

# ON THE INTERPLAY BETWEEN FLAVOUR ANOMALIES AND NEUTRINO PROPERTIES

ANTÓNIO PESTANA MORAIS

DEPARTAMENTO DE FÍSICA DA UNIVERSIDADE DE AVEIRO AND CENTER FOR  
RESEARCH AND DEVELOPMENT IN MATHEMATICS AND APPLICATIONS(CIDMA)

CO-AUTHORS: R. PASECHNIK, J. GONÇALVES, W. POROD, F. FREITAS

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BASED UPON: 2206.01674

The SM is a tremendously successful theory that explains  
“boringly” well all its predictions!

However, it fails to...

- Explain neutrino masses
- Explain dark matter
- Explain CP violation and matter/anti-matter assymetry
- Explain the observed flavour structure

And it is in tension with several emergent anomalies

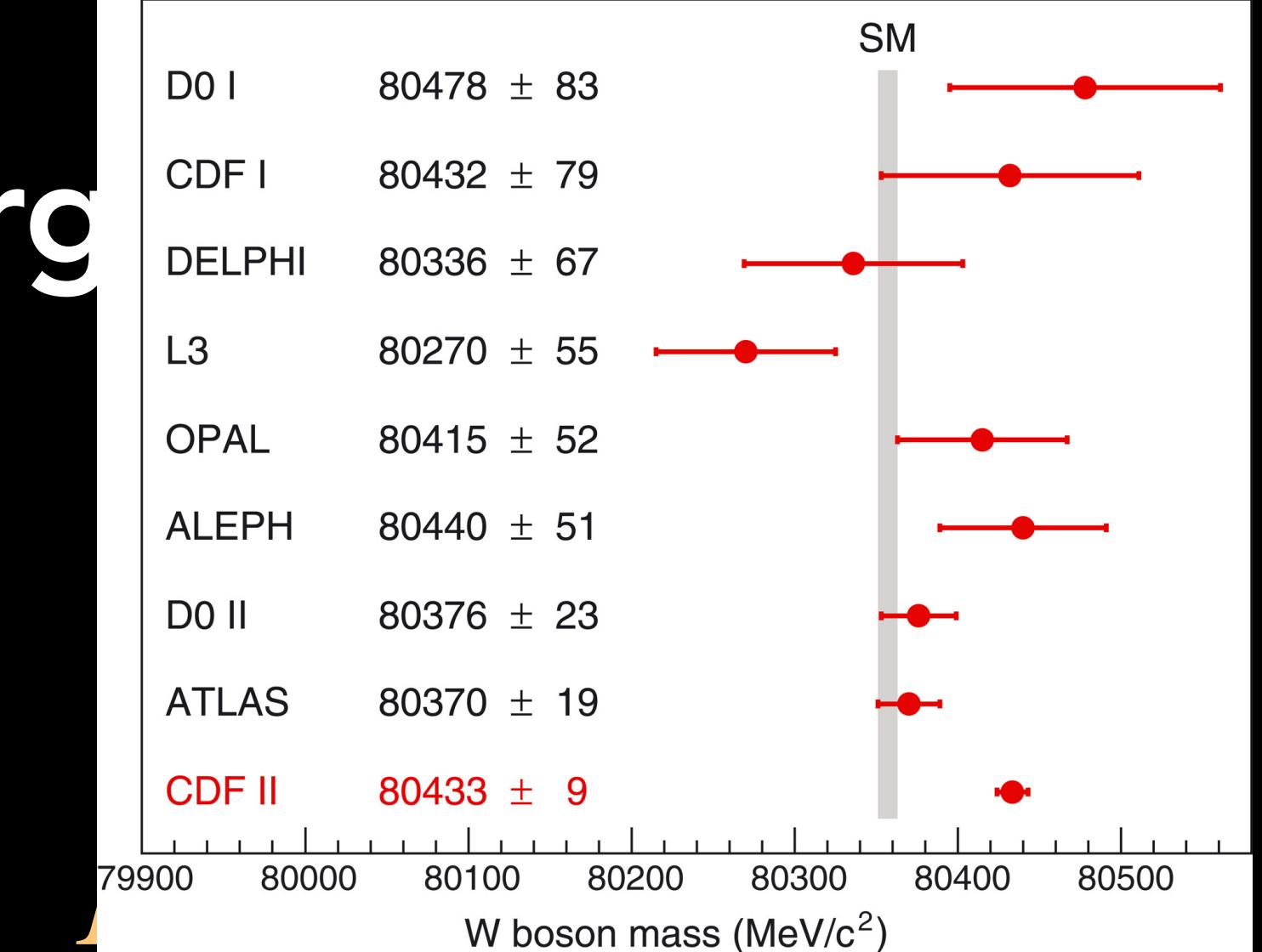
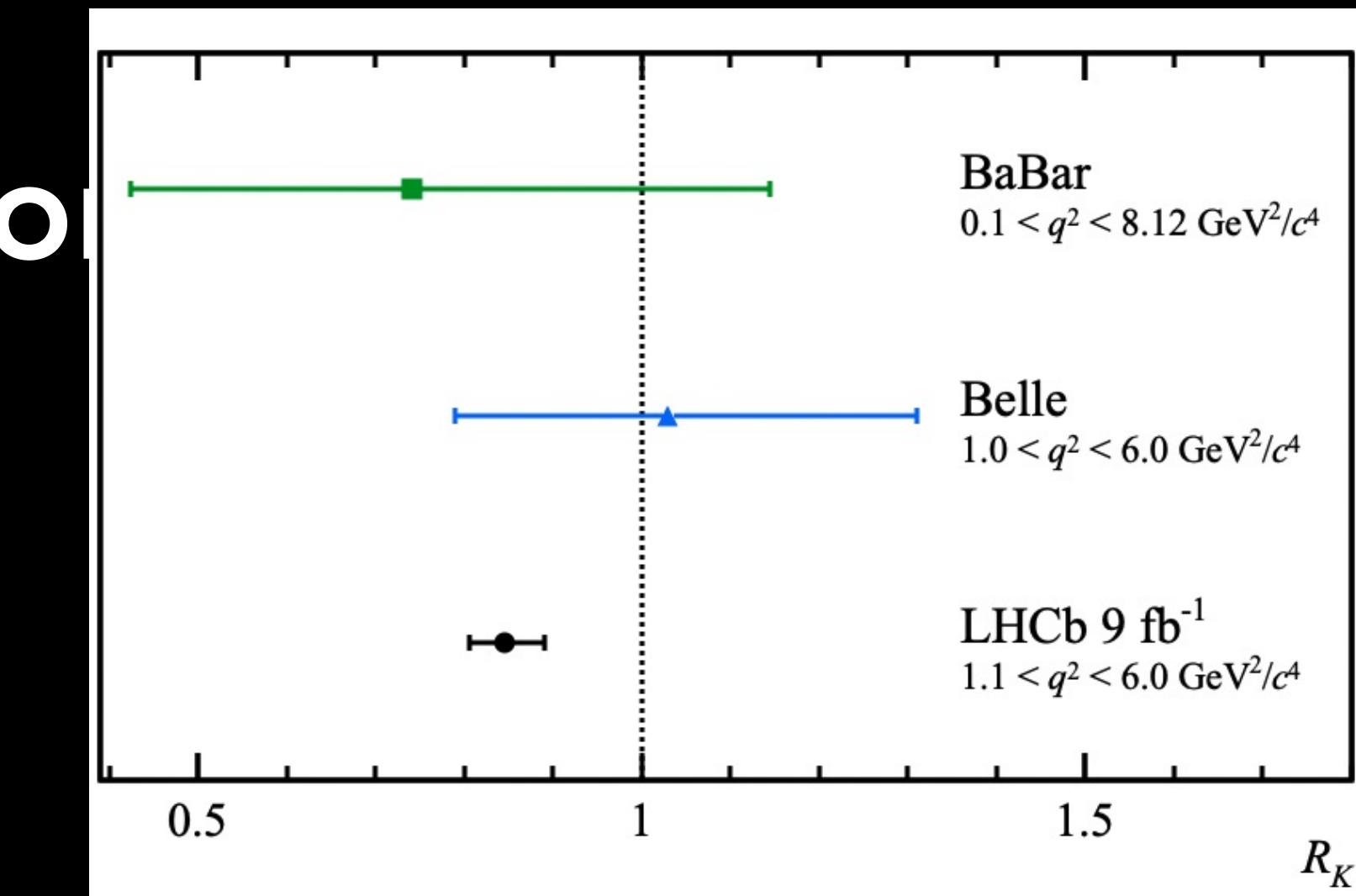
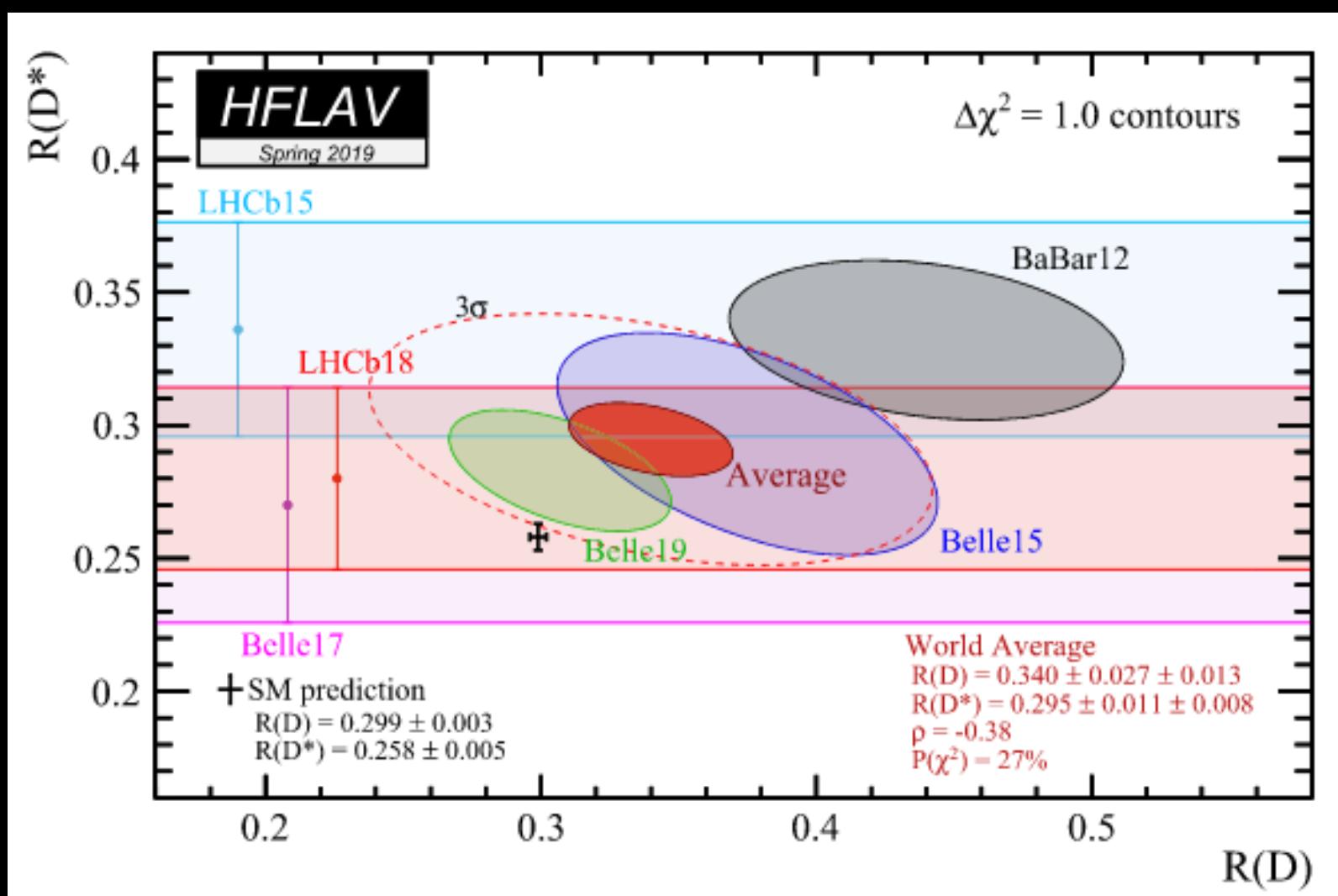
## B-physics

