Theory lessons from flavor data

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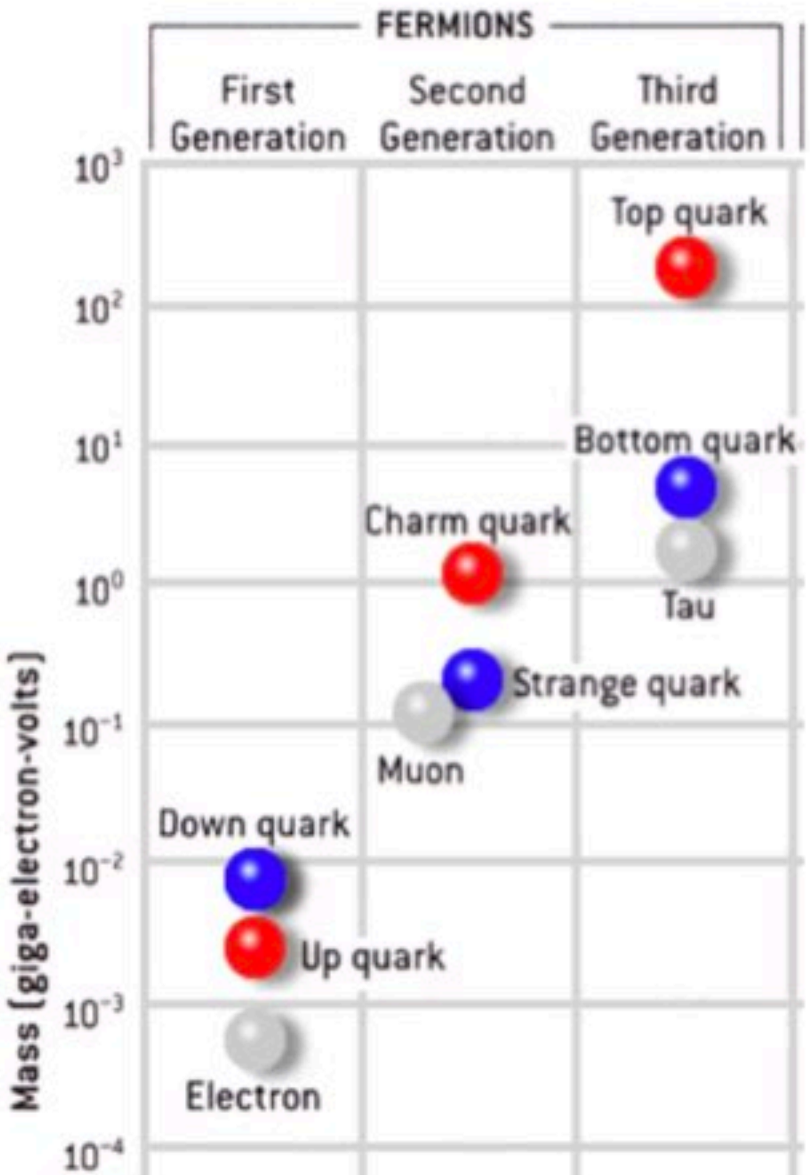
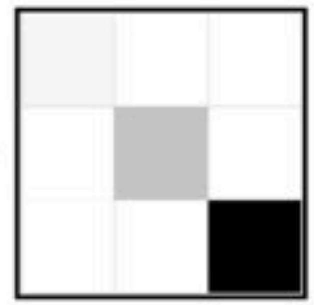
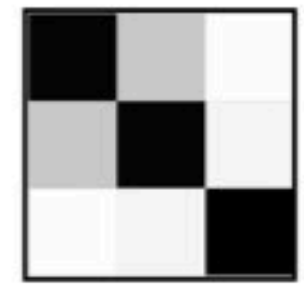
11th Edition of the Large Hadron Collider Physics Conference - Belgrade

Flavor data 1: the flavor puzzle

- **Flavor puzzle**: very hierarchical structures



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

$V_{\mathrm{CKM}} \sim$ 

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

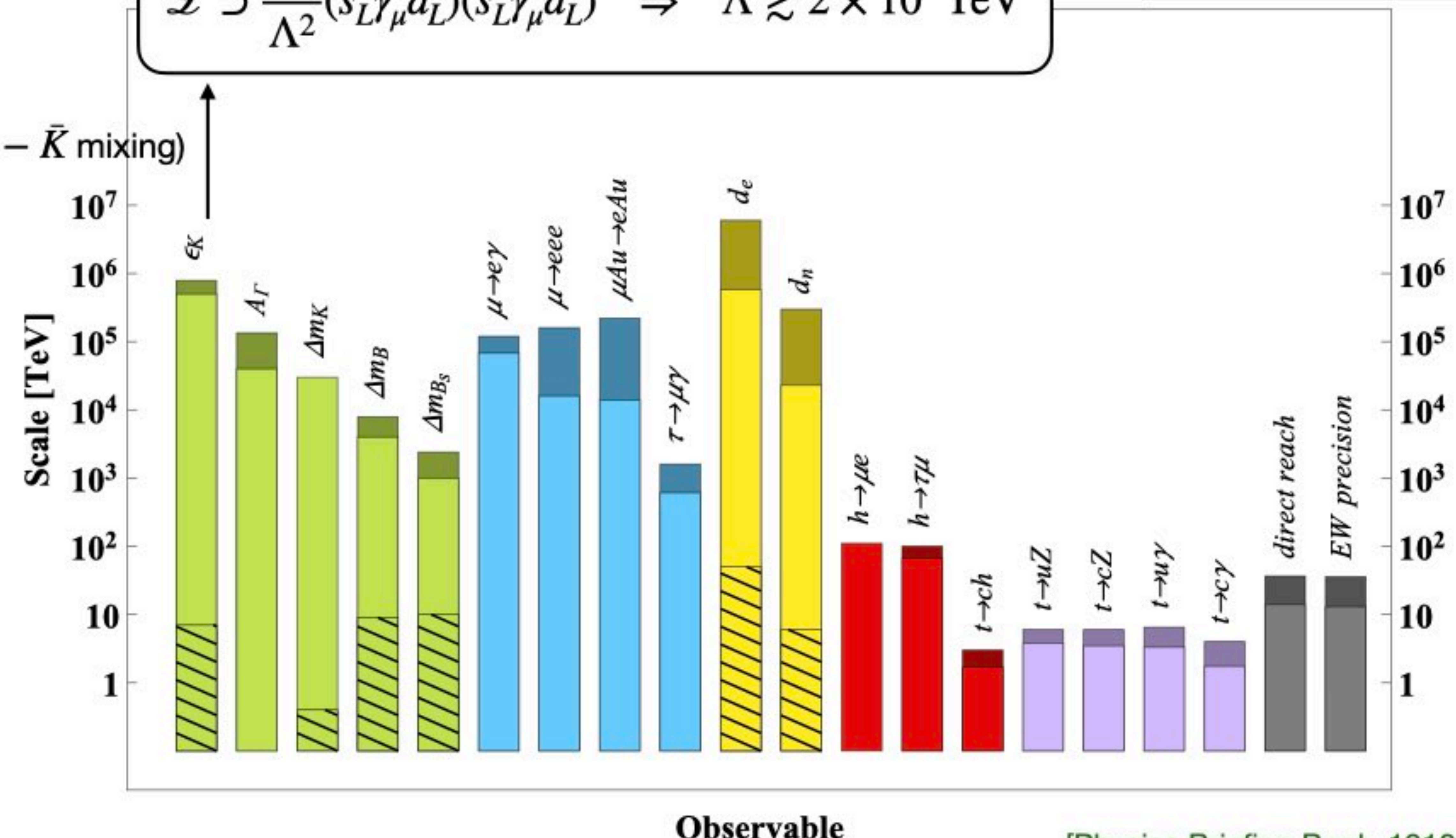
Flavor data 2: NP bounds

$$\mathscr{L} \supset \frac{e^{i\phi}}{\Lambda^2}(\bar{s}_L\gamma_\mu d_R)(\bar{s}_R\gamma_\mu d_L) \quad \Rightarrow \quad \Lambda \gtrsim 5\times 10^5\,\text{TeV}$$

$$\mathscr{L} \supset \frac{e^{i\phi}}{\Lambda^2}(\bar{s}_L\gamma_\mu d_L)(\bar{s}_L\gamma_\mu d_L) \quad \Rightarrow \quad \Lambda \gtrsim 2\times 10^4\,\text{TeV}$$

Scalar op. more constrained

($K - \bar{K}$ mixing)



[Physics Briefing Book, 1910.11775]

Theory lessons?

- NP addressing the 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.

⬇

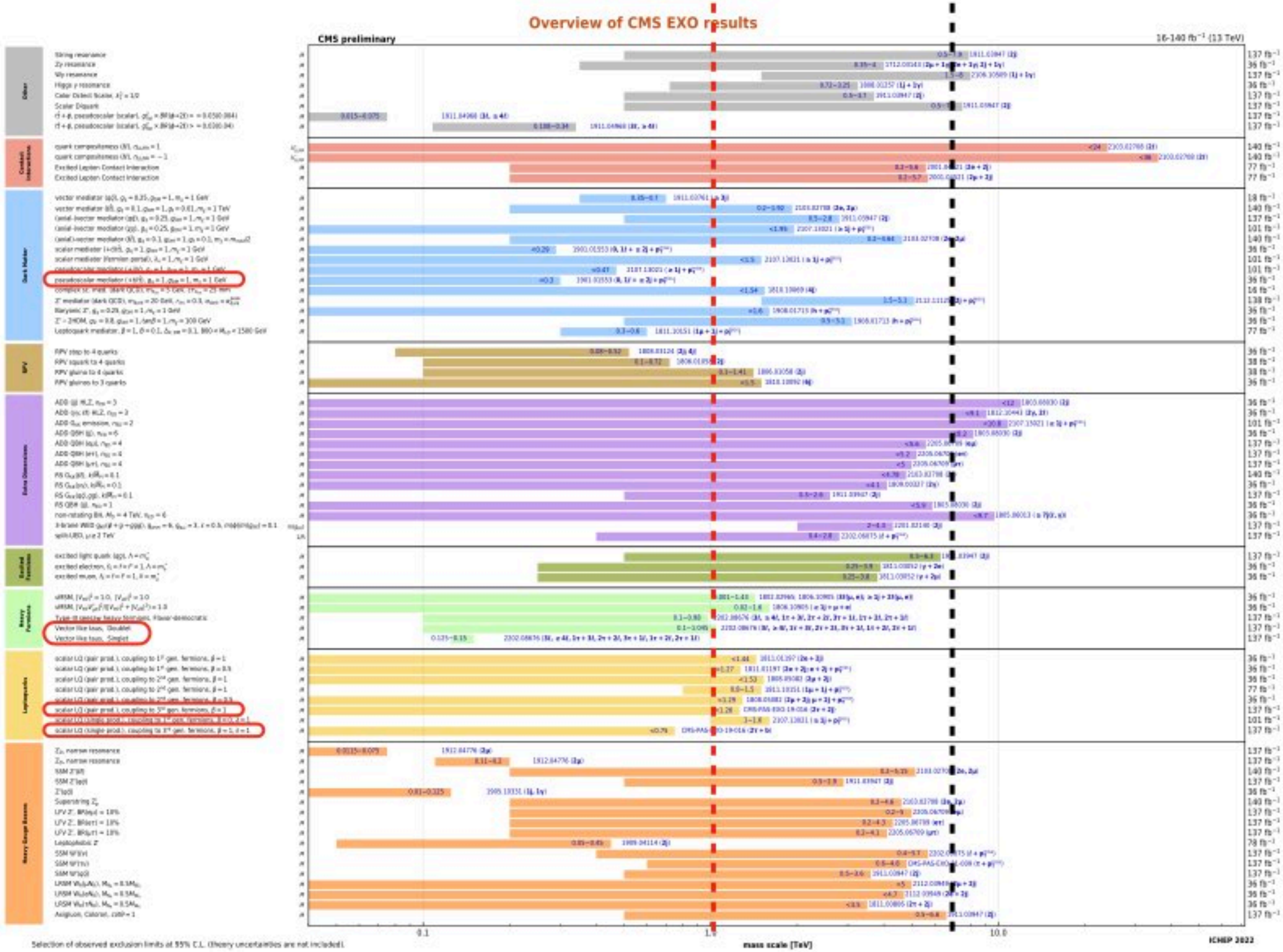
- NP at the TeV scale cannot address the puzzle problem.
- Universal NP at the TeV?

