Implications of LFU anomalies for high-energy physics

Gino Isidori
[*University of Zürich*]

- Introduction [LFU *and accidental symmetries*]
- A closer look to B-physics data
- EFT and simplified models
- Speculations on UV completions
- Conclusions

University of Zurich^UZH

European Research Council
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Introduction

What is Lepton Flavor Universality and why we care about it?

LFU is an accidental approximate symmetry of the SM Lagrangian.
(*exact SM global symmetry in the limit where we neglect lepton Yukawa's*):

$$\mathscr{L}_{\mathrm{SM}} = \mathscr{L}_{\mathrm{gauge}} + \mathscr{L}_{\mathrm{Higgs}} \Big|_{y_l = 0} \longrightarrow$$

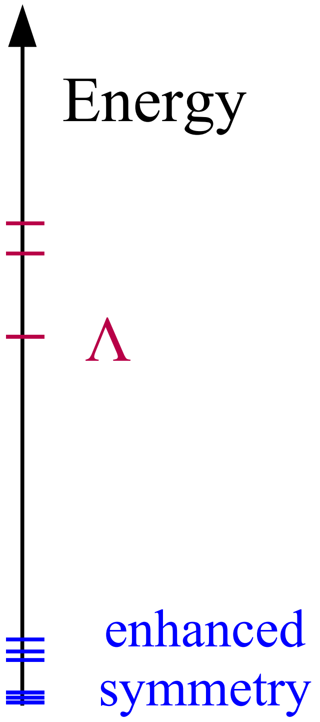
3×3 (unitary) transformations
of lepton fields in flavor space

LFU is badly broken in the Yukawa sector: $y_e \sim 3\times10^{-6}$, $y_\mu \sim 3\times10^{-4}$, $y_\tau \sim 10^{-2}$

But all the lepton Yukawa couplings are small compared to SM gauge couplings, giving rise to the (*approximate*) universality of decay amplitudes which differ only by the different lepton species involved

Introduction

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \underbrace{\sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}}\, O_i^{d\geq 5}}_{\boxed{\text{Violations of accidental symmetries}}}$$



Accidental symmetries are excellent probes of high-energy dynamics,

as we know from well-known examples in the past:

Eg: *Low-energy theory:* QED + QCD
Accidental symm.: Flavor [$U(1)_{n_f}$]
Violated by: <u>Weak interactions</u> → $G_F \sim (250\ \text{GeV})^{-2}$

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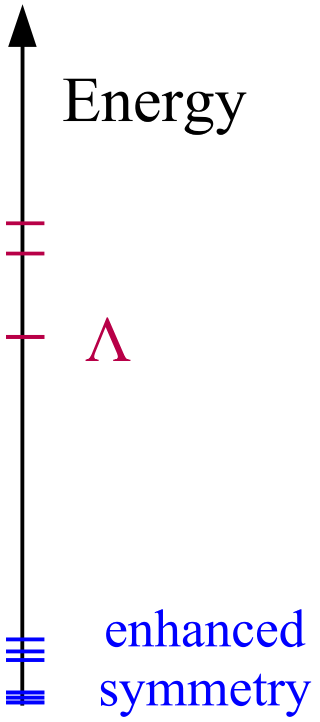
Violations of accidental symmetries



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Accidental symm.: CP
Violated by: <u>"Super-weak" interactions</u>

(single evidence of the violation in K-$\bar{K}$ mixing for long time)

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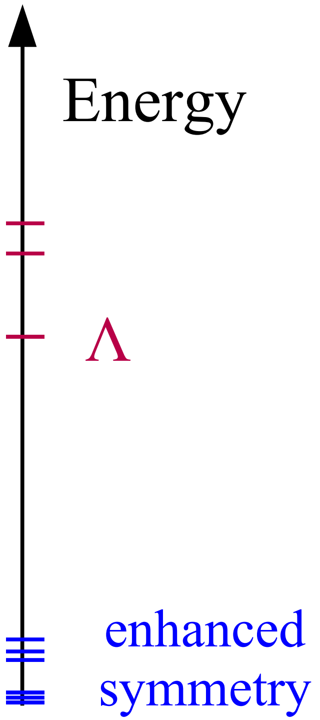
Energy

