B-physics anomalies: *facts*, *hopes*, *dreams*, & *worries*

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European Research Council
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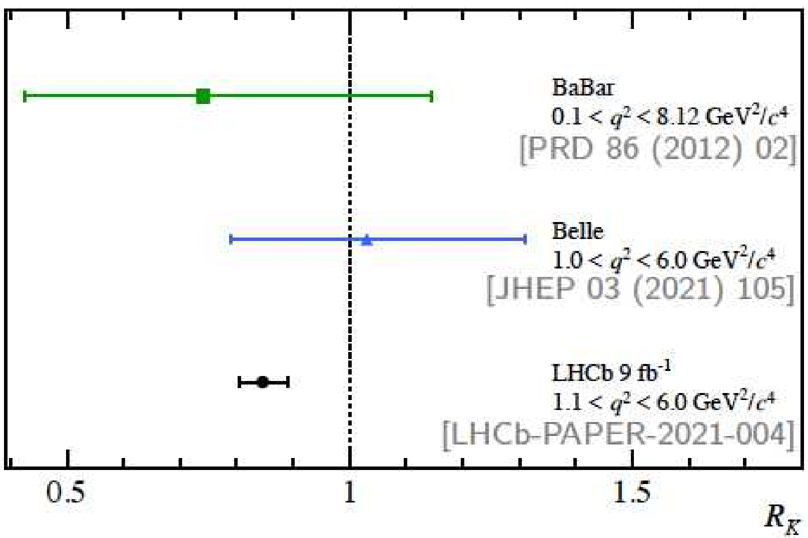
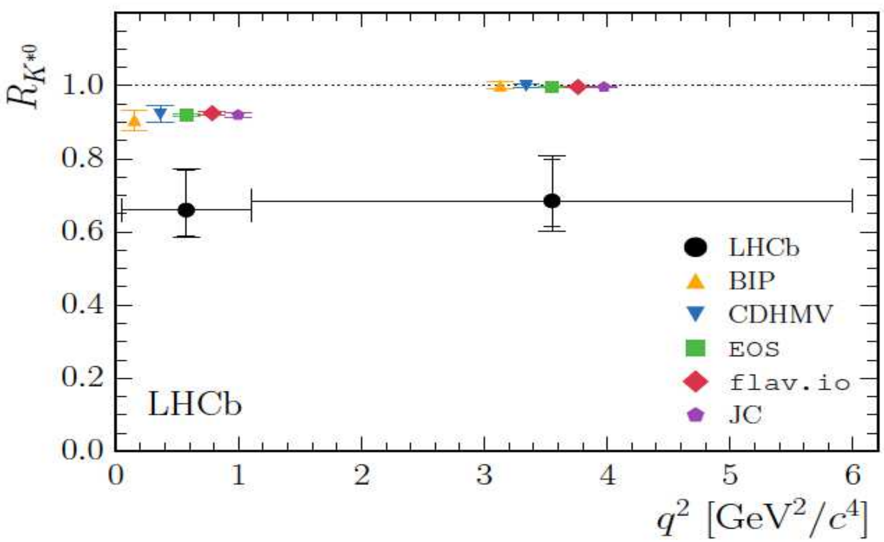
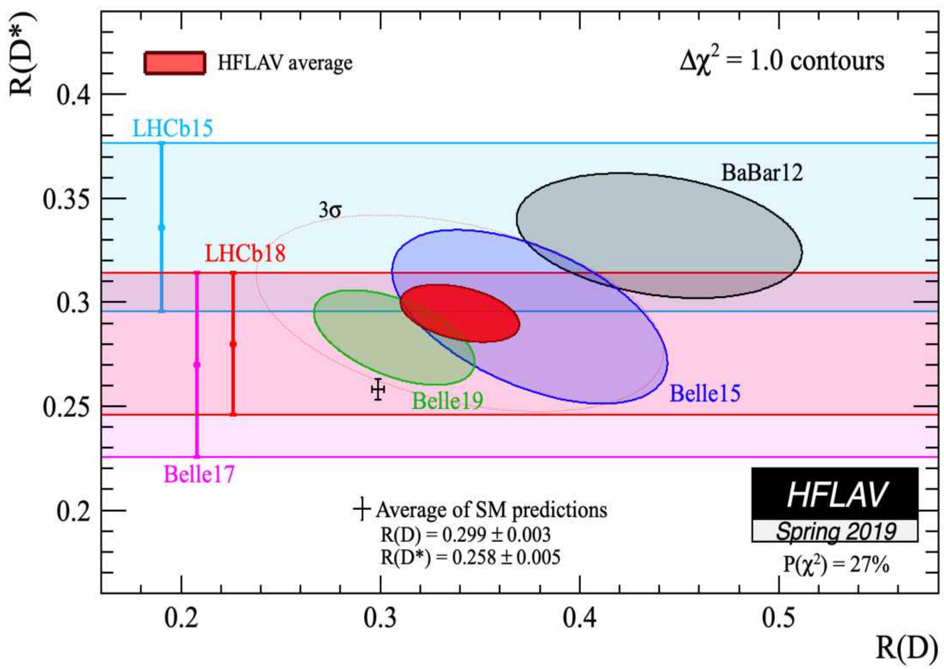
Facts [*a closer look to the data*]







A closer look to the data

Since 2013 results in semi-leptonic B decays started to exhibit tensions with the SM predictions connected to a possible violation of Lepton Flavor Universality

More precisely, we seem to observe a different behavior (*beside pure kinematical effects*) of different lepton species in the following processes:

- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e
- $b \to c\, l\nu$ (charged currents): τ vs. light leptons (μ, e)

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- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e NEW!
- $b \to c\, l\nu$ (charged currents): τ vs. light leptons (μ, e)

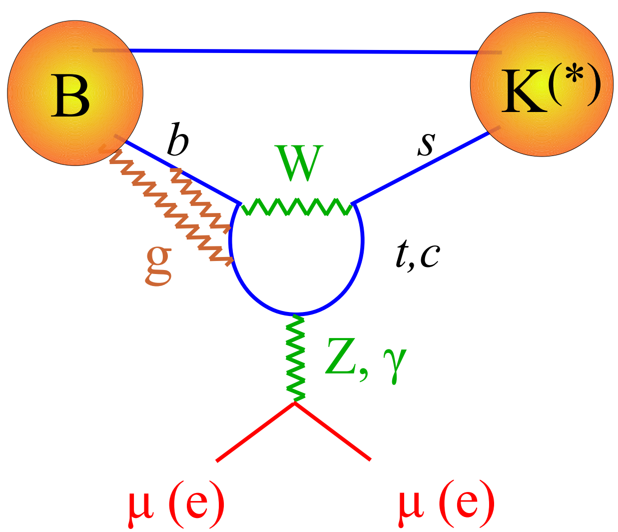
3.1σ from single "clean" observable [R_K]

A closer look to the data

- $b \to s\, l^+ l^-$ (neutral currents)

List of the observables:

- P'_5 anomaly [$B \to K^* \mu\mu$ angular distribution]
- Smallness of all $B \to H_s\, \mu\mu$ rates [H_s=K, K^*, ϕ (from B_s)]
- LFU ratios (μ vs. e) in $B \to K^* \ell\ell$ & $B \to K\, \ell\ell$
- Smallness of BR($B_s \to \mu\mu$)



Some of these observables are affected by irreducible theory errors (*form factors + long-distance contributions*)

The new result strength the overall consistency of the picture: all data coherently point to well-defined non-SM contributions of short-distance origin.

A closer look to the data

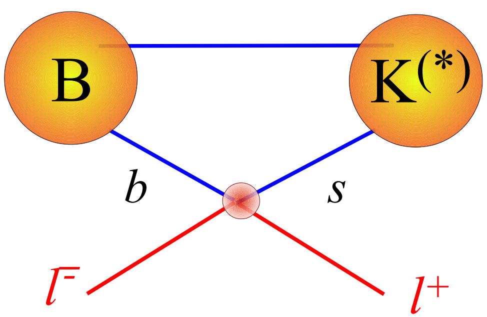
To describe b → s*ll* decays we
- build an EFT Lagrangian
- evolve it down to $\mu \sim m_b$
- evaluate hadronic matrix elements

$$\mathcal{L}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \sum_i \mathcal{C}_i \mathcal{O}_i$$

FCNC operators:

$$\mathcal{O}_{10}^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_{9}^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

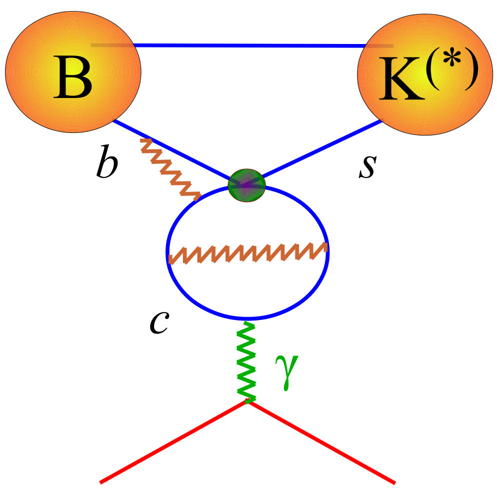


easy & "clean"

Four-quark operators:

$$\mathcal{O}_2 = (\bar{s}_L \gamma_\mu b_L)(\bar{c}_L \gamma_\mu c_L)$$

$$\vdots$$



difficult & "dirty"

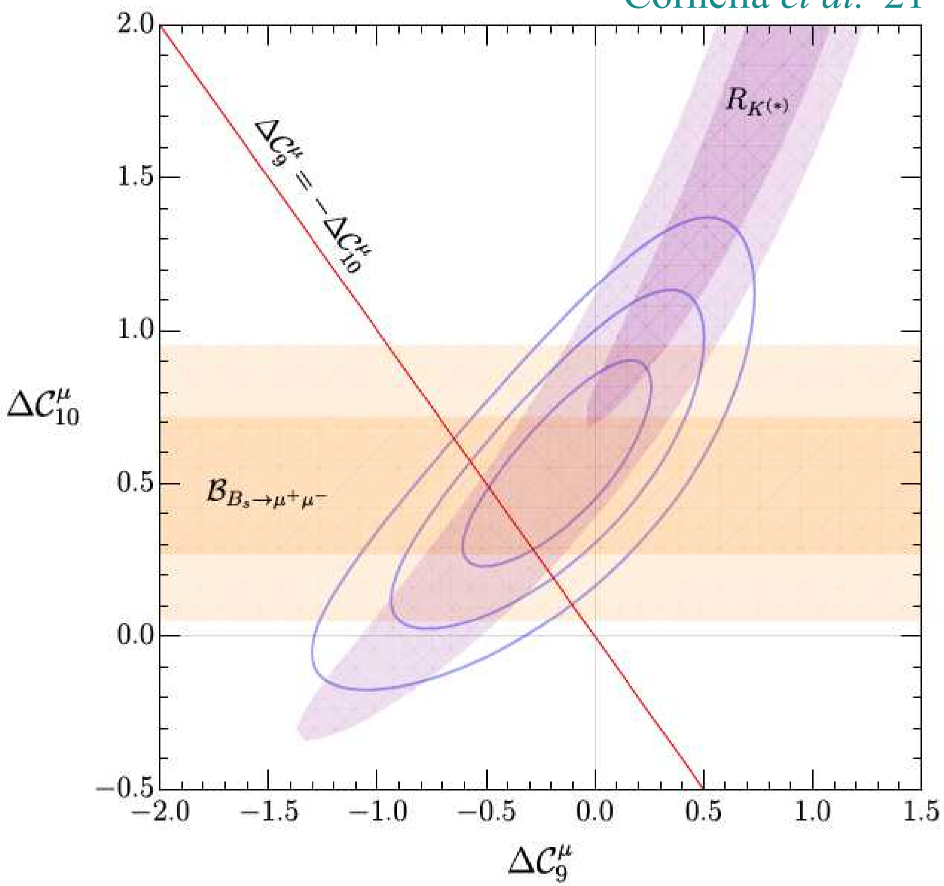
↓

induces $\Delta C_9^{\rm Univ}$

N.B.: long-distance effect cannot induce LFU breaking terms (→ LFU ratios *"clean"*) and cannot induce axial-current contributions (→ $B_s \to \mu\mu$ *"clean"*)

A closer look to the data

Cornella *et al.* '21



Conservative fit using "clean obs." only [$\Delta C_i^\mu = C_i^\mu - C_i^e$]:

4.6σ significance of NP hypothesis $\Delta C_9^\mu = -\Delta C_{10}^\mu$ vs. SM

LFU ratios:

$$R_H = \frac{\int d\Gamma(B \to H\,\mu\mu)}{\int d\Gamma(B \to H\,ee)} \quad (H = K, K^*)$$

