



University of  
Zurich<sup>UZH</sup>

# A multi-scale origin for flavor

---

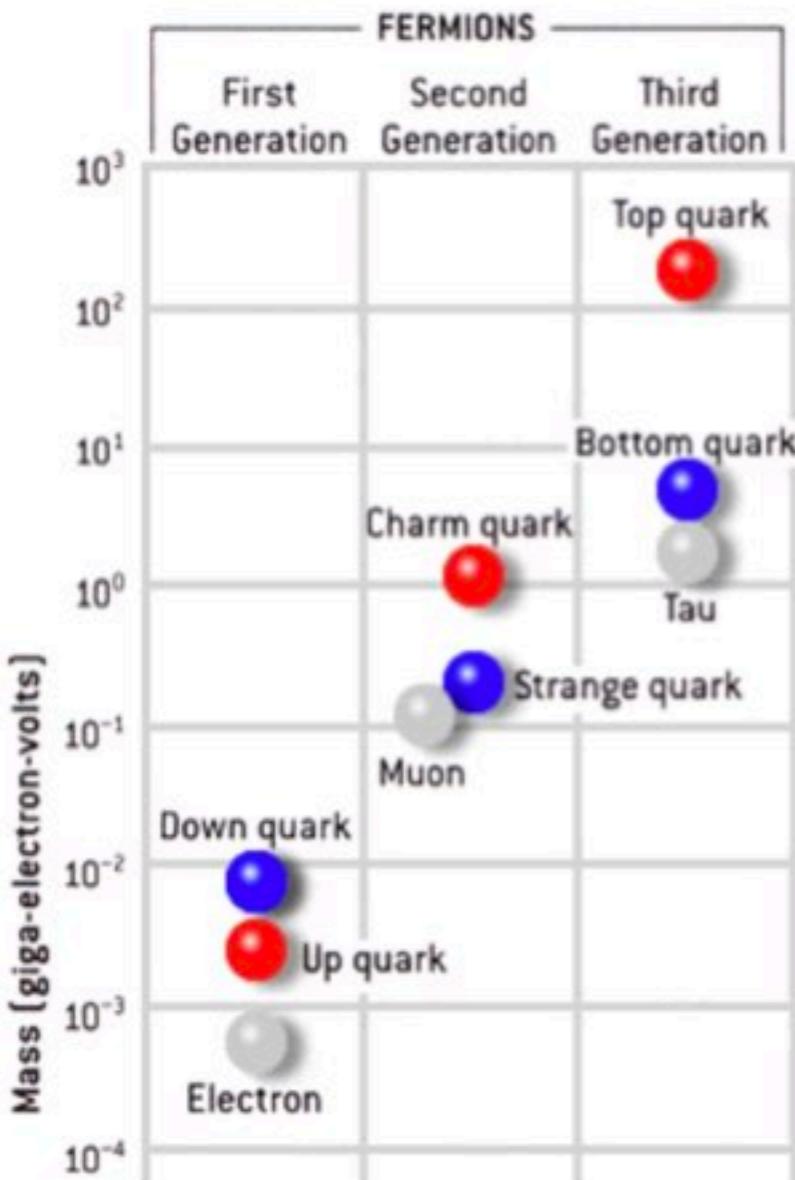
**Javier M. Lizana**  
Zurich University

Based on: [2203.01952](#), [2302.11584](#), [2306.09178](#)

**SUSY 2023 - The 30th International Conference on Supersymmetry and  
Unification of Fundamental Interactions**

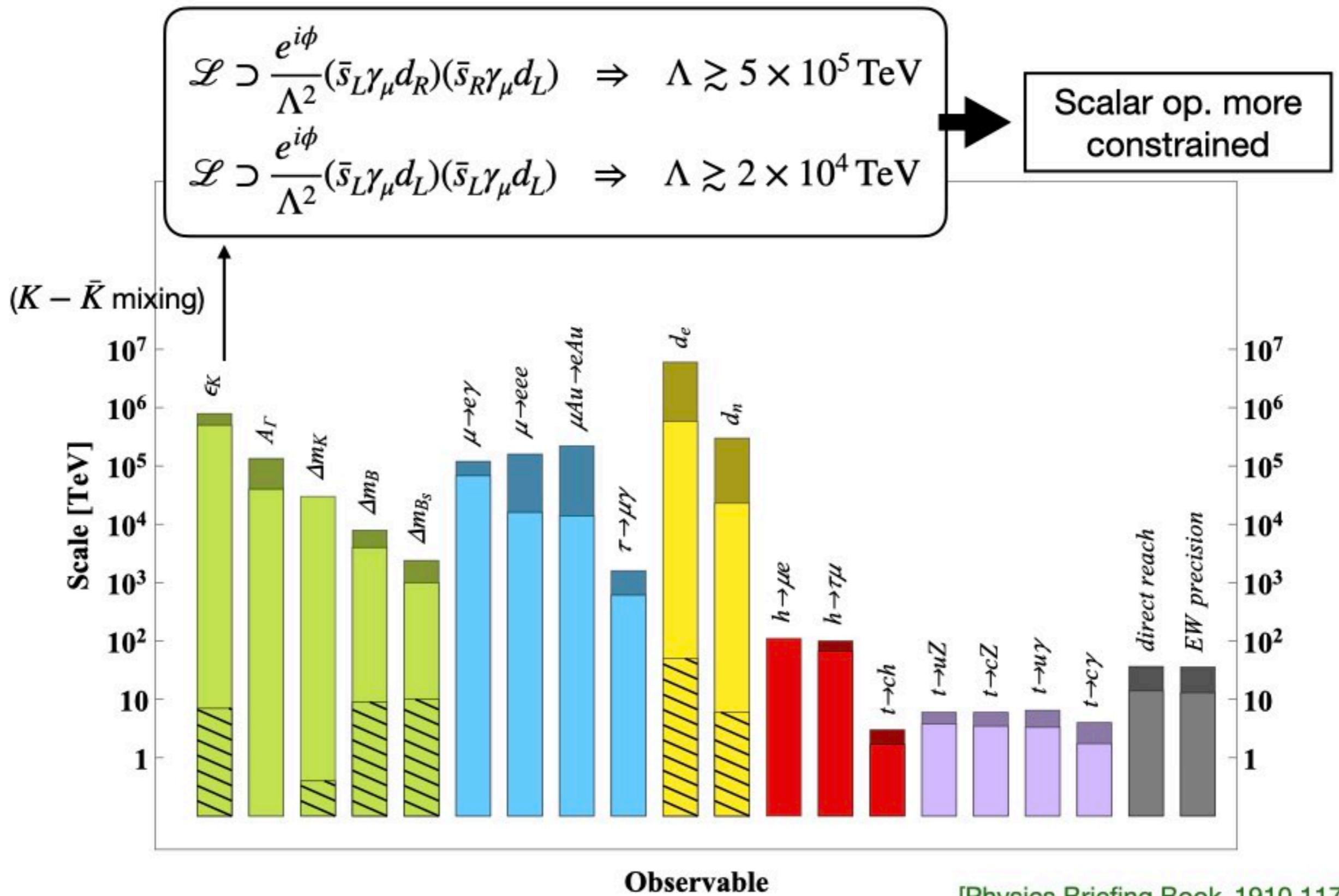
# A first flavor puzzle

- **Flavor puzzle:** very hierarchical structures



$$M_{u,d,e} \sim \begin{bmatrix} & & \\ & & \\ & & \end{bmatrix}$$
$$V_{\text{CKM}} \sim \begin{bmatrix} & & \\ & & \\ & & \end{bmatrix}$$
$$|V_{\text{CKM}}| = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}$$

# A second flavor puzzle



[Physics Briefing Book, 1910.11775]

# Consequences?

- NP addressing the first flavor puzzle will create dangerous contributions to flavor observables.
- No NP up to very high scales?
- But hierarchy problem: we expect NP at the TeV scale at least coupled to the 3rd family.



Naive conclusions:

- NP at the TeV scale cannot address the flavor puzzle.
- Universal NP at the TeV? More and more constrained by LHC....

**Let's explore other possibilities**

# Flavor symmetries of SM

- Flavor symmetry  $U(3)^5$ , only broken by Yukawas:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + \bar{\psi}_a \not{D} \psi_a + |D_\mu H|^2 - V(H) + (Y_{ab} \bar{\psi}_L^a H \psi_R^b + \text{h.c.})$$

$$U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_e \times U(3)_e$$

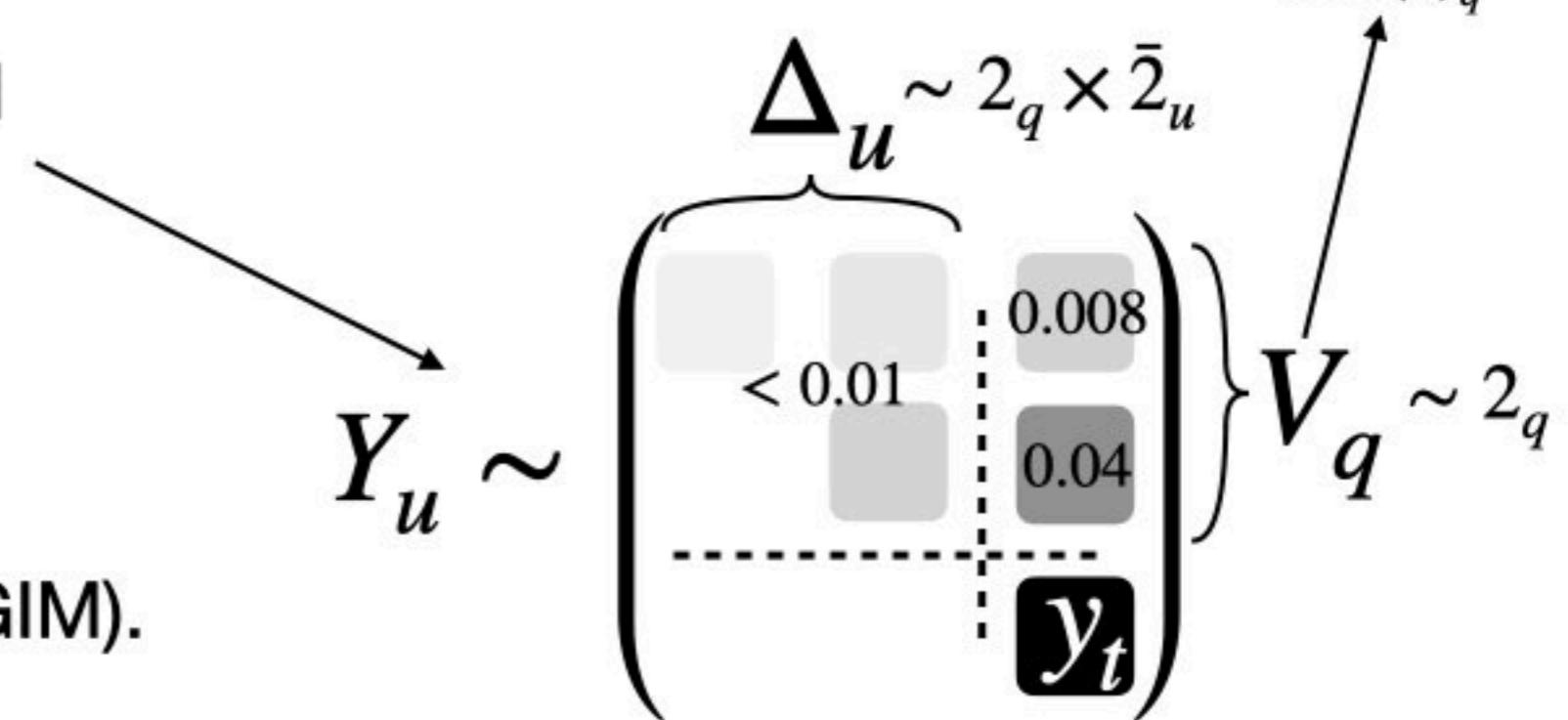
Largest breaking  
of  $U(2)_q$

- $Y_{u,d,e}$  very hierarchical

- To leading order:

$$U(3)^5 \xrightarrow{\text{3rd fam. Yuk.}} U(2)^5$$

- Protection in FCNC (GIM).



A good way to improve flavor bounds on NP is to preserve flavor symmetries and use similar spurions!

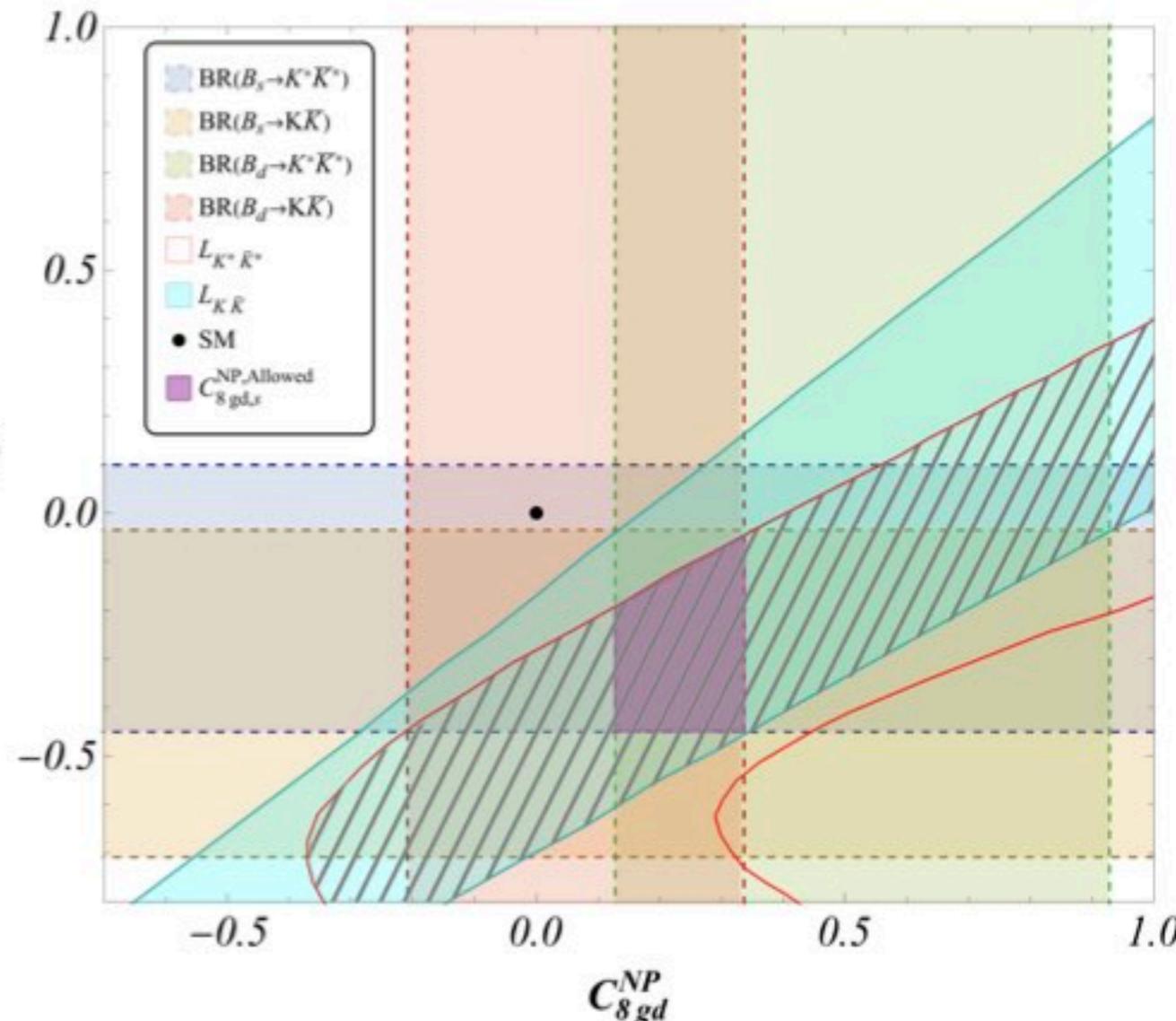
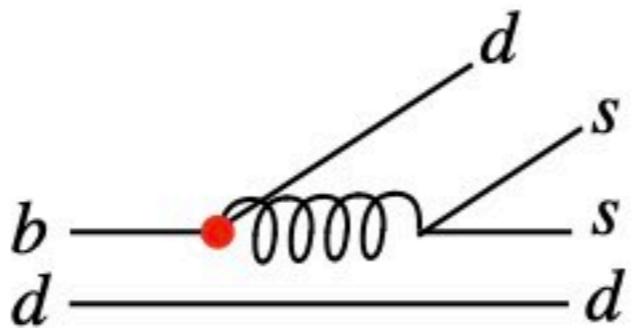
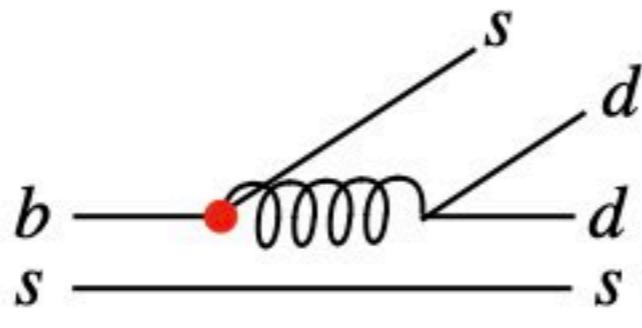
# Example: NP in $b \rightarrow s(d)qq$

$$\bar{B}_s \rightarrow K^{(*)}\bar{K}^{(*)} \\ (b \rightarrow sqq)$$

**vs**

$$\bar{B}_d \rightarrow K^{(*)}\bar{K}^{(*)} \\ (b \rightarrow dqq)$$

Chromod. dipole



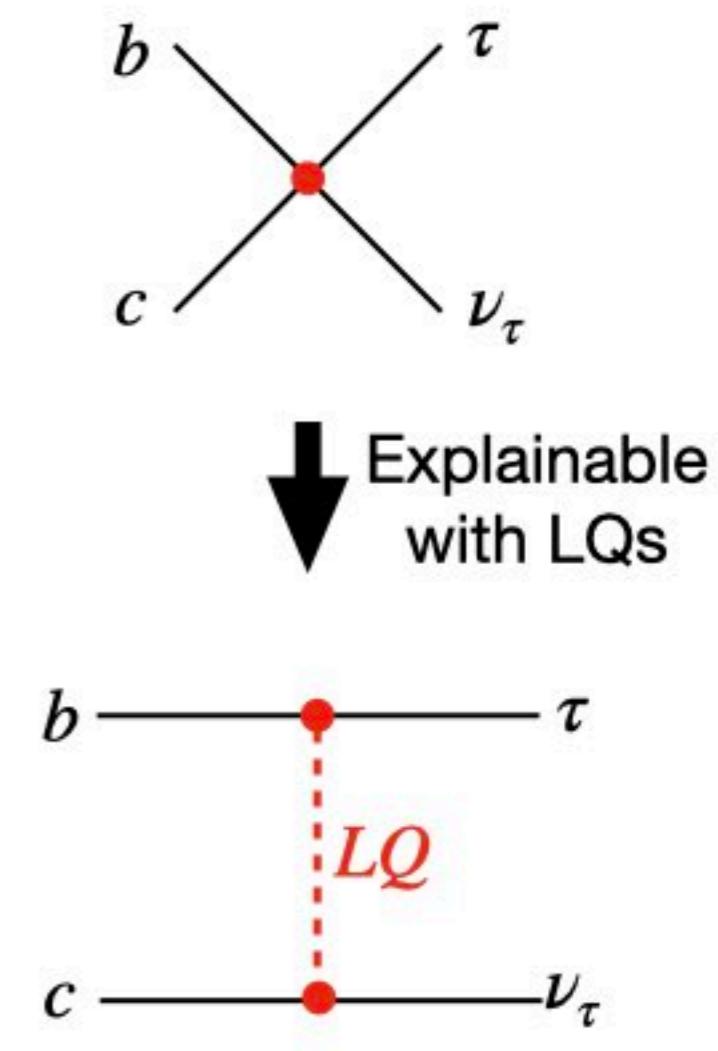
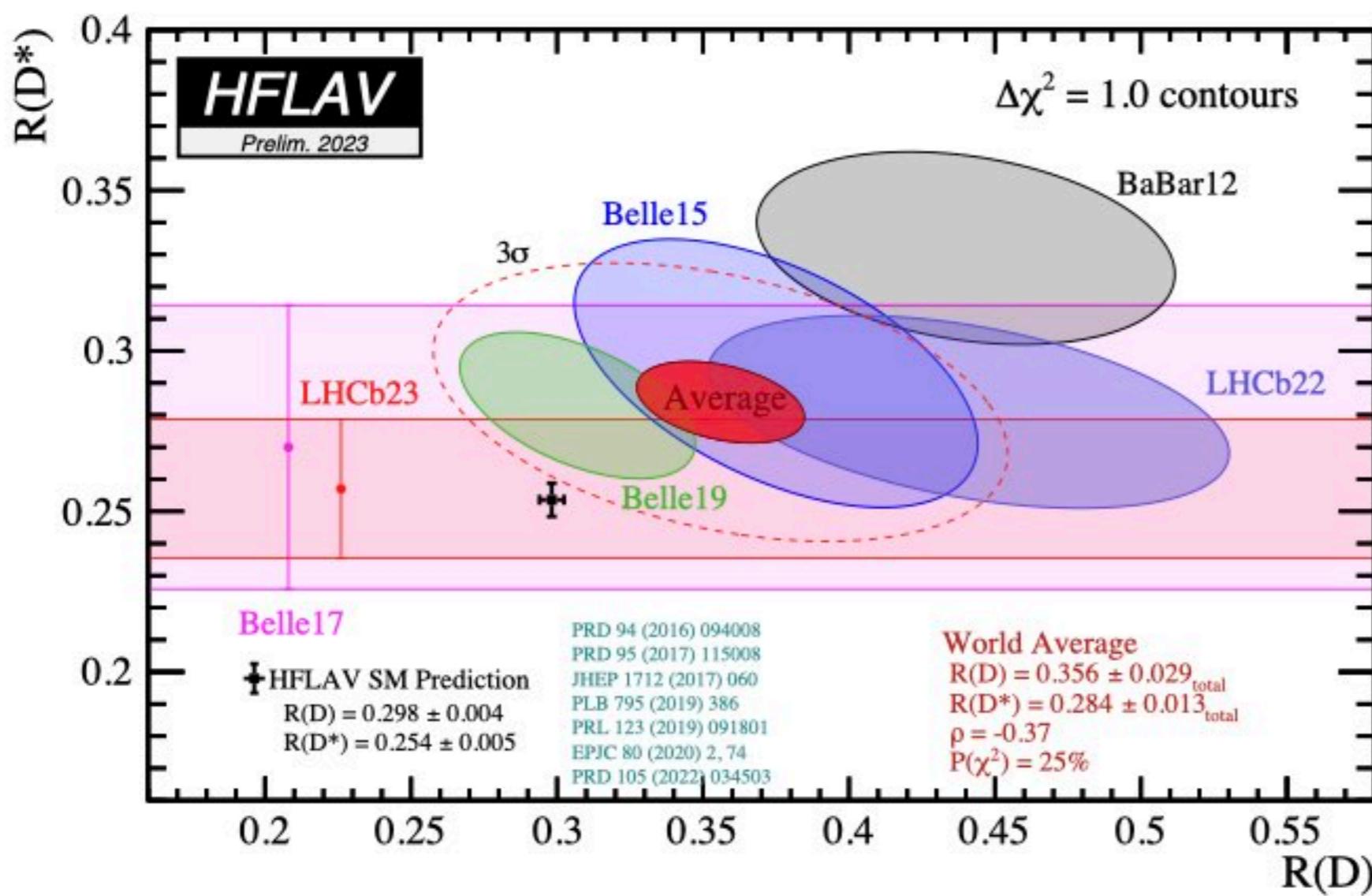
[Algueró, Crivellin, Descotes-Genon, Matias, Novoa-Brunet, [2011.07867](#)]  
 [Biswas, Descotes-Genon, Matias, Tetlalmatzi-Xolocotzi [2301.10542](#)]