$$\overline{B} \rightarrow D^{(*)} \ell \bar{\nu}_\ell \quad B \rightarrow K^* \ell^+ \ell^- \quad B^+ \rightarrow K^+ \ell^+ \ell^-$$

$$B_s \rightarrow \mu^+ \mu^- \quad B^0 \rightarrow \mu^+ \mu^-$$

$$a_\mu^{(?)}$$

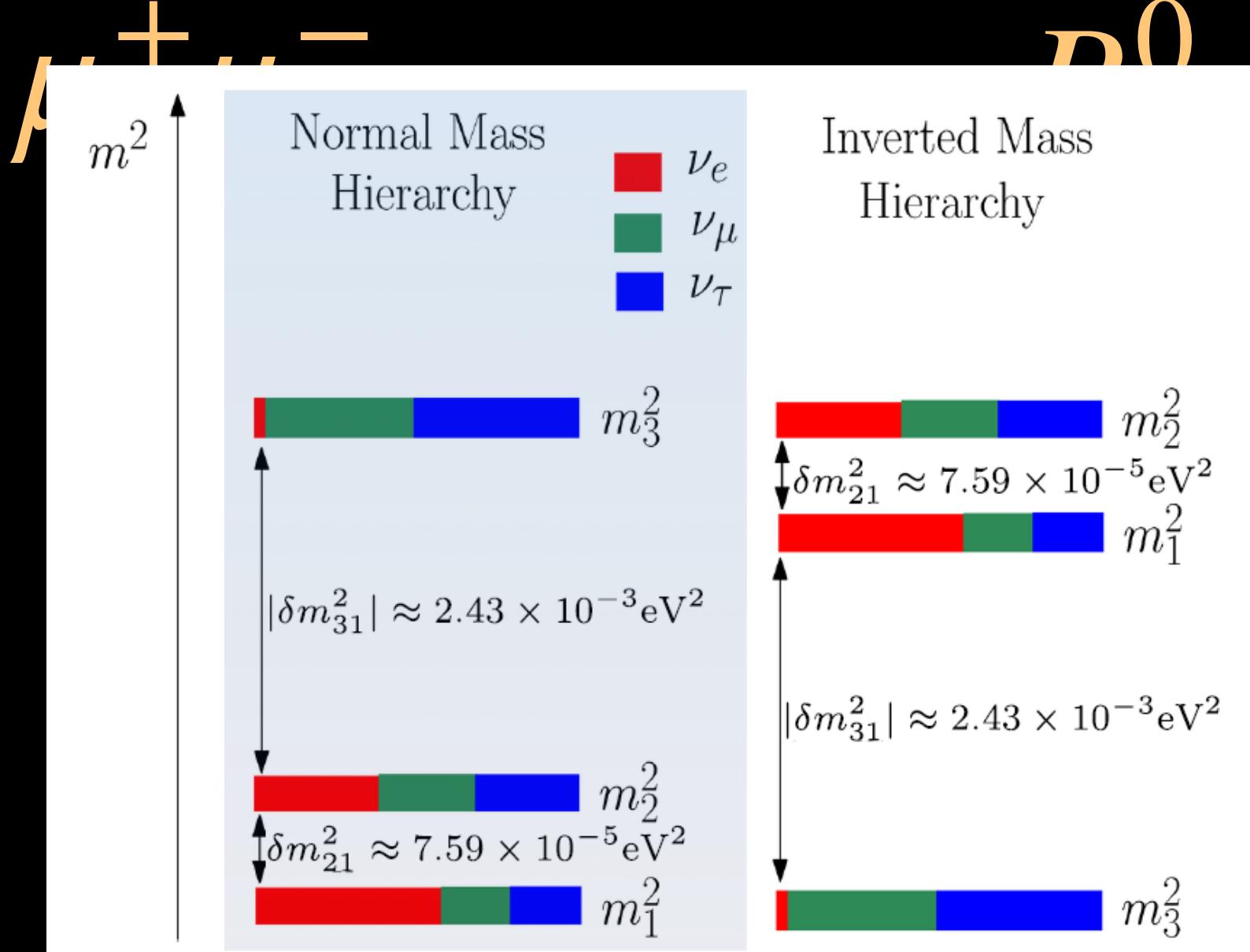
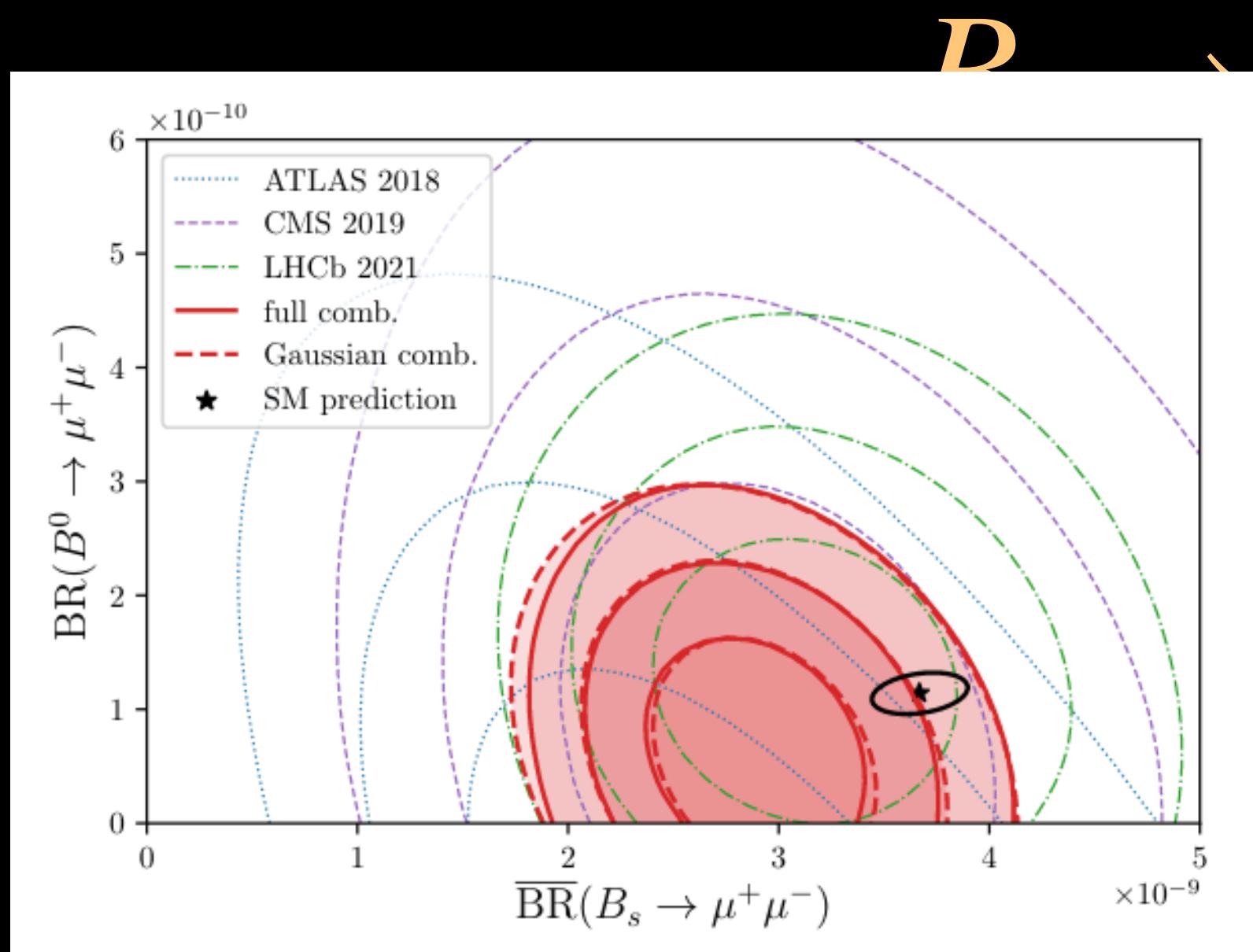
$$m_W^{\text{CDF}} (?)$$



[Eur. Phys. J. C 81, 226 (2021)]

[Nature Phys. 18, 277 (2022)]

[Science 376, n6589, 170-176 (2022)]



[Eur. Phys. J. C 81, 952 (2021)]

[Taken from mpi-hg.mpg.de]

[K. Szabo talk at Moriond 2022 on behalf of the BMW collaboration]

Our proposal: Accommodate all the above in the most economical framework

B-physics +  $a_\mu + m_W + m_\nu + V_{\text{PMNS}} + V_{\text{CKM}} +$

$m_\ell + m_q +$

LFV + QFV + LFC Z decays

SM + Singlet leptoquark + Doublet leptoquark

$$S_1 \sim (\bar{3}, 1)_{1/3}^-$$

$$\tilde{R}_2 \sim (3, 2)_{1/6}^-$$

$$\mathbb{P}_B = (-1)^{3B+2S} \longrightarrow q_{\text{L,R}}^+, \ell_{\text{L,R}}^-$$

Field content and B-parity emergent in a FUT

See Roman Pasechnik's talk last Thursday, Formal Theory 12:00 - 12:15

# The model

$$\mathcal{L}_Y = \Theta_{ij} \bar{Q}_j^c L_i S + \Omega_{ij} \bar{L}_i d_j R^\dagger + \Upsilon_{ij} \bar{u}_j e_i S^\dagger + \text{h.c.}$$

$$V \supset -\mu^2 |H|^2 + \mu_S^2 |S|^2 + \mu_R^2 |R|^2 + \lambda (H^\dagger H)^2 + g_{HR} (H^\dagger H)(R^\dagger R) + g'_{HR} (H^\dagger R)(R^\dagger H) + g_{HS} (H^\dagger H)(S^\dagger S) + (\textcolor{brown}{a}_1 R S H^\dagger + \text{h.c.}) .$$