LHCb '14 - '21

$B_s \to \mu\mu$:

$$BR(B_s \to \mu\mu)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$

Beneke *et al.* '19

$$BR(B_s \to \mu\mu)_{exp} = (2.85 \pm 0.32) \times 10^{-9}$$

ATLAS+CMS+LHCb '21

▶ A closer look to the data

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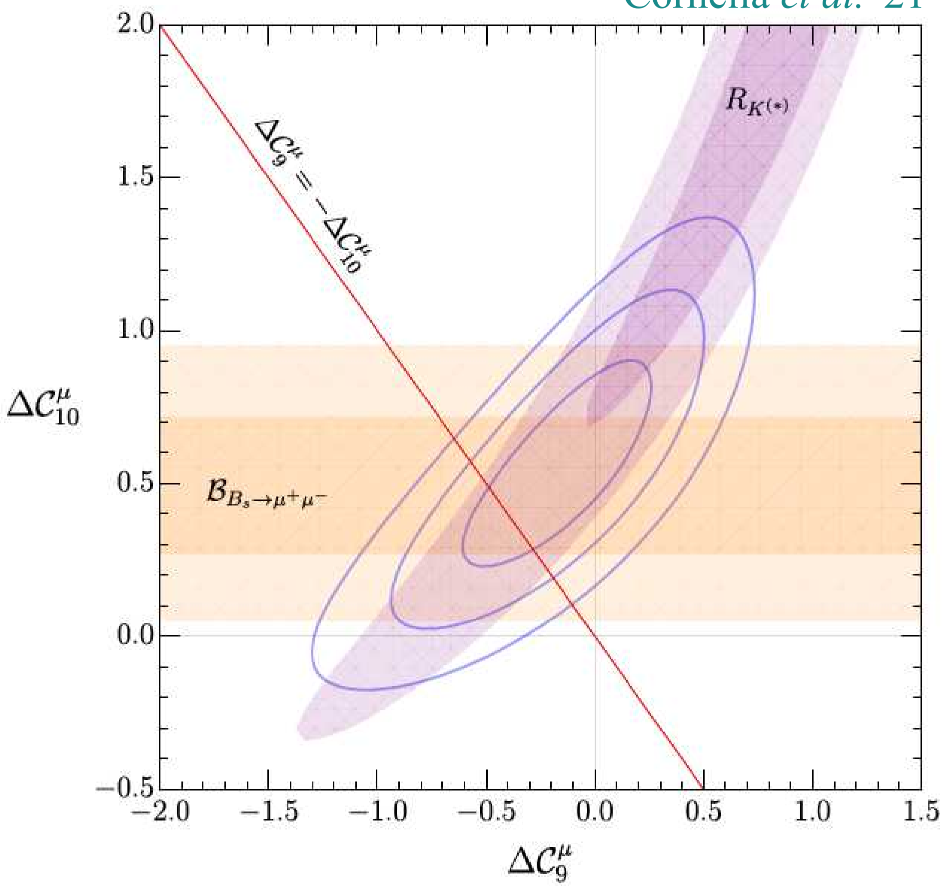

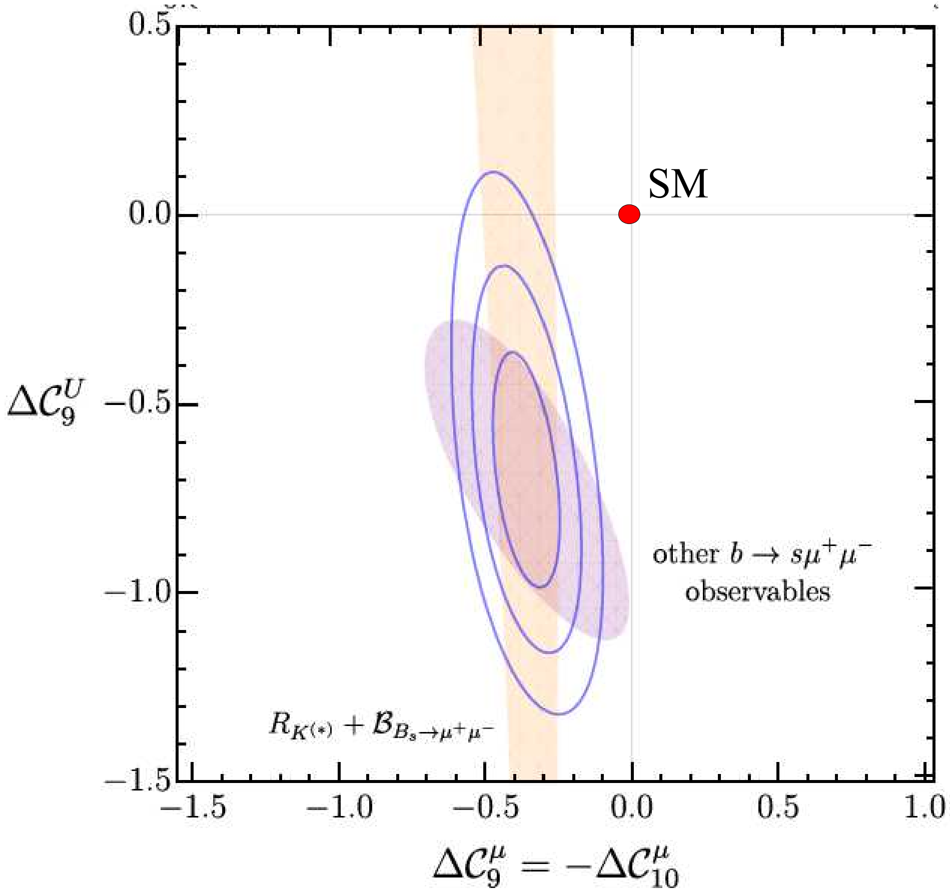

Conservative fit using "clean obs." only [$\Delta C_i^\mu = C_i^\mu - C_i^e$]:

4.6σ significance of NP hypothesis $\Delta C_9^\mu = -\Delta C_{10}^\mu$ vs. SM

> 5σ with current best estimate of charm contrib.

Alguero *et al.* '19
Ciuchini *et al.* '20
Li-Sheng Geng *et al.* '21
Altmanshofer & Stangl '21

A closer look to the data

The "nσ" quoted by various th. groups (global fits) holds for specific NP hypotheses, motivated, but made *a posteriori* (*after looking at the data*) → *local significance* [*like resonance peak in a specific point of a given spectrum*]

The arguments (*of the non-believers...*) against combining data:

- Even concentrating only on the clean observables, or even only in the LFU ratios, there can be different correlations depending on the underlying NP → you must explore all possible NP directions → Look Elsewhere Effect (LEE)

- The choice of the operator basis is arbitrary: how can the significance depend on the basis choice?

- You cannot do cherry-picking in selecting the observables and only few exhibit deviations → small significance once you include them al

⬇

We need to provide a solid estimate of the *global significance*

A closer look to the data

The "nσ" quoted by various th. groups (global fits) holds for specific NP hypotheses, motivated, but made *a posteriori* (*after looking at the data*) → *local significance*

The *global significance* of observing any form of heavy new physics in $b \to sll$ can be estimated via the following procedure

- Employ the most general eff. Lagrangian for $b \to sll$ [*full basis with 9* C_i^{NP}]
- Consider all the observables O_i with good sensitivity to (*at least some of*) the C_i^{NP} [*taking into account conservative th. errors* → $d\Gamma/dq^2$ *not good because of charm loops*]
- Generate pseudo-data to evaluate the O_i [*assuming SM theory & exp. errors*]
- Fit the simulated O_i with generic C_i^{NP} → $\Delta\chi^2$ distribution of the pseudo-data
- Evaluate probability $P(\Delta\chi^2 > \Delta\chi^2_{obs})$

↑ *probability that data randomly align to one of the possible NP directions*

Lancierini, GI, Owen, Serra, '21

▶ *A closer look to the data*

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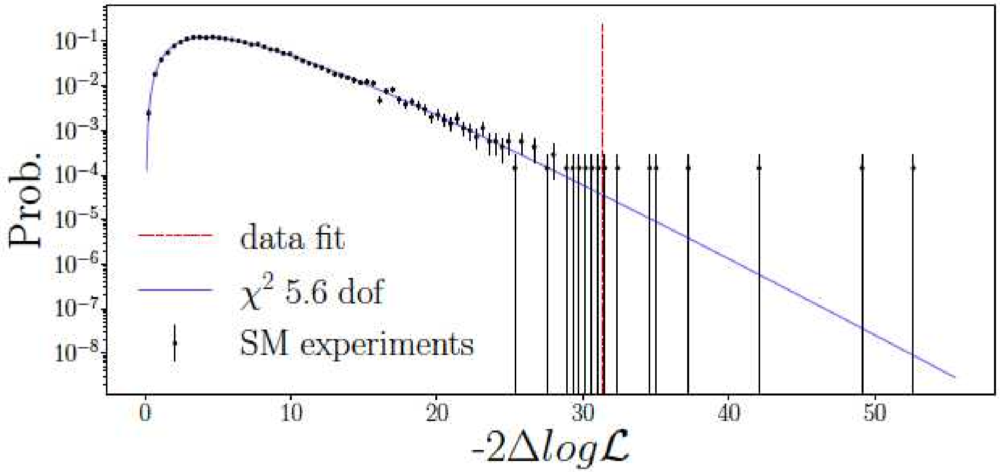
3.9σ *global significance* with respect to any form of heavy NP

Lancierini, GI, Owen, Serra, '21

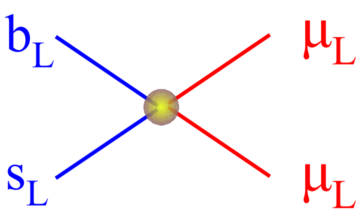


Remarkably high !
[*despite being very conservative*]

A closer look to the data

Coming back to the theory interpretation (→ *th. motivated fits are essential* !)
Data point to (short-distance) NP effects in operators of the type

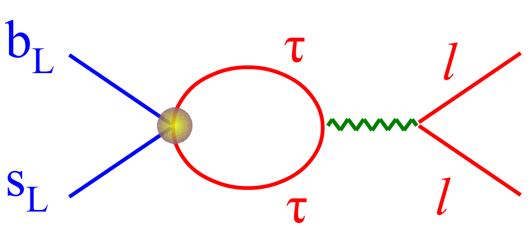
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j) = \frac{1}{2}\left[\mathcal{O}_{\ell q}^{(1)} + \mathcal{O}_{\ell q}^{(3)}\right]^{ij\alpha\beta}$$



$\sim 2\times10^{-5}\, G_{Fermi}$

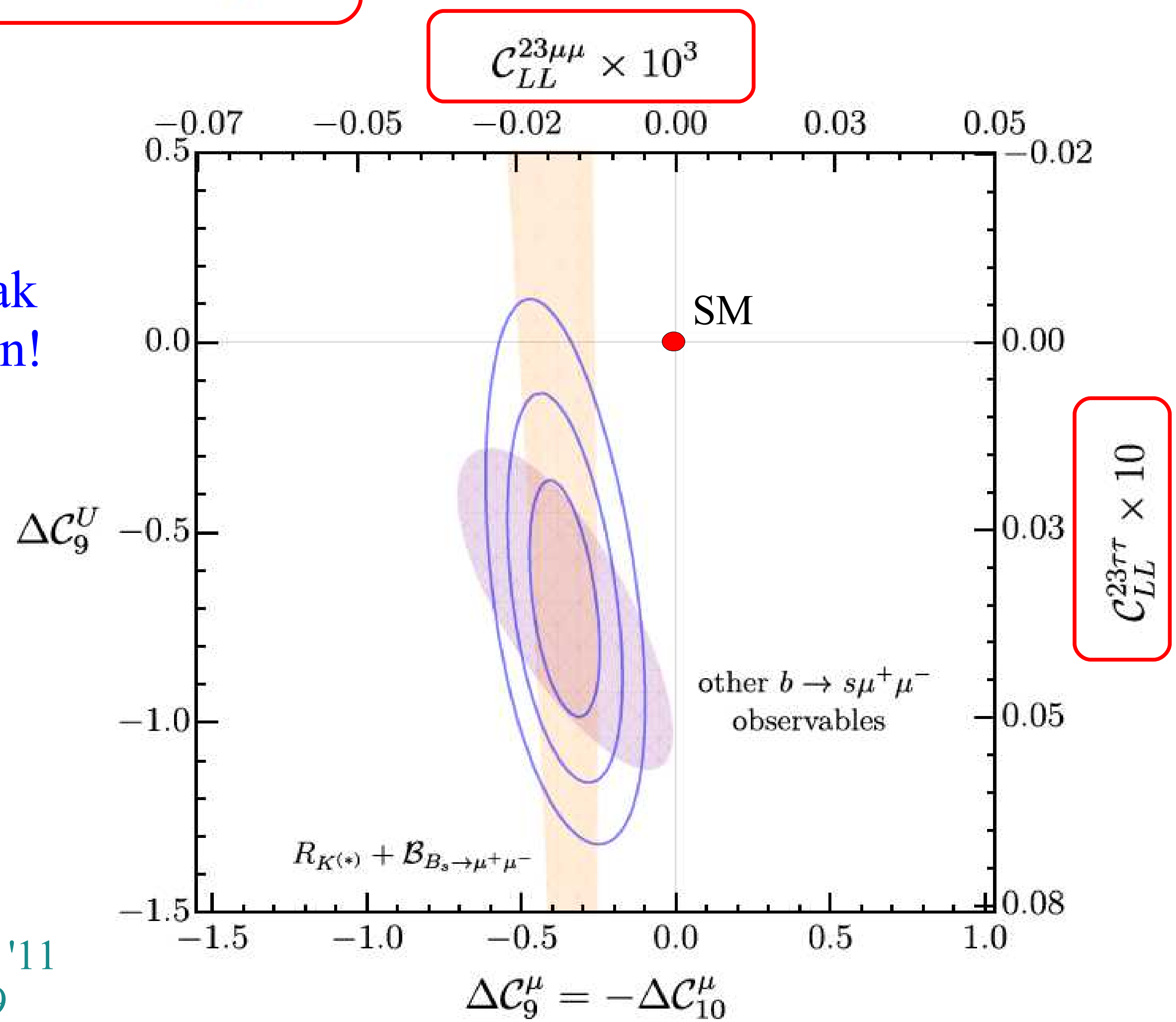
super-weak interaction!