...and  $b \rightarrow c\tau\nu$ :  $R_D^{(*)}$

$$R_{D^{(*)}} = \frac{Br(B \rightarrow D^{(*)}\tau\nu)}{Br(B \rightarrow D^{(*)}l\nu)}$$

$\gtrsim 3\sigma$

Enhancement of  
 $\sim 10\%$  over SM



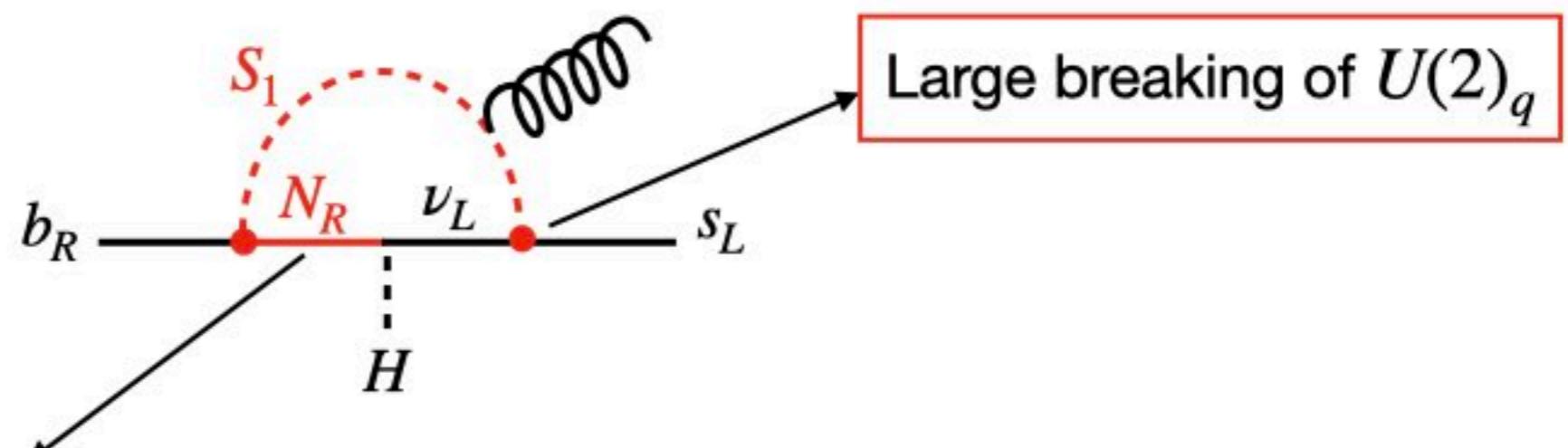
[J. Aebischer, G. Isidori, M. Pesut, B. Stefanek, F. Wilsch, [2210.13422](#)]

$B \rightarrow D^{(*)}\tau\nu$   
 $(b \rightarrow c\tau\nu)$

# Example: NP in $b \rightarrow s(d)qq$



- A scalar LQ  $S_1 \sim (3, 1)_{-1/3}$  can generate the dipole and address  $R_{D^{(*)}}$ .



We need a TeV  $N_R$  with a *large* Yukawa  $\rightarrow$  Inverse seesaw

$$\mathcal{L} \supset -y_\nu \bar{\ell}_L^3 \tilde{H} N_R - M_R \bar{N}_L N_R - \frac{1}{2} \mu \bar{N}_L N_L^c \quad (\mu \ll M_R)$$

$$\nu_L^3 \rightarrow \cos(\theta_\tau) \nu_L^3 + \sin(\theta_\tau) N_L$$

$$\sin(\theta_\nu) = y_\nu v_{EW}/M_R \rightarrow W \text{ (W boson)} \rightarrow \tau_L \text{ (tau lepton)} \rightarrow \nu_L \text{ (neutrino)}$$

$\theta_\tau \lesssim 0.05$   
 (EWPD +  $\tau$  decays)

[JML, Matias, Stefanek, 2306.09178]

# Example: NP in $b \rightarrow s(d)qq$

$pp \rightarrow \tau\tau$  &  $pp \rightarrow \tau E_T^{\prime}$

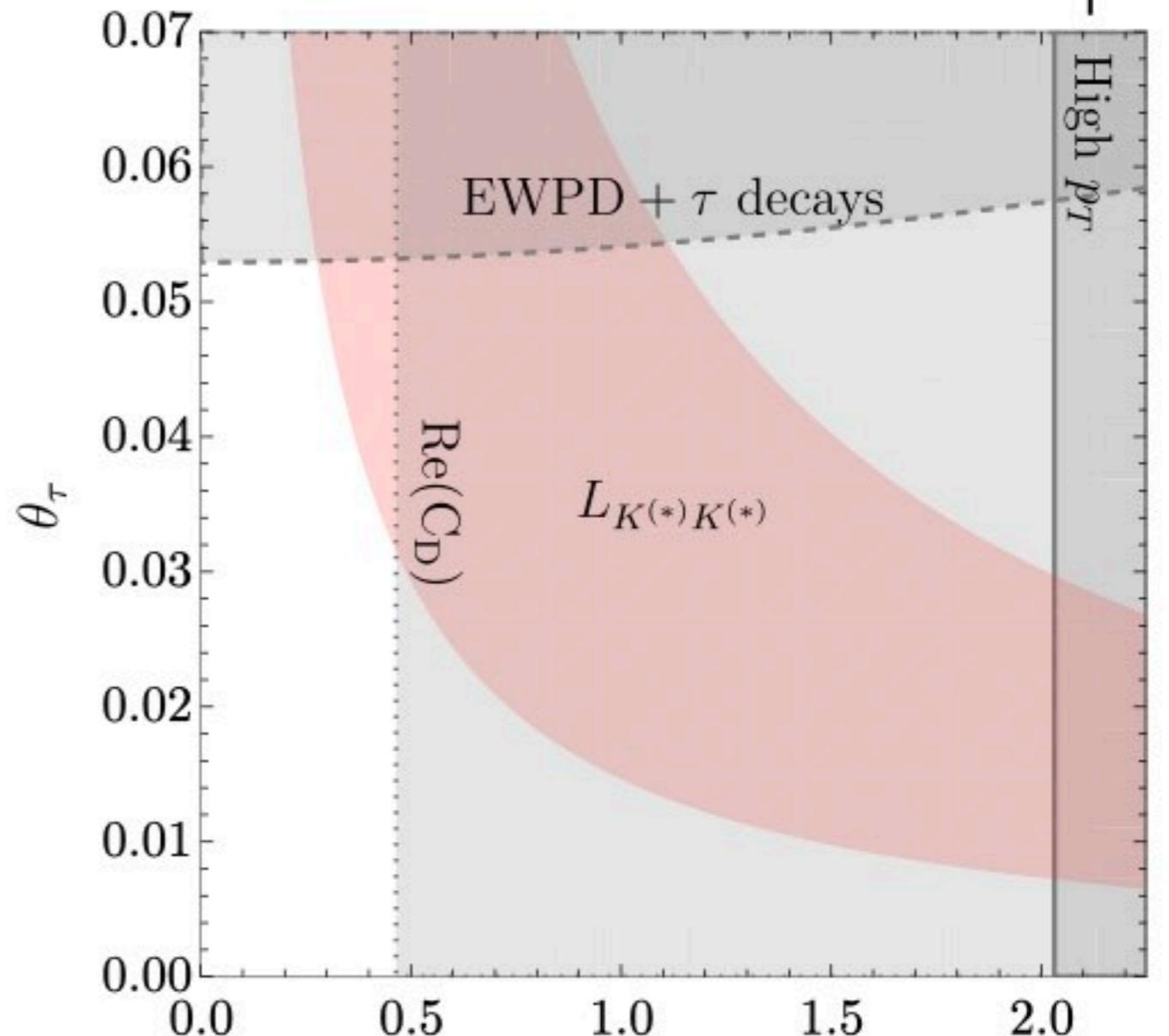
- Strong bounds from  $K \rightarrow \pi\nu\nu$  and  $D - \bar{D}$  mixing:

$$q_L^2 = \begin{pmatrix} V_{ud} c_L + V_{us} u_L \\ s_L \end{pmatrix}$$

$S_1$   $\tau_L$   $\ell_L^3$

$u_L \quad \tau_L \quad c_L$

$c_L \quad \tau_L \quad u_L$



[JML, Matias, Stefanek, [2306.09178](#)]

( $M_{S_1} = 2$  TeV,  $\lambda_R^b = -2$ )

# Example: $U(2)$ to the rescue



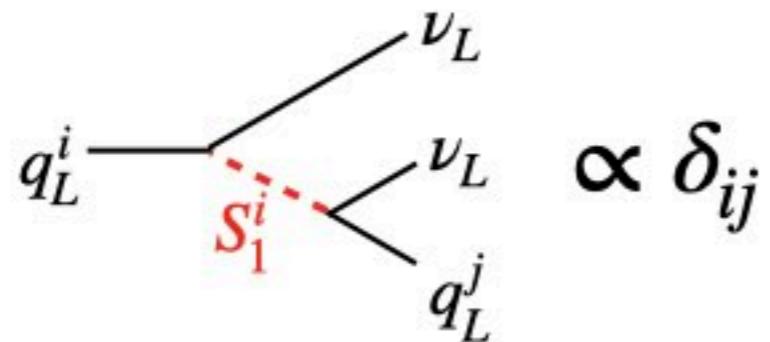
- Idea to improve the situation: promote  $S_1$  to a doublet of  $U(2)_q$ :

$$S_1 \longrightarrow (S_1^d, S_1^s)$$

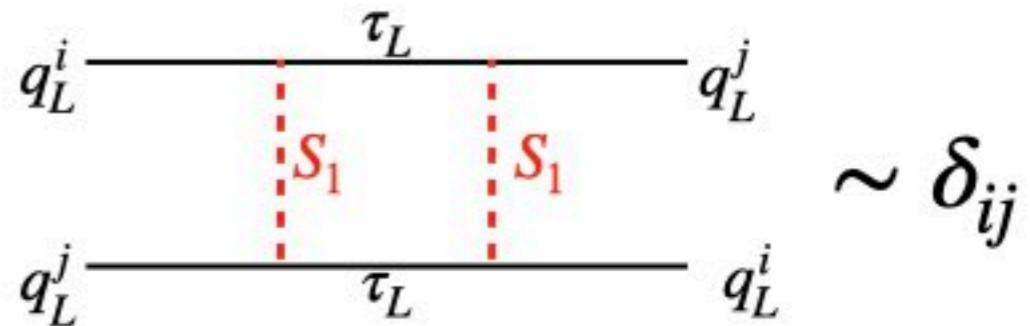
$$\lambda_L^s (\bar{q}_L^2 \epsilon \ell_3^c) S_1 \longrightarrow \lambda_L (\bar{q}_L^i \epsilon \ell_3^c) S_1^i$$

$$\mathcal{L} \supset \lambda_L (\bar{q}_L^i \epsilon \ell_L^{c3}) S_1^i + \textcolor{red}{V_R^i} \bar{b}_R^c N_R S_1^i - M_1 S_1^{\dagger i} S_1^i$$

- No  $K^+ \rightarrow \pi^+ \nu \nu$  at tree level:  
Possible NP in  $b \rightarrow d$  transitions.
- Suppressed contributions  $O(V_{ub}^2)$  to meson mixing.



$$\propto \delta_{ij}$$



$$\sim \delta_{ij}$$

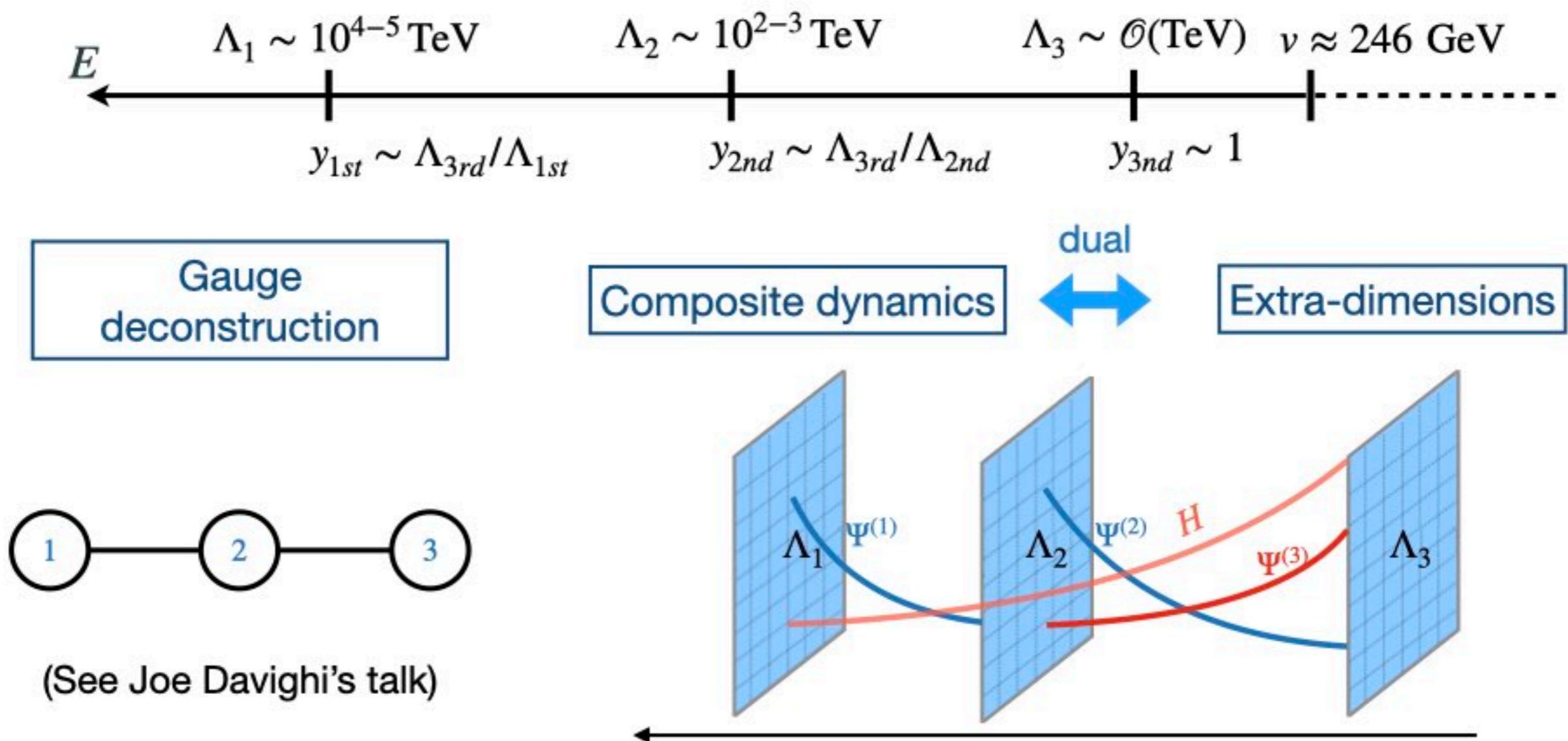
[JML, Matias, Stefanek, 2306.09178]

# Preserving flavor symmetries

- Promoting NP fields to  $U(2)$  or  $U(3)$  representations can be an effective way to preserve flavor symmetries and suppress FCNC in the light sector.
- A bit ad hoc and not addressing flavor hierarchies.
- Can this kind of NP emerge dynamically?
- $U(3) \Rightarrow$  Minimal Flavor Violation, emerging dynamically if flavor is explained at a higher scale.
- $U(2) \Rightarrow$  Emerging dynamically in a multi-scale explanation of flavor.