Λ

enhanced symmetry

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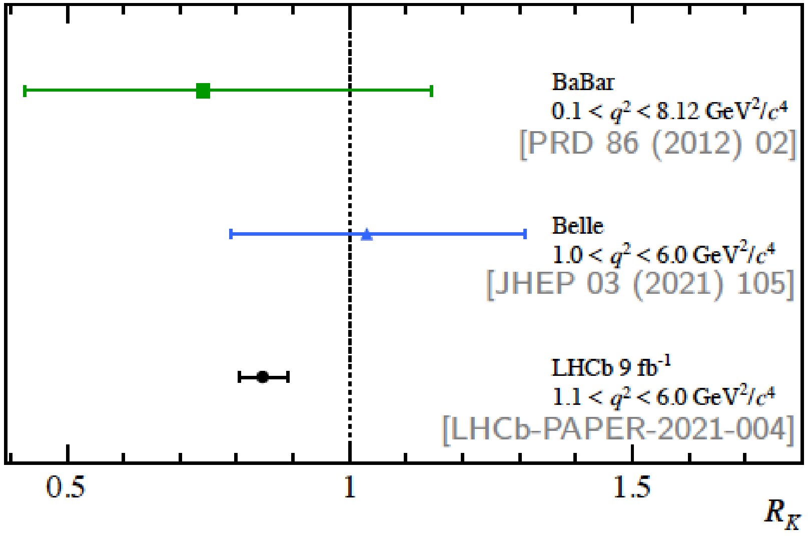
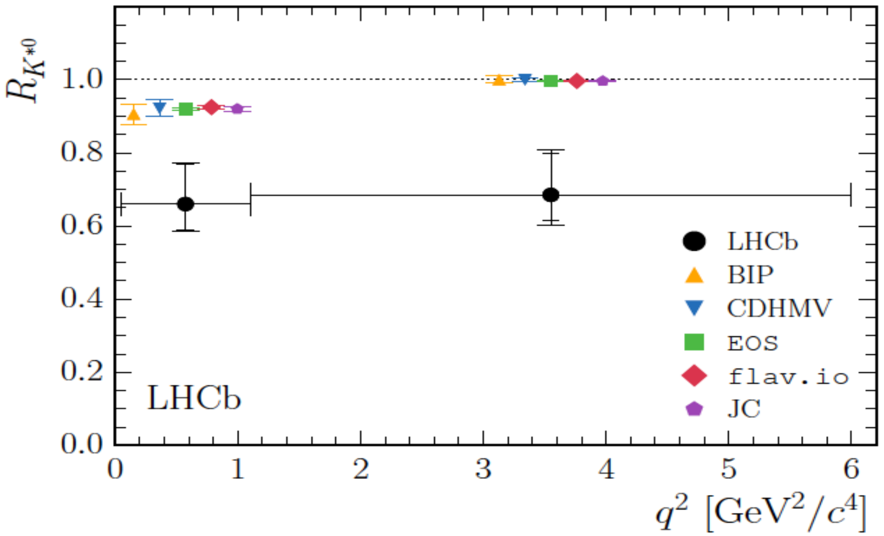
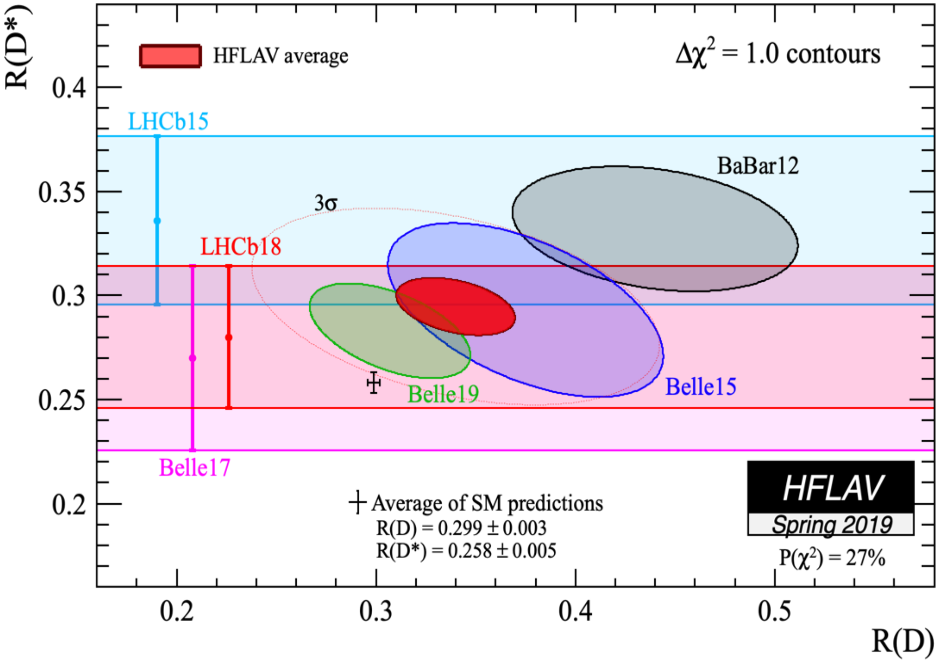
Eg: *Low-energy theory:* SM, 2 generations
Accidental symm.: CP
Violated by: "Super-weak" interactions → $\frac{(G_F m_t V_{ts} V_{td})^2}{4\pi^2} \sim (10^4\ \text{TeV})^{-2}$