$C_{LL}^{23\mu\mu}$ ➜ $\Delta C_9^\mu = -\Delta C_{10}^\mu$



$C_{LL}^{23\tau\tau}$ ➜ ΔC_9^{Univ}

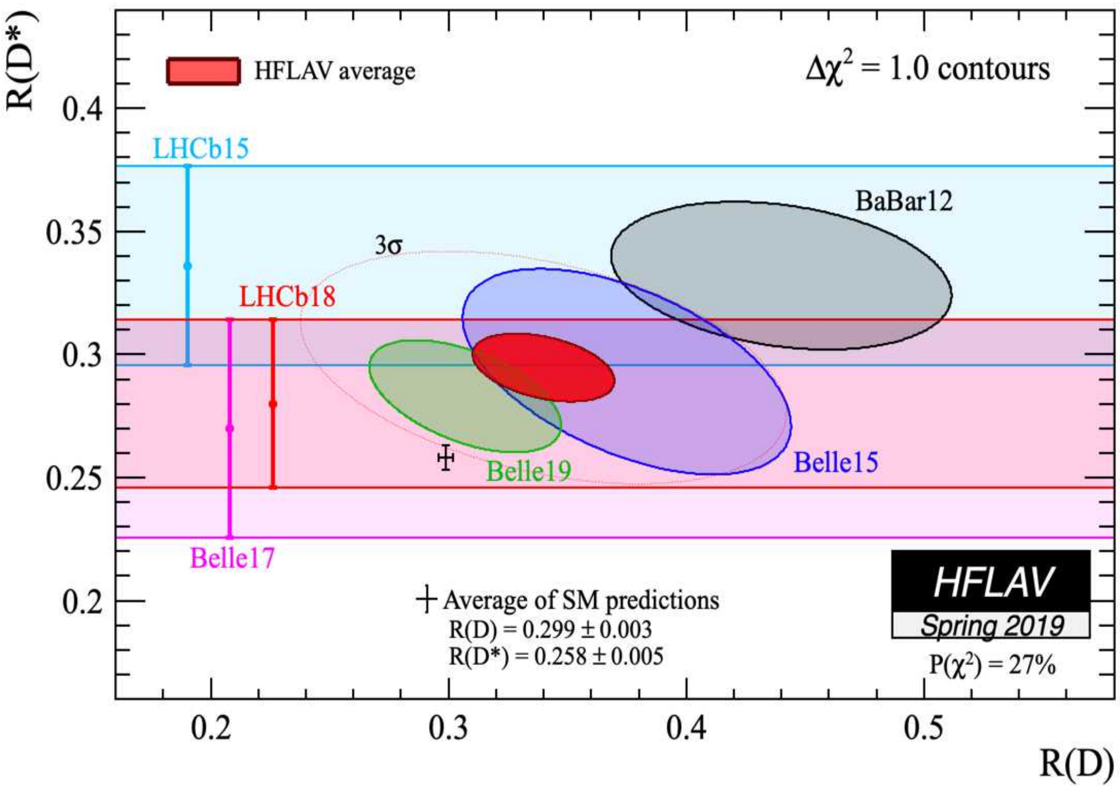
Bobeth & Haisch '11
Crivellin et al. '19

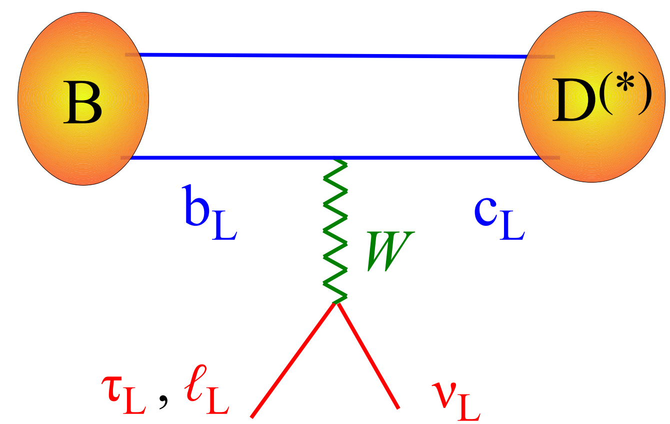


A closer look to the data

- b → c *lν* (charged currents): τ vs. light leptons (μ, e)

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})} \qquad X = \text{D or D}^*$$



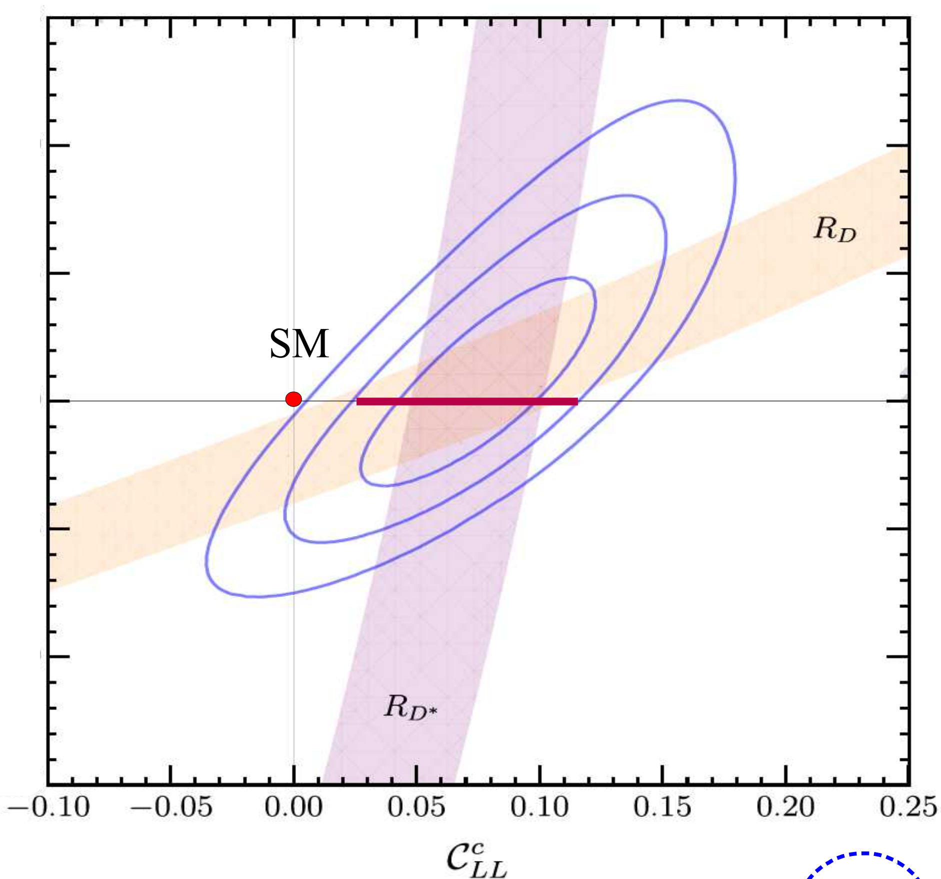


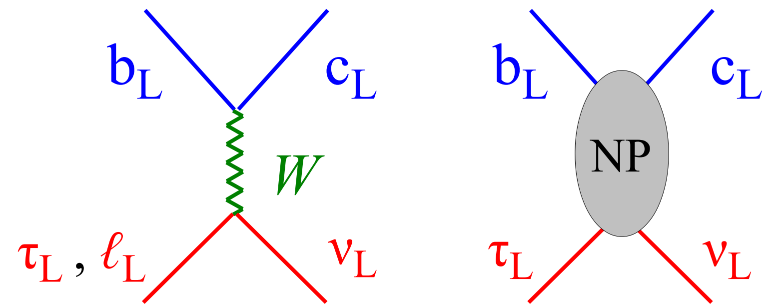
- Consistent results by three different exps. ~ 3.1σ excess over SM (*D and D* combined*)
- SM predictions quite "clean": hadronic uncertainties cancel (*to large extent*) in the ratios

A closer look to the data

• b → c $l\nu$ (charged currents): τ vs. light leptons (μ, e)

Cornella *et al.* '21





Data consistent with a universal enhancement (10-20%) of τ modes

$$\frac{V_{cb}\,\mathcal{C}^{33\tau\tau}_{LL} + V_{cs}\,\mathcal{C}^{23\tau\tau}_{LL}}{V_{cb}}$$

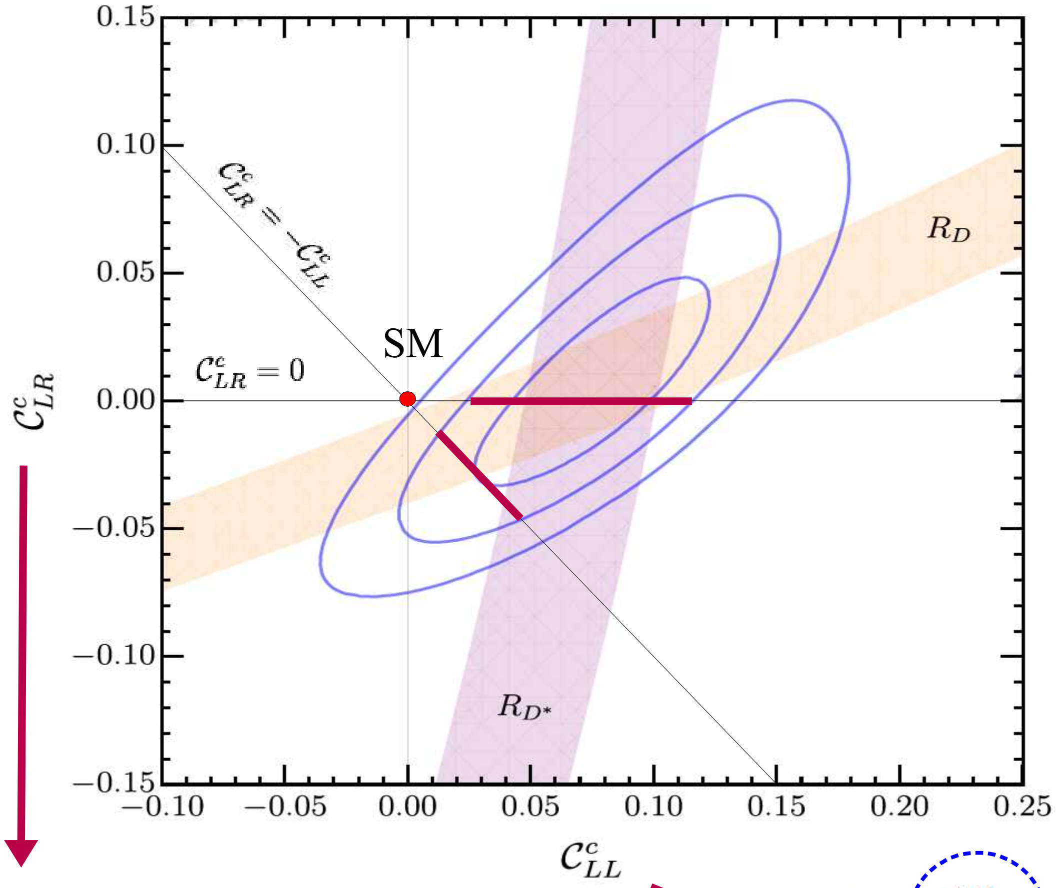
Same operator contributing to b → s ll

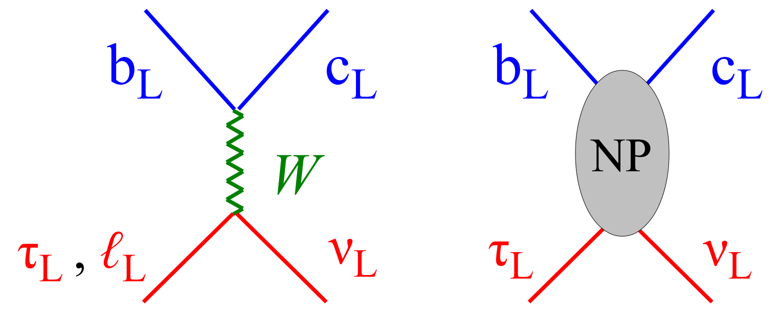
all 3rd gen. (contribute via CKM rotation)

A closer look to the data

- b → c *lν* (charged currents): τ vs. light leptons (μ, e)

Cornella *et al.* '21





Data consistent with a universal enhancement (10-20%) of τ modes

But other options (*RH currents*) possible

$(\bar{q}^i_L \gamma_\mu \tau_L)(\bar{\tau}_R \gamma_\mu b_R)$

CKM "weighted mix" as for C^c_{LL}

$$\frac{V_{cb}\,\mathcal{C}^{33\tau\tau}_{LL} + V_{cs}\,\mathcal{C}^{23\tau\tau}_{LL}}{V_{cb}}$$

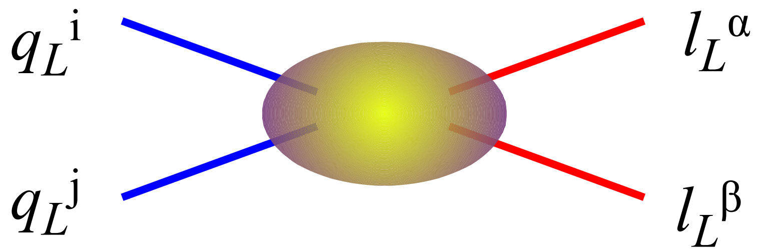
Same operator contributing to b → s *ll*

all 3rd gen. (contribute via CKM rotation)

Hopes I. [*EFT-type considerations*]

EFT considerations

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- We definitely need non-vanishing left-handed current-current operators although other contributions are also possible



