Connecting b→s anomalies with neutrino masses, dark matter and charged LFV

Jean Orloff
Laboratoire de Physique de Clermont

Based on: JHEP 1811 (2018) 011
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In collaboration with
G. Kumar, C. Hati, and A. M. Teixeira

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Outline

- Motivations and approach Beyond the Standard Model
- Neutrino mass models crash review: tree & loop
- Lepton Flavour Universality Violation (LFUV) in B decays?
- A minimal model connecting these with Dark Matter (DM)
- Parameters and pheno constraints:
  - Neutrino masses
  - DM relic density
  - Charged Lepton Flavour Violation (cLFV)

Introduction

The Standard Model (SM): Highly successful but incomplete ...

Hundreds of theoretical models with various th./aesthetical motivations :

- Flavour puzzle
- Unification of interactions
- Hierarchy Problem
- Matter-antimatter asymmetry
- ???

Strategy:

- Start from solid BSM evidence:
  Neutrino Oscillations!!!
  => neutrino masses
  => New physics beyond the SM
  (SM neutrinos are strictly massless)
- If possible, help the Dark Matter (DM) problem
- Seek further guidance from (prelim.) experimental anomalies: B-decays, $(g\text{-}2)_\mu$, ...

Neutrino mass models

Neutrino Mass Models: Dirac mass term

Simplest implementation of observed neutrino kinematical mass:

$$\mathcal{L}_D = Y_{D,ij}\bar{\nu}_{R,i}\phi^\dagger L_j + h.c.$$

- requires **3 new fields** $\nu R,i$ **with no SM charge (?check?)**
- However nothing, except (anomalous) L-number, then forbids

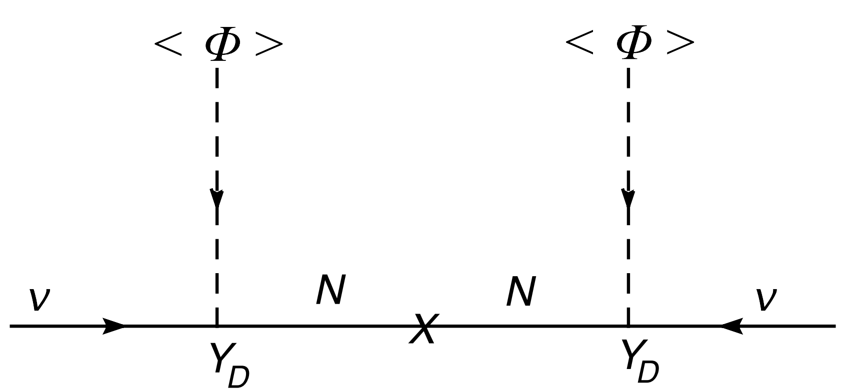
$$\mathcal{L}_M = M_{ij}\bar{\nu}^c_{R,i}\nu_{R,j} + h.c.$$

  lifting Dirac degeneracy: in terms of Majorana spinors $N = \nu_R + C\bar{\nu}_R^T$

$$\mathcal{L}_M + \mathcal{L}_D = \frac{1}{2}\begin{pmatrix}\bar{\nu} & \bar{N}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M\end{pmatrix}\begin{pmatrix}\nu \\ N\end{pmatrix}$$

- In the limit of large $M \approx MN$, **see-saw formula :**

$$m_\nu \approx -m_D^T \frac{1}{M} m_D \; ; \quad m_D = Y_D\langle\phi\rangle$$



✳ GUT: $YD \sim 1 \rightarrow M \sim$ 1015GeV

✳ νMSM: $M < EEW \rightarrow YD$ « 10-8 *(??)*

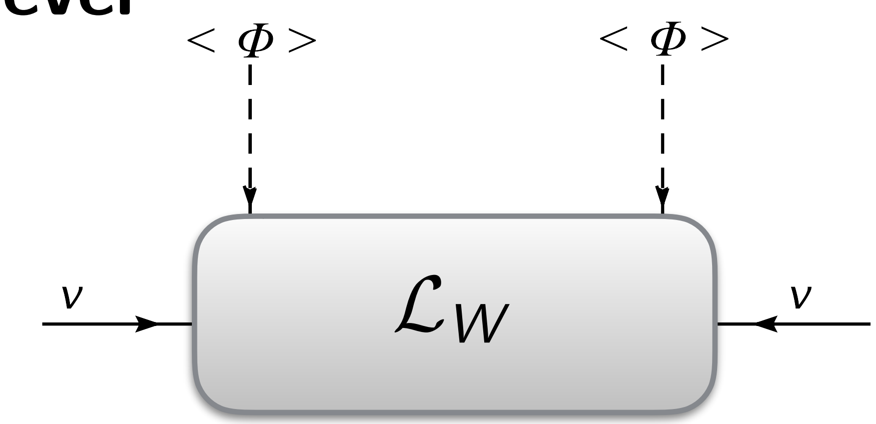
Neutrino Mass Models: See-Saw = tree inside Weinberg

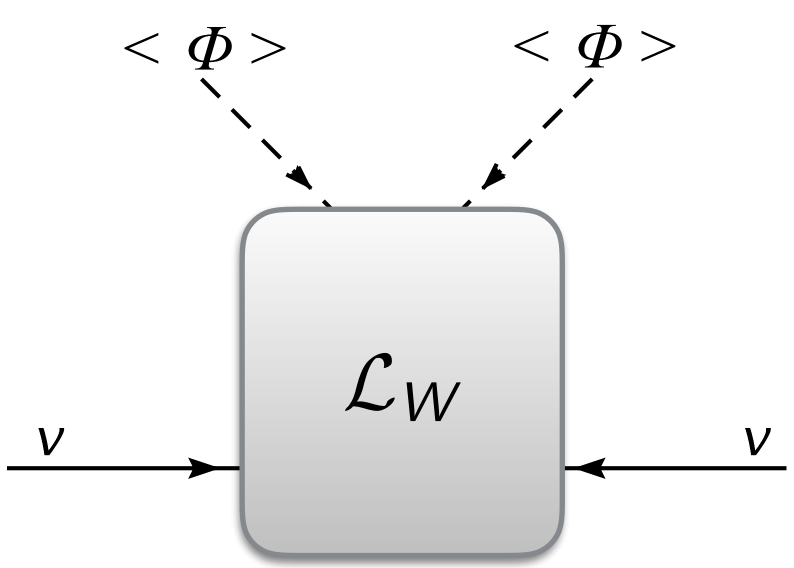
Step back: without new fields, need effective dim. 5 operator

- **Weinberg operator**

$$\mathcal{L}_W = \frac{m_\nu}{v^2}(L^T i\sigma_2 \phi) C (\phi^T i\sigma_2 L)$$

3 possible **renormalisable** «blow-up» by **tree-level** single field exchange, giving $m_\nu \sim m_{new}^{-1(2)}$:





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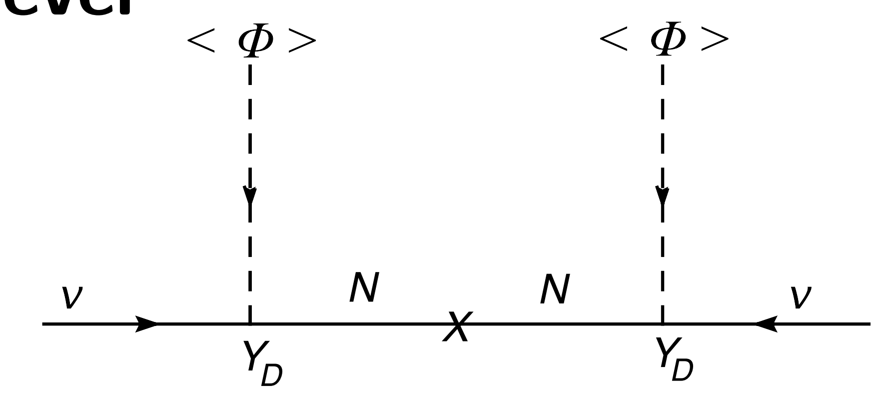
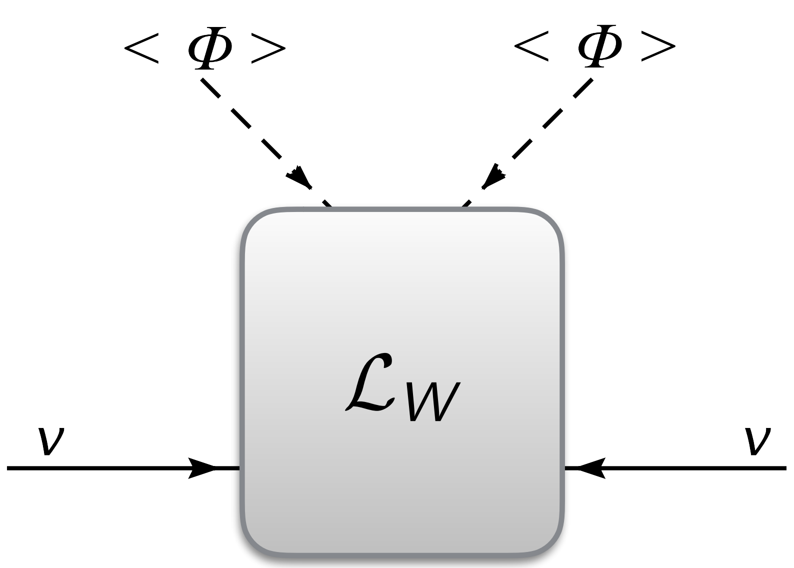


- **Type I:** SU(2)-singlet fermion N (see above)



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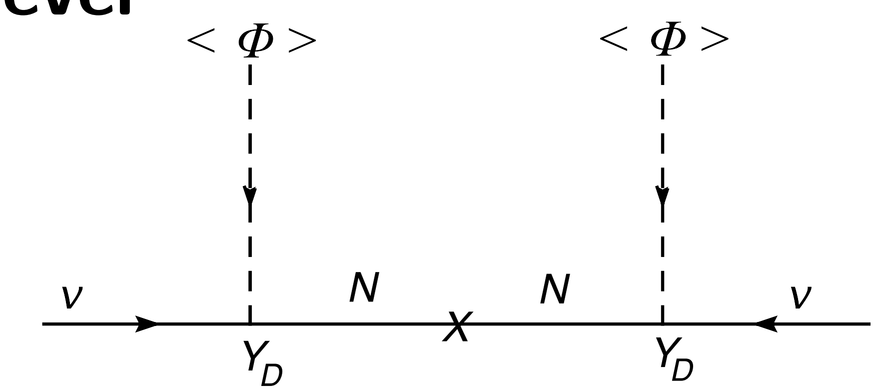

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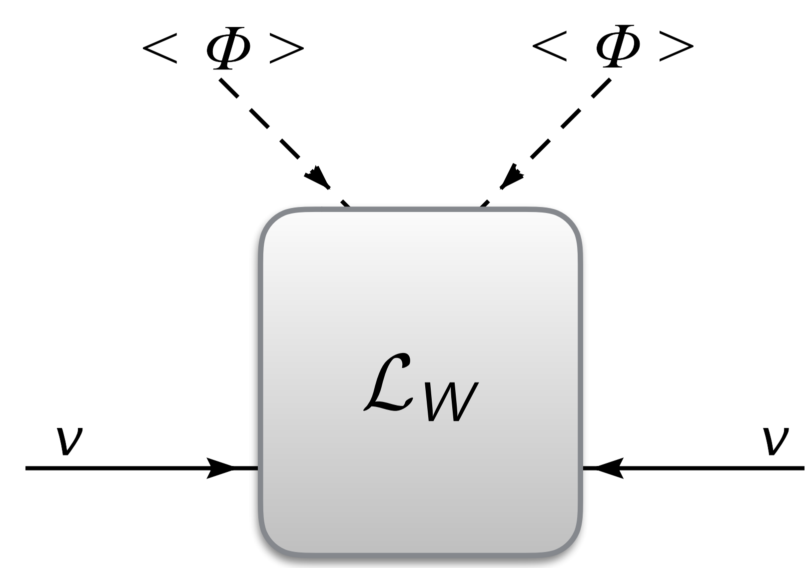

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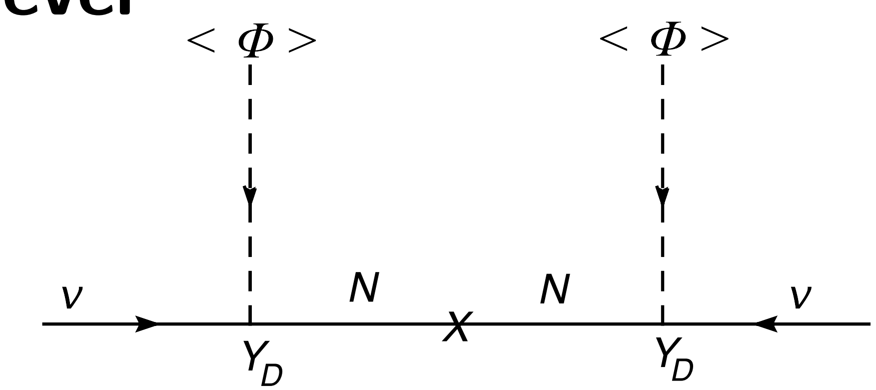

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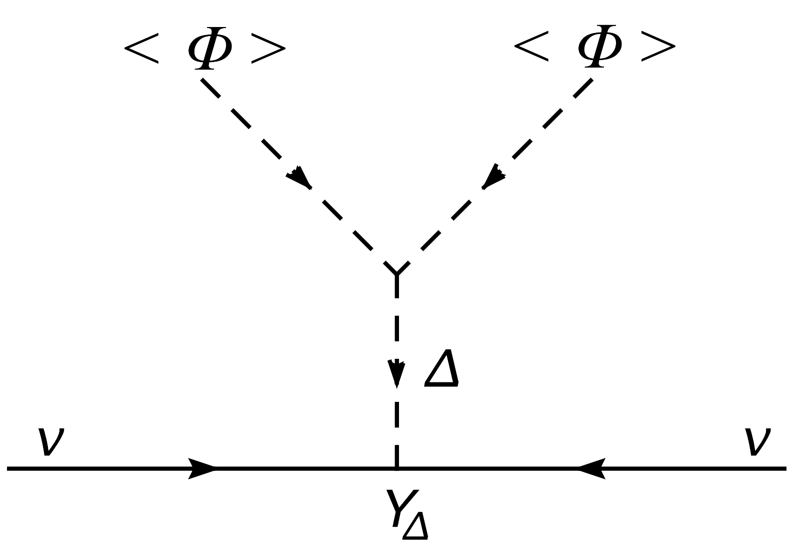

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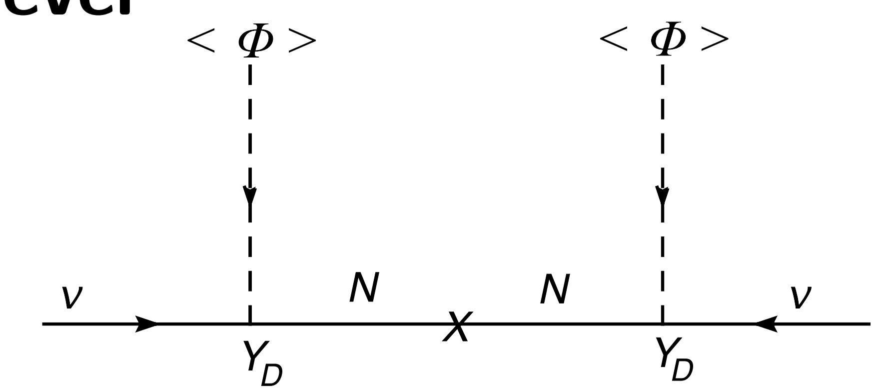

