



University of
Zurich^{UZH}

A multi-scale origin for flavor

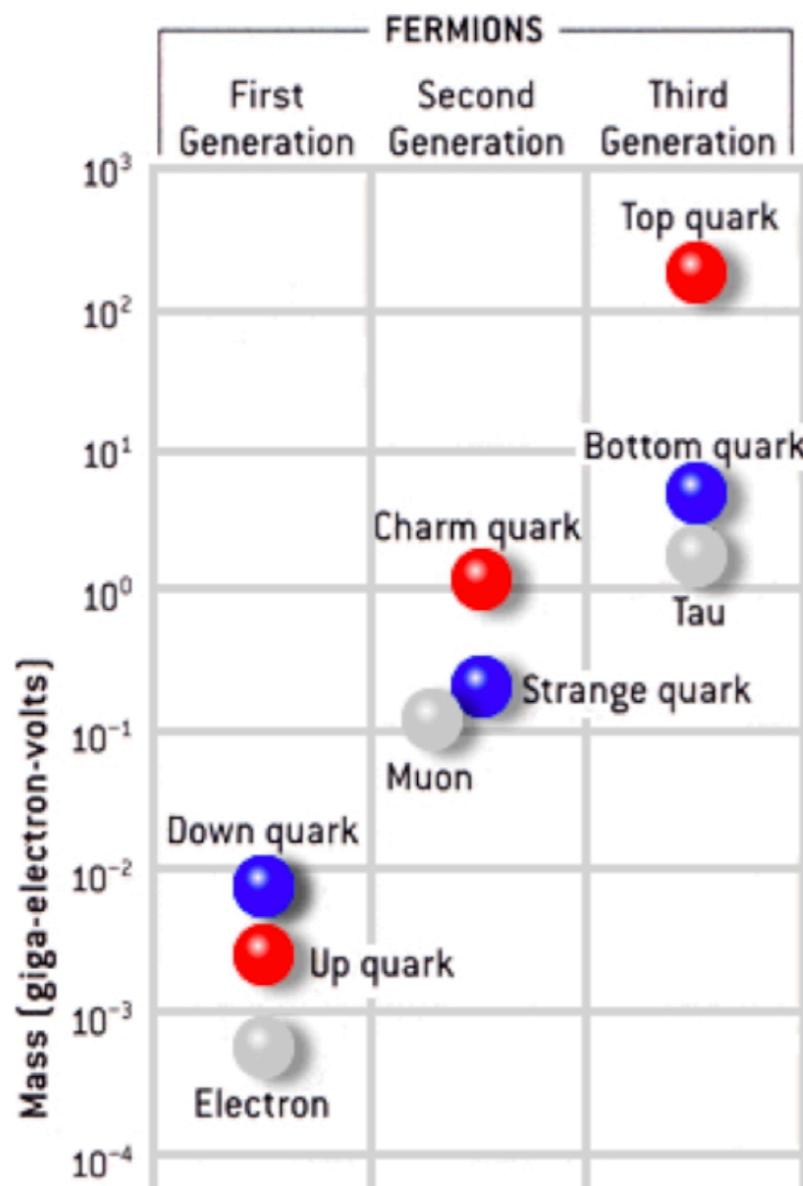
Javier M. Lizana
Zurich University

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

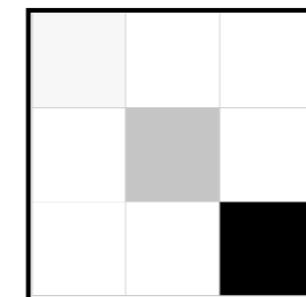
**SUSY 2023 - The 30th International Conference on Supersymmetry and
Unification of Fundamental Interactions**

A first flavor puzzle

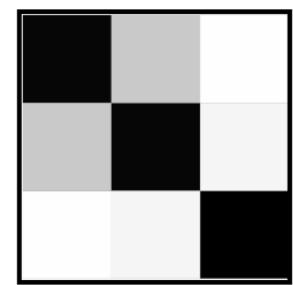
- **Flavor puzzle:** very hierarchical structures



$$M_{u,d,e} \sim$$

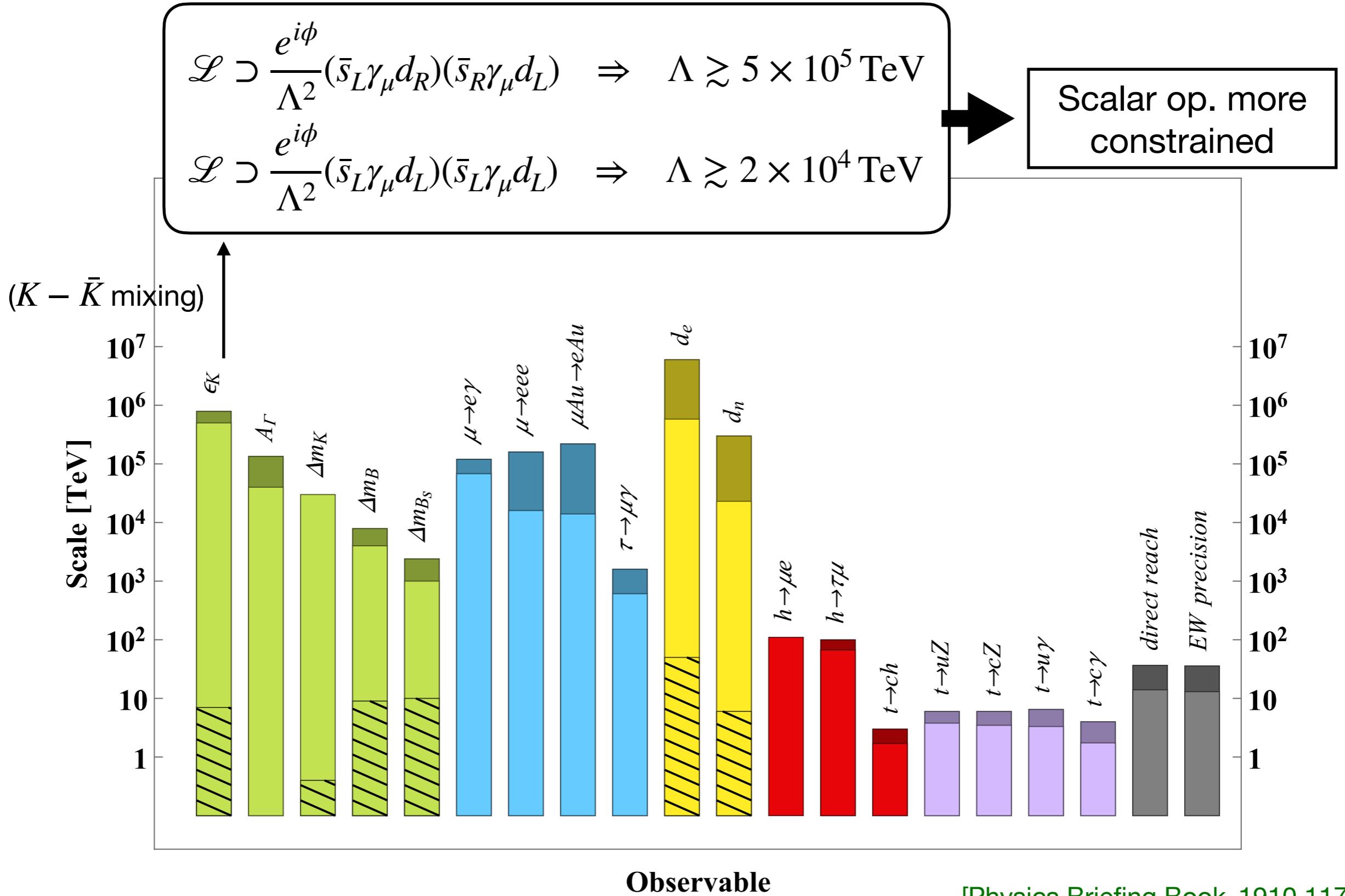


$$V_{\text{CKM}} \sim$$



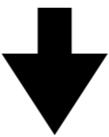
$$|V_{\text{CKM}}| = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}$$

A second flavor puzzle



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:

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

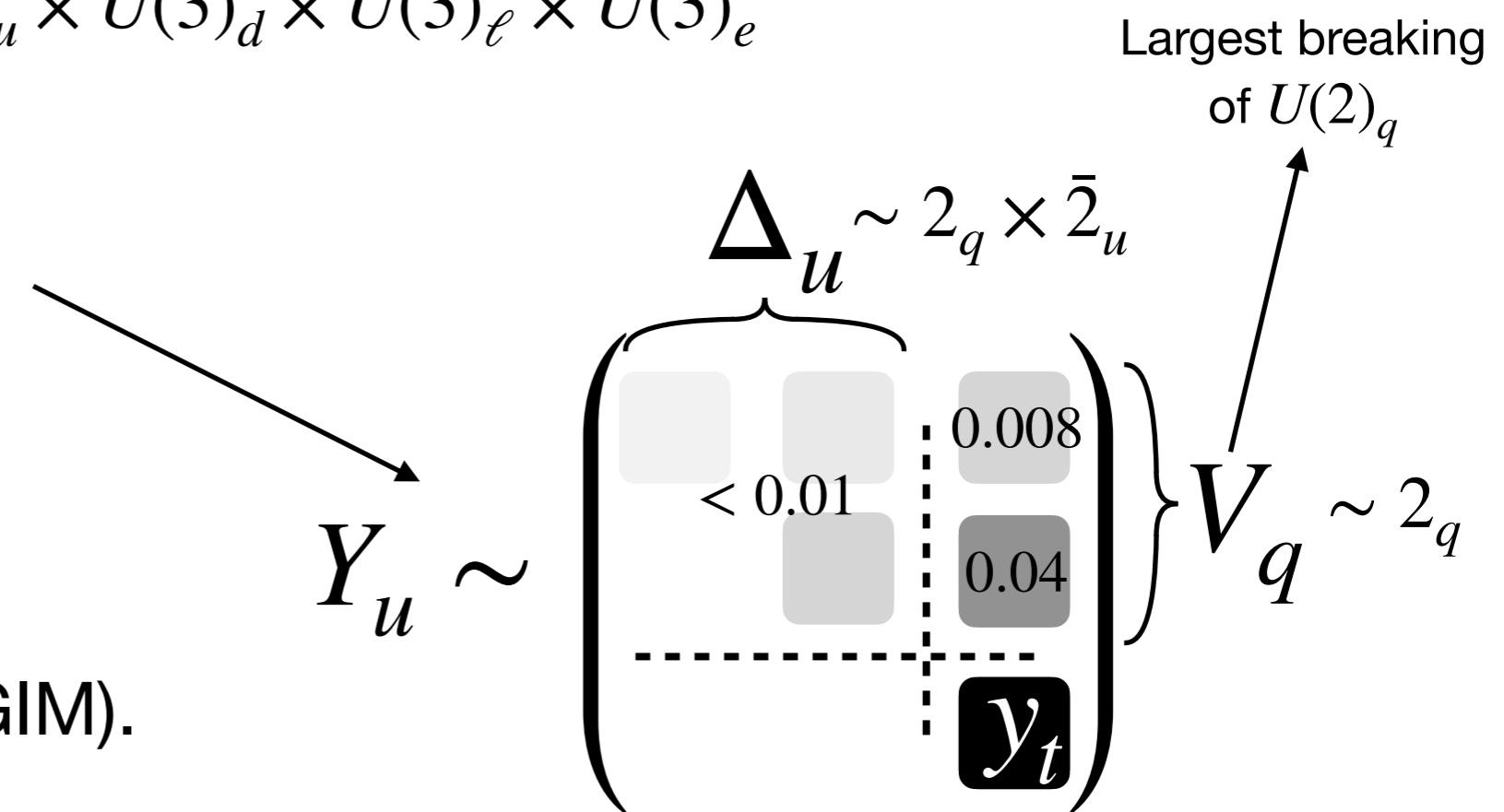
$$U(3)^5 = U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$

- $Y_{u,d,e}$ 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!

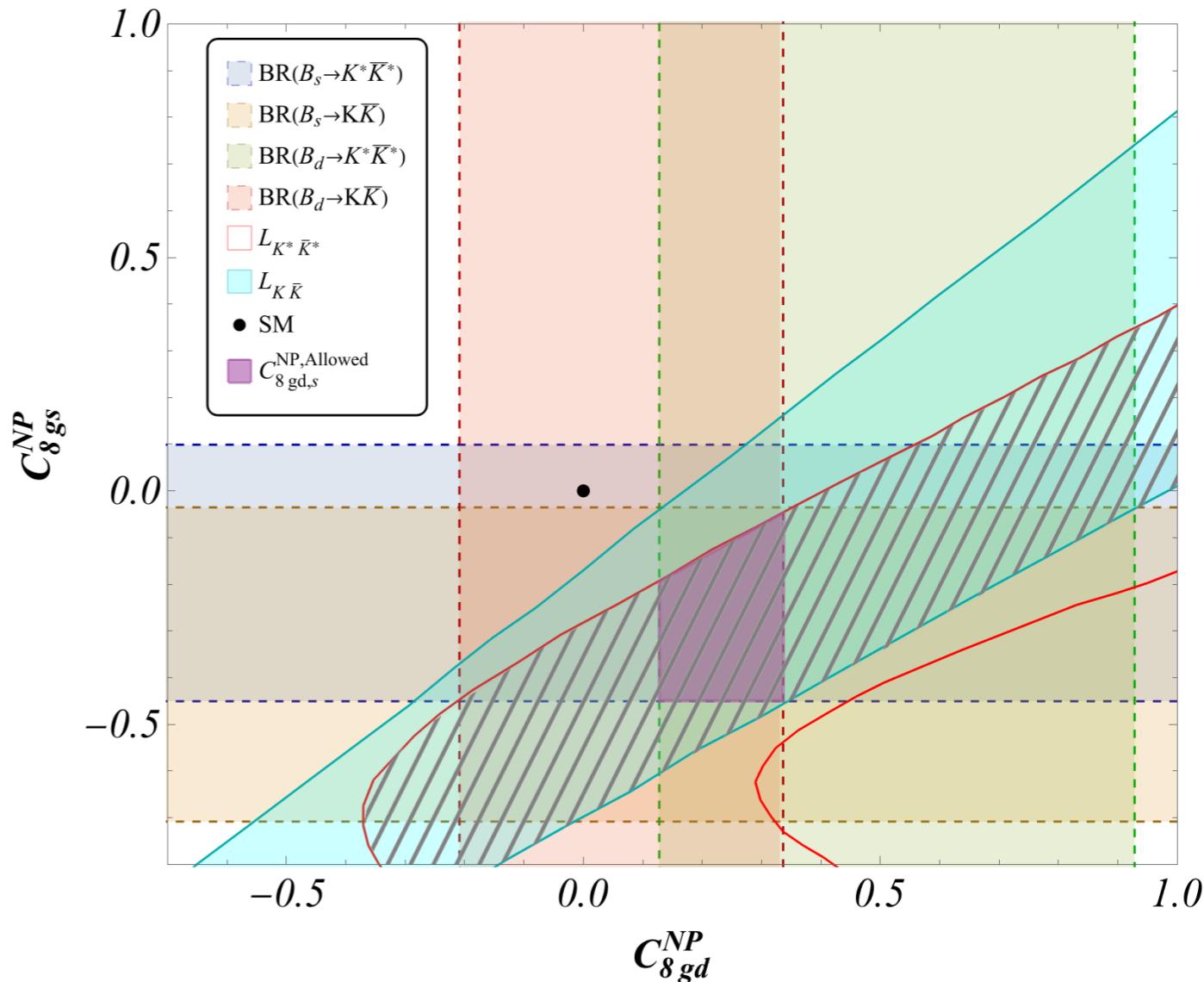
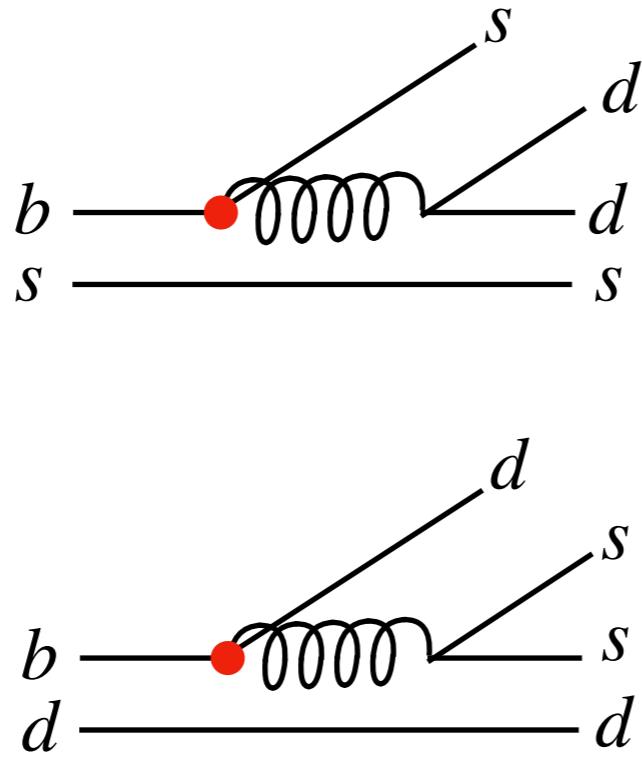
Example: NP in $b \rightarrow s(d)qq$