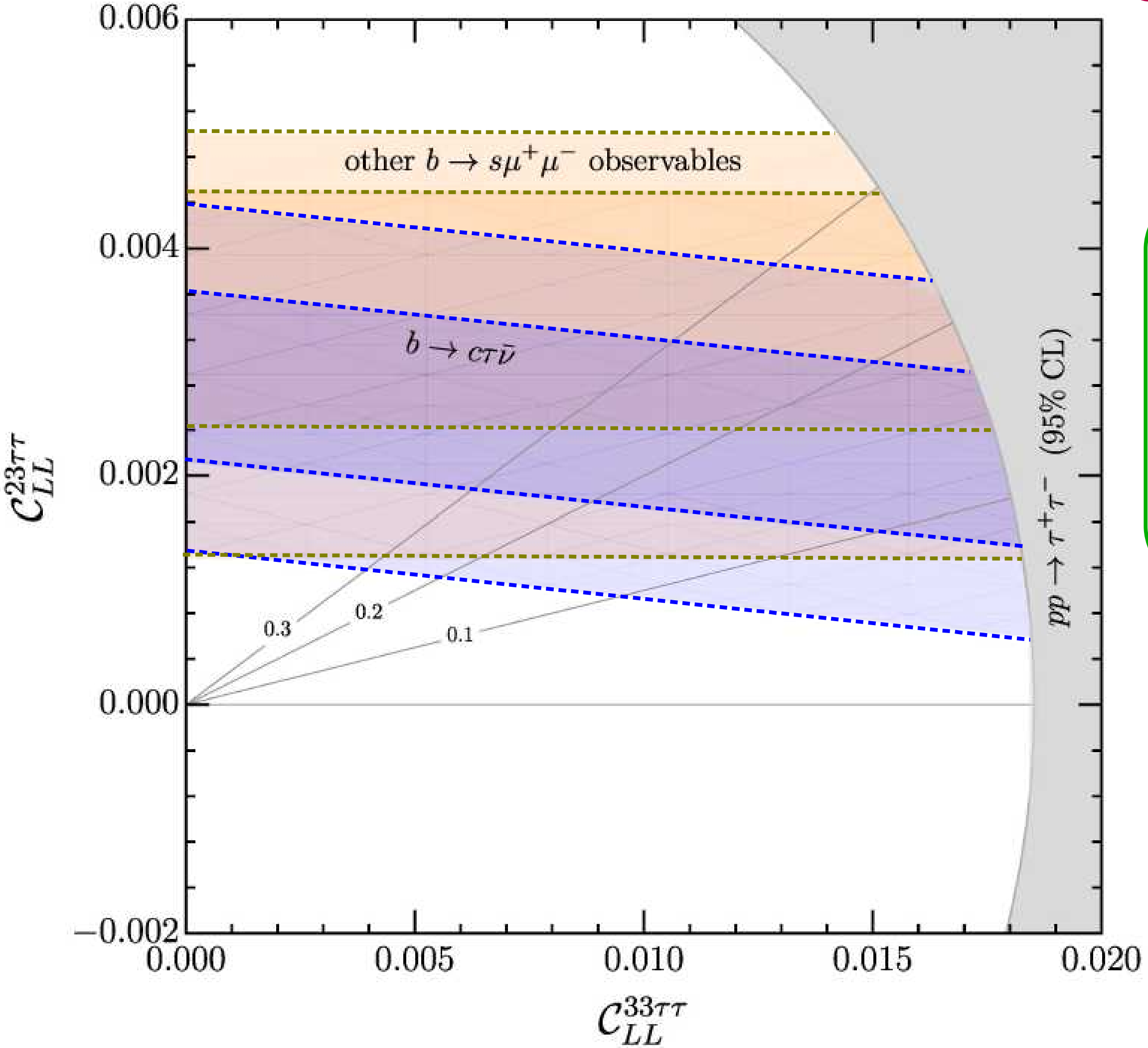
Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

- Large coupling [*competing with SM tree-level*] in $bc \to l_3 \nu_3$ [R_D, R_{D*}]
- Small coupling [*competing with SM loop-level*] in $bs \to l_2\ l_2$ [R_K, R_{K*}, ...]

↓

$$T_{ij\alpha\beta} = (\delta_{i3}\times\delta_{3j})\times(\delta_{\alpha3}\times\delta_{3\beta}) \ +$$ small terms for 2nd (& 1st) generations → *Link to pattern of the Yukawa couplings !*

EFT considerations



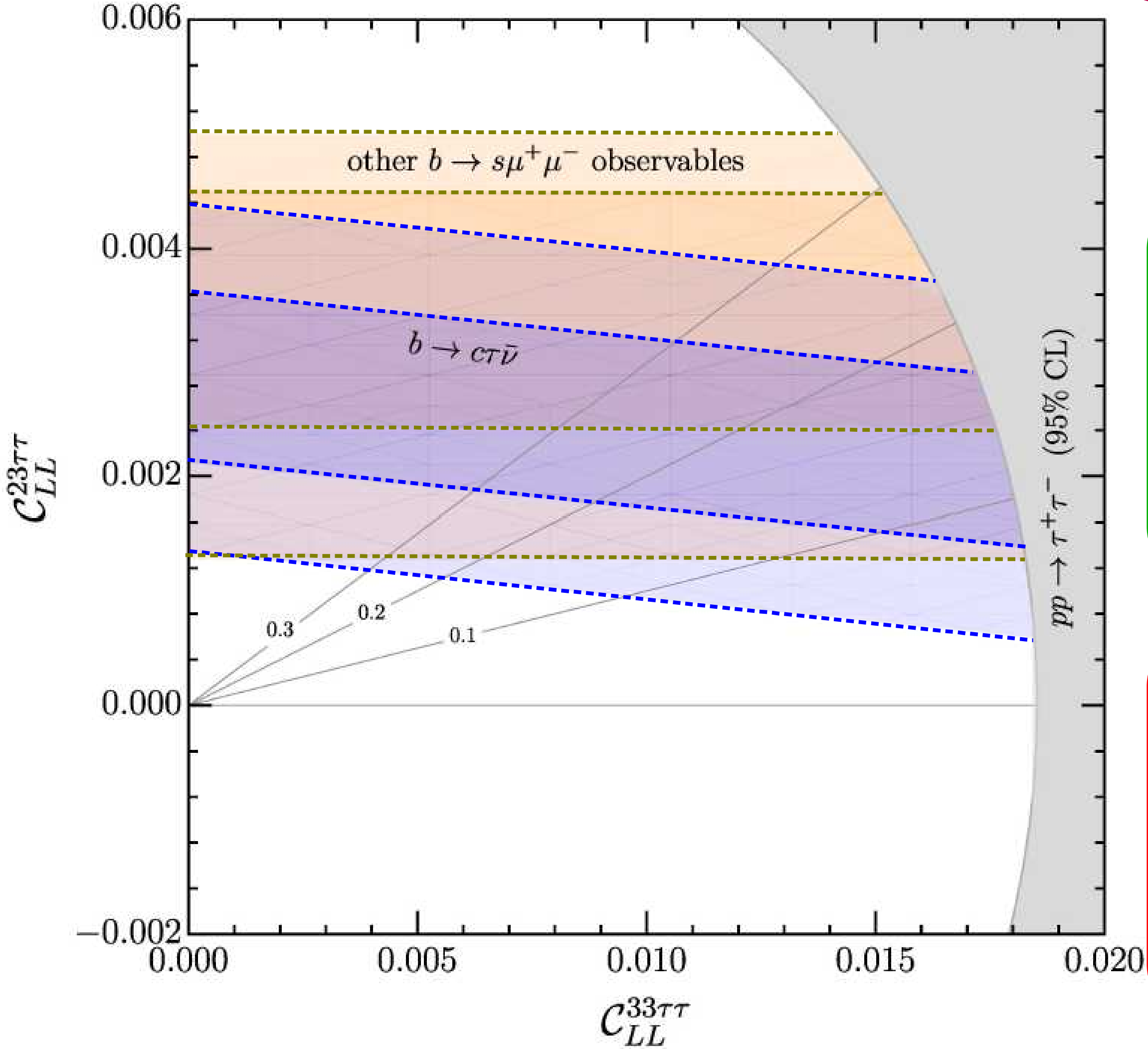
$$(\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j) = \frac{1}{2}\left[\mathcal{O}_{\ell q}^{(1)} + \mathcal{O}_{\ell q}^{(3)}\right]^{ij\alpha\beta}$$

Pattern emerging from data in 2 ↔ 3 sector:

- ~ 10^{-1} for each 2nd gen. q_L or l_L
  - → $|C^{23\mu\mu}| \sim 10^{-3}\,|C^{33\tau\tau}|$
  - → $|V_{ts}| \sim 0.4\times10^{-1}$
- Nice consistency among the two sets of anomalies

▶ *EFT considerations*

$$(\bar{q}^i_L \gamma_\mu \ell^\alpha_L)(\bar{\ell}^\beta_L \gamma_\mu q^j_L) = \frac{1}{2}\left[\mathcal{O}^{(1)}_{\ell q} + \mathcal{O}^{(3)}_{\ell q}\right]^{ij\alpha\beta}$$



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Additional ~10^{-2} (~loop) suppression for

- ✖ Four-quarks (ΔF=2)
- ✖ Four-leptons (τ→μνν)
- ✖ Semi-leptonic $O^{(1-3)}$ (b→sνν)

EFT considerations

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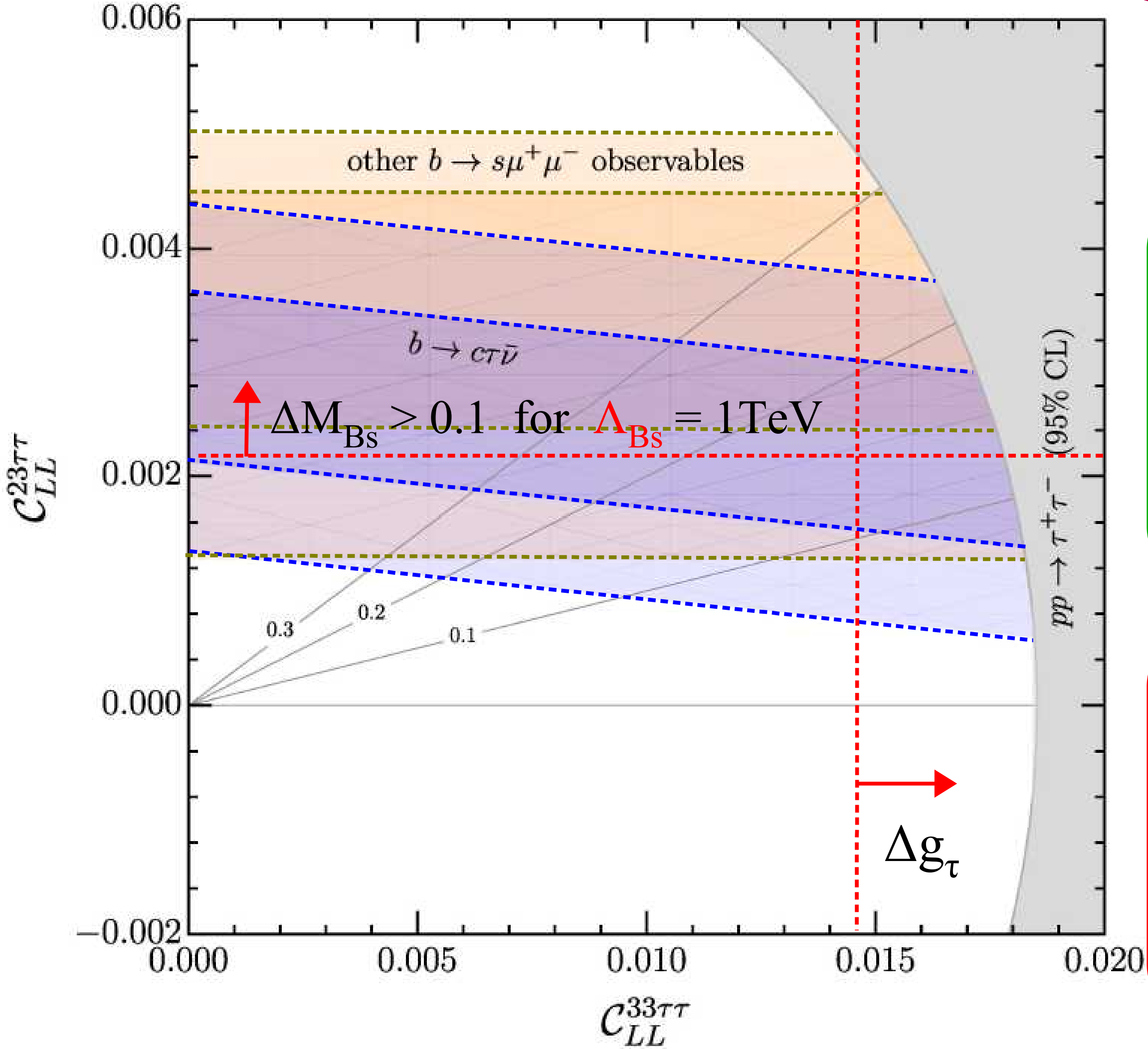

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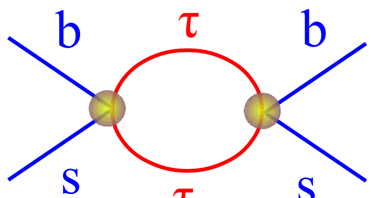
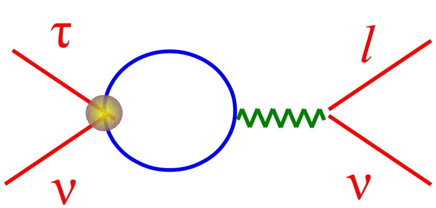