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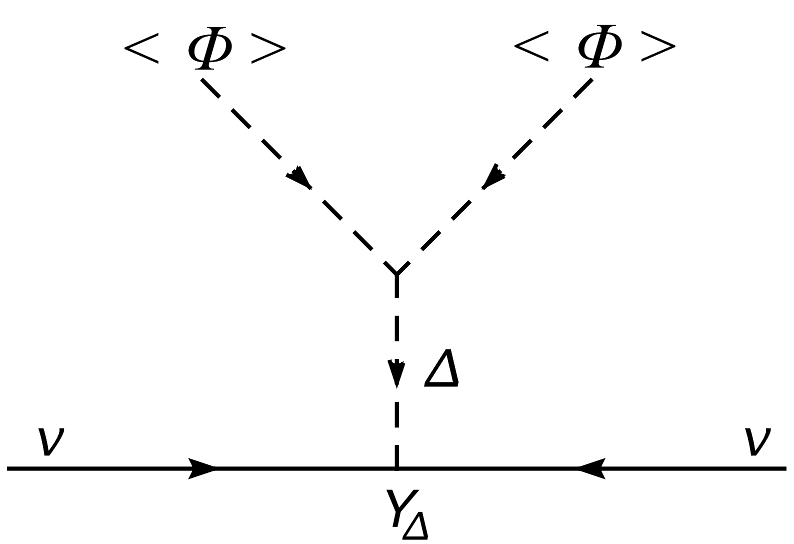
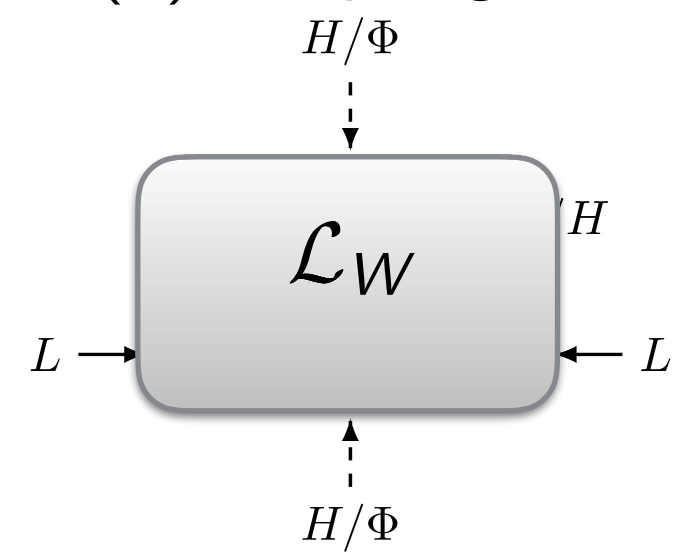


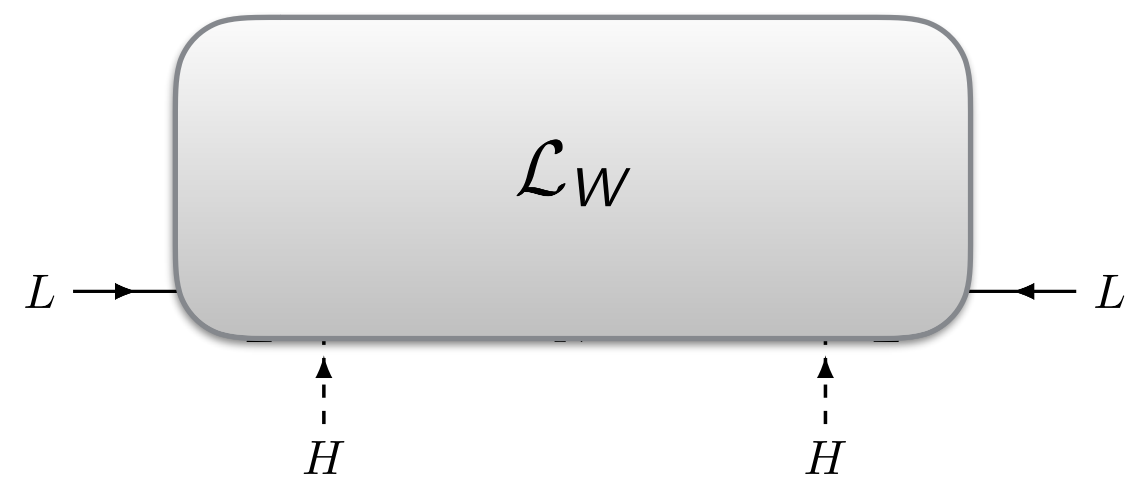
In all cases, small m_ν for Y~O(1) require large, out of reach, m_{new}

Neutrino Mass Models : radiative = loop(s) inside Weinberg

review: Cai'1706.08524

Loop(s) allow to lower the new physics scale for O(1) couplings:





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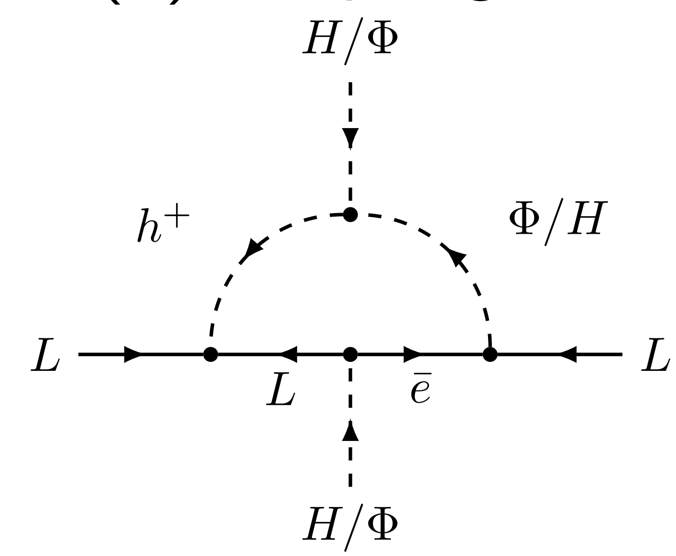
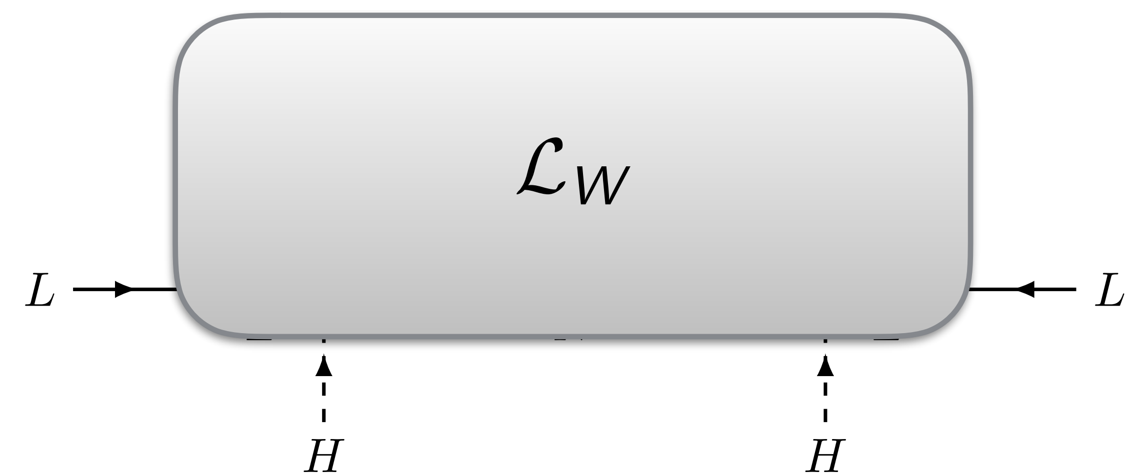
Zee'80: 1 loop

- 2 new scalars: singlet h^+ and doublet Φ





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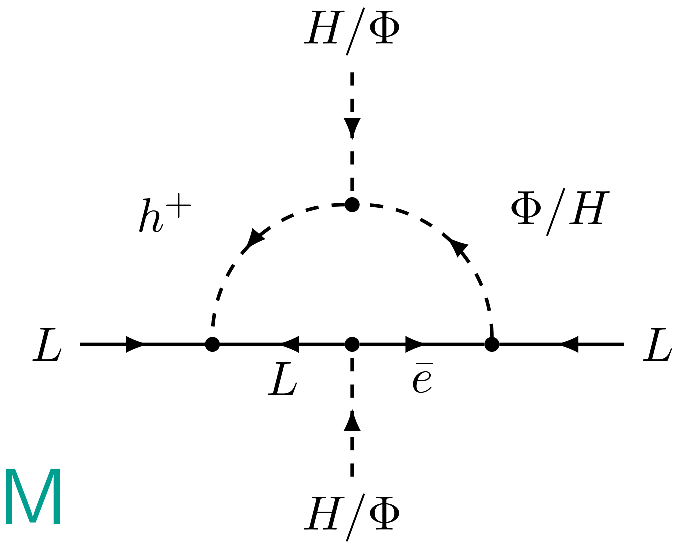
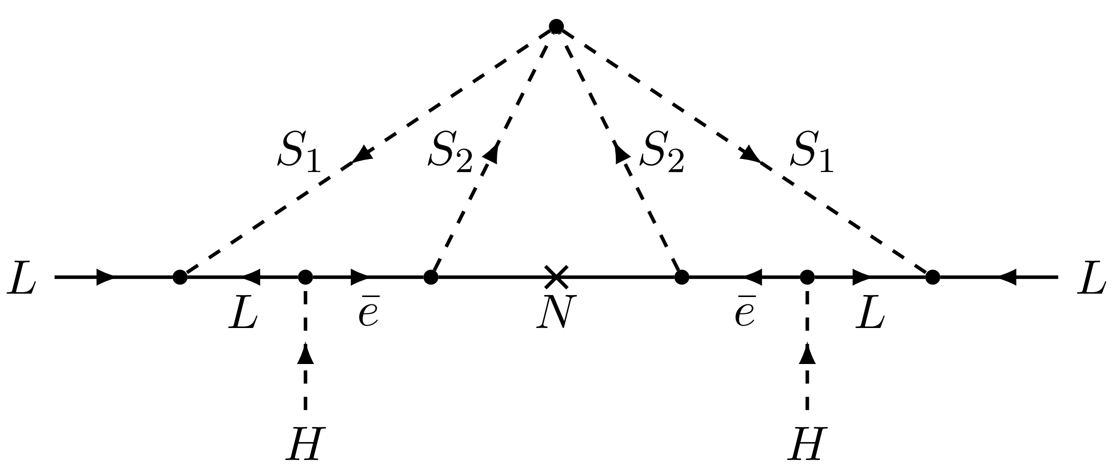


Krauss,Nasri,Trodden(KNT)'03: 3 loops with DM

- S_1, S_2: 2 charged, SU_2 singlet, scalars



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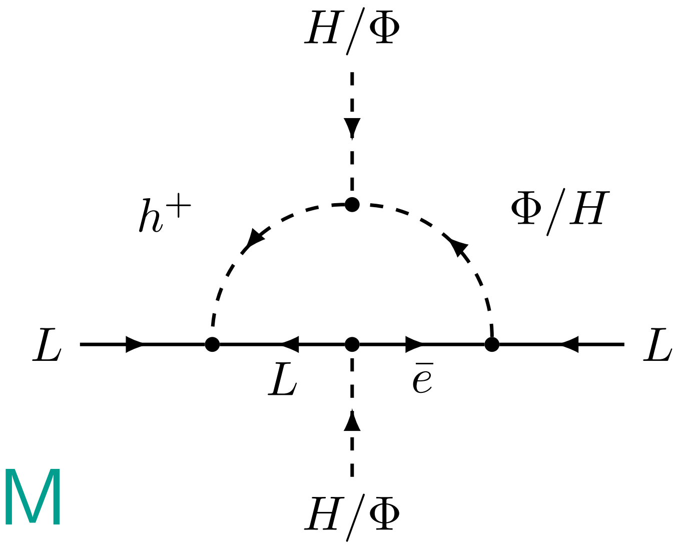

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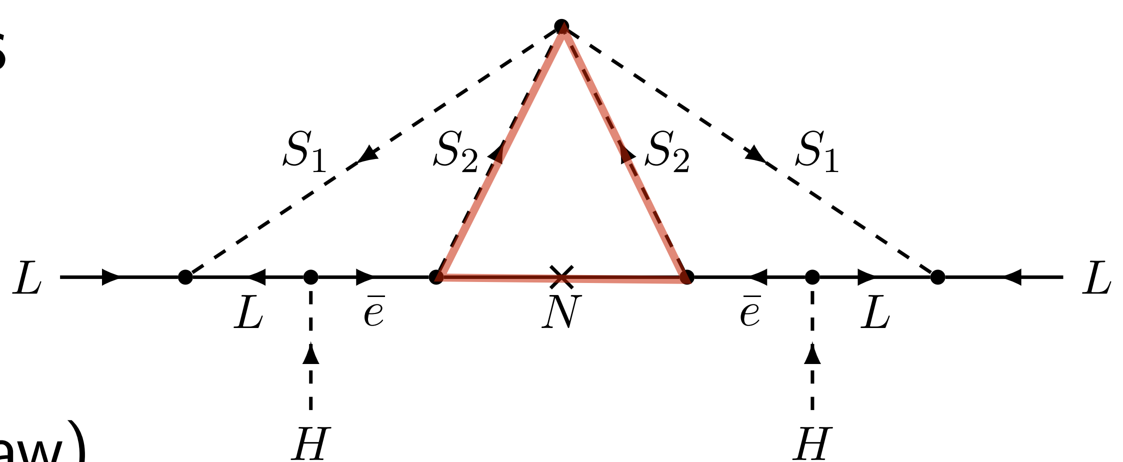

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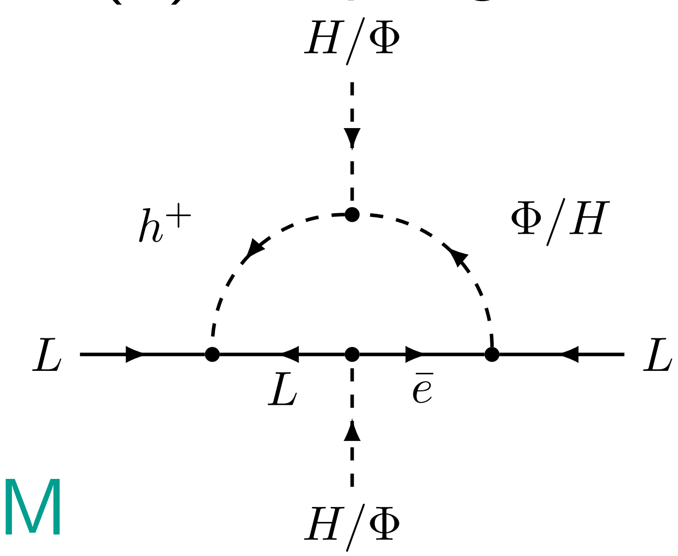

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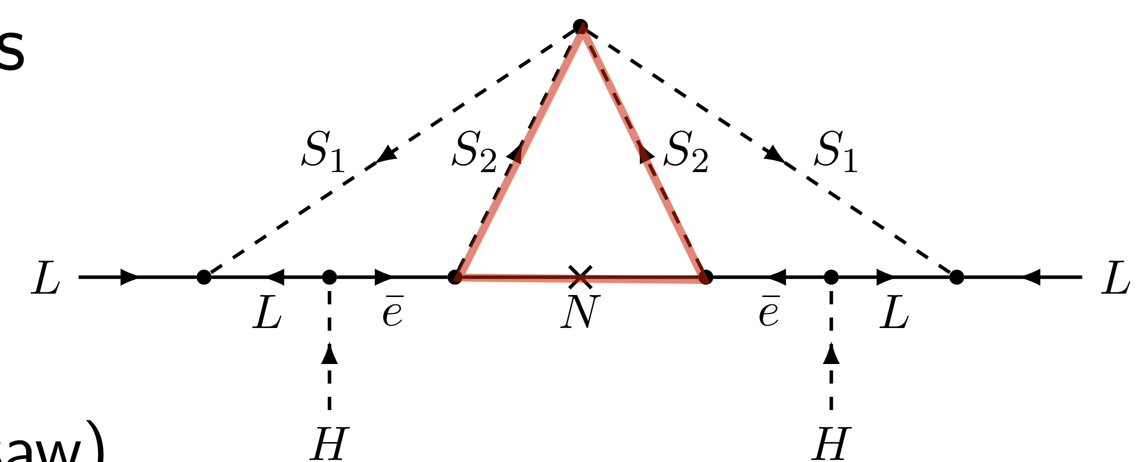