(single evidence of the violation in K-$\bar{\text{K}}$ mixing for long time)

A closer look to B-physics data



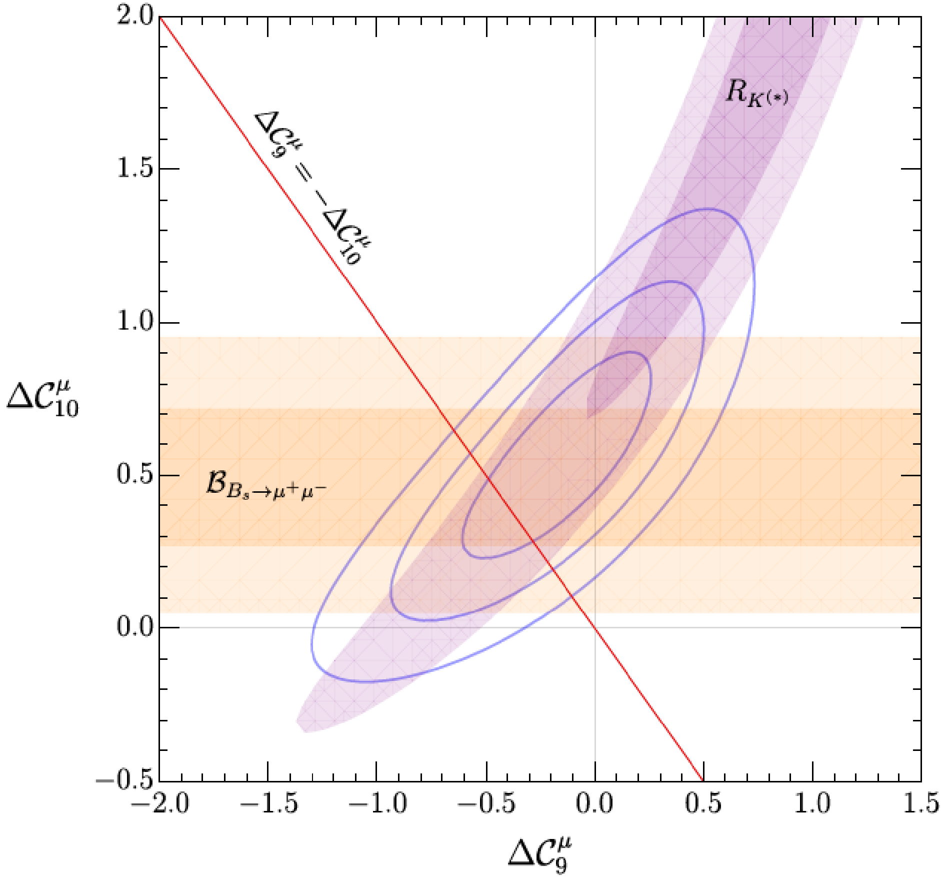




▶ A closer look to B-physics data

- b → s l^+l^- (neutral currents)

Cornella *et al.* '21



FCNC operators:

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

$$\mathcal{O}_9^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$$

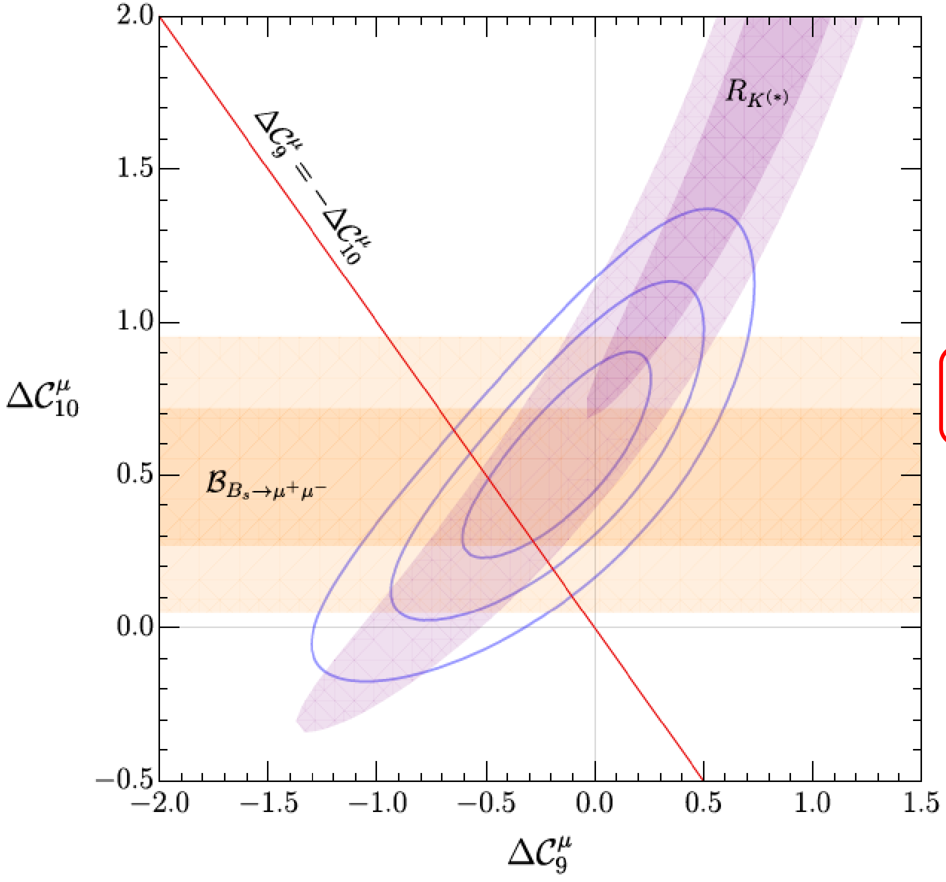
$$\Delta C_i^\mu = C_i^\mu - C_i^e$$

Conservative fit using “clean observables” only” [= R_K , R_{K^*} , $B_s \to \mu\mu$]

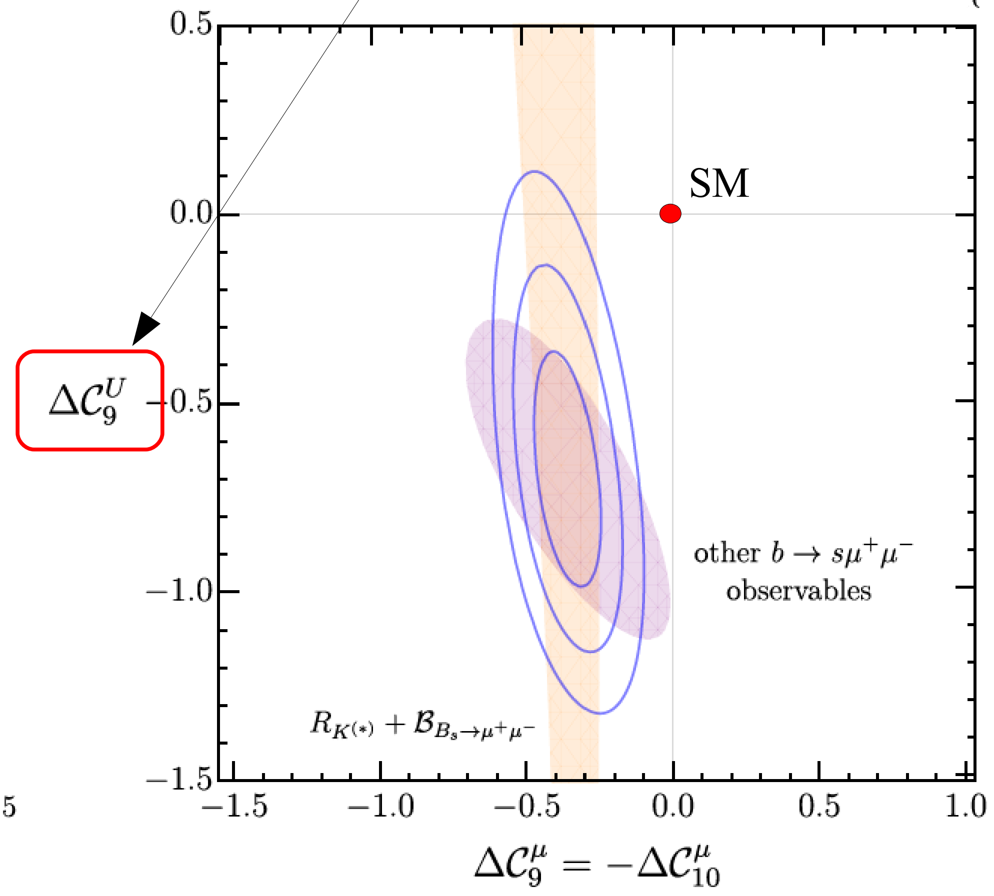
$\boxed{4.6\sigma}$ significance of NP hypothesis $\Delta C_9^\mu = -\Delta C_{10}^\mu$ vs. SM

A closer look to B-physics data

Cornella *et al.* '21



Lepton-universal shift to C_9
(*sensitive to charm re-scattering*)