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

vs

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

Chromod. dipole

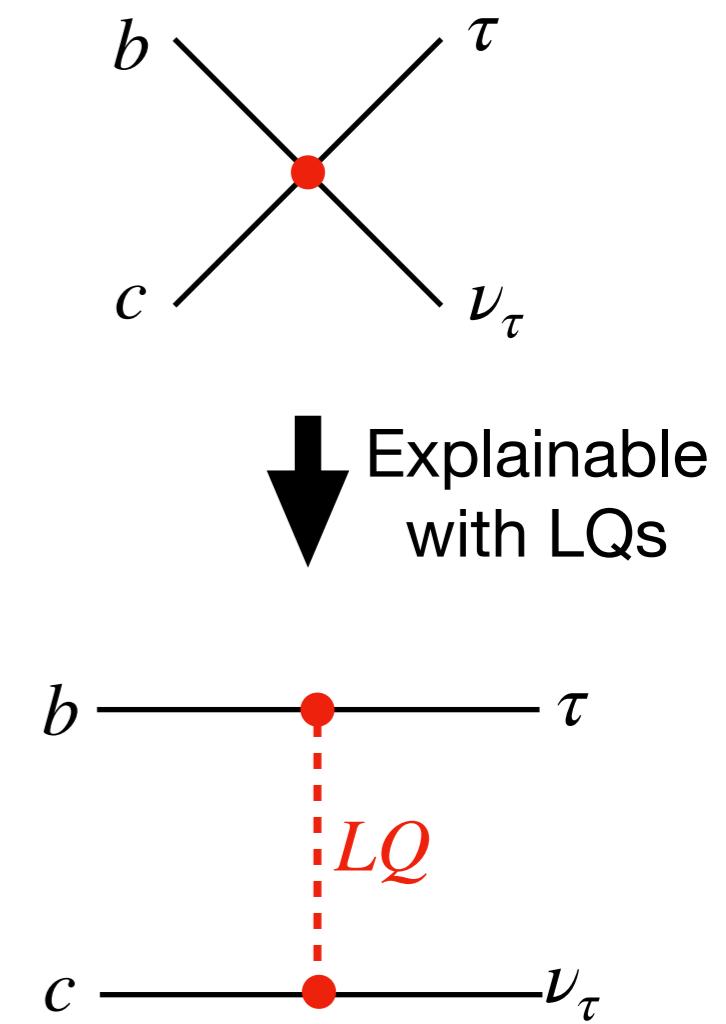
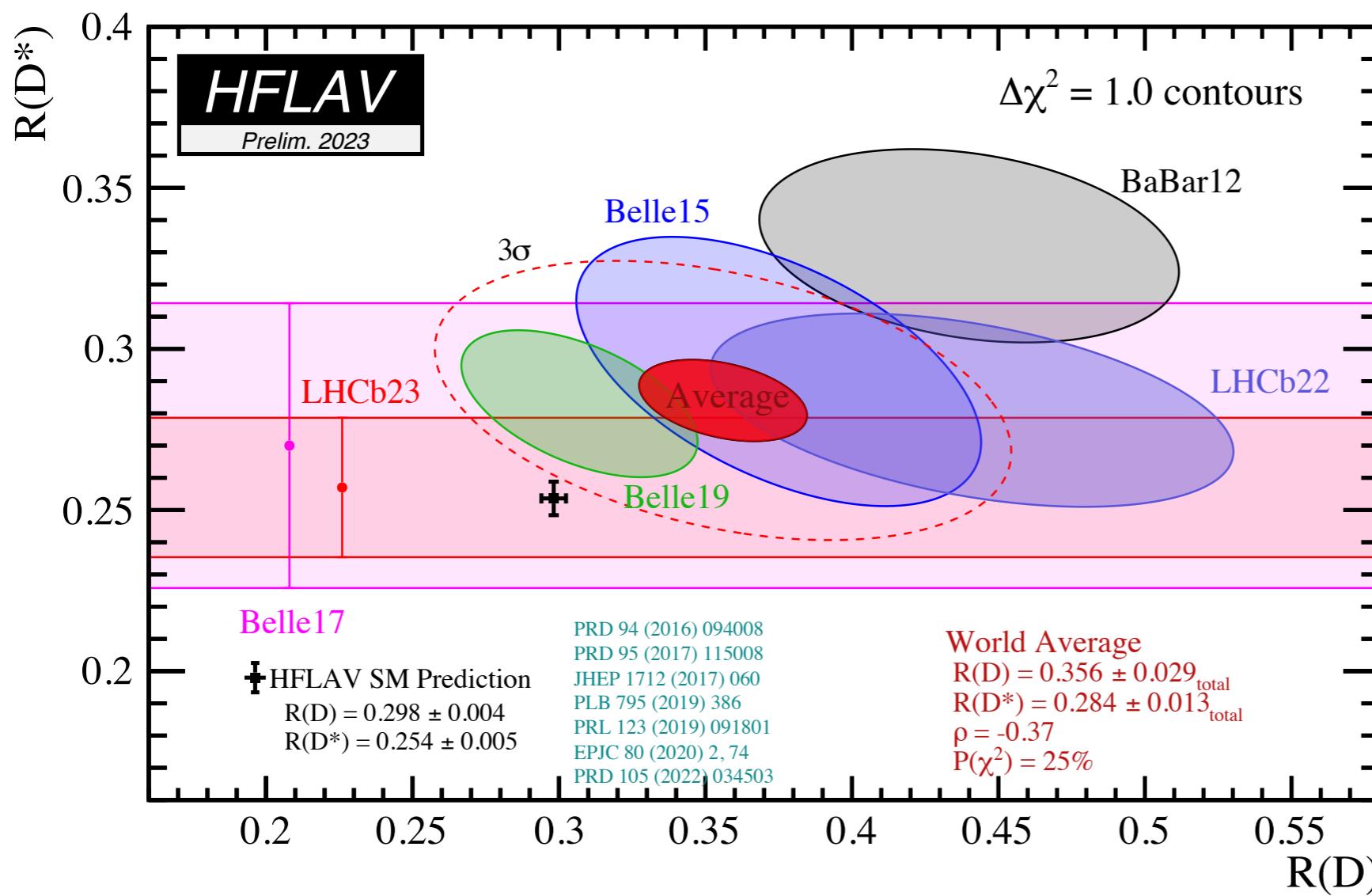


...and $b \rightarrow c\tau\nu$: $R_D^{(*)}$

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

$\gtrsim 3\sigma$

Enhancement of
 $\sim 10\%$ over SM



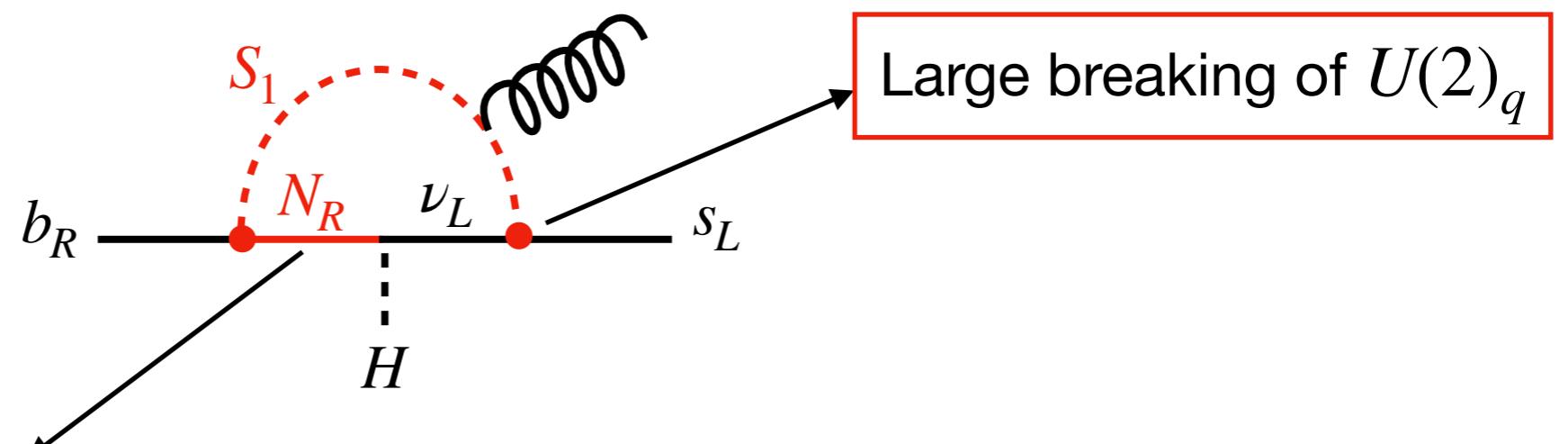
[J. Aebischer, G. Isidori, M. Pesut, B. Stefanek, F. Wilsch, [2210.13422](#)]

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

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

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

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

$$\sin(\theta_\nu) = y_\nu v_{EW}/M_R \rightarrow W \text{ (wavy line)} \rightarrow \begin{array}{c} \tau_L \\ \nu_L \end{array}$$

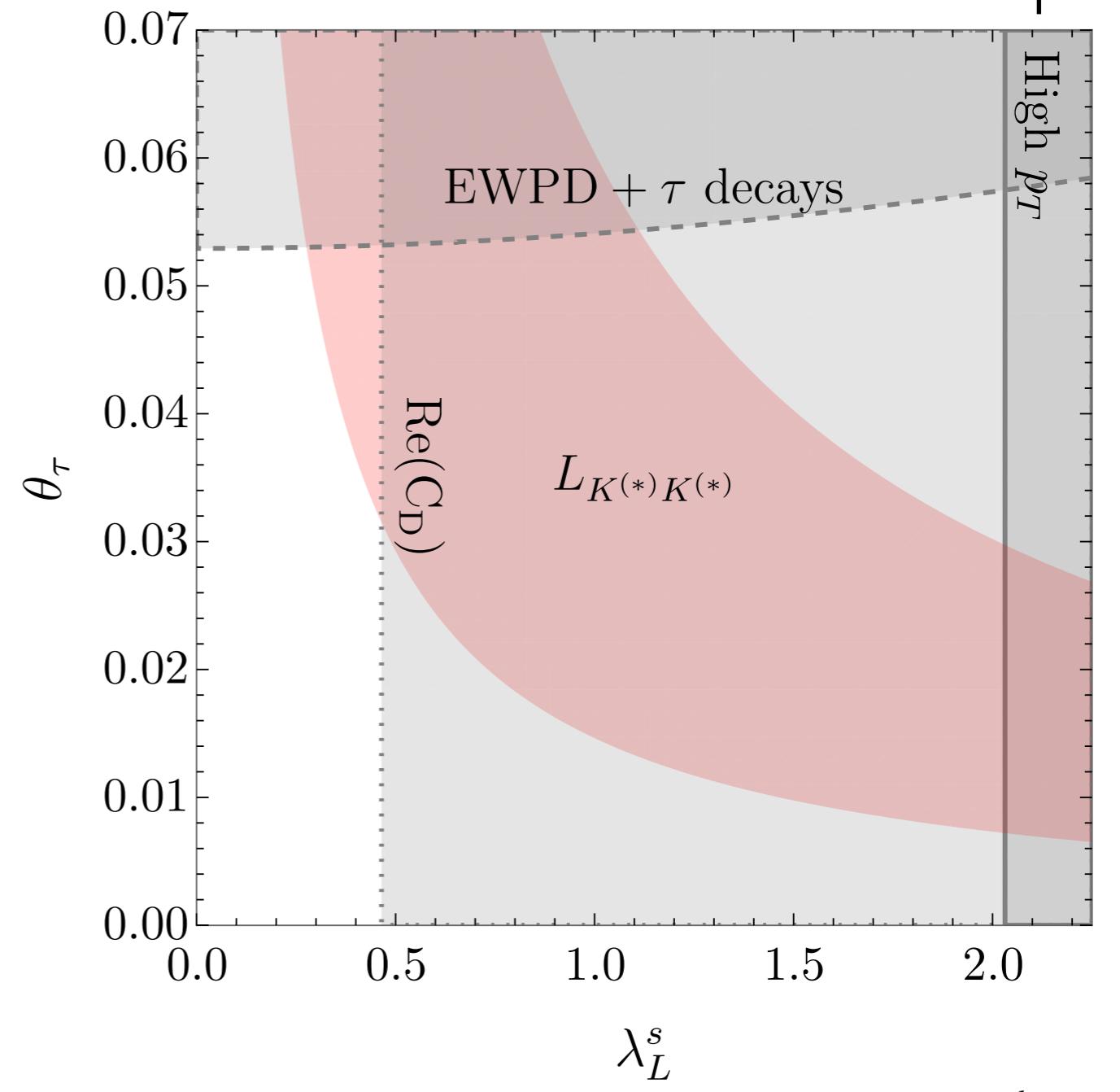
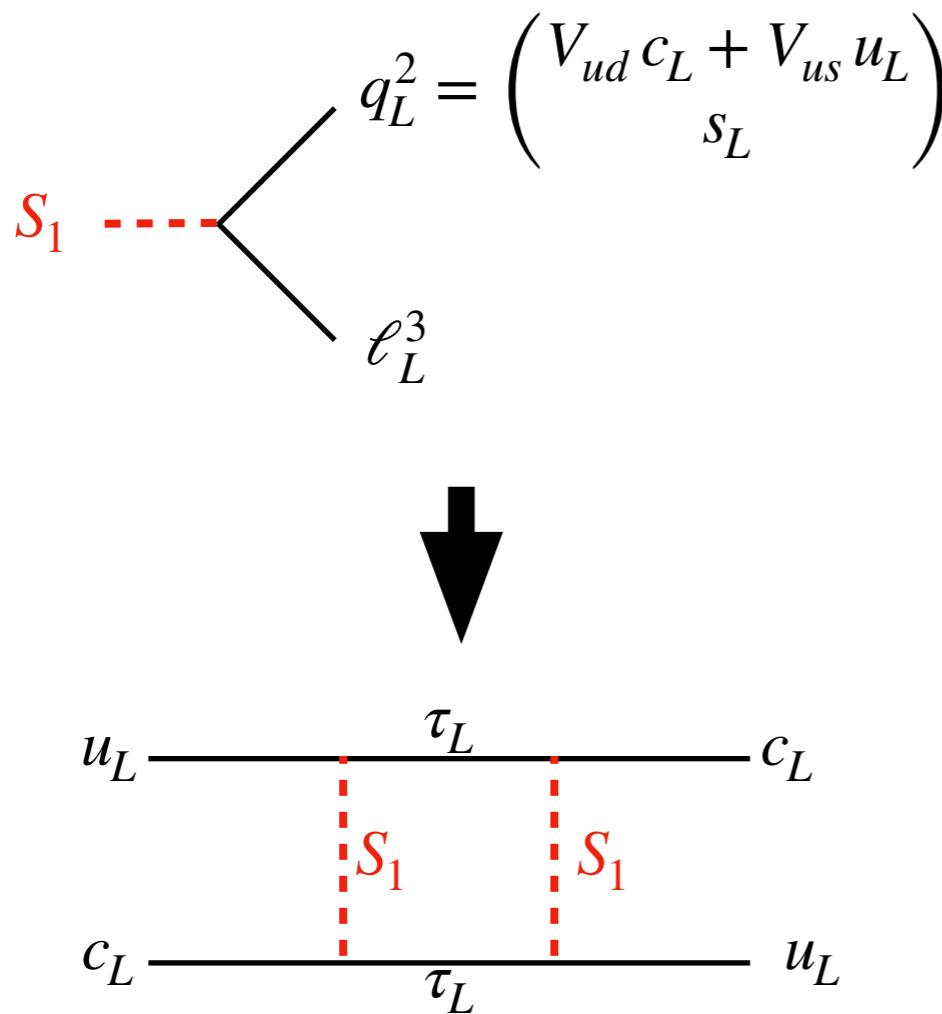
$\theta_\tau \lesssim 0.05$
 (EWPD + τ decays)

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

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

$pp \rightarrow \tau\tau$ & $pp \rightarrow \tau E_T^{\cancel{/\!}} \tau$

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



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

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

Example: $U(2)$ to the rescue



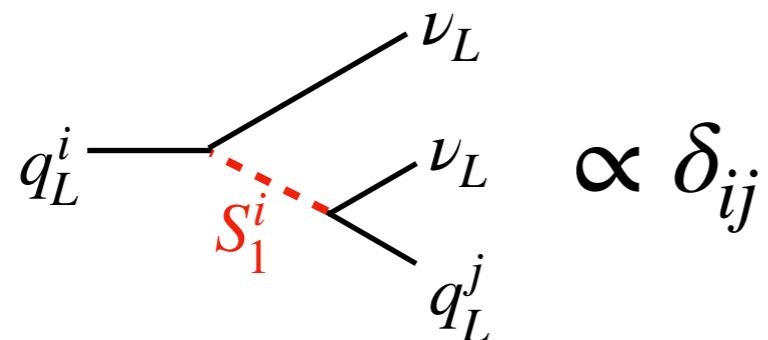
- Idea to improve the situation: promote S_1 to a doublet of $U(2)_q$:

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

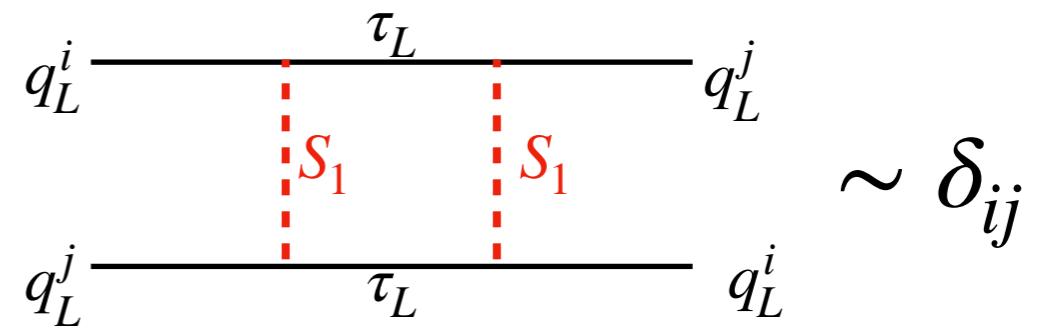
$$\lambda_L^s (\bar{q}_L^2 \epsilon \ell_3^c) S_1 \longrightarrow \lambda_L (\bar{q}_L^i \epsilon \ell_3^c) S_1^i$$

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

- 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.



$$\propto \delta_{ij}$$



$$\sim \delta_{ij}$$

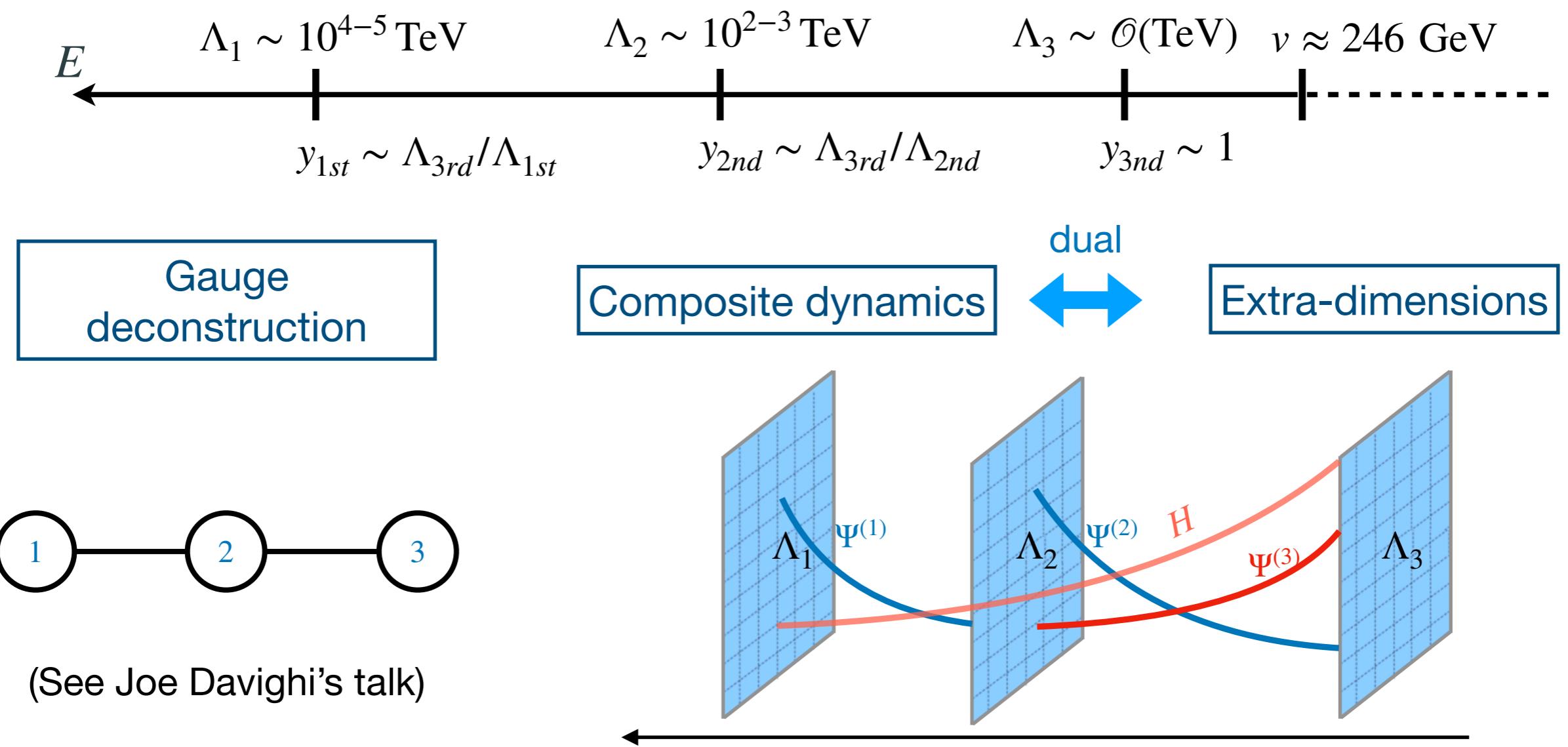
[JML, Matias, Stefanek, [2306.09178](#)]

