University of Zurich[UZH]

Theory lessons from flavor data

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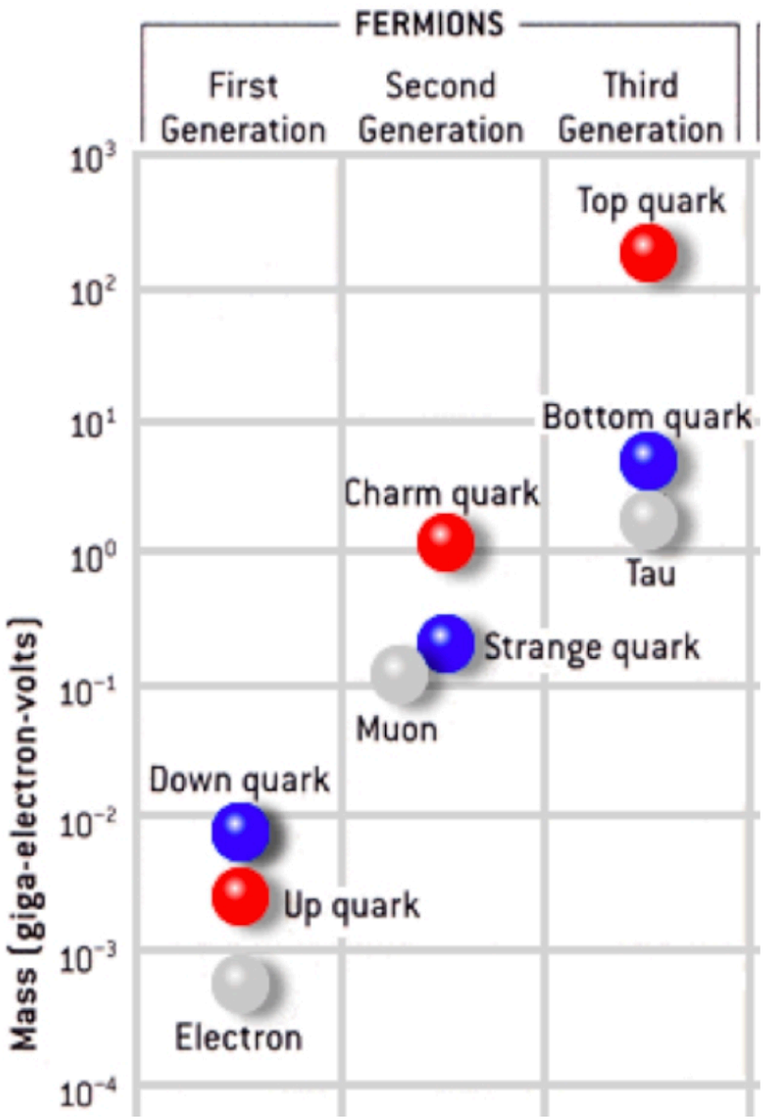
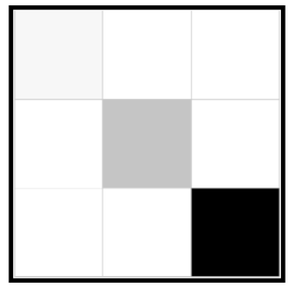
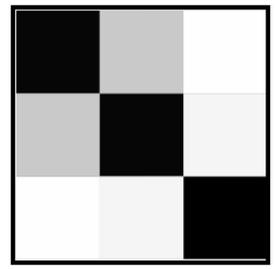
11th Edition of the Large Hadron Collider Physics Conference - Belgrade

Flavor data 1: the flavor puzzle

- **Flavor puzzle**: very hierarchical structures



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

$V_{\rm CKM} \sim$ 

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

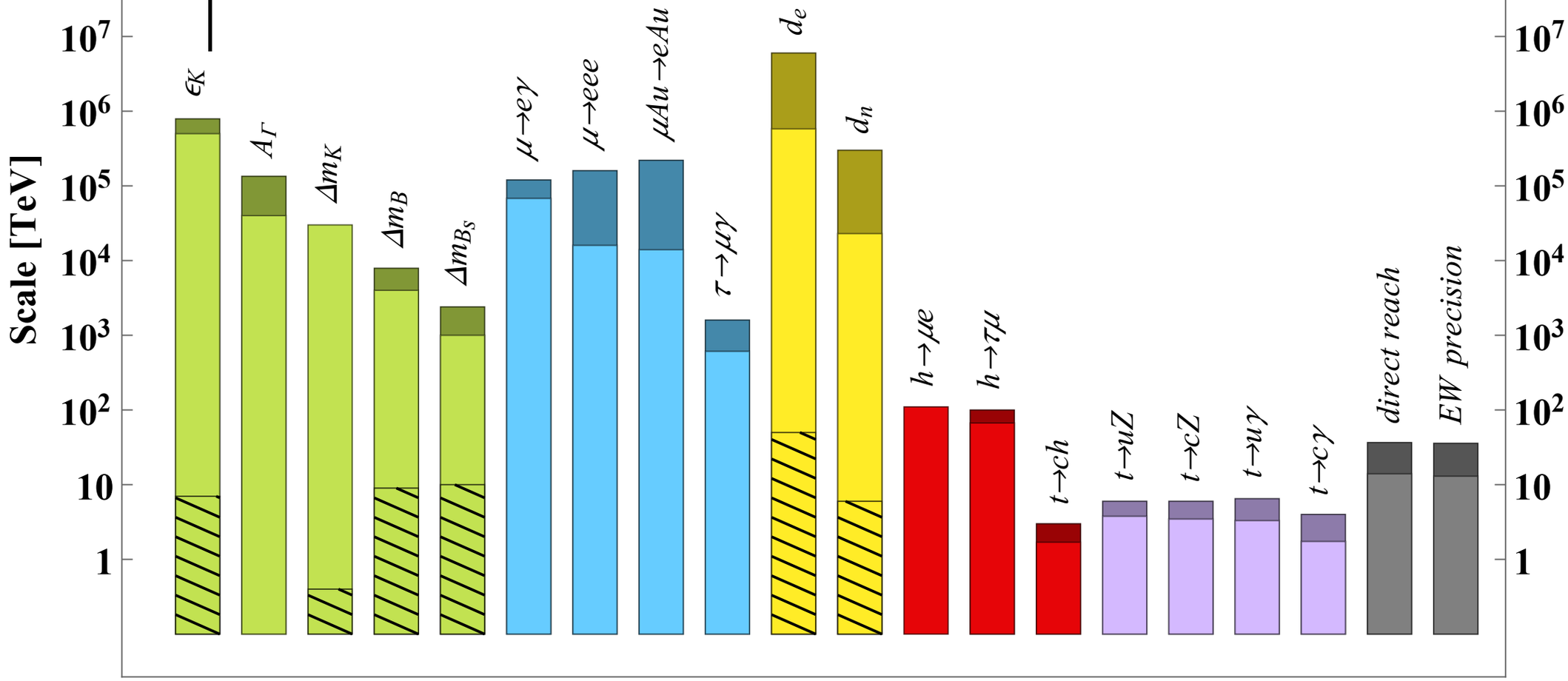
Flavor data 2: NP bounds

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

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

Scalar op. more constrained

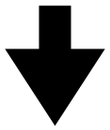
($K-\bar{K}$ mixing)



[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.



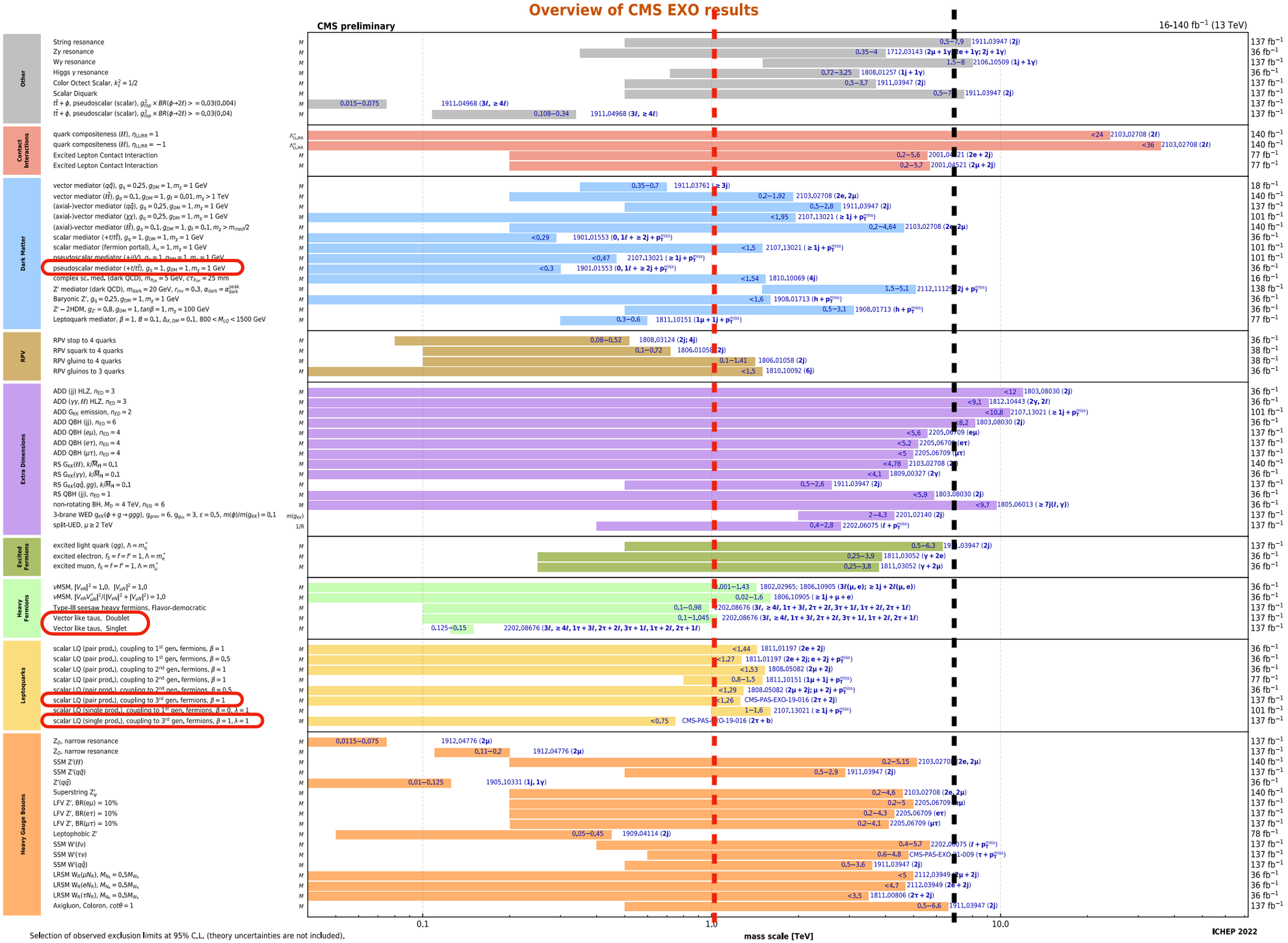
- NP at the TeV scale cannot address the puzzle problem.
- Universal NP at the TeV?