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

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$>> 5\sigma$ with current best estimate of charm contributions

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

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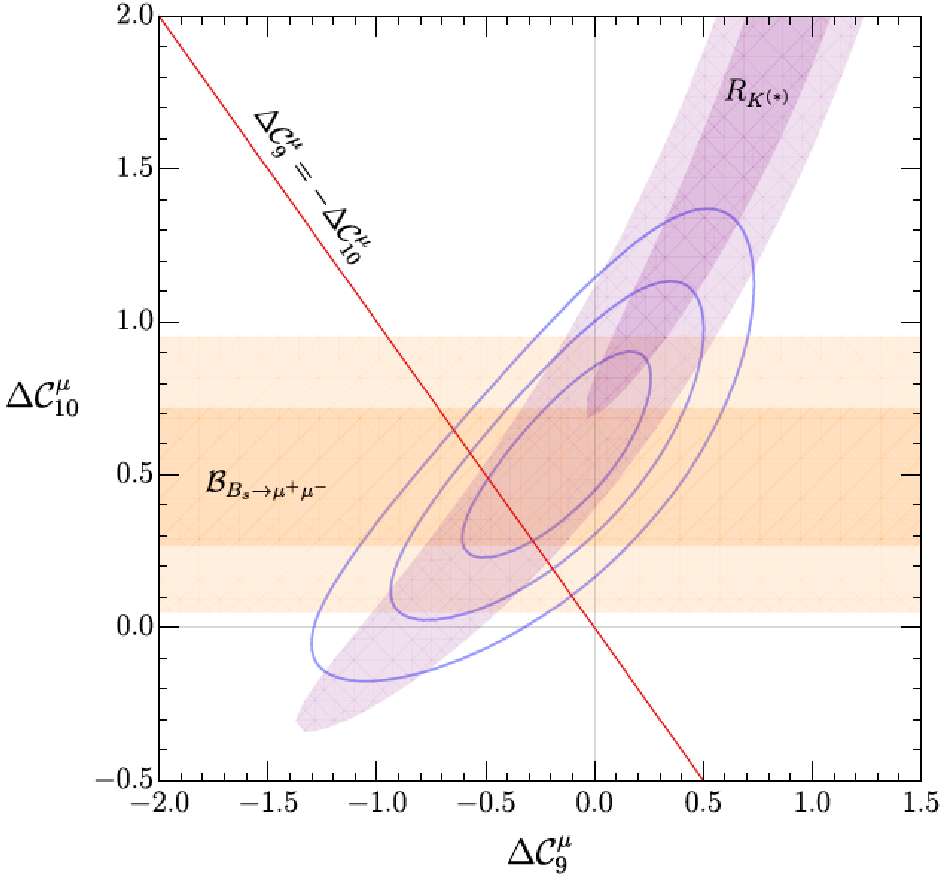