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

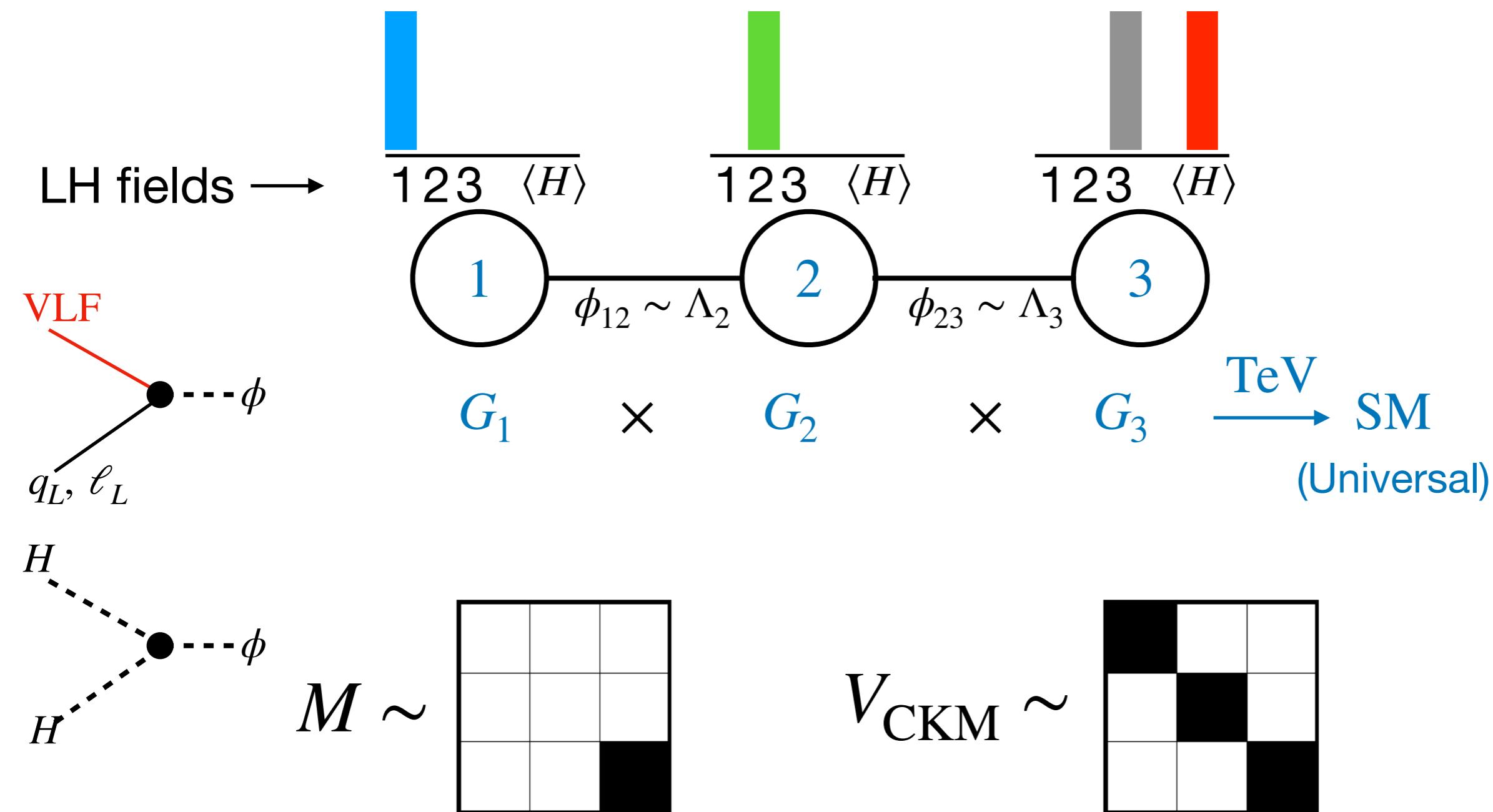
- Minimally broken $U(2)$ emerges naturally in a **multiscale origin of the flavor hierarchies**:



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

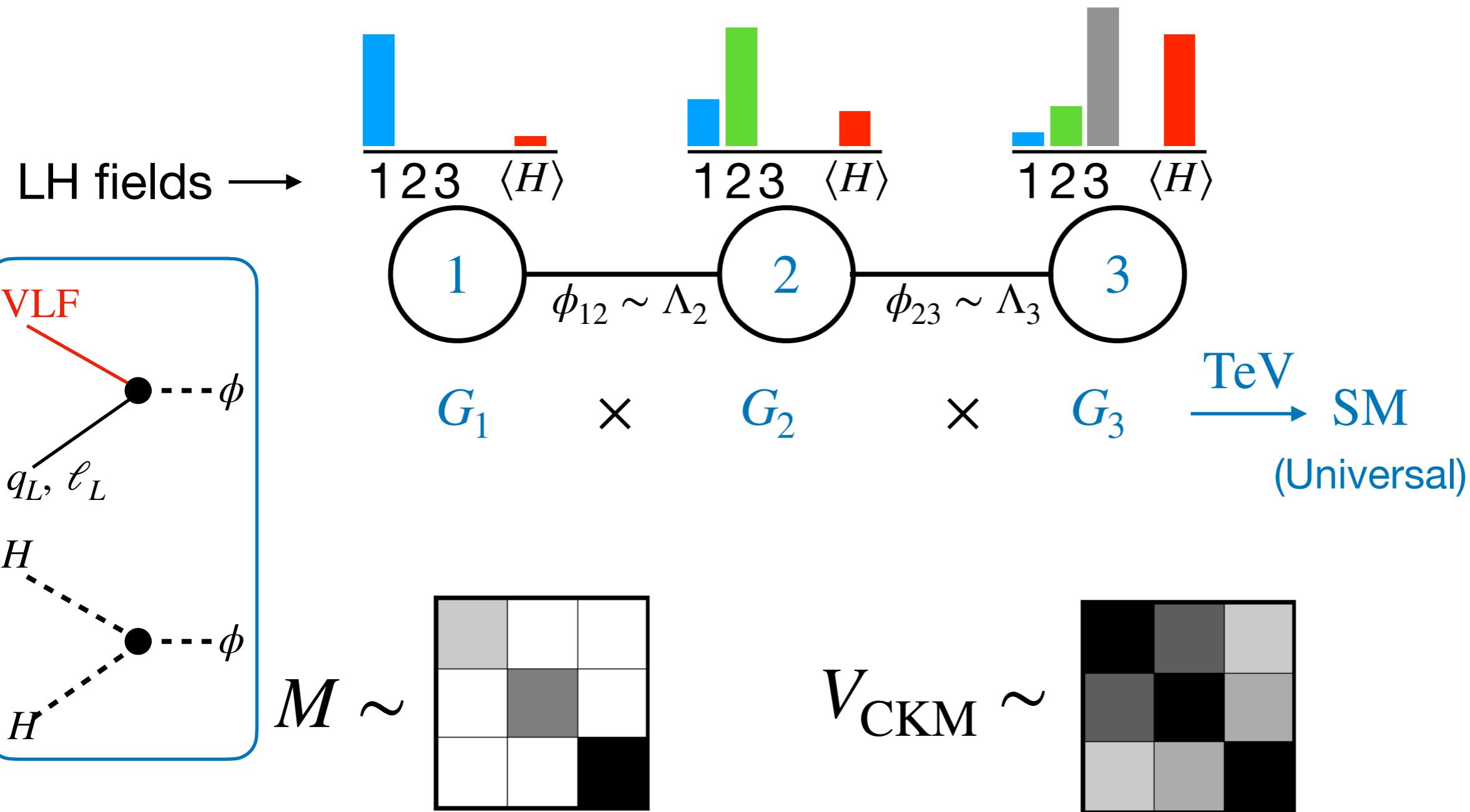
[Bordone, Cornella, Fuentes-Martin, Isidori,
[1712.01368](#),
Davighi, Isidori, [2303.01520](#),
Fernández-Navarro, King, [2305.07690](#),
Davighi, Stefanek, [2305.16280](#)]

Deconstructing flavor



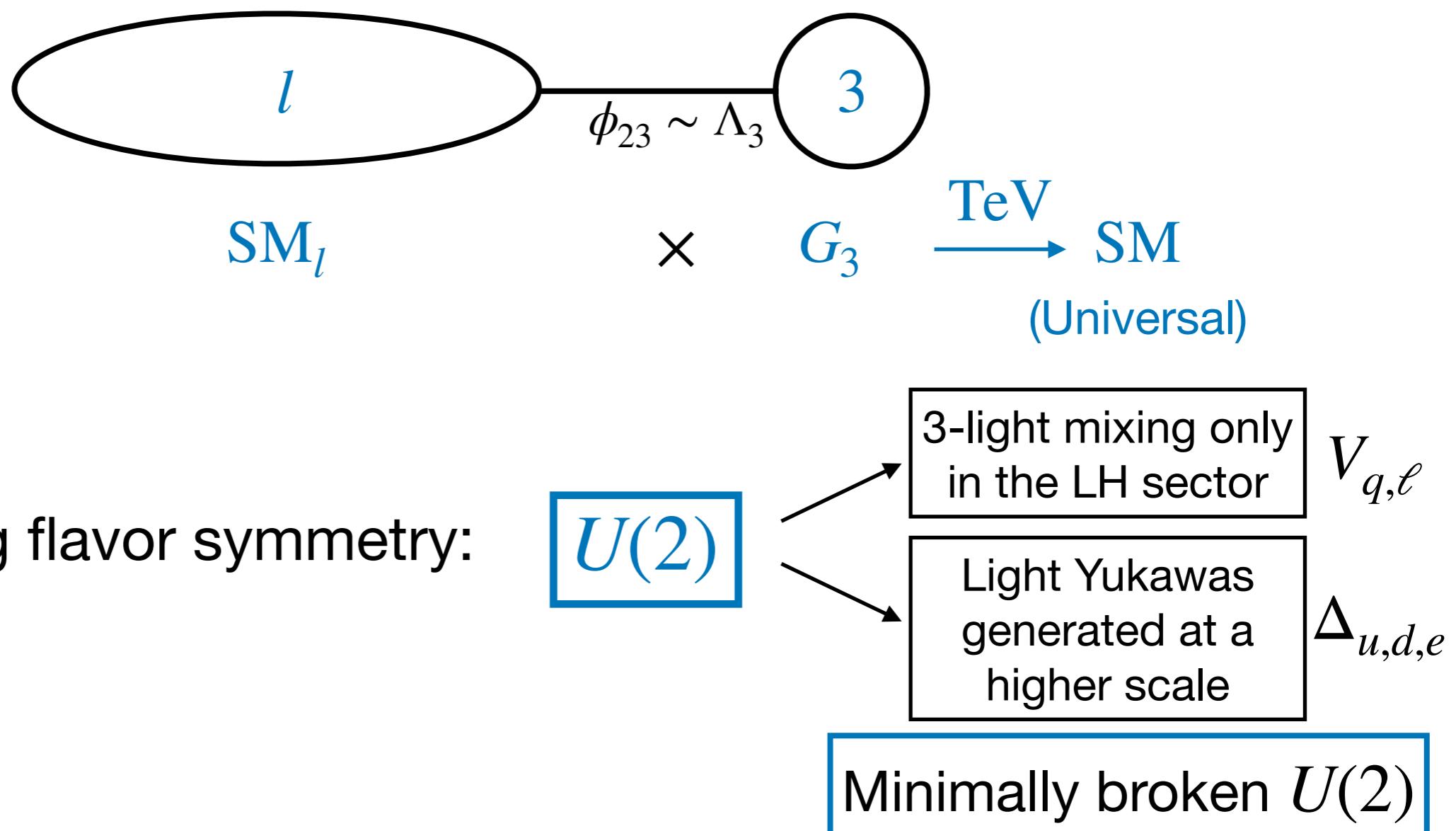
Deconstructing flavor

[Bordone, Cornella, Fuentes-Martin, Isidori, [1712.01368](#),
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Deconstructing flavor

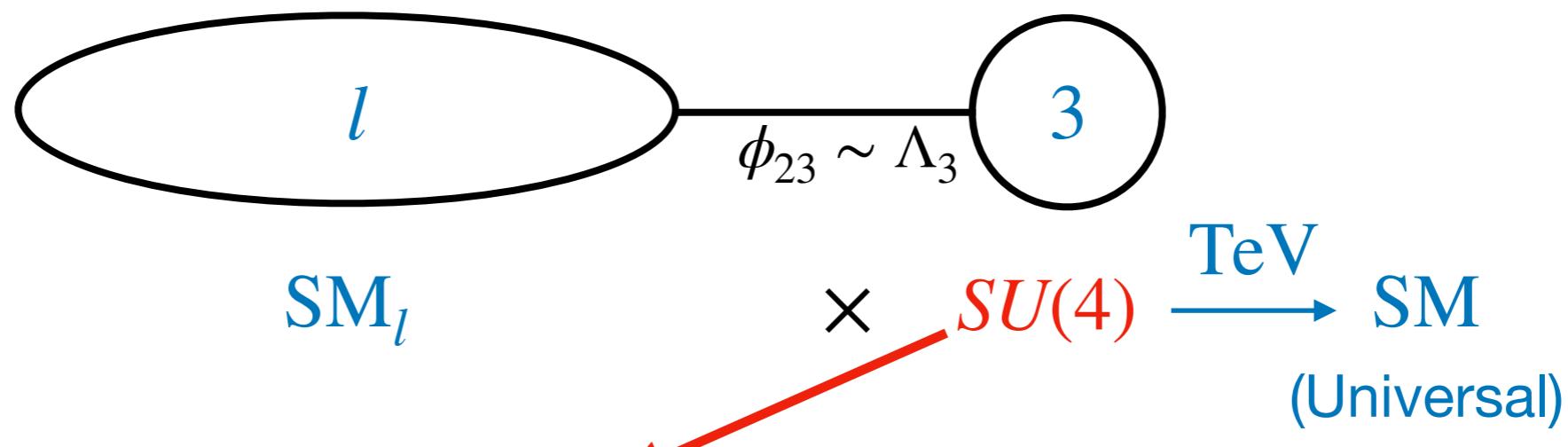
- From the TeV, we see...



- Emerging flavor symmetry:

Deconstructing flavor

- From the TeV, we see...



4321 model

Quark-lepton unification of 3rd fam. à la Pati-Salam

U_1 LQ dominantly coupled to third family $\Rightarrow R_{D^{(*)}}$

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

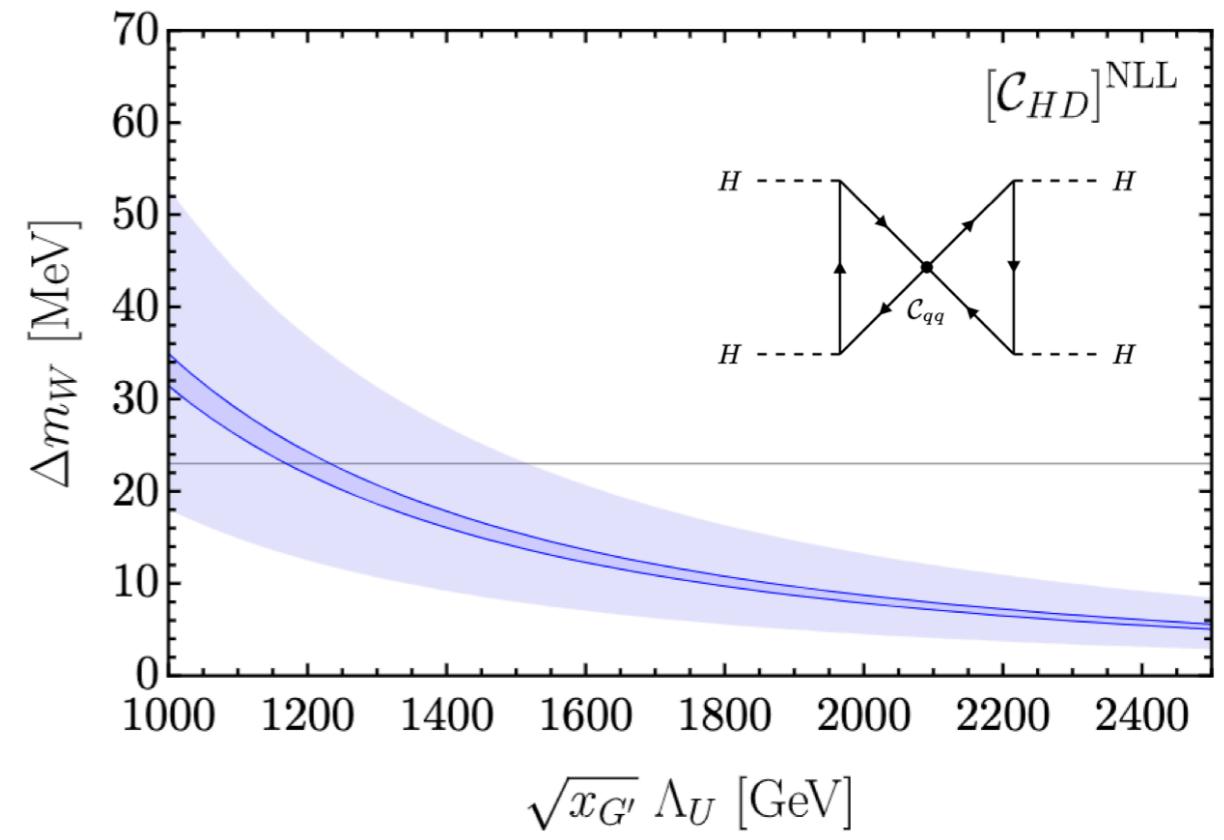
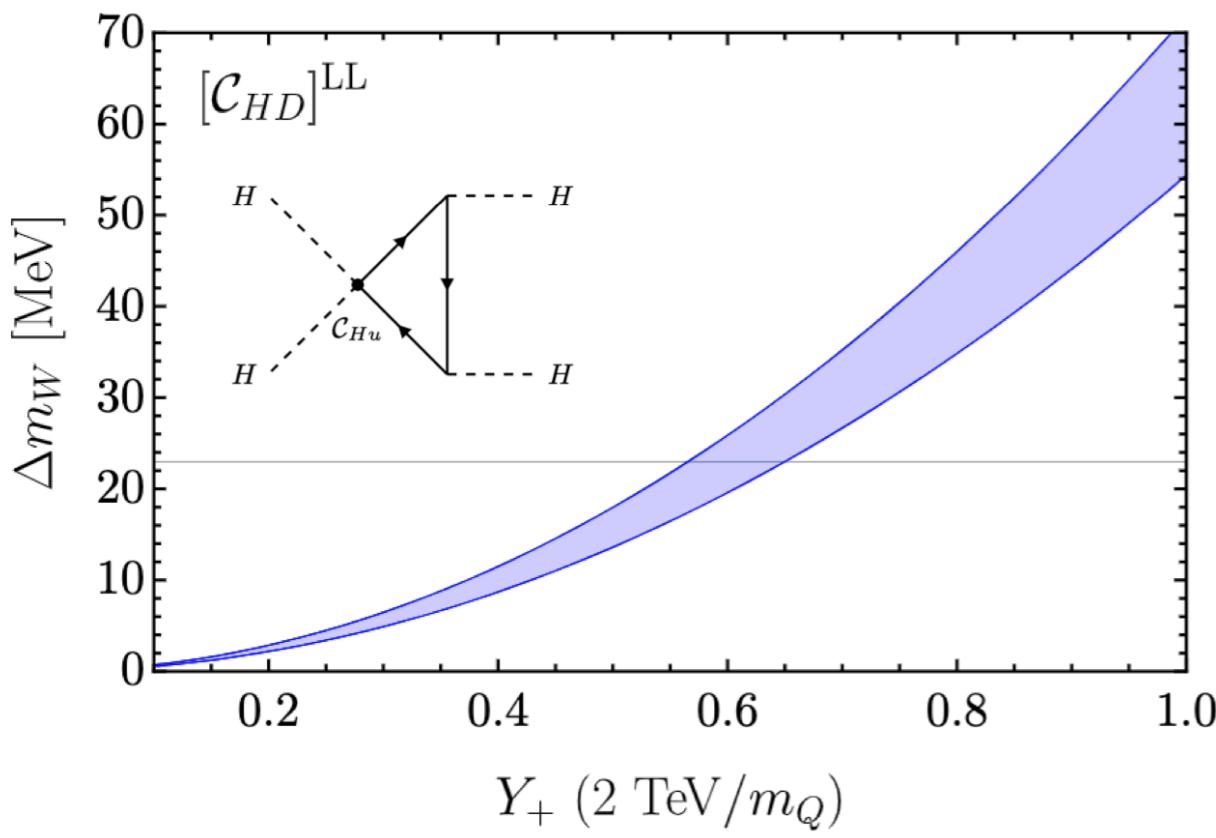
[Greljo, Stefanek, [1802.04274](#), Crosas, Isidori, JML, Selimović, Stefanek, [2203.01952](#), Allwicher, Isidori, JML, Selimović, Stefanek, [2302.11584](#)]