Too naive?

LHC searches

3rd fam. NP (1 TeV)

Universal NP (Multi TeV)



LHC searches

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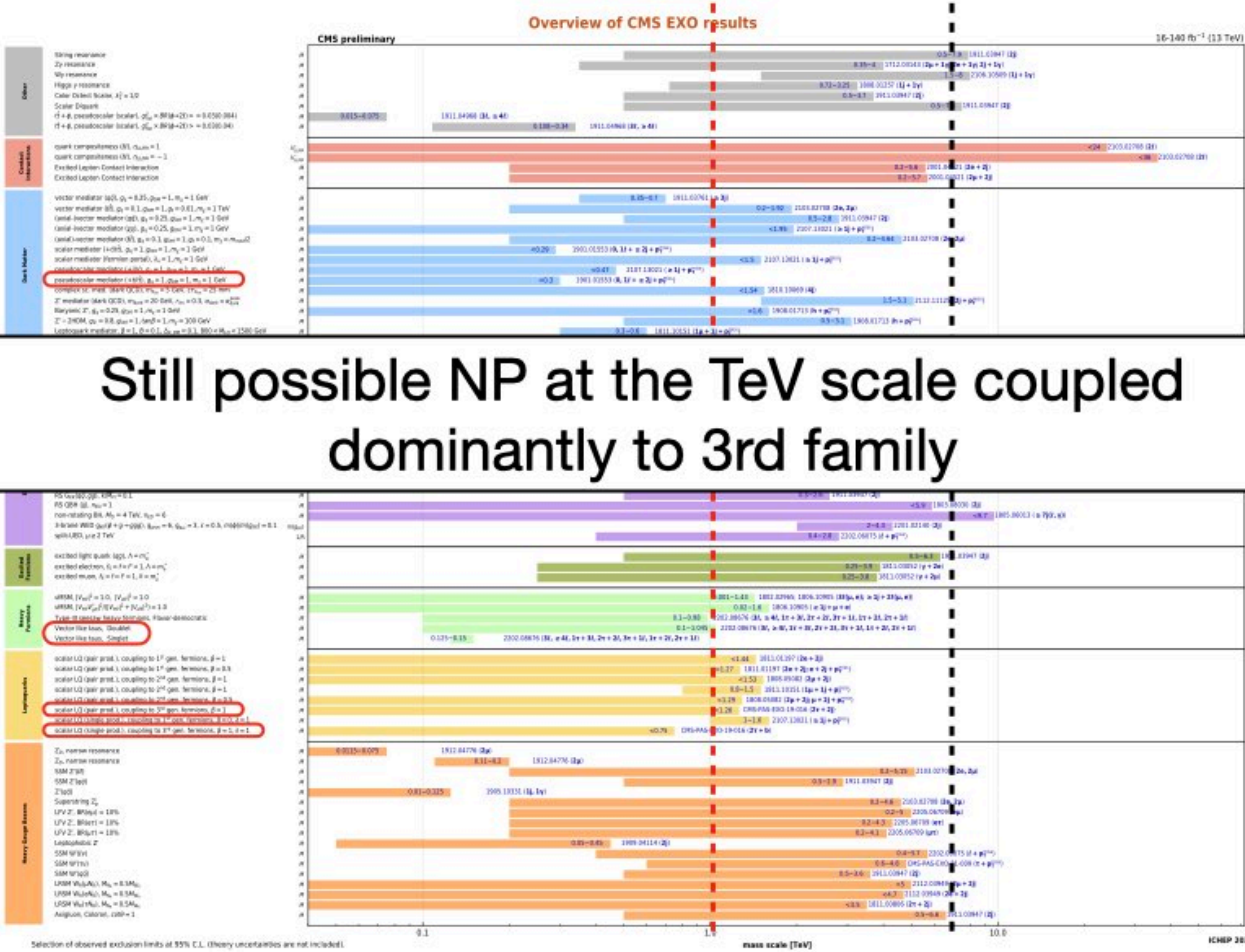
Universal NP (Multi TeV)



Still possible NP at the TeV scale coupled dominantly to 3rd family

Flavor symmetries of SM

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

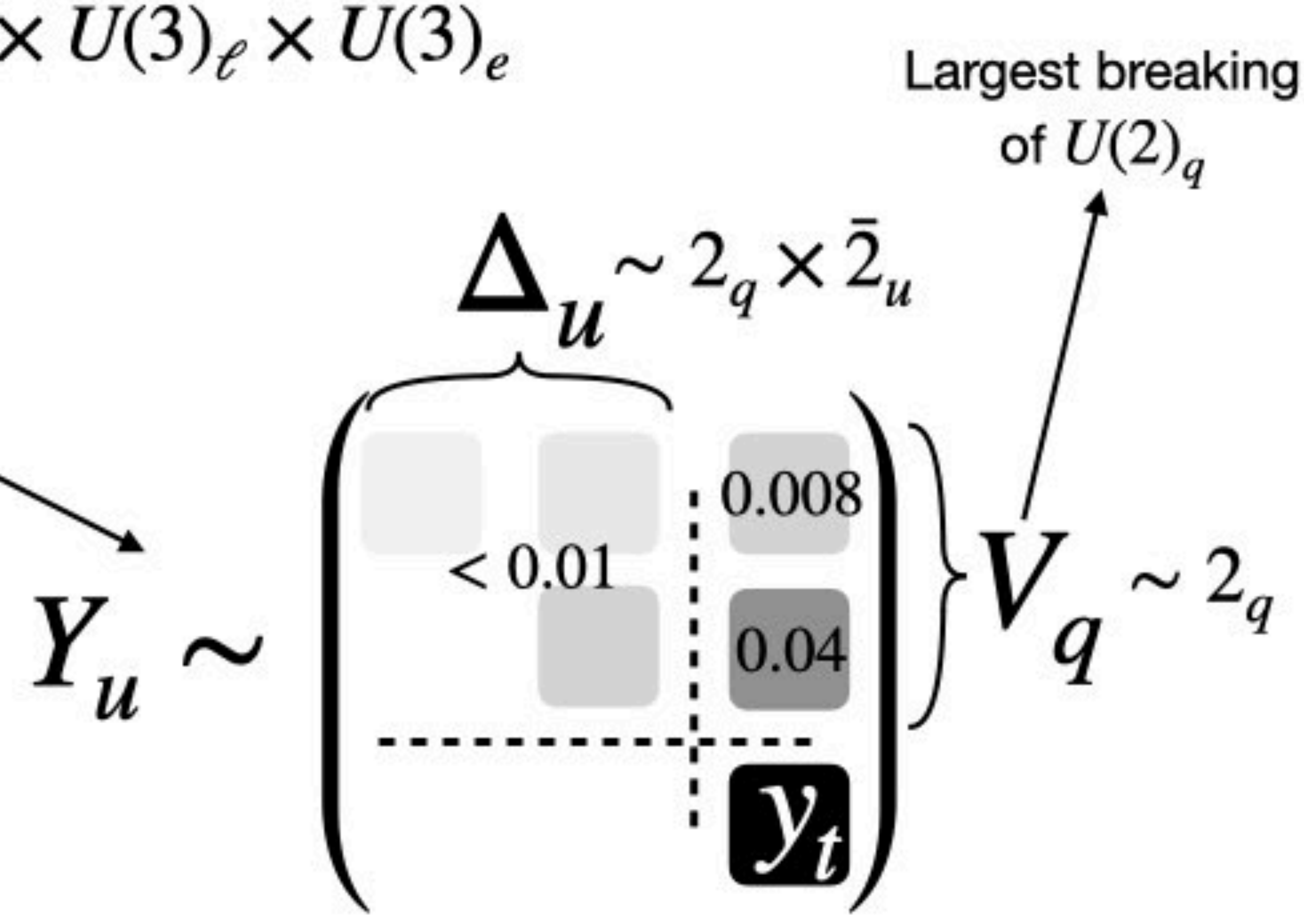
$$\mathscr{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + \bar{\psi}_a \not{D} \psi_a + |D_\mu H|^2 - V(H) + (Y_{ab}\bar{\psi}^a_L H \psi^b_R + \mathrm{h.c.})$$

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

- $Y_{u,d,e}$ very hierarchical
- To leading order:

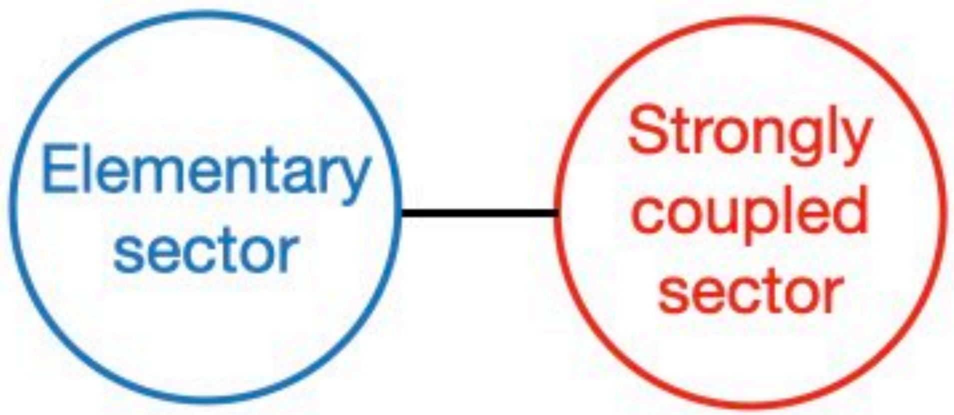
$$U(3)^5 \xrightarrow[\text{3rd fam. Yuk.}]{} U(2)^5$$

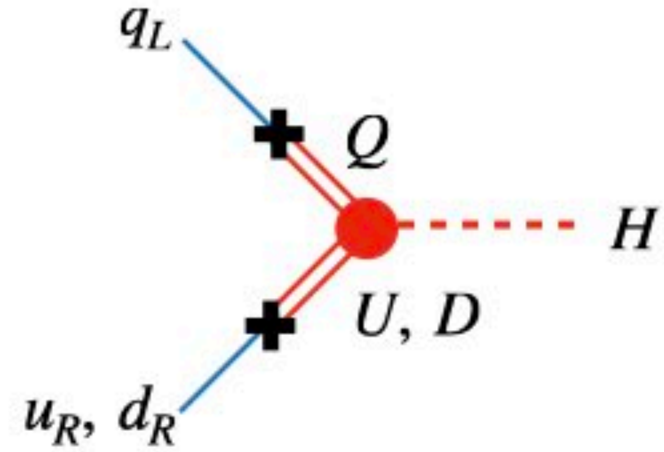
- Protection in FCNC (GIM).