Too naive?

LHC searches

3rd fam. NP (1 TeV)

Universal NP (Multi TeV)

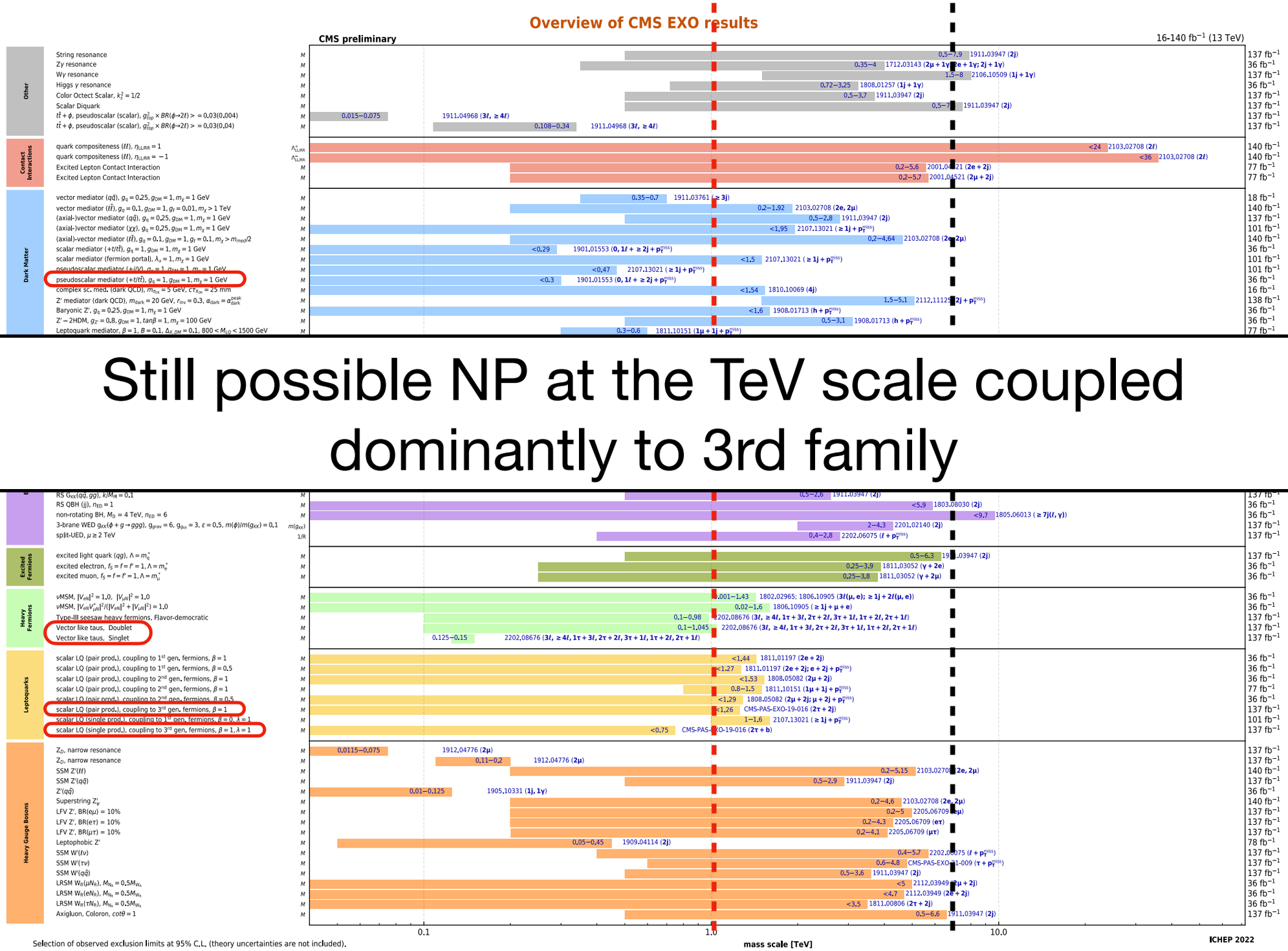


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

LHC searches

3rd fam. NP (1 TeV)

Universal NP (Multi TeV)



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

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Flavor symmetries of SM

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

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

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

Largest breaking of $U(2)_q$

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

$$U(3)^5 \longrightarrow U(2)^5$$

3rd fam. Yuk.

- Protection in FCNC (GIM).

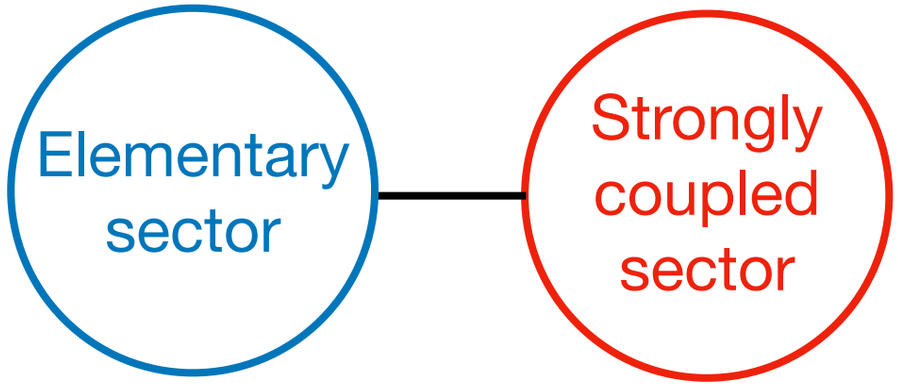
$$Y_u \sim \overbrace{\begin{pmatrix} & & \\ & & 0.008 \\ & & 0.04 \\ & & y_t \end{pmatrix}}^{\Delta_u \sim 2_q \times \bar{2}_u} \Big\}\, V_q \sim 2_q$$

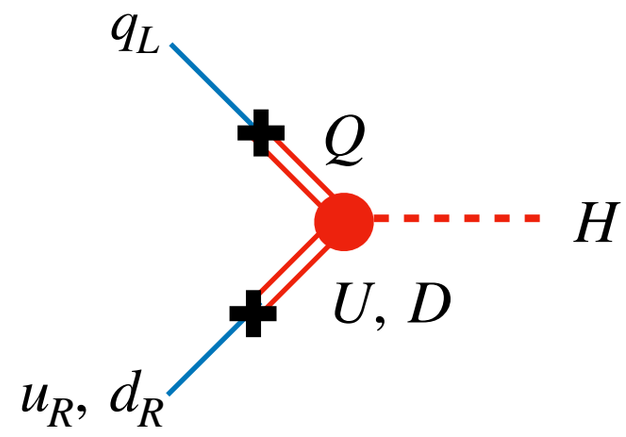
< 0.01

[Kaplan, 1991]

Example: partial compositeness

- Strong sector stabilising the Higgs mass





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

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

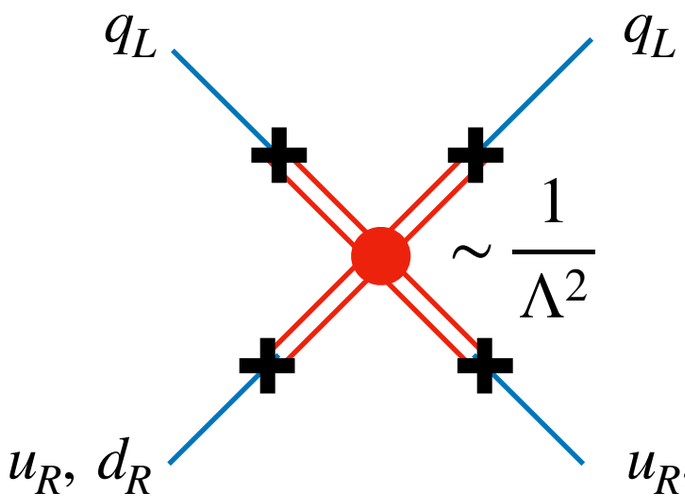
$U(2)$ protection

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

$$\begin{cases} \lambda_q \sim 2_q \\ \lambda_u \sim 2_u \\ \lambda_d \sim 2_d \end{cases}$$

VS

$$\left.\begin{array}{l} V_q \sim 2_q \\ \Delta_u \sim 2_q \times \bar{2}_u \\ \Delta_d \sim 2_q \times \bar{2}_d \end{array}\right\}$$