# Multiscale flavor

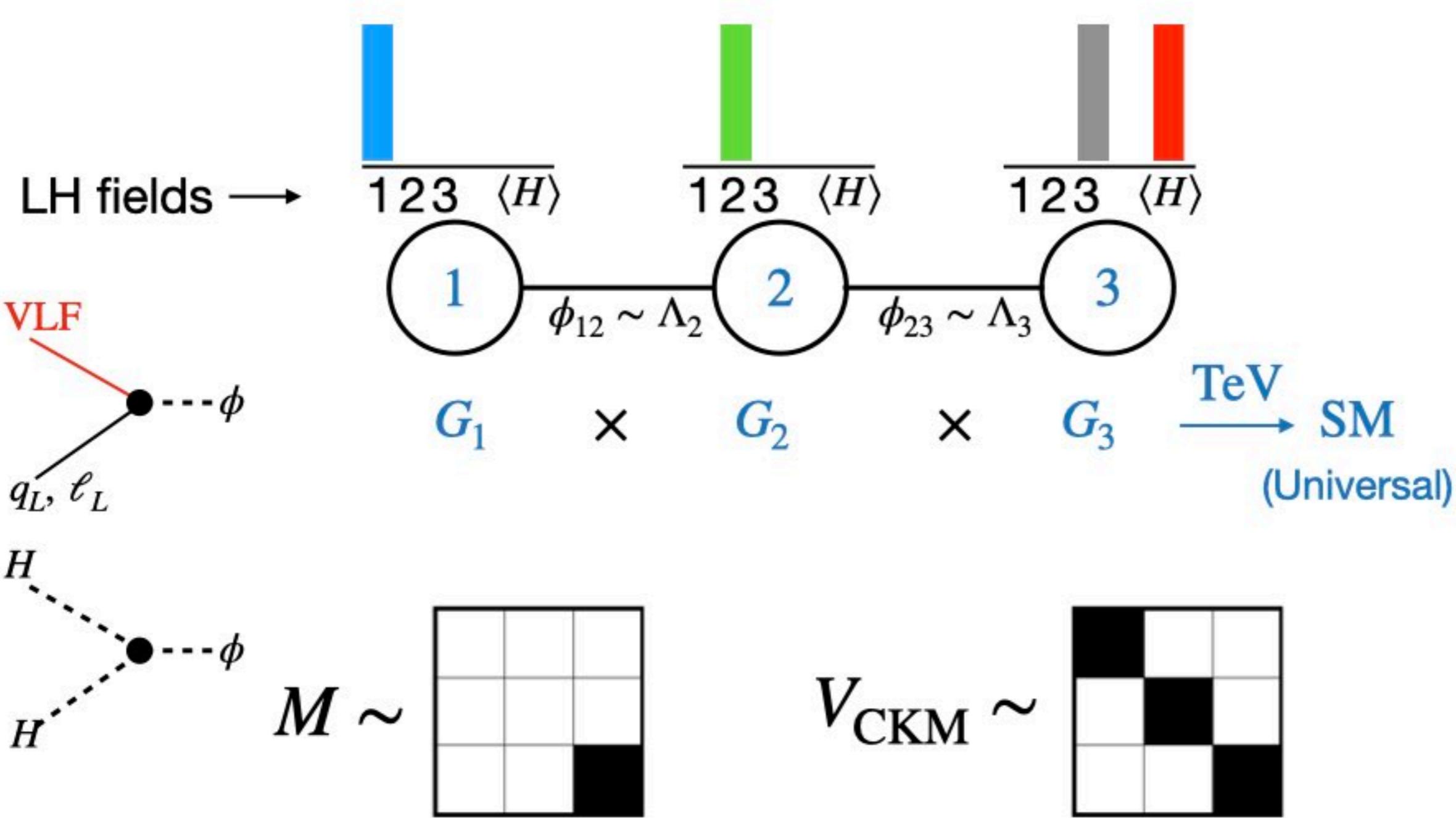
- Minimally broken  $U(2)$  emerges naturally in a **multiscale origin of the flavor hierarchies**:



[Panico, Pomarol, [1603.06609](#); Fuentes-Martin, Isidori, Pages, Stefanek [2012.10492](#);  
 Fuentes-Martin, Isidori, JML, Selimovic, Stefanek, [2203.01952](#)]

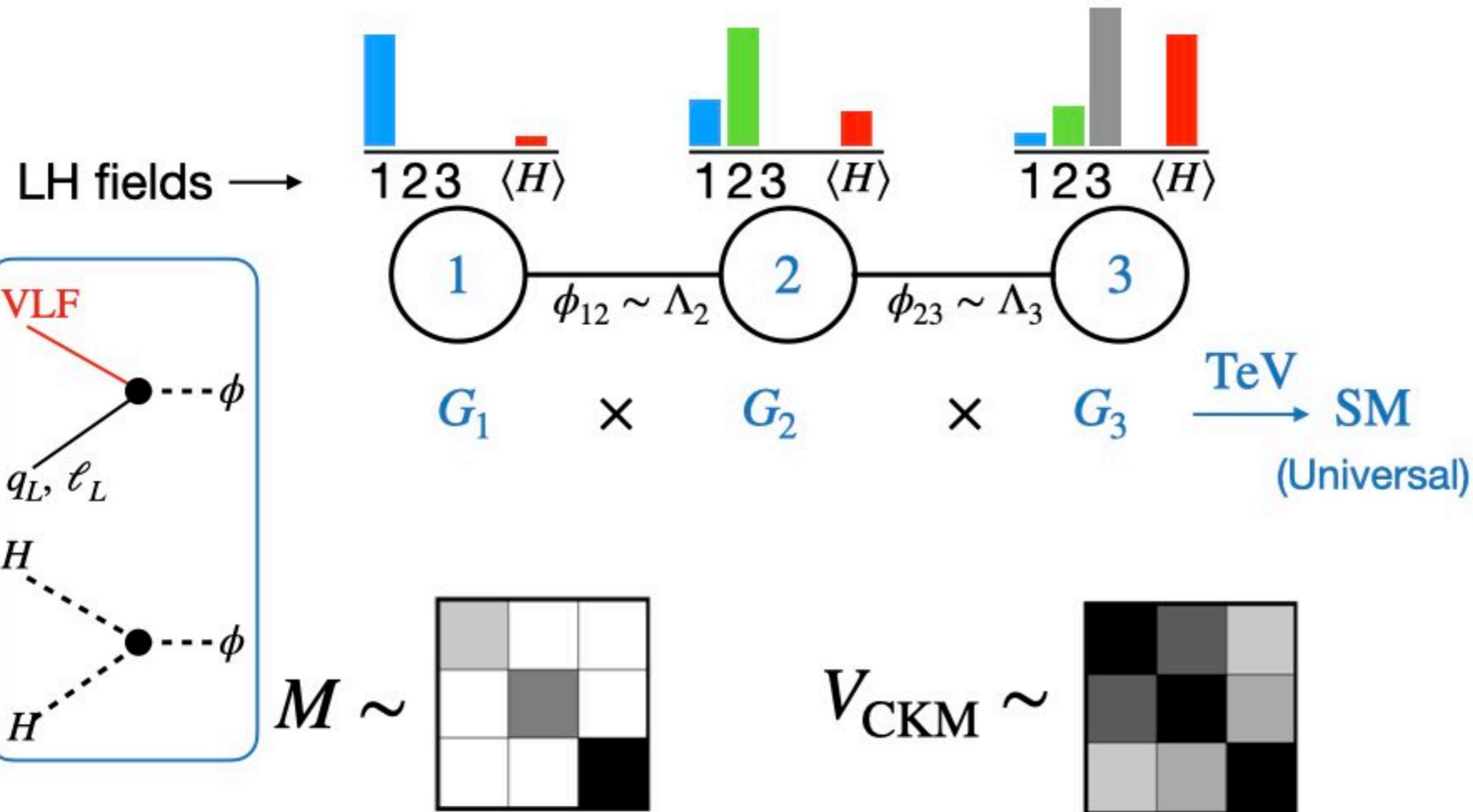
[Bordone, Cornella, Fuentes-Martin, Isidori,  
[1712.01368](#),  
Davighi, Isidori, [2303.01520](#),  
Fernández-Navarro, King, [2305.07690](#),  
Davighi, Stefanek, [2305.16280](#)]

# Deconstructing flavor



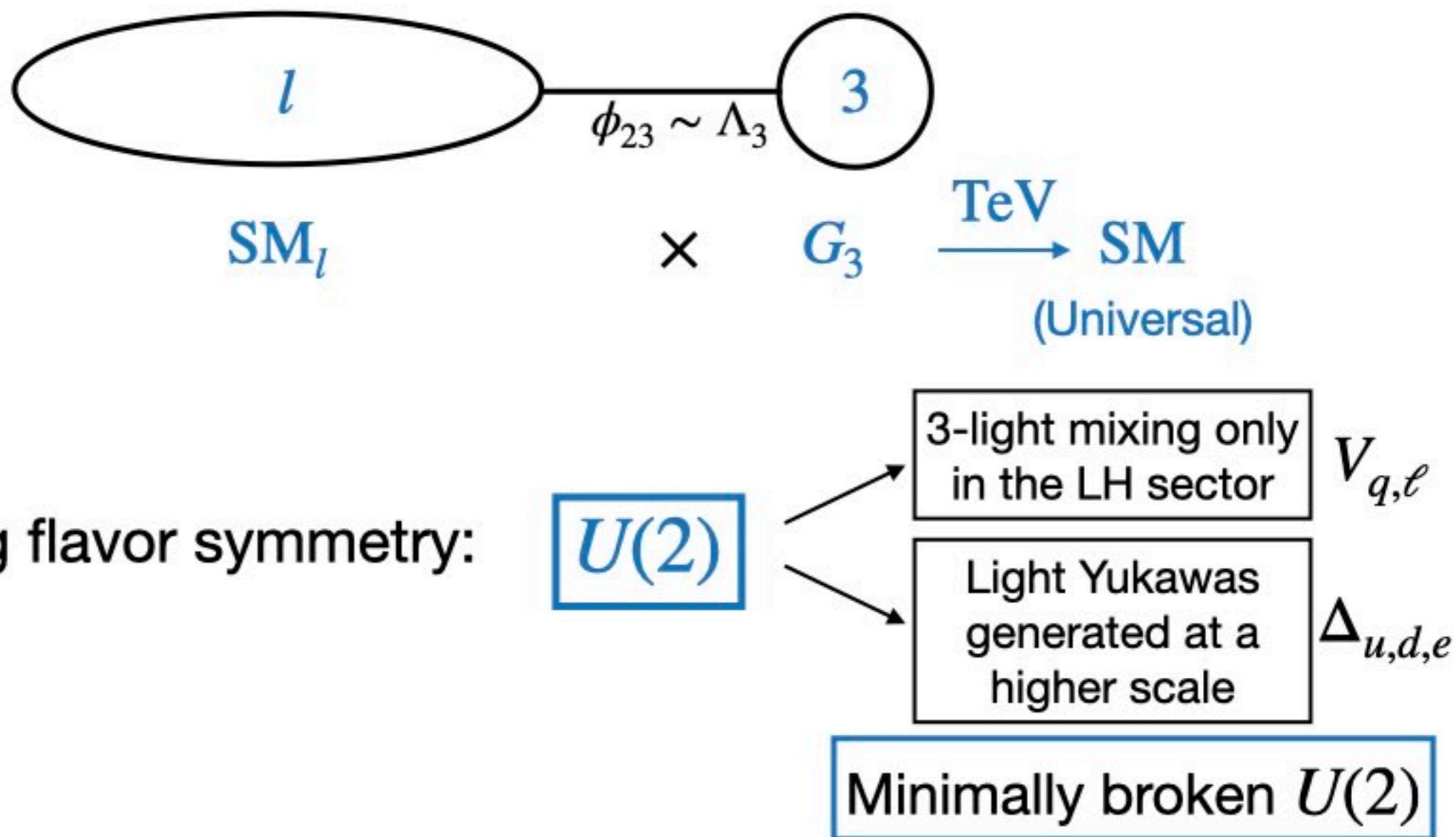
[Bordone, Cornella, Fuentes-Martin, Isidori,  
[1712.01368](#),  
Davighi, Isidori, [2303.01520](#),  
Fernández-Navarro, King, [2305.07690](#),  
Davighi, Stefanek, [2305.16280](#)]

# Deconstructing flavor



# Deconstructing flavor

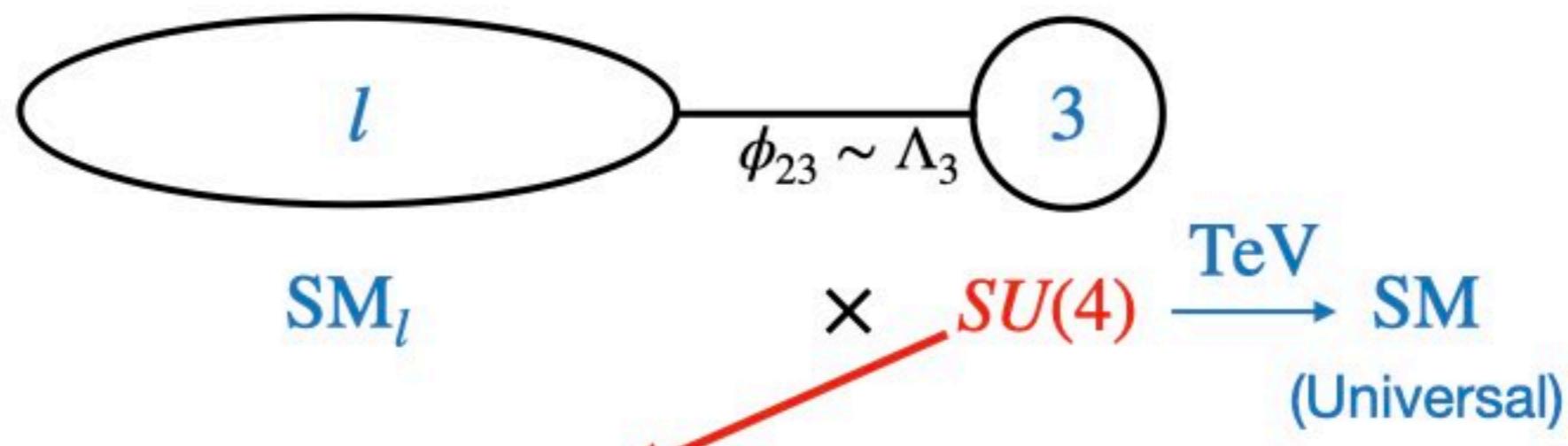
- From the TeV, we see...



- Emerging flavor symmetry:

# Deconstructing flavor

- From the TeV, we see...



$$\Psi_{L/R} = \begin{pmatrix} q_{L,R}^1 \\ q_{L,R}^2 \\ q_{L,R}^3 \\ \ell_{L,R} \end{pmatrix}$$

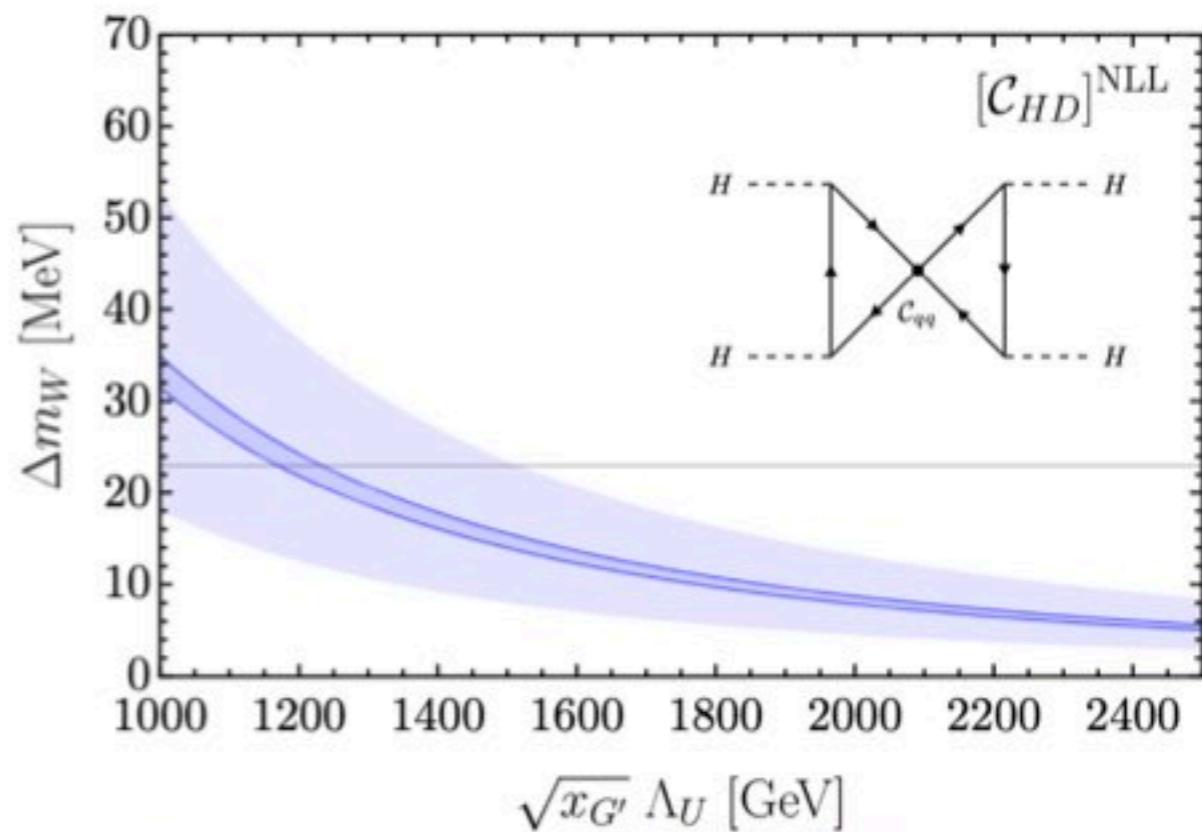
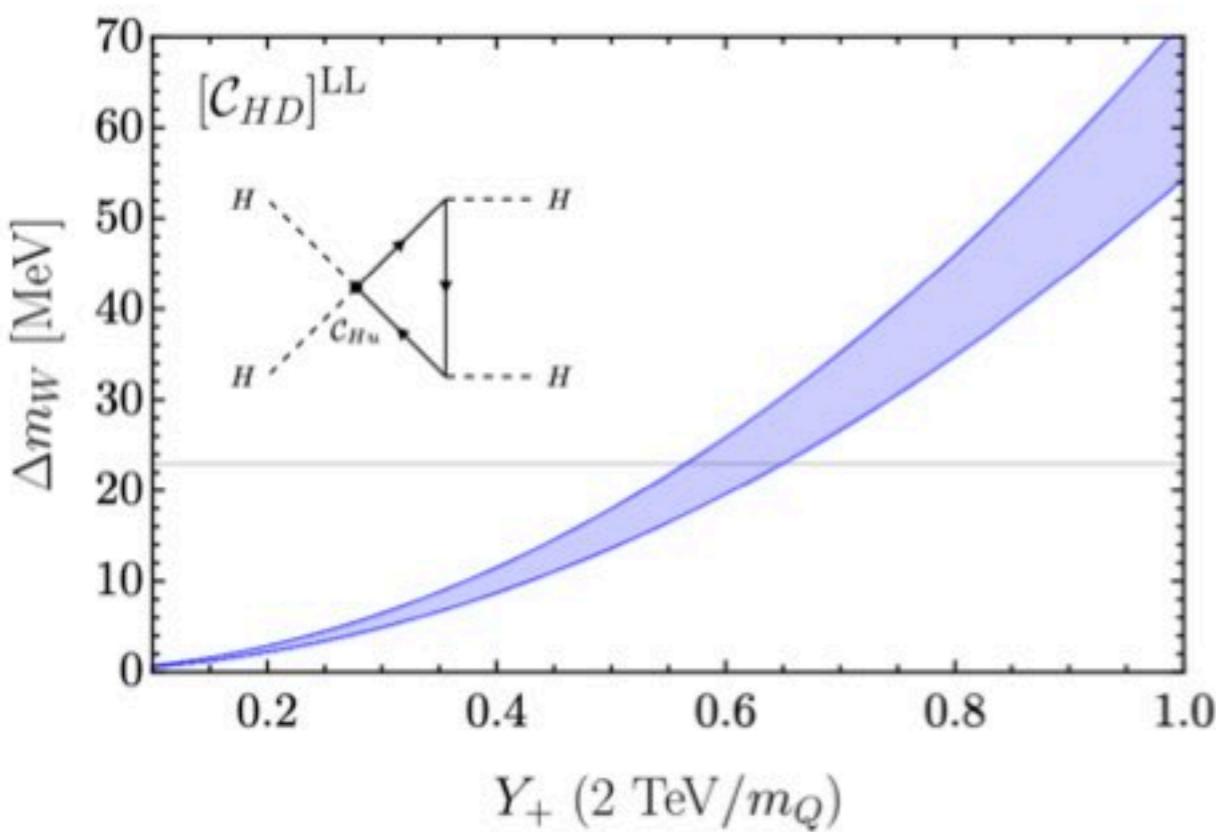
[Greljo, Stefanek, [1802.04274](#), Crosas, Isidori, JML, Selimović, Stefanek, [2203.01952](#),  
Allwicher, Isidori, JML, Selimović, Stefanek, [2302.11584](#)]

# Rich pheno of 4321: EW observables

- Provides an explanation for  $R_{D^{(*)}}$  through a  $U_1 \sim (3, 1)_{2/3}$  leptoquark.
- Extra neutral vector bosons  $G' \sim (\mathbf{8}, \mathbf{1})_0$ ,  $Z_1 \sim (\mathbf{1}, \mathbf{1})_0$  and vector like fermions,  $Q \sim (\mathbf{3}, \mathbf{2})_{1/6}$ ,  $L \sim (\mathbf{1}, \mathbf{2})_{-1/2}$ .
- New colored  $Q, G'$  states can give sizeable shift in the W-mass via RGE effects.

$$\begin{array}{c} C_{Hu} \\ \searrow \\ C_{qq} \end{array}$$

$$\frac{\Delta m_W}{m_W} \supset -\frac{v^2}{4} \frac{g_L^2}{g_L^2 - g_Y^2} C_{HD}$$