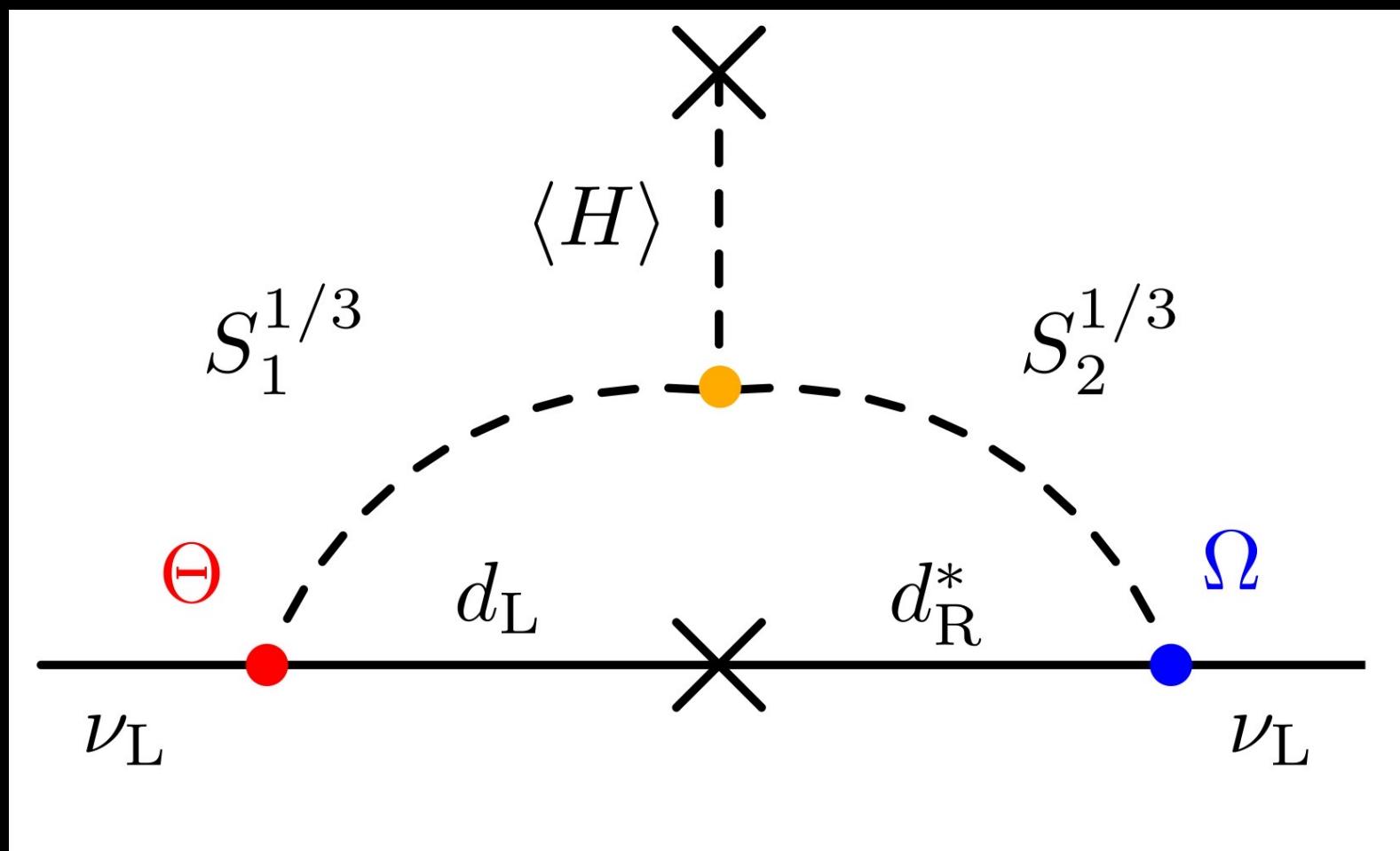
Gauge Basis

$$R \equiv \begin{pmatrix} R^{2/3} \\ R^{1/3} \end{pmatrix}, S$$

Mass Basis

$$S_1^{1/3}, S_2^{1/3}, S^{2/3}$$

# Neutrino Masses



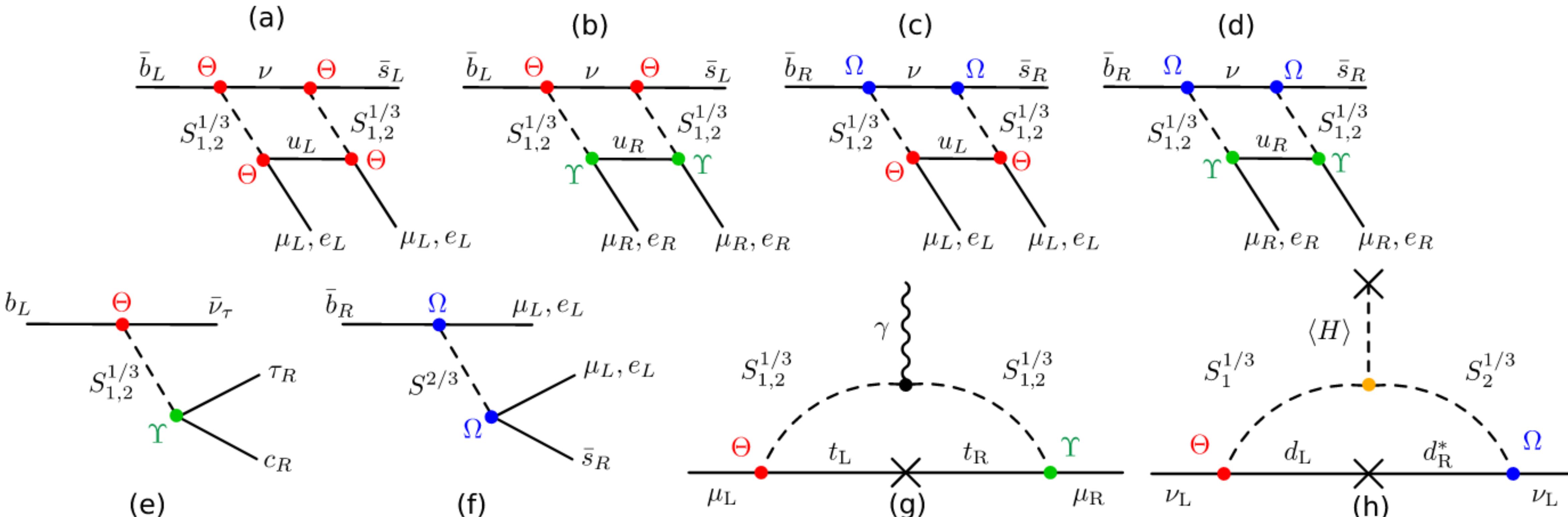
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- [42] D. Zhang, JHEP **07**, 069 (2021), 2105.08670.
- [43] H. Päs and E. Schumacher, Phys. Rev. D **92**, 114025 (2015), 1510.08757.
- [44] Y. Cai, J. Herrero-García, M. A. Schmidt, A. Vicente, and R. R. Volkas, Front. in Phys. **5**, 63 (2017), 1706.08524

$$(M_\nu)_{ij} = \frac{3}{16\pi^2(m_{S_2^{1/3}}^2 - m_{S_1^{1/3}}^2)} \frac{v a_1}{\sqrt{2}} \ln \left( \frac{m_{S_2^{1/3}}^2}{m_{S_1^{1/3}}^2} \right) \sum_{m,a} (m_d)_a V_{am} (\Theta_{im} \Omega_{ja} + \Theta_{jm} \Omega_{ia}),$$

No flavour ansatz in  $\Theta$  and  $\Omega$  with several texture zeros

Left generic as well as  $\Upsilon$

**CHALLENGE:** Keep all LFV, QFV and LFC observables  
under control while improving B-physics  
and  $a_\mu$



# Numerical Results

- Use SPheno for spectrum generation, calculate Br's and Wilson Coefficients
- Use flavio to calculate flavour observables