Example: partial compositeness

- Strong sector stabilising the Higgs mass





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

- Large mixing for 3rd family and suppressed mixing for light families

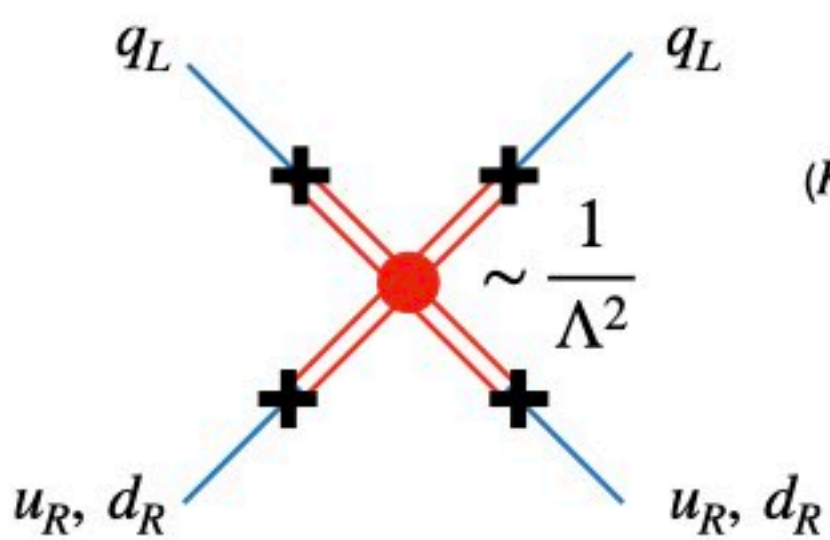
$U(2)$ protection

Enough?

[Kaplan, 1991]

Example: partial compositeness

- Important constraints from flavor:



ϵ_K

($K - \bar{K}$ mixing)

Strong sector scale

$$\Lambda \gtrsim \sqrt{y_d y_s}\, 5 \times 10^5\,\text{TeV} \sim 30\,\text{TeV}$$

(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

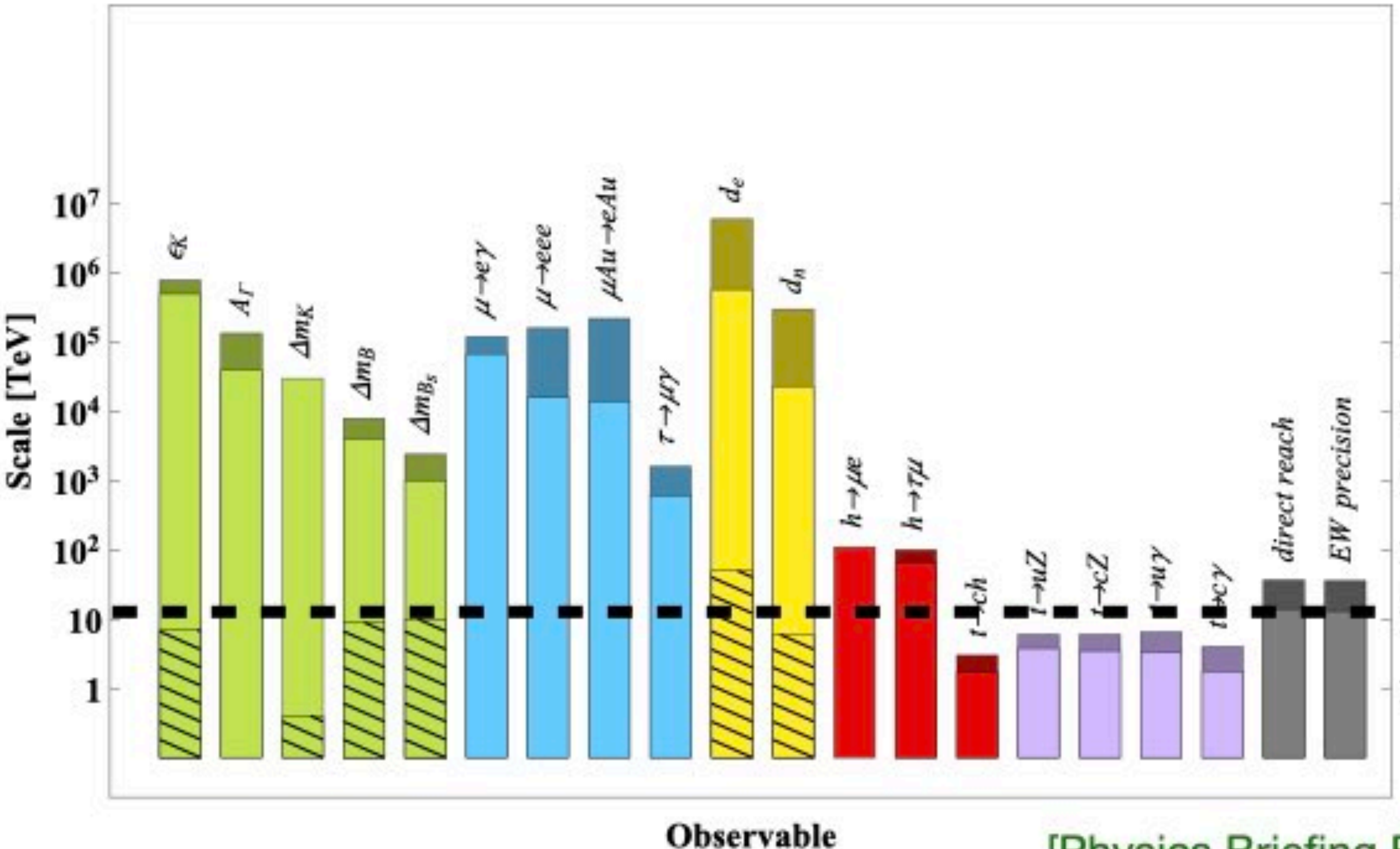
Minimal Flavor Violation

- Yukawas are the only spurious breaking $U(3)$.
- Example: Largest breaking of $U(3)_q$:

$$\mathscr{L} \supset (\bar{q}_L Y_u Y_u^\dagger \gamma_\mu q_L)\, J^\mu_{\rm NP} \;\longrightarrow\; \mathscr{L}_{\rm SMEFT} \supset \frac{1}{\Lambda^2}(\bar{q}_L Y_u Y_u^\dagger \gamma_\mu q_L)\,(\bar{q}_L Y_u Y_u^\dagger \gamma_\mu q_L)$$

$\epsilon_K,\ \Delta m_{B_s},\ \Delta m_{B_d}$

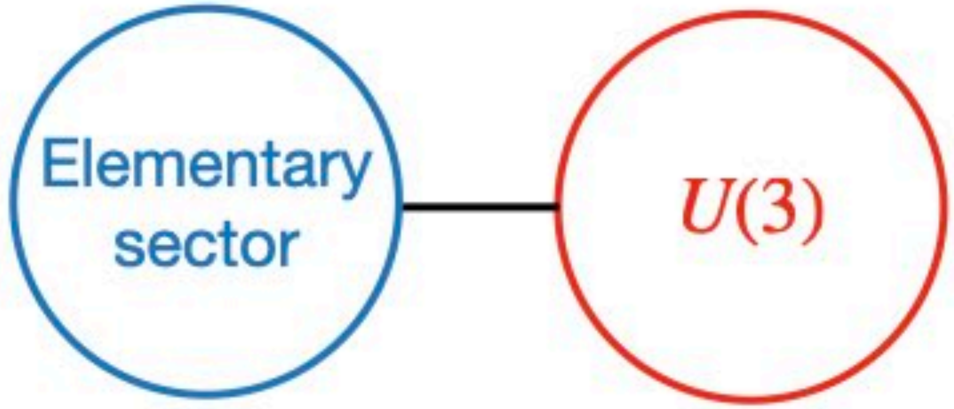
$$\Lambda \gtrsim |V_{ts}V_{td}|\, 2\times 10^4\,\text{TeV} \sim 10\,\text{TeV}$$

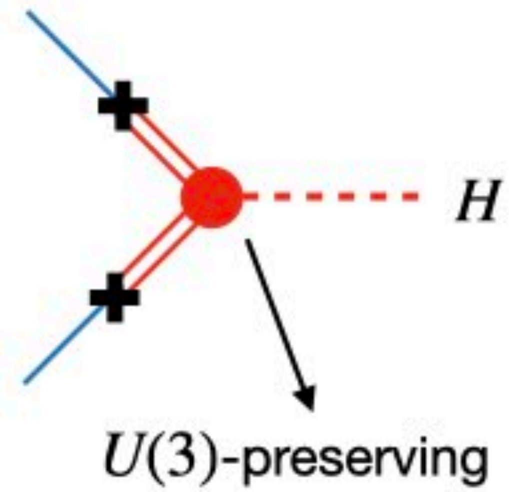


[Physics Briefing Book, 1910.11775]

Minimal Flavor Violation

- Achievable imposing flavor symmetries. For example:





$$\mathscr{L} \supset \lambda_q \bar{q}_L Q + Y_u \bar{u}_R U + Y_d \bar{d}_R D$$

$\lambda_q \to U(3)$; $\quad Y_u, Y_d \to$ ~~$U(3)$~~

$$Q,\, U,\, D \sim 3_q$$

(Ok, but ad hoc, and no explanation of flavor puzzle)