[Allwicher, Isidori, JML, Selimović, Stefanek, 2302.11584]

$$y_\nu = y_t \cos(\chi) - Y_+ \sin(\chi)$$

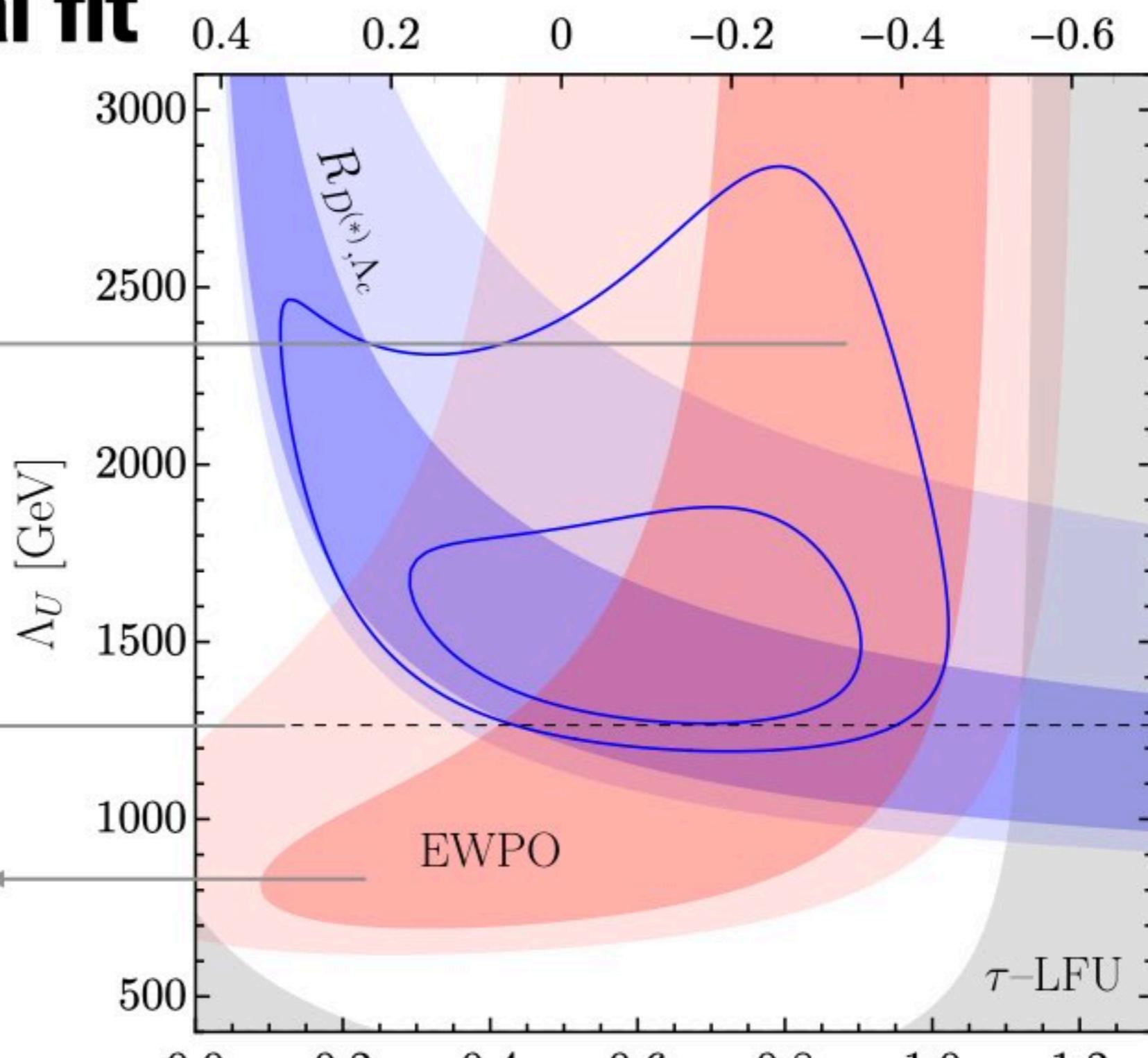
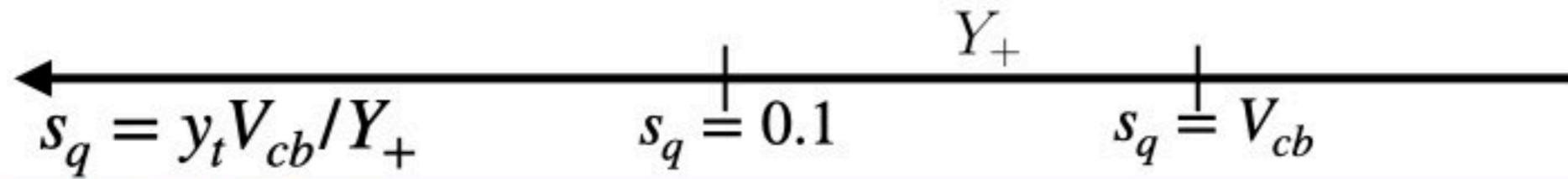
# 4321 Global fit

$m_W$  with CDF

$\mathcal{Q} \rightarrow \mathcal{O}_{HD}$

95 % CL CMS  $pp \rightarrow \tau\tau$

$\mathcal{G}' \rightarrow \mathcal{O}_{HD}$



# Conclusions

- The use of the flavor symmetries as  $U(2)$  is helpful to build models avoiding the strong flavor constraints.
- A multiscale explanation of the flavor hierarchies is highly interesting:
  - It would explain flavor at lower energies than traditional approaches.
  - It provides dynamical realizations of NP having  $U(2)$  at the TeV scale (perhaps addressing the hierarchy problem?).
- Non-universal gauge extensions of the SM become a natural possibility for BSM.
- It opens the possibility to have quark-lepton unification of the third family à la Pati-Salam at the TeV scale with a rich phenomenology.

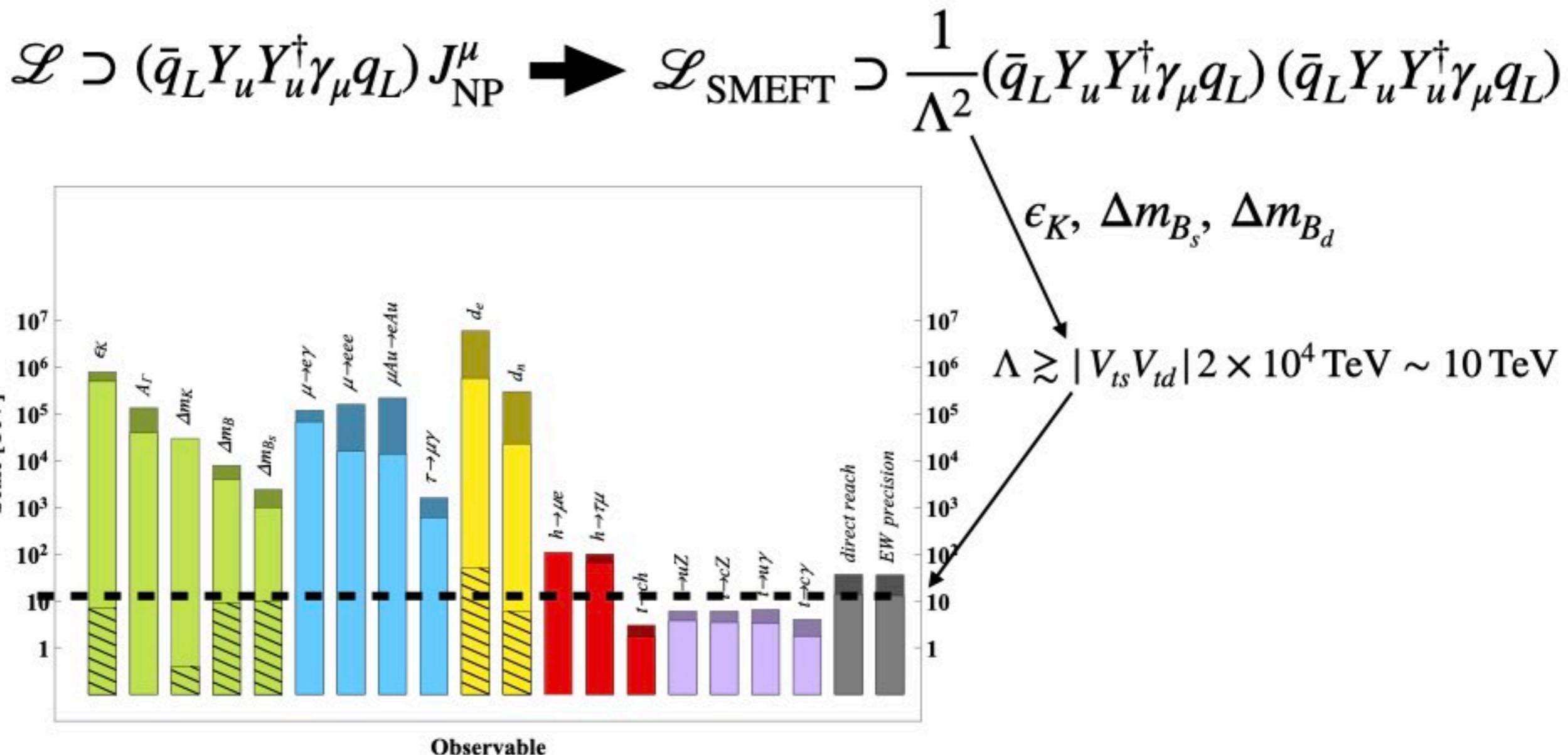
Thank you!

# **Backup**

# **Flavor symmetries**

# Minimal Flavor Violation

- NP couplings follow the same spurions,  $Y_{u,d,e} \sim 3_q \times \bar{3}_{u,d,e}$



[Physics Briefing Book, 1910.11775]

# Minimally broken $U(2)$

- A more interesting approach after LHC results: decorrelate light and 3rd families.

Exact $U(3)$	Exact $U(2)$
$\bar{q}_L^a \gamma_\mu q_L^a$	$c_h \bar{q}_L^3 \gamma_\mu q_L^3 + c_l \bar{q}_L^i \gamma_\mu q_L^i$

- NP with  $U(2)$  symmetry only broken by the SM spurions:

$$Y_{u,d,e} \sim \left( \begin{array}{c|c}
\Delta_{u,d,e} & \\
\hline
\begin{matrix} \text{---} & \text{---} \\ \vdots & \vdots \\ \text{---} & \text{---} \end{matrix} & \begin{matrix} \text{---} \\ \vdots \\ \text{---} \\ \hline \mathbf{y}_3 \end{matrix} \end{array} \right) \left. V_{q,\ell} \right\}$$

$V_q \sim 2_q \quad V_\ell \sim 2_\ell$   
 $\Delta_u \sim 2_q \times \bar{2}_u$   
 $\Delta_d \sim 2_q \times \bar{2}_d$   
 $\Delta_e \sim 2_q \times \bar{2}_\ell$

# Pheno of minimally broken $U(2)$

- Interesting signals:

Operator	Process
$(\bar{q}_L^i V_q^i \gamma_\mu q_L^3)^2$	$B_s$ mixing
$(\bar{q}_L^i V_q^i \gamma_\mu q_L^3)(\bar{\ell}_L^3 \gamma^\mu \ell_L^3)$	$R_{D^{(*)}}, B \rightarrow K\nu\nu,$ $B \rightarrow K\tau\tau, B_s \rightarrow \tau\tau$
$(\bar{q}_L^i V_q^i \tau^a \gamma_\mu q_L^3)(\bar{\ell}_L^3 \tau^a \gamma^\mu \ell_L^3)$	$B \rightarrow K\ell\ell, B_s \rightarrow \ell\ell$
$(\bar{q}_L^i V_q^i \gamma_\mu q_L^3)(\bar{H} i D^\mu H)$	
$(\bar{q}_L^i V_q^i \tau^a \gamma_\mu q_L^3)(\bar{\ell}_L^i V_\ell^i \tau^a \gamma^\mu V_\ell^{\dagger i} \ell_L^i)$	$R_{K^{(*)}}$

↓  
It becomes a bound on  $V_\ell$

# **Non-leptonic B decays**

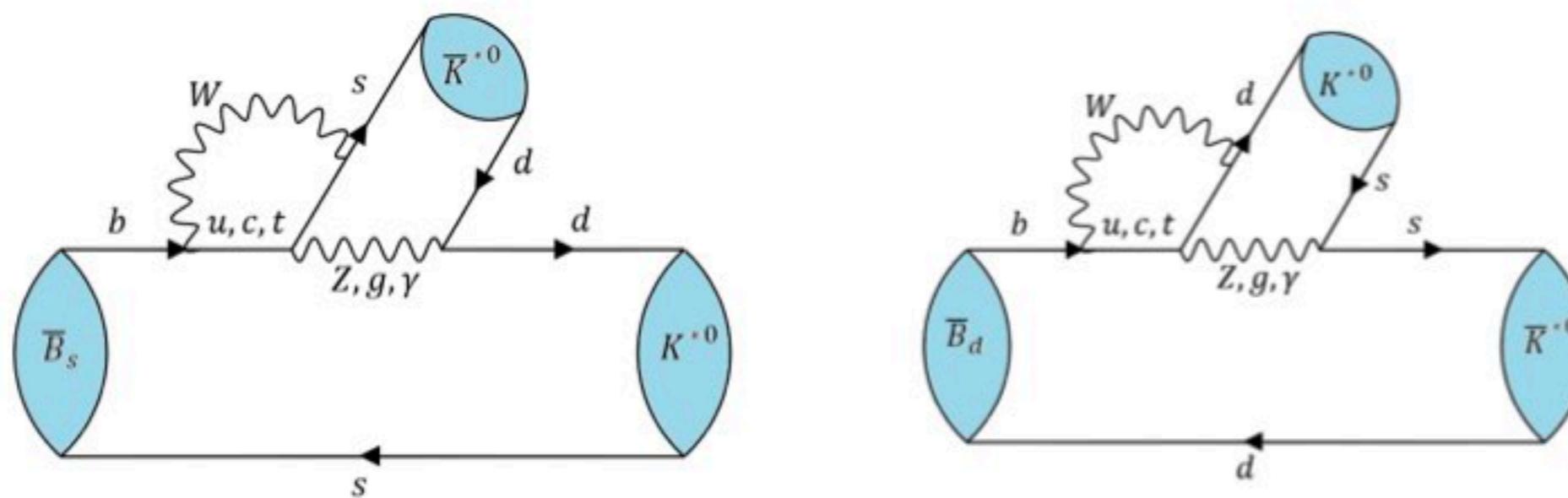
# $L_{K^{(*)}\bar{K}^{(*)}}$ observables

- Something is going on with the non-leptonic B decays.
- We focus on the  $L_{K^{(*)}\bar{K}^{(*)}}$  observables:

$$L_{K^*\bar{K}^*} = \rho(m_{K^{*0}}, m_{\bar{K}^{*0}}) \frac{\mathcal{B}(\bar{B}_s \rightarrow K^{*0}\bar{K}^{*0})}{\mathcal{B}(\bar{B}_d \rightarrow K^{*0}\bar{K}^{*0})} \frac{f_L^{B_s}}{f_L^{B_d}} = \frac{|A_0^s|^2 + |\bar{A}_0^s|^2}{|A_0^d|^2 + |\bar{A}_0^d|^2}$$

Longitudinal component of  $B \rightarrow K^{(*)}\bar{K}^{(*)}$

$$L_{K\bar{K}} = \rho(m_{K^0}, m_{\bar{K}^0}) \frac{\mathcal{B}(\bar{B}_s \rightarrow K^0\bar{K}^0)}{\mathcal{B}(\bar{B}_d \rightarrow K^0\bar{K}^0)} = \frac{|A^s|^2 + |\bar{A}^s|^2}{|A^d|^2 + |\bar{A}^d|^2}$$



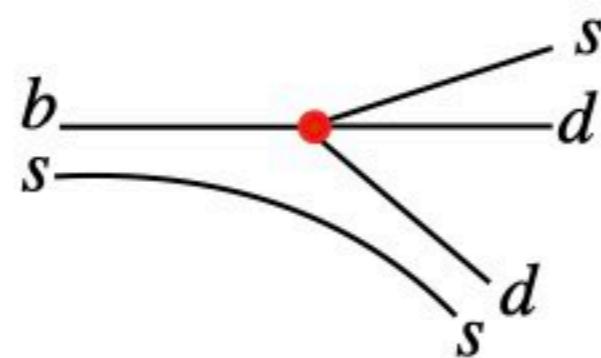
# NP in $L_{K^{(*)}\bar{K}^{(*)}}$

$$L_{K^*\bar{K}^*}^{\text{SM}} = 19.53^{+9.14}_{-6.64} \quad L_{K^*\bar{K}^*}^{\text{exp}} = 4.43 \pm 0.92 \rightarrow 2.6\sigma$$

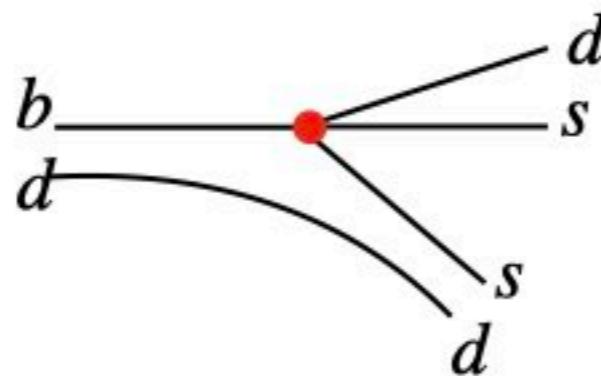
$$L_{K\bar{K}}^{\text{SM}} = 26.00^{+3.88}_{-3.59} \quad L_{K\bar{K}}^{\text{exp}} = 14.58 \pm 3.37 \rightarrow 2.4\sigma$$

4-quark op.

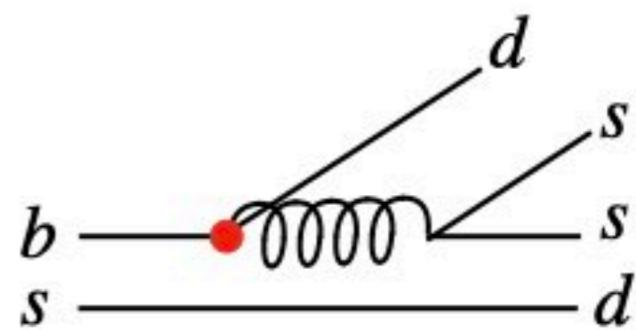
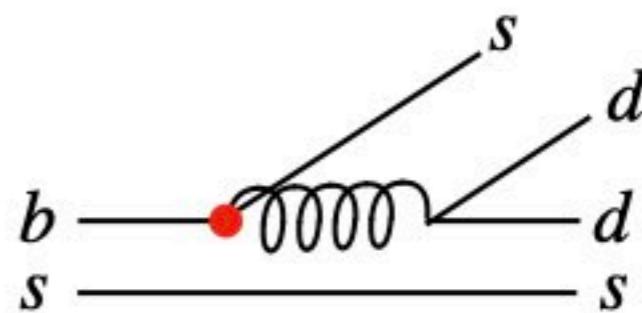
$$\bar{B}_s \rightarrow K^{(*)}\bar{K}^{(*)} \\ (b \rightarrow s)$$



$$\bar{B}_d \rightarrow K^{(*)}\bar{K}^{(*)} \\ (b \rightarrow d)$$

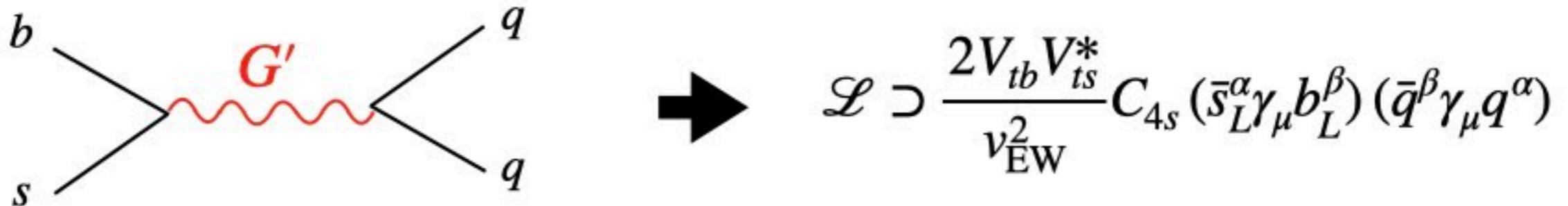


Chromod. dipole



# $C_{4s}$ : Coloron

$$G' \sim (\mathbf{8}, \mathbf{1})_0$$



$$\mathcal{L} \supset \Delta_{sb}^L (\bar{s}_L \gamma^\mu b_L) G'_\mu + \Delta_{sb}^R (\bar{s}_R \gamma^\mu b_R) G'_\mu + \sum_i \Delta_{qq} (\bar{q}_i \gamma^\mu q_i) G'_\mu$$

- $L_{K^{(*)}\bar{K}^{(*)}}$  observables:

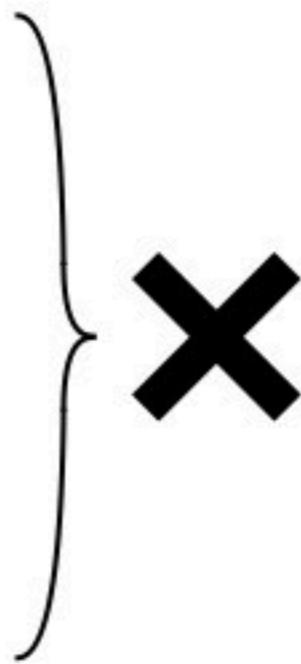
$$\frac{\Delta_{sb}\Delta_{qq}}{m_{G'}^2} \sim \frac{1}{(5 \text{ TeV})^2}$$

- From di-jet searches:

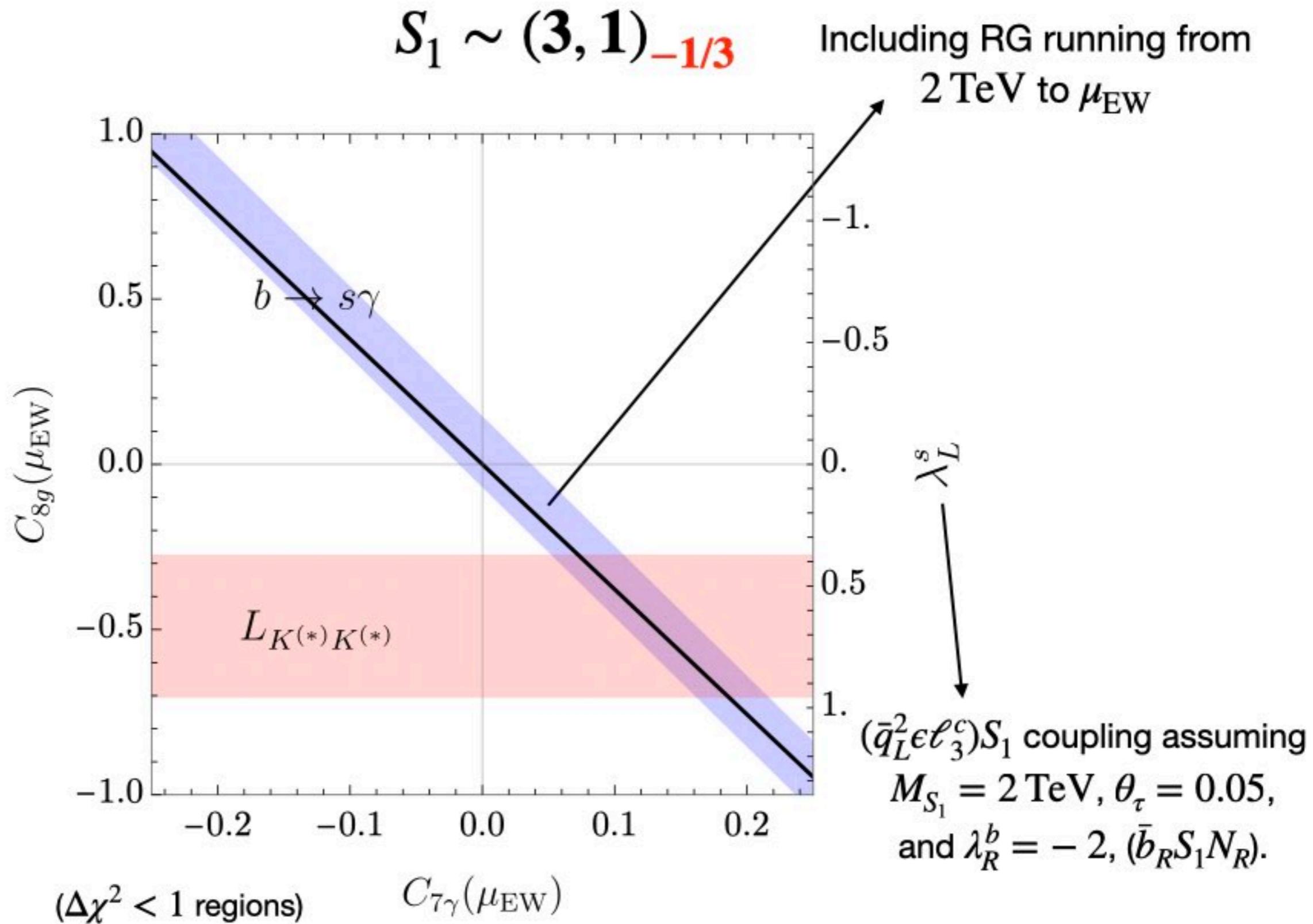
$$\frac{\Delta_{qq}^2}{m_{G'}^2} \lesssim \frac{1}{(5 \text{ TeV})^2}$$

- $B_s$  mixing:

$$\frac{\Delta_{sb}^2}{m_{G'}^2} \lesssim \frac{1}{(100 \text{ TeV})^2}$$



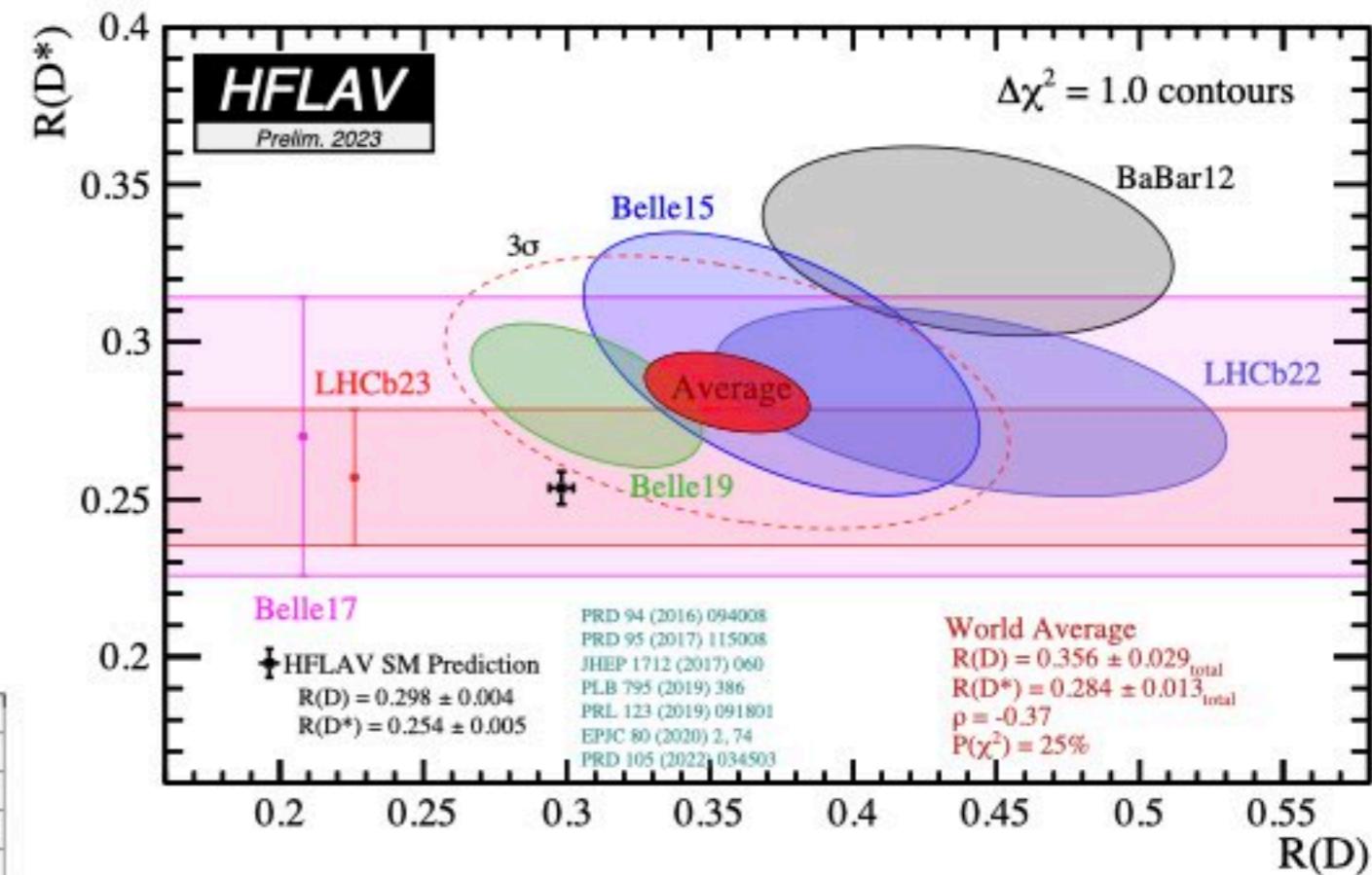
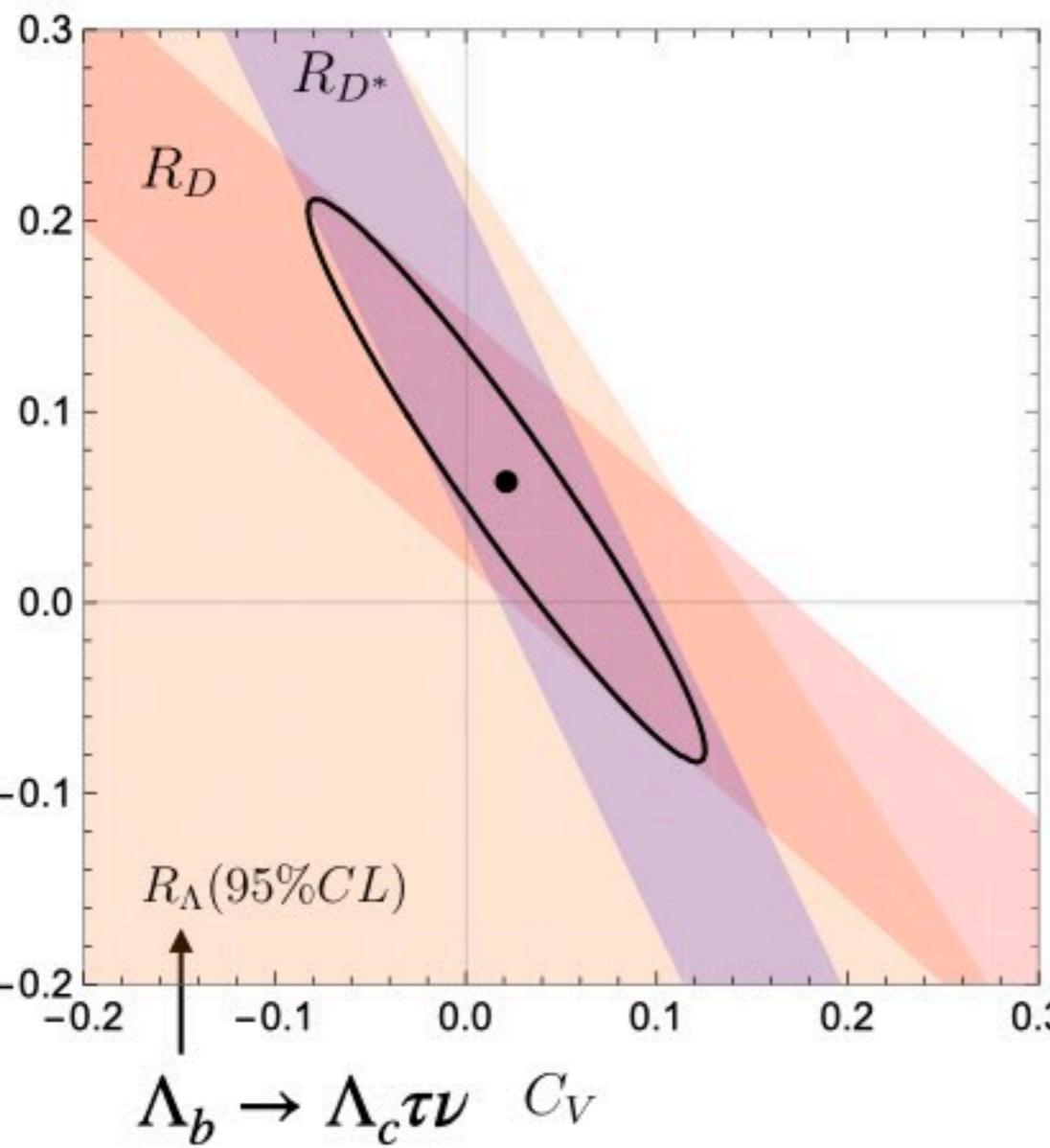
# The EM dipole



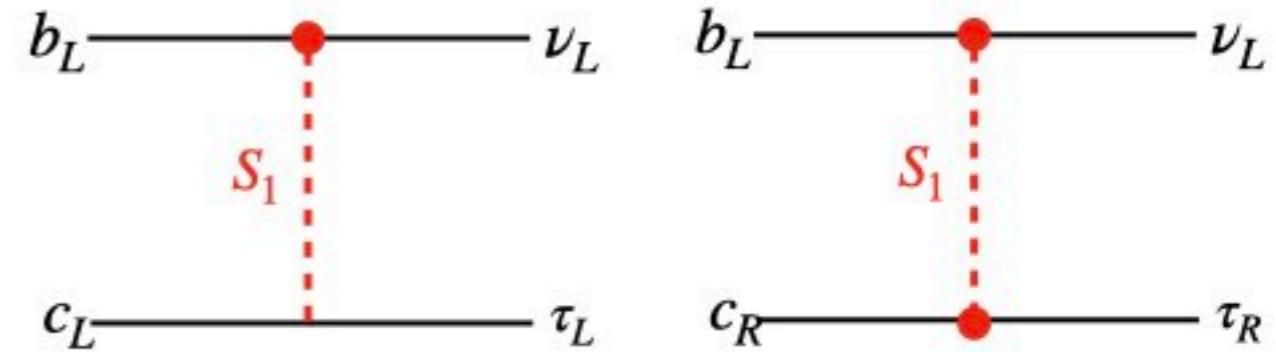
# $b \rightarrow c\tau\nu$ data

$$R_{D^{(*)}} = \frac{Br(B \rightarrow D^{(*)}\tau\nu)}{Br(B \rightarrow D^{(*)}l\nu)}$$

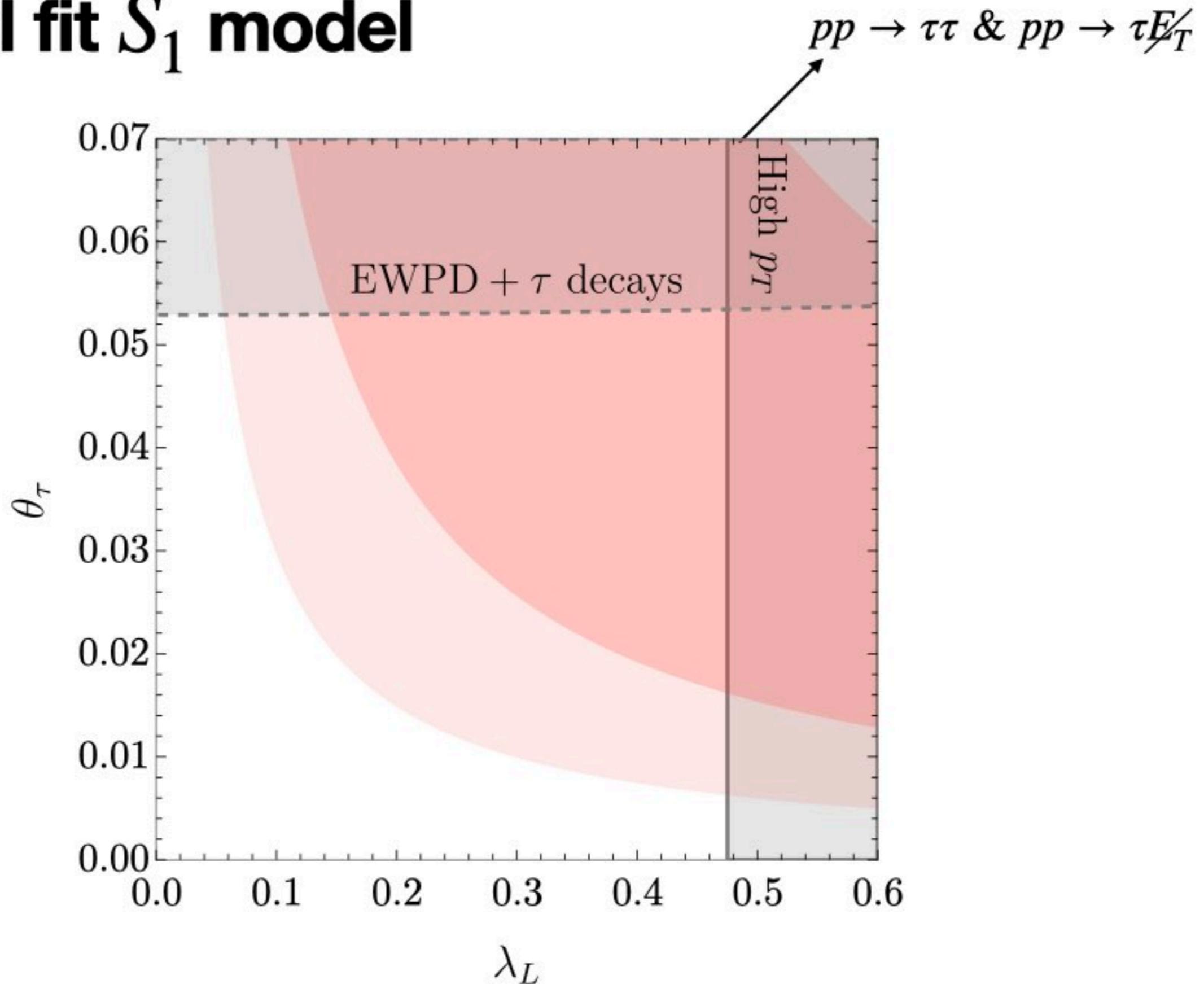
$\sim 3\sigma$



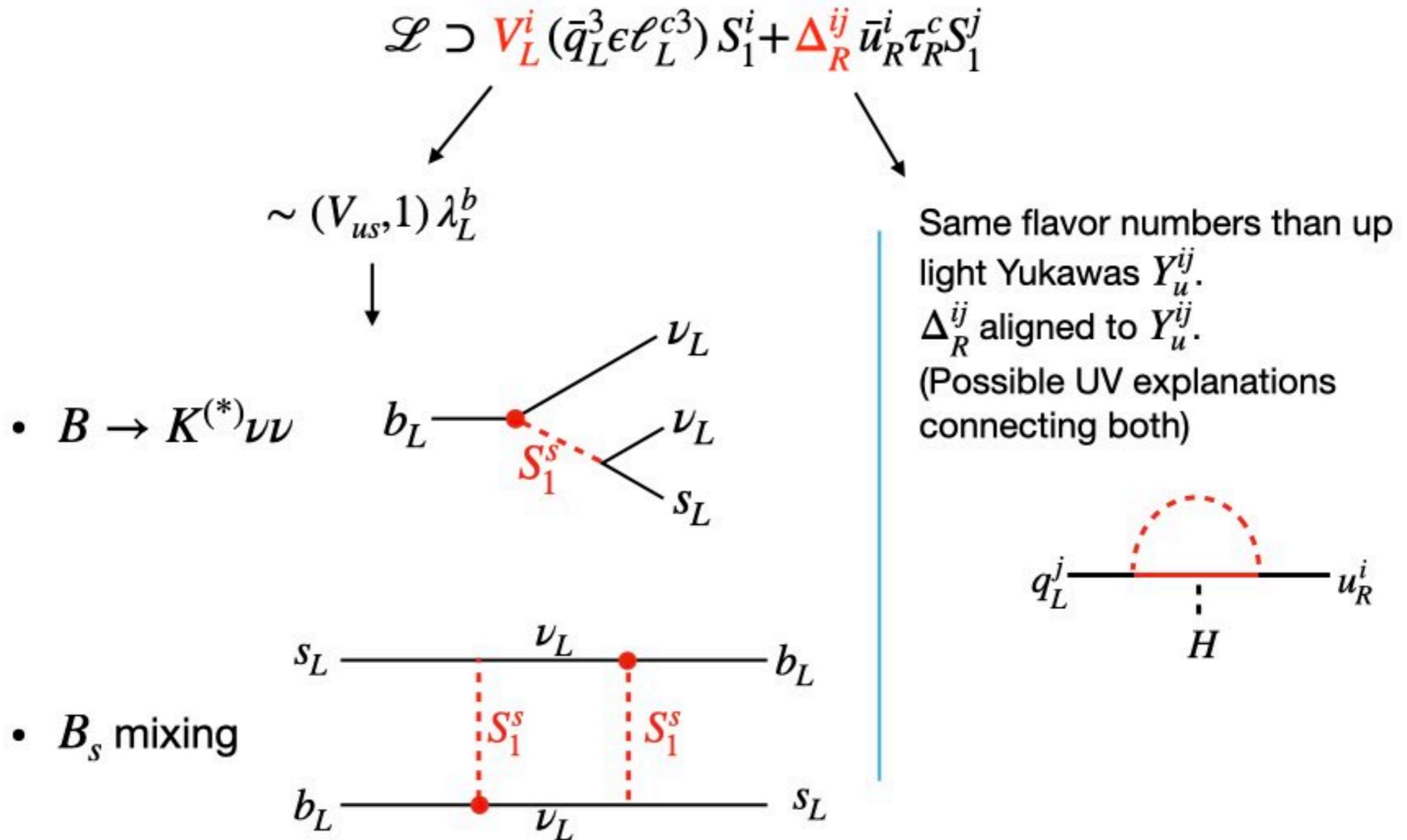
$$\begin{aligned} \mathcal{L} \supset & \frac{2}{v_{\text{EW}}^2} V_{cb} \left[ (1 + C_V)(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) \right. \\ & \left. + C_{S,T} \left( (\bar{c}_R b_L)(\bar{\tau}_R \nu_L) - \frac{1}{4} (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right) \right] \end{aligned}$$