# Wilson Coefficients

- Use SPheno for sp
- Use flavio to calc

Observable	Experimental measurement	Observable	Experimental measurement
$(g - 2)_\mu$	$(251 \pm 59) \times 10^{-11}$ [8]	$F_L(B^+ \rightarrow K\mu\mu)$	$0.34 \pm 0.10 \pm 0.06$ [80]
$\hat{T}$	$(0.88 \pm 0.14) \times 10^{-3}$ [21]	$S_3(B^+ \rightarrow K\mu\mu)$	$0.14^{+0.15+0.02}_{-0.14-0.02}$ [80]
$R_K[1.1, 6.0]$	$0.846^{+0.042+0.013}_{-0.039-0.012}$ [18]	$S_4(B^+ \rightarrow K\mu\mu)$	$-0.04^{+0.17+0.04}_{-0.16-0.04}$ [80]
$R_{K^*}[1.1, 6.0]$	$0.685^{+0.113+0.047}_{-0.069-0.047}$ [75]	$S_5(B^+ \rightarrow K\mu\mu)$	$0.24^{+0.12+0.04}_{-0.15-0.04}$ [80]
$R_K[0.045, 1.1]$	$0.660^{+0.110+0.024}_{-0.070-0.024}$ [75]	$A_{FB}(B^+ \rightarrow K\mu\mu)$	$-0.05 \pm 0.12 \pm 0.03$ [80]
$R_D$	$0.340 \pm 0.027 \pm 0.013$ [76]	$S_7(B^+ \rightarrow K\mu\mu)$	$-0.01^{+0.19+0.01}_{-0.17-0.01}$ [80]
$R_{D^*}$	$0.295 \pm 0.011 \pm 0.008$ [76]	$S_8(B^+ \rightarrow K\mu\mu)$	$0.21^{+0.22+0.05}_{-0.20-0.05}$ [80]
$\text{BR}(h \rightarrow e\mu)$	$< 6.1 \times 10^{-5}$ [95% CL] [63]	$S_9(B^+ \rightarrow K\mu\mu)$	$0.28^{+0.25+0.06}_{-0.12-0.06}$ [80]
$\text{BR}(h \rightarrow e\tau)$	$< 4.7 \times 10^{-3}$ [95% CL] [63]	$P_1(B^+ \rightarrow K\mu\mu)$	$0.44^{+0.38+0.11}_{-0.40-0.11}$ [80]
$\text{BR}(h \rightarrow \mu\tau)$	$< 2.5 \times 10^{-3}$ [95% CL] [63]	$P_2(B^+ \rightarrow K\mu\mu)$	$-0.05 \pm 0.12 \pm 0.03$ [80]
$\text{BR}(\mu \rightarrow e\gamma)$	$< 4.2 \times 10^{-13}$ [90% CL] [63]	$P_3(B^+ \rightarrow K\mu\mu)$	$-0.42^{+0.20+0.05}_{-0.21-0.05}$ [80]
$\text{BR}(\mu \rightarrow eee)$	$< 1.0 \times 10^{-12}$ [90% CL] [63]	$P'_4(B^+ \rightarrow K\mu\mu)$	$-0.092^{+0.36+0.12}_{-0.35-0.12}$ [80]
$\text{BR}(\tau \rightarrow e\gamma)$	$< 3.3 \times 10^{-8}$ [90% CL] [63]	$P'_5(B^+ \rightarrow K\mu\mu)$	$0.51^{+0.30+0.12}_{-0.28-0.12}$ [80]
$\text{BR}(\tau \rightarrow \mu\gamma)$	$< 4.4 \times 10^{-8}$ [90% CL] [63]	$P'_6(B^+ \rightarrow K\mu\mu)$	$-0.02^{+0.40+0.06}_{-0.34-0.06}$ [80]
$\text{BR}(\tau \rightarrow eee)$	$< 2.7 \times 10^{-8}$ [90% CL] [63]	$P'_8(B^+ \rightarrow K\mu\mu)$	$-0.45^{+0.50+0.09}_{-0.39-0.09}$ [80]
$\text{BR}(\tau \rightarrow e\mu\mu)$	$< 2.7 \times 10^{-8}$ [90% CL] [63]	$F_L(B^0 \rightarrow K\mu\mu)$	$0.255 \pm 0.032 \pm 0.007$ [81]
$\text{BR}(\tau \rightarrow \mu ee)$	$< 1.5 \times 10^{-8}$ [90% CL] [63]	$S_3(B^0 \rightarrow K\mu\mu)$	$0.034 \pm 0.044 \pm 0.003$ [81]
$\text{BR}(Z \rightarrow \mu e)$	$7.5 < \times 10^{-7}$ [95% CL] [63]	$S_4(B^0 \rightarrow K\mu\mu)$	$0.059 \pm 0.050 \pm 0.004$ [81]
$\text{BR}(Z \rightarrow \tau e)$	$9.8 < \times 10^{-6}$ [95% CL] [63]	$S_5(B^0 \rightarrow K\mu\mu)$	$0.227 \pm 0.041 \pm 0.008$ [81]
$\text{BR}(Z \rightarrow \mu\tau)$	$1.2 < \times 10^{-5}$ [95% CL] [63]	$A_{FB}(B^0 \rightarrow K\mu\mu)$	$-0.004 \pm 0.040 \pm 0.004$ [81]
$\text{BR}(\tau \rightarrow \pi e)$	$< 8.0 \times 10^{-8}$ [90% CL] [63]	$S_7(B^0 \rightarrow K\mu\mu)$	$0.006 \pm 0.042 \pm 0.002$ [81]
$\text{BR}(\tau \rightarrow \pi\mu)$	$< 1.1 \times 10^{-7}$ [90% CL] [63]	$S_8(B^0 \rightarrow K\mu\mu)$	$-0.003 \pm 0.051 \pm 0.001$ [81]
$\text{BR}(\tau \rightarrow \phi e)$	$< 3.1 \times 10^{-8}$ [90% CL] [63]	$S_9(B^0 \rightarrow K\mu\mu)$	$-0.055 \pm 0.041 \pm 0.002$ [81]
$\text{BR}(\tau \rightarrow \phi\mu)$	$< 8.4 \times 10^{-8}$ [90% CL] [63]	$P_1(B^0 \rightarrow K\mu\mu)$	$0.090 \pm 0.119 \pm 0.009$ [81]
$\text{BR}(\tau \rightarrow \rho e)$	$< 1.8 \times 10^{-8}$ [90% CL] [63]	$P_2(B^0 \rightarrow K\mu\mu)$	$-0.003 \pm 0.038 \pm 0.003$ [81]
$\text{BR}(\tau \rightarrow \rho\mu)$	$< 1.2 \times 10^{-8}$ [90% CL] [63]	$P_3(B^0 \rightarrow K\mu\mu)$	$-0.073 \pm 0.057 \pm 0.003$ [81]
$d_e$	$< 1.1 \times 10^{-29}$ e.cm [90% CL] [63]	$P'_4(B^0 \rightarrow K\mu\mu)$	$-0.135 \pm 0.118 \pm 0.003$ [81]
$d_\mu$	$< 1.8 \times 10^{-19}$ e.cm [95% CL] [63]	$P'_5(B^0 \rightarrow K\mu\mu)$	$-0.521 \pm 0.095 \pm 0.024$ [81]
$d_\tau$	$< (1.15 \pm 1.70) \times 10^{-17}$ e.cm [95% CL] [77]	$P'_6(B^0 \rightarrow K\mu\mu)$	$-0.015 \pm 0.094 \pm 0.007$ [81]
$\text{BR}(B^0 \rightarrow \mu\mu)$	$(0.56 \pm 0.70) \times 10^{-10}$ [19]	$P'_8(B^0 \rightarrow K\mu\mu)$	$-0.007 \pm 0.122 \pm 0.002$ [81]
$\text{BR}(B_s \rightarrow \mu\mu)$	$(2.93 \pm 0.35) \times 10^{-9}$ [19]	$C_9^{bs\mu\mu}$	$-0.82 \pm 0.23$ [81]
$R(B \rightarrow \chi_s \gamma)$	$1.009 \pm 0.075$	$C_{10}^{bs\mu\mu}$	$0.14 \pm 0.23$ [81]
$R_K^{\nu\nu}$	$3.9$ [78]	$C_9^{bs\mu\mu}$	$-0.10 \pm 0.34$ [81]
$R_{K^*}^{\nu\nu}$	$2.7$ [78]	$C_{10}^{bs\mu\mu}$	$-0.33 \pm 0.23$ [81]
$ \text{Re } \delta g_R^e $	$\leq 2.9 \times 10^{-4}$ [37, 79]	$C_9^{bsee}$	$-0.24 \pm 1.17$ [81]
$ \text{Re } \delta g_L^e $	$\leq 3.0 \times 10^{-4}$ [37, 79]	$C_{10}^{bsee}$	$-0.24 \pm 0.78$ [81]
$ \text{Re } \delta g_R^\mu $	$\leq 1.3 \times 10^{-3}$ [37, 79]	$\varepsilon_K^{\text{NP}} / \varepsilon_K^{\text{SM}}$	$1.00 \pm 0.14$
$ \text{Re } \delta g_L^\mu $	$\leq 1.1 \times 10^{-3}$ [37, 79]	$\Delta M_d^{\text{NP}} / \Delta M_d^{\text{SM}}$	$1.00 \pm 0.11$
$ \text{Re } \delta g_R^\tau $	$\leq 6.2 \times 10^{-4}$ [37, 79]	$\Delta M_s^{\text{NP}} / \Delta M_s^{\text{SM}}$	$1.000 \pm 0.0054$
$ \text{Re } \delta g_L^\tau $	$\leq 5.8 \times 10^{-4}$ [37, 79]		

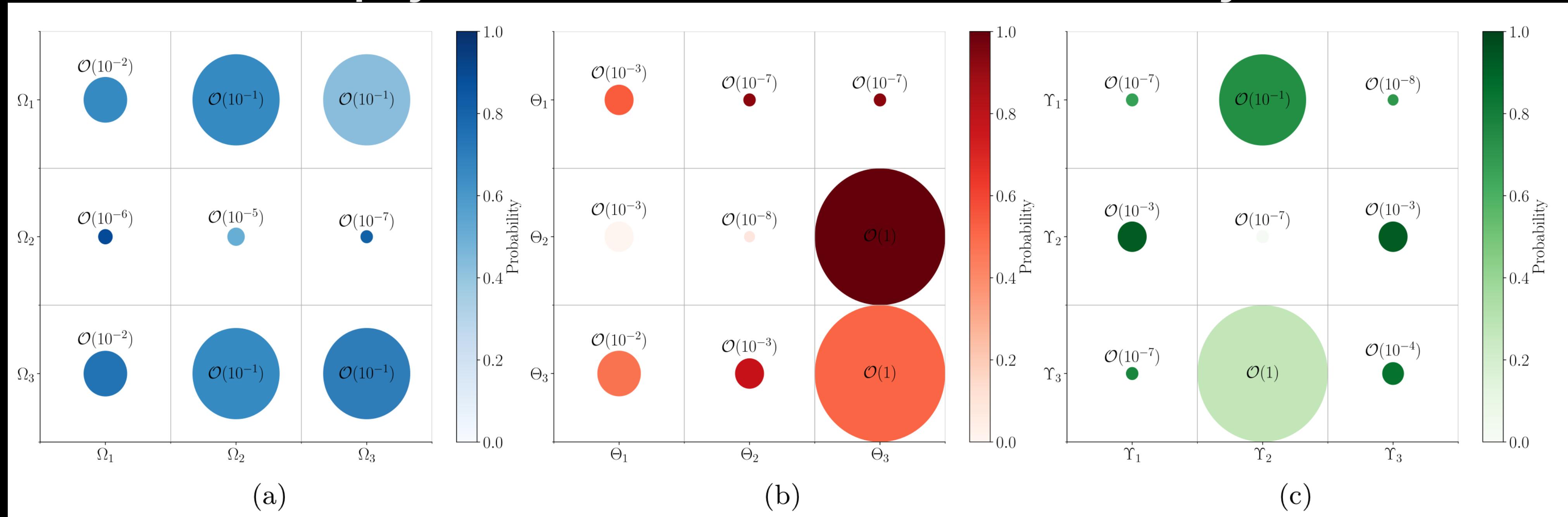
To assess the quality of the results one uses the likelihood function:

$$\chi^2 = (\mathcal{O}_{\text{exp}} - \mathcal{O}_{\text{th}})^T (\Sigma_{\text{th}} + \Sigma_{\text{exp}})^{-1} (\mathcal{O}_{\text{exp}} - \mathcal{O}_{\text{th}})$$

- Take a conservative approach by assuming that  $\chi^2_{\text{SM,LFV}} = 0$
- Use reported experimental correlations and determine theoretical ones with sampled points
- Consider 3 scenarios:
  - a)  $a_\mu$  and  $m_W$  both consistent with SM,
  - b) only  $m_W$  consistent with SM,
  - c) neither of them consistent with SM

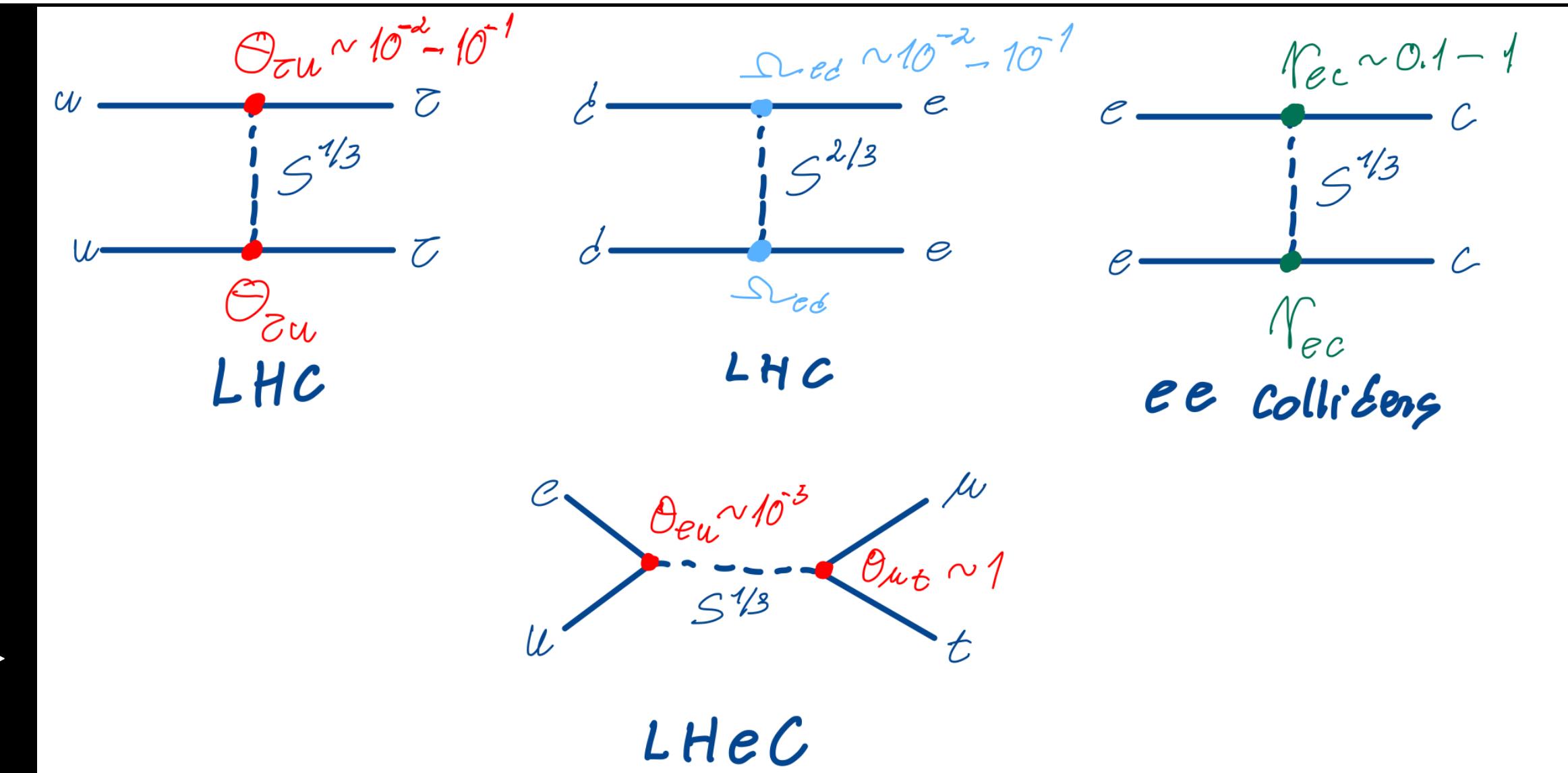
- **a)**  $\chi^2/\text{d.o.f.} = 3.18$ ,  $m_{S_1^{1/3}} = 2.53 \text{ TeV}$ ,  $m_{S_2^{1/3}} = 3.56 \text{ TeV}$ ,  $m_{S_2^{2/3}} = 3.57 \text{ TeV}$
- **b)**  $\chi^2/\text{d.o.f.} = 3.46$ ,  $m_{S_1^{1/3}} = 2.03 \text{ TeV}$ ,  $m_{S_2^{1/3}} = 4.49 \text{ TeV}$ ,  $m_{S_2^{2/3}} = 4.48 \text{ TeV}$
- **c)**  $\chi^2/\text{d.o.f.} = 4.74$ ,  $m_{S_1^{1/3}} = 1.80 \text{ TeV}$ ,  $m_{S_2^{1/3}} = 6.16 \text{ TeV}$ ,  $m_{S_2^{2/3}} = 6.17 \text{ TeV}$