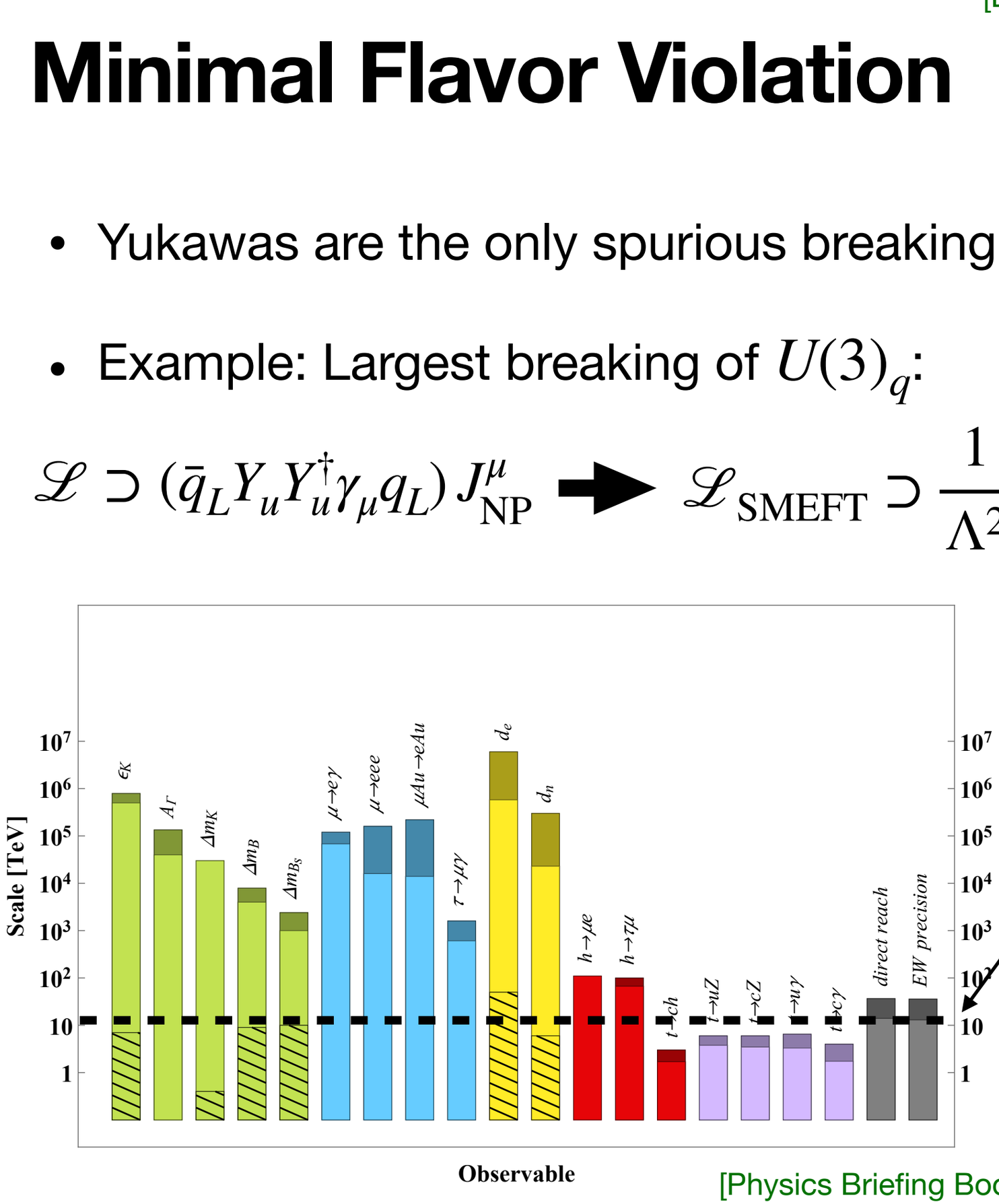
SM spurions

[D'Ambrosio, Giudice, Isidori, Strumia, 0207036]

Minimal Flavor Violation

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

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



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

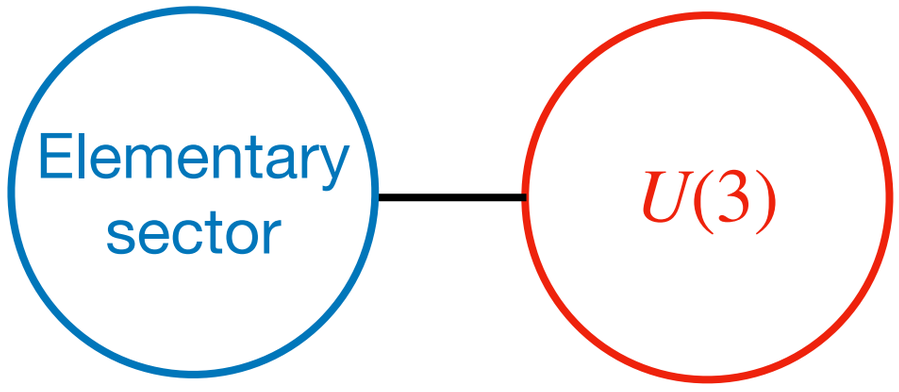
$$\Lambda \gtrsim |V_{ts}V_{td}|\, 2\times 10^4\,\text{TeV} \sim 10\,\text{TeV}$$

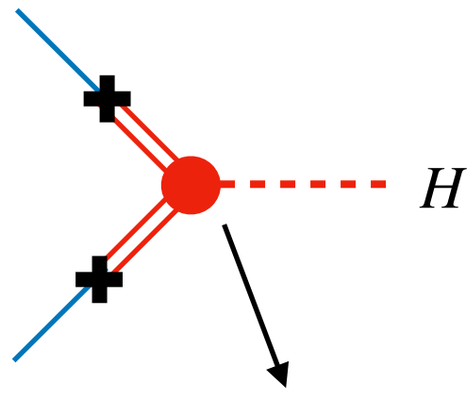
[Physics Briefing Book, 1910.11775]

[D'Ambrosio, Giudice, Isidori, Strumia, 0207036]

Minimal Flavor Violation

- Achievable imposing flavor symmetries. For example:





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

$U(3)$ $\quad$ ~~$U(3)$~~

$U(3)$-preserving

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

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

- Emerging dynamically if flavor is explained at a higher scale

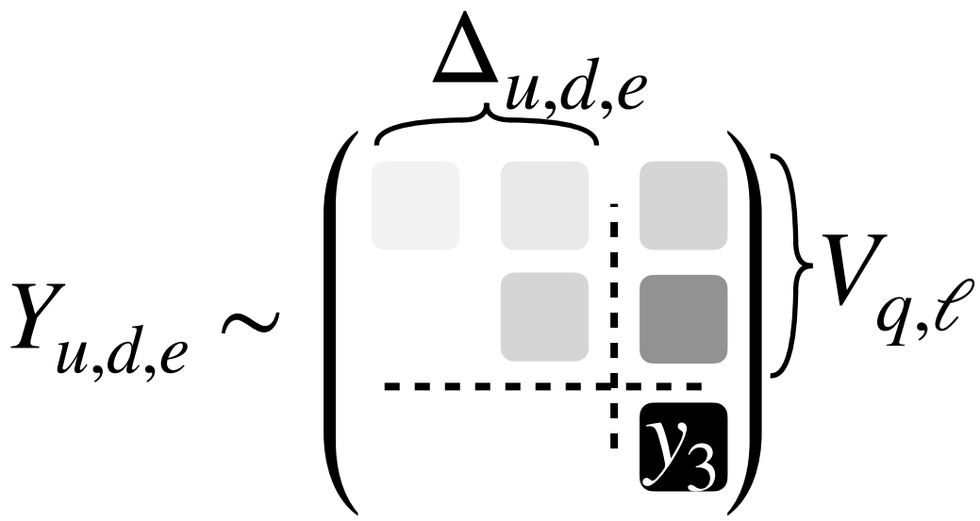
[Barbieri, Isidori, Jones-Perez, Lodone, Straub, 1105.2296]

Minimally broken $U(2)$

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

Exact $U(3)$	Exact $U(2)$
$\bar{q}^a_L \gamma_\mu q^a_L$	$c_h\, \bar{q}^3_L \gamma_\mu q^3_L + c_l\, \bar{q}^i_L \gamma_\mu q^i_L$

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



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

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

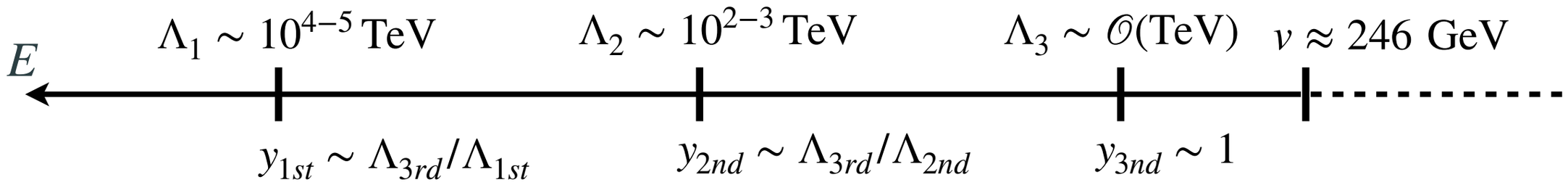
$$\Delta_d \sim 2_q \times \bar{2}_d$$

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

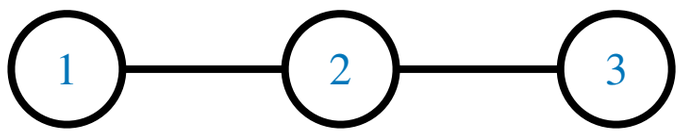
Multiscale flavor

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

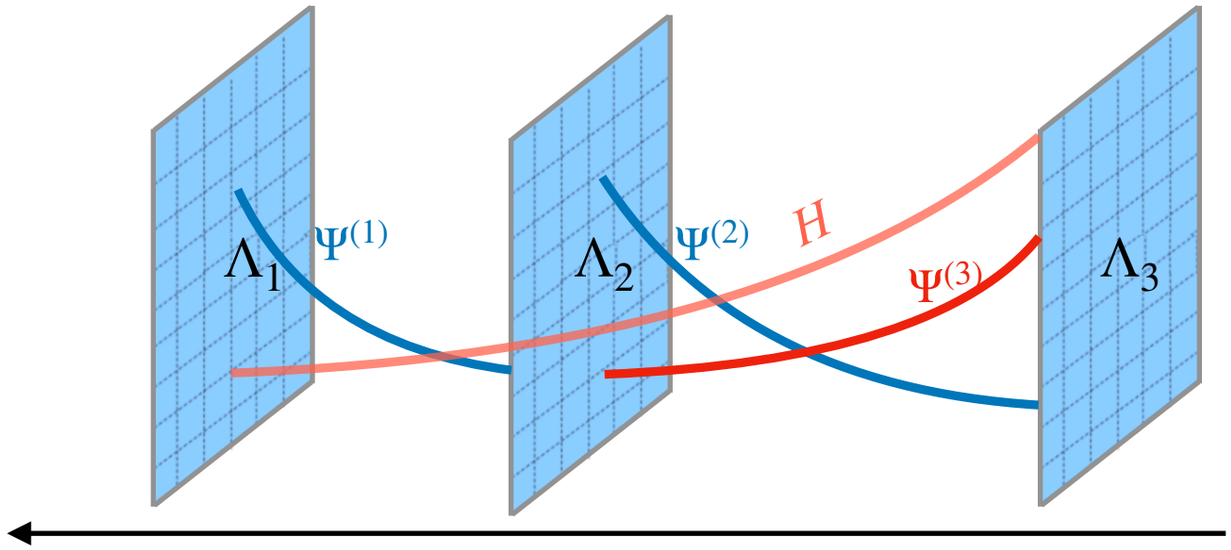
- Minimally broken $U(2)$ emerges naturally in a **multiscale origin of the flavor hierarchies**:



Gauge deconstruction



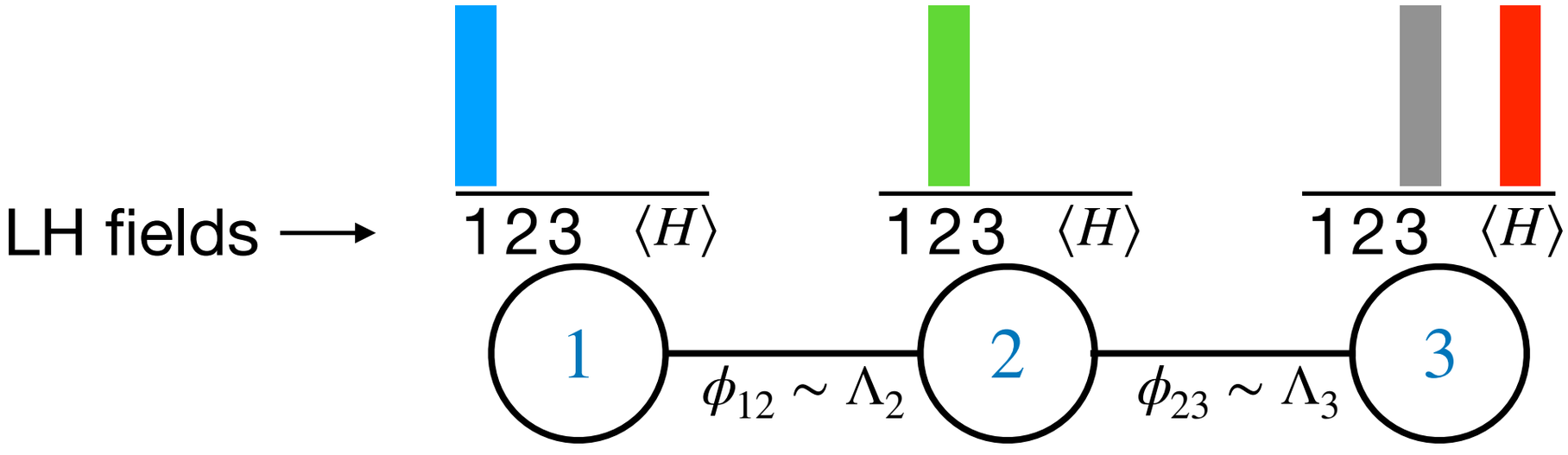
Composite dynamics ⟷ Extra-dimensions (dual)



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

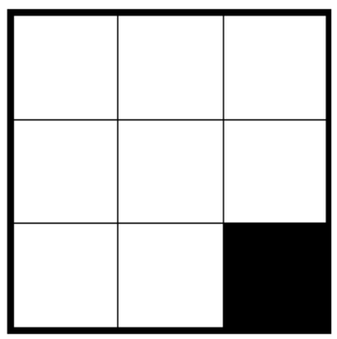
Deconstructing flavor

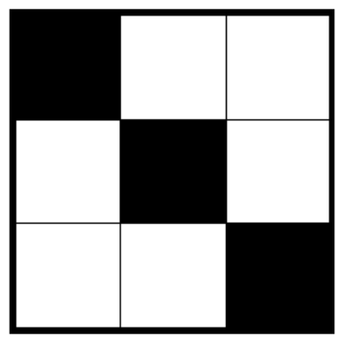
[Bordone, Cornella, Fuentes-Martin, Isidori, 1712.01368,
Allwicher, Isidori, Thomsen, 2011.01946,
Davighi, Isidori, 2303.01520
Fernández-Navarro, King, 2305.07690]



$$G_1 \times G_2 \times G_3 \xrightarrow{\text{TeV}} \text{SM}$$

(Universal)

$$M \sim$$ 

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

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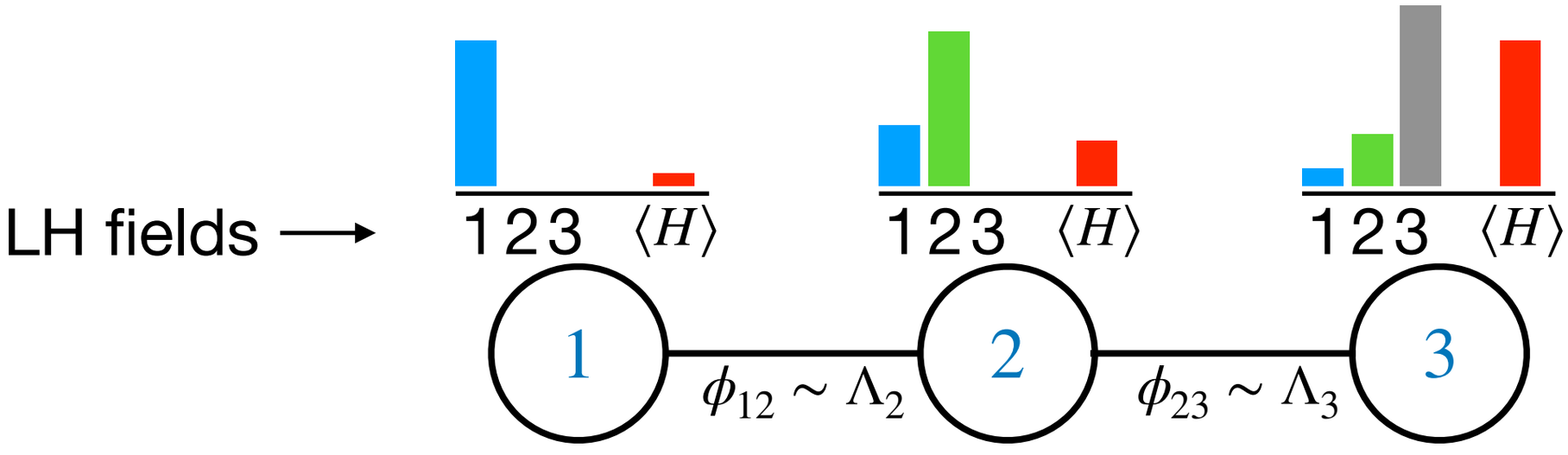
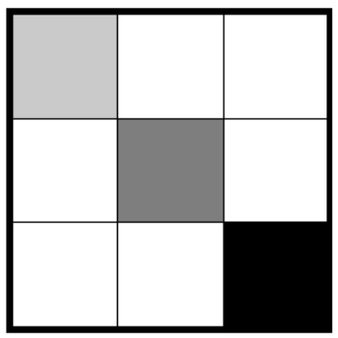
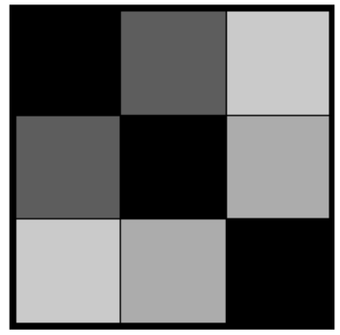


$$G_1 \times G_2 \times G_3 \xrightarrow{\text{TeV}} \text{SM}$$

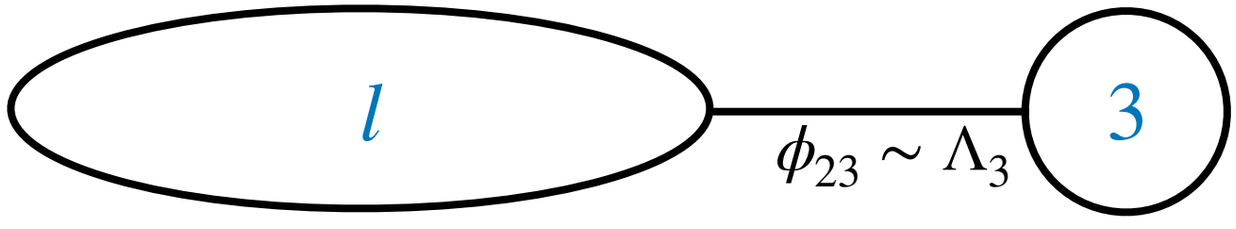
(Universal)

$$M \sim$$ 

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

Deconstructing flavor

- From the TeV, we see…



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

(Universal)

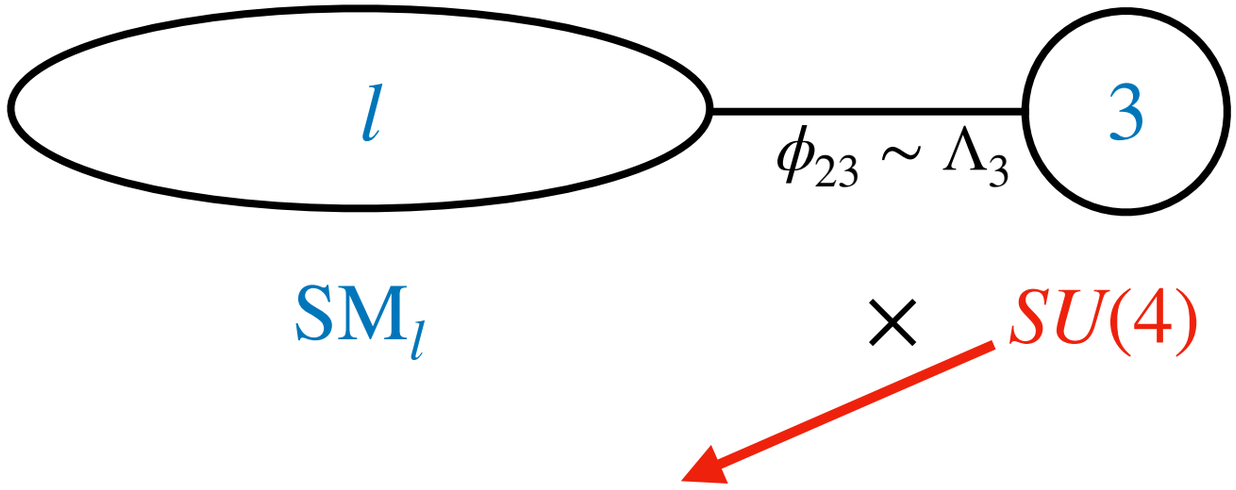
- Emerging flavor symmetry: $U(2)$

- 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…



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:

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

$SU(3)_h \longrightarrow SU(3)_c$ (with $SU(3)_h \cap SU(4)_h$ and $SU(3)_c \uparrow SU(3)_l$)

$U(1)_{(B-L)_h} \cup SU(4)_h \longrightarrow U(1)_Y$ (with $U(1)_{R+\frac{(B-L)_l}{2}} \downarrow U(1)_Y$)

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

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

$$g_4 \gg g_3$$

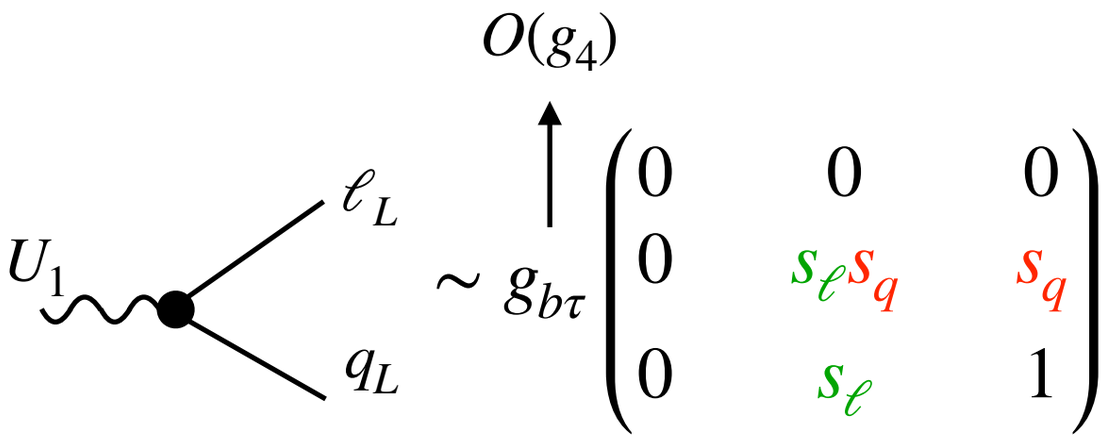
$$g_s \approx g_3$$
$$g_h^{G'} \approx g_4$$
$$g_l^{G'} \approx g_s^2/g_4$$

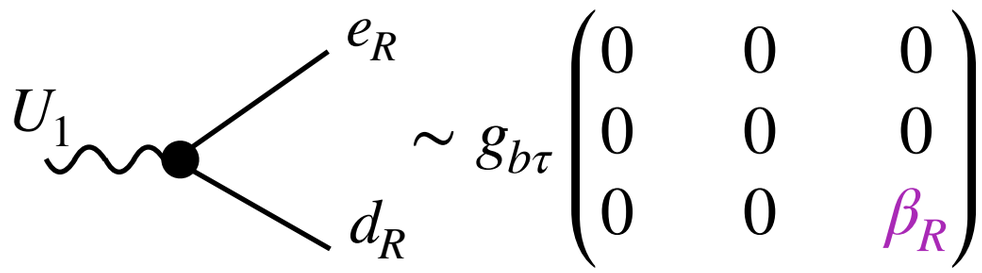
LHC bounds:

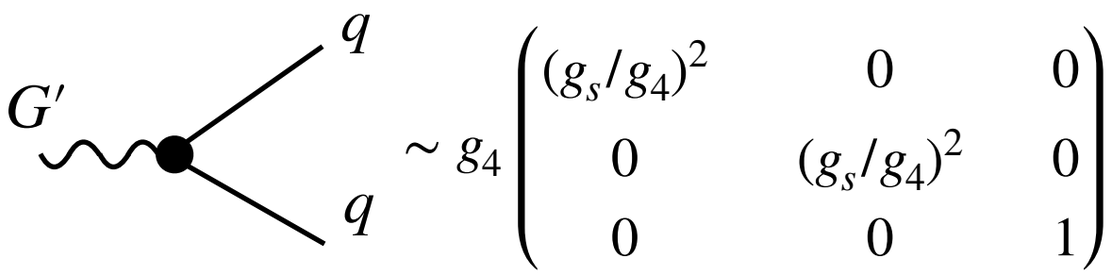
$$M_{G'} \gtrsim 3 - 3.5\,\text{TeV}$$

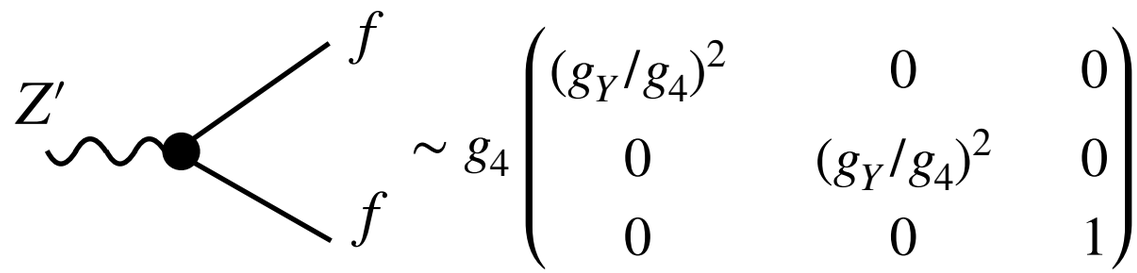
[Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558]