# Global fit $S_1$ model



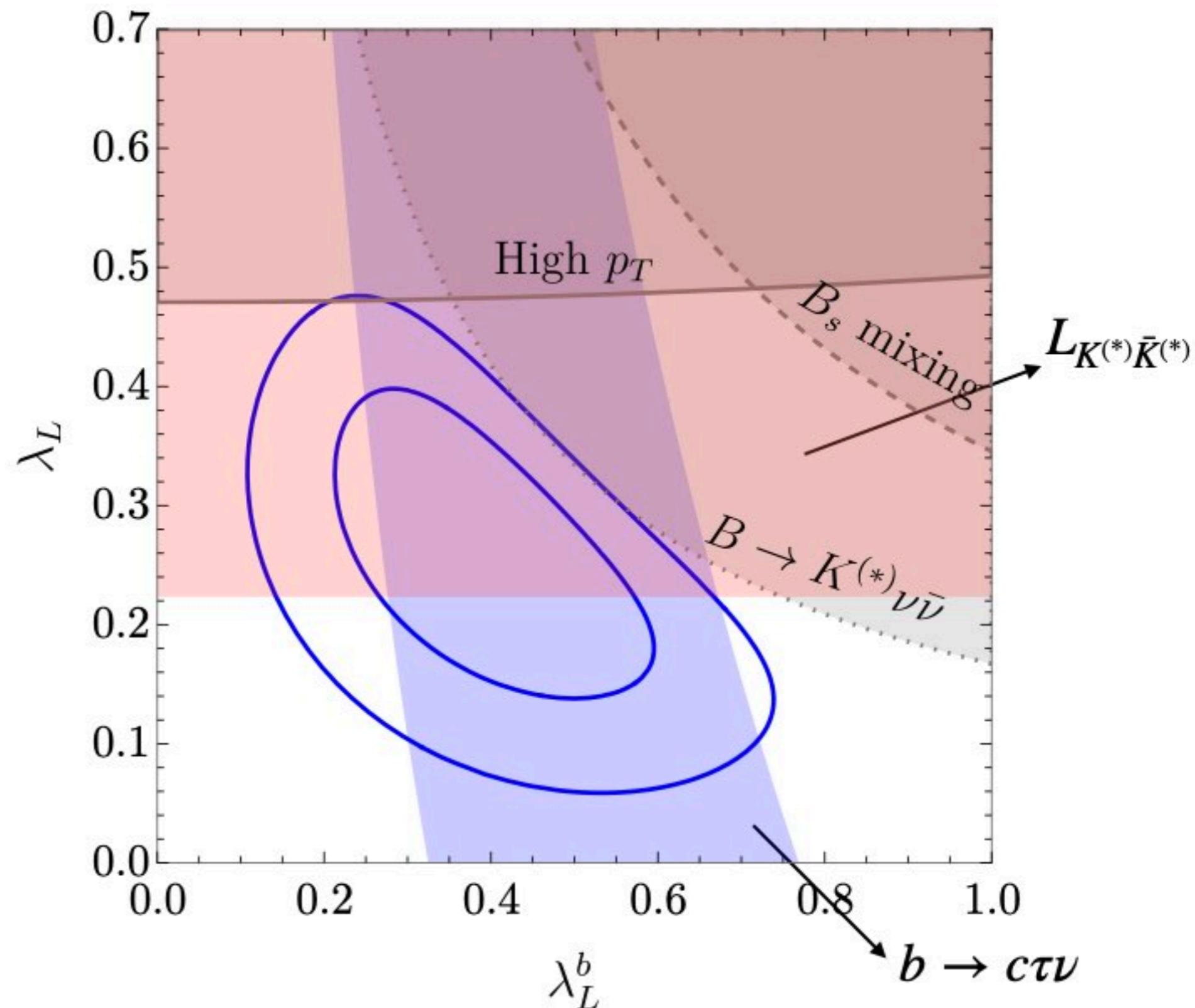
# New couplings, new constraints:



# Global fit $S_1$ model

Prediction for  $B \rightarrow K^{(*)}\nu\bar{\nu}$ :  $R_{K^{(*)}}^\nu = 2.3 \pm 0.5$

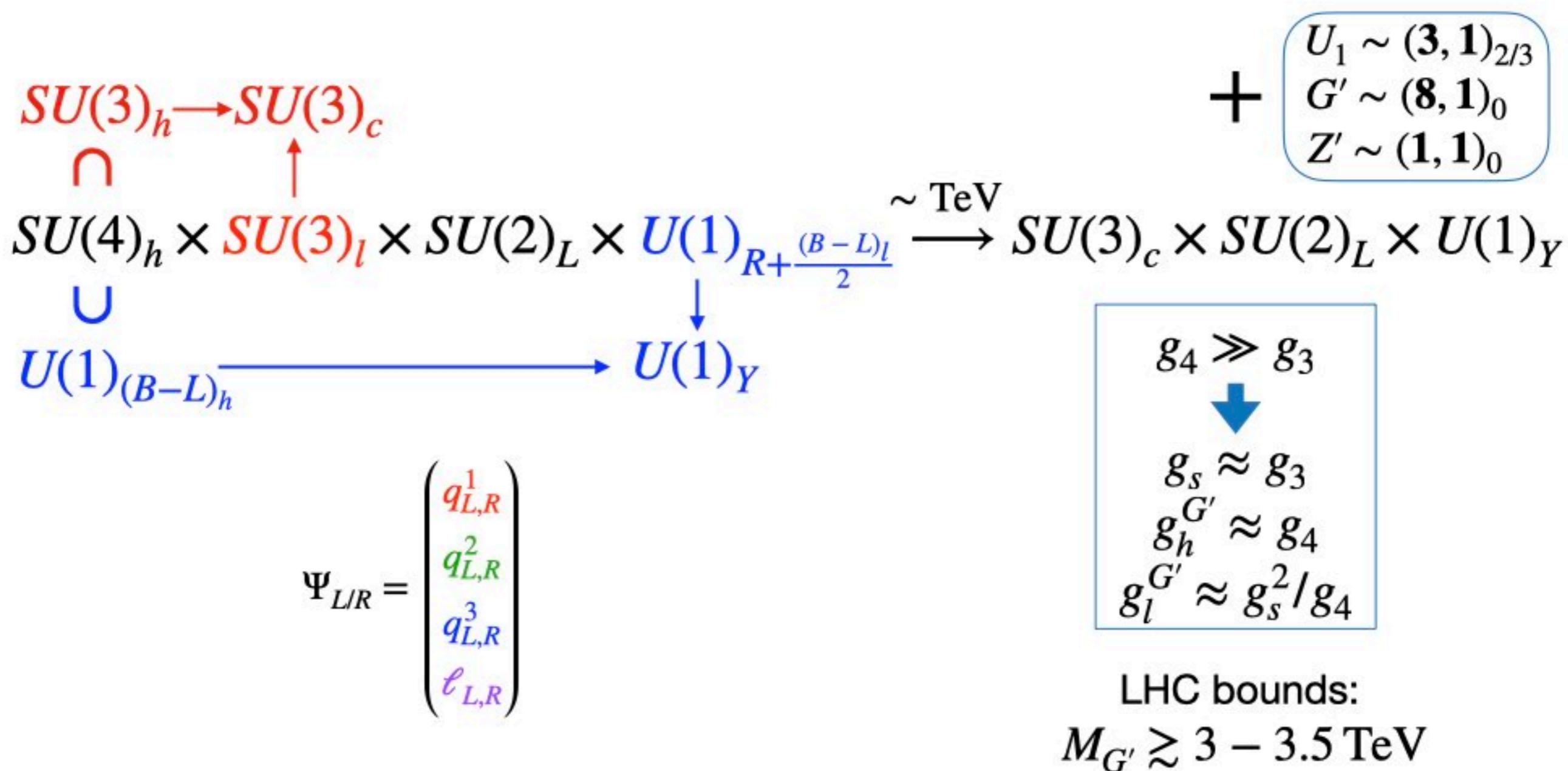
- $L_{K^{(*)}\bar{K}^{(*)}}$
- $b \rightarrow c\tau\nu$
- $B \rightarrow K^{(*)}\nu\bar{\nu}$
- $B_s$  mixing
- High  $p_T$ :
  - $pp \rightarrow \tau\tau$
  - $pp \rightarrow \tau E_T$
  - Others:  
 $b \rightarrow s/d\gamma$ , EWPT,  
 $\tau$  decays, ...



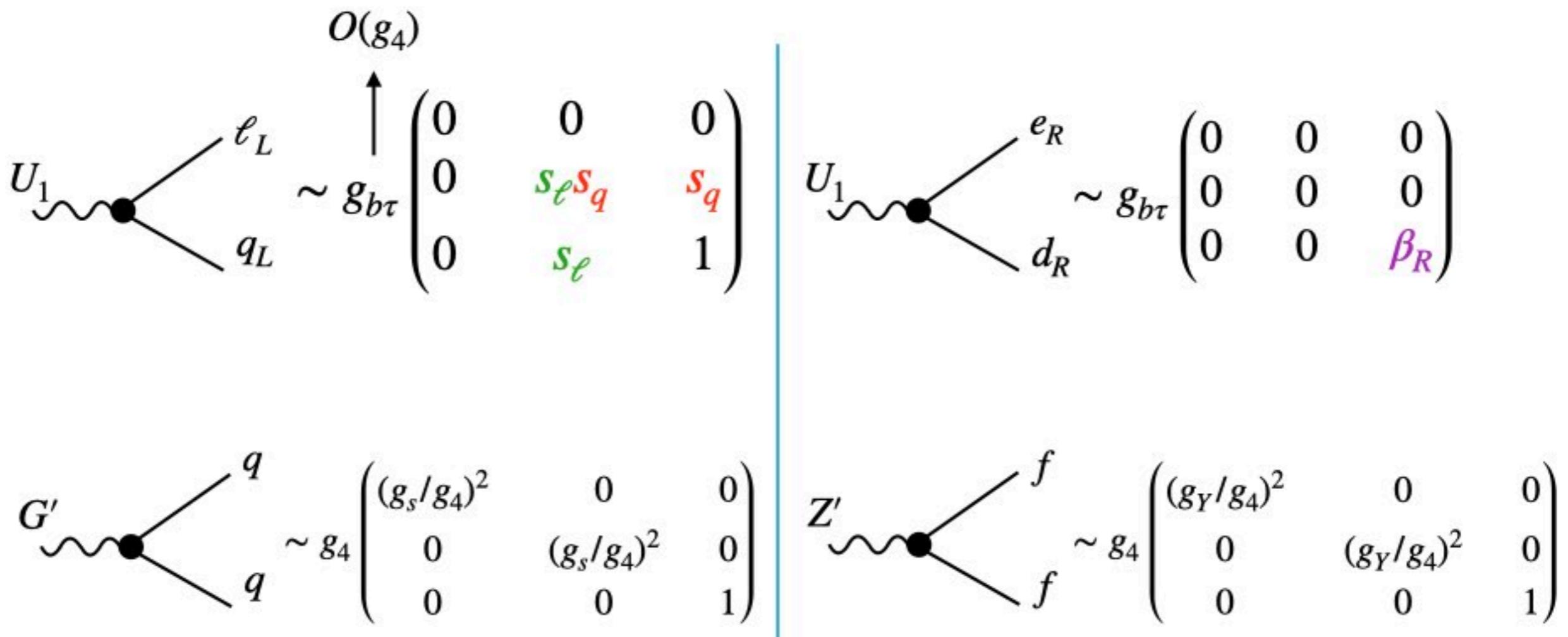
# **4321 model**

# 4321 model

**Third family quark-lepton unification:**



# 4321 massive vector bosons



$$\Lambda_U = \sqrt{2} m_{U_1} / g_{b\tau}$$

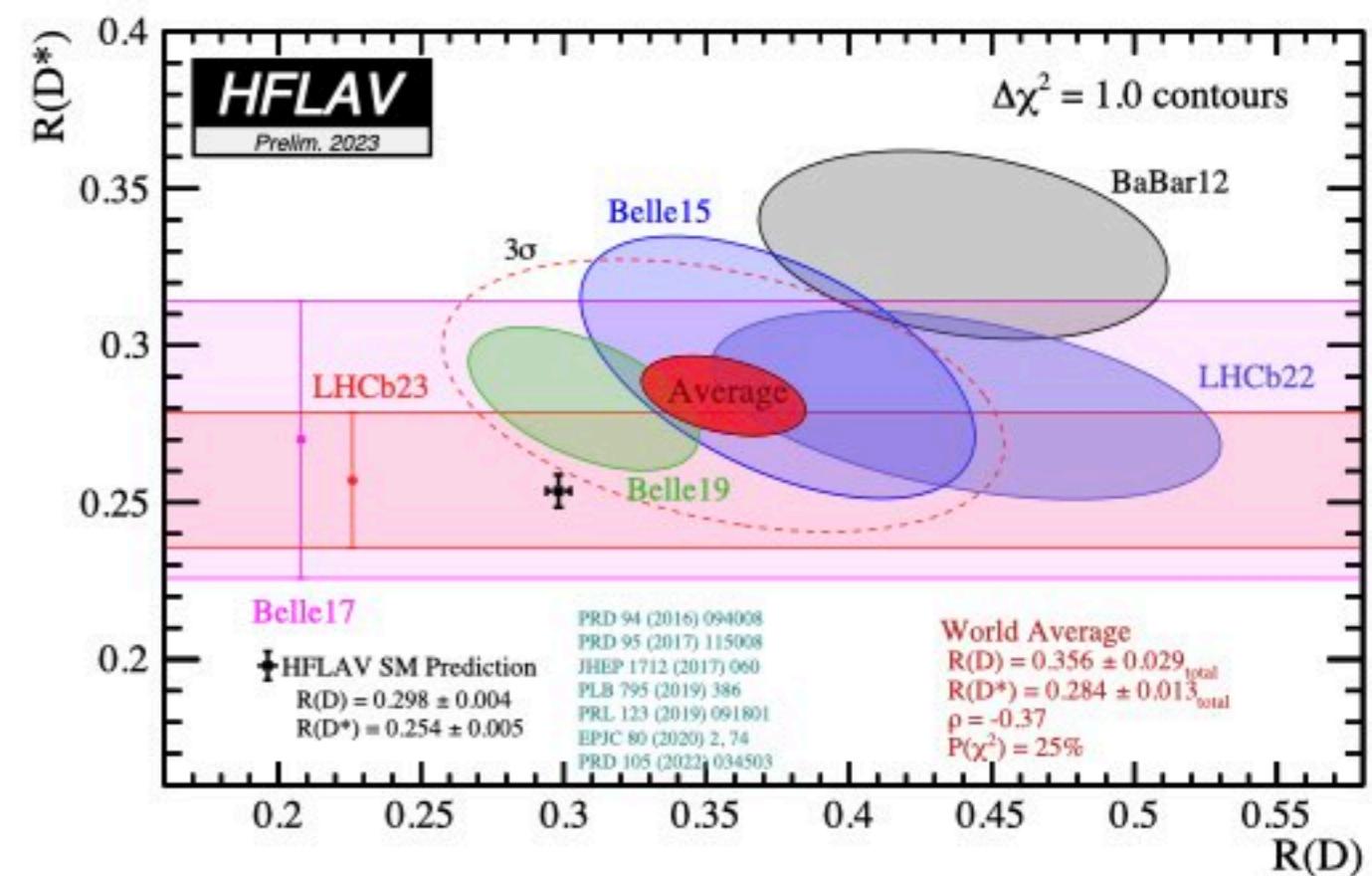
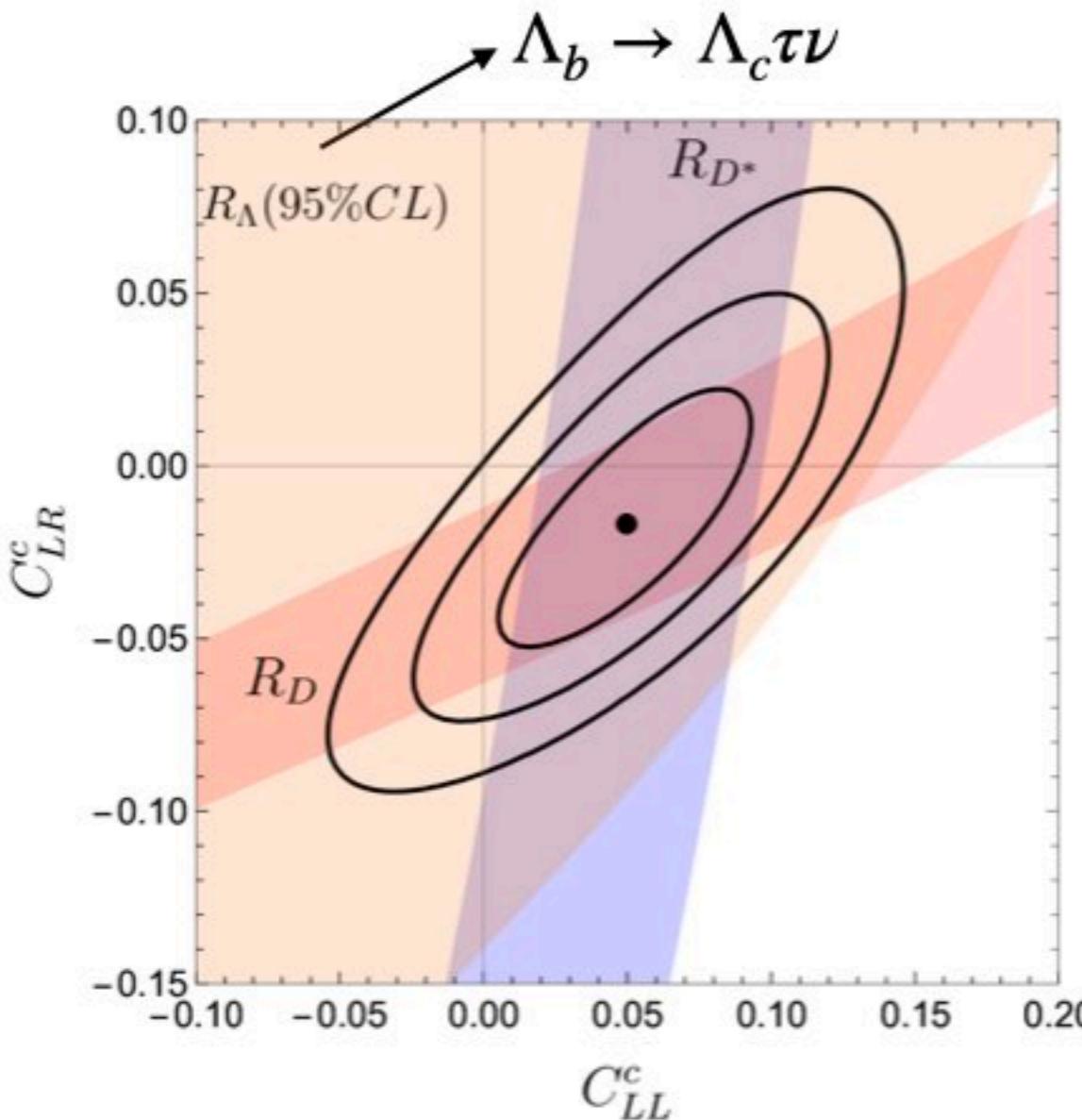
$\Lambda_U, s_q, s_\ell, \beta_R$

Necessary for CKM

# B-anomalies: $R_{D^{(*)}}$

$$R_{D^{(*)}} = \frac{Br(B \rightarrow D^{(*)}\tau\nu)}{Br(B \rightarrow D^{(*)}l\nu)}$$

$\sim 3.2\sigma$

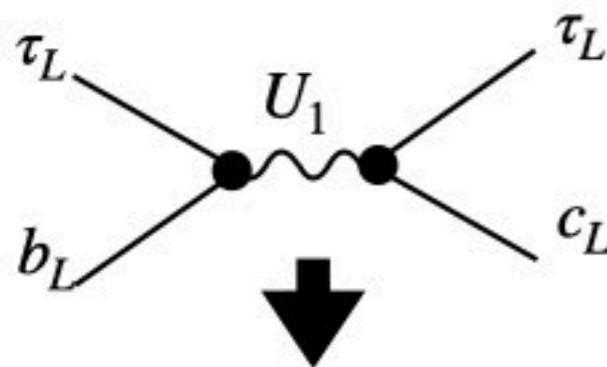


$$\mathcal{L} \supset \frac{2}{v^2} V_{cb} \left[ (1 + C_{LL}^c)(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) - 2C_{LR}^c (\bar{c}_L b_R)(\bar{\tau}_L \nu_L) \right]$$

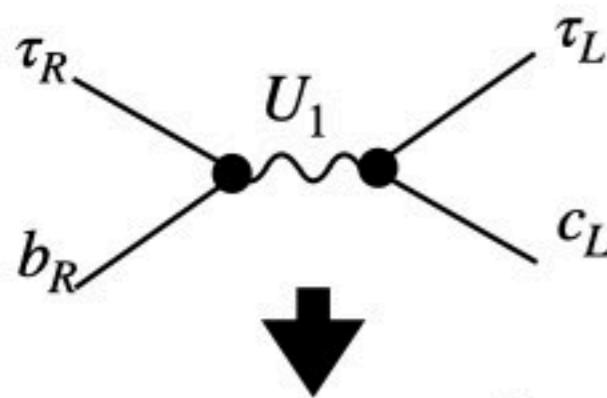
[J. Aebischer, G. Isidori, M. Pesut, B. Stefanek, F. Wilsch, [2210.13422](#)]