# Preferred sizes to simultaneously address all anomalies in consistency with neutrino physics, LFV, QFV and LFC $Z \rightarrow \ell\ell$ decays



Provides information to potentially falsify the models at colliders

E.g. of single production  $\rightarrow$

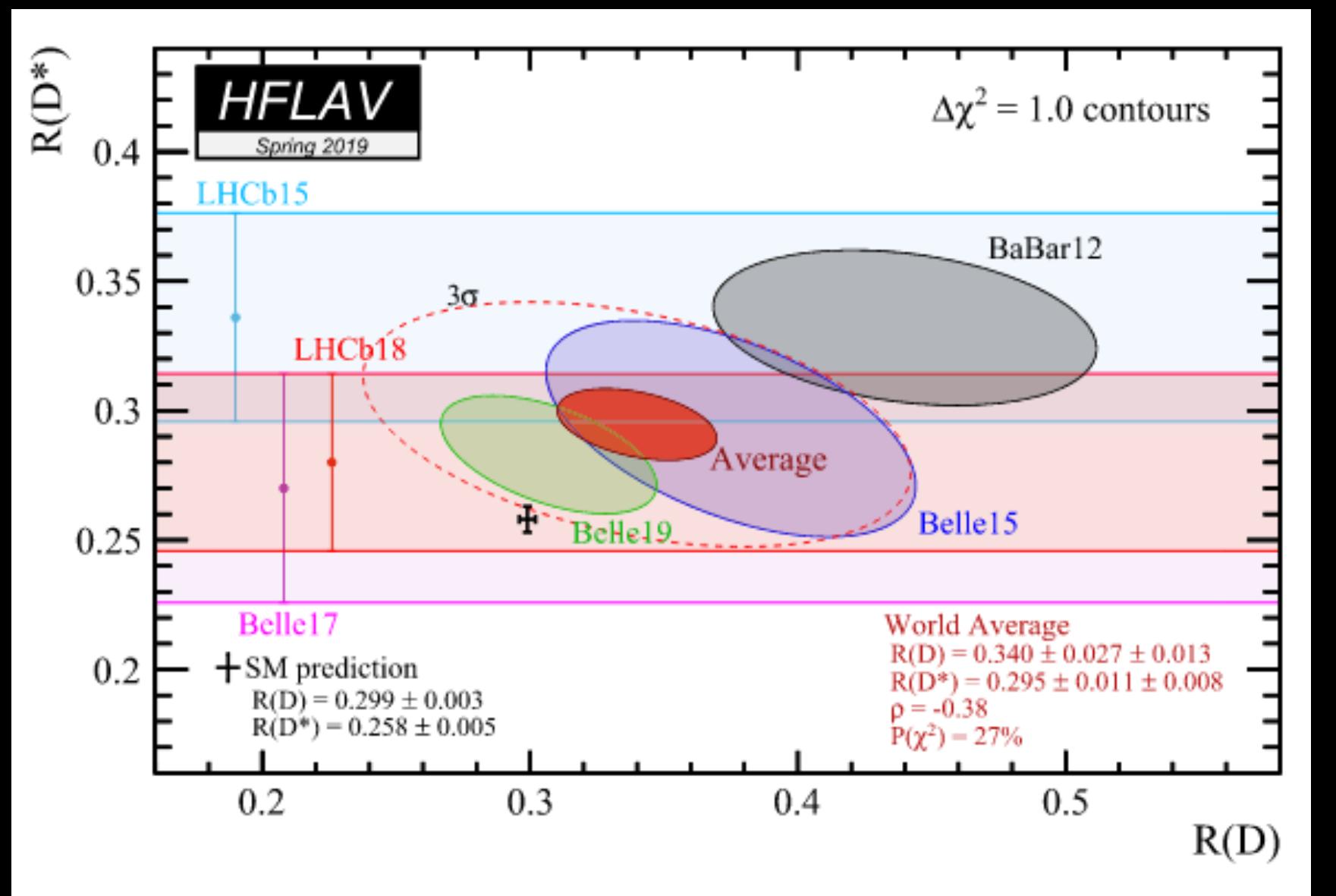


# Concluding remarks

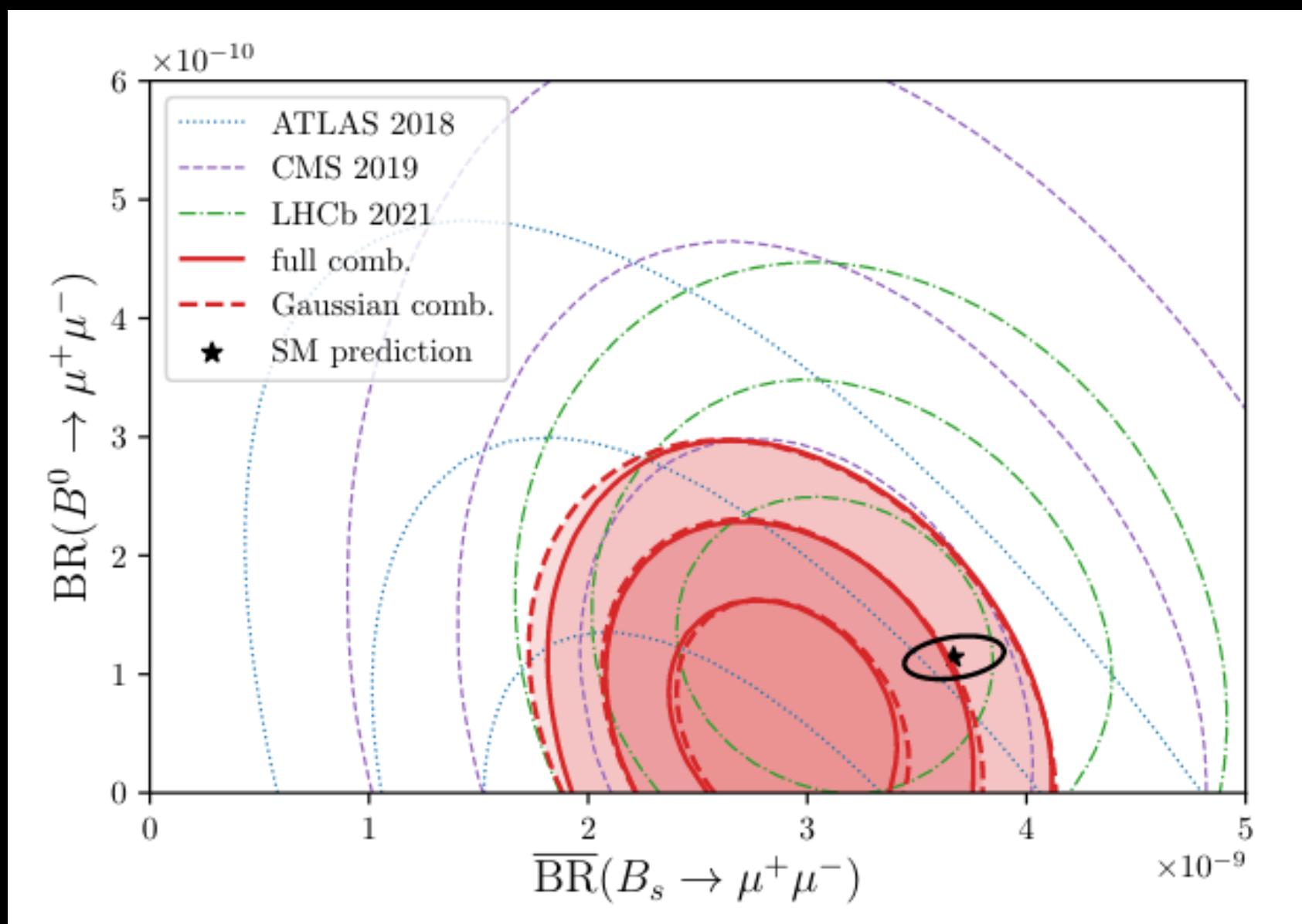
- Simple, economical, constrained and falsifiable model
- Well motivated by unification principles
- Can explain B-physics,  $a_\mu$ ,  $m_\nu$  in consistency with LFV, QFV and LFC Z-boson decays:  $\chi^2/\text{d.o.f.} = 3.18$
- Can also potentially address W-mass anomaly while slightly disfavoured:  $\chi^2/\text{d.o.f.} = 4.74$
- Falsifiable at colliders