4321 massive vector bosons









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

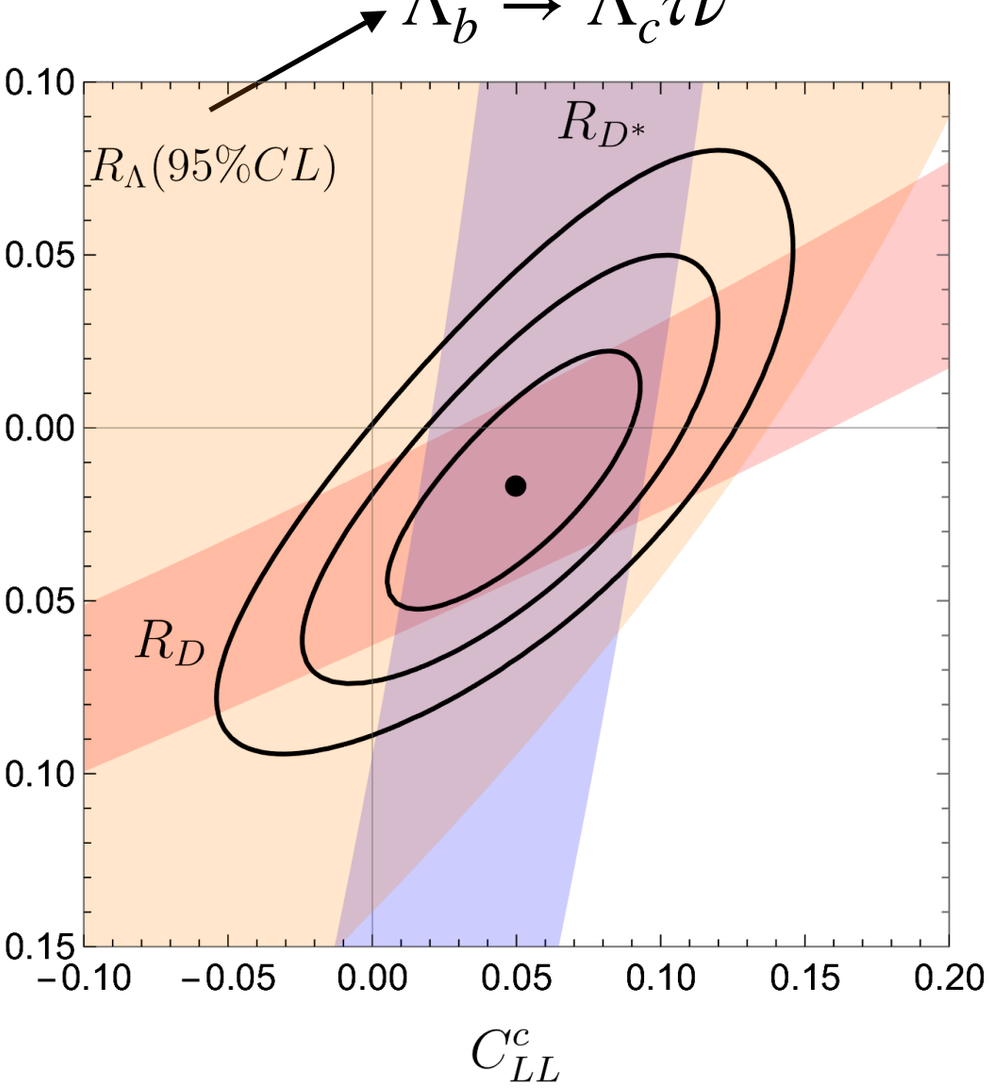
$\Lambda_U,\ s_q,\ s_\ell,\ \beta_R$

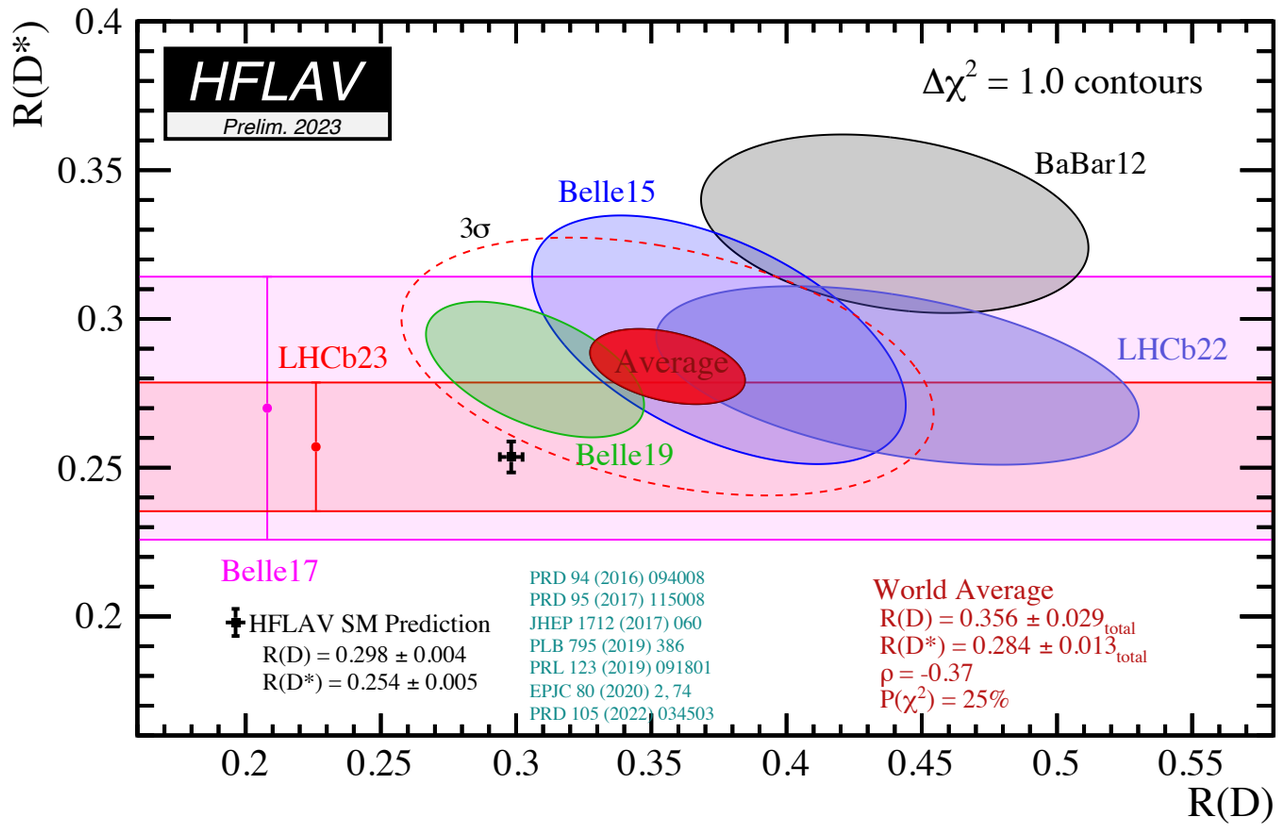
Necessary for CKM

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

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

$\sim 3.2\sigma$



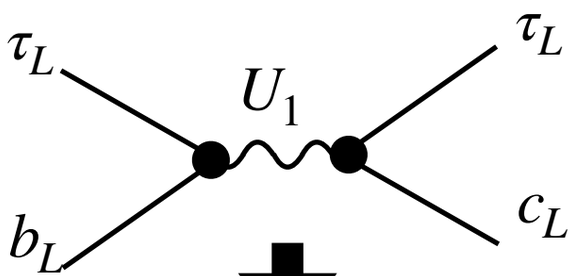


$$\mathscr{L} \supset \frac{2}{v^2} V_{cb}\Big[\big(1 + C^c_{LL}\big)(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L) - 2C^c_{LR}(\bar{c}_L b_R)(\bar{\tau}_L\nu_L)\Big]$$

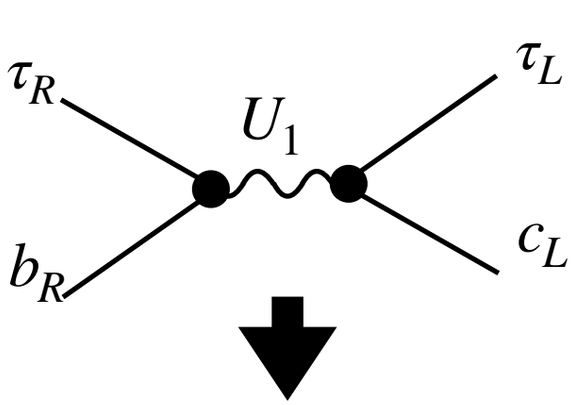
[J. Aebischer, G. Isidori, M. Pesut, B. Stefanek, F. Wilsch, 2210.13422]

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

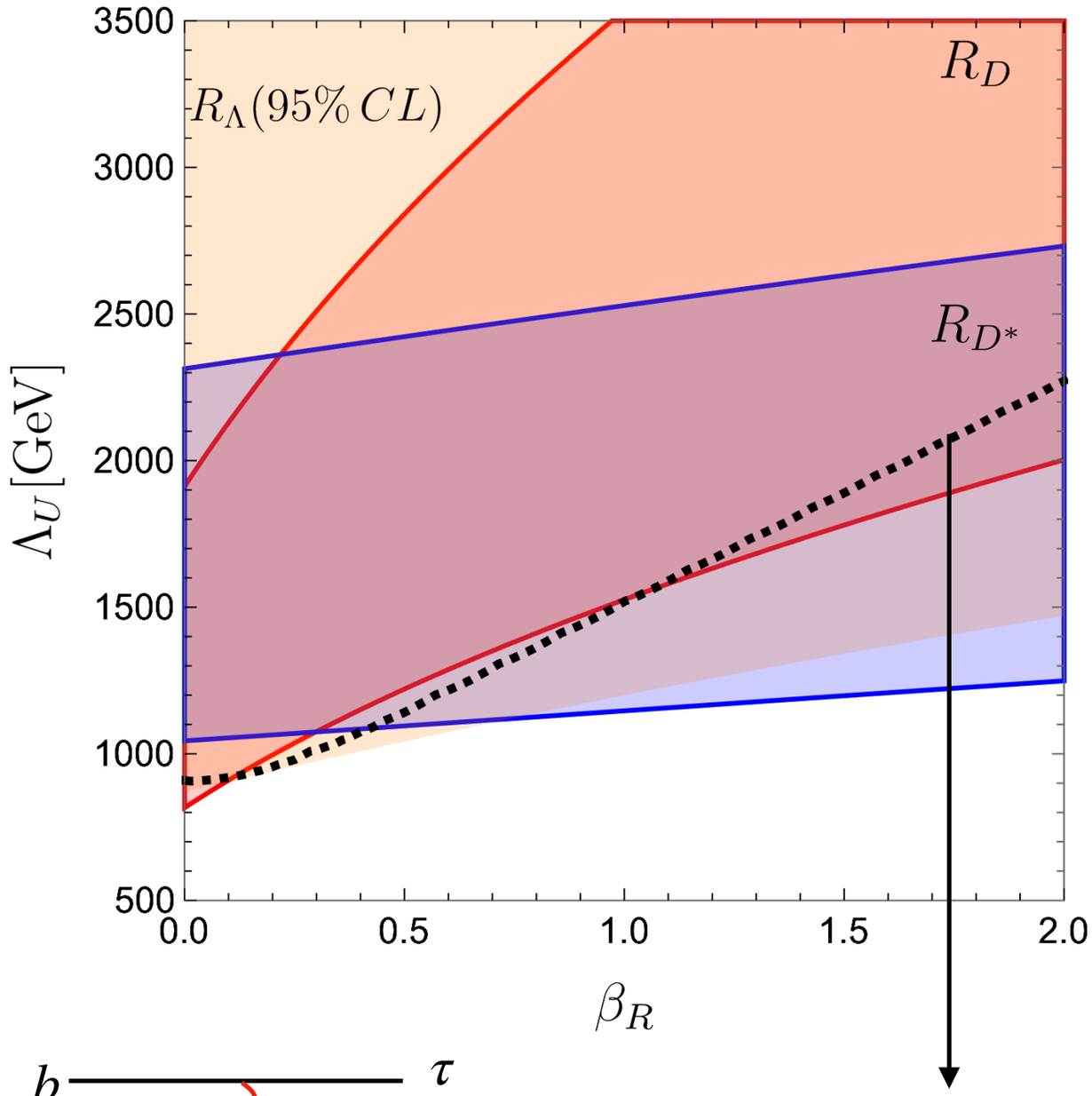
$$s_q = 0.1 \approx 2.4 V_{cb}$$

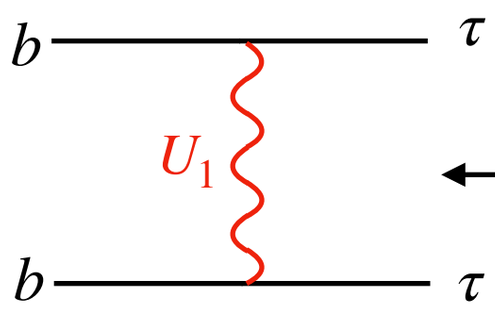


$$C^c_{LL} \propto \frac{s_q}{\Lambda^2}$$



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





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

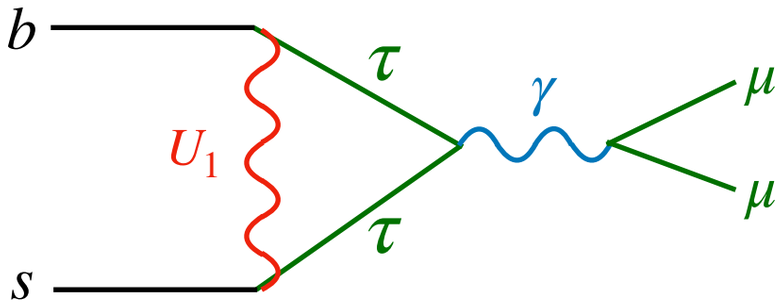
[W. Altmannshofer, P. Stangl, 2103.13370]