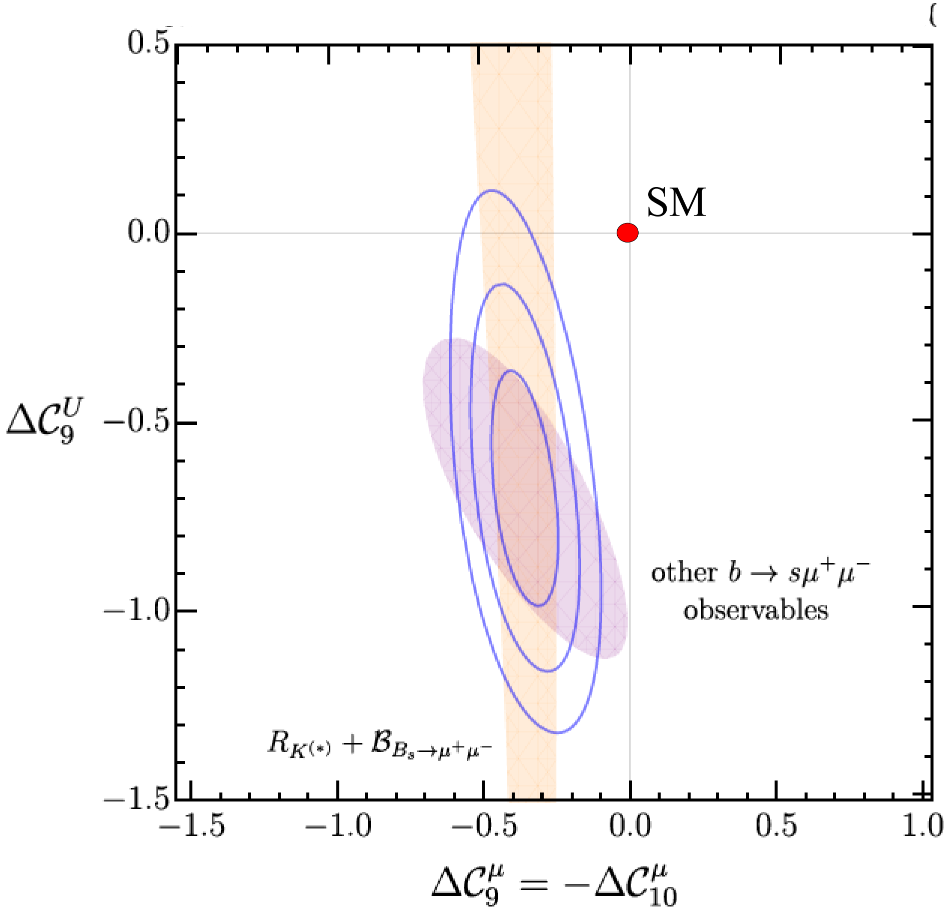

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Altmanshofer & Stangl '21

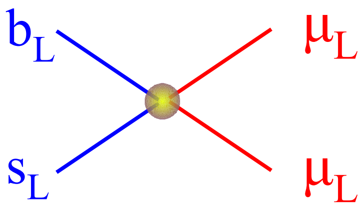
3.9σ *global significance* of NP (*most conservative estimate*)

Lancierini, GI, Owen, Serra, '21

A closer look to B-physics data

Data point to (short-distance) NP effects in operators of the type

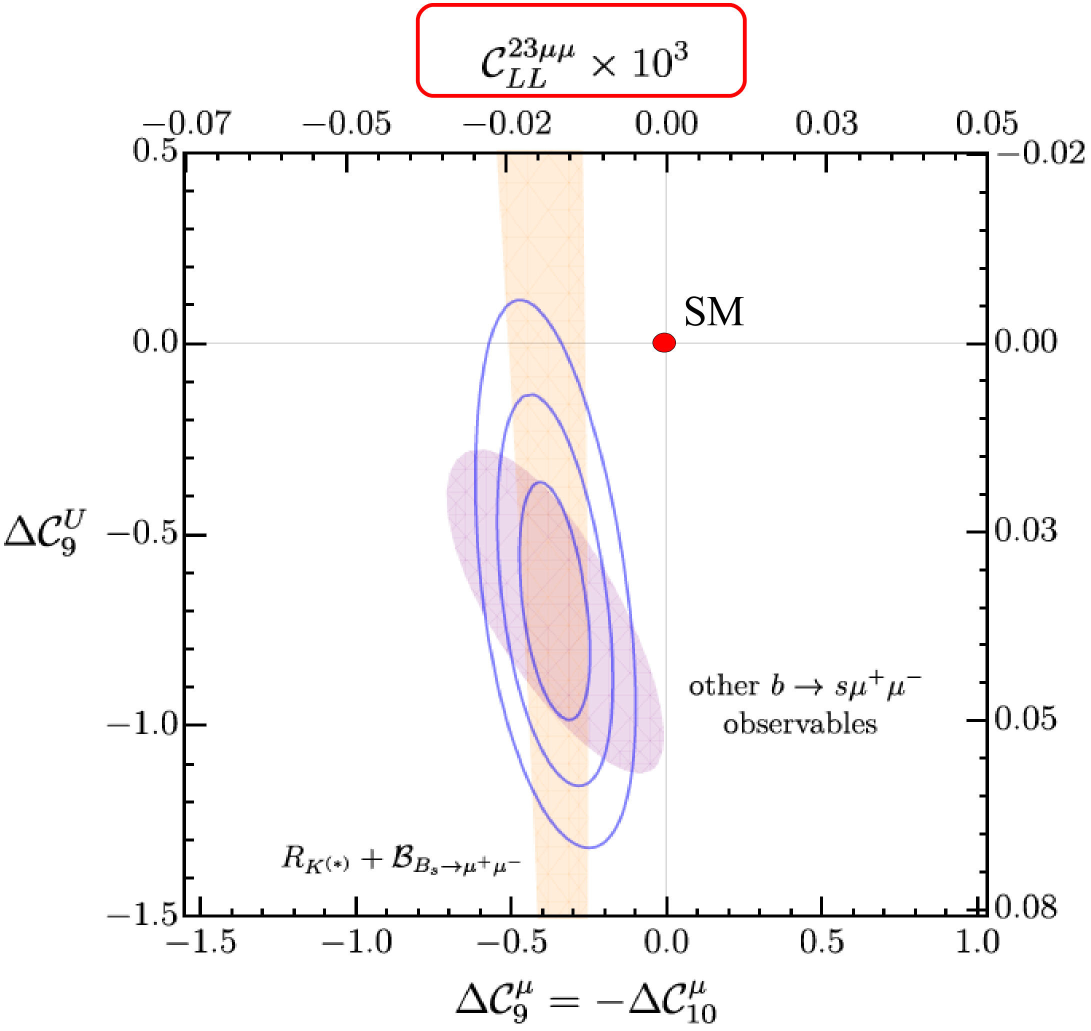
$$\boxed{\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)}$$



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

super-weak interaction!