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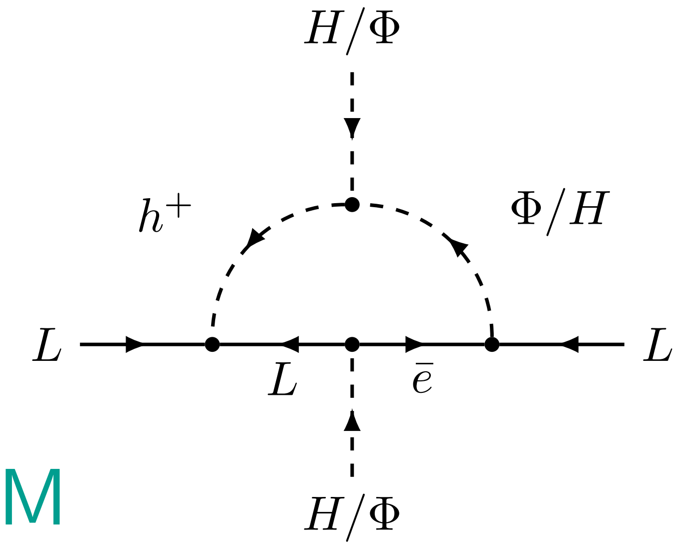

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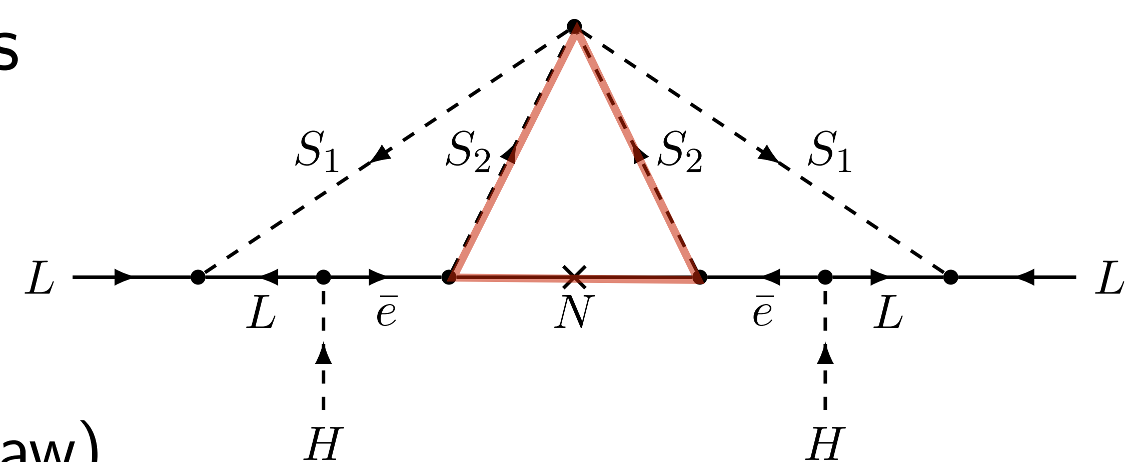


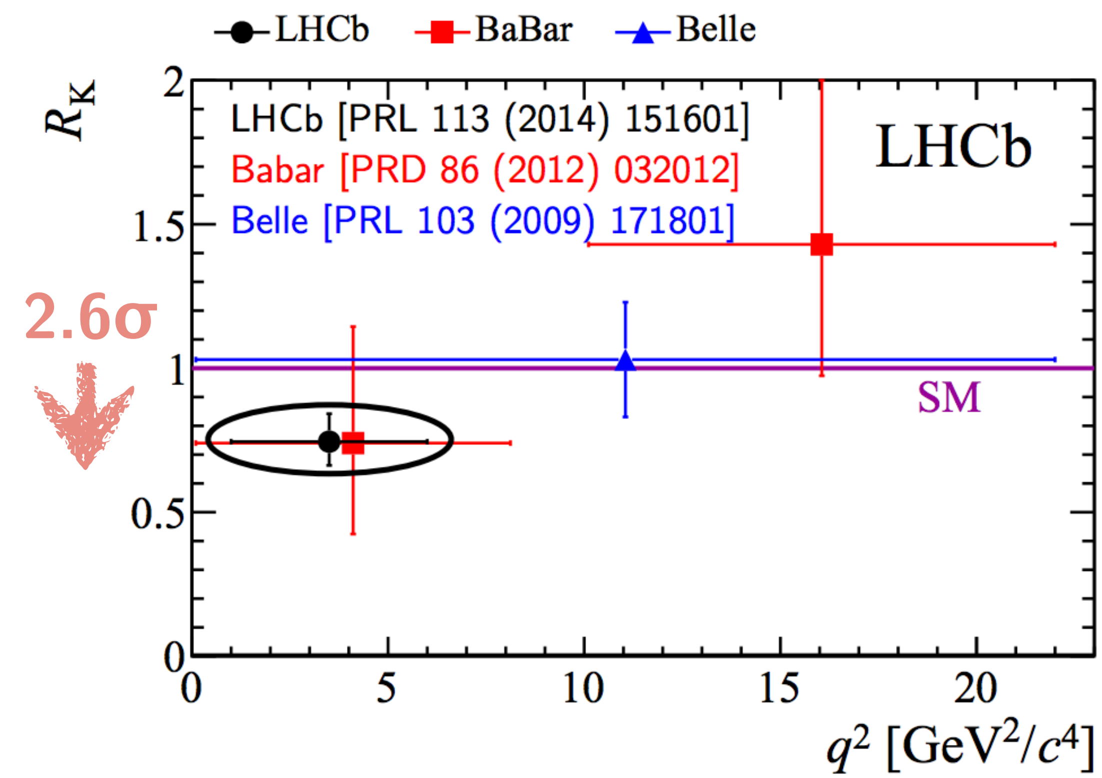
- Allows an interesting link between neutrino mass, and DM
- Somewhat artificial: why S1, S2? Why no seesaw?

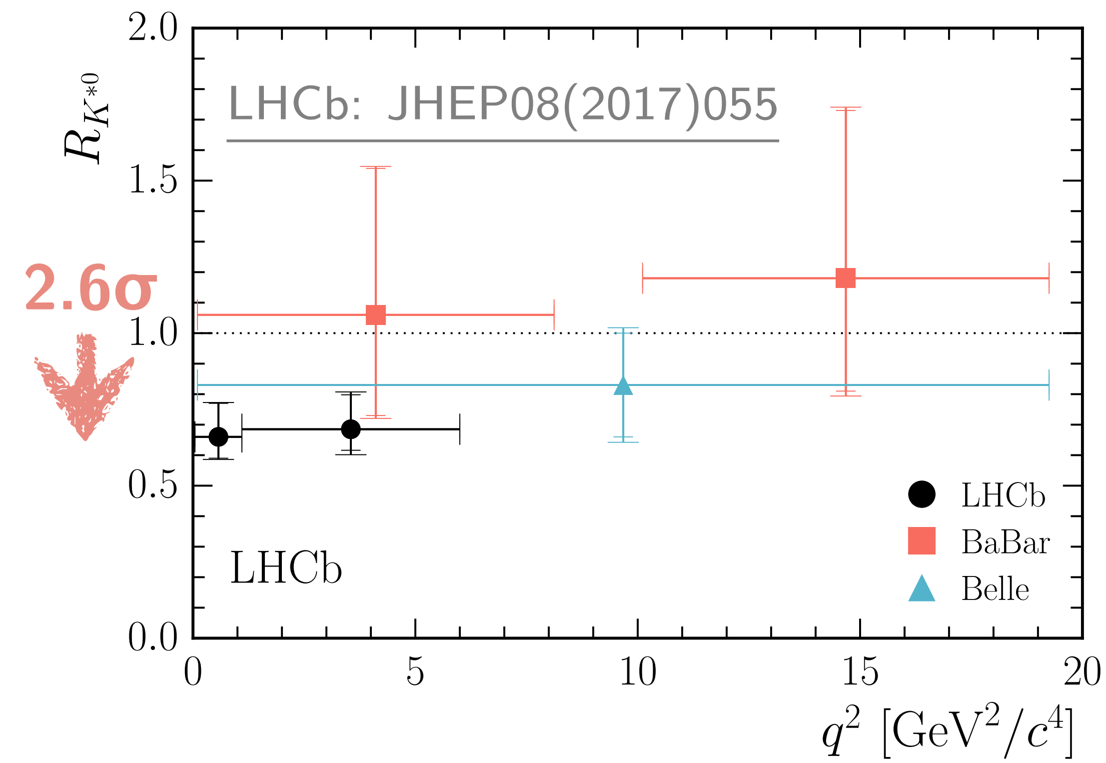
Beyond the Standard Model: hints at LFUV?

~2.5σ deviations from the SM Lepton Flavour Universality in B meson decays **New physics ?**

$$R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)}$$

$$R^{\mathrm{exp}}_{K^{(*)}} < R^{\mathrm{SM}}_{K^{(*)}}$$





« Too few muons » ?

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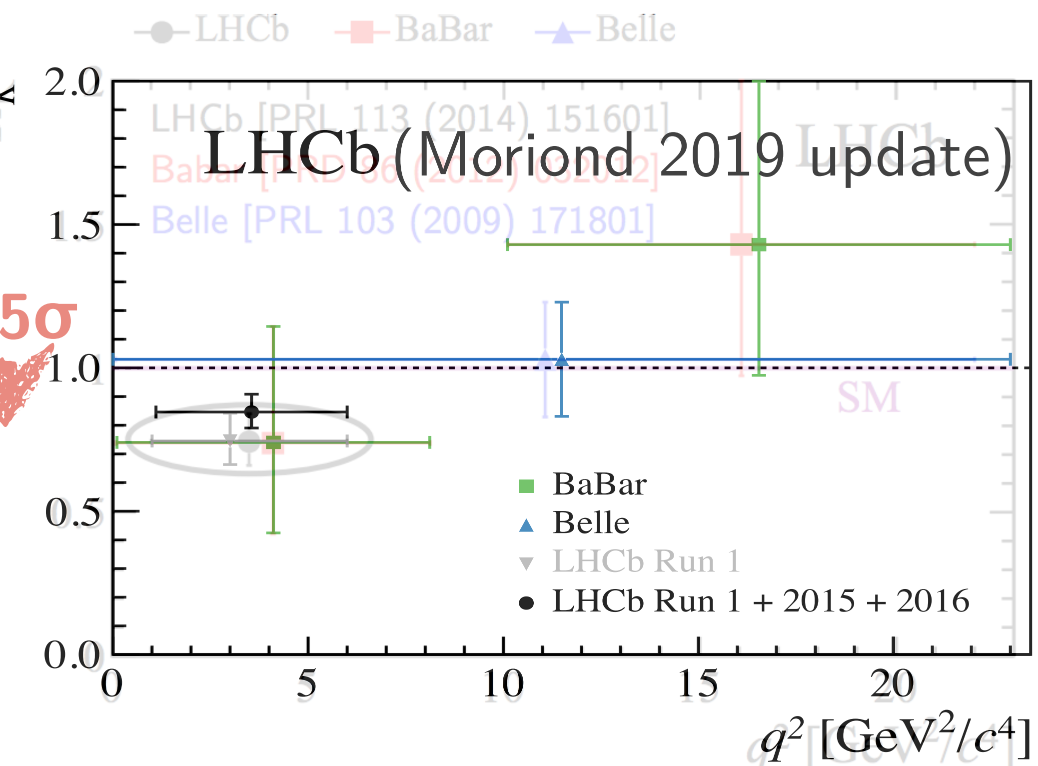
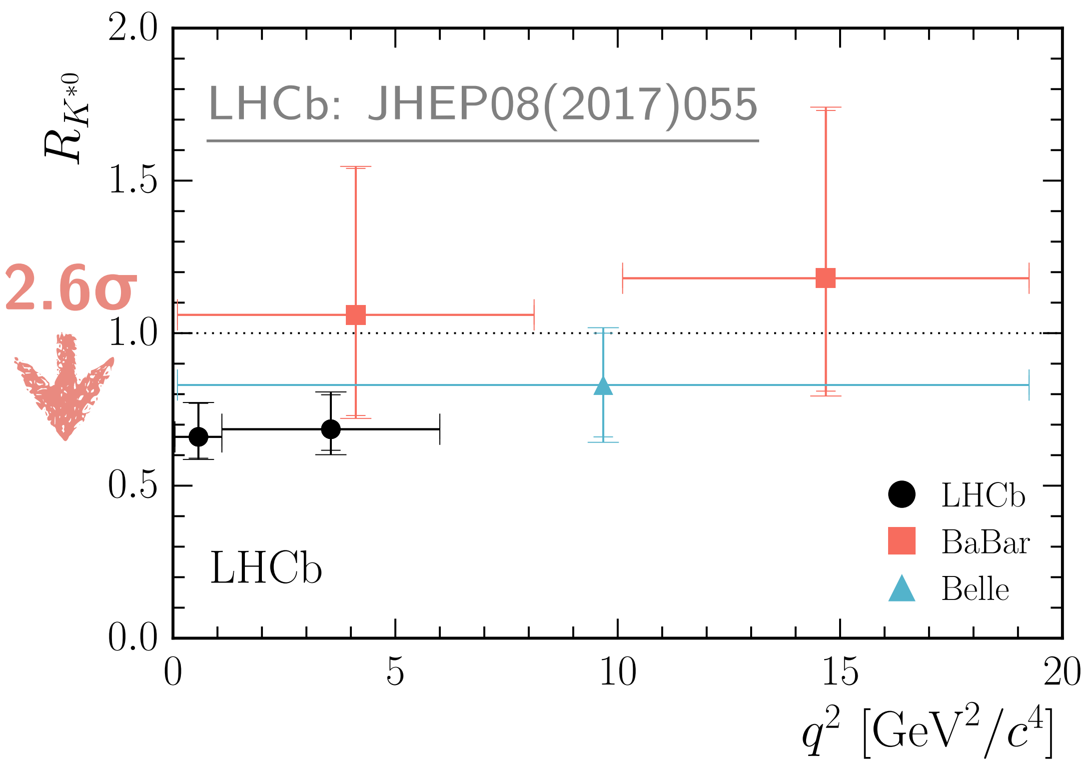
2.5σ