Rich pheno of 4321: EW observables

- Provides an explanation for $R_{D^{(*)}}$ through a $U_1 \sim (\mathbf{3}, \mathbf{1})_{2/3}$ 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

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

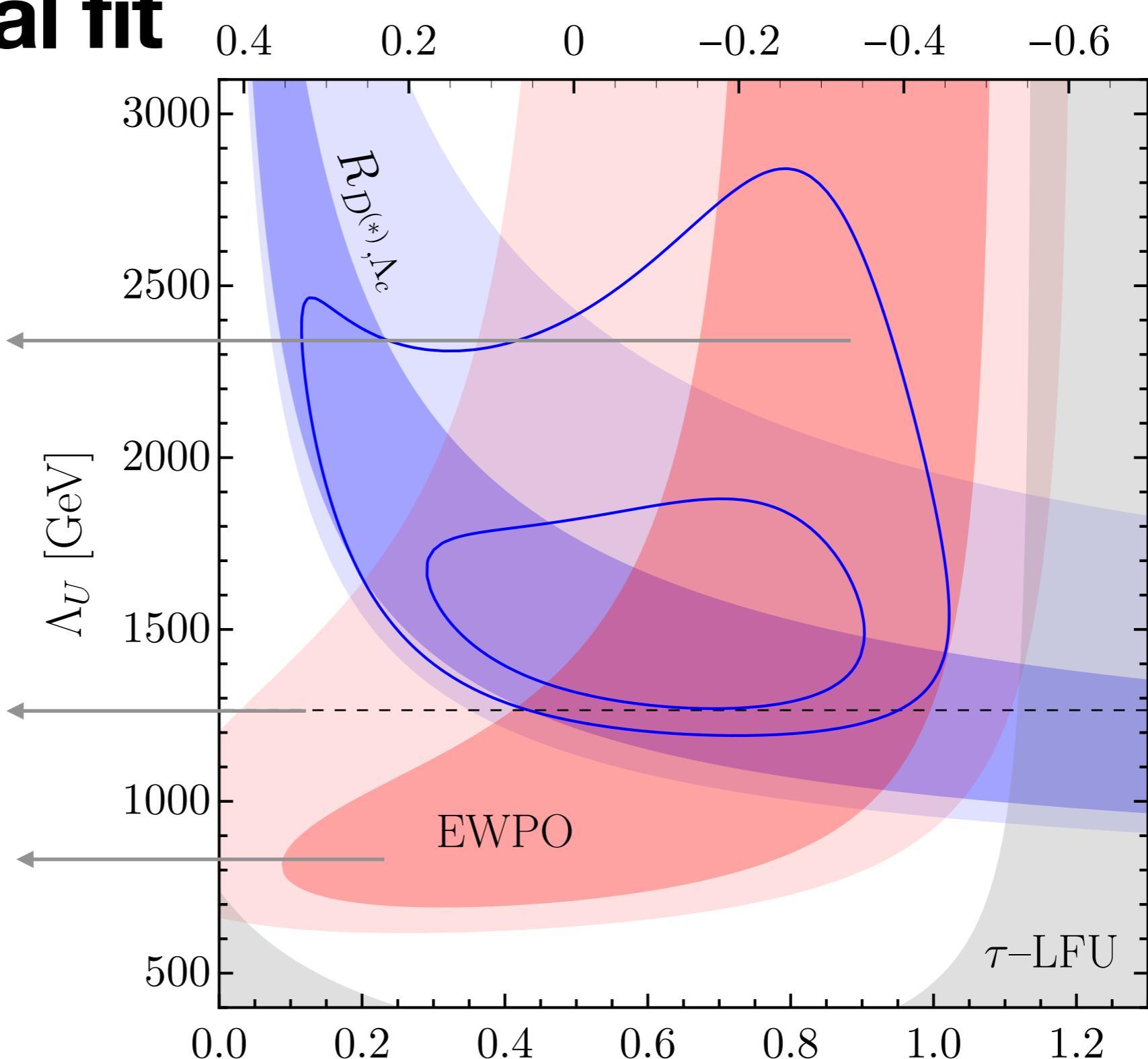
95 % CL CMS $pp \rightarrow \tau\tau$

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

$$s_q = y_t V_{cb} / Y_+$$

$$s_q \stackrel{?}{=} 0.1$$

$$s_q \stackrel{?}{=} V_{cb}$$



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!

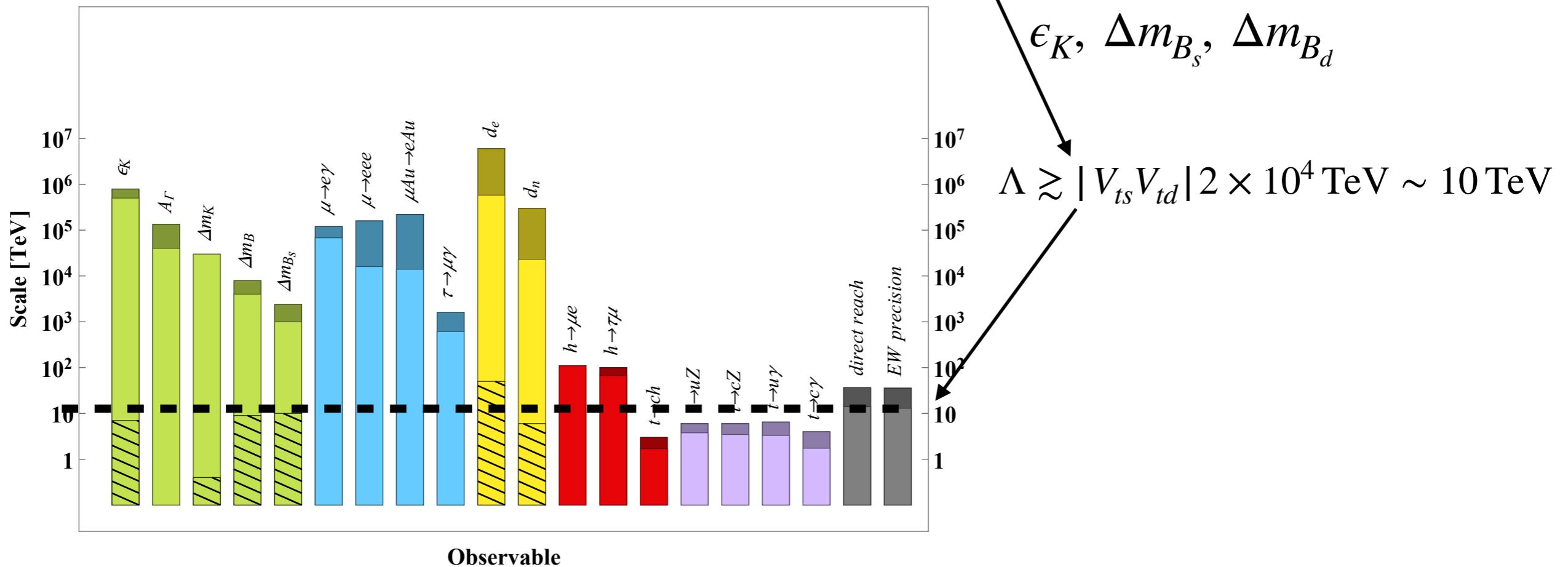
Backup

Flavor symmetries

Minimal Flavor Violation

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

$$\mathcal{L} \supset (\bar{q}_L Y_u Y_u^\dagger \gamma_\mu q_L) J_{\text{NP}}^\mu \rightarrow \mathcal{L}_{\text{SMEFT}} \supset \frac{1}{\Lambda^2} (\bar{q}_L Y_u Y_u^\dagger \gamma_\mu q_L) (\bar{q}_L Y_u Y_u^\dagger \gamma_\mu q_L)$$



[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:

$$Y_{u,d,e} \sim \left(\begin{array}{c|c} \Delta_{u,d,e} & \\ \hline \begin{array}{|c|c|c|} \hline & & \\ \hline & & \\ \hline & & \\ \hline \end{array} & \begin{array}{|c|} \hline y_3 \\ \hline \end{array} \end{array} \right) \{ V_{q,\ell} \}$$

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

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

↓
It becomes a bound on V_ℓ

Non-leptonic B decays

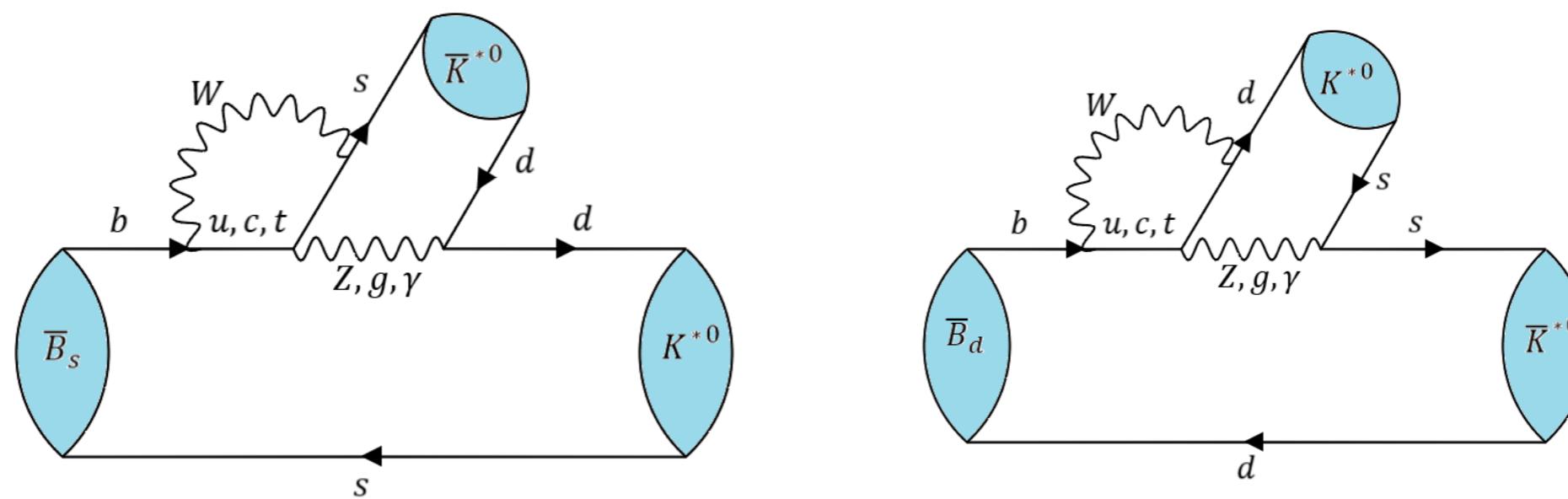
$L_{K^{(*)}\bar{K}^{(*)}}$ observables

- 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 $B \rightarrow K^{(*)}\bar{K}^{(*)}$

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



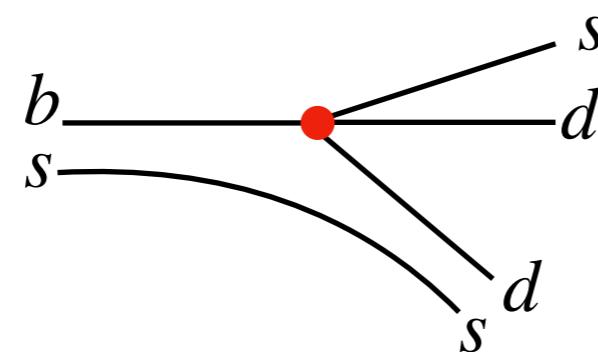
NP in $L_{K^{(*)}\bar{K}^{(*)}}$

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

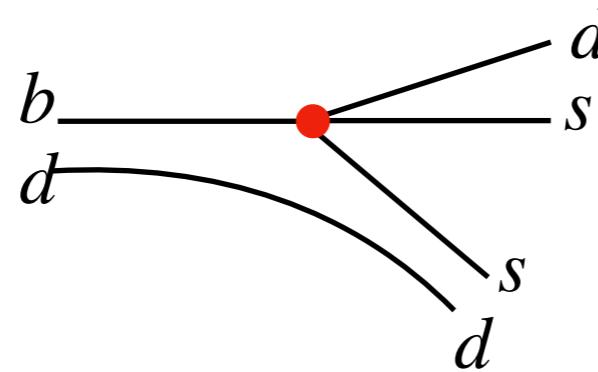
$$L_{K\bar{K}}^{\text{SM}} = 26.00^{+3.88}_{-3.59} \quad L_{K\bar{K}}^{\text{exp}} = 14.58 \pm 3.37 \quad \rightarrow 2.4\sigma$$

4-quark op.

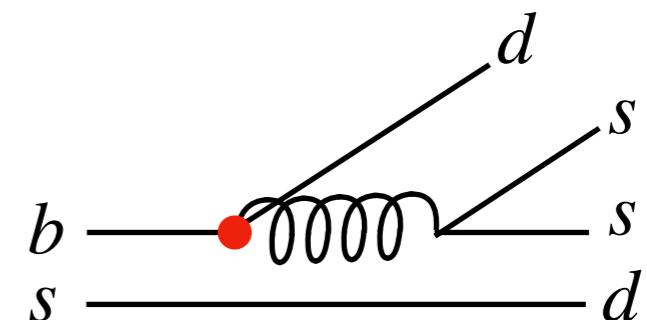
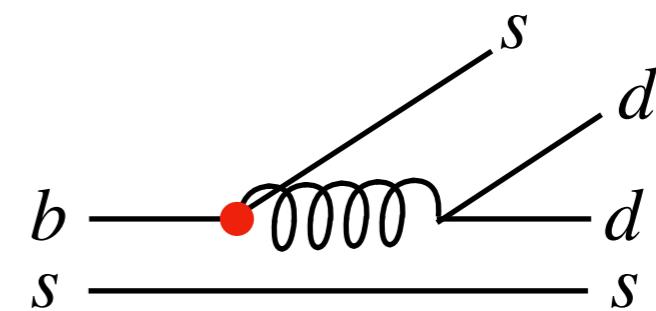
$$\bar{B}_s \rightarrow K^{(*)}\bar{K}^{(*)} \\ (b \rightarrow s)$$



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

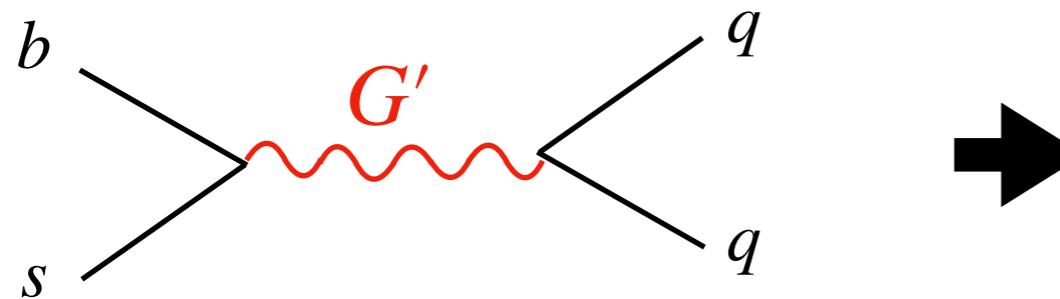


Chromod. dipole



C_{4S} : Coloron

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



$$\mathcal{L} \supset \frac{2V_{tb}V_{ts}^*}{v_{\text{EW}}^2} C_{4S} (\bar{s}_L^\alpha \gamma_\mu b_L^\beta)(\bar{q}^\beta \gamma_\mu q^\alpha)$$

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

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

$$\left. \begin{aligned} \frac{\Delta_{sb}\Delta_{qq}}{m_{G'}^2} &\sim \frac{1}{(5 \text{ TeV})^2} \\ \frac{\Delta_{qq}^2}{m_{G'}^2} &\lesssim \frac{1}{(5 \text{ TeV})^2} \end{aligned} \right\} \times$$

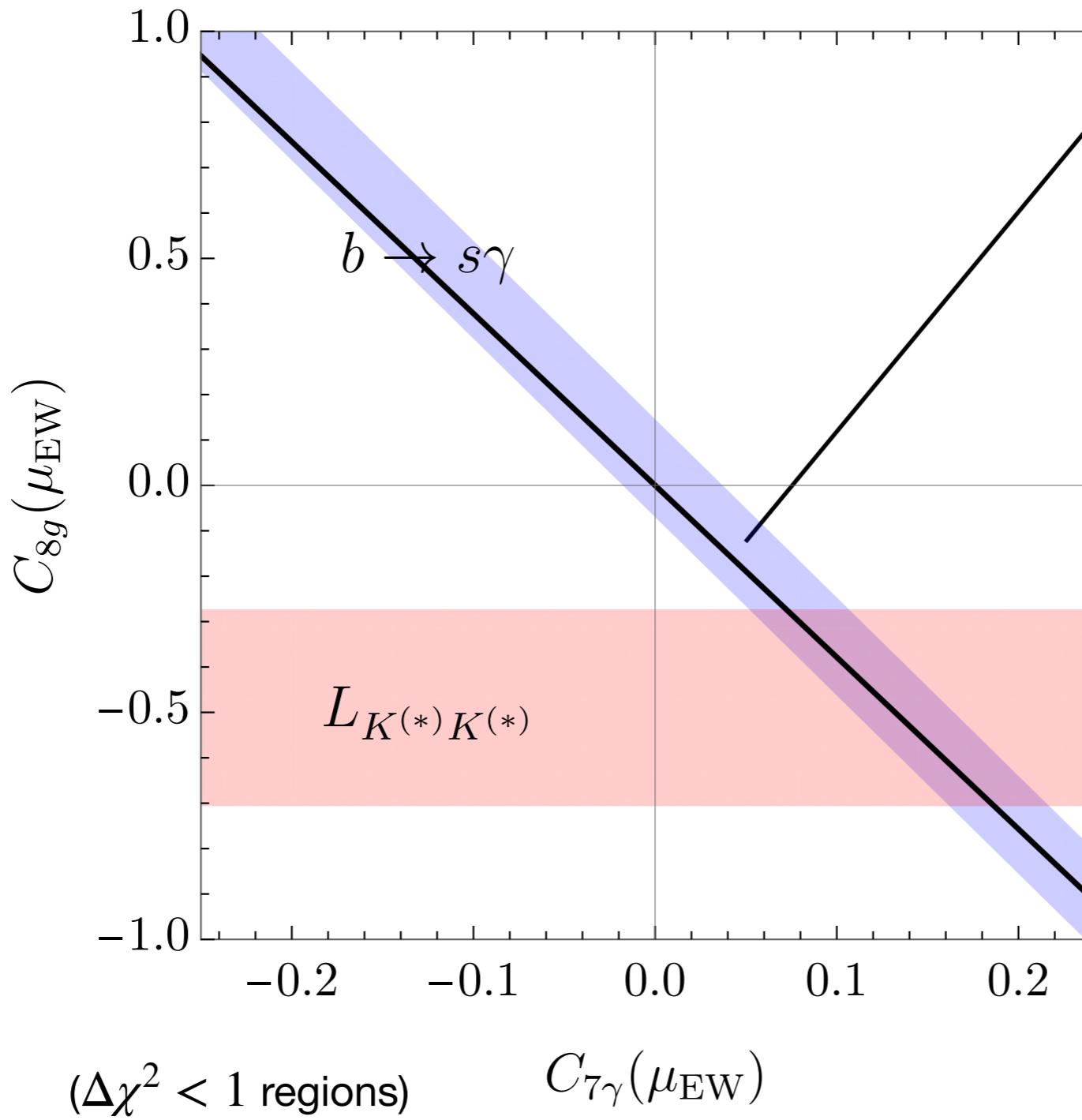
- From di-jet searches:

- B_s mixing:

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

The EM dipole

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



Including RG running from
2 TeV to μ_{EW}

λ_L^s

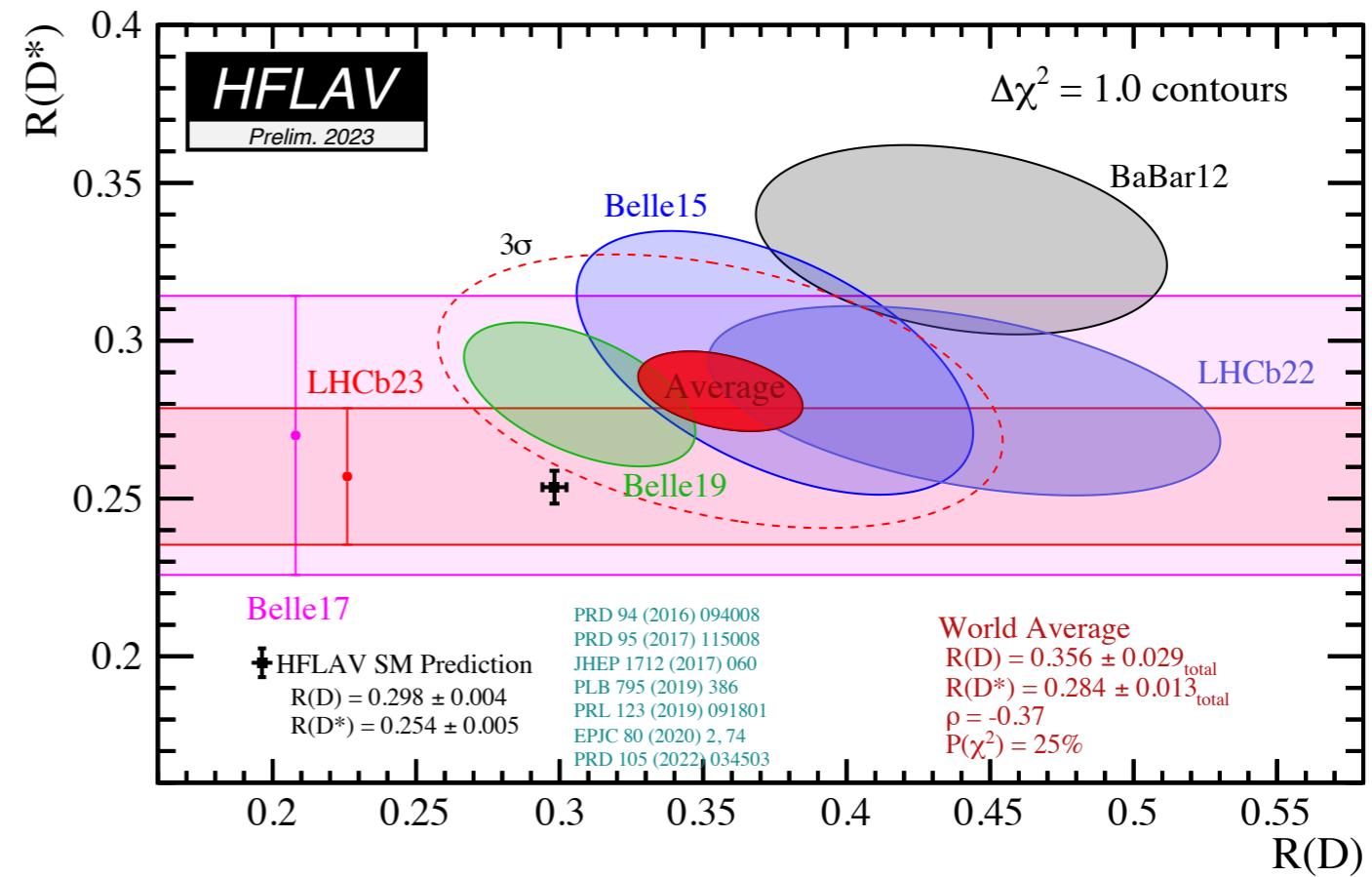
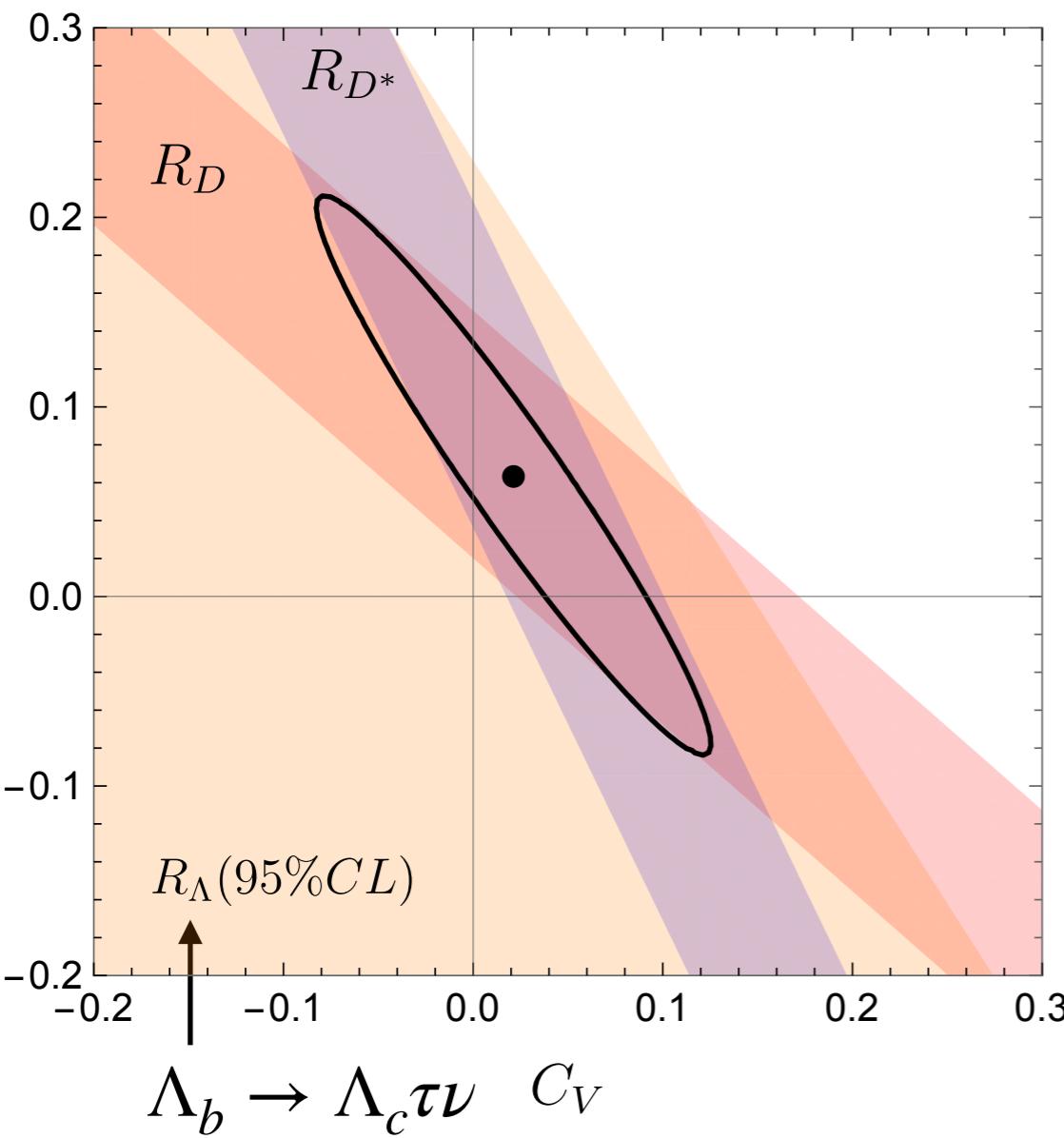
-1.
-0.5
0.
0.5
1.

$(\bar{q}_L^2 \epsilon \ell_3^c) S_1$ coupling assuming
 $M_{S_1} = 2 \text{ TeV}$, $\theta_\tau = 0.05$,
and $\lambda_R^b = -2$, $(\bar{b}_R S_1 N_R)$.

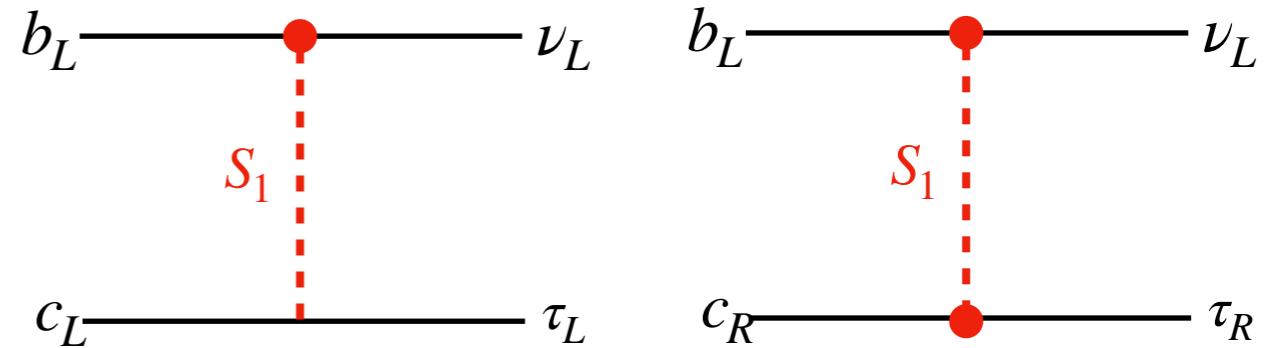
$b \rightarrow c\tau\nu$ data

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

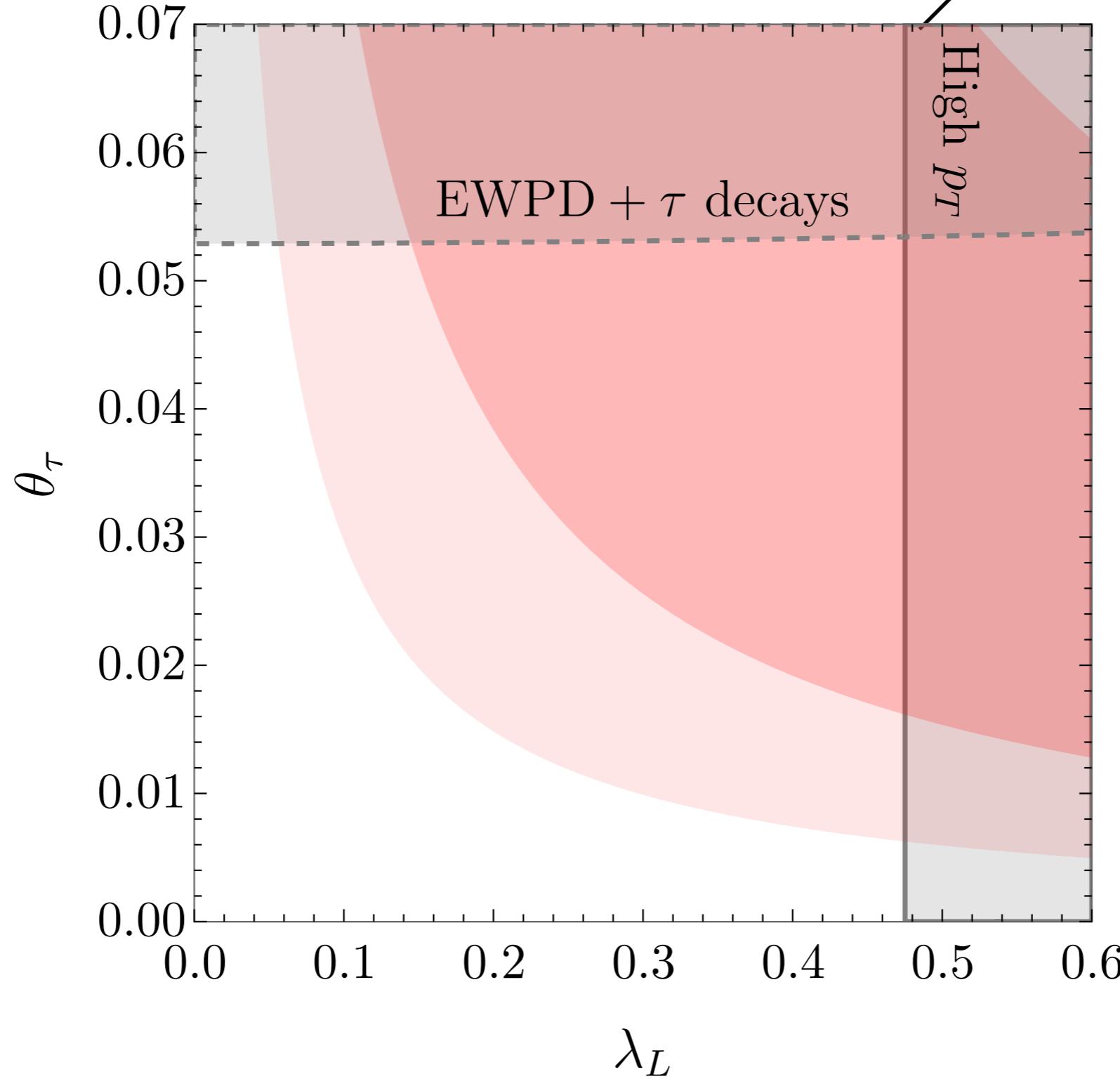
$\sim 3\sigma$



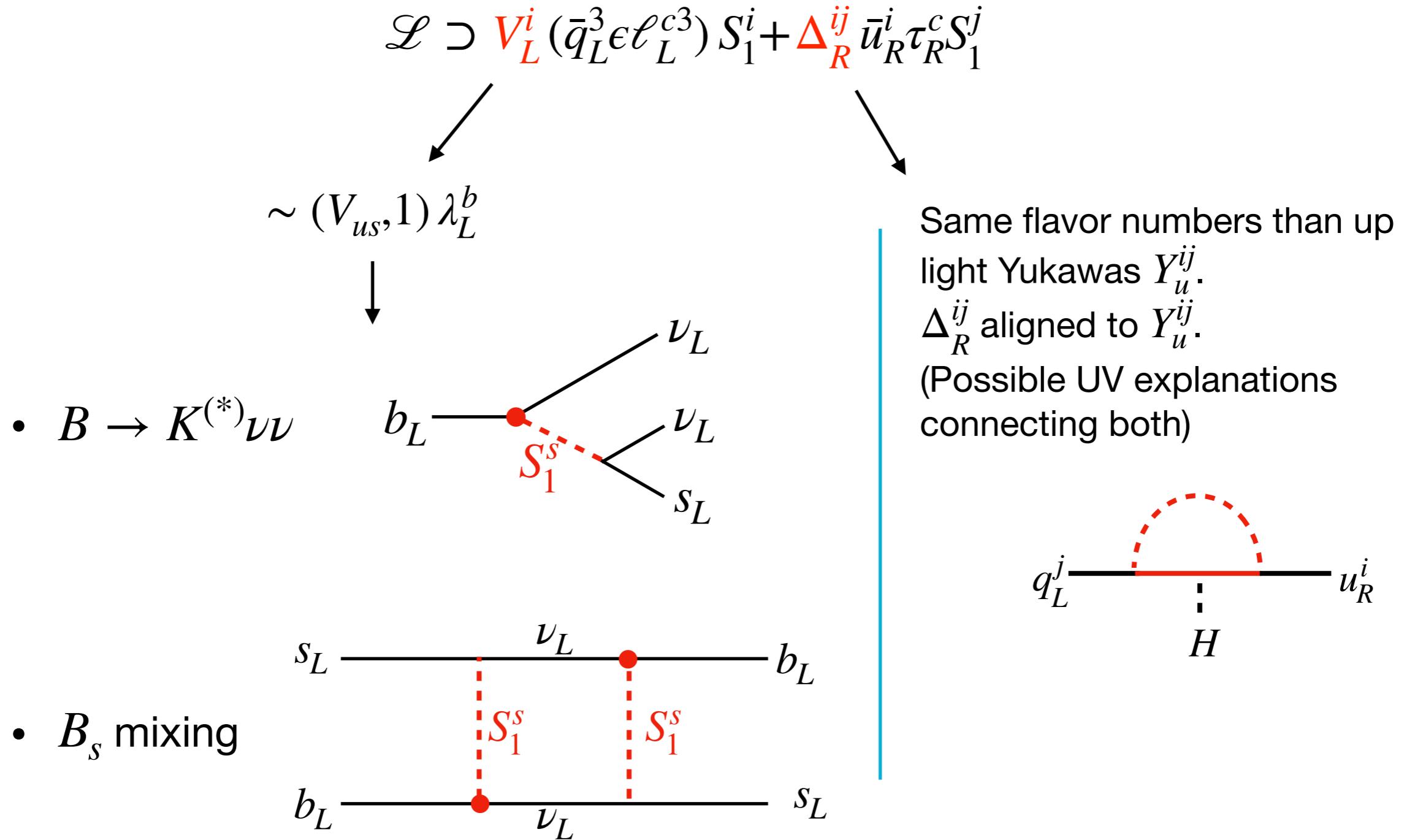
$$\begin{aligned} \mathcal{L} \supset & \frac{2}{v_{\text{EW}}^2} V_{cb} \left[(1 + C_V)(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) \right. \\ & \left. + C_{S,T} \left((\bar{c}_R b_L)(\bar{\tau}_R \nu_L) - \frac{1}{4} (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right)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



Global fit S_1 model



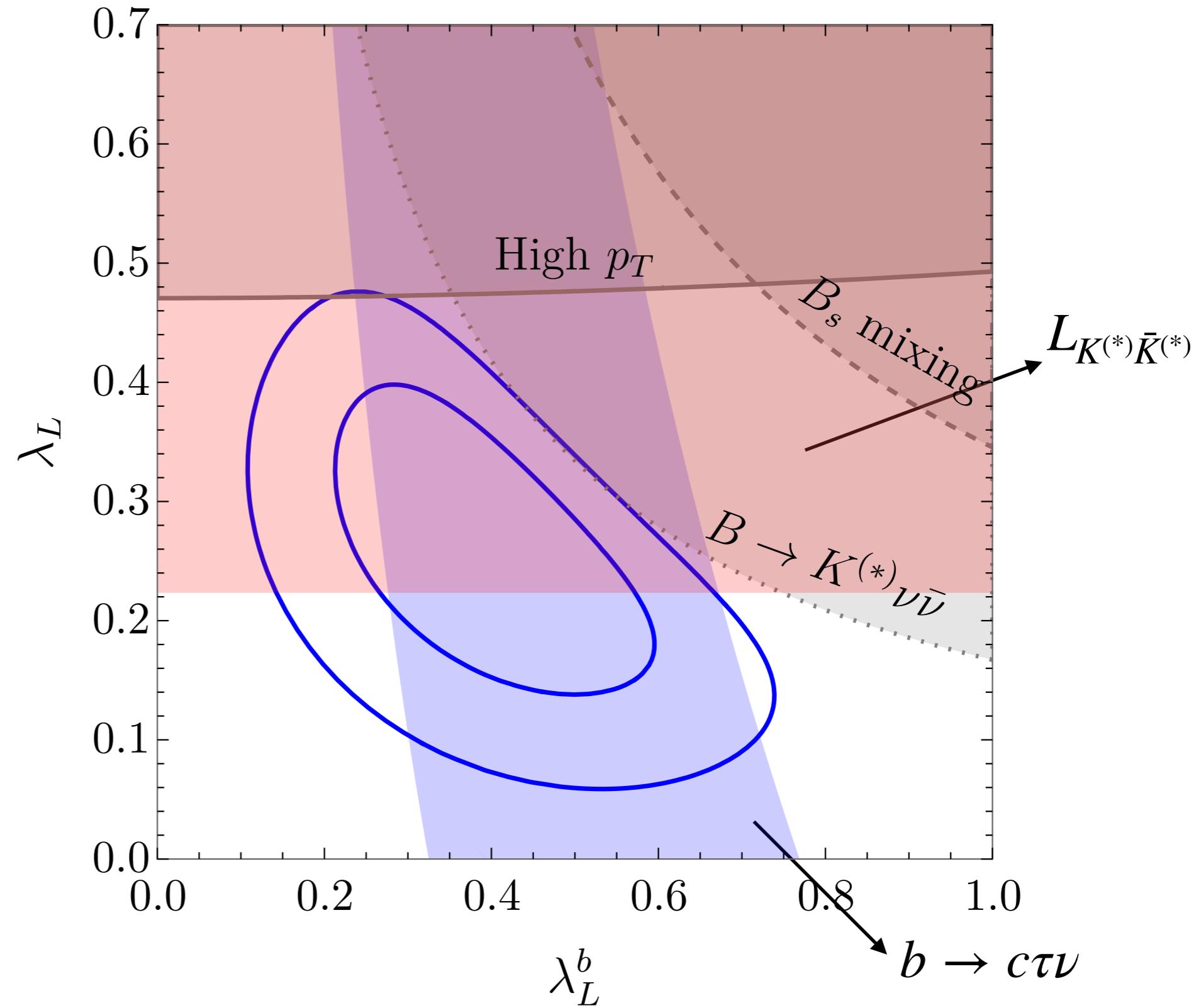
New couplings, new constraints:



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 :
 - $pp \rightarrow \tau\tau$
 - $pp \rightarrow \tau E_T^{\cancel{T}}$
- Others:
 $b \rightarrow s/d\gamma$, EWPT,
 τ decays, ...

