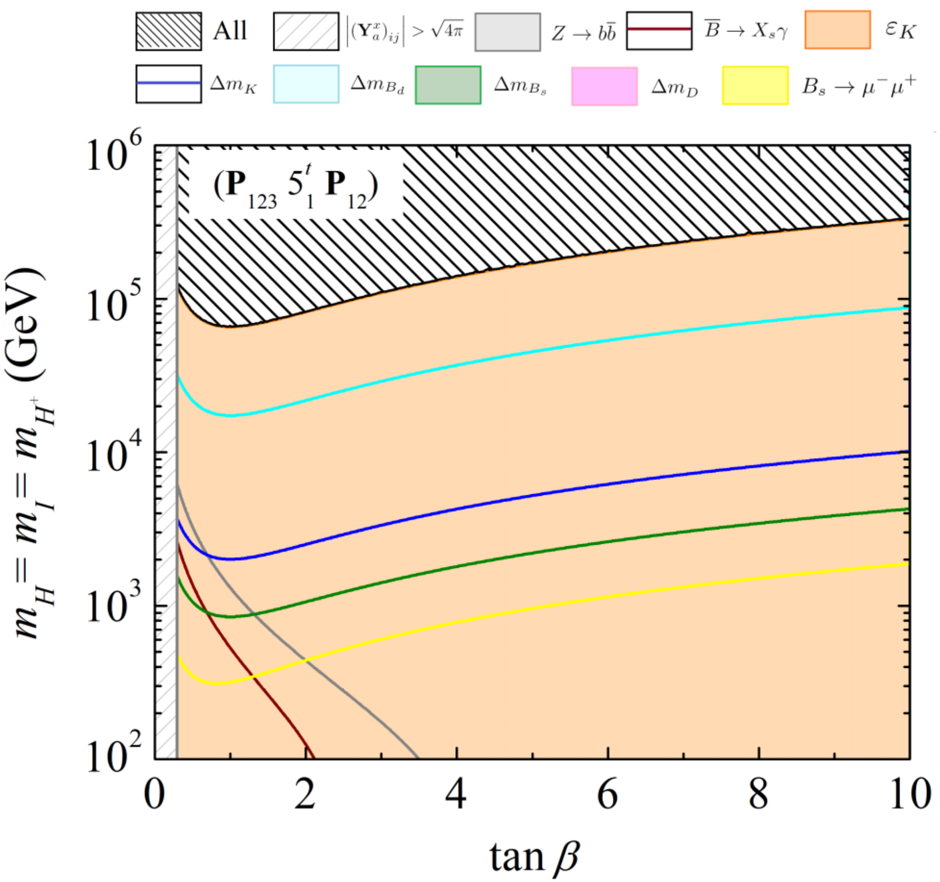
None of the most restrictive constraints are automatically satisfied.

Numerical procedure and phenomenological analysis



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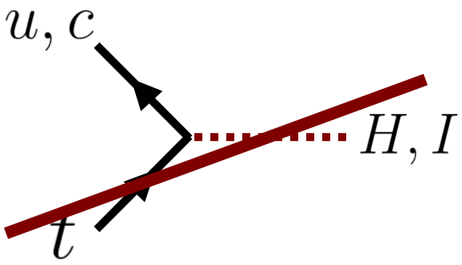
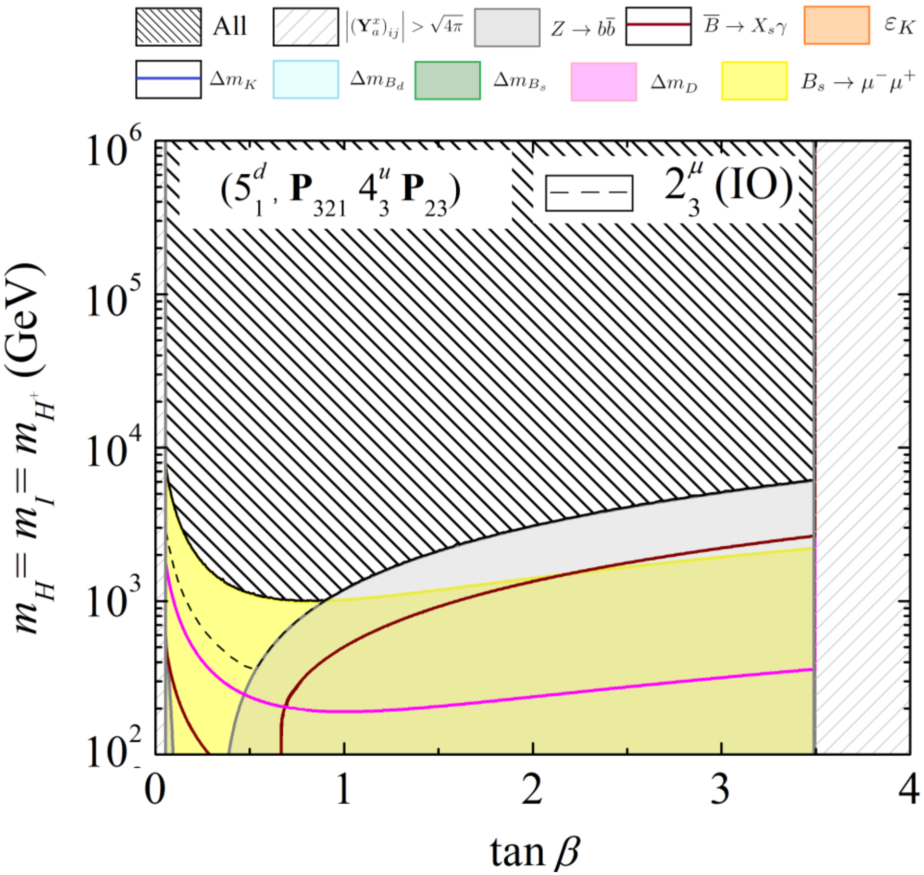