2.6σ



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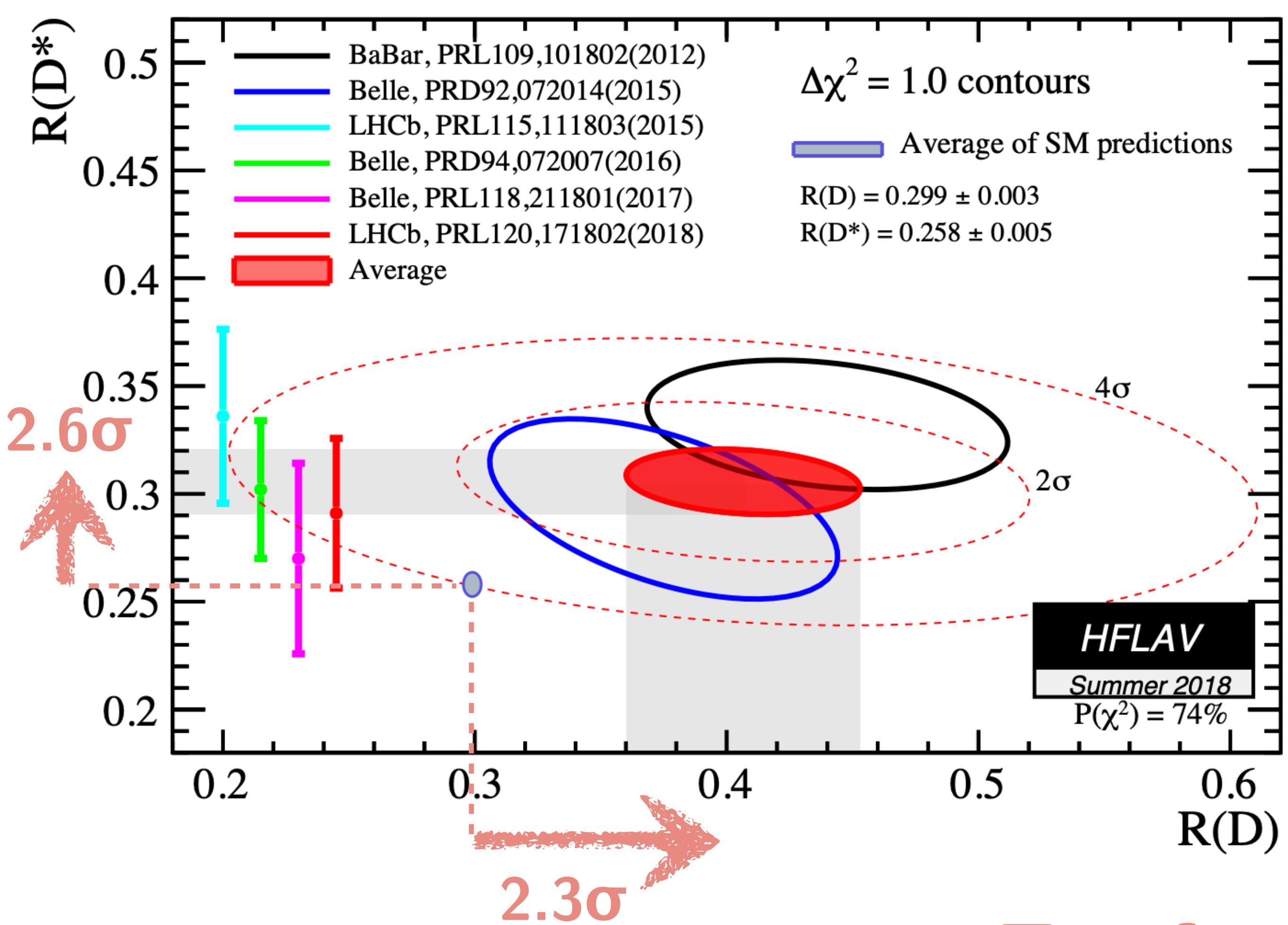
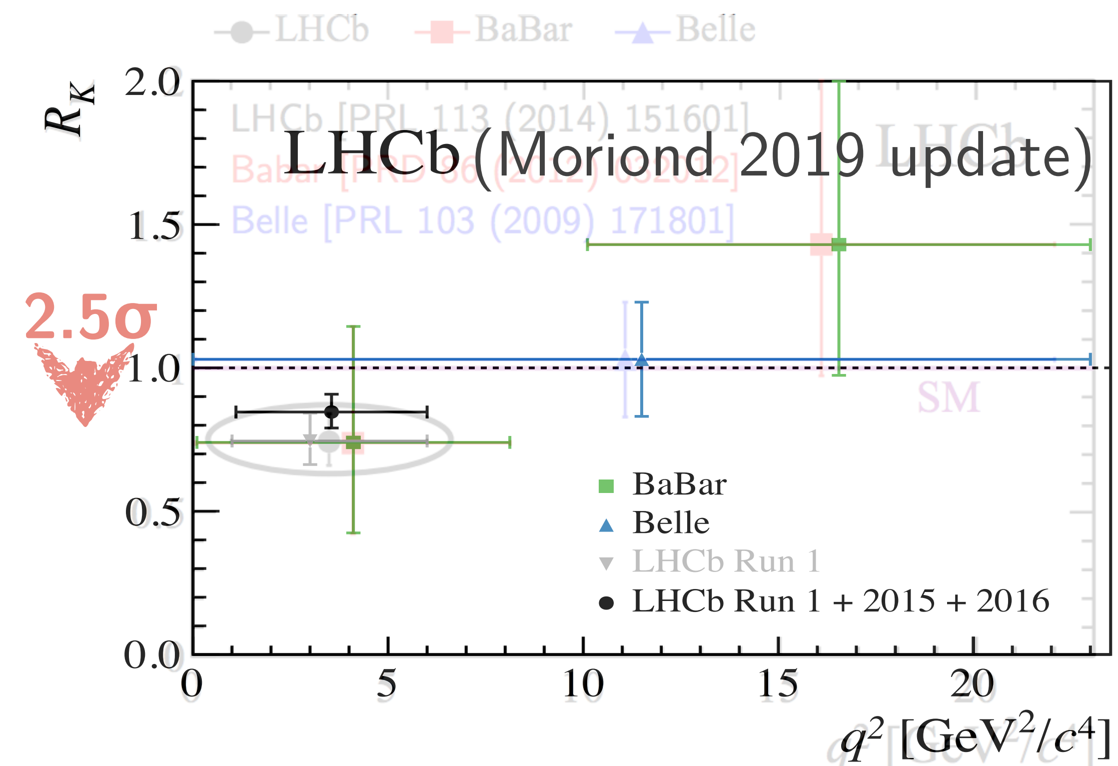
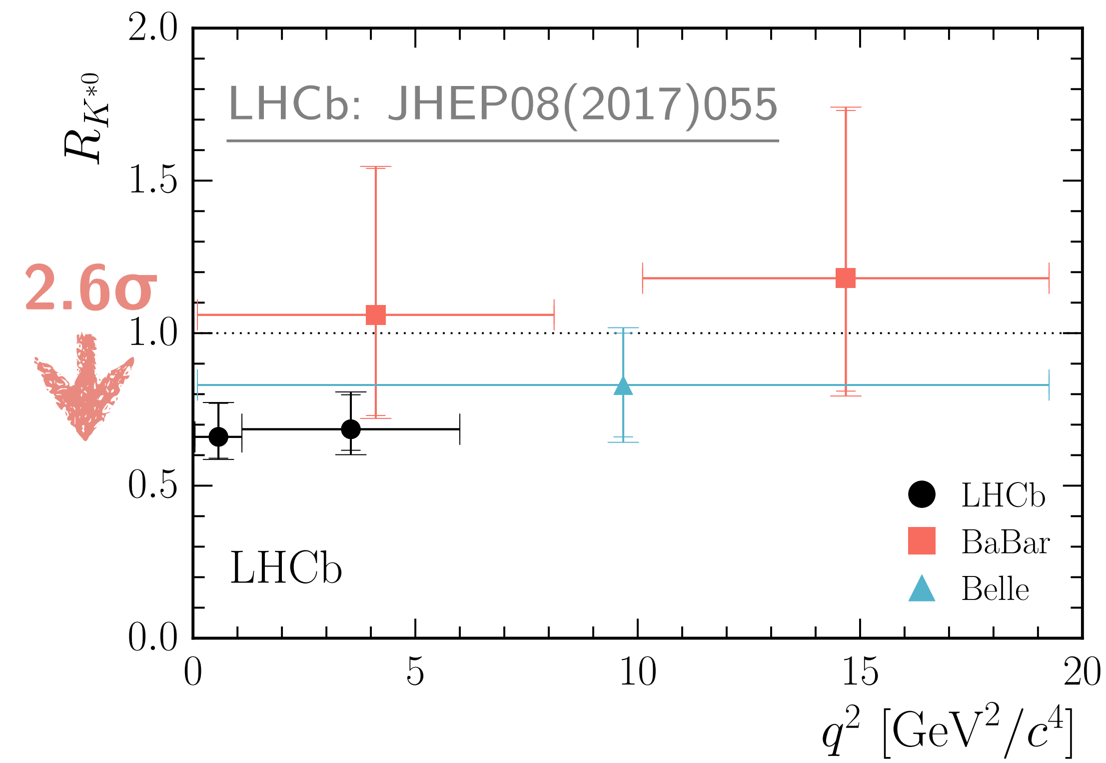






« Too few muons » ?

Phenomenological bottom-up approach to LFUV

Simplest working solutions for LFUV anomalies :
Scalar **leptoquark** triplet: (3, 3, 1/3); Vector leptoquark singlet: (3, 1, 2/3); ...

SM+ Scalar LQ triplet + ??

Motivation

- R_K and R_{K^*}
- (R_D and R_{D^*})
- Neutrino masses & oscillation data
- Dark matter
- Unification?
- Baryogenesis?

Constraints/Predictions

- $P \to P'\nu\bar{\nu}$, $P \to V\nu\bar{\nu}$
- $P \to \ell^- \ell'^+$
- Neutral meson mixings
- $\ell \to \ell'\gamma$
- $\ell \to \ell'\ell'\ell'$
- μ–e conversion
- Collider
- EDM?

Our model: SM + 2 Scalar LQ + Triplet Majorana fermions

	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Z_2
Fermions (3 gen.)	$Q_L \equiv (u,d)_L^T$	$(\mathbf{3},\mathbf{2},\ 1/6)$	1
	u_R	$(\mathbf{3},\mathbf{1},\ 2/3)$	1
	d_R	$(\mathbf{3},\mathbf{1},\ -1/3)$	1
	$\ell_L \equiv (\nu,\ e)_L^T$	$(\mathbf{1},\mathbf{2},\ -1/2)$	1
	e_R	$(\mathbf{1},\mathbf{1},\ -1)$	1
	Σ_R	$(\mathbf{1},\mathbf{3},\ 0)$	-1
Scalars	H	$(\mathbf{1},\mathbf{2},\ 1/2)$	1
	h_1	$(\mathbf{3},\mathbf{3},\ -1/3)$	1
	h_2	$(\mathbf{3},\mathbf{3},\ -1/3)$	-1

A rôle for each BSM field:
→ contains DM candidate
→ controls B-anomalies
→ allows KNT ν masses

Z_2 symmetry makes lightest Σ_R stable, and forbids type III seesaw

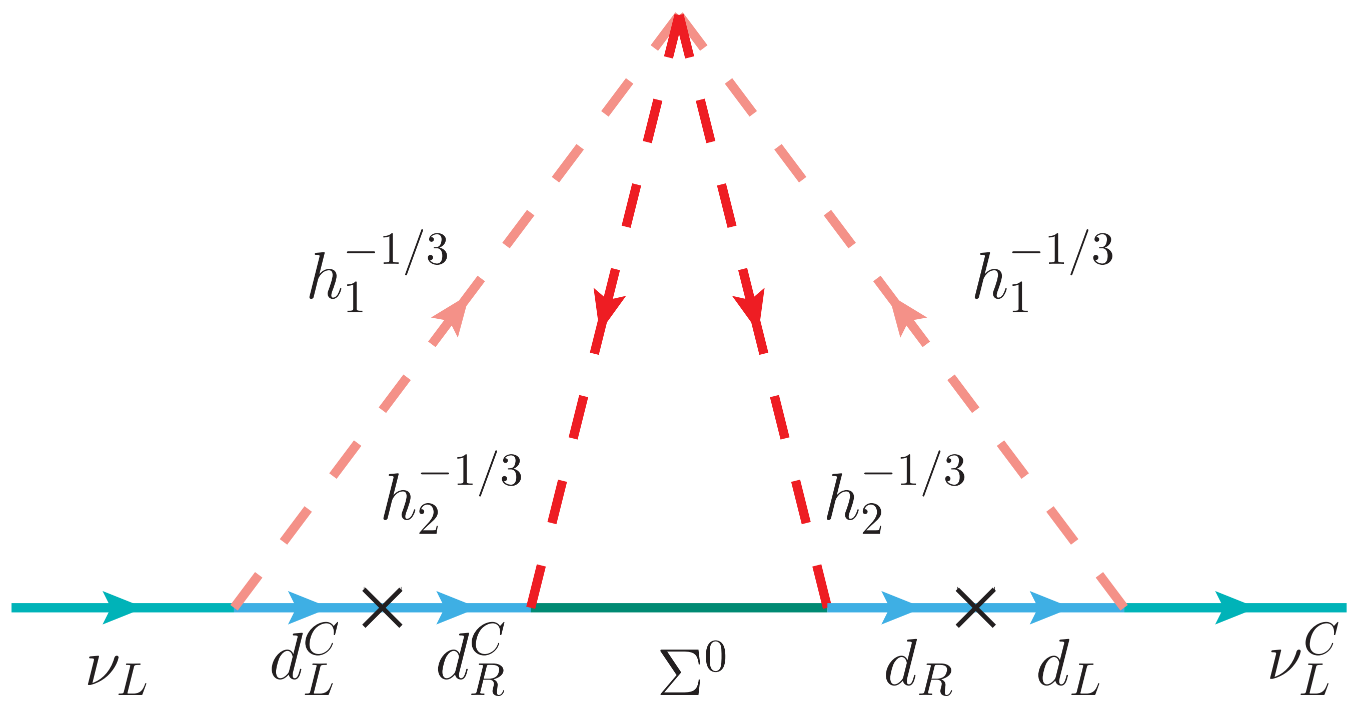
→ ν masses « feel » B anomalies

Couplings:

ignored (not needed)

$$\mathcal{L} \supset +y_{ij}\bar{Q}_L^{C\,i}\epsilon(\vec{\tau}.\vec{h}_1)L_L^j + z_{ij}\bar{Q}_L^{C\,i}\epsilon(\vec{\tau}.\vec{h}_1)^\dagger Q_L^j + \tilde{y}_{ij}\overline{(\vec{\tau}.\vec{\Sigma})_R}^{C\,i,ab}[\epsilon(\vec{\tau}.\vec{h}_2)\epsilon^T]^{ba}d_R^j$$
$$-\frac{1}{2}\overline{\Sigma^C}^i M_{ij}^\Sigma \Sigma^j + \text{h.c.} - V(H,h_1,h_2) \supset \lambda_h(h_1.h_2)^2$$

Radiative neutrino masses and parametrisation



$$m_\nu^{\rm diag} = U^T\, y^T\, m_d\, \tilde{y}^T\, F(\lambda_h, m_\Sigma, m_{h_{1,2}})\, \tilde{y}\, m_d\, y\, U$$

A parameterisation à la Casas-Ibarra

$$(\sqrt{m_\nu^{diag}}^{-1} U^T\, y^T\, m_d\, \tilde{y}^T \sqrt{F}\,)(\sqrt{F}\,\tilde{y}\, m_d\, y\, U\, \sqrt{m_\nu^{diag}}^{-1}) = \mathbb{1} = \mathcal{R}^T\mathcal{R},$$

$$\boxed{\tilde{y} = F^{-1/2}\mathcal{R}\,\sqrt{m_\nu^{diag}}\, U^\dagger y^{-1} m_d^{-1}}$$

$\mathcal{R}$ is a complex orthogonal matrix determining $\tilde{y}$

Using this parametrisation allows to fit oscillation data...

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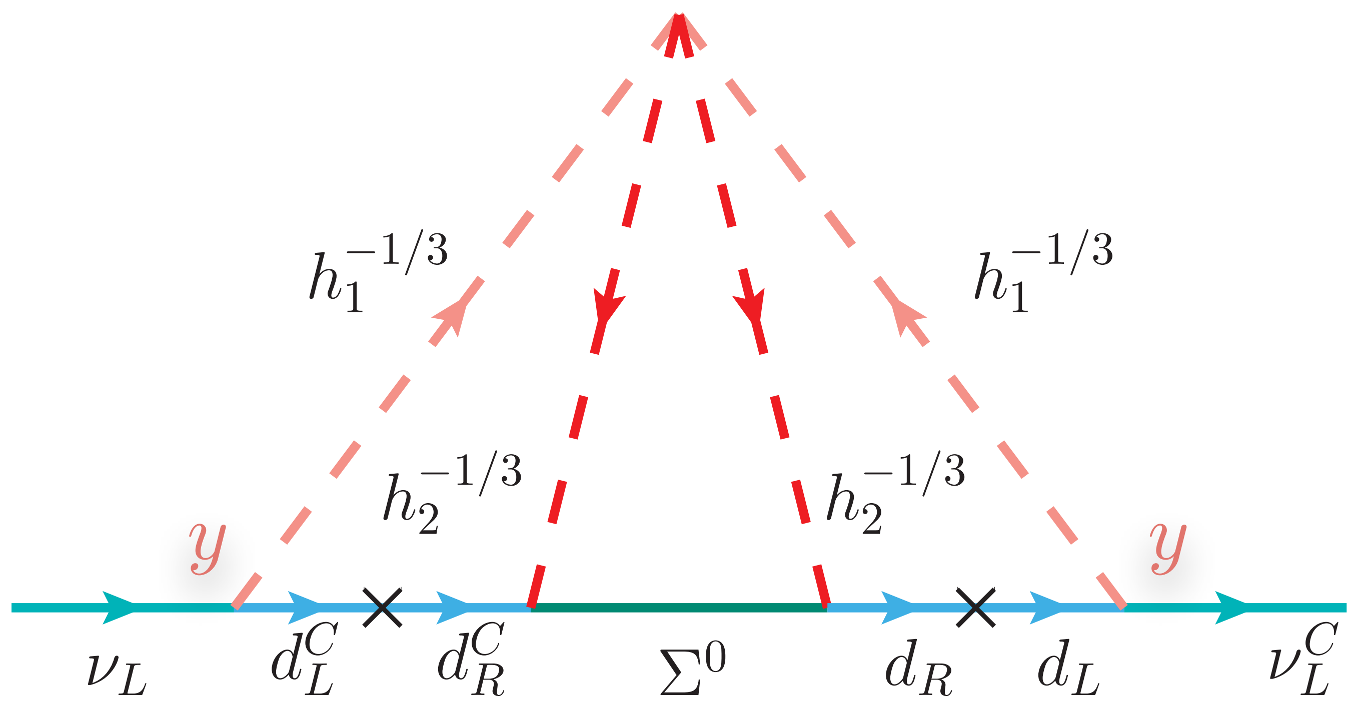