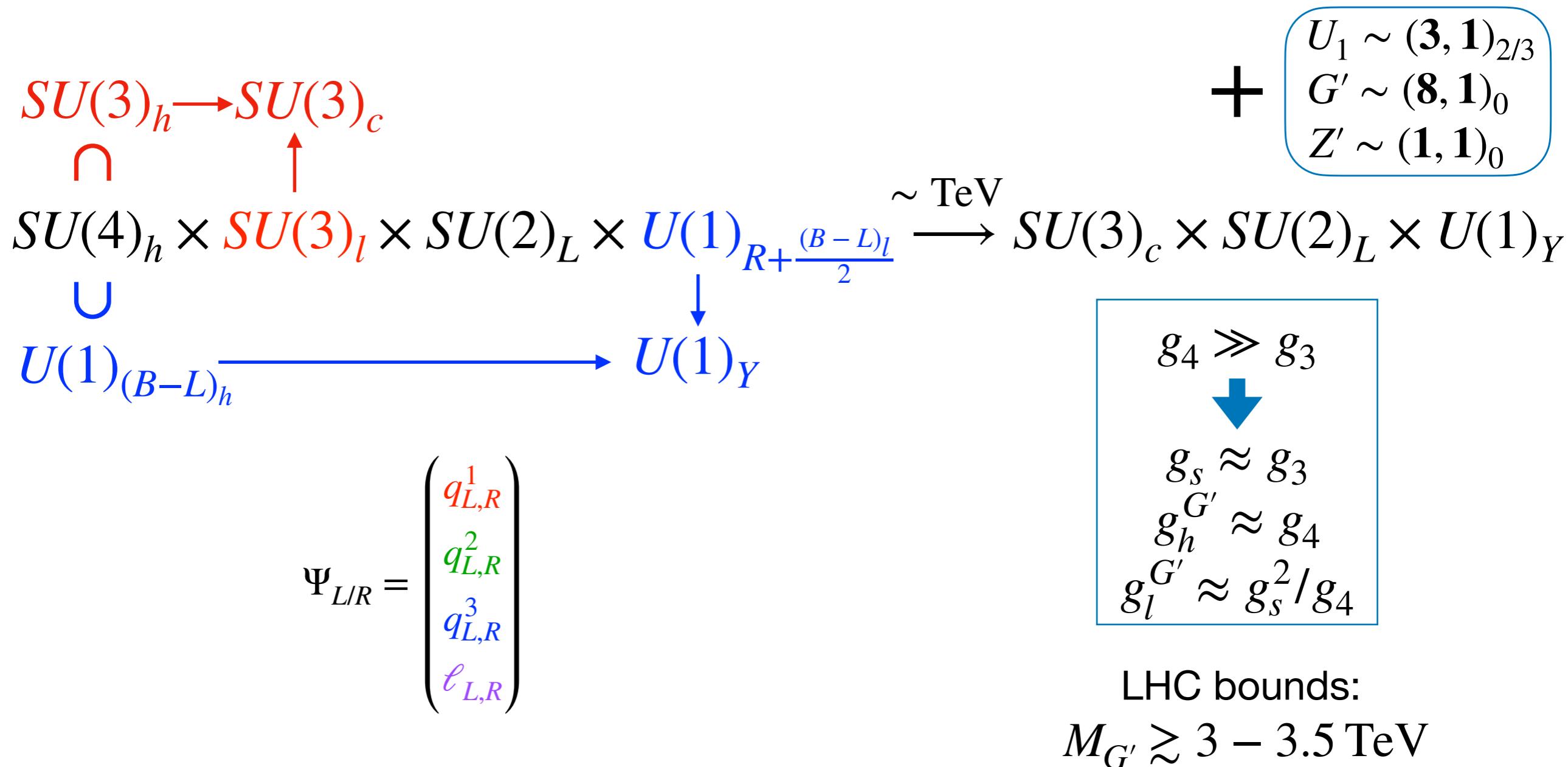


4321 model

[Bordone, Cornella, Fuentes-Martin, Isidori, [1712.01368](#), [1805.09328](#);
 Greljo, Stefanek, [1802.04274](#);
 Cornella, Fuentes-Martin, Isidori [1903.11517](#)]

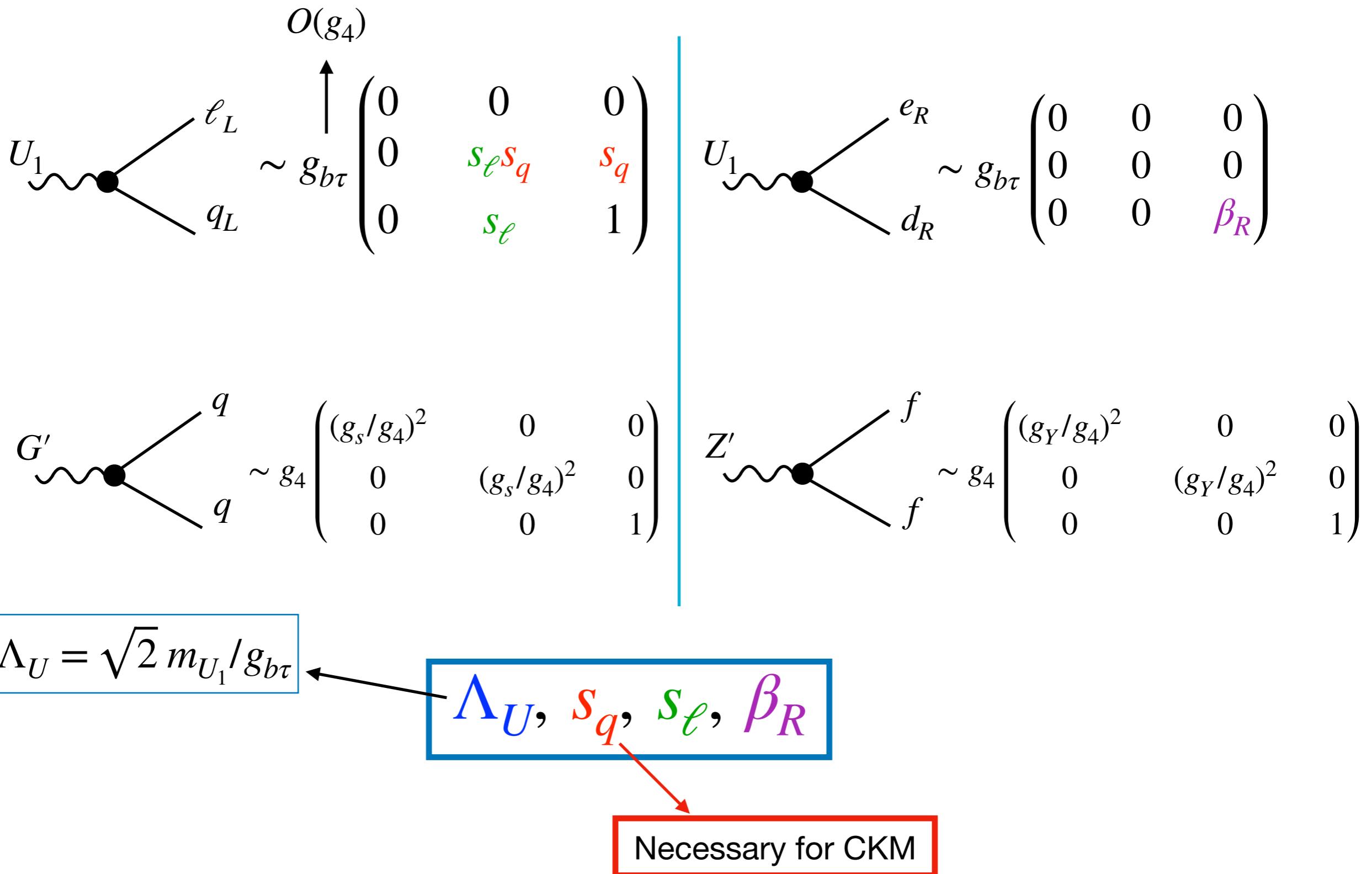
4321 model

Third family quark-lepton unification:



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

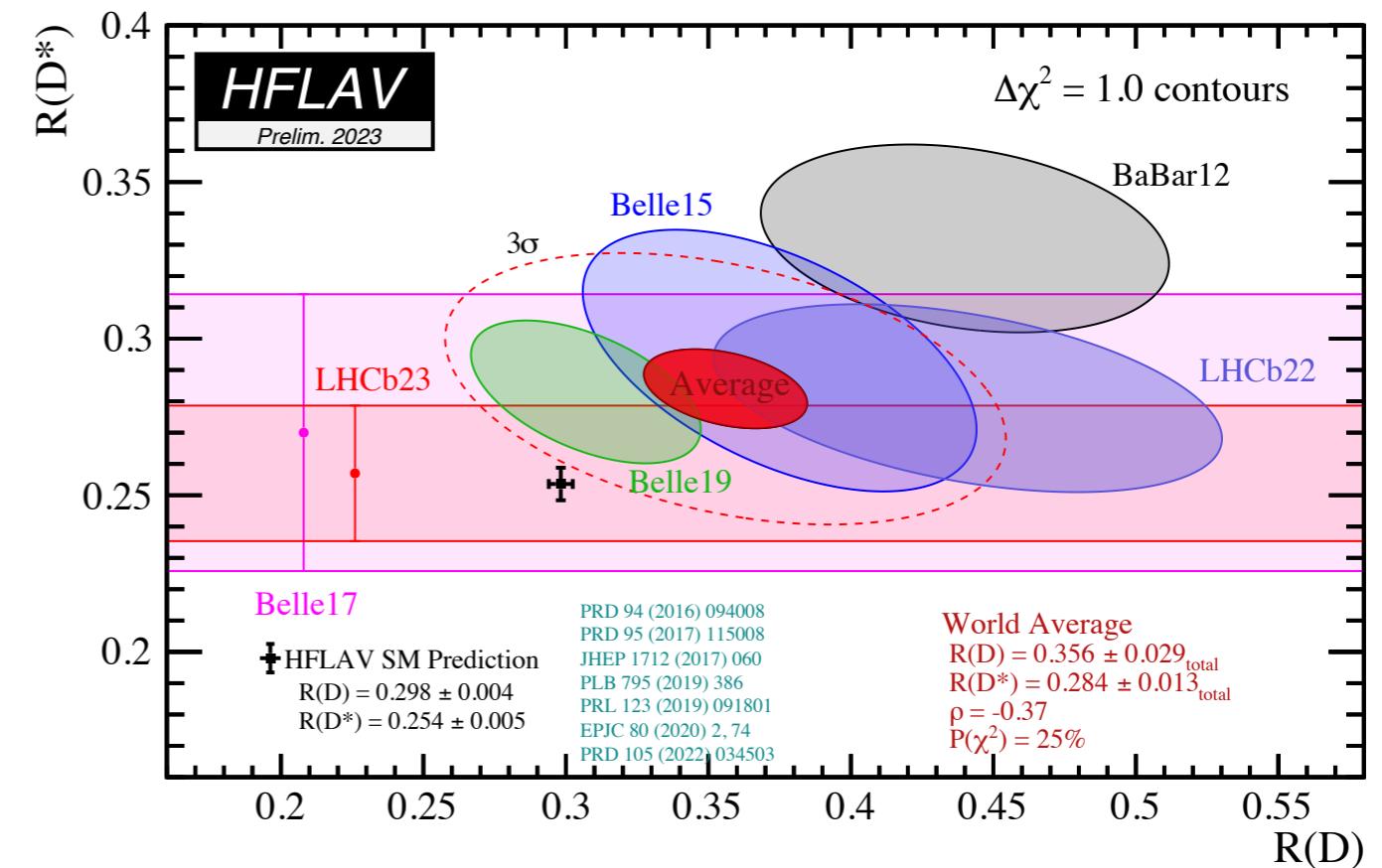
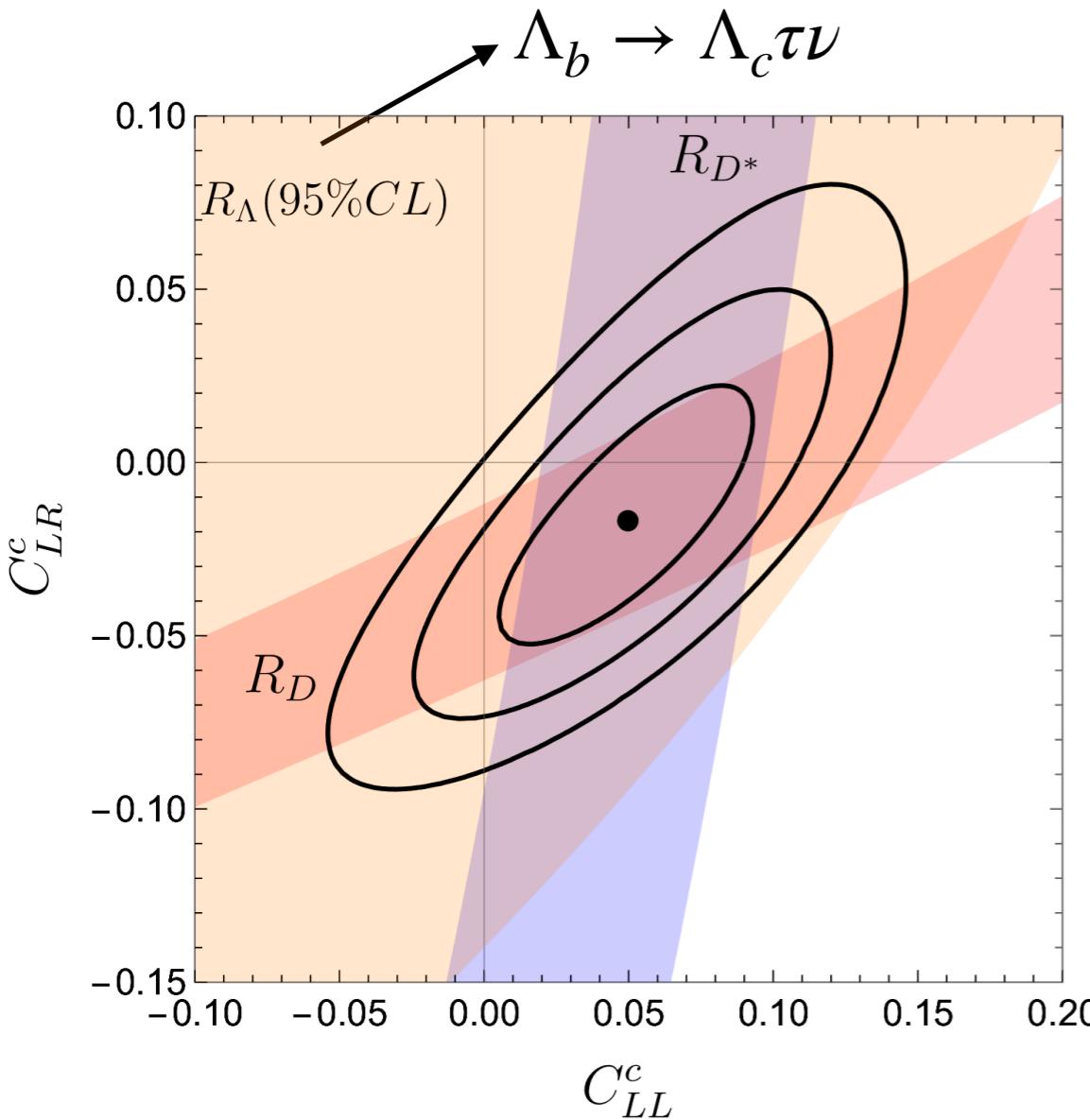
4321 massive vector bosons



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

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

$\sim 3.2\sigma$

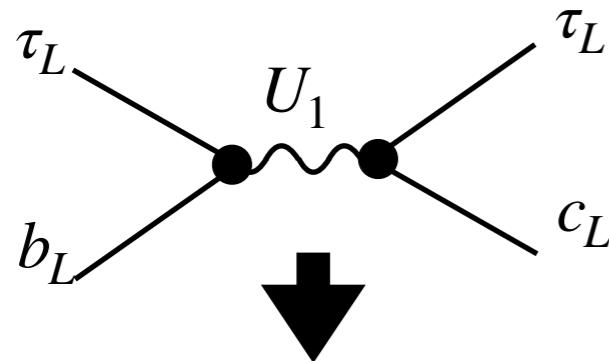


$$\mathcal{L} \supset \frac{2}{v^2} V_{cb} \left[(1 + C_{LL}^c)(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) - 2C_{LR}^c (\bar{c}_L b_R)(\bar{\tau}_L \nu_L) \right]$$

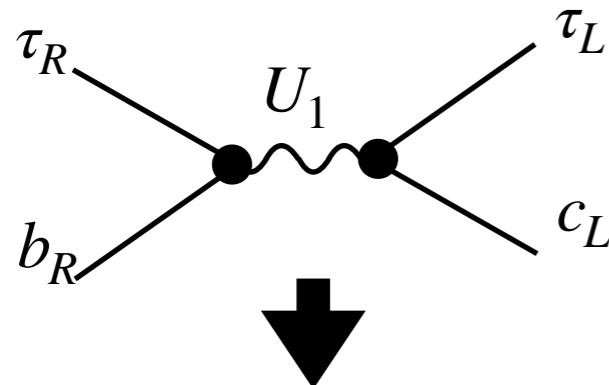
[J. Aebischer, G. Isidori, M. Pesut, B. Stefanek, F. Wilsch, [2210.13422](#)]