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



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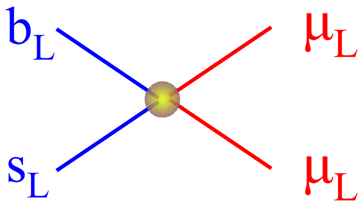

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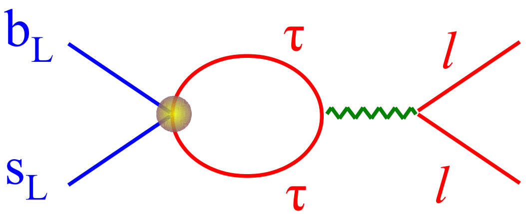
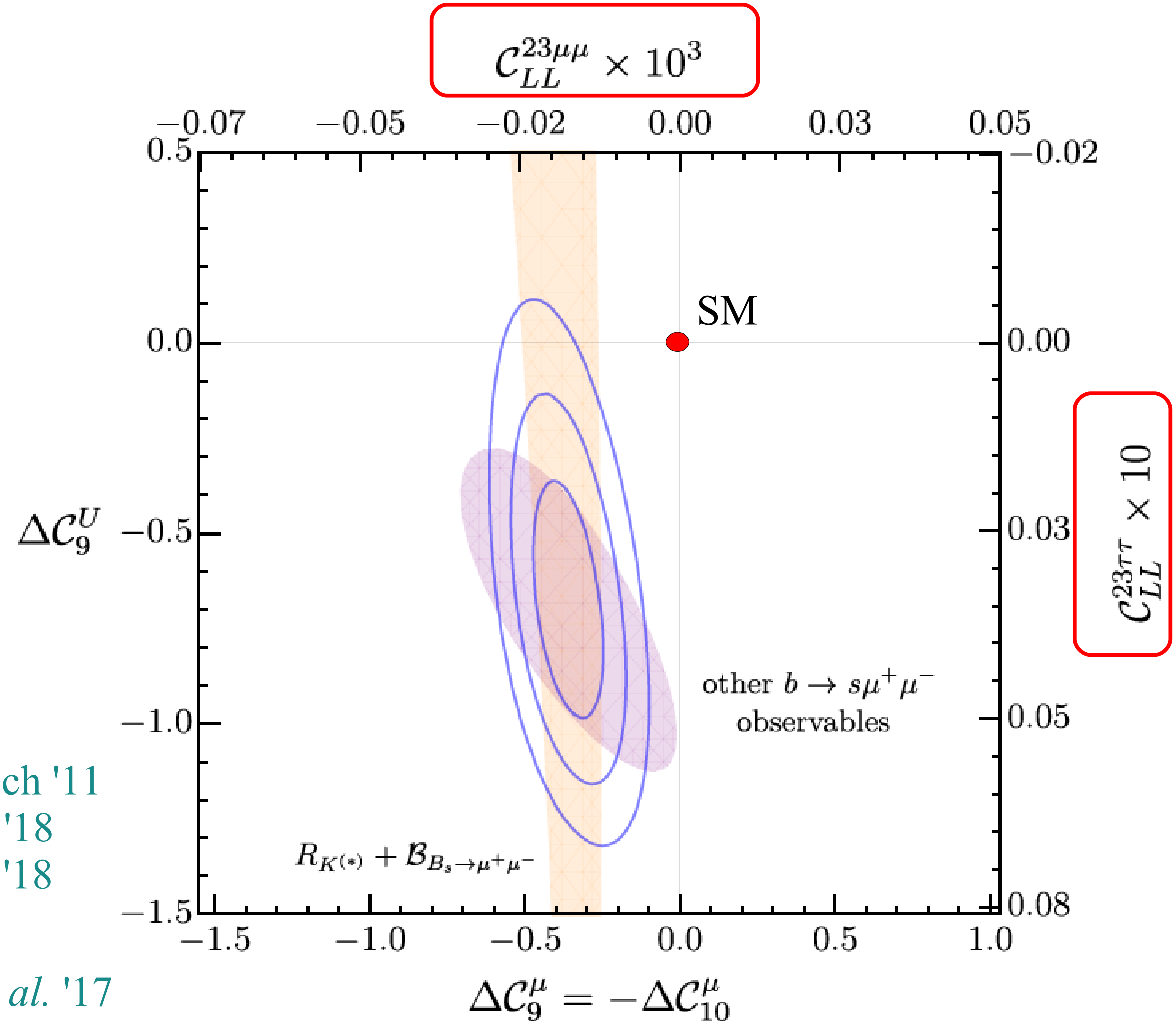
$C_{LL}^{23\mu\mu} \Rightarrow \Delta C_9^\mu = -\,\Delta C_{10}^\mu$