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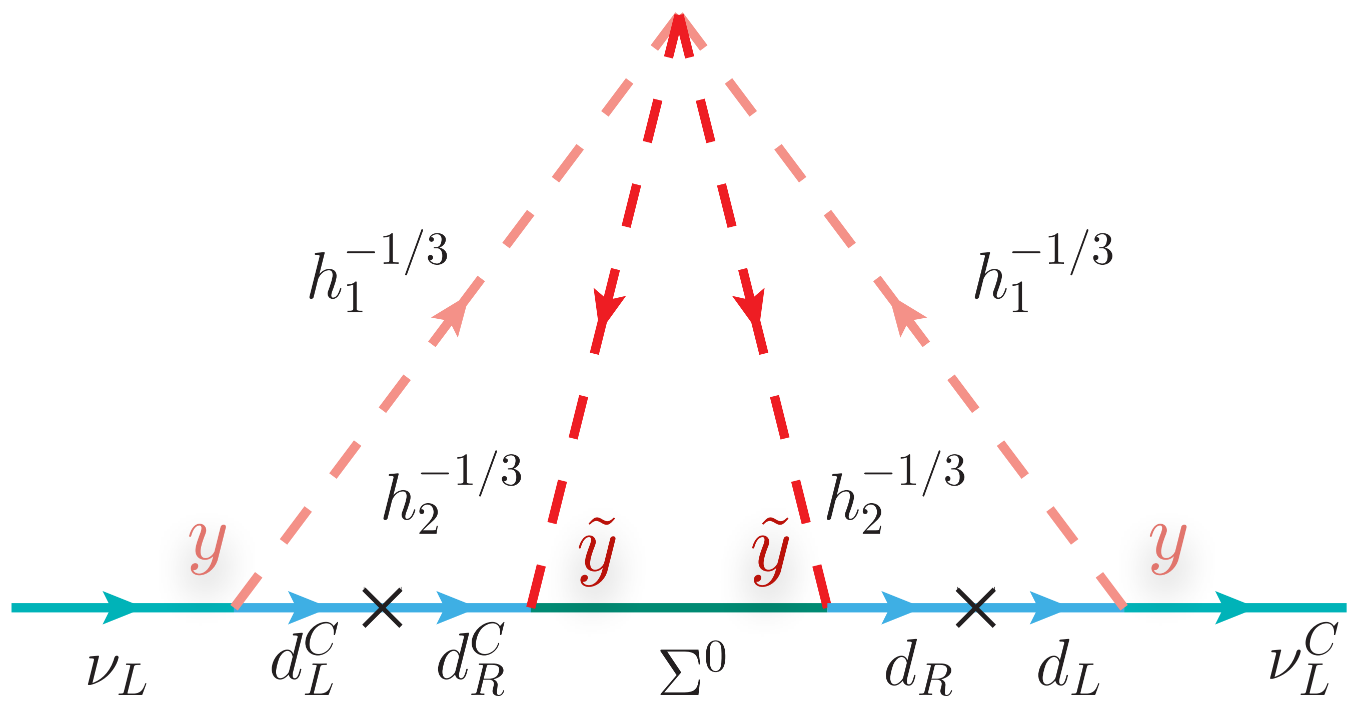

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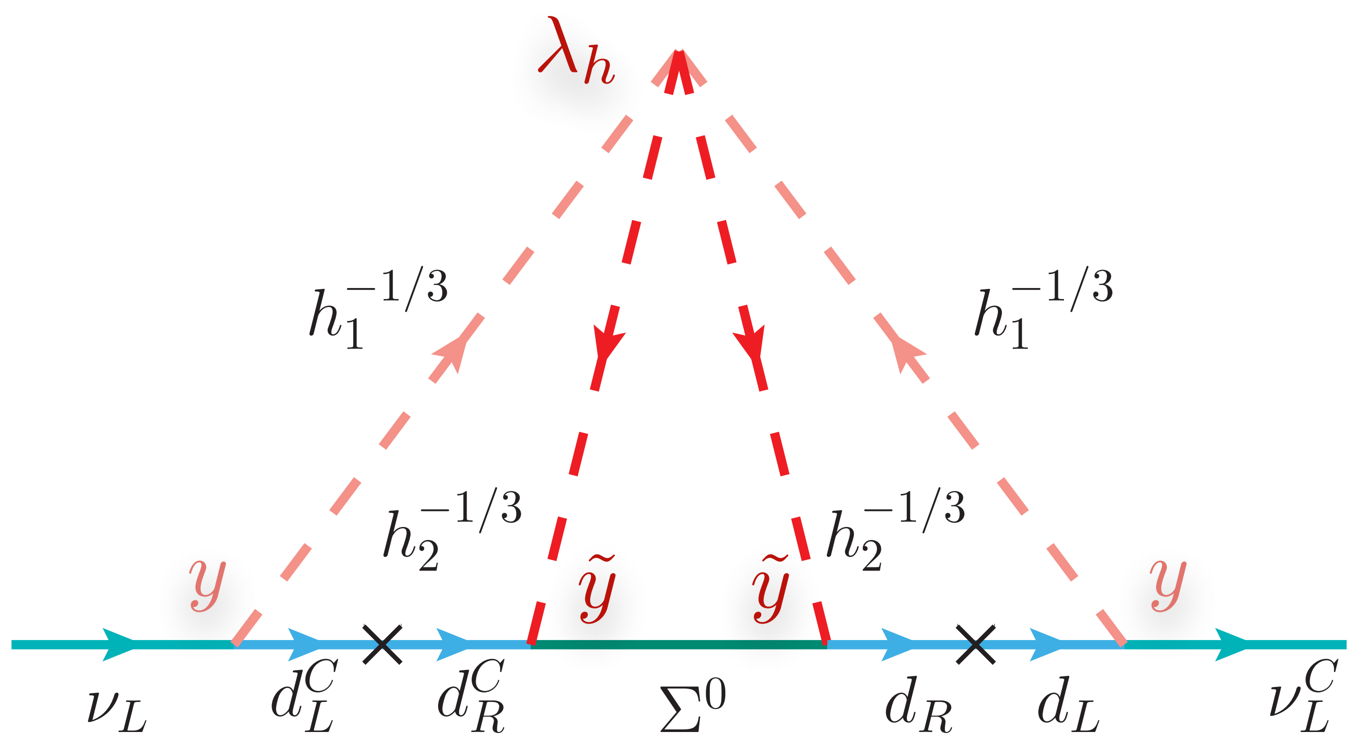

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$$\boxed{\tilde{y} = F^{-1/2} \mathcal{R} \sqrt{m_\nu^{diag}}\, U^\dagger y^{-1} m_d^{-1}}$$

$\mathcal{R}$ is a complex orthogonal matrix determining $\tilde{y}$

Using this parametrisation allows to fit oscillation data...

A viable dark matter candidate

Electroweak radiative corrections: m($\Sigma\pm$) − m($\Sigma 0$) ~ 166 MeV   Cirelli, Fornengo, Strumia'06

Z2 symmetry => Σ_R is odd =>

Σ^0 (the lightest "exotic" stable state) = dark matter candidate

Σ_R co-annihilate via gauge interactions

s-channel

$$\Sigma^0\Sigma^\pm \to W^\pm \to W^\pm W^0, W^\pm H, \bar{f}f\prime$$

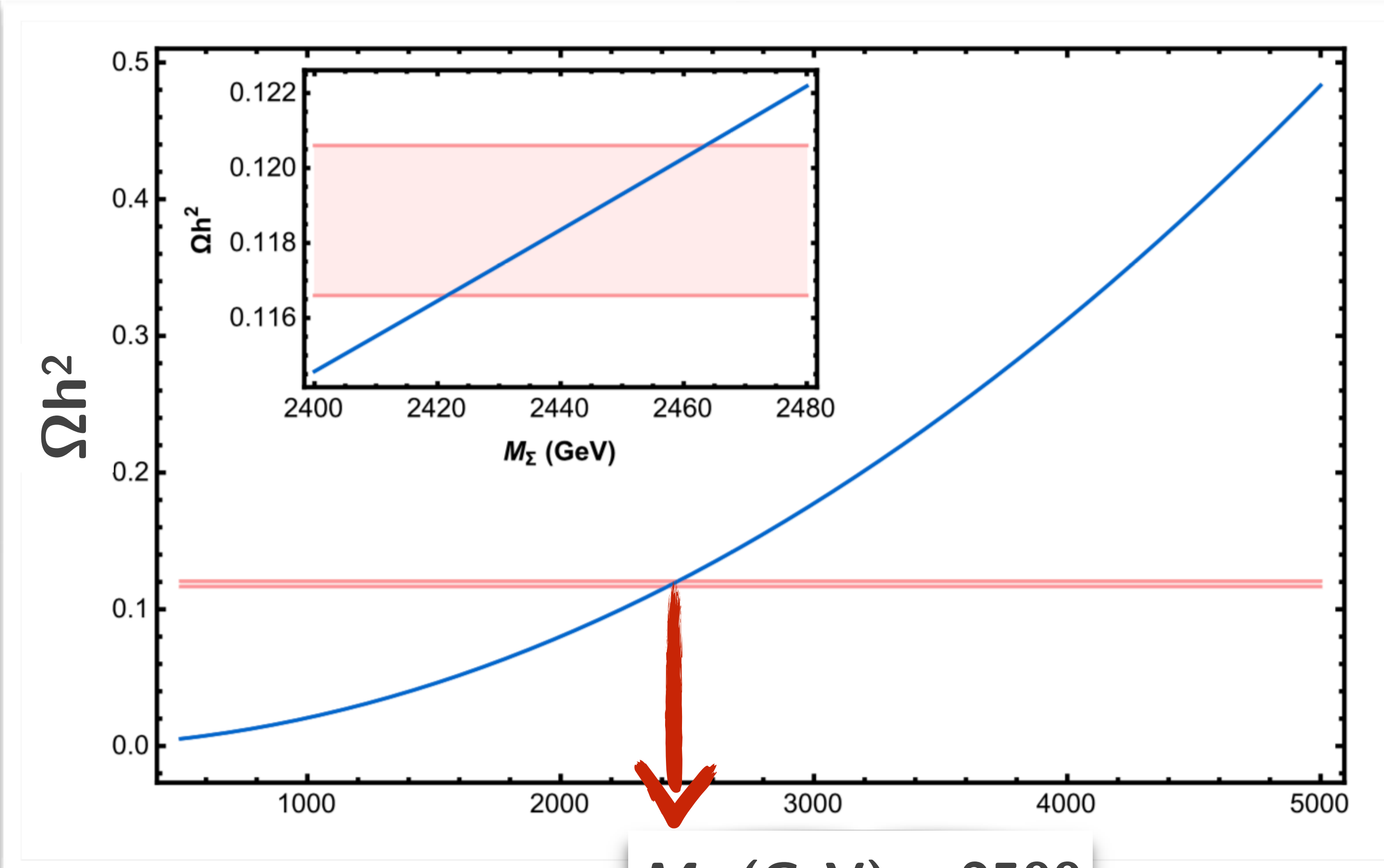
$$\Sigma^+\Sigma^- \to W^0 \to W^+W^-, W^0H, \bar{f}f$$

t-channel

$$\Sigma^0\Sigma^0 \to W^+W^- \qquad \Sigma^0\Sigma^\pm \to W^\pm W^0$$

$$\Sigma^+\Sigma^- \to W^0W^0(W^+W^-)$$

$$\Sigma^\pm\Sigma^\pm \to W^\pm W^\pm$$



M_Σ (GeV) ~ 2500

Neutral current anomalies: R_K and R_{K^*}

$$\mathcal{H}_{\rm eff} \supset -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=7,8,9,10,P,S,\dots} \left(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \right)$$

Relevant operators for: $b \to s\ell^-\ell'^+$

$$\mathcal{O}_9^{\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell') \,,$$

$$\mathcal{O}_{10}^{\ell\ell'} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell')$$

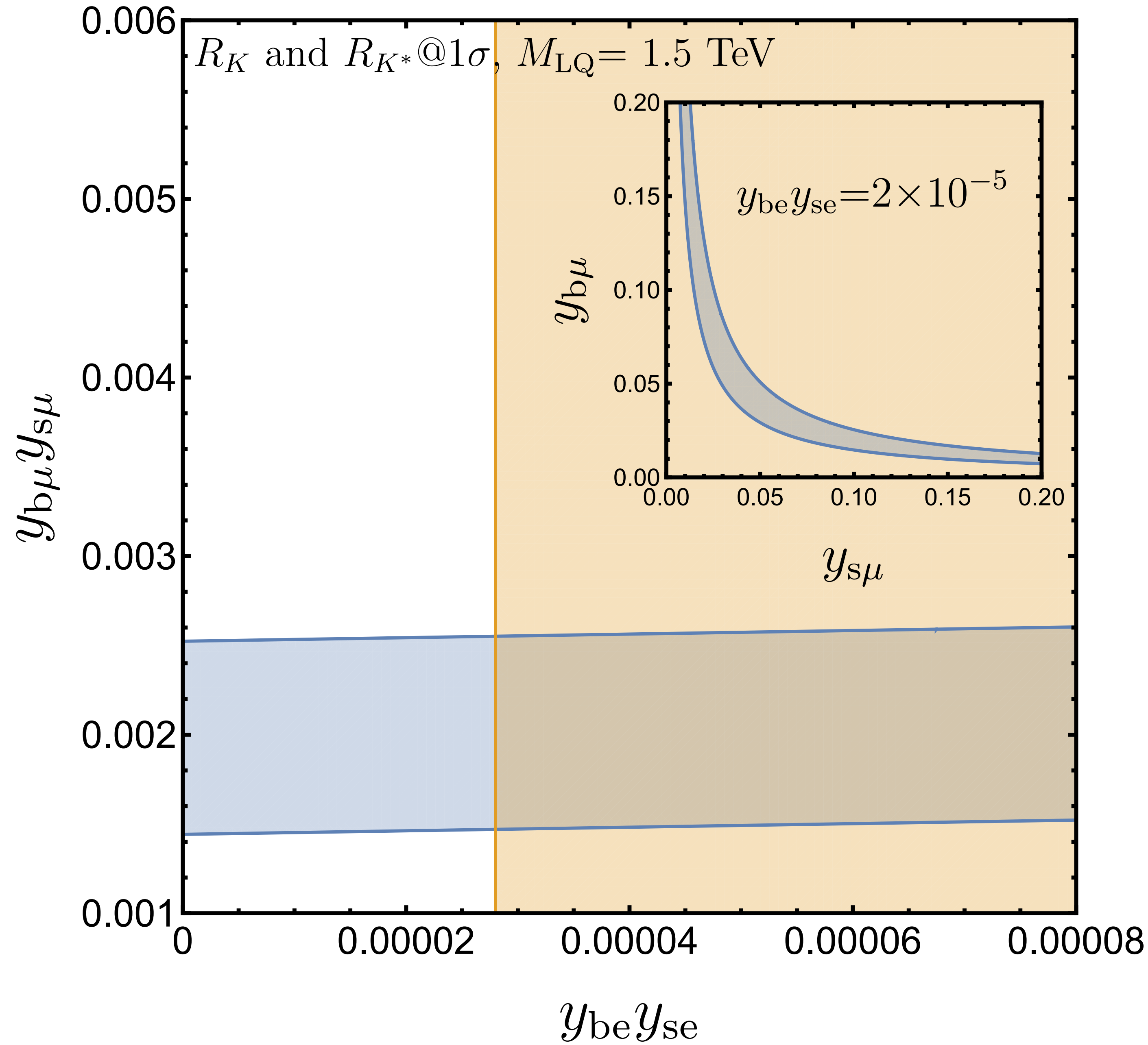
Taking $C_9^{\ell\ell'} = -C_{10}^{\ell\ell'}$

the 1σ best fit to R_K and R_{K^*} data

$$-1.4 \lesssim 2\,\mathrm{Re}[C_{9,\rm NP}^{\mu\mu} - C_{9,\rm NP}^{ee}] \lesssim -0.8$$

see e.g. Hiller, Nisandzic 2017, Capdevila et al. 2018
Hurth et al. 2016, Bečirević et al. 2015, ...

$$C_9^{\ell\ell'} = -C_{10}^{\ell\ell'} = \frac{\pi v^2}{\alpha_e V_{tb} V_{ts}^*} \frac{y_{b\ell'} y_{s\ell}^*}{m_{h_1}^2}$$



Charged current anomalies: R_D and R_{D*}

$$\mathcal{H}_{\rm eff}(d_k \to u_j \ell \bar{\nu}_i) = \frac{4G_F}{\sqrt{2}} V_{cb} \left[U_{\ell i} - \frac{v^2}{4V_{cb}\, m_{h_1}^2} (yU)_{ki} (Vy^*)_{j\ell} \right] (\bar{u}_j \gamma^\mu P_L d_k)(\bar{\ell}\gamma_\mu P_L \nu_i)$$

Using $\quad x_{j\ell} = \left(v^2/4V_{cb} m_{h_1}^2\right)(Vy^*)_{j\ell}$

$$\frac{R_D}{R_{D,\rm SM}} = \frac{R_{D^*}}{R_{D^*,\rm SM}} = \frac{1 - 2\,{\rm Re}\,(x_{c\tau}\, y_{b\tau})}{1 - 2\,{\rm Re}\,(x_{c\mu}\, y_{b\mu})}$$

~ **SM like** after taking into account the constraints from flavour changing process

$$R^{\mu/e}_{D^{(*)}} = \frac{1 - 2\,{\rm Re}\,(x_{c\mu}\, y_{b\mu})}{1 - 2\,{\rm Re}\,(x_{ce}\, y_{be})}$$

Belle Collaboration:

$$R_D^{\mu/e,\,\rm exp} = 0.995 \pm 0.022 \pm 0.039$$

$$R_{D^*}^{e/\mu,\,\rm exp} = 1.04 \pm 0.05 \pm 0.01$$

If this signal is confirmed, this minimal model needs to be extended!