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

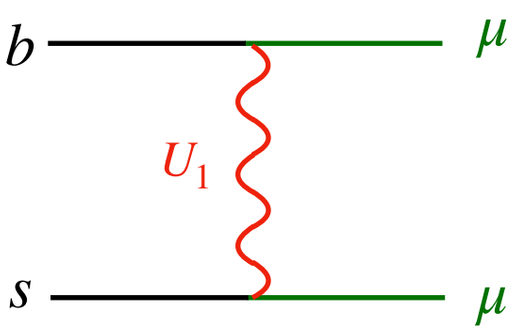
$$B \to K^*\mu\mu$$

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

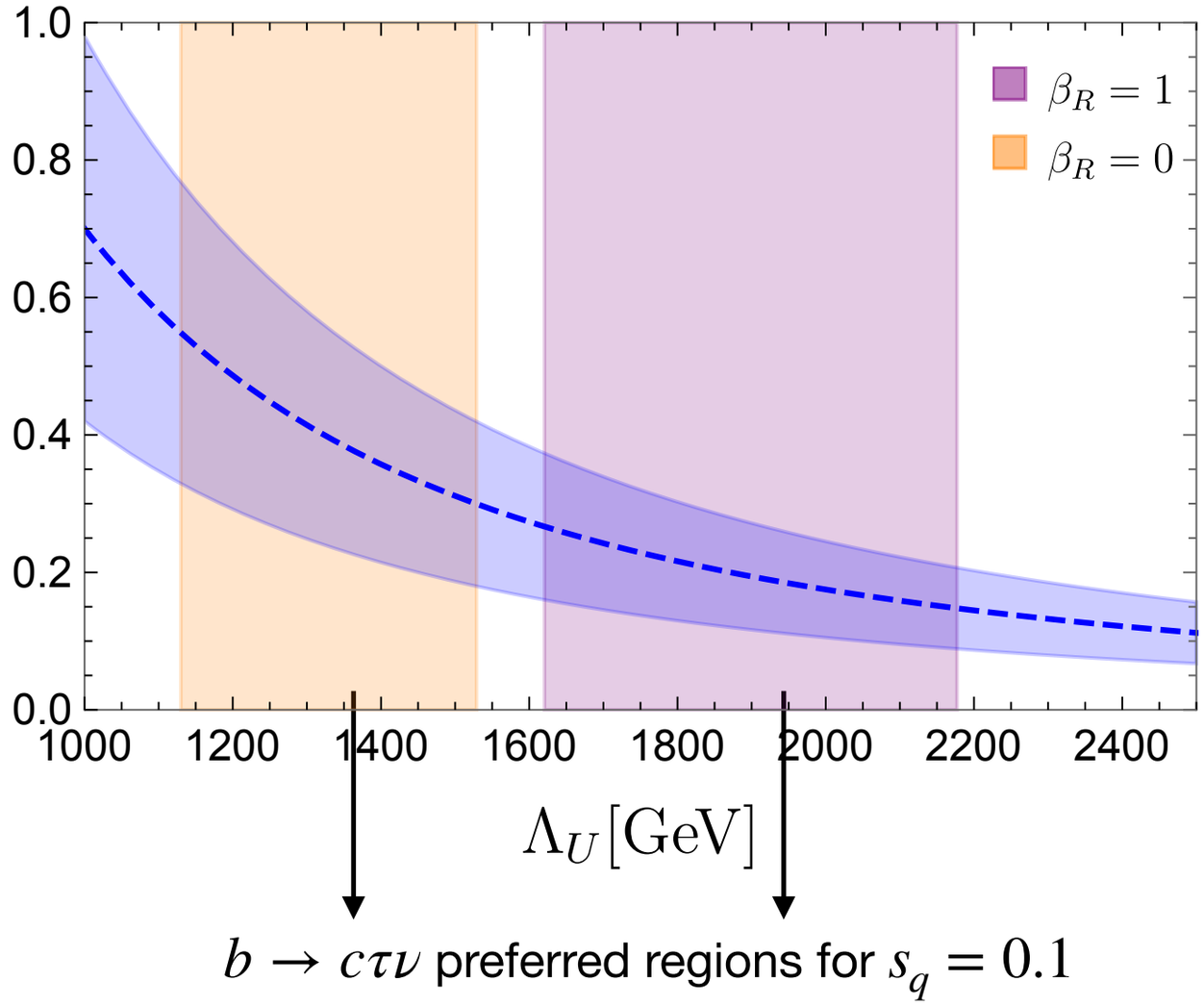
$$C_9^{\rm NP} = -0.75 \pm 0.23 \;\; (\sim 3.4\sigma)$$



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

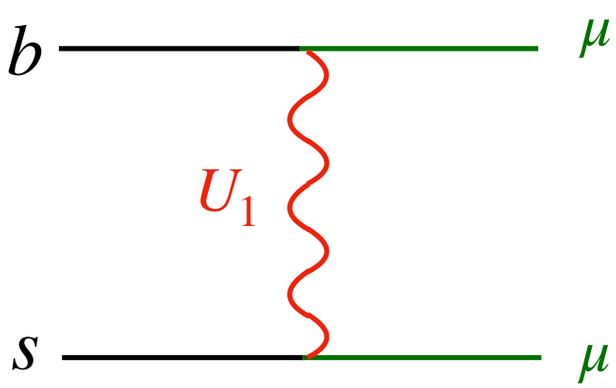


$$\sim \frac{s_q\, s_l^2}{\Lambda_U^2}$$

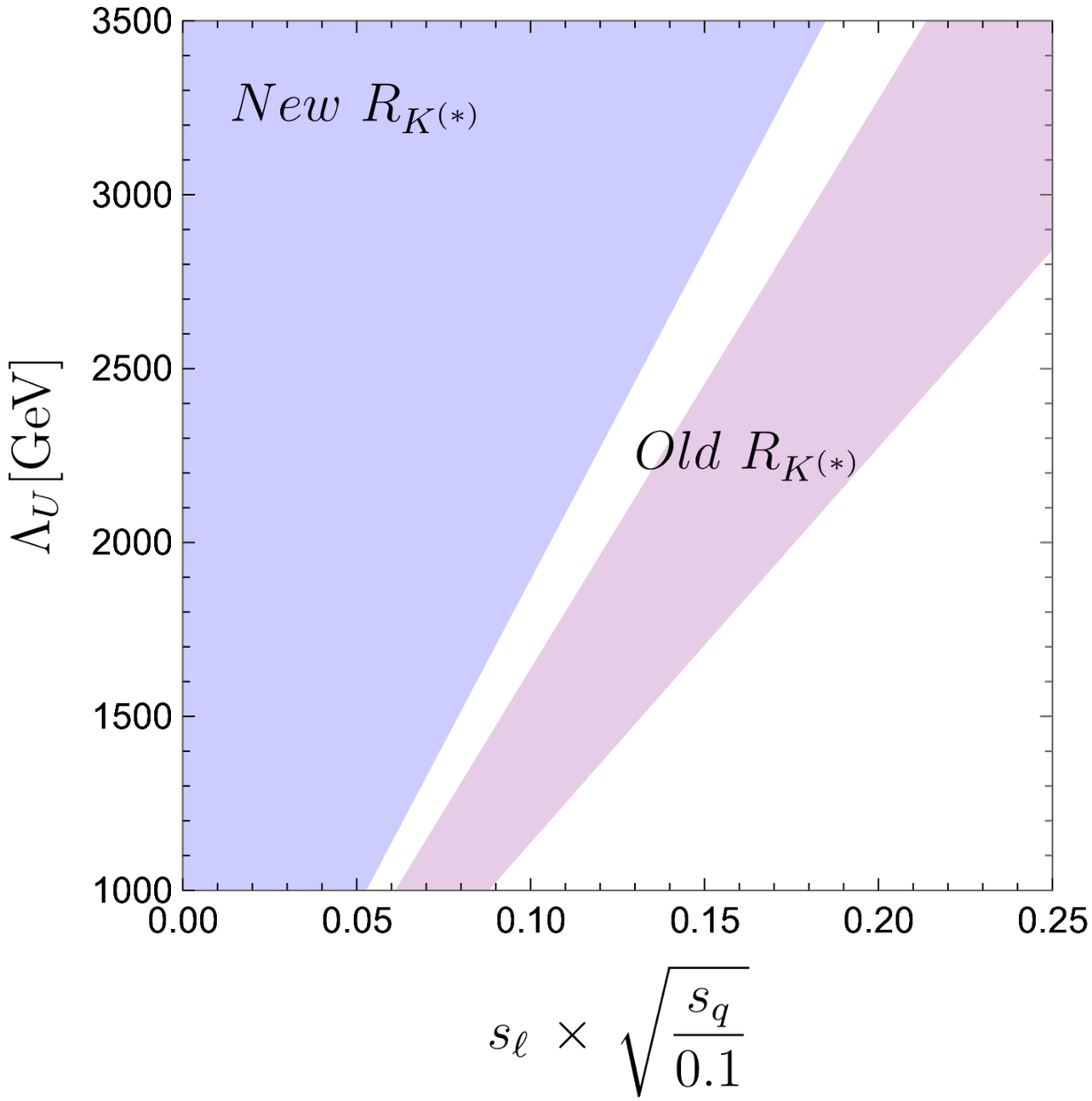


And what about $R_{K^{(*)}}$...?