THANK YOU

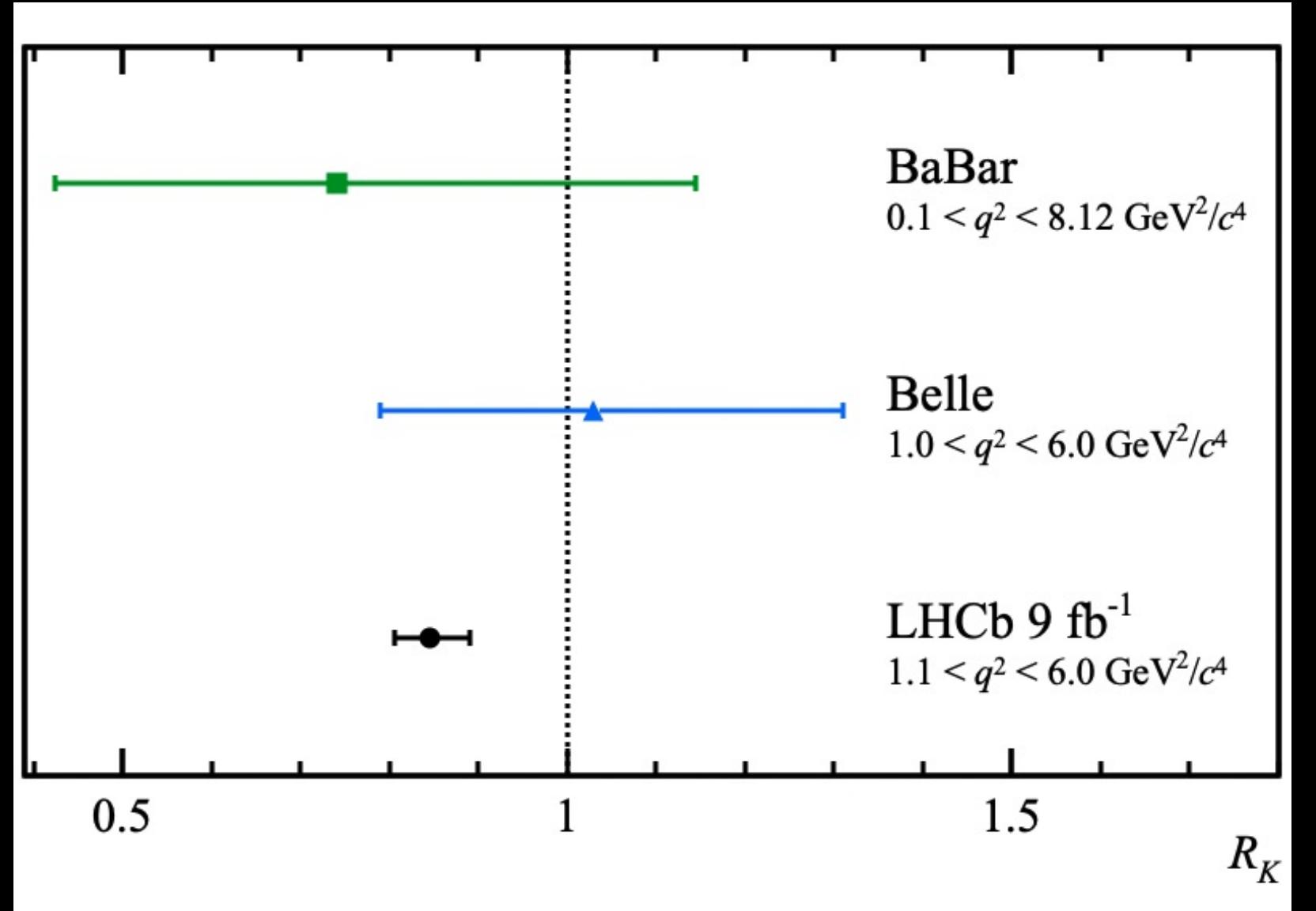


[Eur. Phys. J. C 81, 226 (2021)]



[Eur. Phys. J. C 81, 952 (2021)]

$$R_K = \frac{Br(B^+ \rightarrow K^+ \mu^+ \mu^-)}{Br(B^+ \rightarrow K^+ e^+ e^-)} = 0.846^{+0.055}_{-0.051}$$



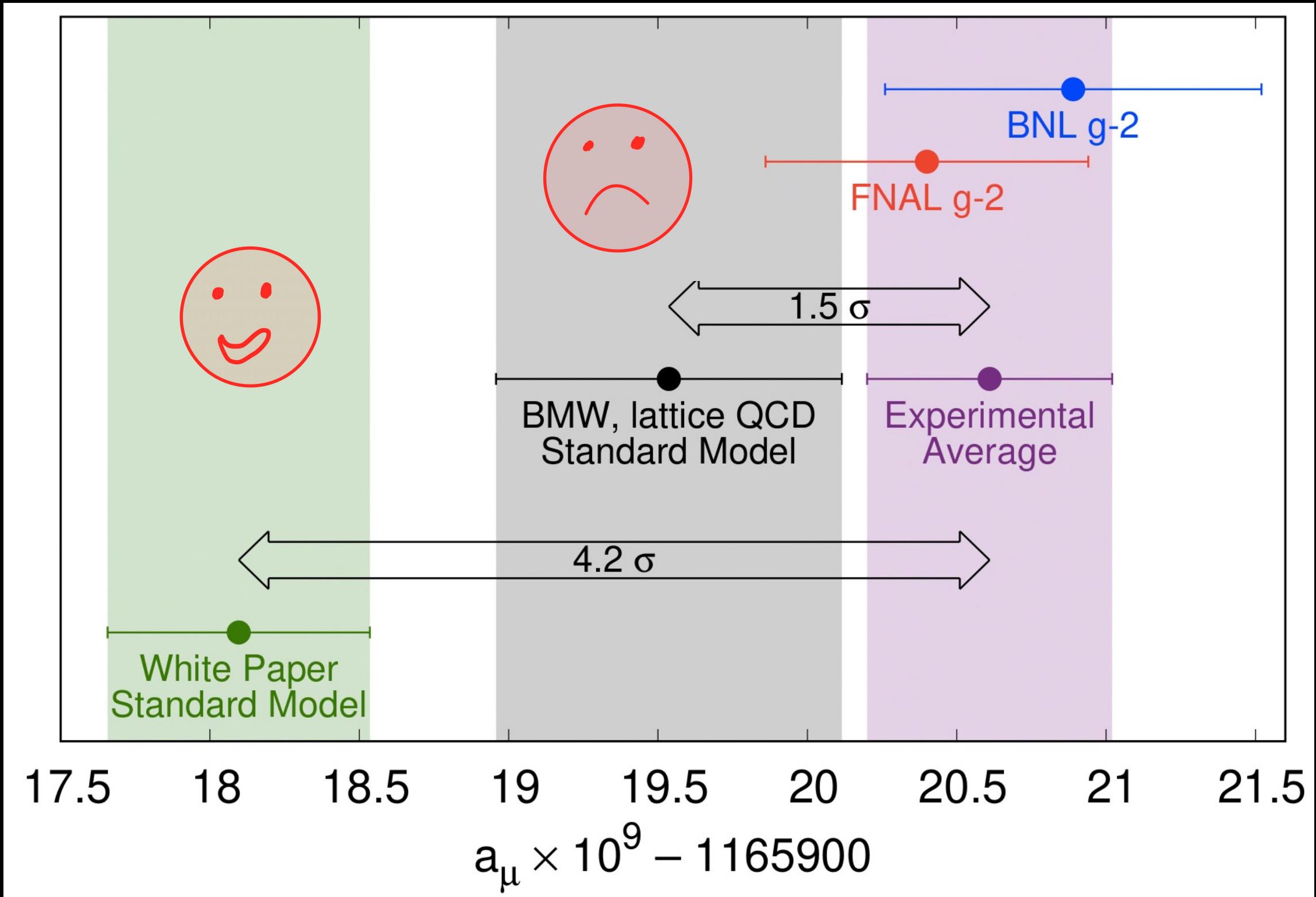
[Nature Phys. 18, 277 (2022)]

$$R_{K^*} = \frac{Br(B \rightarrow K^* \mu^+ \mu^-)}{Br(B \rightarrow K^* e^+ e^-)} = 0.685^{+0.160}_{-0.116}$$

[Phys. Rev. D 96, 095000 (2017)]

# Tantalising hints for new physics in B decays

# $a_\mu$ (?)



[K. Szabo talk at Moriond 2022 on behalf of the BMW collaboration]

$$a_\mu = 2.51(59) \times 10^{-9}$$

[Phys. Rev. Lett. 126, 141801 (2021)]

# $m_W^{\text{CDF}}$ (?)

CDF-II reported a  $7.2\sigma$  deviation

[Science 376, n6589, 170-176 (2022)]

Modification to the T-parameter ( $S = U = 0$ )

- Pre CDF-II:  $\hat{T} = (0.39 \pm 0.47) \times 10^{-3}$  [PDG]
- CDF-II:  $\hat{T} = (0.88 \pm 0.14) \times 10^{-3}$  [A. Strumia 2204:04191]

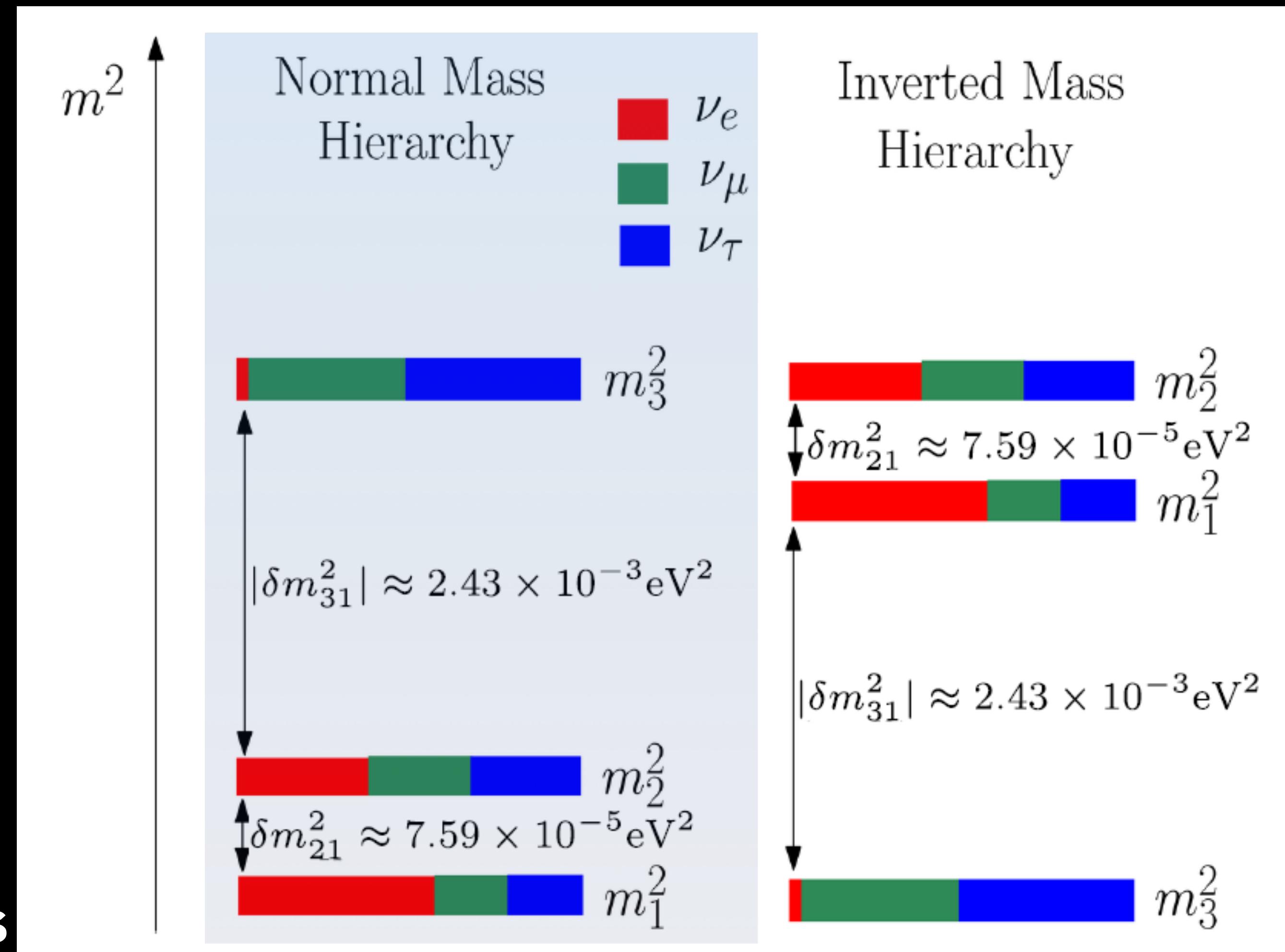
Must be independently confirmed

# Neutrinos

On its own, neutrino masses  
are an extraordinary indication  
for new physics (NP)

Can neutrino properties and B-  
anomalies be two faces of the  
same NP?