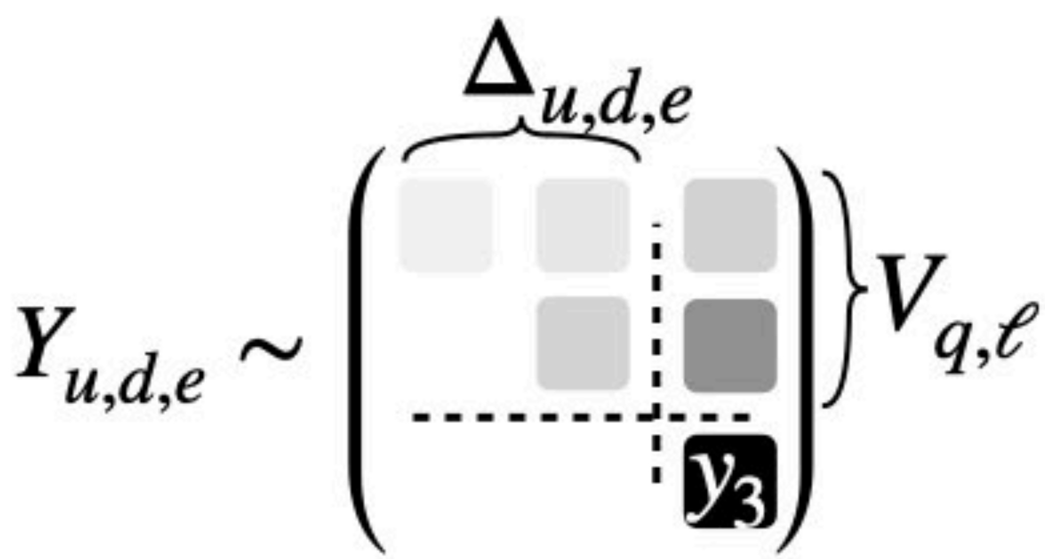
- Emerging dynamically if flavor is explained at a higher scale

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:



$$V_q \sim 2_q \quad V_\ell \sim 2_\ell$$

$$\Delta_u \sim 2_q \times \bar{2}_u$$

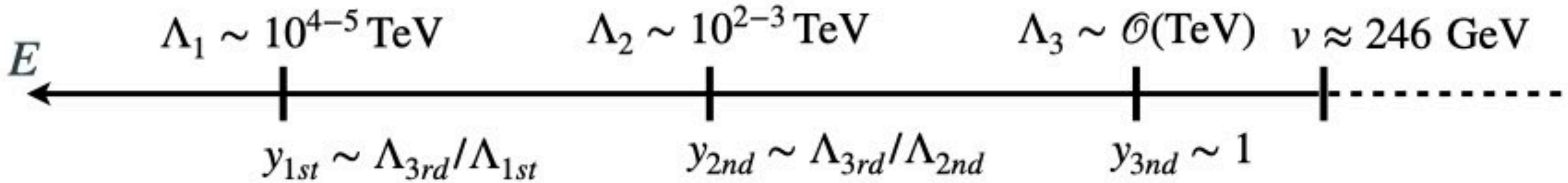
$$\Delta_d \sim 2_q \times \bar{2}_d$$

$$\Delta_e \sim 2_q \times \bar{2}_\ell$$

Multiscale flavor

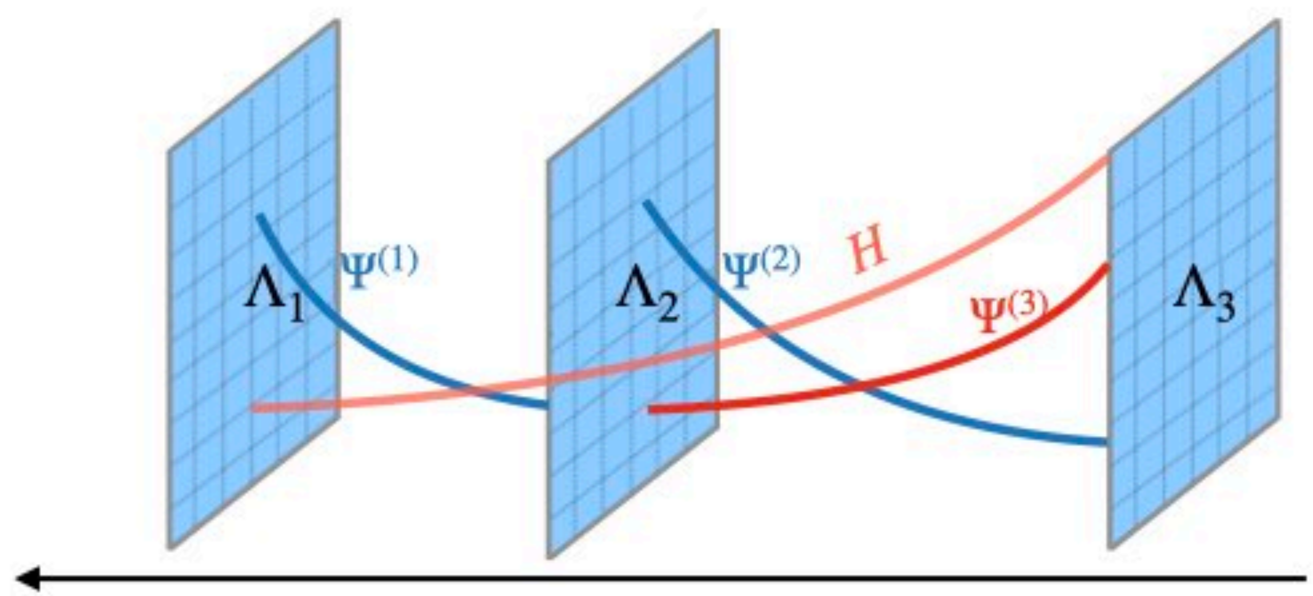
[Dvali, Shiftman, hep-ph/0001072,Panico, Pomarol, 1603.06609
Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368
Barbieri, 2103.15635]

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



Gauge deconstruction

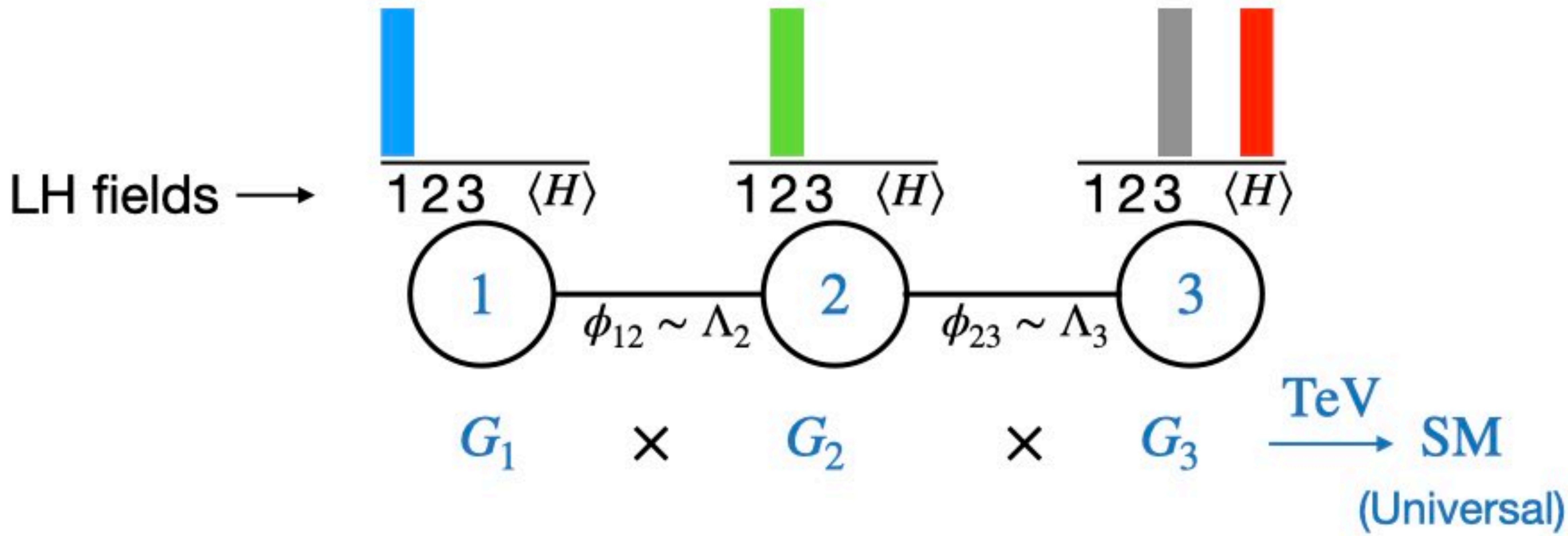
Composite dynamics ⟷ (dual) Extra-dimensions

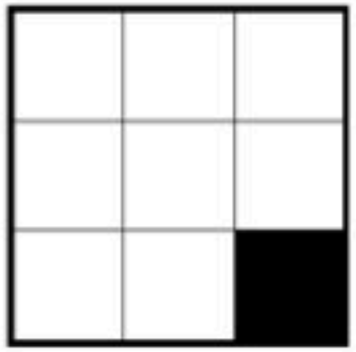
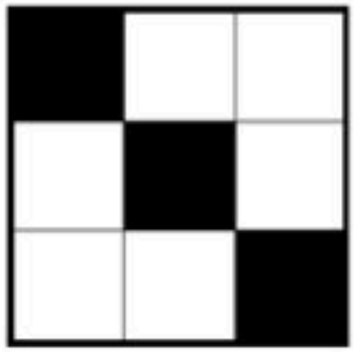


[Panico, Pomarol, 1603.06609; Fuentes-Martin, Isidori, Pages, Stefanek 2012.10492; Fuentes-Martin, Isidori, JML, Selimovic, Stefanek, 2203.01952]

Deconstructing flavor

[Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368,
Allwicher, Isidori, Thomsen, 2011.01946,
Davighi, Isidori, 2303.01520
Fernández-Navarro, King, 2305.07690]