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

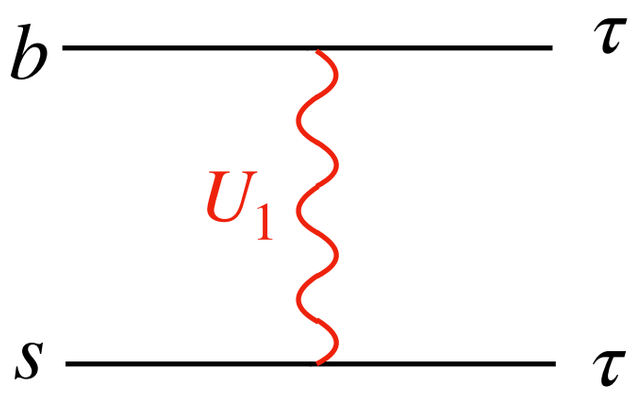


$$\propto \frac{s_q\, s_l^2}{\Lambda_U^2}$$



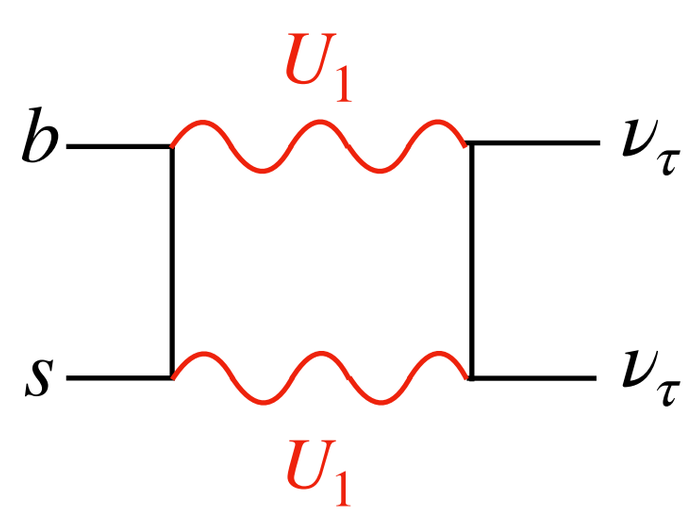
Other interesting observables

- $B_s \to \tau\tau$



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

- $B \to K\tau\tau$



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

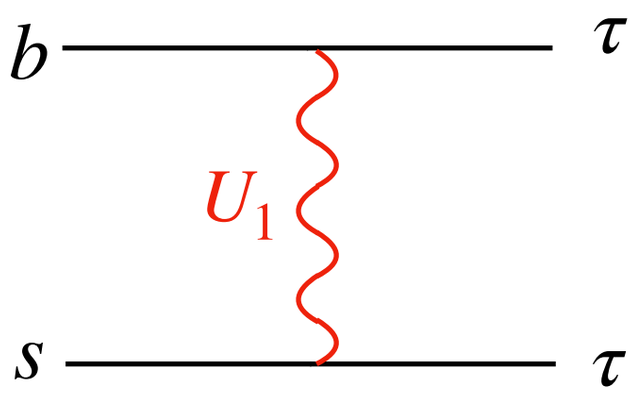
- $B \to K\nu\bar{\nu}$

- …

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

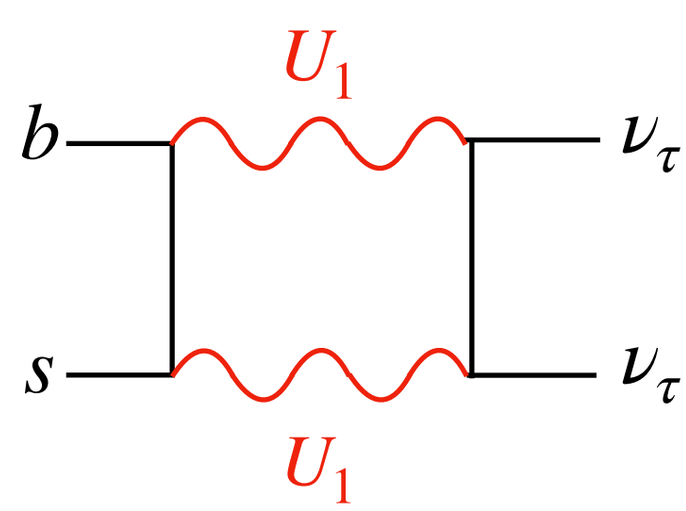
Other interesting observables

- $B_s \to \tau\tau$



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

- $B \to K\tau\tau$



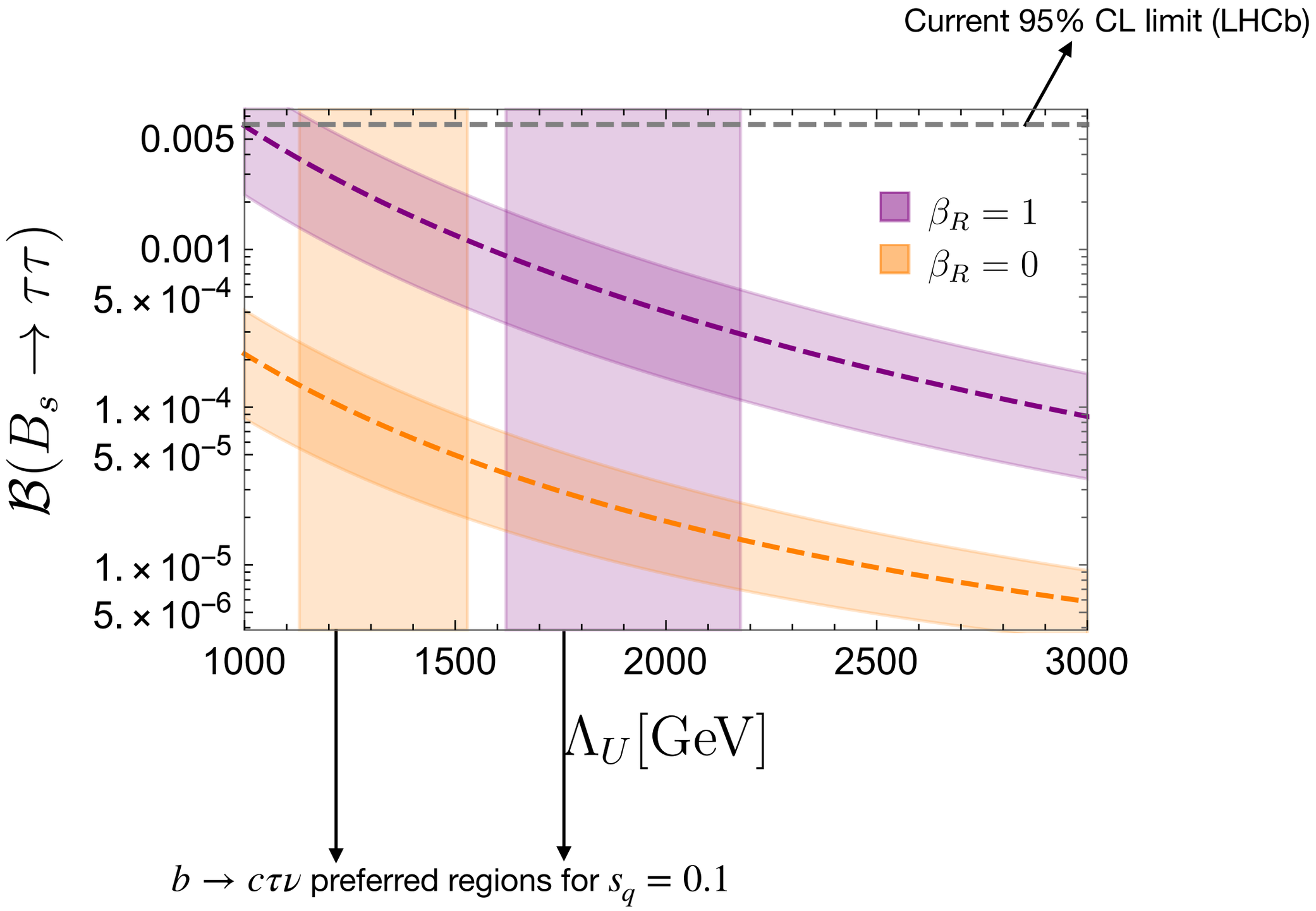
$$\sim \frac{s_q}{\Lambda_U^2} \times \text{loop}$$

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

- …

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

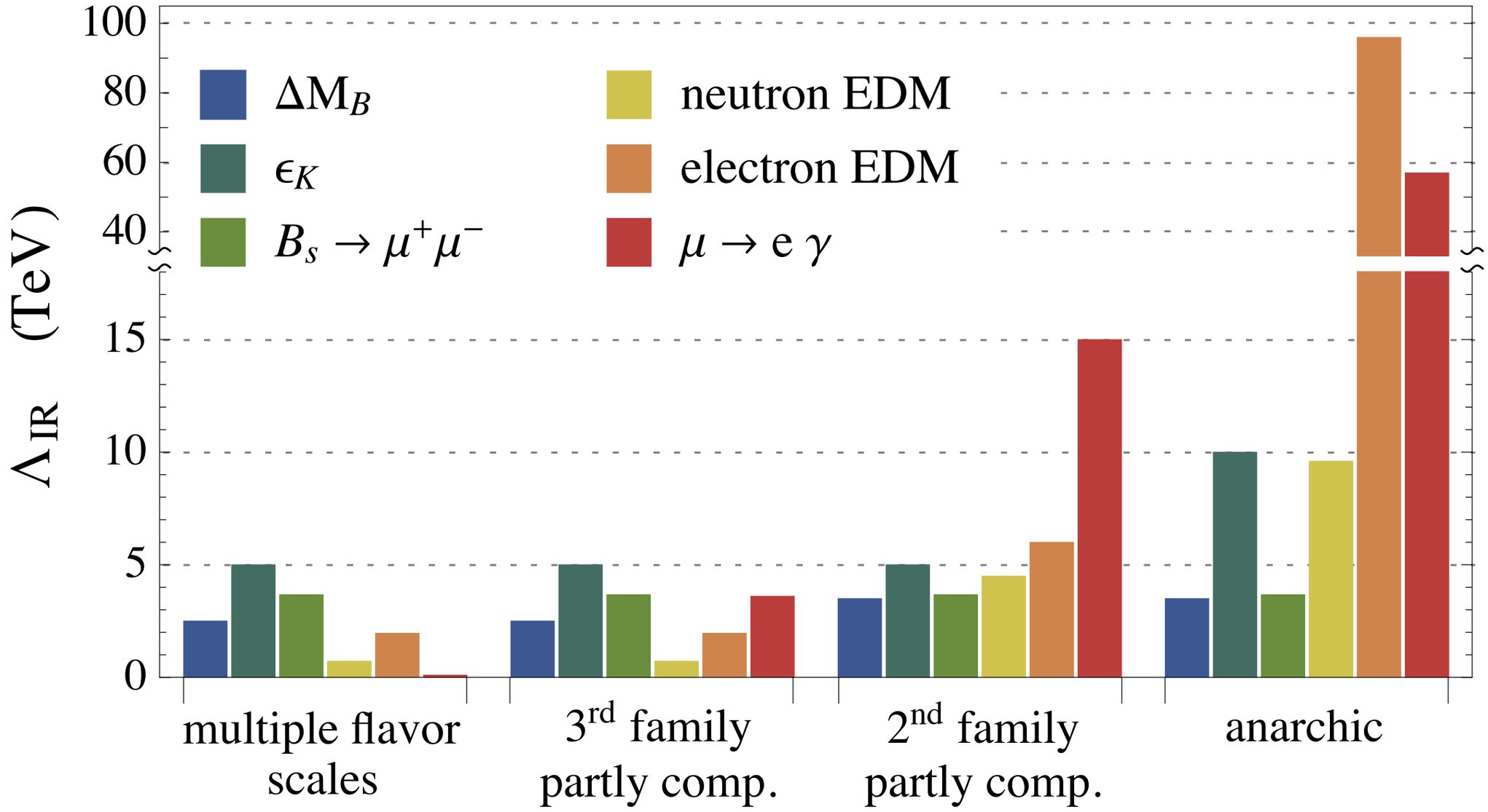
Other interesting observables



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

Multiscale flavor

- Composite models/RS:



[Panico, Pomarol, 1603.06609]