Use N.O. and PMNS mixing as  
input parameters in our analysis



[Taken from [mpi-hg.mpg.de](http://mpi-hg.mpg.de)]

**Inputs SM + neutrinos:**  $v$ ,  $m_h$ ,  $m_q$ ,  $m_\ell$ ,  $m_\nu$ ,  $V_{\text{CKM}}$ ,  $V_{\text{PMNS}}$

$$1.5 < m_{\text{LQs}}/\text{TeV} < 8$$

$$-100 < a_1/\text{GeV} < 100$$

**Inputs LQs:**

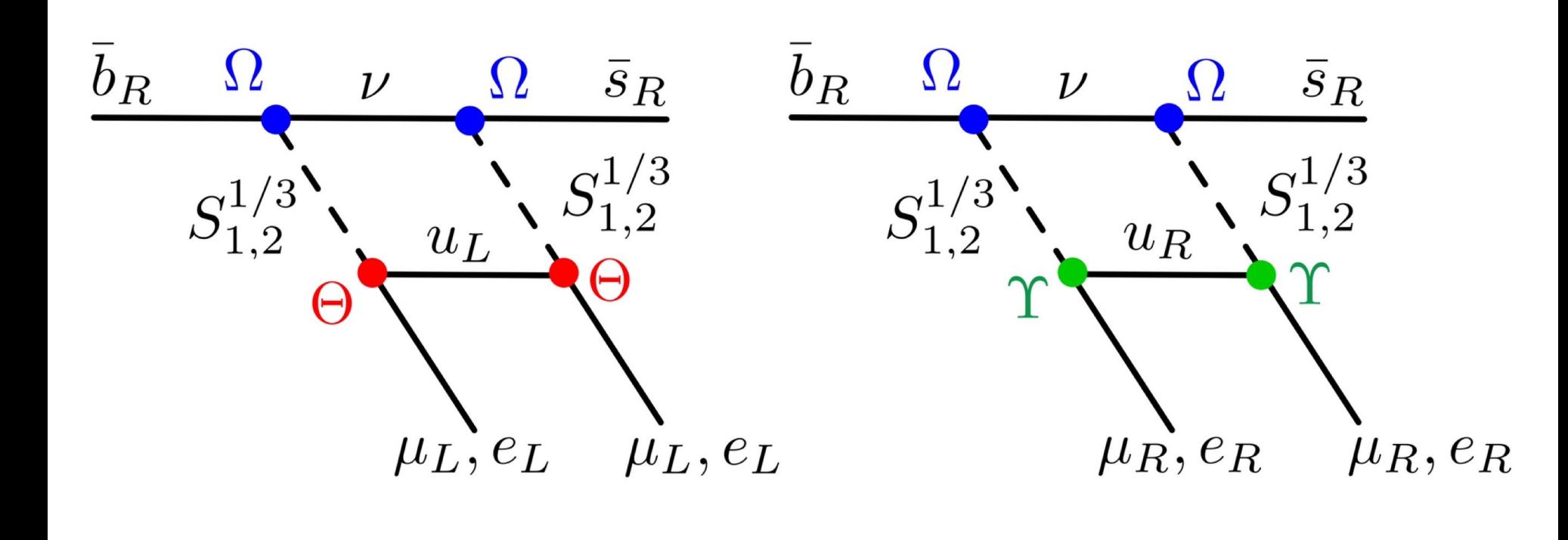
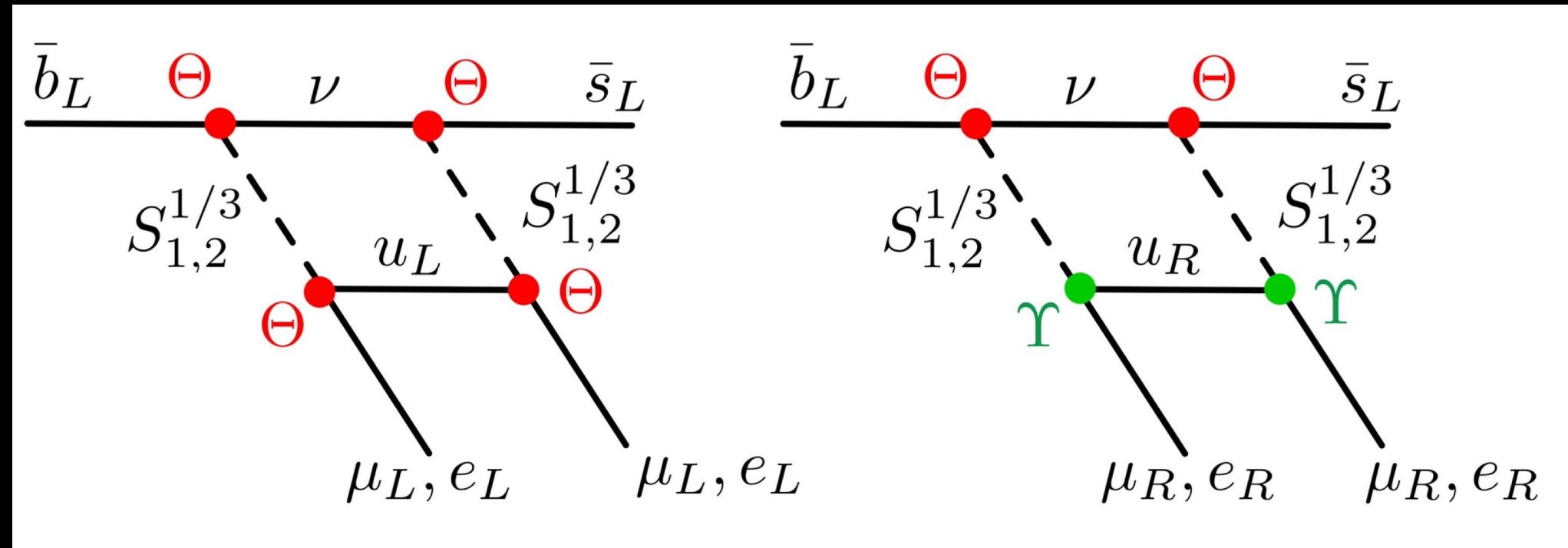
$$g_{HS}, g_{HR}, g'_{HR} \in \pm [10^{-8}, 4\pi] \quad \Upsilon, \Theta, \Omega \in \pm [10^{-8}, \sqrt{4\pi}]$$

$$m_{S_{1,2}^{1/3}}^2 = \begin{bmatrix} \mu_S^2 + \frac{g_{HS}v^2}{2} & \frac{va_1^*}{\sqrt{2}} \\ \frac{va_1}{\sqrt{2}} & \mu_R^2 + \frac{Gv^2}{2} \end{bmatrix} \quad m_{S^{2/3}}^2 = \mu_R^2 + \frac{Gv^2}{2} \quad G = (g_{HR} + g'_{HR})$$

Obtain a total of 9 entries of the  $\Theta$  and  $\Omega$  inverting the neutrino mass form

$$(M_\nu)_{ij} = \frac{3}{16\pi^2(m_{S_2^{1/3}}^2 - m_{S_1^{1/3}}^2)} \frac{v\textcolor{brown}{a}_1}{\sqrt{2}} \ln \left( \frac{m_{S_2^{1/3}}^2}{m_{S_1^{1/3}}^2} \right) \sum_{m,a} (m_d)_a V_{am} (\Theta_{im} \Omega_{ja} + \Theta_{jm} \Omega_{ia}),$$

*b* → *sℓℓ*



$$C_9^{bs\ell\ell}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\ell)$$

$$C_{10}^{bs\ell\ell}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu\gamma^5\ell)$$

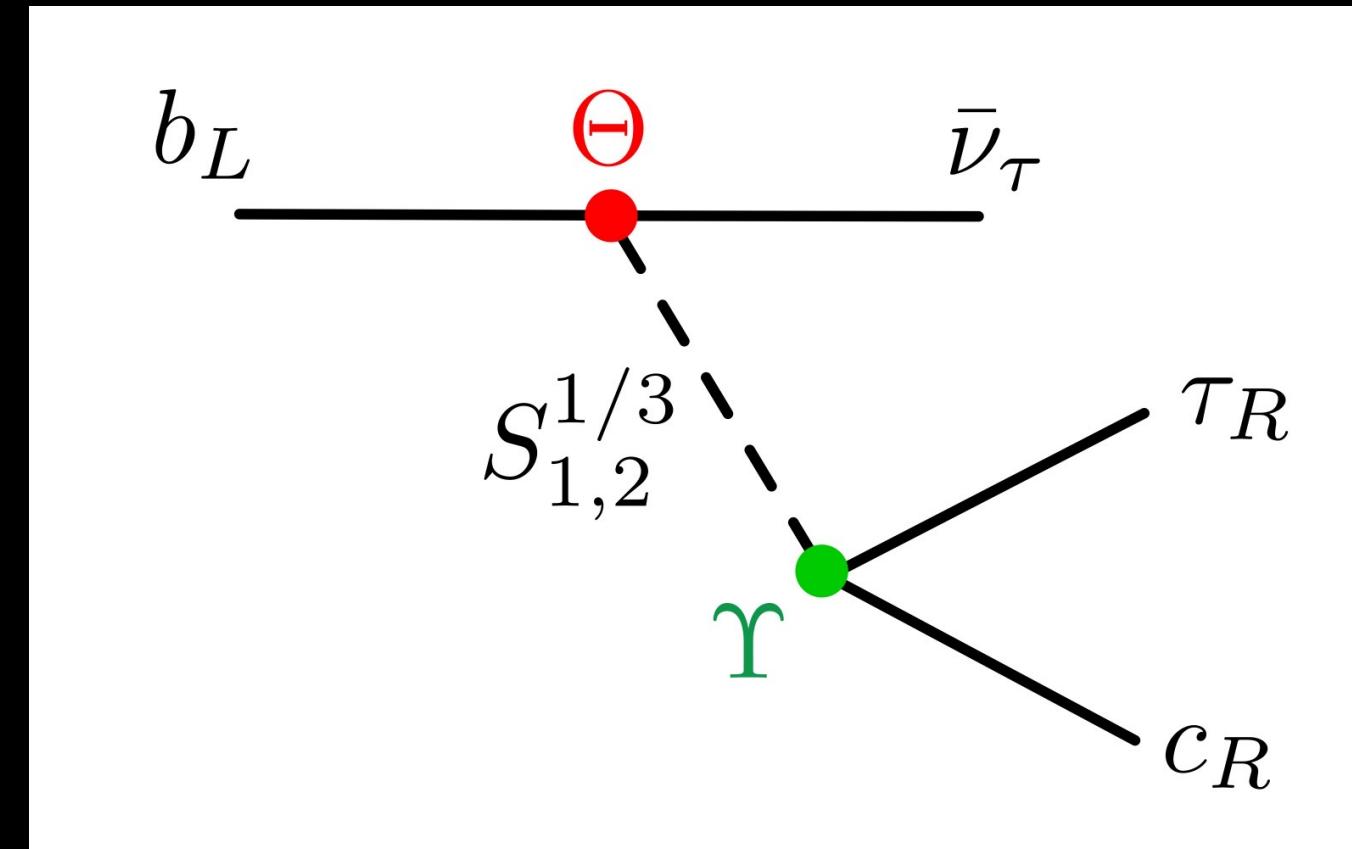
$$C_9'^{bs\ell\ell}(\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu\ell)$$

$$C_{10}'^{bs\ell\ell}(\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu\gamma^5\ell)$$

$$C_{9,10}^{bs\mu\mu} \text{ and } C_{9,10}^{bsee} \rightarrow R_K, R_{K^*} < 1$$

$$C_{9,10}^{bs\mu\mu} \text{ and } C_{9,10}^{bsee} \rightarrow R_K < 1 \text{ and } R_{K^*} > 1 \\ \text{or } R_K > 1 \text{ and } R_{K^*} < 1$$

$$b \rightarrow c\tau\bar{\nu}$$



$(\bar{c}_R b_L)(\bar{\tau}_R \nu_\tau)$  only to  $R_D$  as QCD form factor  $\langle D^* | \bar{c}b | \bar{B} \rangle = 0$