$M \sim$  $V_{CKM} \sim$ 

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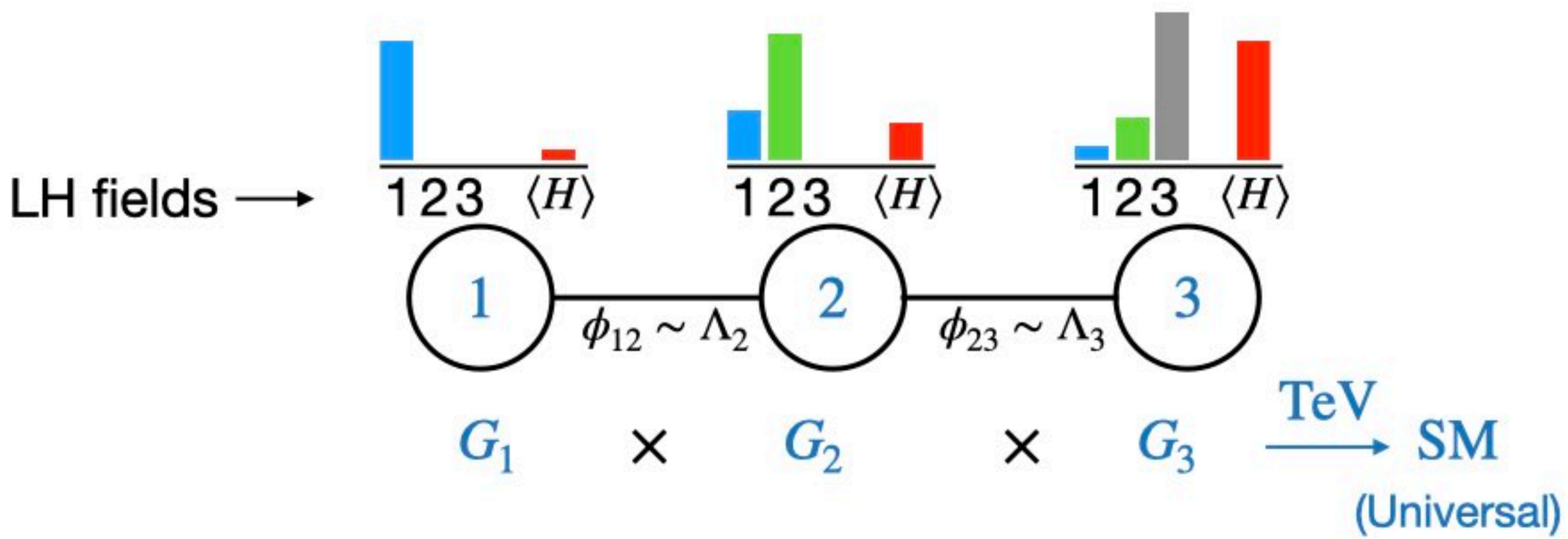

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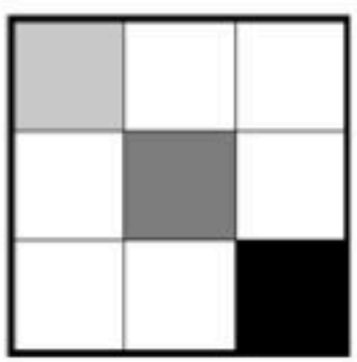


$V_{\mathrm{CKM}} \sim$

Deconstructing flavor

- From the TeV, we see…

$\mathrm{SM}_l \times G_3 \xrightarrow{\mathrm{TeV}} \mathrm{SM}$

(Universal)

- Emerging flavor symmetry: $U(2)$

→ 3-light mixing only in the LH sector $V_{q,\ell}$

→ Light Yukawas generated at a higher scale $\Delta_{u,d,e}$

Minimally broken $U(2)$

Deconstructing flavor

- From the TeV, we see…

$$\mathrm{SM}_l \times SU(4) \xrightarrow{\text{TeV}} \mathrm{SM}$$

(Universal)

4321 model

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

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

(see Ben Stefanek's talk)

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

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

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

It becomes a bound on V_ℓ

Conclusions

- A multiscale solution to the flavor puzzle is highly interesting:
  - It would explain flavor at lower energies than traditional approaches.
  - It improves flavor bounds on NP necessary for 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 B-physics phenomenology ($R_{D^{(*)}}$, $B \to K\ell\ell$, $B \to K\nu\nu$, etc…).

Thank you!

Backup

4321 model

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

Third family quark-lepton unification:

$$SU(3)_h \rightarrow SU(3)_c$$

$$SU(3)_h \subset SU(4)_h, \quad SU(3)_l \rightarrow SU(3)_c$$

$$SU(4)_h \times SU(3)_l \times SU(2)_L \times U(1)_{R+\frac{(B-L)_l}{2}} \xrightarrow{\sim \text{TeV}} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$U(1)_{(B-L)_h} \subset SU(4)_h, \quad U(1)_{R+\frac{(B-L)_l}{2}} \rightarrow U(1)_Y, \quad U(1)_{(B-L)_h} \longrightarrow U(1)_Y$$

$$+ \quad U_1 \sim (\mathbf{3},\mathbf{1})_{2/3}, \quad G' \sim (\mathbf{8},\mathbf{1})_0, \quad Z' \sim (\mathbf{1},\mathbf{1})_0$$

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

$$g_4 \gg g_3$$

$$\Downarrow$$

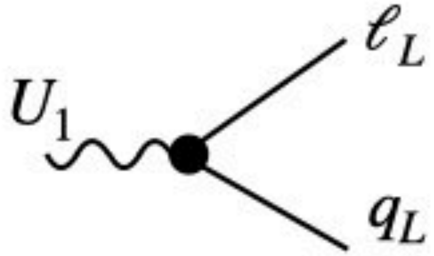
$$g_s \approx g_3$$
$$g_h^{G'} \approx g_4$$
$$g_l^{G'} \approx g_s^2/g_4$$

LHC bounds:

$$M_{G'} \gtrsim 3 - 3.5\,\text{TeV}$$

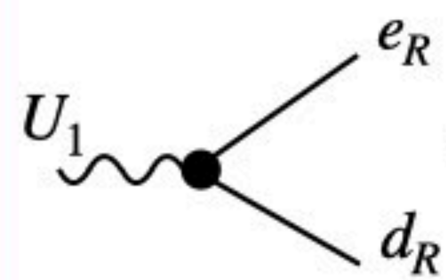
[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558]

4321 massive vector bosons

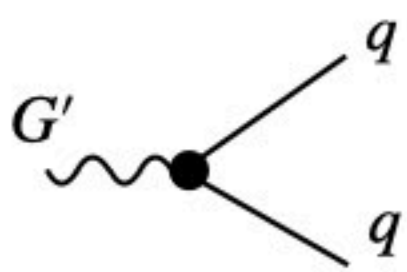


$O(g_4)$ ↑

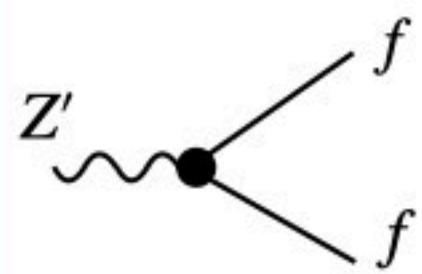
$$\sim g_{b\tau} \begin{pmatrix} 0 & 0 & 0 \\ 0 & s_\ell s_q & s_q \\ 0 & s_\ell & 1 \end{pmatrix}$$



$$\sim g_{b\tau} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_R \end{pmatrix}$$



$$\sim g_4 \begin{pmatrix} (g_s/g_4)^2 & 0 & 0 \\ 0 & (g_s/g_4)^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



$$\sim g_4 \begin{pmatrix} (g_Y/g_4)^2 & 0 & 0 \\ 0 & (g_Y/g_4)^2 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