# B-anomalies: $R_{D^{(*)}}$

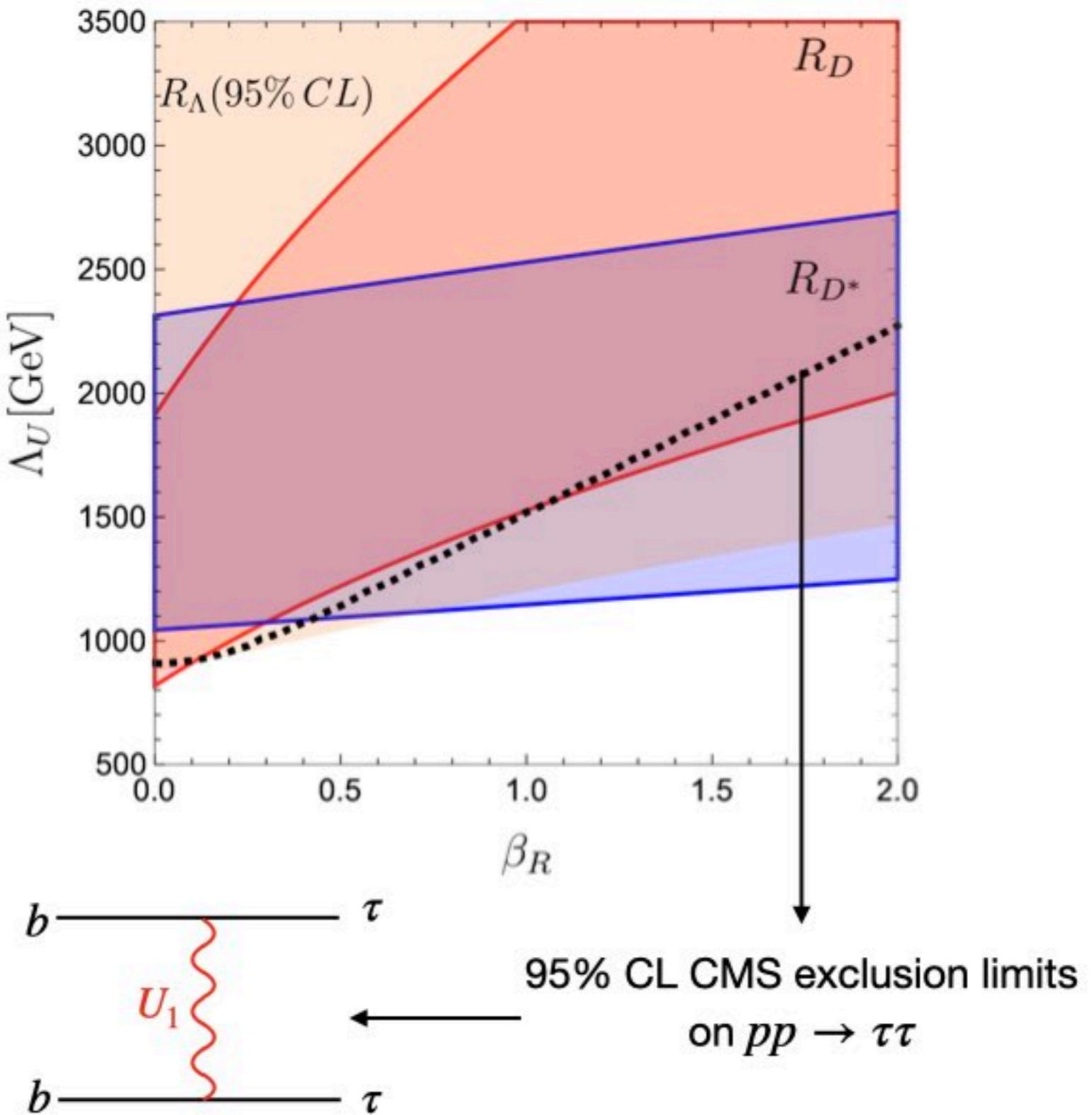
$$s_q = 0.1 \approx 2.4 V_{cb}$$



$$C_{LL}^c \propto \frac{s_q}{\Lambda^2}$$



$$C_{LR}^c \propto \frac{\beta_R s_q}{\Lambda_U^2}$$



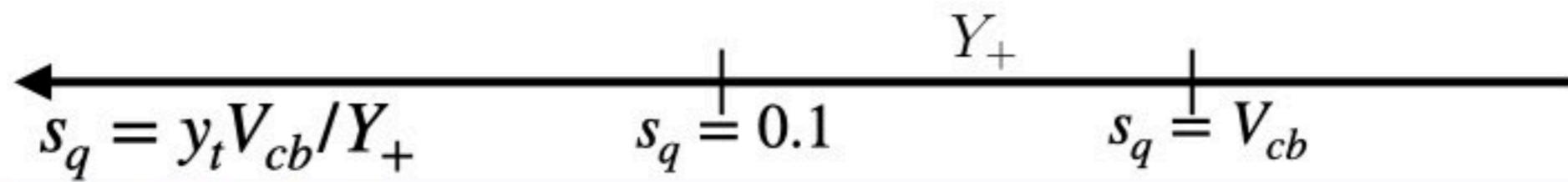
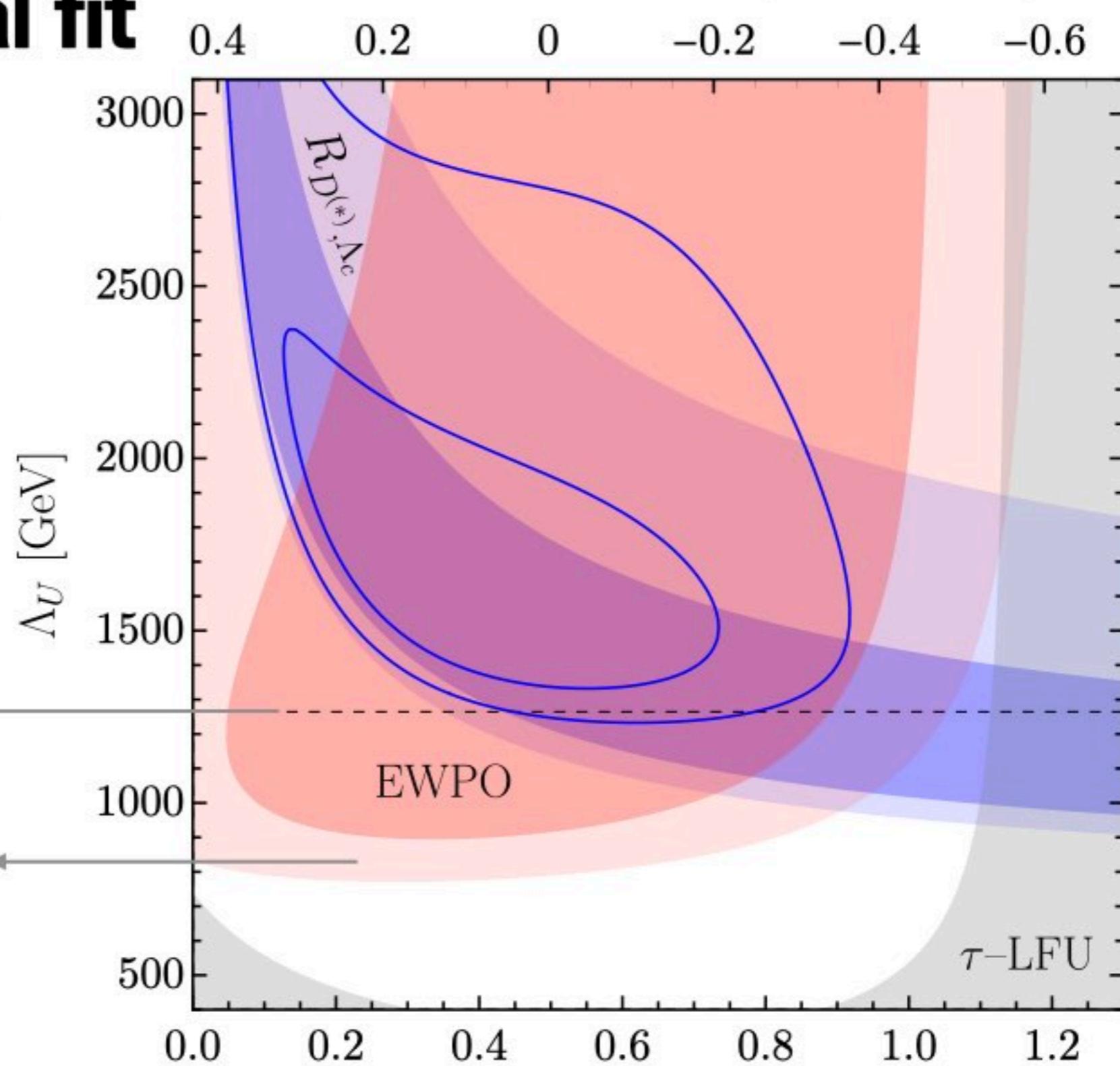
$$y_\nu = y_t \cos(\chi) - Y_+ \sin(\chi)$$

# 4321 Global fit

$m_W$  without CDF

95 % CL CMS  $pp \rightarrow \tau\tau$

$G' \rightarrow \mathcal{O}_{HD}$

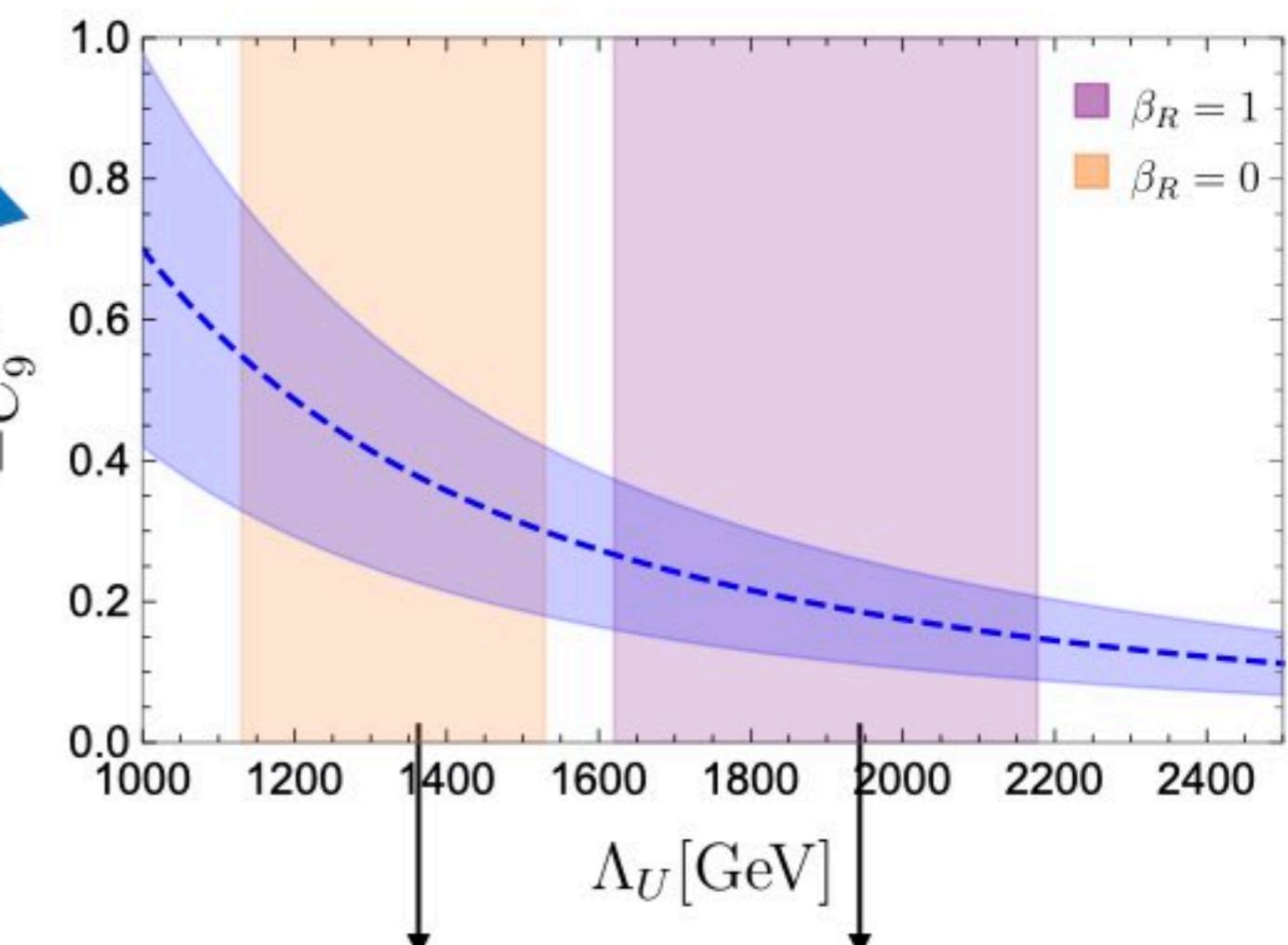
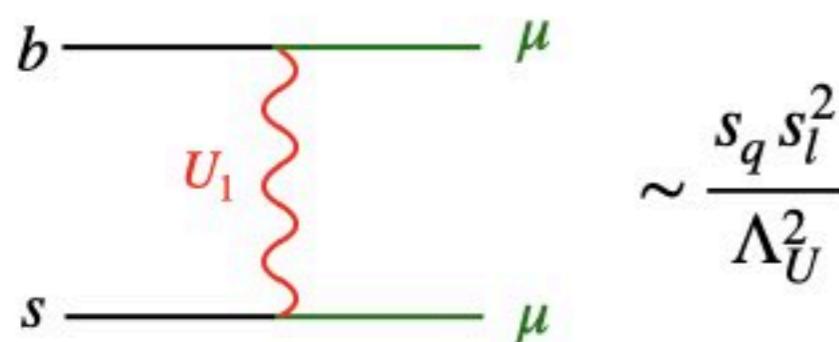
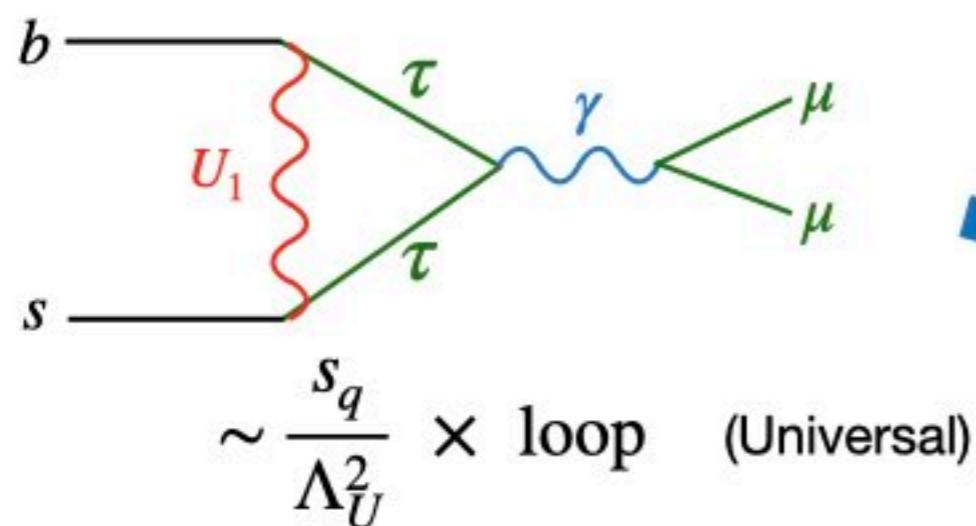


# B-anomalies: $b \rightarrow s\mu\mu$

$$B \rightarrow K^* \mu\mu$$

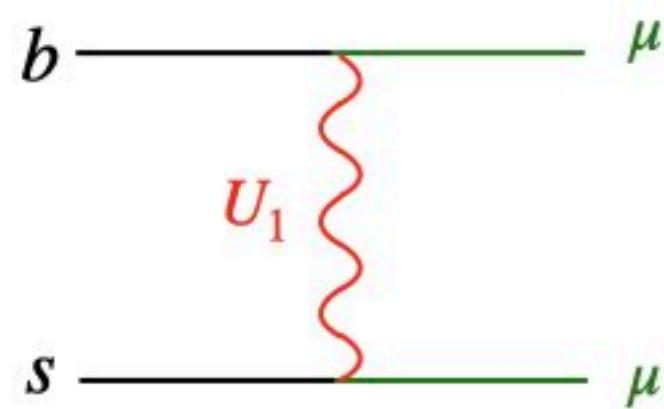
$$\mathcal{L} \supset \frac{2}{v^2} V_{ts}^* V_{tb} C_9 (\bar{s}_L \gamma^\mu b_L) (\mu \gamma_\mu \mu)$$

$$C_9^{\text{NP}} = -0.75 \pm 0.23 \quad (\sim 3.4\sigma)$$

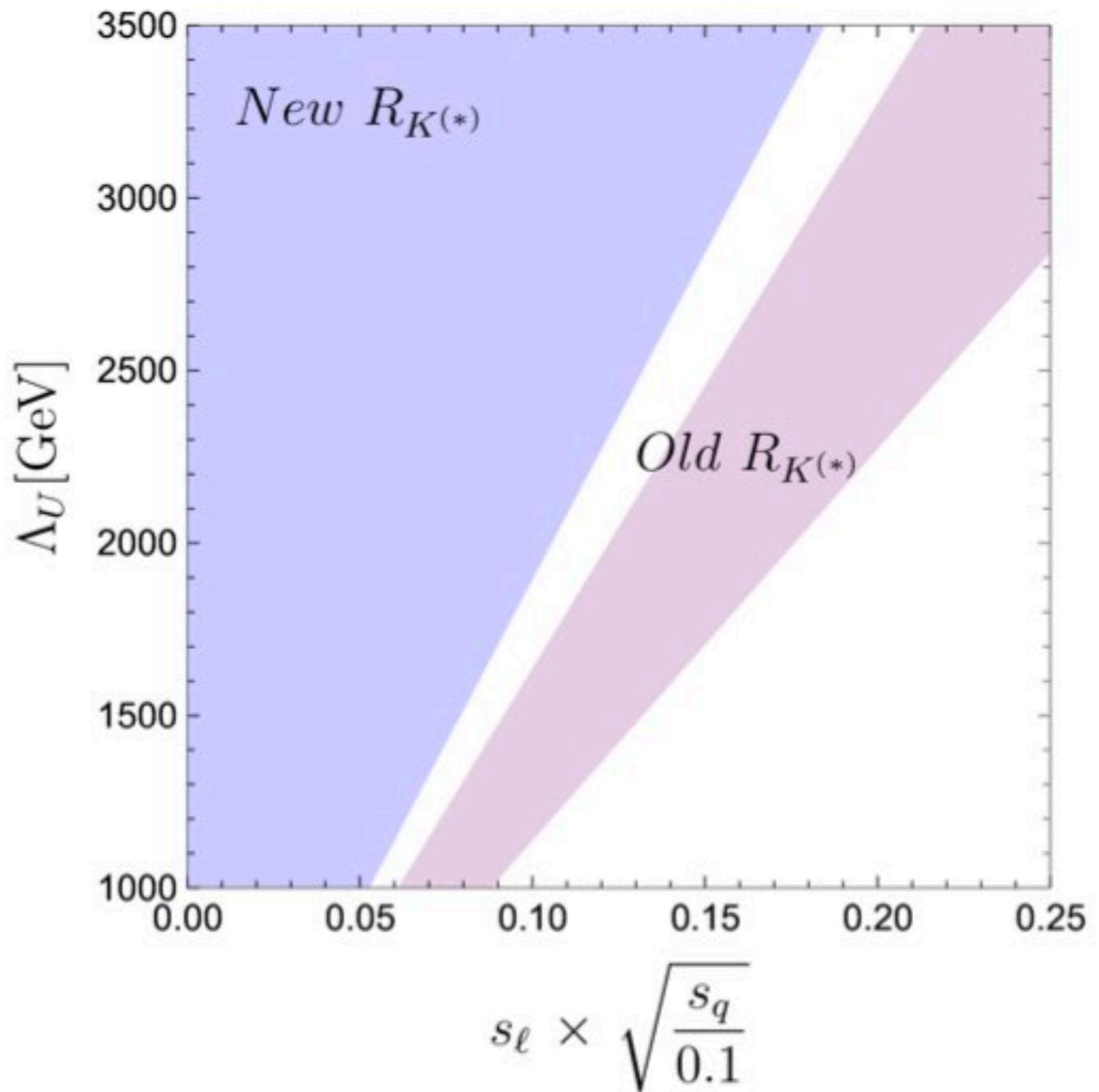


# And what about $R_{K^{(*)}}\dots$ ?

$$R_{K^{(*)}} = \frac{Br(B \rightarrow K^{(*)}\mu\mu)}{Br(B \rightarrow K^{(*)}ee)}$$

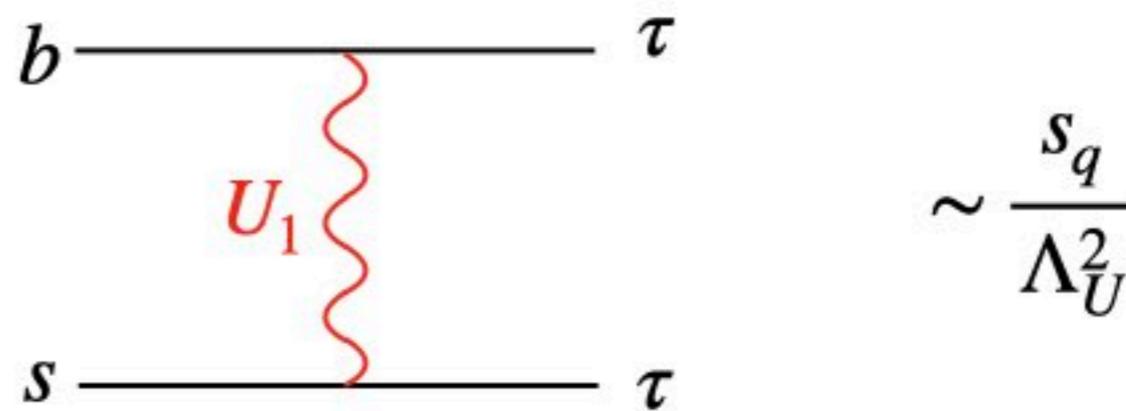


$$\propto \frac{s_q s_l^2}{\Lambda_U^2}$$



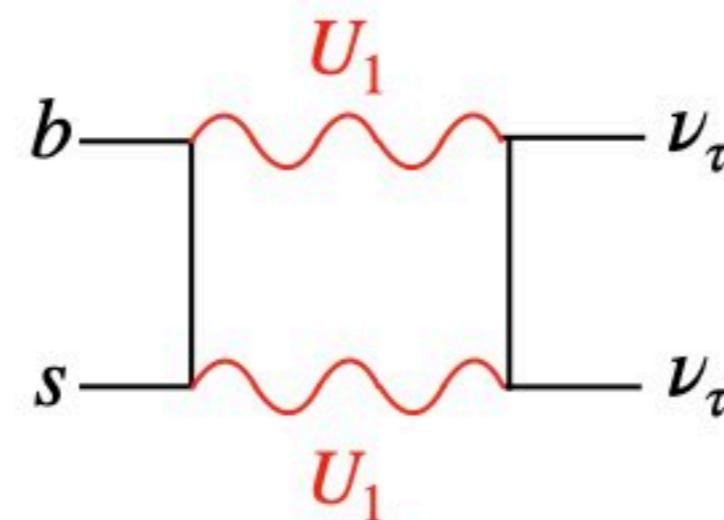
# Other interesting observables

- $B_s \rightarrow \tau\tau$
- $B \rightarrow K\tau\tau$



$$\sim \frac{s_q}{\Lambda_U^2}$$

- $B \rightarrow K\nu\bar{\nu}$



$$\sim \frac{s_q}{\Lambda_U^2} \times \text{loop}$$

- ...