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

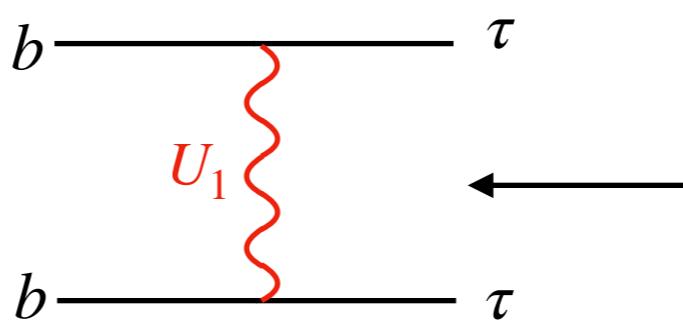
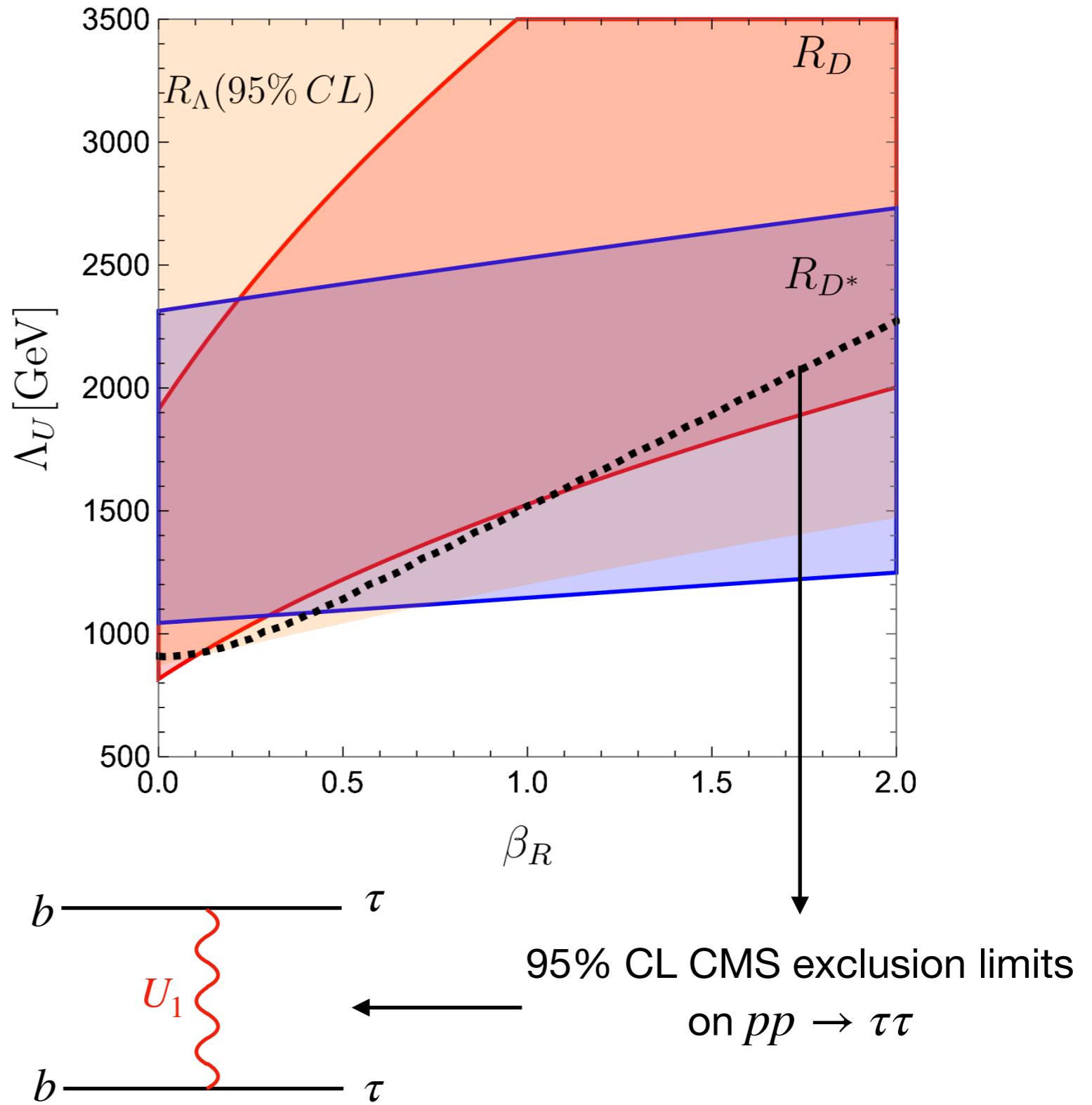
$$s_q = 0.1 \approx 2.4 V_{cb}$$



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



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



95% CL CMS exclusion limits
on $pp \rightarrow \tau\tau$

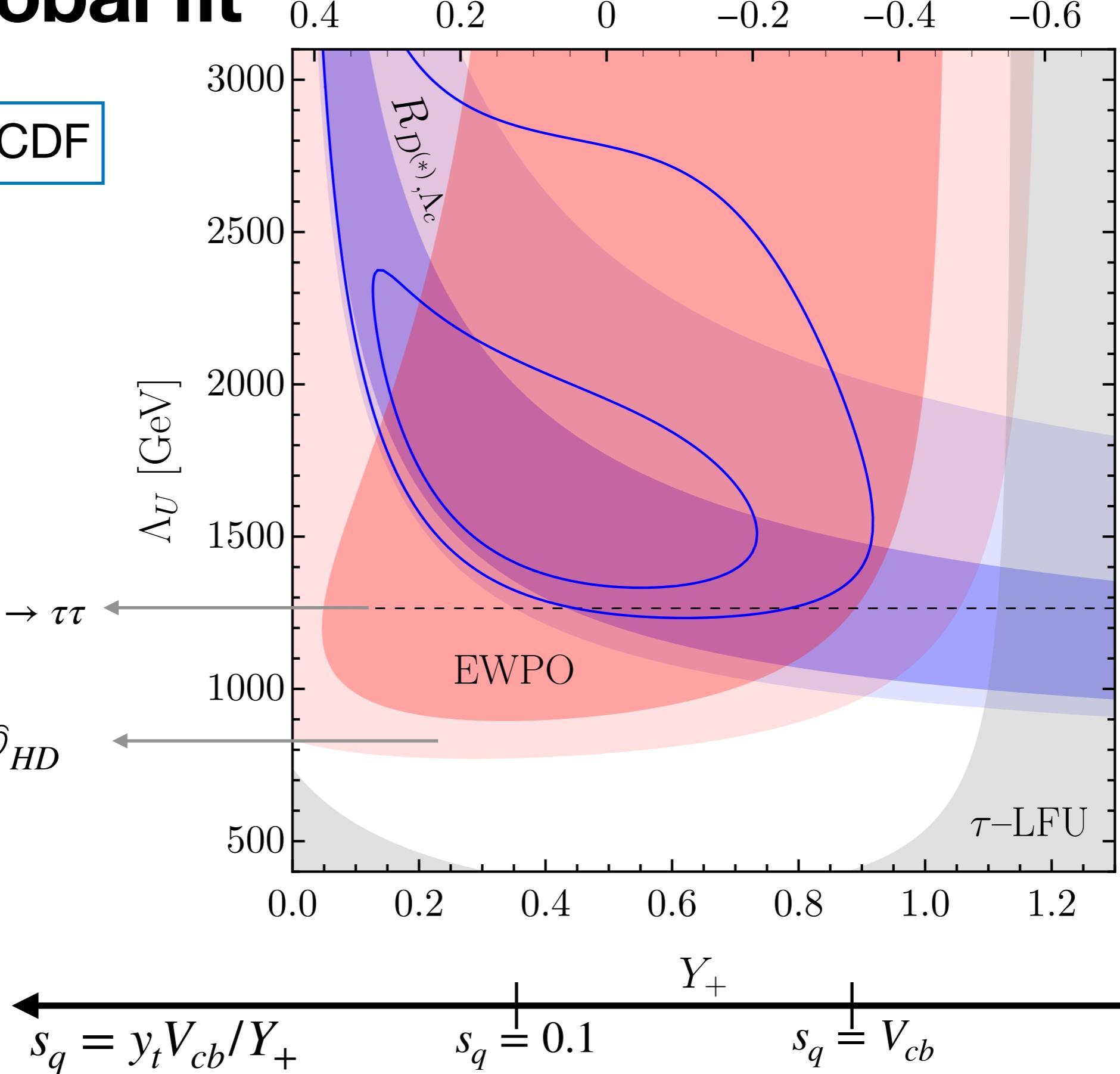
$$y_\nu = y_t \cos(\chi) - Y_+ \sin(\chi)$$

4321 Global fit

m_W without CDF

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

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

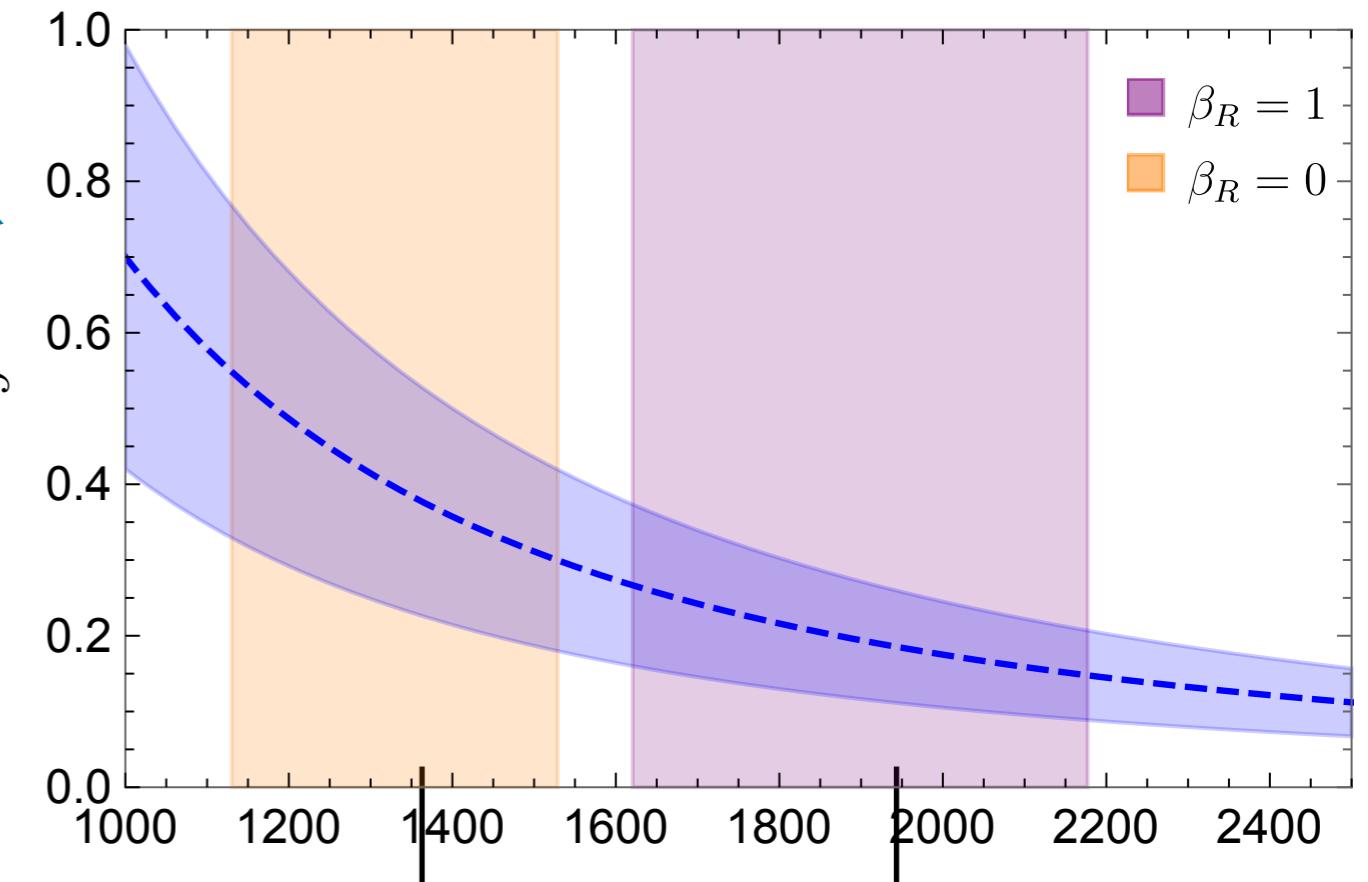
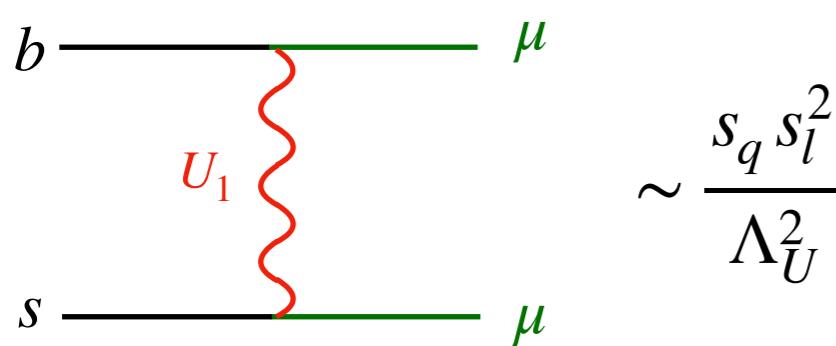
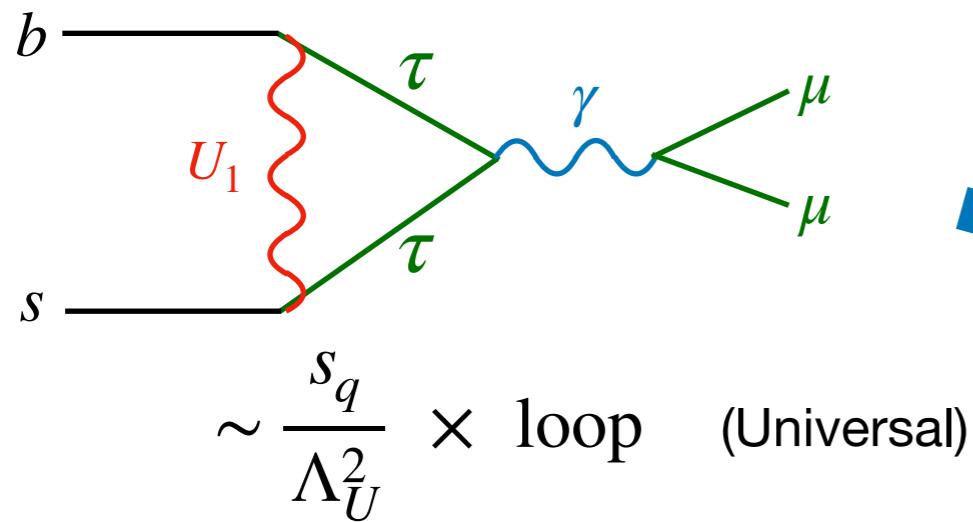


B-anomalies: $b \rightarrow s\mu\mu$

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

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

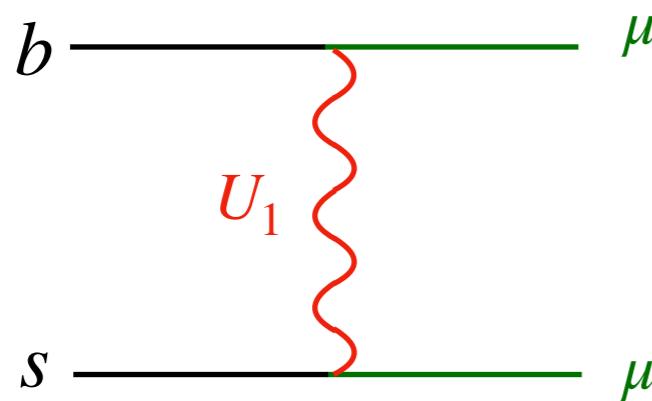
$$C_9^{\text{NP}} = -0.75 \pm 0.23 \quad (\sim 3.4\sigma)$$



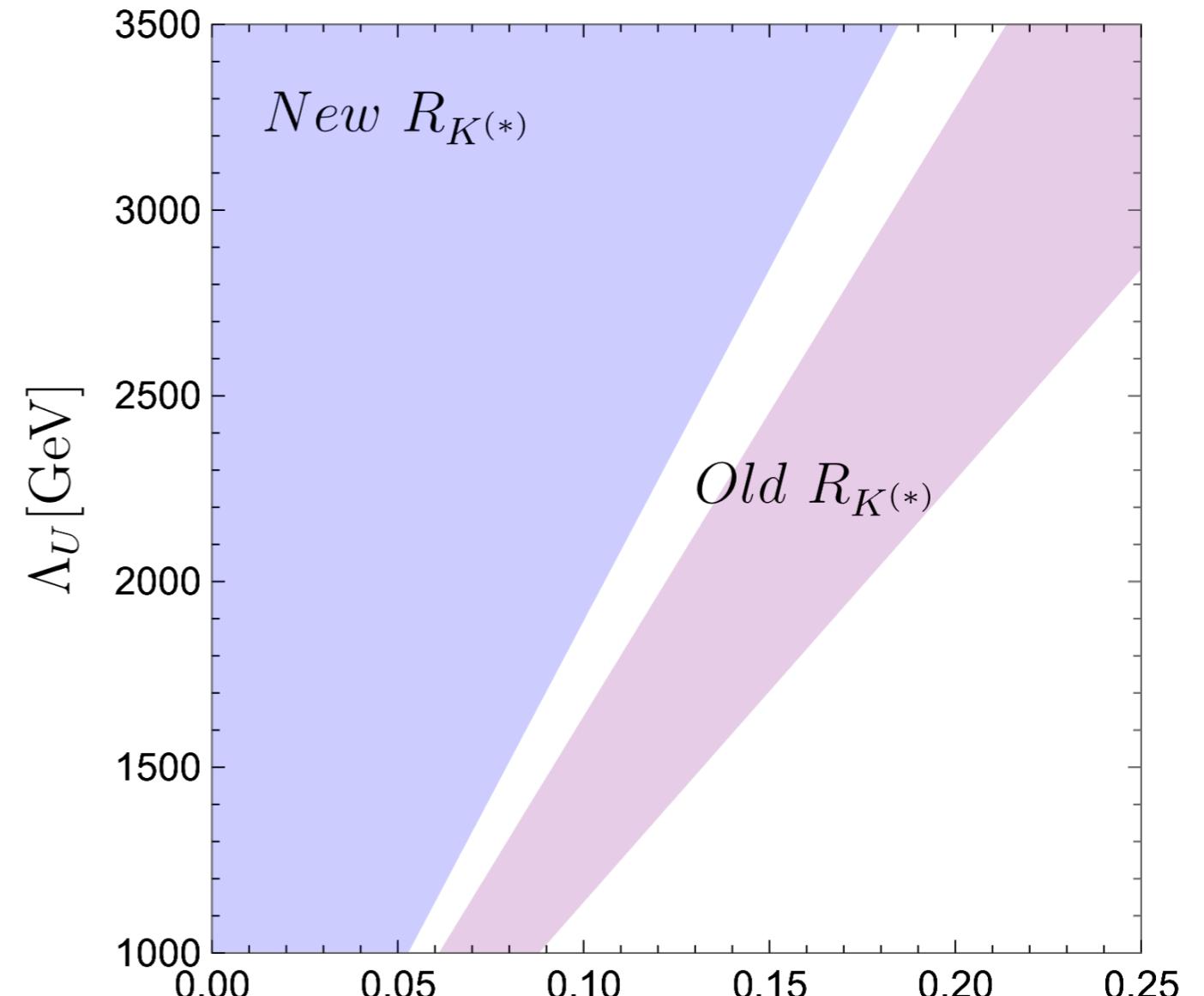
$b \rightarrow c\tau\nu$ preferred regions for $s_q = 0.1$

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

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



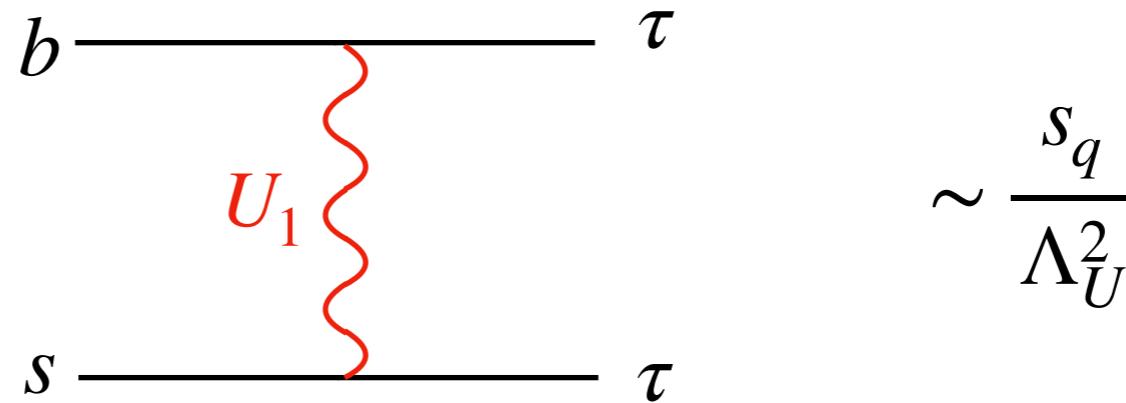
$$\propto \frac{s_q s_l^2}{\Lambda_U^2}$$



$$s_\ell \times \sqrt{\frac{s_q}{0.1}}$$

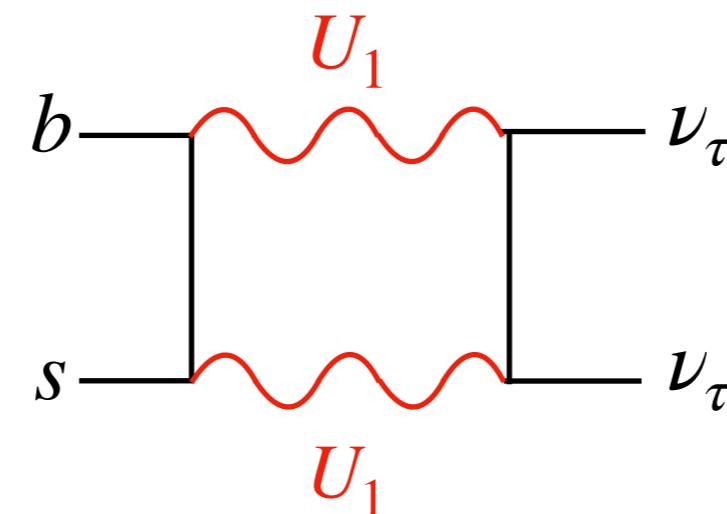
Other interesting observables

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



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

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



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

- ...