Eg: include additional leptoquark $R_2 = (3, 2, 7/6)$ / $S_1 = (3, 1, 1/3)$?

See for example: Becirevic et al. 18
Crivellin et al. 17

Details: flavour structure of scalar triplet LQ

How to implement a flavour structure for y ?

$$y \sim \begin{pmatrix} \epsilon^{n_{11}} & \epsilon^{n_{12}} & \epsilon^{n_{13}} \\ \epsilon^{n_{21}} & \epsilon^{n_{22}} & \epsilon^{n_{23}} \\ \epsilon^{n_{31}} & \epsilon^{n_{32}} & \epsilon^{n_{33}} \end{pmatrix}$$

Hierarchy parameter ϵ inspired by Froggatt-Nielsen/flavour symmetry/...

To select a benchmark ϵ , we parametrise $R_{K(*)}$ data best fit value as ($\mathbf{m_{h_1}} \sim$ 1.5 TeV)

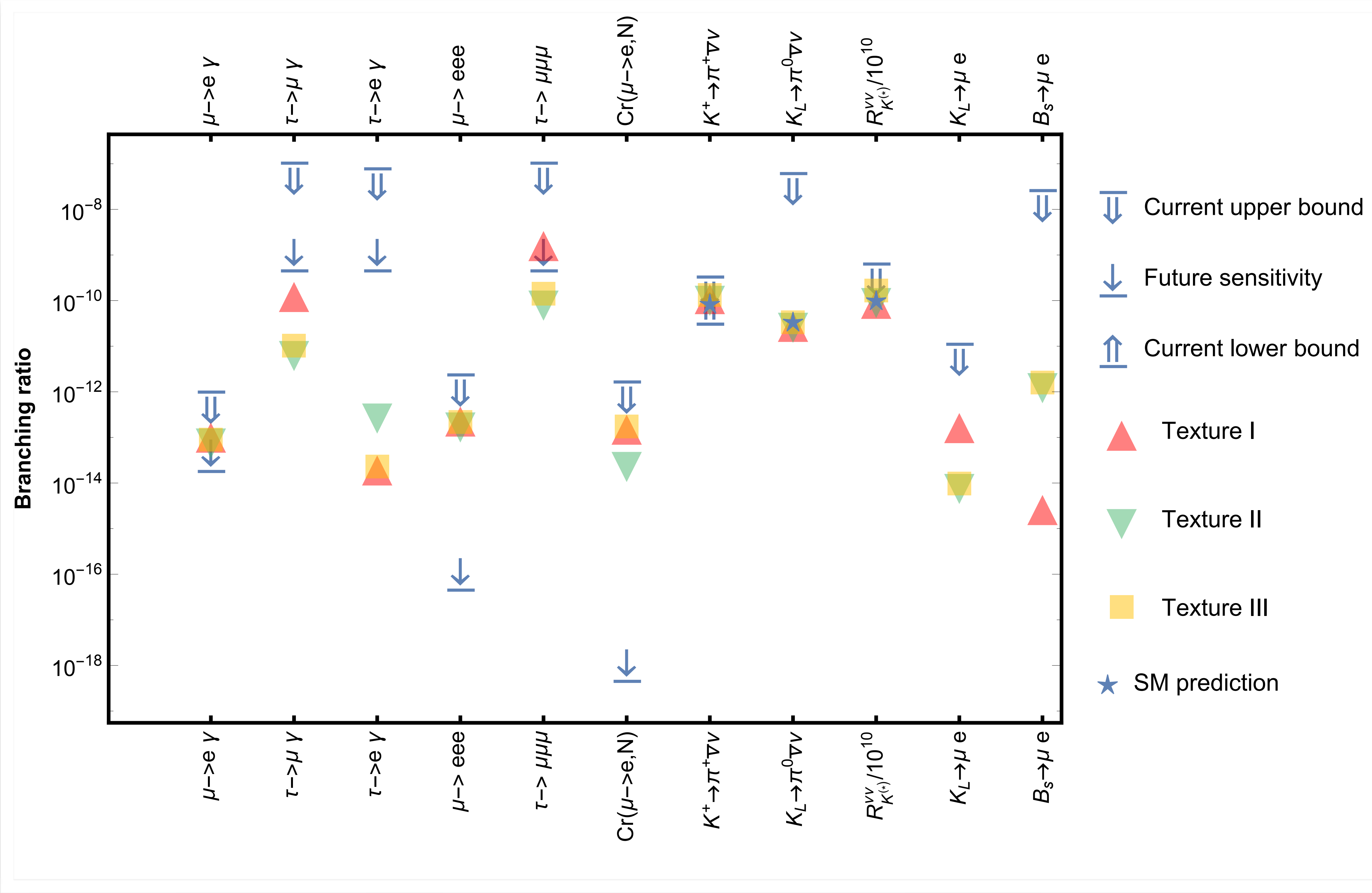
$$\epsilon^4 \sim y_{22}y_{32} \sim 2.1555 \times 10^{-3} \quad \boxed{n_{22} + n_{32} = 4} \quad \Rightarrow \epsilon \sim 0.215 \sim \sin\theta_C \simeq 0.22\,!$$

Textures consistent with all the constraints from flavour violation:

	Texture type I	Texture type II	Texture type III
CR($\mu - e$,N), $K \to \pi\nu\bar{\nu}$ amongst the most stringent constraints	$\begin{pmatrix} \times & \times & \times \\ \times & \epsilon^3 & \times \\ \times & \epsilon & \times \end{pmatrix}$	$\begin{pmatrix} \times & \times & \times \\ \times & \epsilon^2 & \times \\ \times & \epsilon^2 & \times \end{pmatrix}$	$\begin{pmatrix} \times & \times & \times \\ \times & \epsilon & \times \\ \times & \epsilon^3 & \times \end{pmatrix}$
Generic allowed Textures	$\begin{pmatrix} \epsilon^4 & \epsilon^{\geq 5} & \epsilon^{\geq 2} \\ \epsilon^{\geq 3} & \epsilon^3 & \epsilon^{\geq 4} \\ \epsilon^{\geq 4} & \epsilon & \epsilon^{\geq 1} \end{pmatrix}$	$\begin{pmatrix} \epsilon^6 & \epsilon^{\geq 4} & \epsilon^{\geq 3} \\ \epsilon^{\geq 5} & \epsilon^2 & \epsilon^{\geq 3} \\ \epsilon^{\geq 3} & \epsilon^2 & \epsilon^{\geq 1} \end{pmatrix}$	$\begin{pmatrix} \epsilon^5 & \epsilon^{\geq 5} & \epsilon^{\geq 4} \\ \epsilon^4 & \epsilon & \epsilon^{\geq 2} \\ \epsilon^{\geq 4} & \epsilon^3 & \epsilon^{\geq 1} \end{pmatrix}$

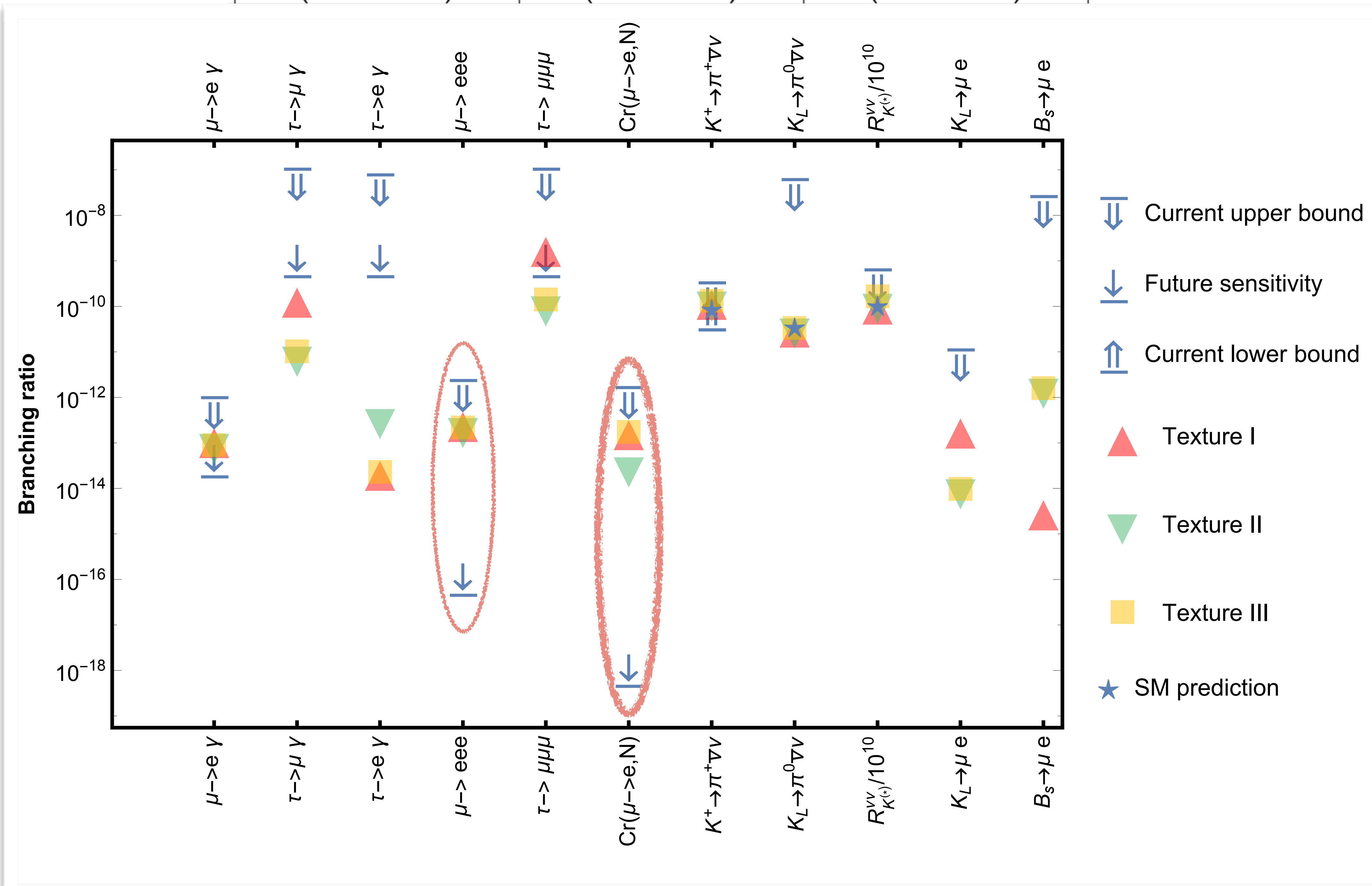
Prospects for flavour violating (LFV) processes

Texture type I	Texture type II	Texture type III
$\begin{pmatrix} \epsilon^4 & \epsilon^5 & \epsilon^2 \\ \epsilon^3 & \epsilon^3 & \epsilon^4 \\ \epsilon^4 & \epsilon & \epsilon \end{pmatrix}$	$\begin{pmatrix} \epsilon^6 & \epsilon^4 & \epsilon^3 \\ \epsilon^5 & \epsilon^2 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & \epsilon \end{pmatrix}$	$\begin{pmatrix} \epsilon^5 & \epsilon^5 & \epsilon^4 \\ \epsilon^4 & \epsilon & \epsilon^2 \\ \epsilon^4 & \epsilon^3 & \epsilon \end{pmatrix}$



Prospects for flavour violating (LFV) processes

Texture type I	Texture type II	Texture type III
$\begin{pmatrix} \epsilon^4 & \epsilon^5 & \epsilon^2 \\ \epsilon^3 & \epsilon^3 & \epsilon^4 \\ \epsilon^4 & \epsilon & \epsilon \end{pmatrix}$	$\begin{pmatrix} \epsilon^6 & \epsilon^4 & \epsilon^3 \\ \epsilon^5 & \epsilon^2 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & \epsilon \end{pmatrix}$	$\begin{pmatrix} \epsilon^5 & \epsilon^5 & \epsilon^4 \\ \epsilon^4 & \epsilon & \epsilon^2 \\ \epsilon^4 & \epsilon^3 & \epsilon \end{pmatrix}$



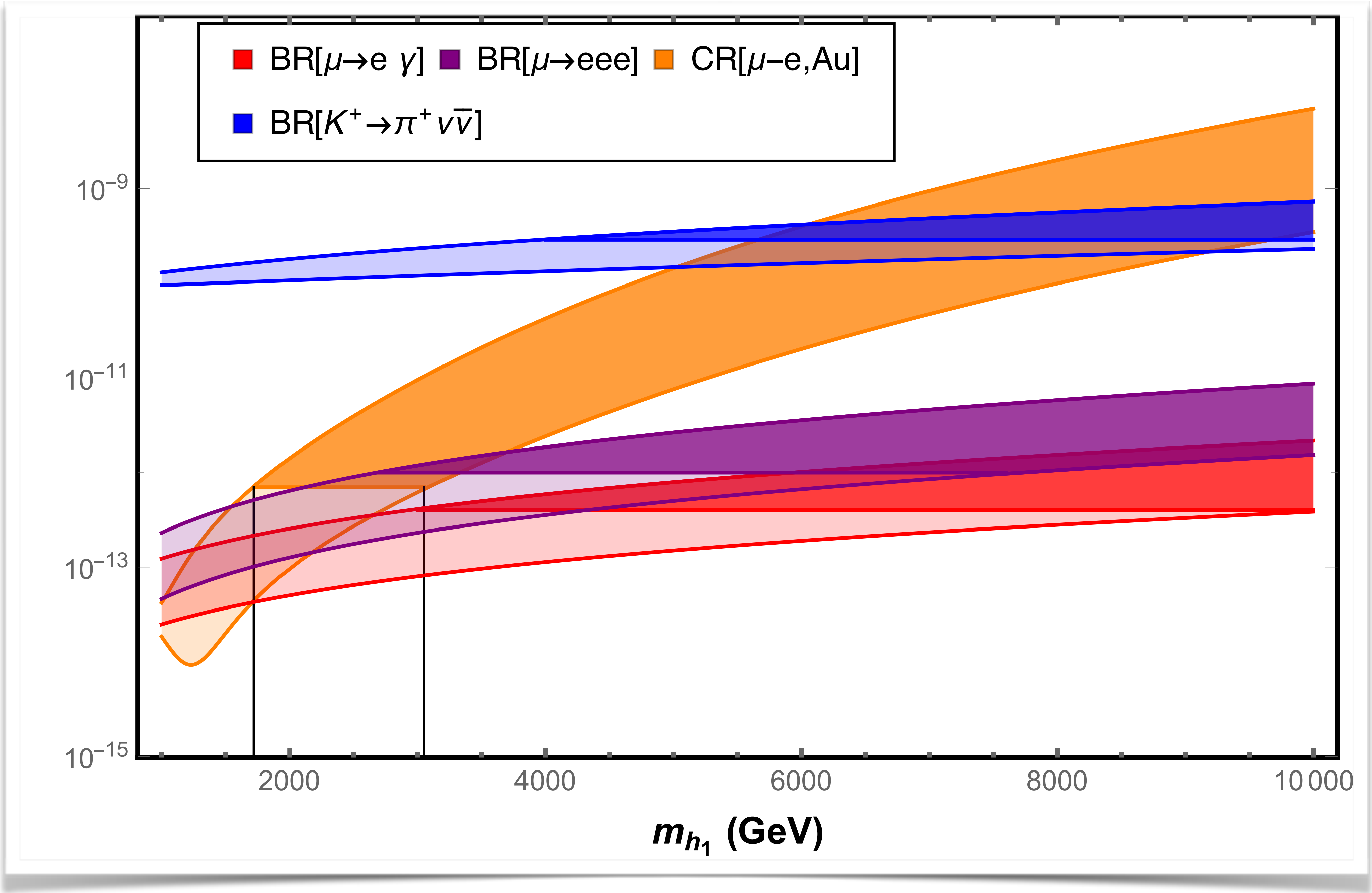
Exciting possibilities to probe leptoquark coupling textures at experiments!