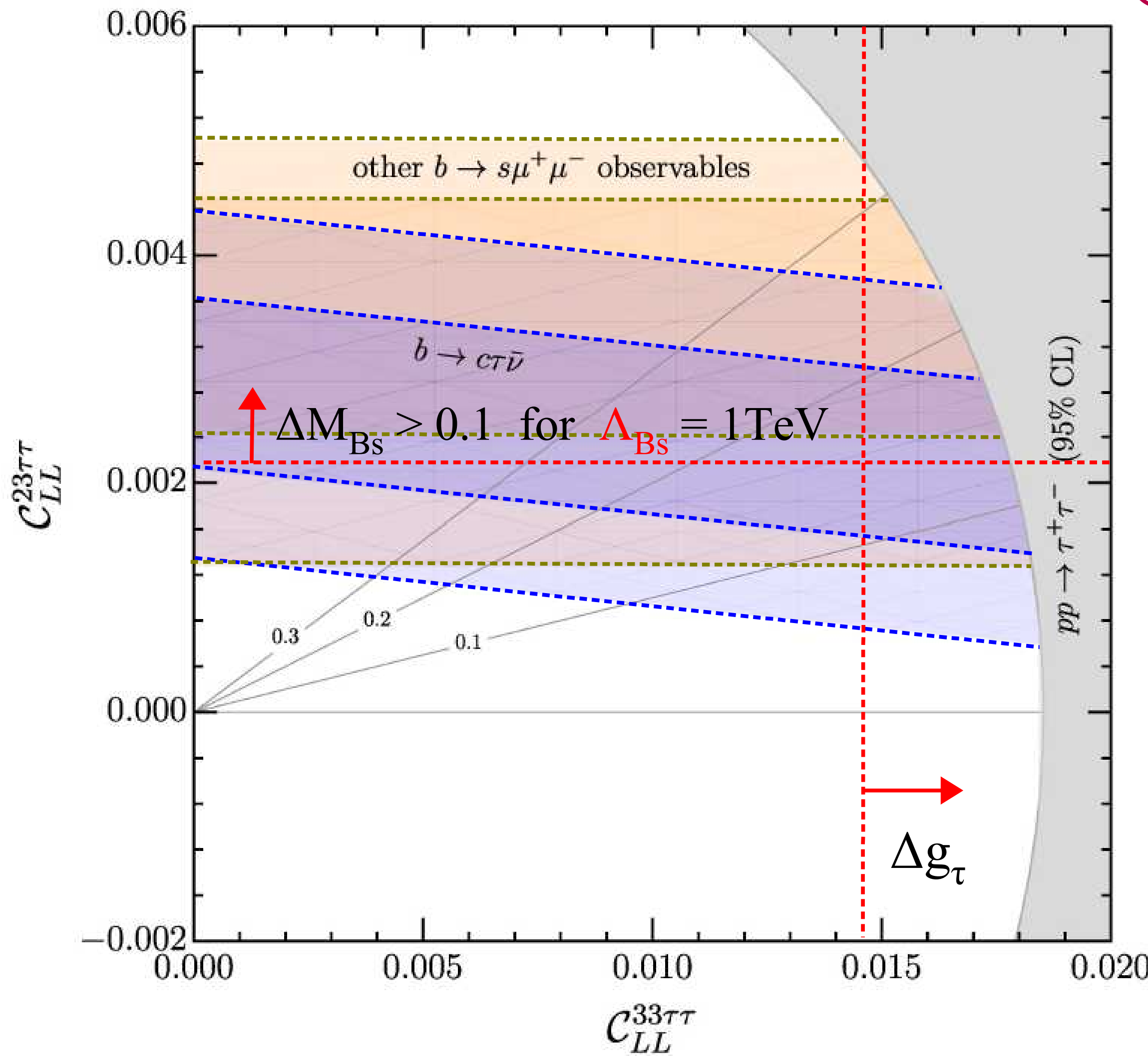
$\Delta M_{Bs} \sim (C^{23\tau\tau})^2\, \Lambda_{Bs}^{\;2}$



$\Delta g_\tau \sim (C^{33\tau\tau})\log(\Lambda/m_t)$

▶ *EFT considerations*

$$(\bar{q}^i_L \gamma_\mu \ell^\alpha_L)(\bar{\ell}^\beta_L \gamma_\mu q^j_L) = \frac{1}{2}\left[\mathcal{O}^{(1)}_{\ell q} + \mathcal{O}^{(3)}_{\ell q}\right]^{ij\alpha\beta}$$



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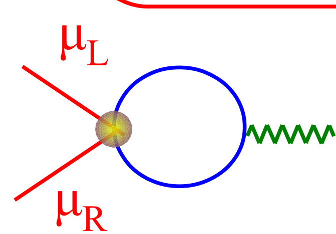
N.B.: with this sets of operators → tiny contribution to $a_\mu = (g-2)_\mu/2$



$\Delta a_\mu << a_\mu^{SM-EW}$

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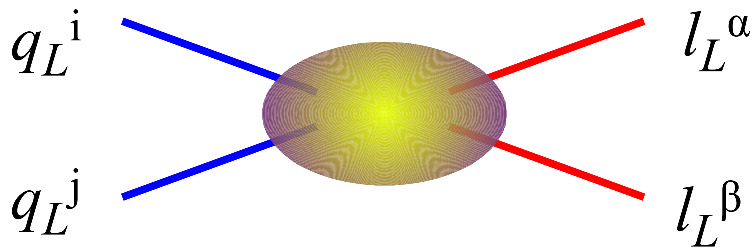


Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

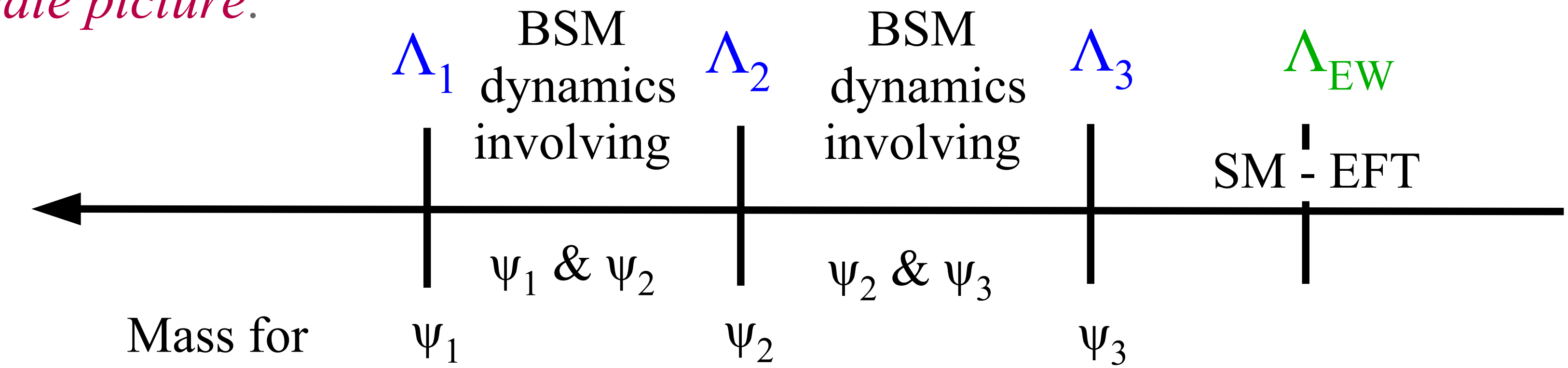
Non-trivial *flavor structure* (↔ *approx. flavor symmetries*) not only to explain the pattern of the anomalies, but also to "protect" against too large effects in other low-energy observables

⬇

New TeV-scale interactions distinguishing the different families

EFT considerations

Possible three-scale picture:



Barbieri '21
Allwicher, GI, Thomsen '20
⋮
Bordone *et al.* '17
Panico & Pomarol '16
⋮
Dvali & Shifman '00

Light families have small masses because they are coupled to heavier states

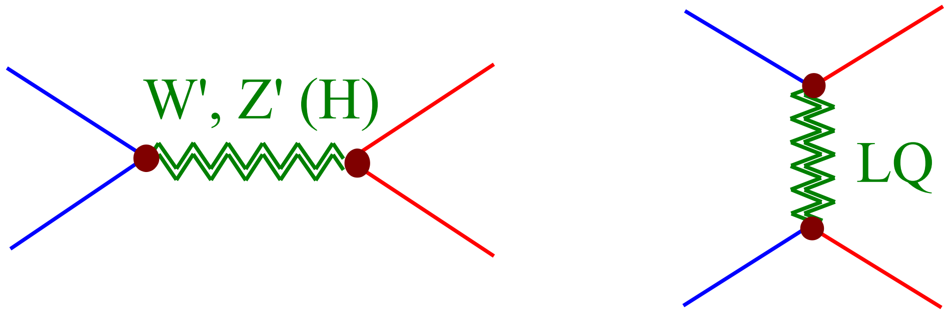
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{Y} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

Non-trivial UV imprints

Hopes II. [*From EFT to simplified models*]

From EFT to simplified models

Which mediators can generate the effective operators required for by the EFT fit?
If we restrict the attention to tree-level mediators, not many possibilities...



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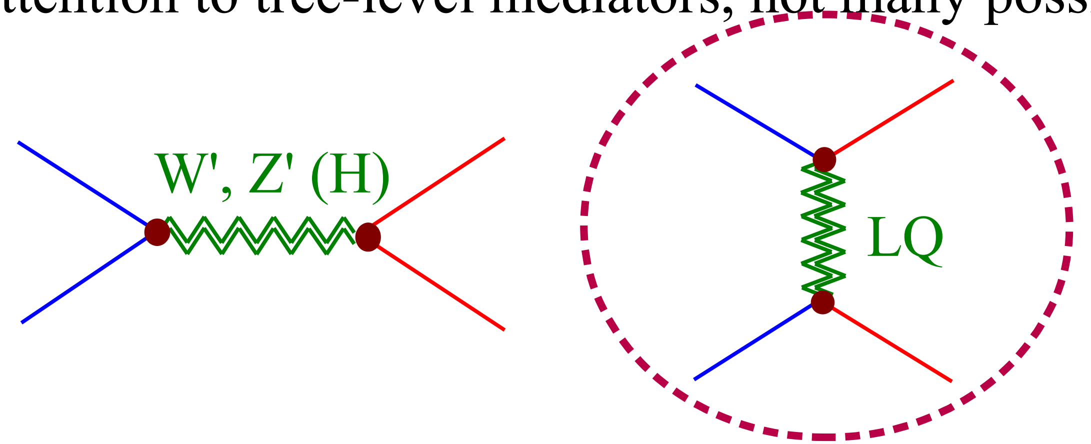
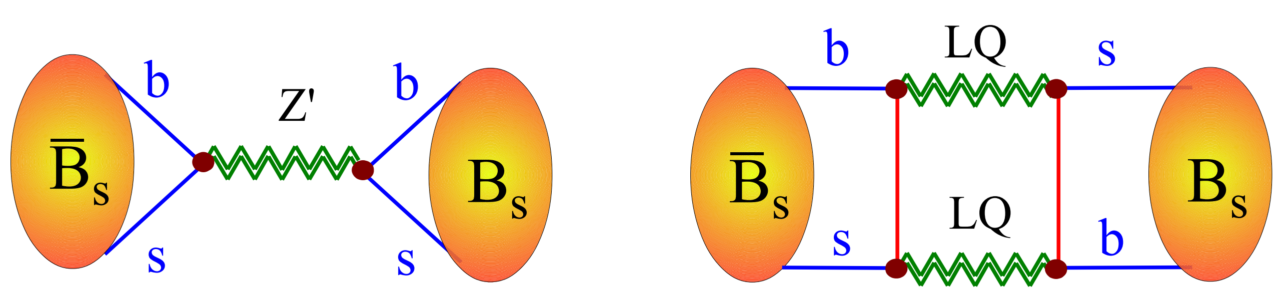


LQ (both scalar and vectors) have two general strong advantages with respect to the other mediators:

I. $\Delta F=2$ & $\tau \to l\nu\nu$



II. Direct searches: 3[rd] gen. LQ are also in better shape as far as direct searches are concerned (*contrary to Z'*...).

From EFT to simplified models

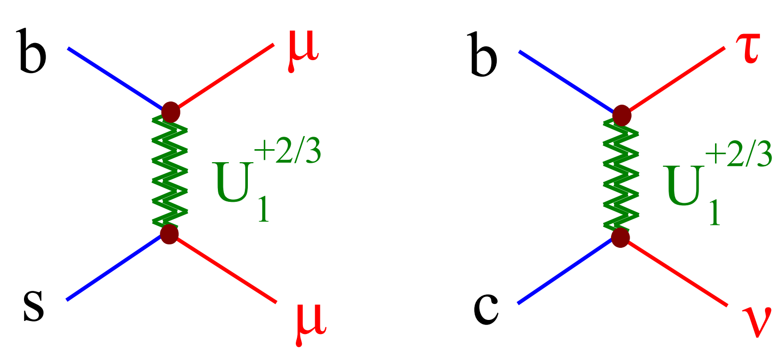
"Renaissance" of LQ models (*to explain the anomalies, but not only...*):

- Scalar LQ as PNG
  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
  Marzocca '18
- Scalar LQ from GUTs & R̸ SUSY
  Hiller & Schmaltz, '14; Becirevic *et al.* '16, Fajfer *et al.* '15-'17; Dorsner *et al.* '17; Crivellin *et al.* '17; Altmannshofer *et al.* '17 Trifinopoulos '18, Becirevic *et al.* '18 + ...
- Vector LQ in GUT gauge models
  Assad *et al.* '17
  Di Luzio *et al.* '17
  Bordone et *al.* '17
  Heeck & Teresi '18
  + ...
- Vector LQ as techni-fermion resonances
  Barbieri *et al.* '15; Buttazzo *et al.* '16, Barbieri, Murphy, Senia, '17
- LQ as Kaluza-Klein excit.
  Megias, Quiros, Salas '17
  Megias, Panico, Pujolas, Quiros '17
  Blanke, Crivellin, '18

Which LQ explains which anomaly?