[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, [2103.16558](#)]

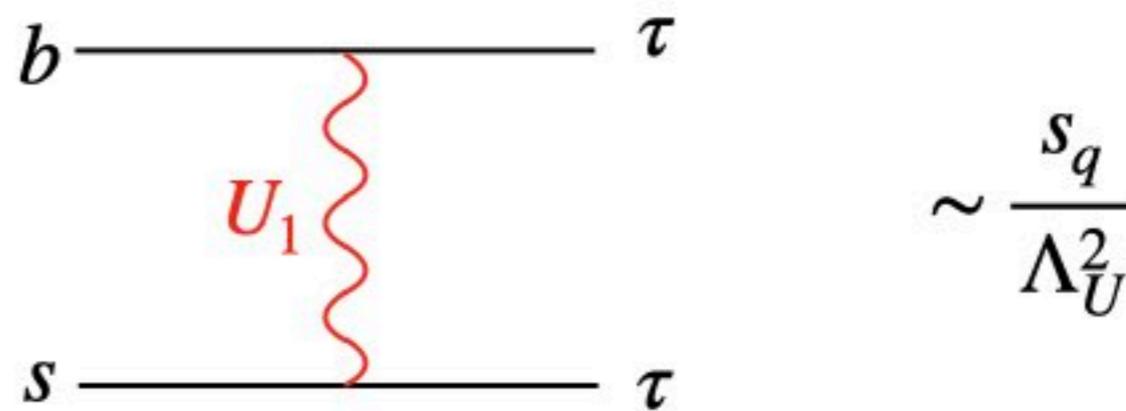
# Other interesting observables

- $B_s \rightarrow \tau\tau$

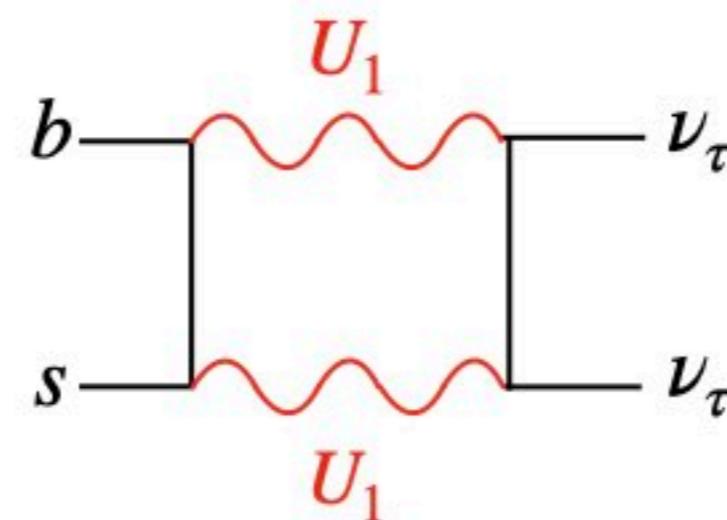
- $B \rightarrow K\tau\tau$

- $B \rightarrow K\nu\bar{\nu}$

- ...



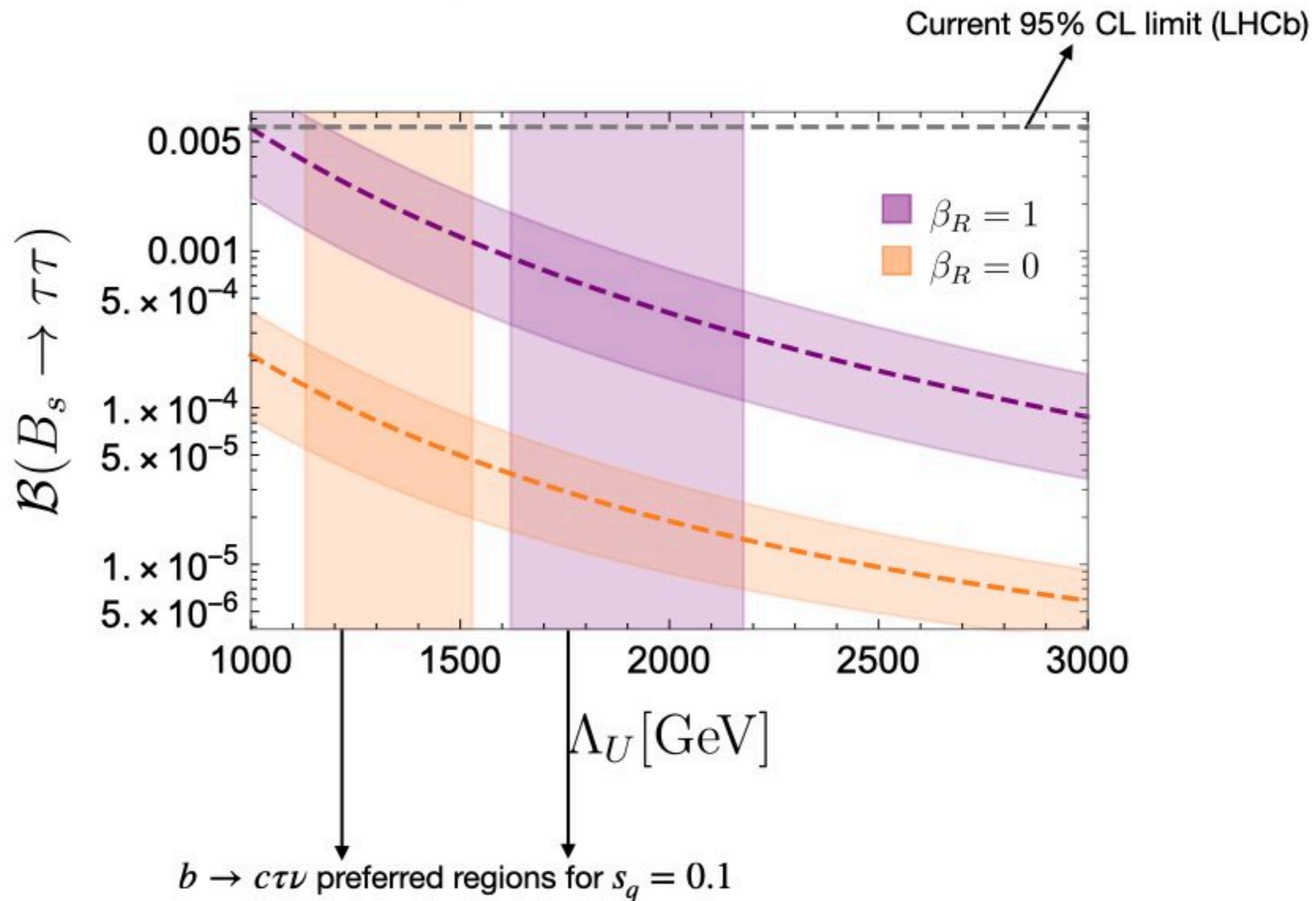
$$\sim \frac{s_q}{\Lambda_U^2}$$



$$\sim \frac{s_q}{\Lambda_U^2} \times \text{loop}$$

[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, [2103.16558](#)]

# Other interesting observables

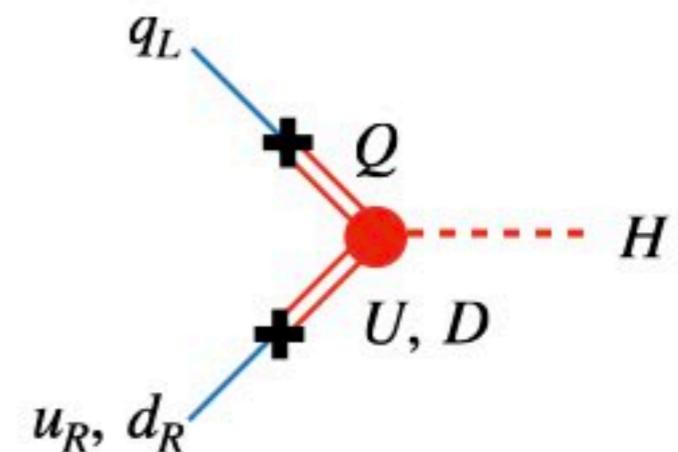
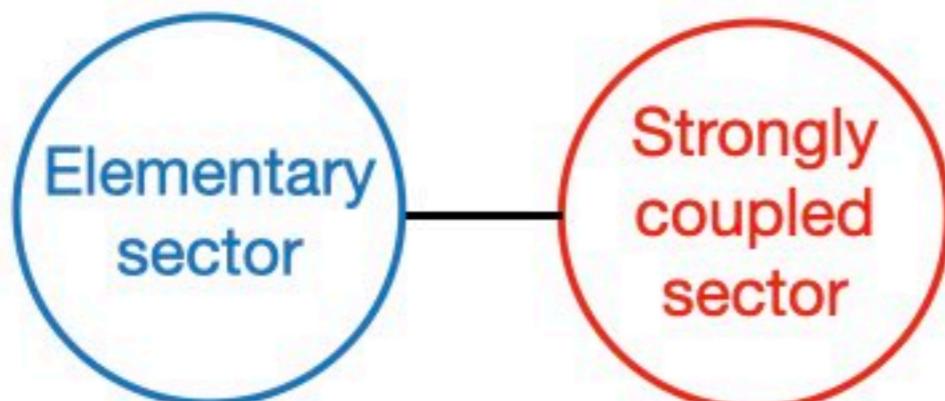


[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, [2103.16558](#)]

# **Partial compositeness and multi-scale**

# Partial compositeness

- Strong sector stabilising the Higgs mass



$$\mathcal{L} \supset \lambda_q \bar{q}_L Q + \lambda_u \bar{u}_R U + \lambda_d \bar{d}_R D$$

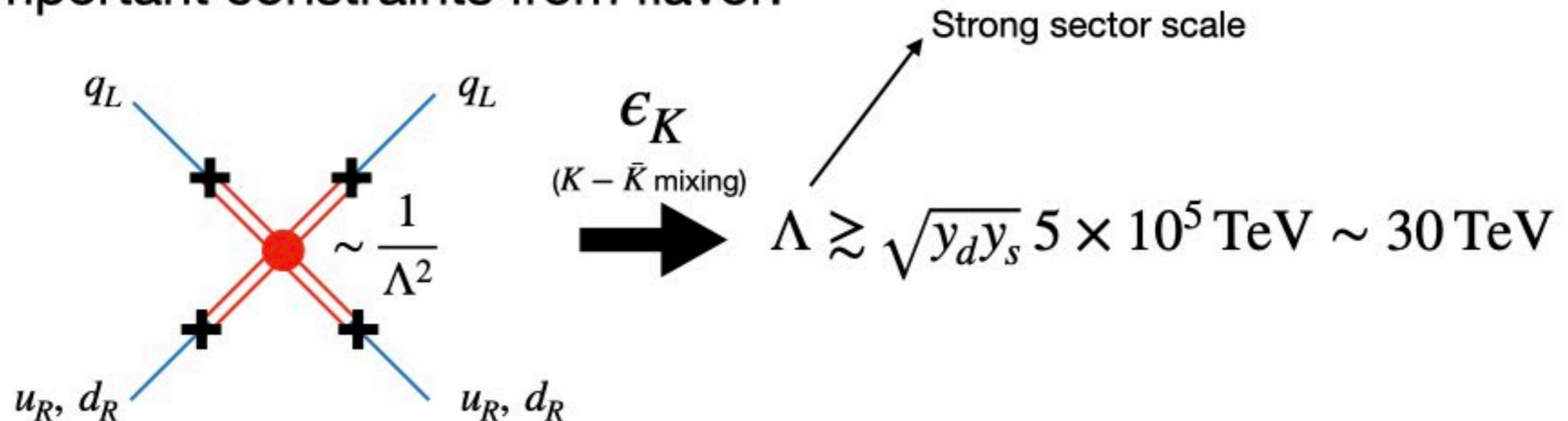
- Large mixing for 3rd family and suppressed mixing for light families due to large anomalous dimensions of the operators of the strongly coupled sector.

**$U(2)$  protection**

Enough?

# Partial compositeness

- Important constraints from flavor:



(Even stronger bounds from EDMs of neutron and electron)

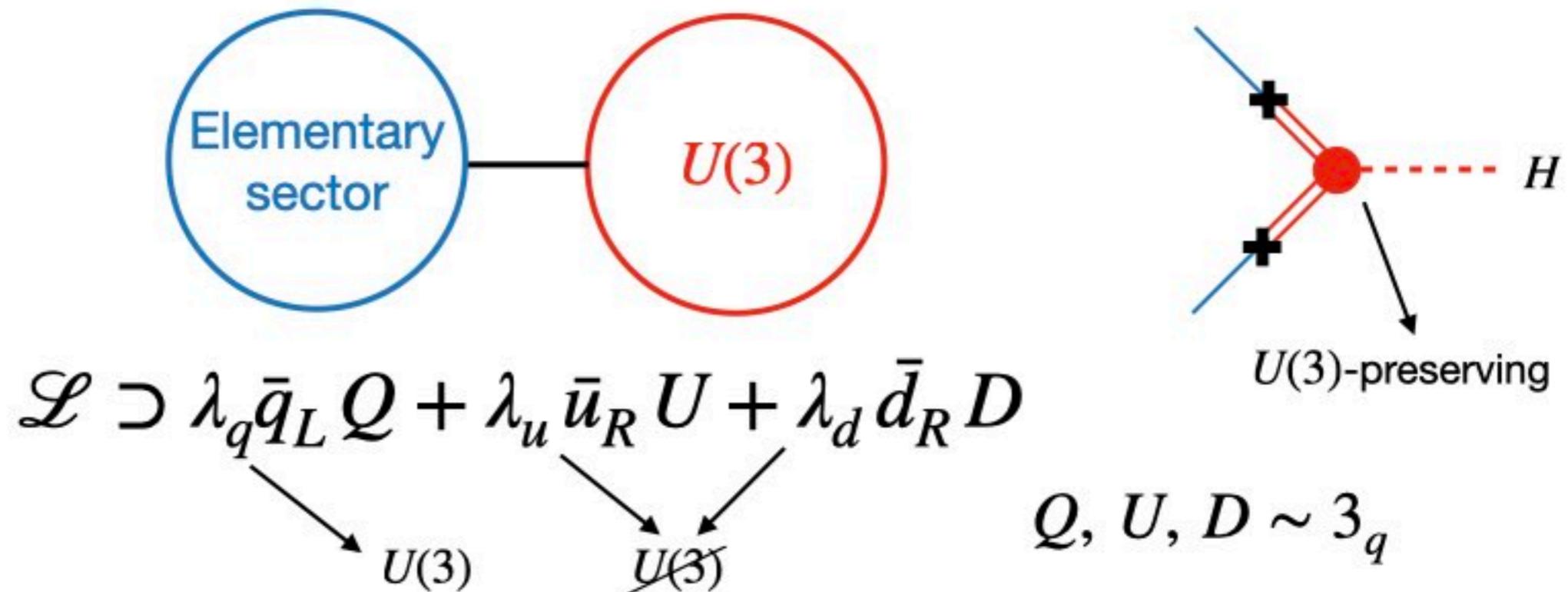
- What did go wrong? The breaking of  $U(2)$  is not SM like...

PC spurions	$\lambda_q \sim 2_q$ $\lambda_u \sim 2_u$ $\lambda_d \sim 2_d$	<b>vs</b>	$V_q \sim 2_q$ $\Delta_u \sim 2_q \times \bar{2}_u$ $\Delta_d \sim 2_q \times \bar{2}_d$	SM spurions
-------------	--	-----------	--	-------------

# Partial compositeness



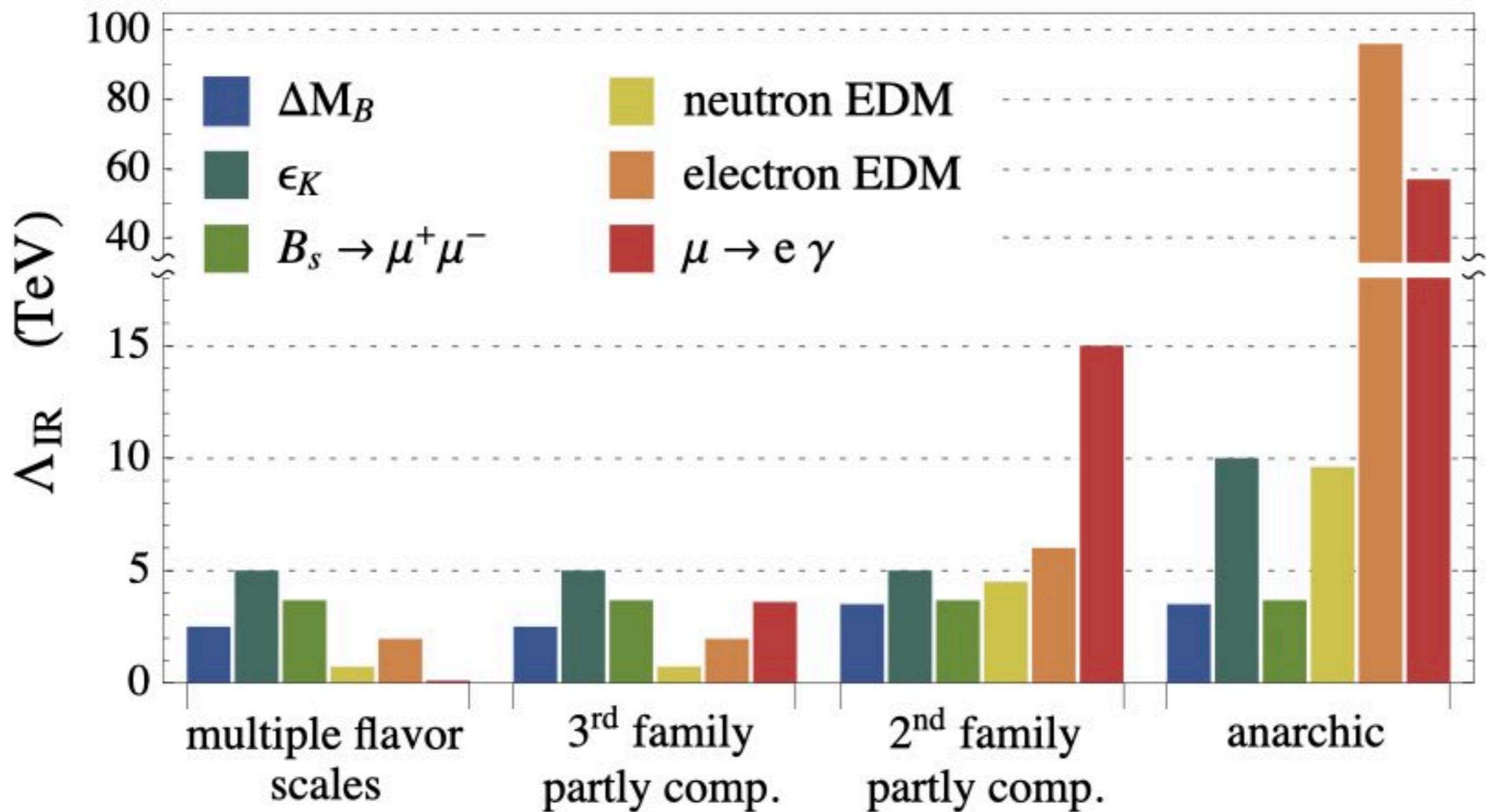
- Use only the SM spurions:



- Spurions breaking  $U(3)$  similar to SM Yukawas:

# Multiscale flavor

- Composite models/RS:



[Panico, Pomarol, [1603.06609](#)]