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

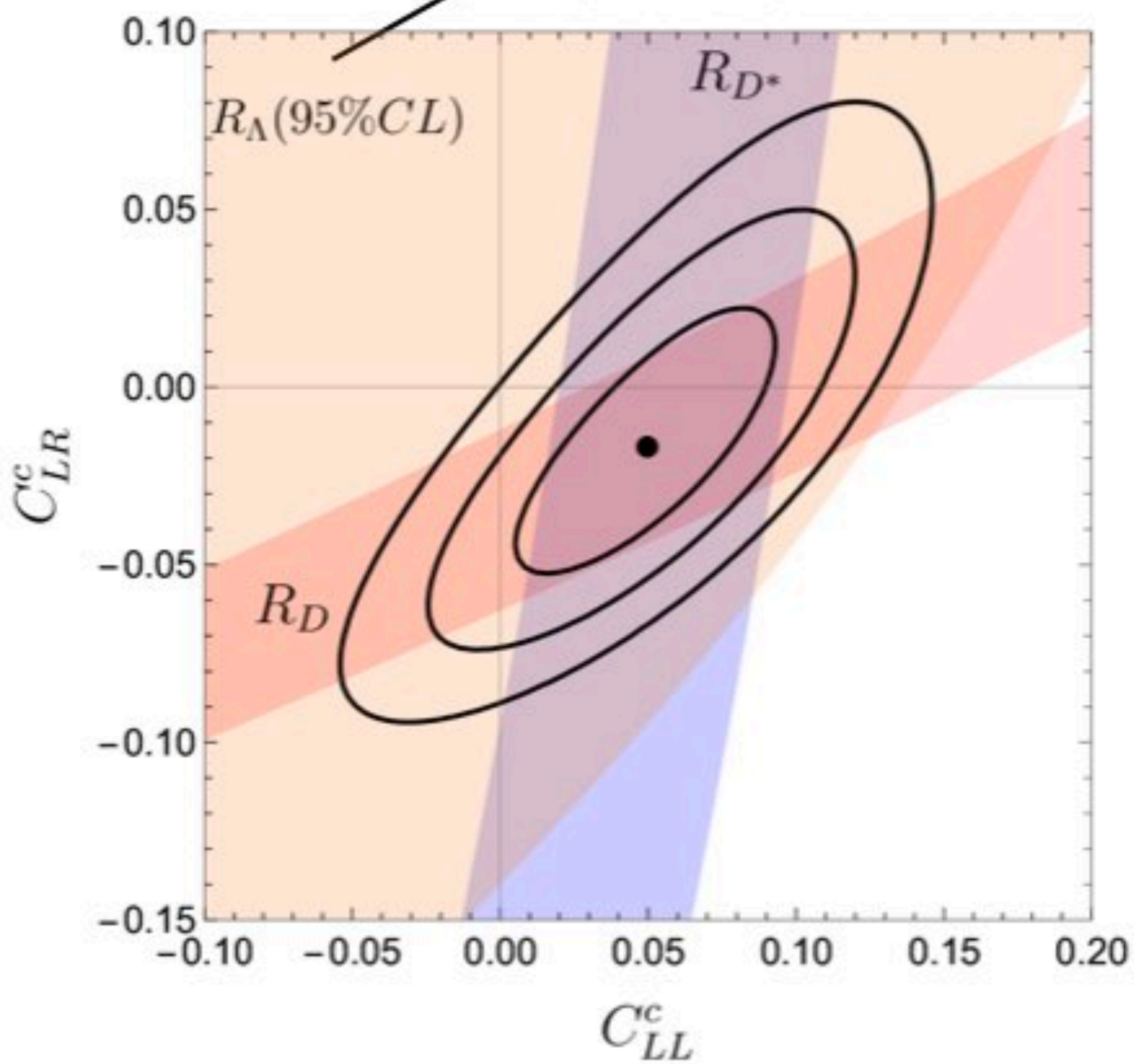
s_q → Necessary for CKM

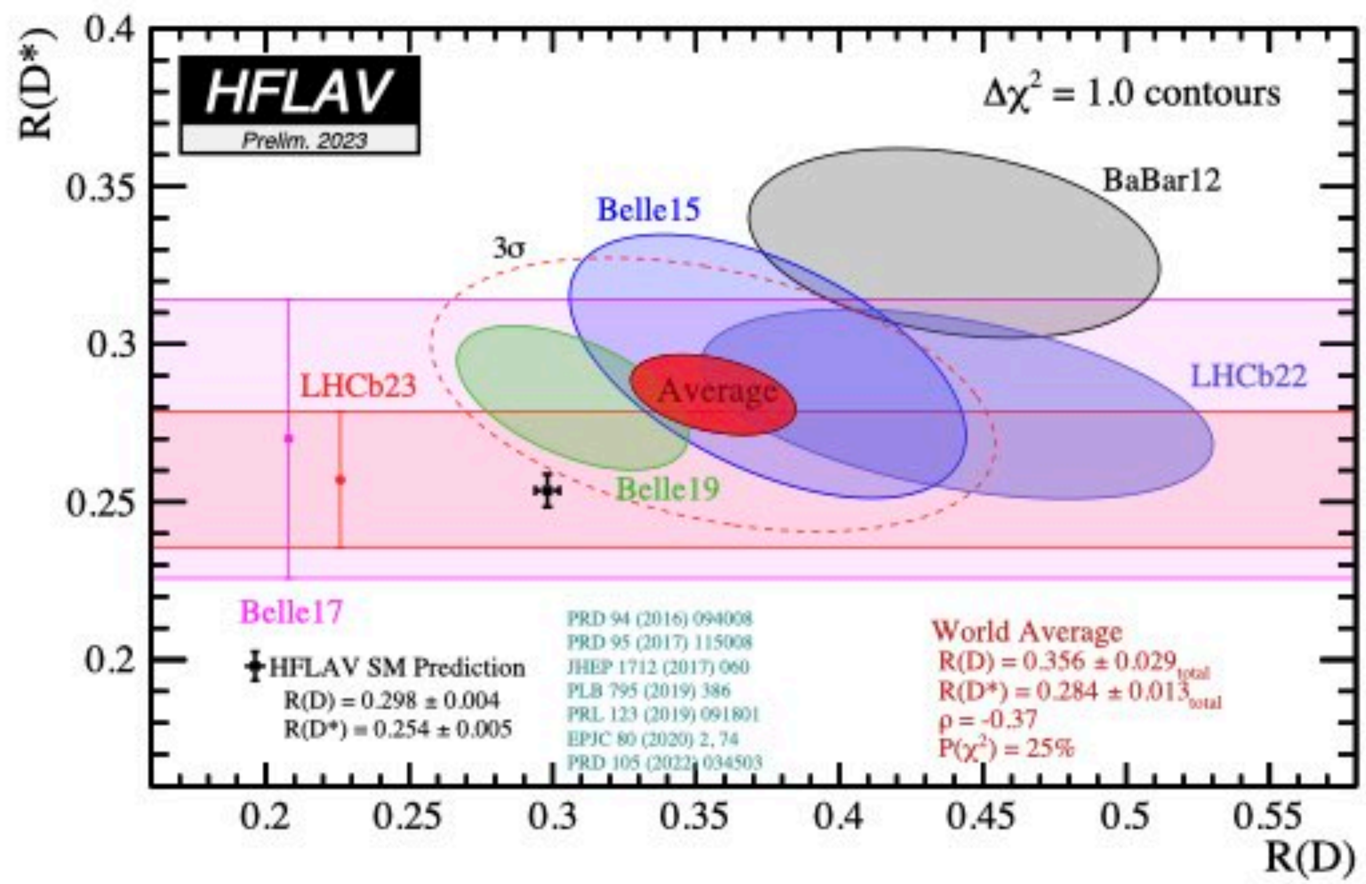
B-anomalies: $R_{D^{(*)}}$

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

$\sim 3.2\sigma$

$\Lambda_b \to \Lambda_c \tau\nu$



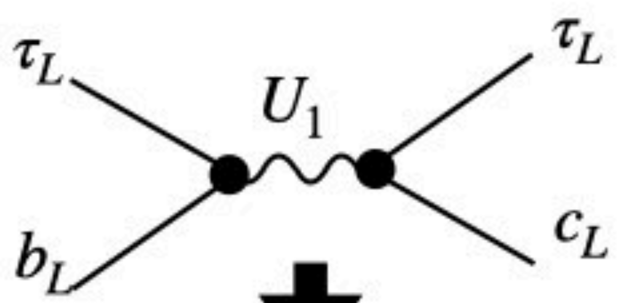


$$\mathscr{L} \supset \frac{2}{v^2} V_{cb}\Big[\left(1 + C^c_{LL}\right)(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L) - 2C^c_{LR}(\bar{c}_L b_R)(\bar{\tau}_L\nu_L)\Big]$$

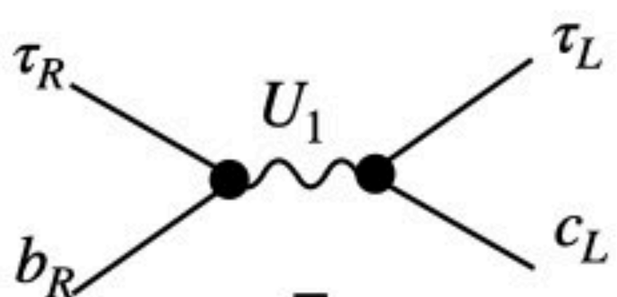
[J. Aebischer, G. Isidori, M. Pesut, B. Stefanek, F. Wilsch, 2210.13422]

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

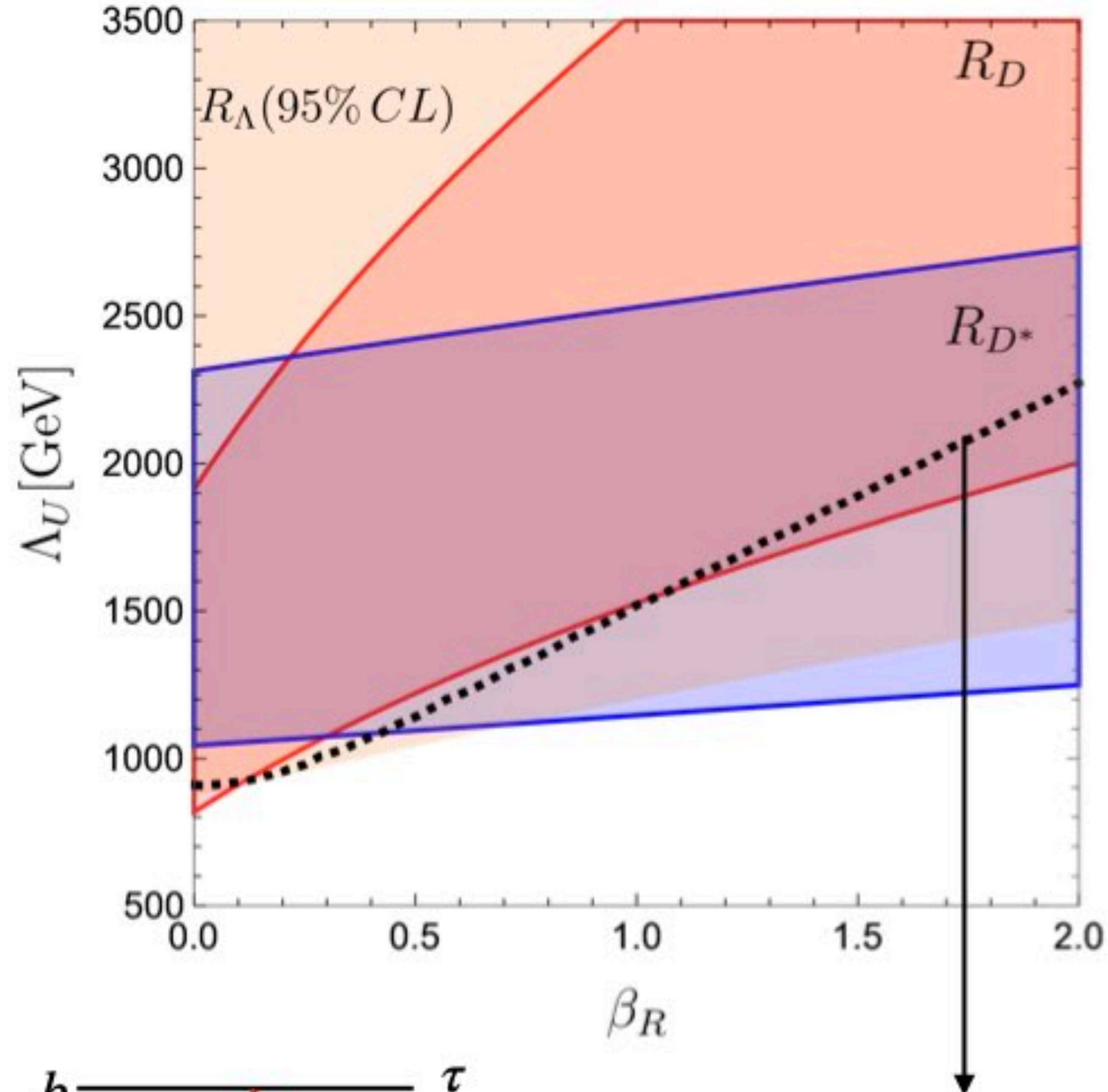
$s_q = 0.1 \approx 2.4 V_{cb}$

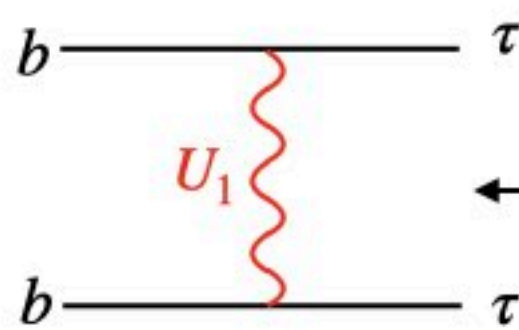


$$C^c_{LL} \propto \frac{s_q}{\Lambda^2}$$



$$C^c_{LR} \propto \frac{\beta_R s_q}{\Lambda_U^2}$$





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

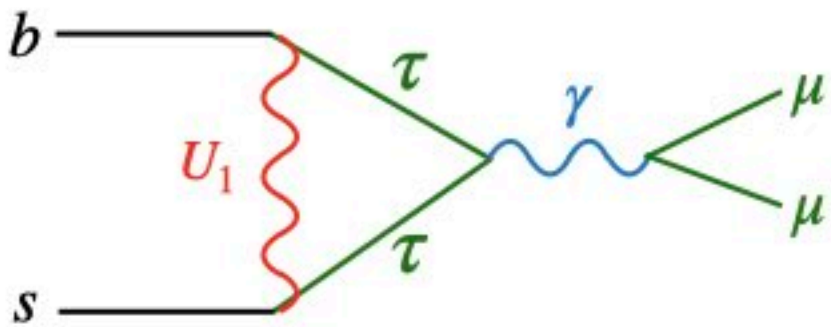
[W. Altmannshofer, P. Stangl, 2103.13370]