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3},\mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3},\mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3},\mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3},\mathbf{3})_{-1/3}$	✓	✗	✗
Vector	$U_1 = (\mathbf{3},\mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3},\mathbf{3})_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]



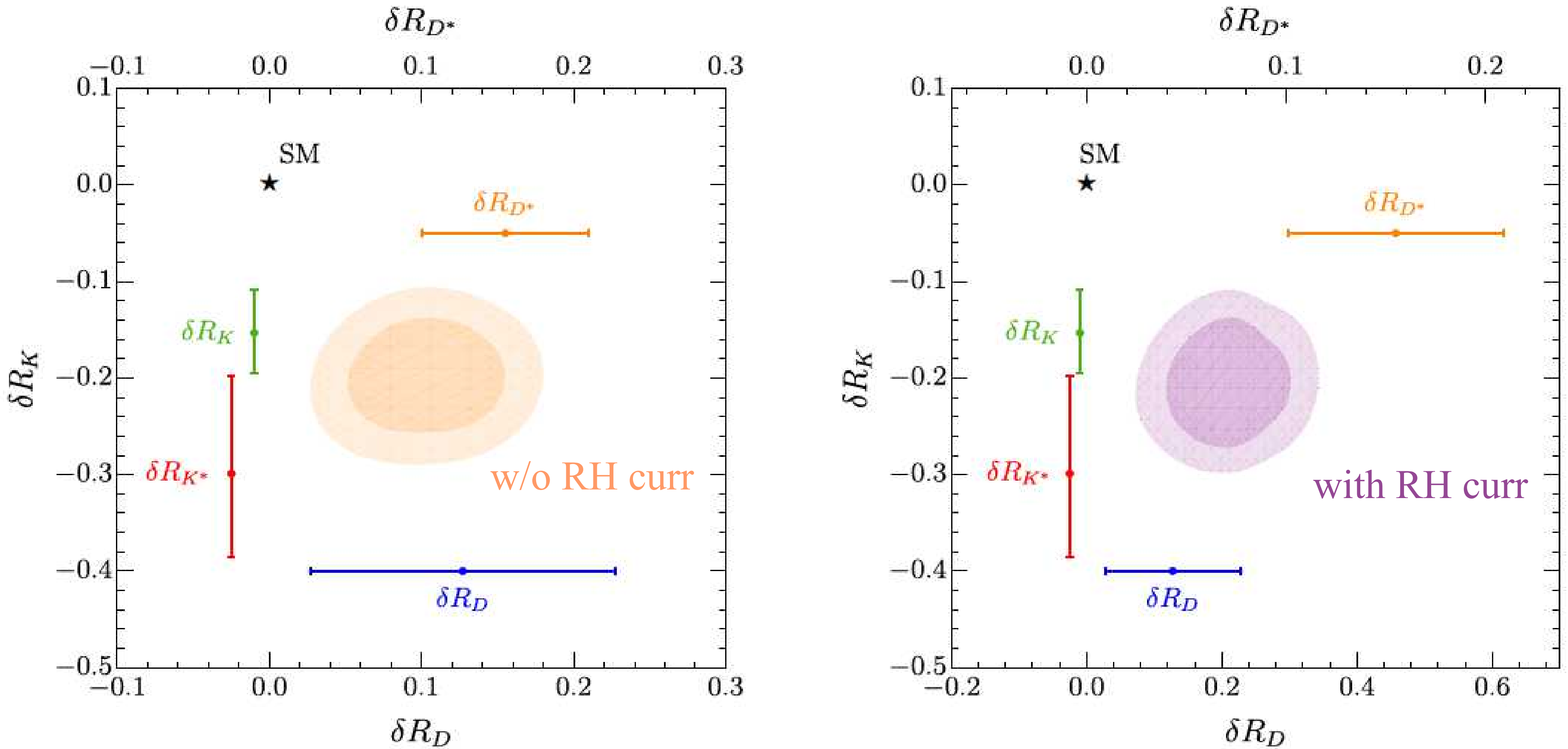
LQ of the Pati-Salam gauge group:
$SU(4)\times SU(2)_L\times SU(2)_R$

From EFT to simplified models

Considering the U_1 only

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) - \beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha) \right] + \text{h.c.}$$

and fitting all low-energy data leads to an excellent description of present data:



▶ *From EFT to simplified models*

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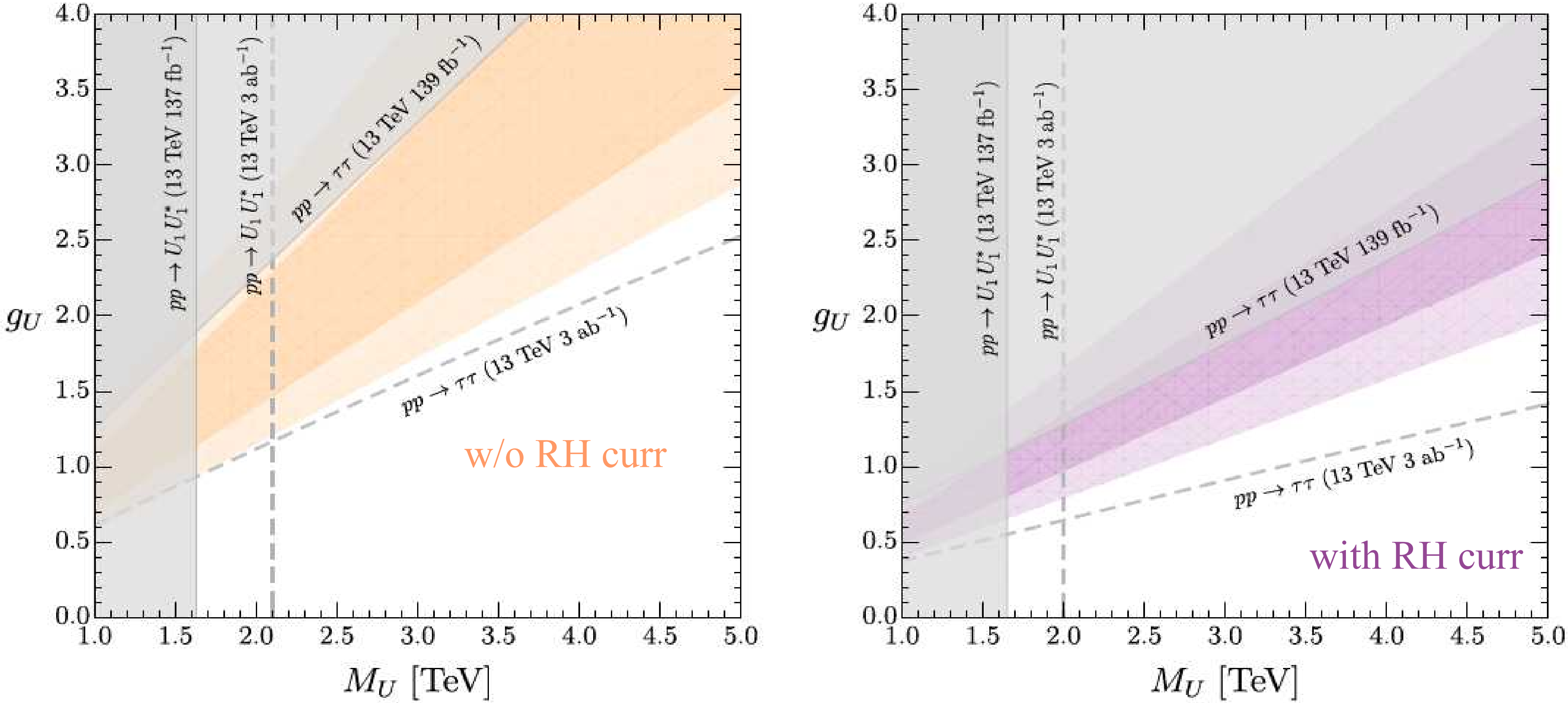
and fitting all low-energy data leads to an excellent description of present data which is fully consistent with high-pT searches [*within the reach of HL-LHC*]:

Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21



From EFT to simplified models

Beside direct searches, an essential role is still played by low-energy observables → many visible BSM effects expected, by consistency, virtually in all models addressing the anomalies

Main message: "super-reach" program for LHCb & Belle-II and other low-energy facilities. This program is essential to confirm/disproof the picture and, if confirmed..., to determine the flavor structure of the new sector.

I. EFT-based (model-independent) correlations on a large class of semi-leptonic processes

[$b \to d\, \mu\mu$, $b \to s\, \tau\tau$, $b \to s\, \tau\mu$, $b \to u\, \tau\nu$, ...]

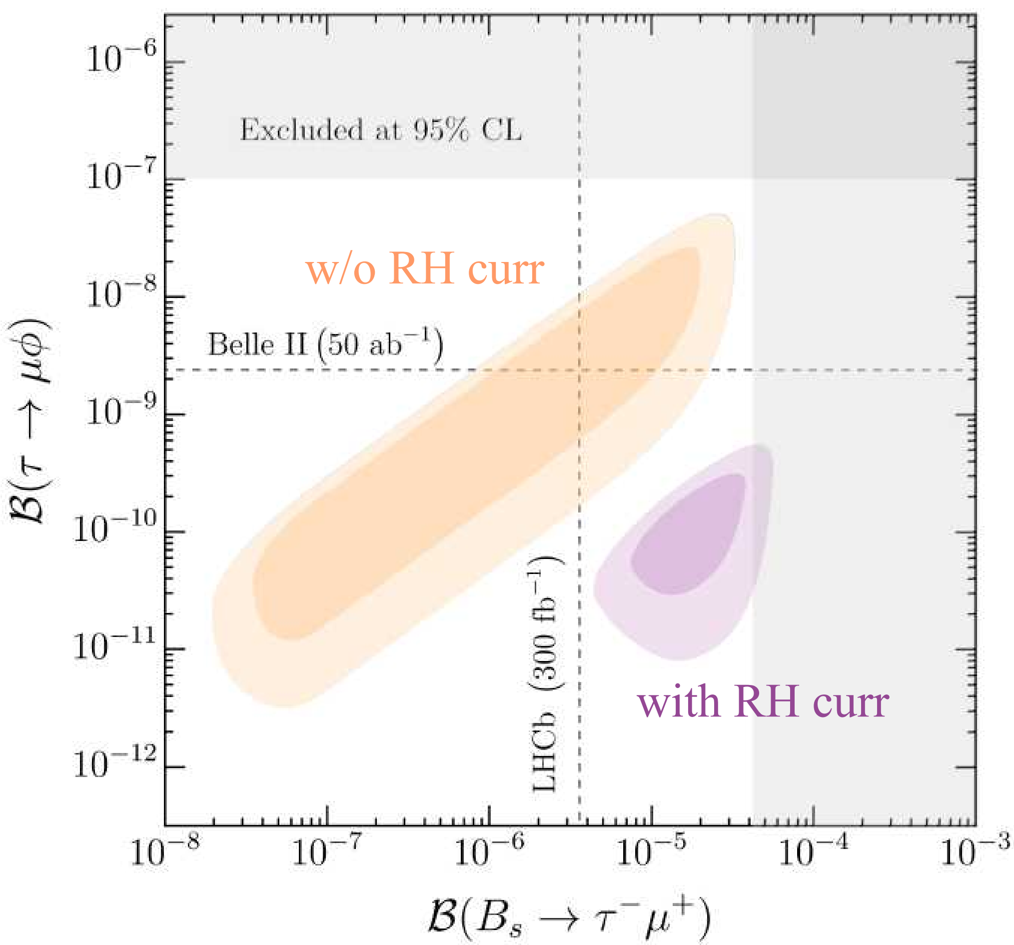
II. Model-dependent correlations for UV-sensitive observables

[$\Delta F=2$, $b \to s\, \nu\nu$, $\tau \to \mu\gamma$, $\tau \to 3\mu$, $\mu N \to e N$, ...]

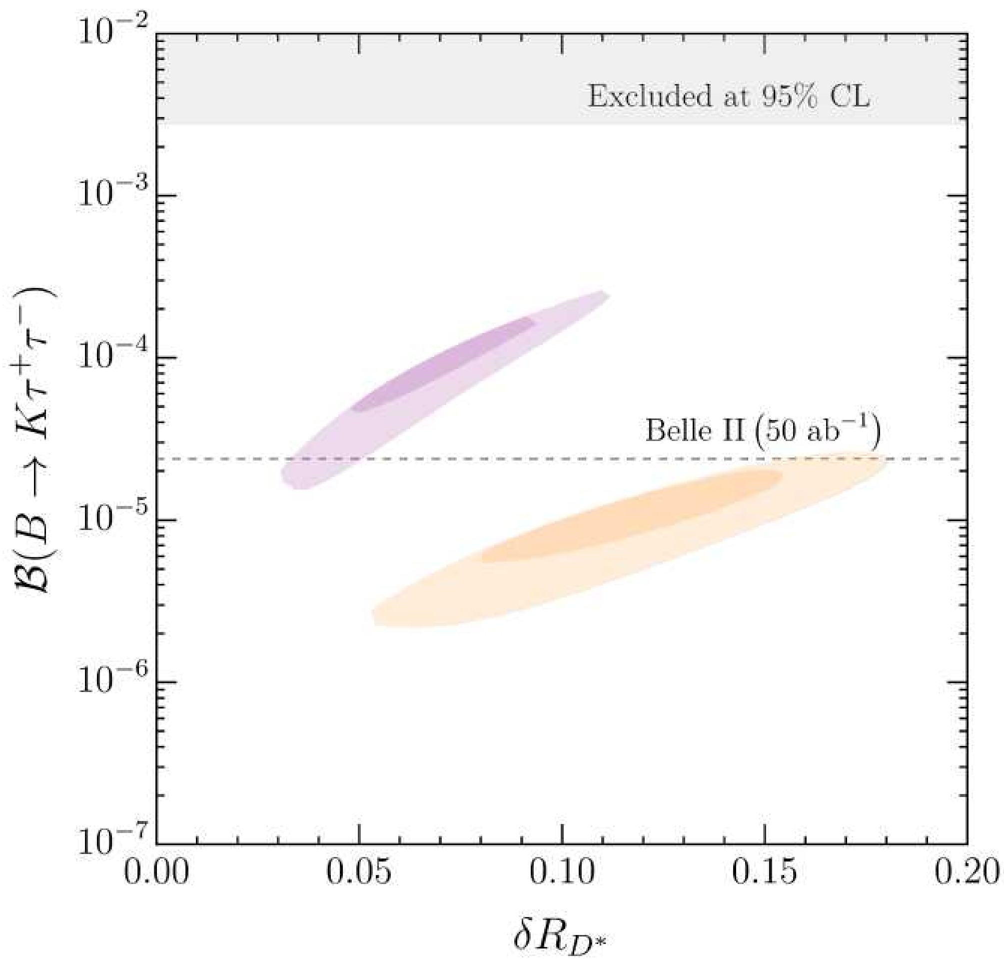
From EFT to simplified models

Examples in class I.