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

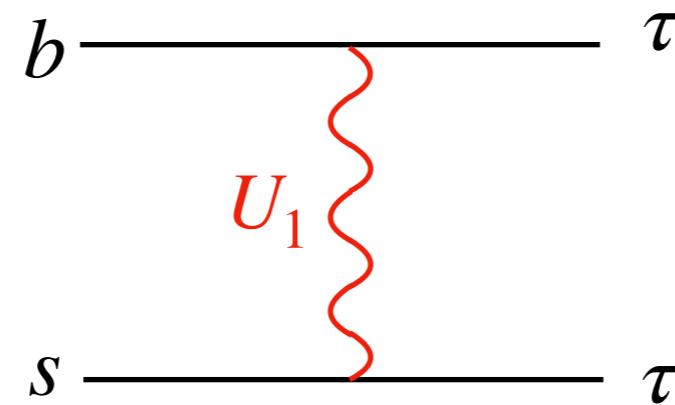
Other interesting observables

- $B_s \rightarrow \tau\tau$

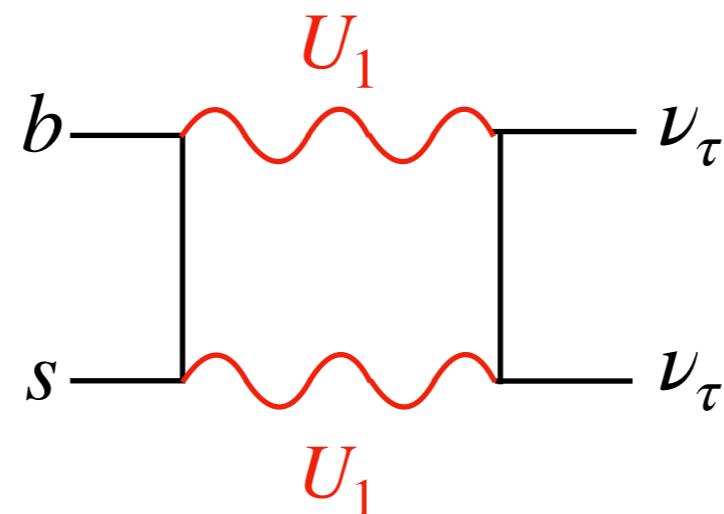
- $B \rightarrow K\tau\tau$

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

- ...



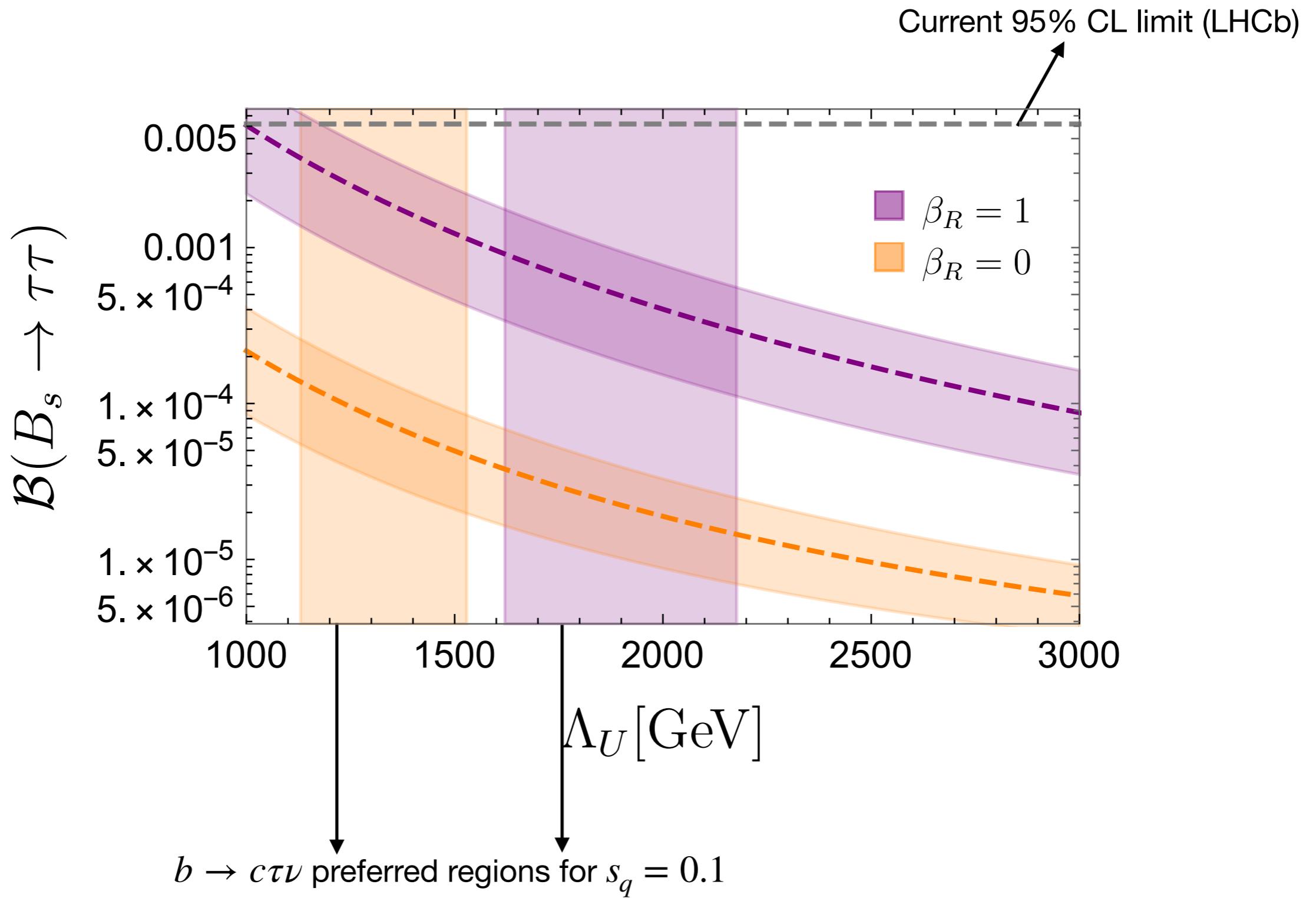
$$\sim \frac{s_q}{\Lambda_U^2}$$



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

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

Other interesting observables

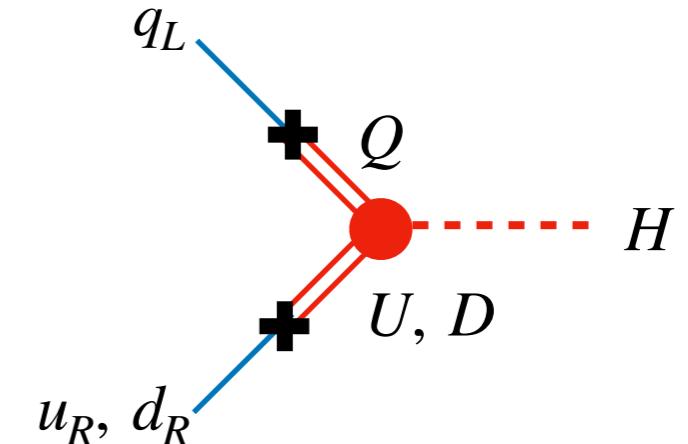
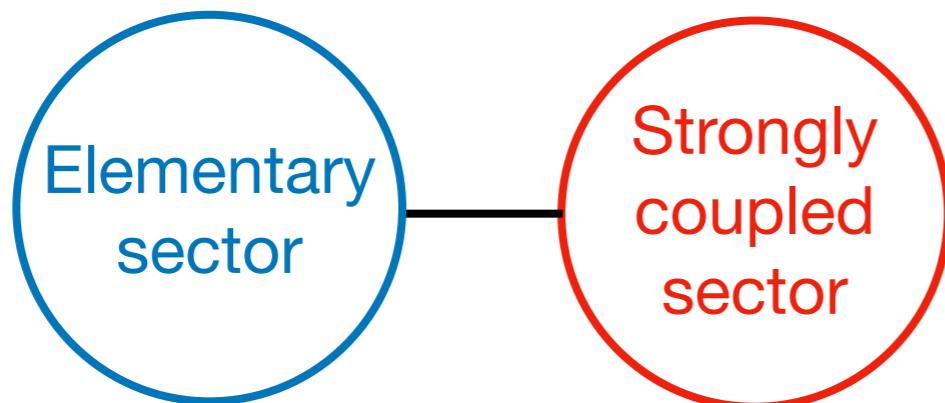


[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, [2103.16558](#)]

Partial compositeness and multi-scale

Partial compositeness

- Strong sector stabilising the Higgs mass



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

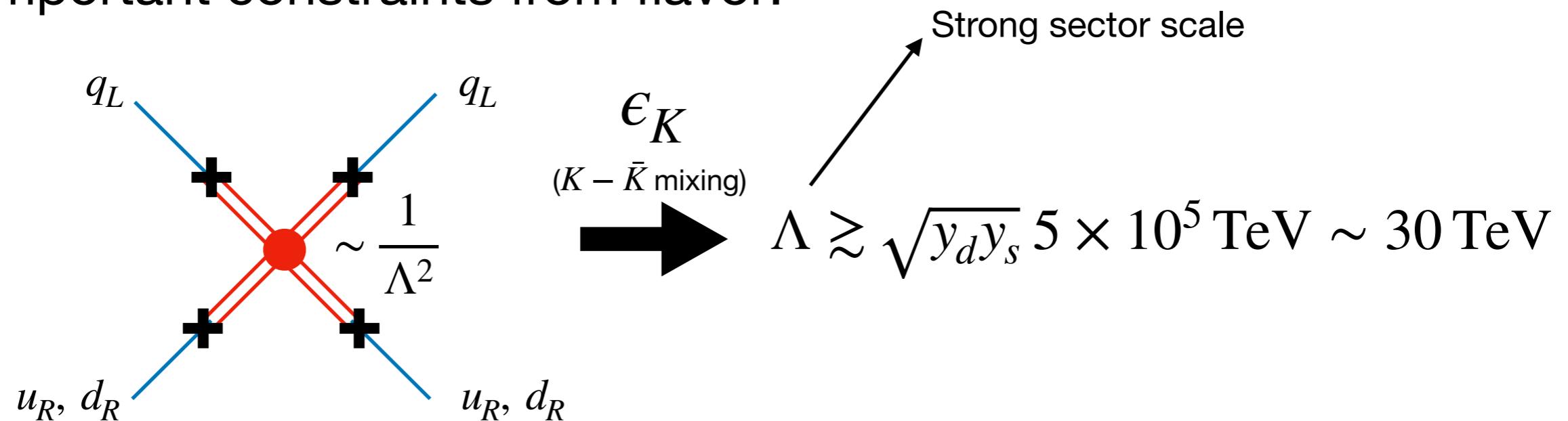
- Large mixing for 3rd family and suppressed mixing for light families due to large anomalous dimensions of the operators of the strongly coupled sector.

$U(2)$ protection

Enough?

Partial compositeness

- Important constraints from flavor:



(Even stronger bounds from EDMs of neutron and electron)

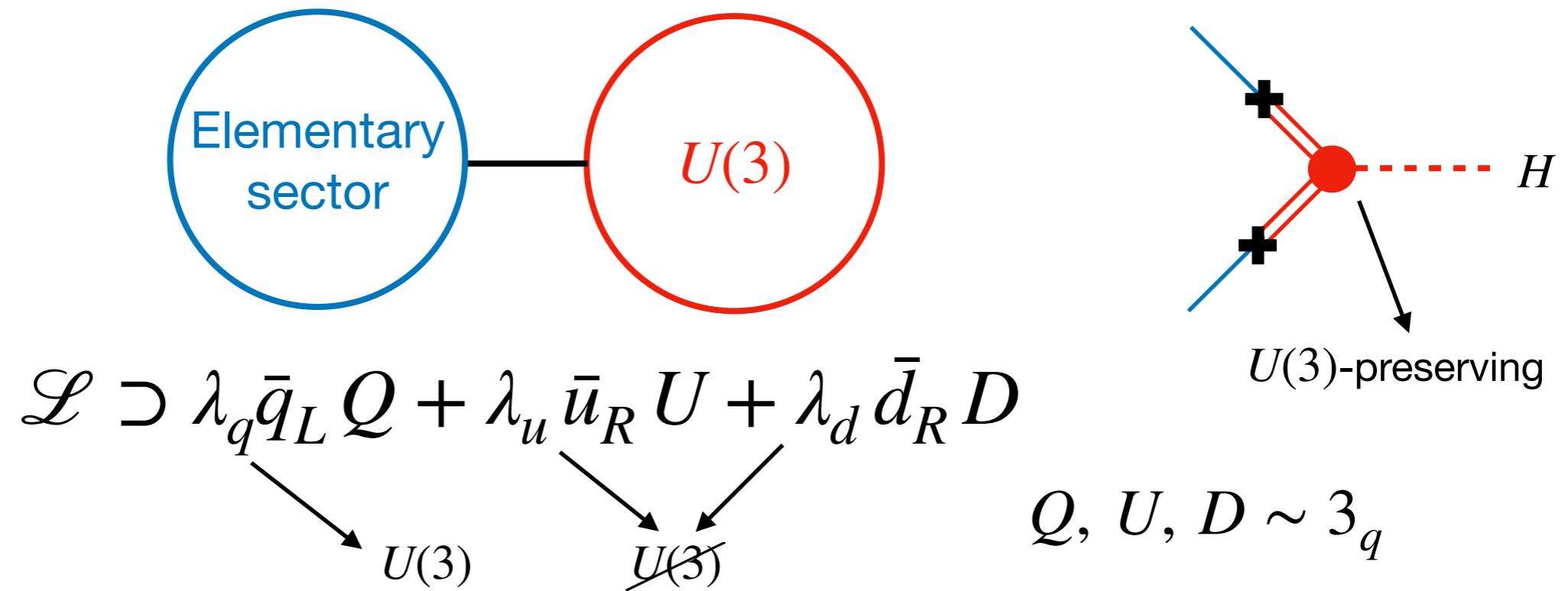
- What did go wrong? The breaking of $U(2)$ is not SM like...

PC spurions	$\left\{ \begin{array}{l} \lambda_q \sim 2_q \\ \lambda_u \sim 2_u \\ \lambda_d \sim 2_d \end{array} \right.$	VS	$\left. \begin{array}{l} V_q \sim 2_q \\ \Delta_u \sim 2_q \times \bar{2}_u \\ \Delta_d \sim 2_q \times \bar{2}_d \end{array} \right\}$	SM spurions
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Partial compositeness



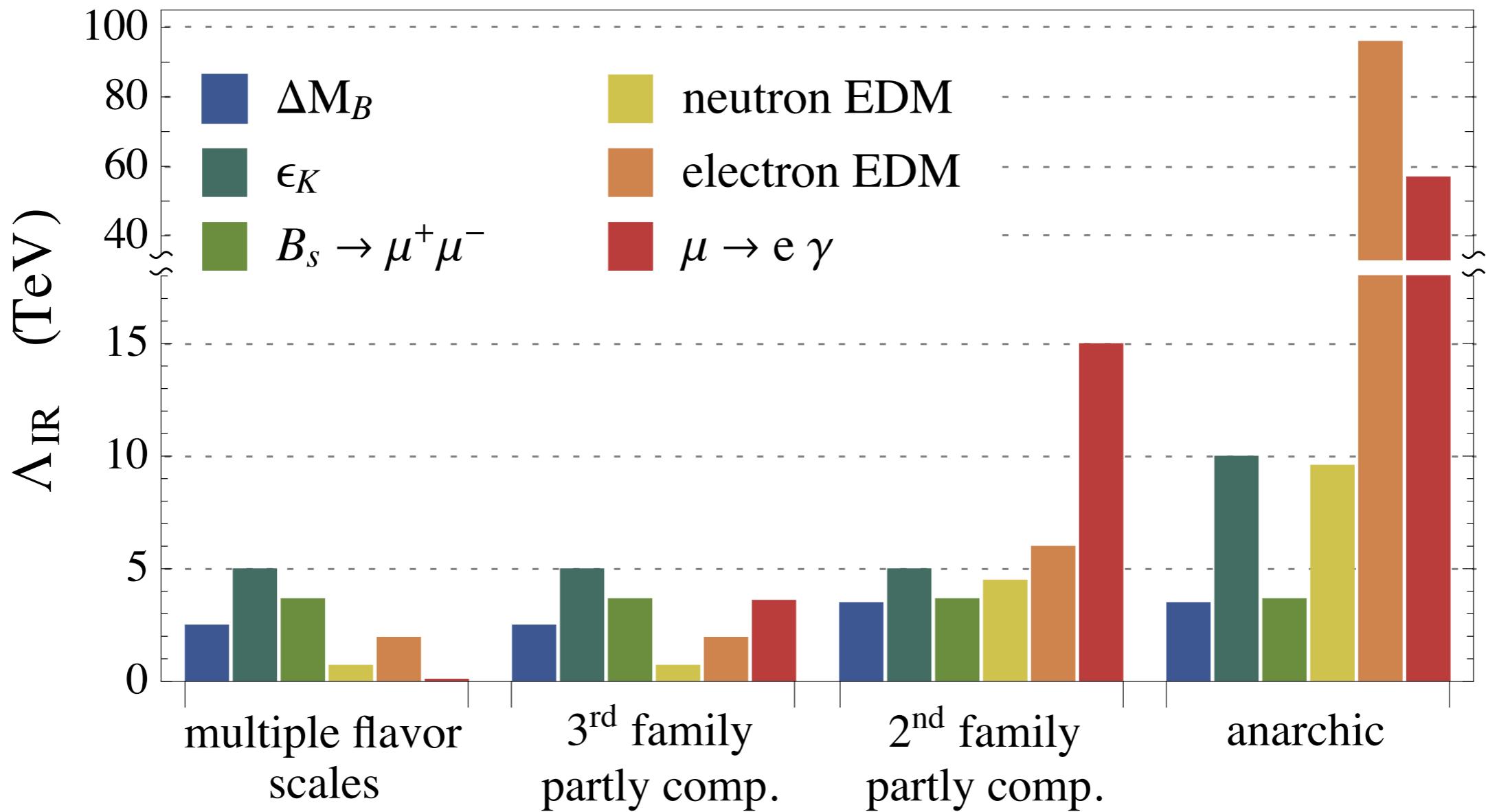
- Use only the SM spurions:



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

Multiscale flavor

- Composite models/RS:



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