None of the most restrictive constraints are automatically satisfied.

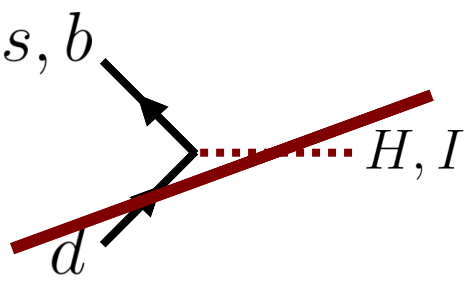
The decoupled state could be picked to satisfy some constraints, for example *d*

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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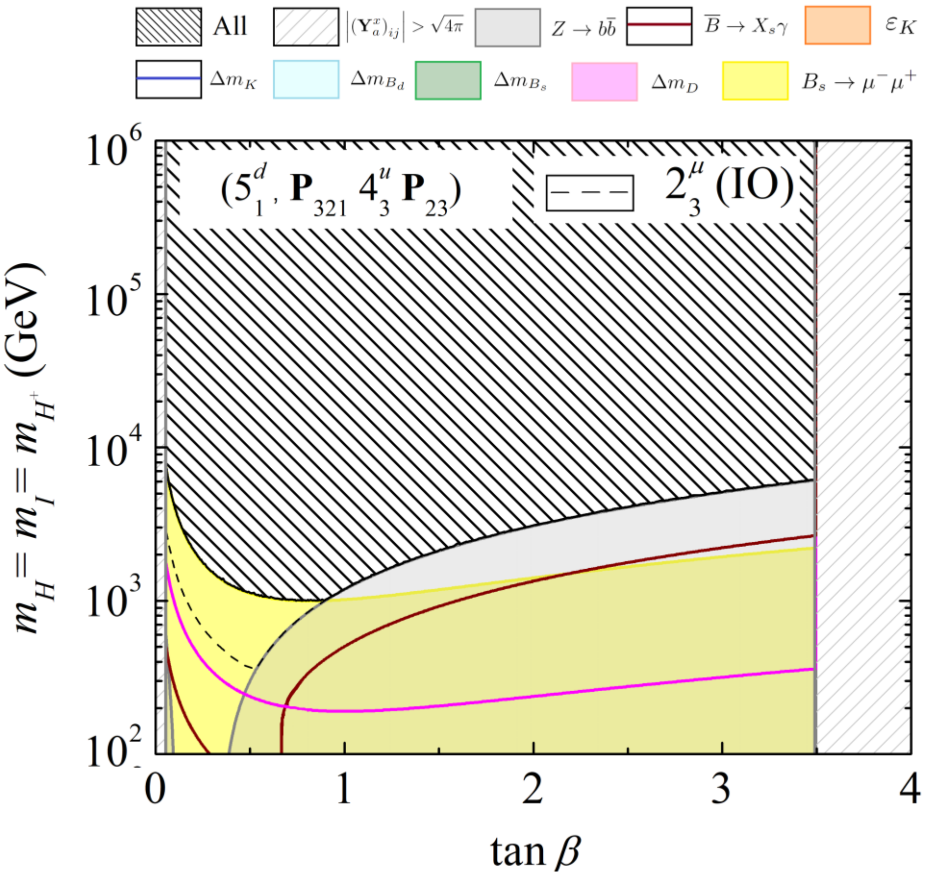

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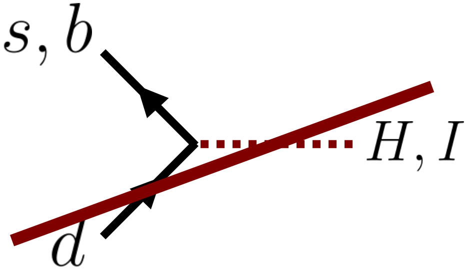

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This model highlights the effectiveness of Abelian flavour symmetries in aligning theoretical frameworks with highly constrained experimental observations.

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;
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Thank you !