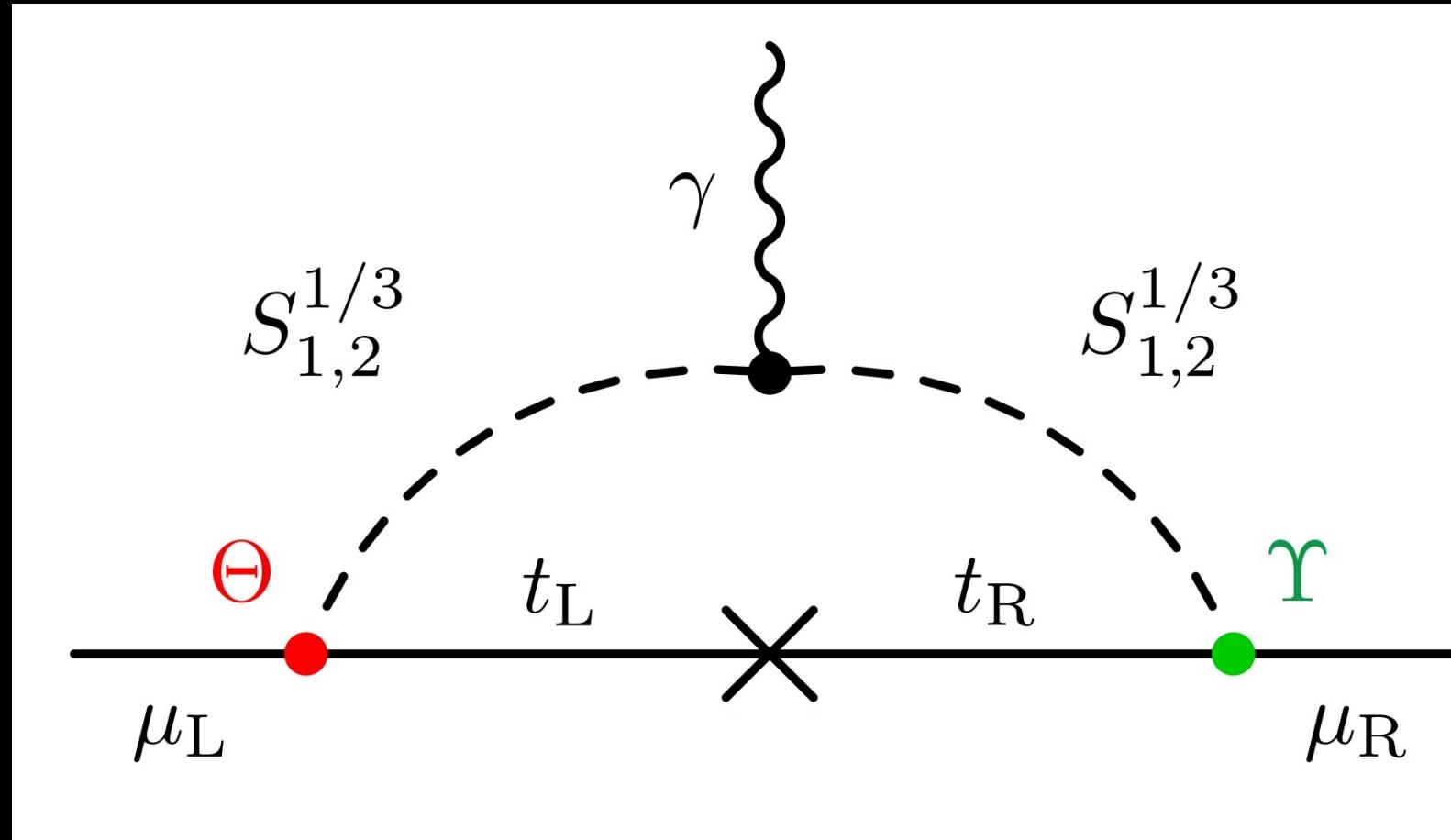
$(\bar{c}_R \gamma_5 b_L)(\bar{\tau}_R \nu_\tau)$  only to  $R_{D^*}$  as QCD form factor  $\langle D | \bar{c}\gamma_5 b | \bar{B} \rangle = 0$

[Bardhan, Bhakti, Ghosh, JHEP 01 (2017) 125]

$R_D$  and  $R_{D^*}$  compete with  $R_{K^*}^{\nu\nu} = \frac{Br(\bar{B} \rightarrow K^* \bar{\nu}\nu)}{Br(\bar{B} \rightarrow K^* \bar{\nu}\nu)^{\text{SM}}} < 2.7$  ( replace  $\Upsilon \rightarrow \Theta$ )

[Phys.Rev.D 96, 091101 (2017), Phys.Rev.D 97, 099902 (2018) addendum]

$a_\mu$



Largest contribution for the pairing:  $\Theta_{\mu t}$  and  $\Upsilon_{\mu t}$

However, other pairings can induce LFV decays as E.g.:

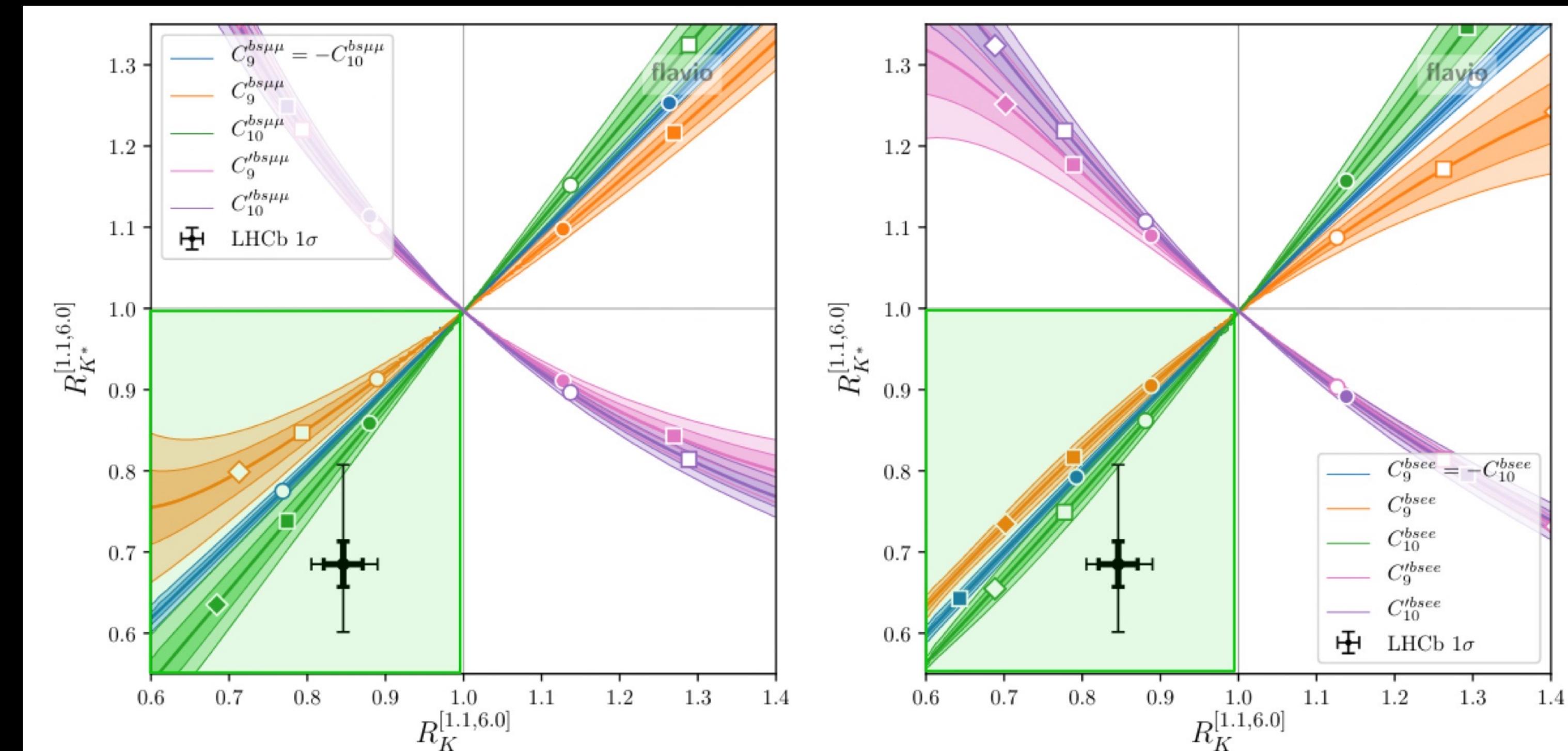
$$\Upsilon_{\mu t} \rightarrow \Upsilon_{et} : \mu \rightarrow e\gamma, \mu \rightarrow eee$$

Hierarchies in the entries of LQ Yukawa matrices needed

# Recall that...

$C_{9,10}^{bs\mu\mu}$  and  $C_{9,10}^{bsee} \rightarrow R_K, R_{K^*} < 1$

$C_{9,10}'^{bs\mu\mu}$  and  $C_{9,10}'^{bsee} \rightarrow R_K < 1$  and  $R_{K^*} > 1$  or  $R_K > 1$  and  $R_{K^*} < 1$



# $[\text{SU}(3)]^3 \times \text{SU}(2)_F \times \text{U}(1)_F \longrightarrow \text{Flavour Unified Theory}$

[Morais, Pasechnik, Porod, Eur. Phys. J. C 80, (2020) 12, 1162]

[Morais, Pasechnik, Porod, Universe 7 (2021) 12, 451]

$$L = \begin{pmatrix} H & \ell_L \\ \ell_R & \phi \end{pmatrix} \quad Q_L = \begin{pmatrix} q_L & D_L \end{pmatrix} \quad Q_R = \begin{pmatrix} q_R^c & D_R^c \\ \tilde{R}_2 & S_1 \end{pmatrix}^\top$$

This FUT contains an emergent  $\mathbb{Z}_2$  B-parity

$$\mathbb{P}_B = (-1)^{3B+2S}$$

$L$	$\tilde{L}$	$Q_L$	$\tilde{Q}_L$	$Q_R$	$\tilde{Q}_R$	
$P_B$	-	+	+	-	+	-

- **Forbids di-quark interactions**

- **Only allows leptoquark interactions**

$$S_1 = \tilde{R}_2$$

$$- + - - - +$$

$$L Q_L \tilde{Q}_R + L \tilde{Q}_L Q_R$$

- **Proton is stable**