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

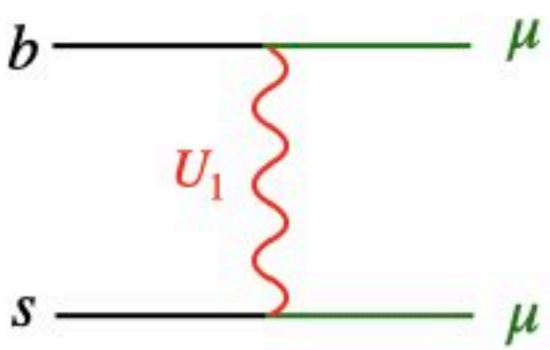
$B \to K^*\mu\mu$

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

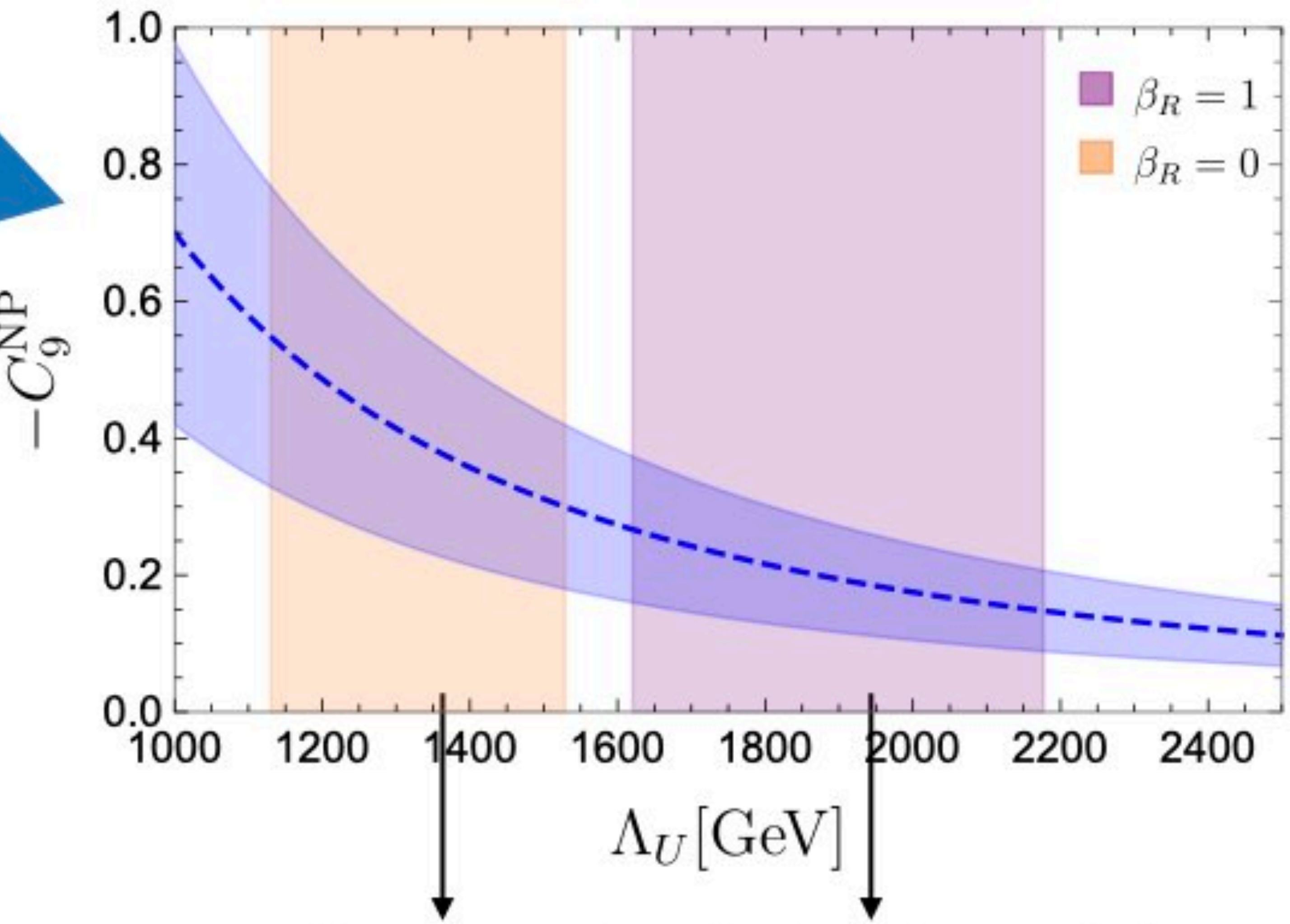
$$C_9^{\rm NP} = -0.75 \pm 0.23 \ \ (\sim 3.4\sigma)$$



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



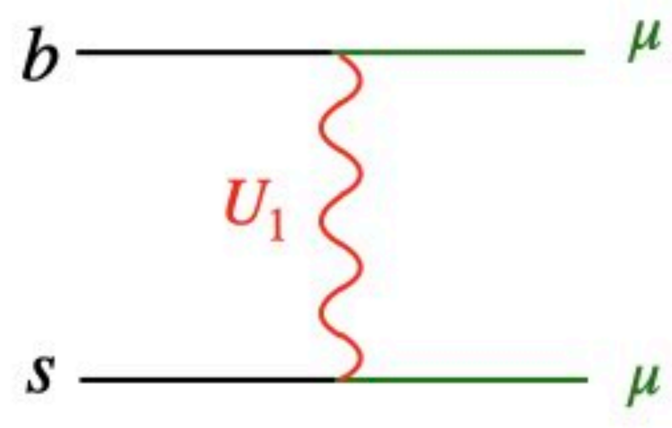
$$\sim \frac{s_q s_l^2}{\Lambda_U^2}$$



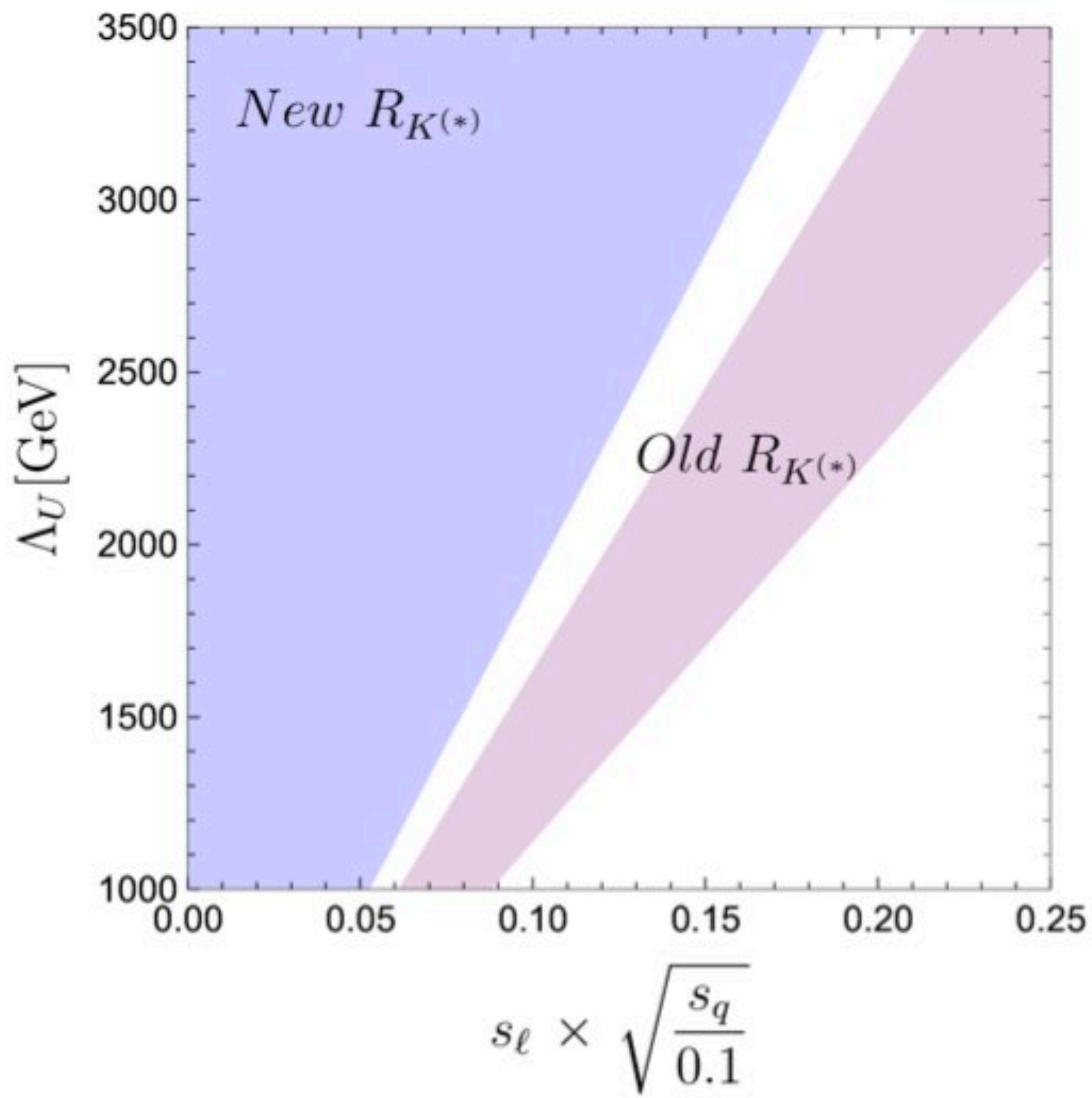
$b \to c\tau\nu$ preferred regions for $s_q = 0.1$