A) LFV in B & τ decays



B) $B \to X\, \tau^+\tau^-$ decays



Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21

Dreams [*speculations on UV completions*]

Speculations on UV completions

First observation: the Pati & Salam group, proposed in the 70's to unify quarks & leptons predicts the only massive LQ that is a good mediator for both anomalies:

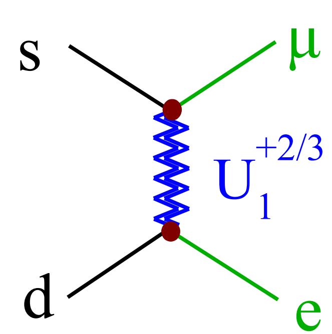
Pati-Salam group: $SU(4)\times SU(2)_L\times SU(2)_R$

Fermions in SU(4): $\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix} \quad \begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$

Main Pati-Salam idea:
Lepton number as "the 4th color"

The massive LQ [U_1] arise from the breaking $SU(4) \to SU(3)_C\times U(1)_{B-L}$

The problem of the "original PS model" are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \to \mu e$]



Attempts to solve this problem simply adding extra fermions or scalars

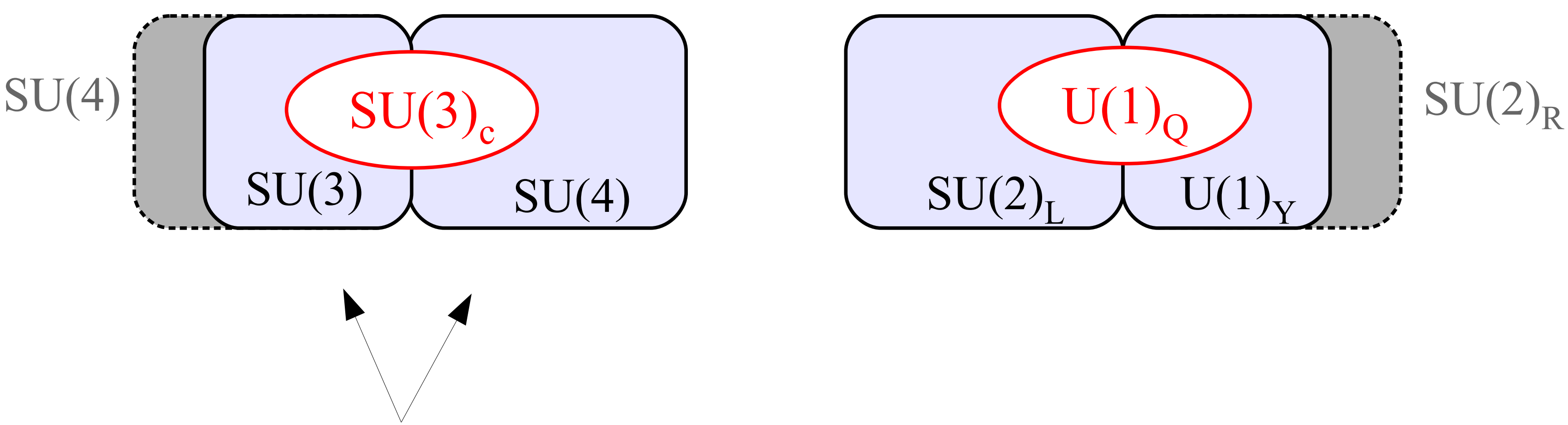
Calibbi, Crivellin, Li, '17;
Fornal, Gadam, Grinstein, '18
Heeck, Teresi, '18

Speculations on UV completions

Second observation: we can "protect" the light families charging under SU(4) only the 3rd gen. or, more generally, "separating" the universal SU(3) component

PS group: $SU(4) \times SU(2)_L \times SU(2)_R$ • *flavor universality*

4321 models: $SU(4) \times SU(3) \times G_{EW} = \begin{cases} SU(2)_L \times SU(2)_R \\ SU(2)_L \times U(1)_Y \end{cases}$



This separation is not flavor blind

Speculations on UV completions

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- *flavor universality*

4321 models: $SU(4)\times SU(3) \times G_{EW} = \begin{cases} SU(2)_L\times SU(2)_R \\ SU(2)_L\times U(1)_Y \end{cases}$

- *Non-universality via mixing*: $SU(4)\times SU(3)$
- *Accidental* U(2)^5 *flavor symm. in the gauge sect.*: $SU(4)_3\times SU(3)_{1,2}$

UV completions

$SU(3)\times G_{EW}\times G_{HC}$
Barbieri, '17

$SU(4)\times SU(3)\times G_{EW}$
Di Luzio, Greljo, Nardecchia, '17

$SU(4)_h\times SU(4)_l\times G_{EW}\times G_{HC}$
Fuentes-Martin & Stangl '20

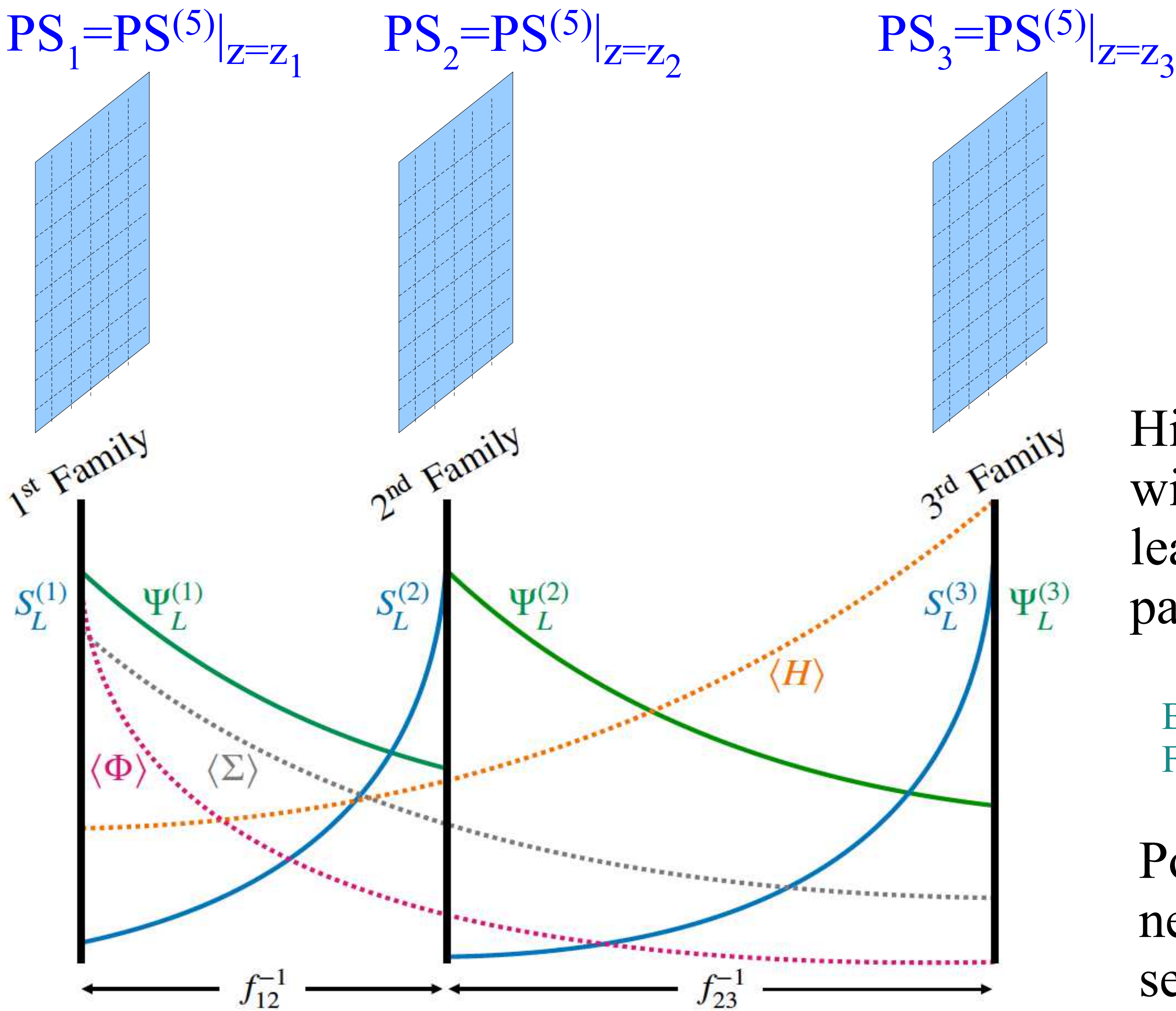
$[PS]^3 = [SU(4)\times G_{EW}]^3$
Bordone *et al.* '17

$[\ PS\ ]_{\text{warped-5d, 3-branes}}$

Fuentes-Martin *et al.* '20 + *work in prog.*

Speculations on UV completions

An ambitious attempt to construct a *full theory of flavor* has been obtained embedding the Pati-Salam gauge group into an extra-dimensional construction:



Flavor ↔ special position (*topological defect*) in an extra (compact) space-like dimension

Dvali & Shifman, '00

Higgs and SU(4)-breaking fields with oppositely-peaked profiles, leading to the desired flavor pattern for masses & anomalies

Bordone, Cornella, Fuentes-Martin, GI '17
Fuentes-Martin, GI, Pages, Stefanek '20

Possible to implement anarchic neutrino masses via an inverse see-saw mechanism

▶ *Speculations on UV completions*

In most *PS-extended models* collider and low-energy pheno are controlled by the effective 4321 gauge group that rules TeV-scale dynamics

Di Luzio, Greljo, Nardecchia, '17

$SU(4)_3 \times SU(3)_{1+2} \times [\, SU(2)_L \times U(1)' \,]$

ψ_3 $\psi_{1,2}$

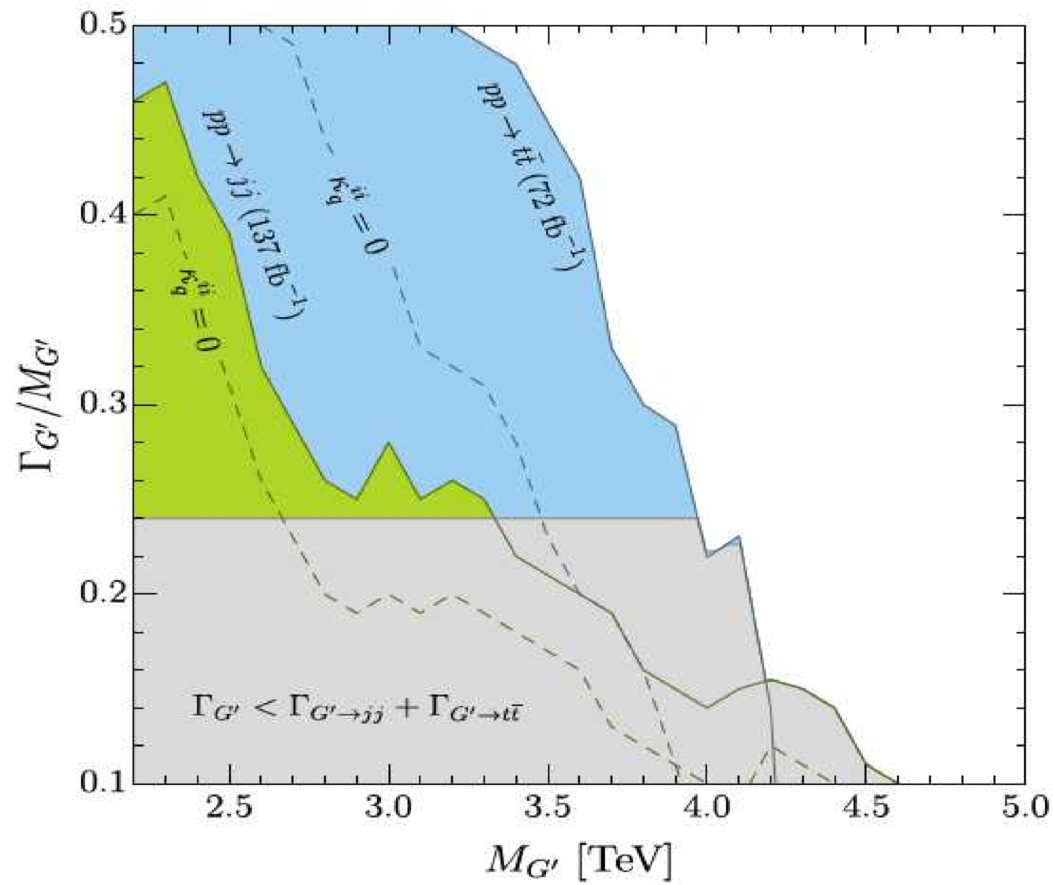
$\downarrow$ $\to$ LQ $[U_1]$ + Z' + G'

SM

Despite the apparent complexity, the construction is highly constrained

- Positive features the EFT reproduced
- Calculability of $\Delta F=2$ processes
- Precise predictions for high-pT data

} *consistent with present data !*

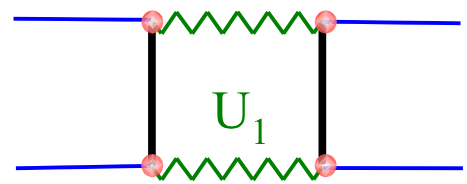


New striking collider signature:
G' ("*coloron*" = *heavy color octet*)