Connection between LFUV and charged LFV

The textures give direct correlations between LFUV data with charged LFV

Texture type I

$$\begin{pmatrix} \epsilon^4 & \epsilon^5 & \epsilon^2 \\ \epsilon^3 & \epsilon^3 & \epsilon^4 \\ \epsilon^4 & \epsilon & \epsilon \end{pmatrix}$$



Current upper bounds (solid colors) on Charged LFV processes translates into
an upper bound on leptoquark masses within collider reach

Impose neutrino oscillation data

$$\tilde{y} = F^{-1/2}\mathcal{R}\,\sqrt{m_\nu^{diag}}\,U^\dagger y^{-1} m_d^{-1}$$

Three generations m_Σ : 2.5, 3.5, 4.5 TeV

$m_{h_2} \sim$ 3 TeV $\quad m_{h_1} \sim 1.5$ TeV

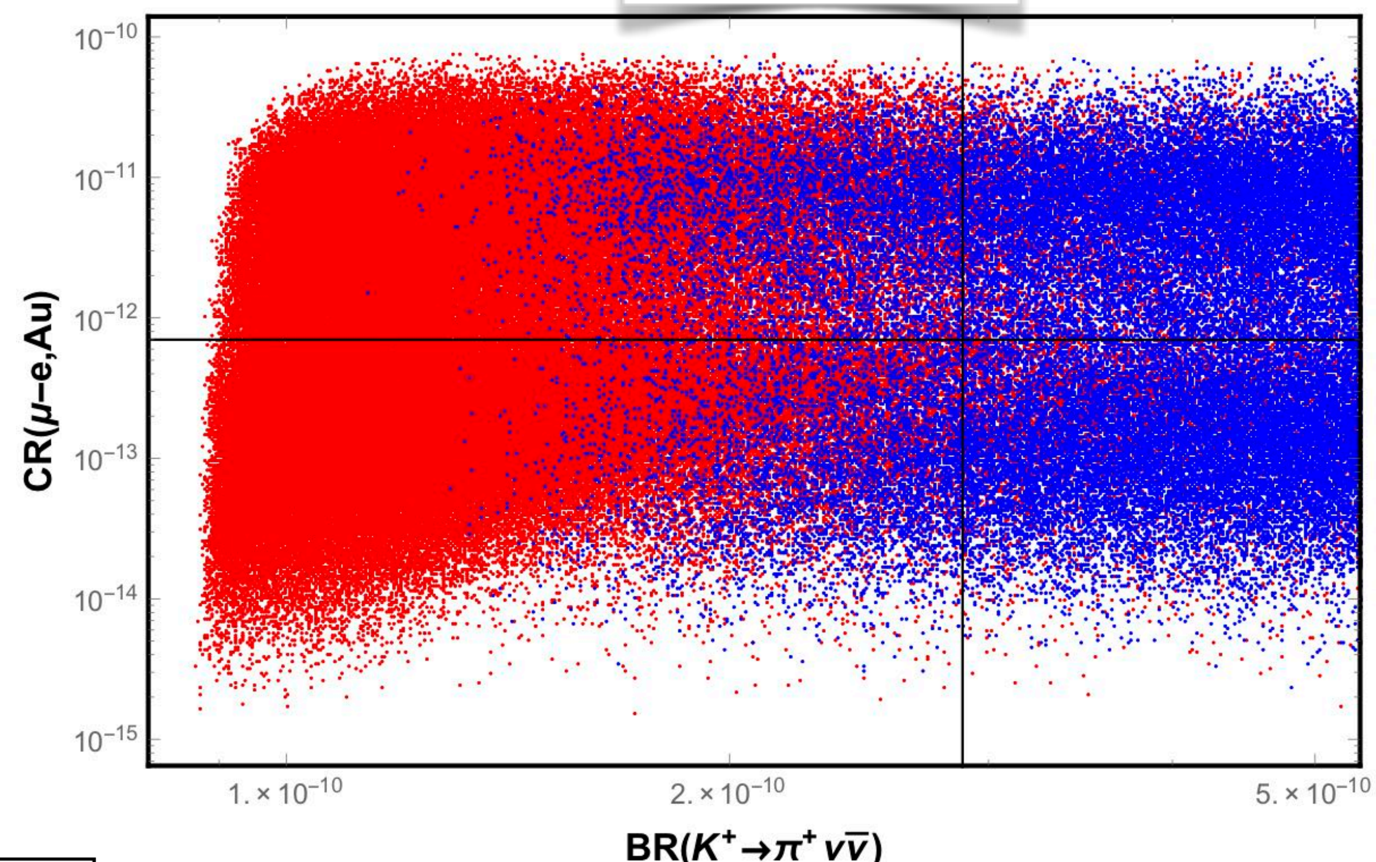
Lightest neutrino mass 0.001 eV

Global best fit values for other oscillation parameters

Scan for y, R **consistent with perturbativity:** $y, \tilde{y} \lesssim 4\pi$ $\quad y, \tilde{y} \gtrsim 4\pi$

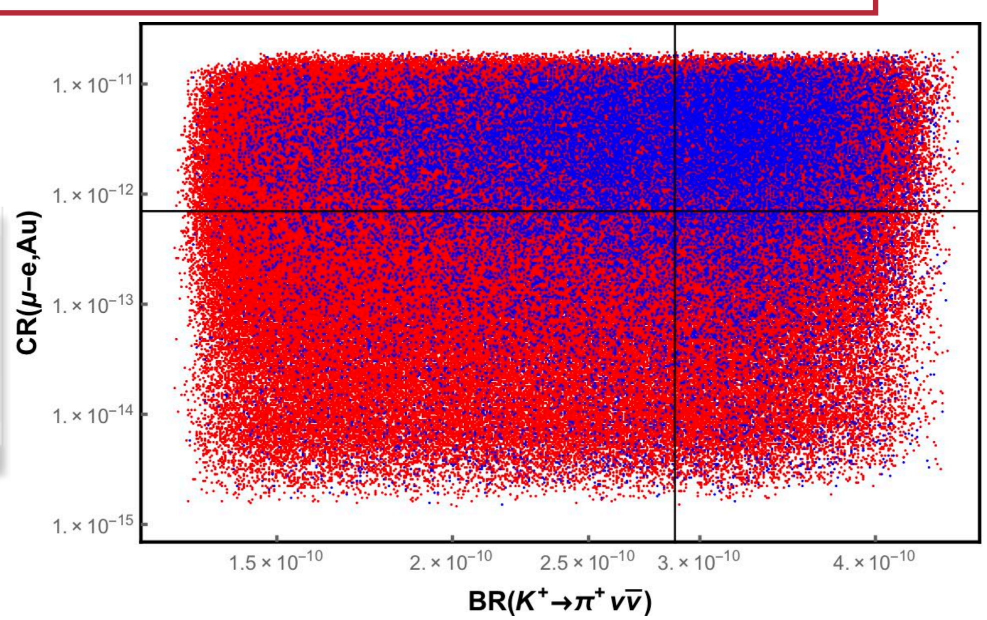
Texture type I

$$\begin{pmatrix} \times & \times & \times \\ \times & \epsilon^3 & \times \\ \times & \epsilon & \times \end{pmatrix}$$



Texture type II

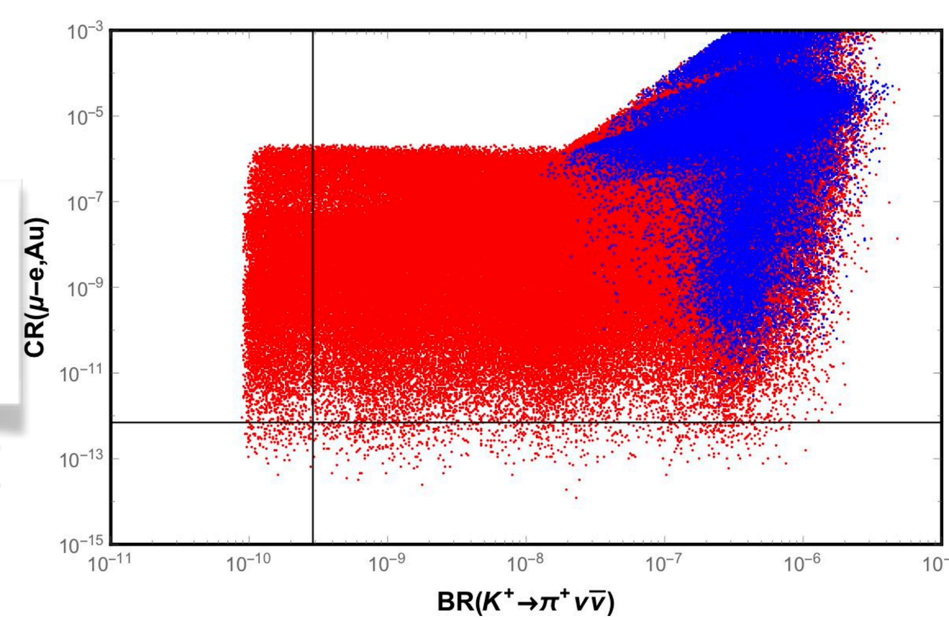
$$\begin{pmatrix} \times & \times & \times \\ \times & \epsilon^2 & \times \\ \times & \epsilon^2 & \times \end{pmatrix}$$



Texture type III

$$\begin{pmatrix} \times & \times & \times \\ \times & \epsilon & \times \\ \times & \epsilon^3 & \times \end{pmatrix}$$

Ruled out !



Concluding Remarks

We considered a simple scalar leptoquark extension
[SM + 2 Scalar LQ + Triplet Majorana fermion (3 gen)] allowing to:

1. Accommodate the latest data on neutrino oscillation parameters
2. Explain the $R_{K^{(*)}}$ anomalies
3. Account for a correct relic abundance for dark matter
4. Consistent with the bounds on the leptoquark couplings from the relevant leptonic and semi-leptonic meson decays, neutral meson anti-meson oscillations, and CLFV processes
5. Exciting prospects for probing the model in future CLFV experiments:
   - μ–e conversion in nuclei and radiative decays $\mu \to e\gamma$, $\tau \to \mu\gamma$, $e\gamma$, $\mu \to 3e$ and $\tau \to 3\mu$

- **Open issues:**
  - Consistent UV completion ?
  - Implementing a mechanism for baryogenesis
  - Computation of EDMs (two-loop)

Backup I: Full Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm int}^{\rm SM} + \mathcal{L}_{\rm int}^{h,\Sigma} + \mathcal{L}_{\rm mass}^{\Sigma} - V_{\rm scalar}^{H,h}$$

$$\mathcal{L}_{\rm int}^{h,\Sigma} = y_{ij}\,\bar{Q}_L^{C\,i}\,\epsilon\,(\vec{\tau}.\vec{h}_1)\,L_L^j + z_{ij}\,\bar{Q}_L^{C\,i}\,\epsilon\,(\vec{\tau}.\vec{h}_1)^\dagger\,Q_L^j + \tilde{y}_{ij}\,\overline{(\vec{\tau}.\vec{\Sigma})_R}^{C\,i,ab}[\epsilon\,(\vec{\tau}.\vec{h}_2)\,\epsilon^T]^{ba}\,d_R^j + \text{H.c.}\,,$$

$$\mathcal{L}_{\rm mass}^{\Sigma} = -\frac{1}{2}\,\overline{\Sigma^C}^i\,M_{ij}^{\Sigma}\,\Sigma^j\,.$$

$$\begin{aligned}
V(H,h_1,h_2) = {}& \mu_H^2 H^\dagger H + \frac{1}{2}\lambda_H\,|H^\dagger H|^2 + \mu_{h_1}^2\,\mathrm{Tr}[h_1^\dagger h_1] + \mu_{h_2}^2\,\mathrm{Tr}[h_2^\dagger h_2] + \\
& + \frac{1}{8}\lambda_{h_1}\,[\mathrm{Tr}(h_1^\dagger h_1)]^2 + \frac{1}{8}\lambda_{h_2}\,[\mathrm{Tr}(h_2^\dagger h_2)]^2 + \frac{1}{4}\lambda'_{h_1}\,\mathrm{Tr}[(h_1^\dagger h_1)]^2 + \frac{1}{4}\lambda'_{h_2}\,\mathrm{Tr}[(h_2^\dagger h_2)]^2 \\
& + \frac{1}{2}\lambda_{Hh_1}\,(H^\dagger H)\,\mathrm{Tr}[h_1^\dagger h_1] + \frac{1}{2}\lambda'_{Hh_1}\,\sum_{i=1}^{3}(H^\dagger\,\tau_i\,H)\,\mathrm{Tr}[h_1^\dagger\,\tau_i\,h_1] + \\
& + \frac{1}{2}\lambda_{Hh_2}\,(H^\dagger H)\,\mathrm{Tr}[h_2^\dagger h_2] + \frac{1}{2}\lambda'_{Hh_2}\,\sum_{i=1}^{3}(H^\dagger\,\tau_i\,H)\,\mathrm{Tr}[h_2^\dagger\,\tau_i\,h_2] + \\
& + \frac{1}{4}\lambda_h\,\mathrm{Tr}[h_1^\dagger\,h_2]^2 + \frac{1}{8}\lambda'_h\,[\mathrm{Tr}\,(h_1^\dagger\,h_2)]^2 + \frac{1}{4}\lambda''_h\,\mathrm{Tr}[h_1^\dagger\,h_1]\,\mathrm{Tr}[h_2^\dagger\,h_2] + \text{H.c.}\,.
\end{aligned}$$

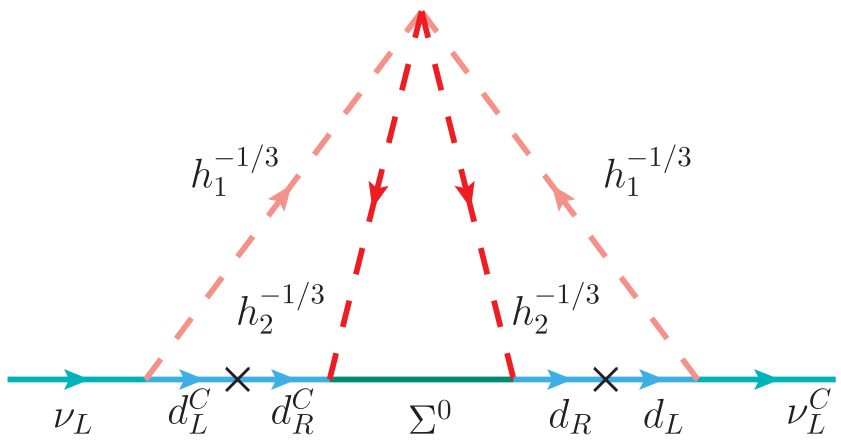
$$h_j^{4/3} = \frac{1}{\sqrt{2}}\left(h_j^{(1)} - i h_j^{(2)}\right), \quad h_j^{-2/3} = \frac{1}{\sqrt{2}}\left(h_j^{(1)} + i h_j^{(2)}\right), \quad h_j^{1/3} = h_j^{(3)} \quad (j = 1,2)\,;$$

$$\Sigma^+ = \frac{1}{\sqrt{2}}\left(\Sigma^{(1)} - i\Sigma^{(2)}\right), \quad \Sigma^- = \frac{1}{\sqrt{2}}\left(\Sigma^{(1)} + i\Sigma^{(2)}\right), \quad \Sigma^0 = \Sigma^{(3)} \quad \text{(for the 3 generations)}\,.$$