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

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

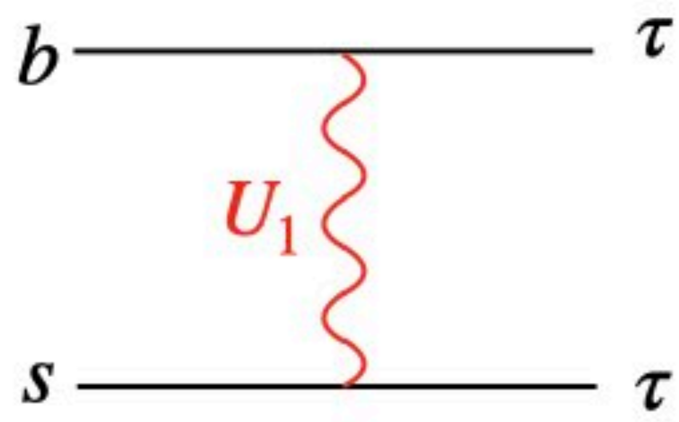


$$\propto \frac{s_q s_l^2}{\Lambda_U^2}$$



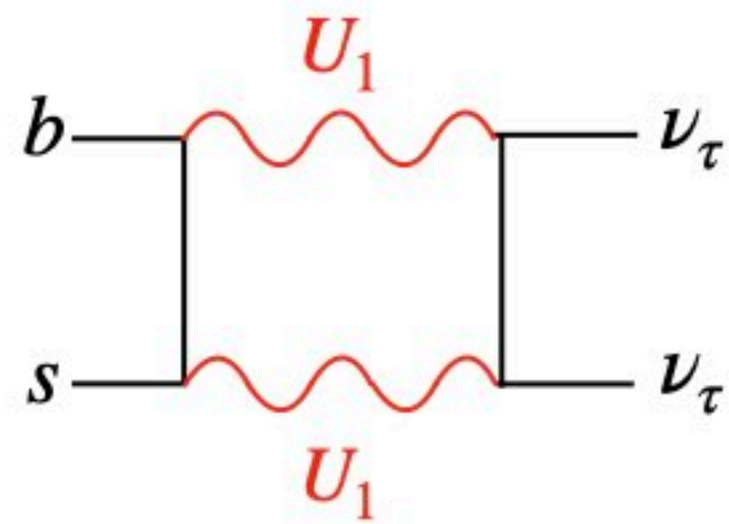
Other interesting observables

- $B_s \to \tau\tau$
- $B \to K\tau\tau$



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

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



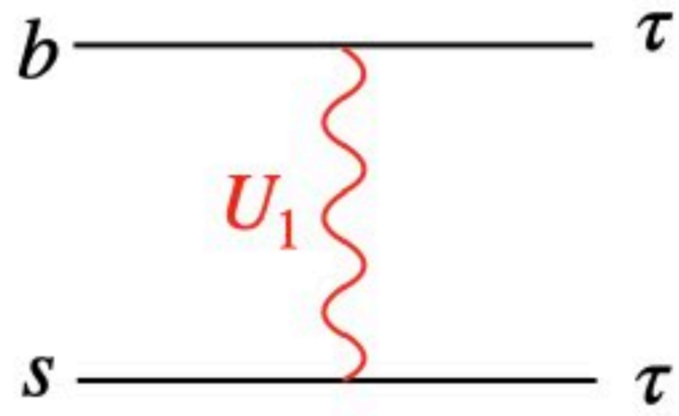
$$\sim \frac{s_q}{\Lambda_U^2} \times \text{loop}$$

- …

[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558]

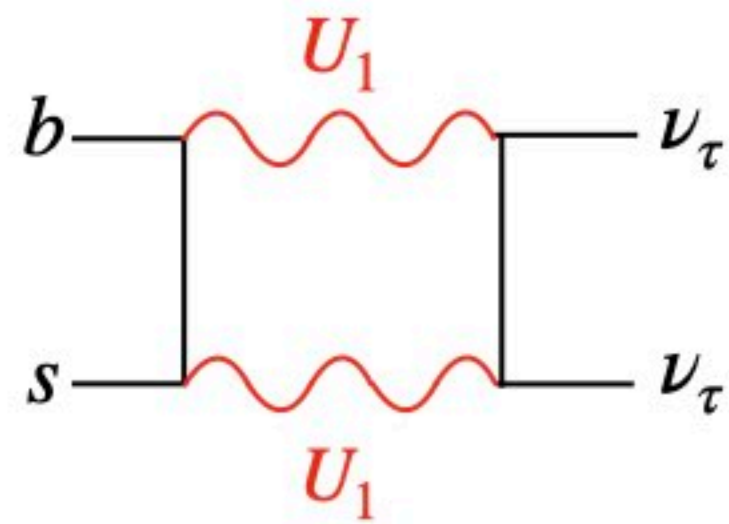
Other interesting observables

- $B_s \to \tau\tau$
- $B \to K\tau\tau$



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

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

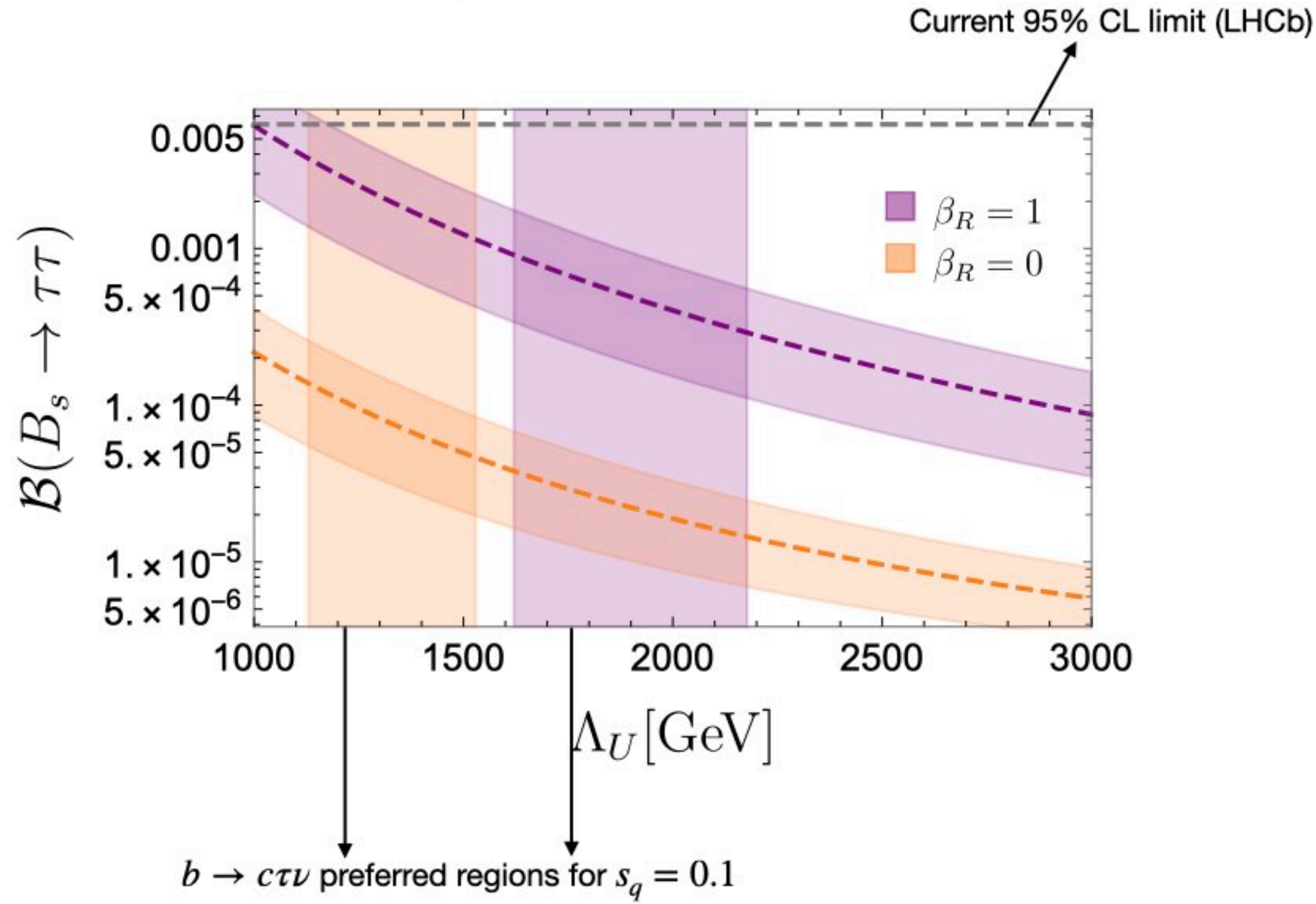


$$\sim \frac{s_q}{\Lambda_U^2} \times \text{loop}$$

- …

[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558]

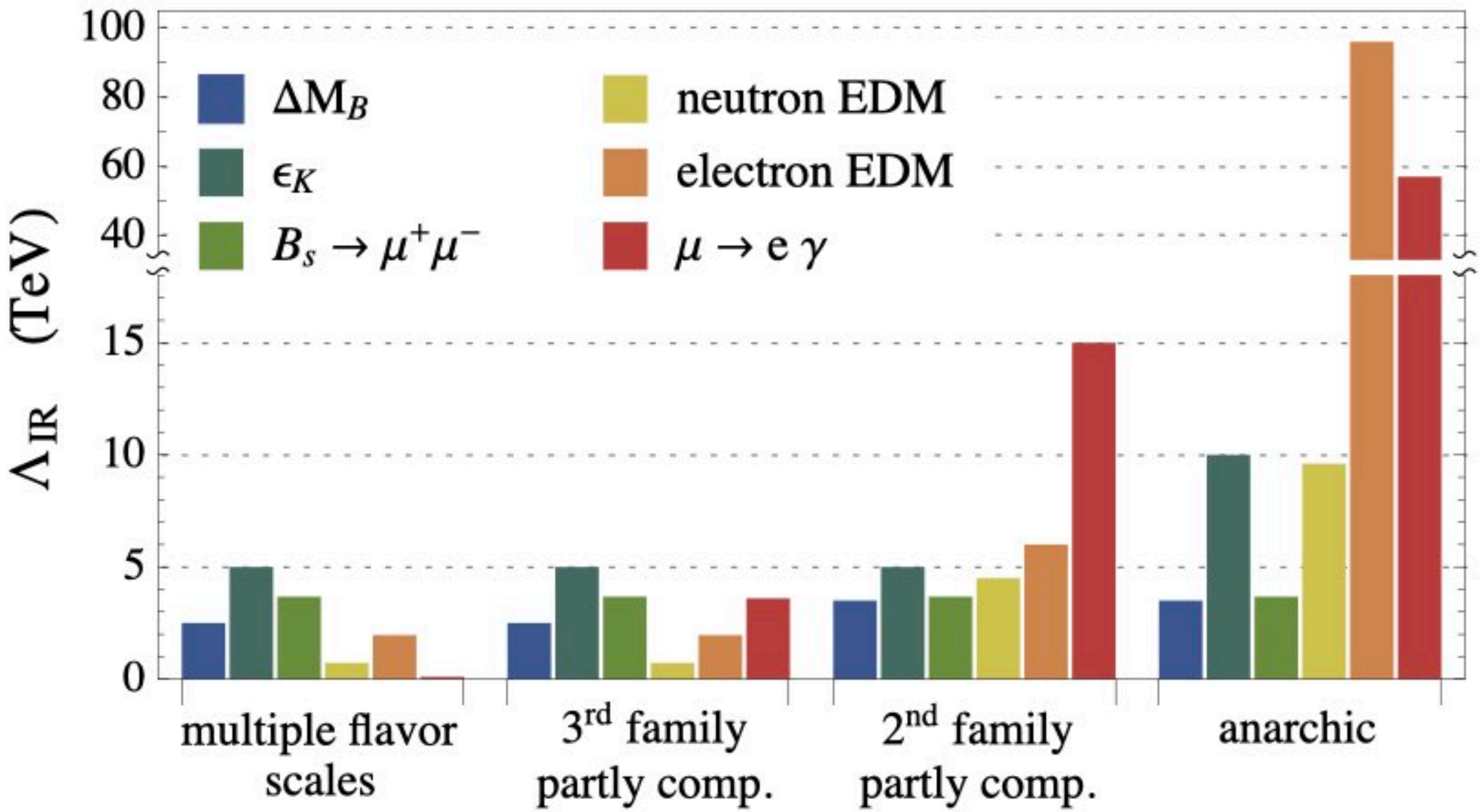
Other interesting observables



[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558]

Multiscale flavor

- Composite models/RS:



[Panico, Pomarol, 1603.06609]