$\to$ strongest constraint on the scale of the model from pp $\to t\,\bar{t}$

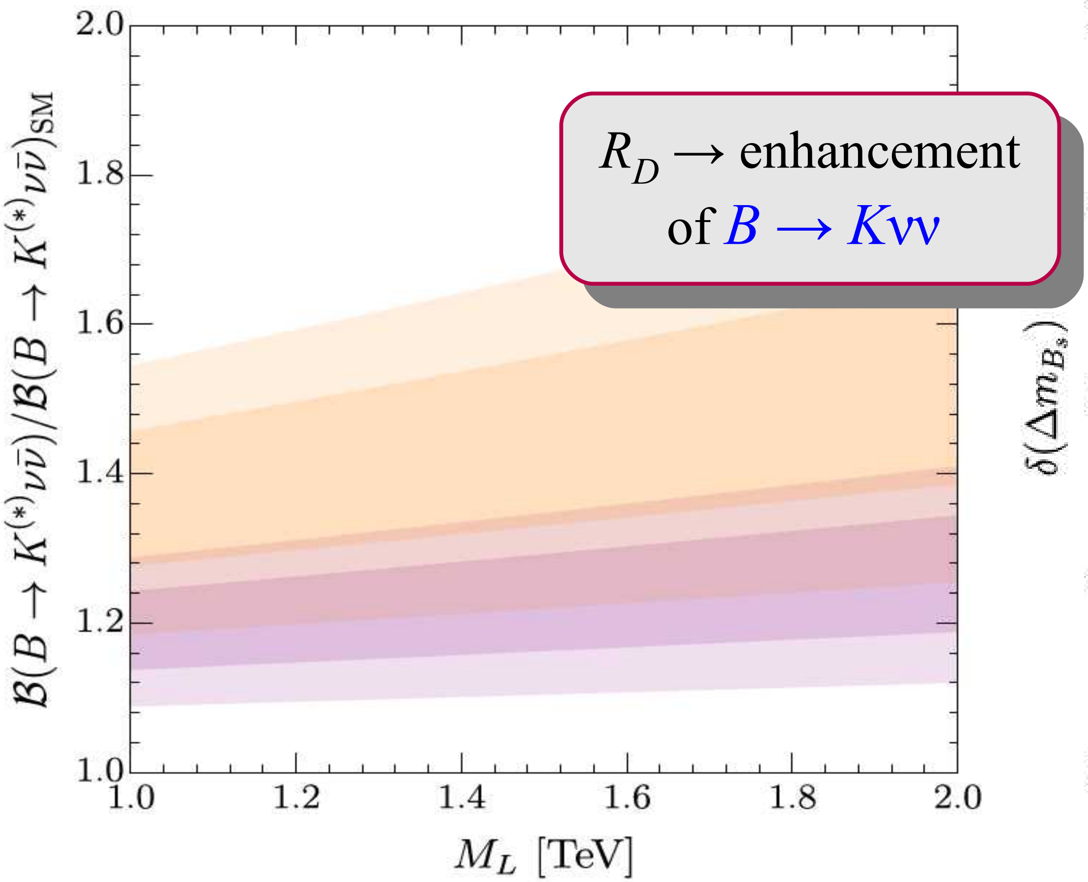
▶ Speculations on UV completions

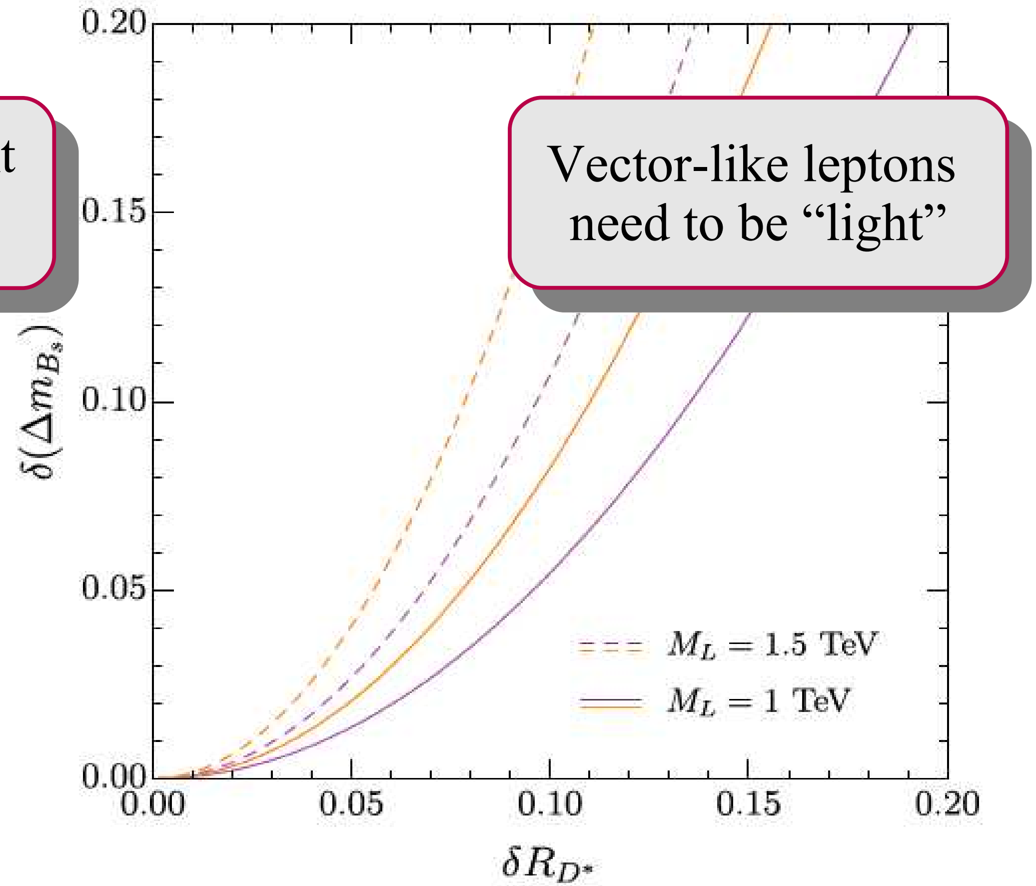
UV-sensitive observables in 4321 models



A) $B \to K\nu\nu$

B) B_s mixing [ΔF=2]





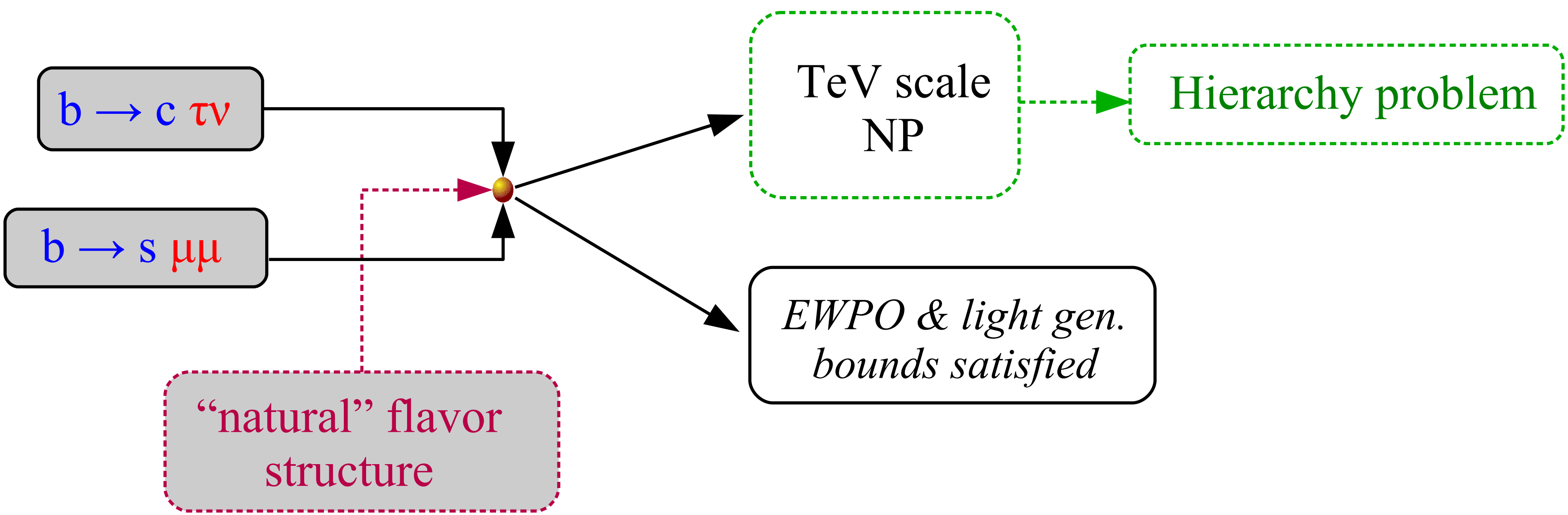
Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21
Fuentes-Martin, GI, Konig, Selimovic, '20

Worries [...]

Worries

There are of course still several worries, and here the personal view becomes even more relevant.... So, let me mention a few of them:

- The $b \to c l\nu$ anomalies are those putting a serious "pressure" on the parameter-space of the model, and their significance is still relatively weak. Why insisting?



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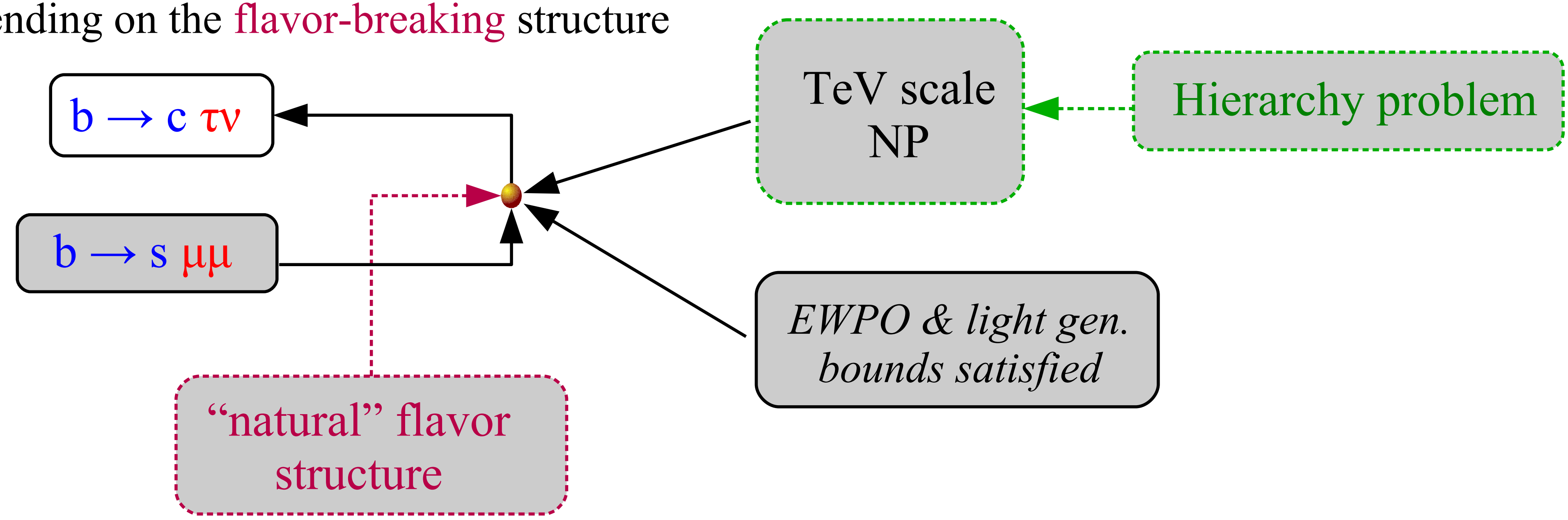
$\Delta R_D \sim (5\% - 30\%)$
depending on the flavor-breaking structure



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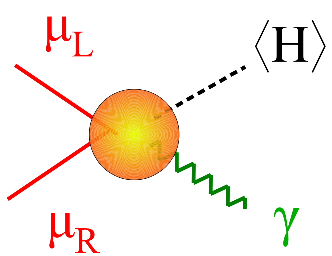
- Not easy to reconcile the $(g-2)_\mu$ anomaly with both flavor anomalies and, more generally, with models with a "natural" flavor structure ($\leftrightarrow Y_{SM}$). Is $(g-2)_\mu$ suggesting something a different way?



Maybe.... examples of recent "attempts":

- $a_\mu \oplus R_K$ with special role of muons [$U(1)_{B-3L_\mu} \subset G$] Greljo, Stangl, Thomsen '21
- $a_\mu \oplus R_K \oplus R_D$ with 2 scalars [$S_1+\phi^+$] and peculiar flavor struct. Marzocca, Trifinopoulos '21

But... $(g-2)_\mu$ is more "flexible" (*no generation change, necessary loop-level*)
→ could come from light NP: no obvious connection to the flavor anomalies

Worries

There are of course still several worries, and here the personal view becomes even more relevant.... So, let me mention a few of them:

- The UV models explaining both anomalies seems to be rather baroque (*many new fields & parameters...*). Is this a problem?

I don't think this is a valid objection: the models are indeed non-trivial extensions of the SM, but they achieve several goals (beside the anomalies)

- ✓ *Unification of quarks & leptons*
- ✓ *Explanation/justification of the flavor hierarchies*
- ✓ *Stabilization/amelioration of the Higgs hierarchy problem*

And, beside a few exceptions, there are no serious tunings

[*most serious: ~ 10% down-alignment (flavor sect.)+ little hierarchy (Higgs)*]

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- Still, I must admit there is a growing number of observables which are "just around the corner" (*both at high-pT and at low-energies...*). *This starts to be disturbing*... [↔ *key connection with central value of* R_D]

Conclusions

- The statistical significance of the LFU anomalies is growing: in the b→s*ll* system the chance this is a pure statistical fluctuation is marginal...
- If combined, the two sets of anomalies point to non-trivial flavor dynamics around the TeV scale, involving mainly the 3rd family → connection to the origin of flavor [multi-scale picture at the origin of flavor hierarchies]
- No contradiction with existing low- & high-energy data, but new non-standard effects should emerge soon in both these areas

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A lot of fun ahead of us...
(both on the exp., the pheno,
and the model-building point of view)

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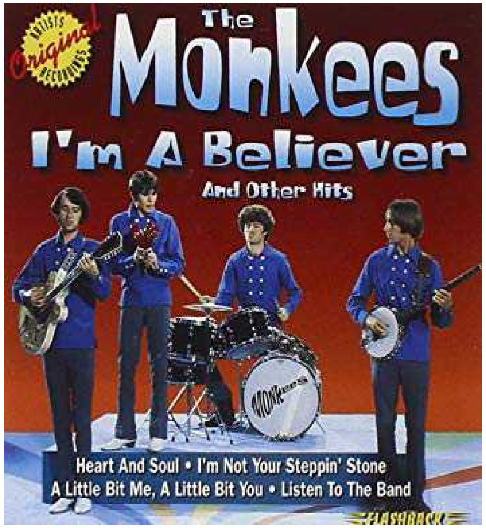

(*already since quite some time...*)