Backup II: Relevant Lagrangian for neutrino masses

$$\mathcal{L} \supset - y_{ij}\bar{d}_L^{C\,i} h_1^{1/3} \nu_L^j - \sqrt{2} y_{ij} \bar{d}_L^{C\,i} h_1^{4/3} e_L^j + \sqrt{2} y_{ij} \bar{u}_L^{C\,i} h_1^{-2/3} \nu_L^j - y_{ij} \bar{u}_L^{C\,i} h_1^{1/3} e_L^j$$
$$- 2\tilde{y}_{ij} \overline{\Sigma^0}_R^{C\,i} h_2^{1/3} d_R^j - 2\tilde{y}_{ij} \overline{\Sigma^+}_R^{C\,i} h_2^{-2/3} d_R^j - 2\tilde{y}_{ij} \overline{\Sigma^-}_R^{C\,i} h_2^{4/3} d_R^j + \text{h.c.}\,.$$

$$V(H, h_1, h_2) \supset \frac{\lambda_h}{4} \mathrm{Tr}(h_1^\dagger h_2 h_1^\dagger h_2)$$



$$(m_\nu)_{\alpha\beta} = -30 \frac{\lambda_h}{(4\pi^2)^3 m_{h_2}} y^T_{\alpha i} m_{D_i} \tilde{y}^T_{ij} \, G_j \left(\frac{m^2_{\Sigma_j}}{m^2_{h_2}}, \frac{m^2_{h_1}}{m^2_{h_2}} \right) \tilde{y}_{jk} m_{D_k} y_{k\beta}$$

$$m_\nu^{diag} = U^T \; y^T \; m_D \; \tilde{y}^T \; F \; \tilde{y} \; m_D \; y \; U$$

U is the PMNS mixing matrix

$$(\sqrt{m_\nu^{diag}}^{-1} U^T \; y^T \; m_d \; \tilde{y}^T \; \sqrt{F}\,)(\sqrt{F} \; \tilde{y} \; m_d \; y \; U \; \sqrt{m_\nu^{diag}}^{-1}) = \mathbb{1} = \mathcal{R}^T \mathcal{R},$$

$$\tilde{y} = F^{-1/2} \mathcal{R} \sqrt{m_\nu^{diag}} \; U^\dagger y^{-1} m_d^{-1}$$

$\mathcal{R}$ is a complex orthogonal matrix

Backup III: Dark matter co-annihilation channels

$$x_f = \ln \frac{0.038\, g_{\rm eff}\, m_{\rm Pl}\, m_\Sigma\, \langle \sigma_{\rm eff}|v|\rangle}{g_*^{1/2} x_f^{1/2}} \qquad g_{\rm eff} = g_0 + 2g_\pm \left(1 + \frac{\Delta_{m_\Sigma}}{m_\Sigma}\right)^{3/2} \exp\left(-\frac{\Delta_{m_\Sigma}}{m_\Sigma} x_f\right)$$

$$\boxed{\Omega h^2 = \frac{1.07 \times 10^9 x_f}{g_*^{1/2}\, m_{\rm Pl}({\rm GeV})\, I_a}} \qquad I_a = x_f \int_{x_f}^{\infty} x^{-2} a_{\rm eff}\, dx$$

The thermally averaged effective cross section $\langle \sigma_{\rm eff}|v|\rangle$ is given by

$$\langle \sigma_{\rm eff}|v|\rangle = \frac{g_0^2}{g_{\rm eff}^2}\sigma(\Sigma^0\Sigma^0)|v| + 4\frac{g_0 g_\pm}{g_{\rm eff}^2}\sigma(\Sigma^0\Sigma^\pm)|v| \left(1 + \frac{\Delta_{m_\Sigma}}{m_\Sigma}\right)^{3/2} \exp\left(-\frac{\Delta_{m_\Sigma}}{m_\Sigma} x_f\right)$$
$$+ \frac{g_\pm^2}{g_{\rm eff}^2}[2\sigma(\Sigma^+\Sigma^-)|v| + 2\sigma(\Sigma^\pm\Sigma^\pm)|v|] \left(1 + \frac{\Delta_{m_\Sigma}}{m_\Sigma}\right)^3 \exp\left(-2\frac{\Delta_{m_\Sigma}}{m_\Sigma} x_f\right).$$

s-channel

$$\Sigma^0\Sigma^\pm \to W^\pm \to W^\pm W^0, W^\pm H, \bar{f} f\prime$$

$$\Sigma^+\Sigma^- \to W^0 \to W^+W^-, W^0 H, \bar{f} f$$

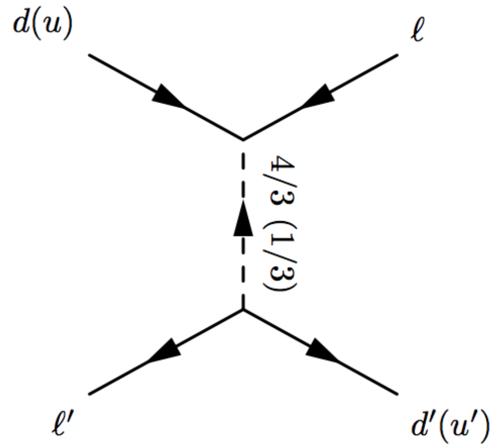
t-channel

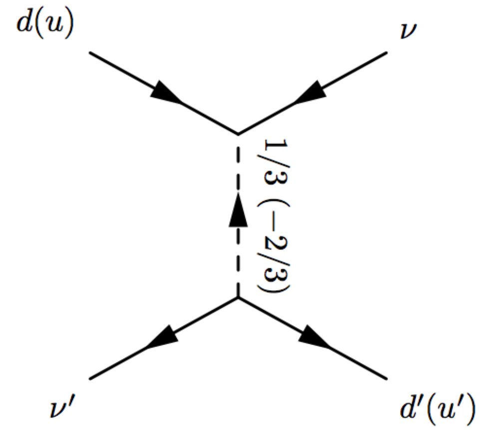
$$\Sigma^0\Sigma^0 \to W^+W^- \qquad \Sigma^0\Sigma^\pm \to W^\pm W^0$$

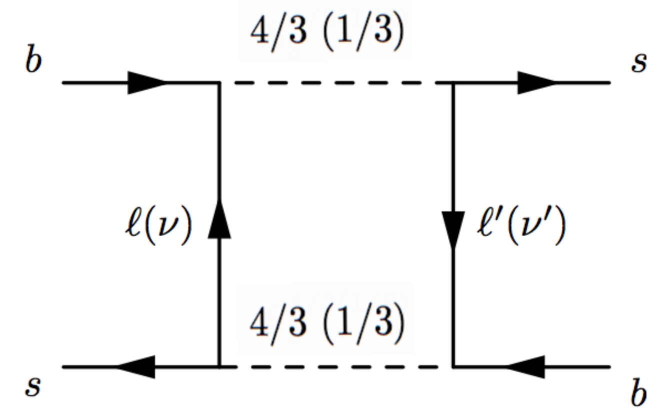
$$\Sigma^\pm\Sigma^\pm \to W^\pm W^\pm$$

$$\Sigma^+\Sigma^- \to W^0 W^0 (W^+W^-)$$

Backup IV:Some important constraints from the mesonic observables

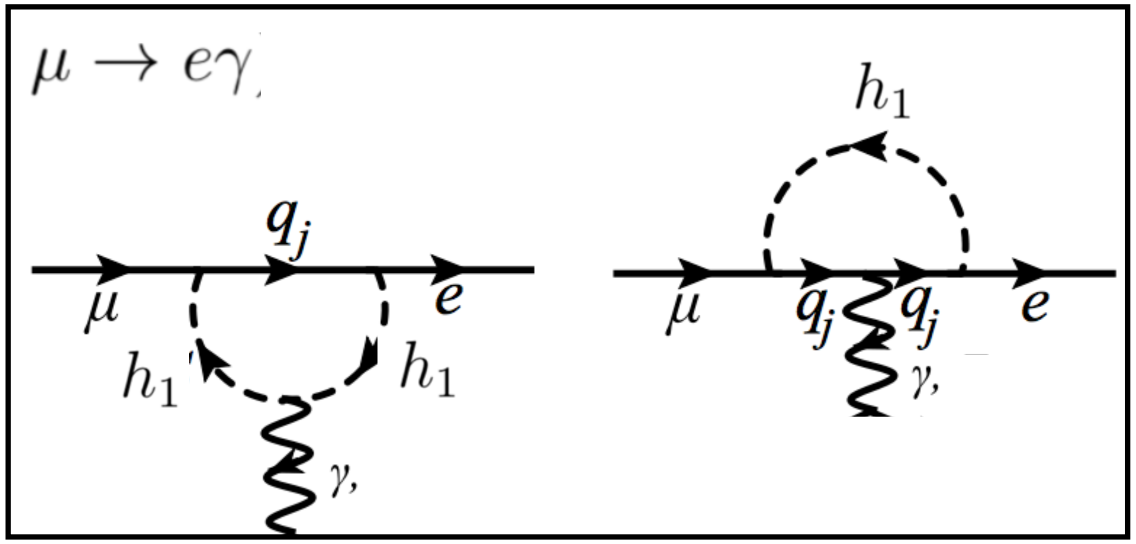


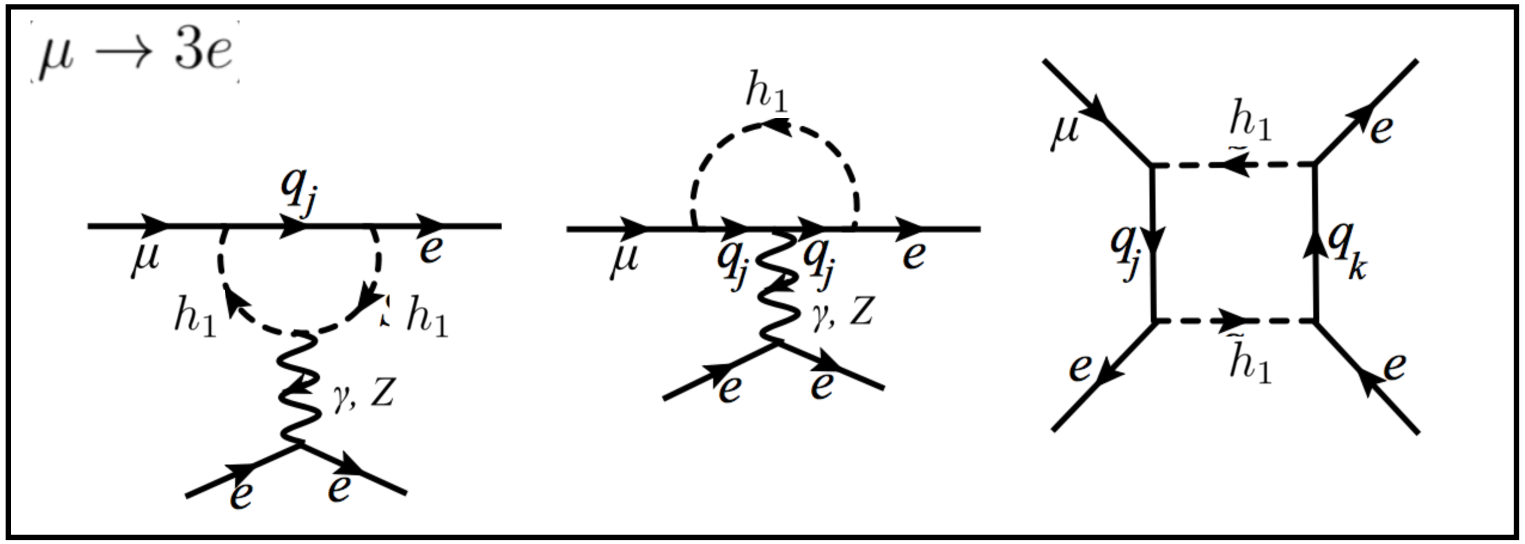




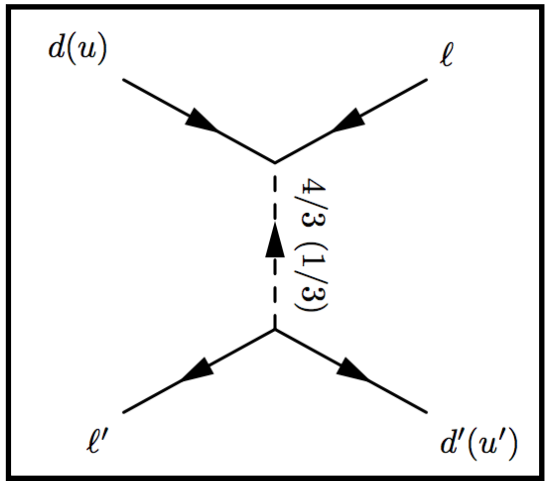
Observables	SM prediction	Experimental data
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$	$(8.4 \pm 1.0) \times 10^{-11}$ (Buras et al.)	$17.3^{+11.5}_{-10.5} \times 10^{-11}$ (E949) $< 11 \times 10^{-10}$ (Na62)
$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})$	$(3.4 \pm 0.6) \times 10^{-11}$ (Buras et al.)	$\leq 2.6 \times 10^{-8}$ (E391a)
$R_K^{\nu\nu}$, $R_{K^*}^{\nu\nu}$ $(B \to K^{(*)} \nu\bar{\nu})$	$R_{K^{(*)}}^{\nu\nu} = 1$	$R_K^{\nu\nu} < 3.9$ (Belle) $R_{K^*}^{\nu\nu} < 2.7$ (Belle)
$B_s^0 - \bar{B}_s^0$ (mixing parameters)	$\Delta_s = \lvert\Delta_s\rvert e^{i\phi_s} = 1$ $\phi_s = 0$	$\lvert\Delta_s\rvert = 1.01^{+0.17}_{-0.10}$ (CKMfitter), $\phi_s[^\circ] = 1.3^{+2.3}_{-2.3}$ (CKMfitter)
$K^0 - \bar{K}^0$ $\Delta m_K/(10^{-15}\mathrm{GeV})$	3.1(1.2) (Brod et al.)	3.484(6) (PDG)
$\mathrm{BR}(K_L \to \mu e)$	—	$< 4.7 \times 10^{-12}$ (PDG)
$\mathrm{BR}(B_s \to \mu e)$	—	$< 1.1 \times 10^{-8}$ (PDG)

Backup V: LFV: current limits and future sensitivities





cLFV process	Current experimental bound	Future sensitivity
$\mathrm{BR}(\mu \to e\gamma)$	4.2×10^{-13} (MEG)	6×10^{-14} (MEG II)
$\mathrm{BR}(\tau \to e\gamma)$	3.3×10^{-8} (BaBar)	10^{-9} (Super B)
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar)	10^{-9} (Super B)
$\mathrm{BR}(\mu \to 3e)$	1.0×10^{-12} (SINDRUM)	$10^{-15(-16)}$ (Mu3e)
$\mathrm{BR}(\tau \to 3e)$	2.7×10^{-8} (Belle)	10^{-9} (Super B)
$\mathrm{BR}(\tau \to 3\mu)$	3.3×10^{-8} (Belle)	10^{-9} (Super B)
$\mathrm{CR}(\mu - e, \mathrm{N})$	7×10^{-13} (Au, SINDRUM)	10^{-14} (SiC, DeeMe) $10^{-15(-17)}$ (Al, COMET) 3×10^{-17} (Al, Mu2e) 10^{-18} (Ti, PRISM/PRIME)



$\mu \to e$ Conversion