$C_{LL}^{23\tau\tau} \Rightarrow \Delta C_9^{\mathrm{Univ}}$

Bobeth & Haisch '11
Crivellin *et al.* '18
Alguero *et al.* '18

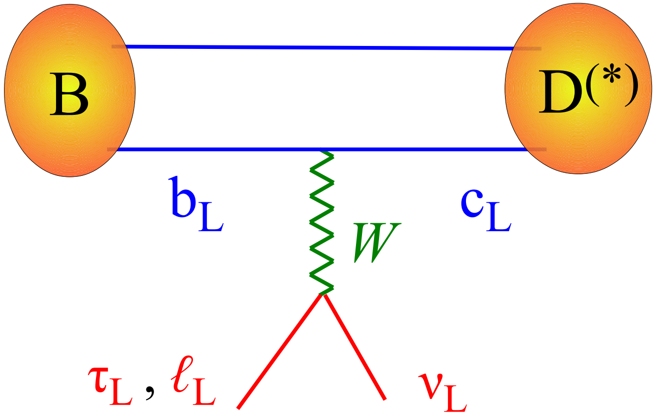
→ Link to CC anomaly Greljo *et al.* '17

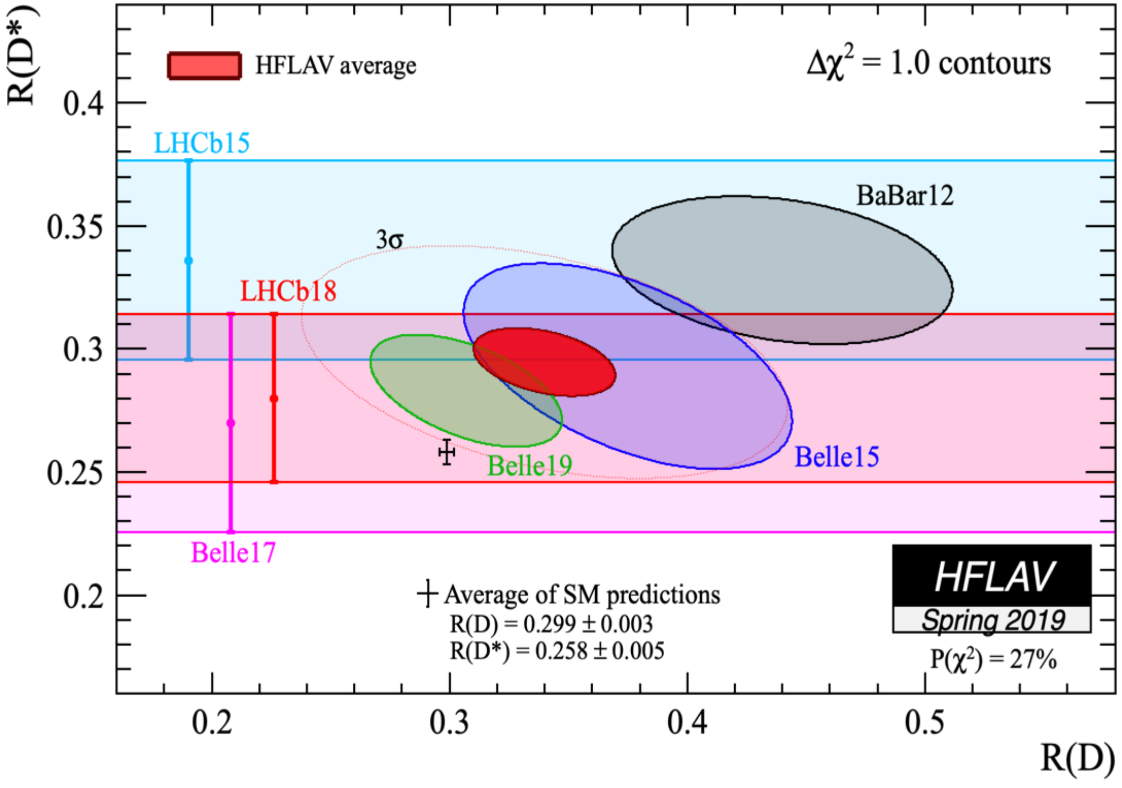


A closer look to B-physics data

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

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





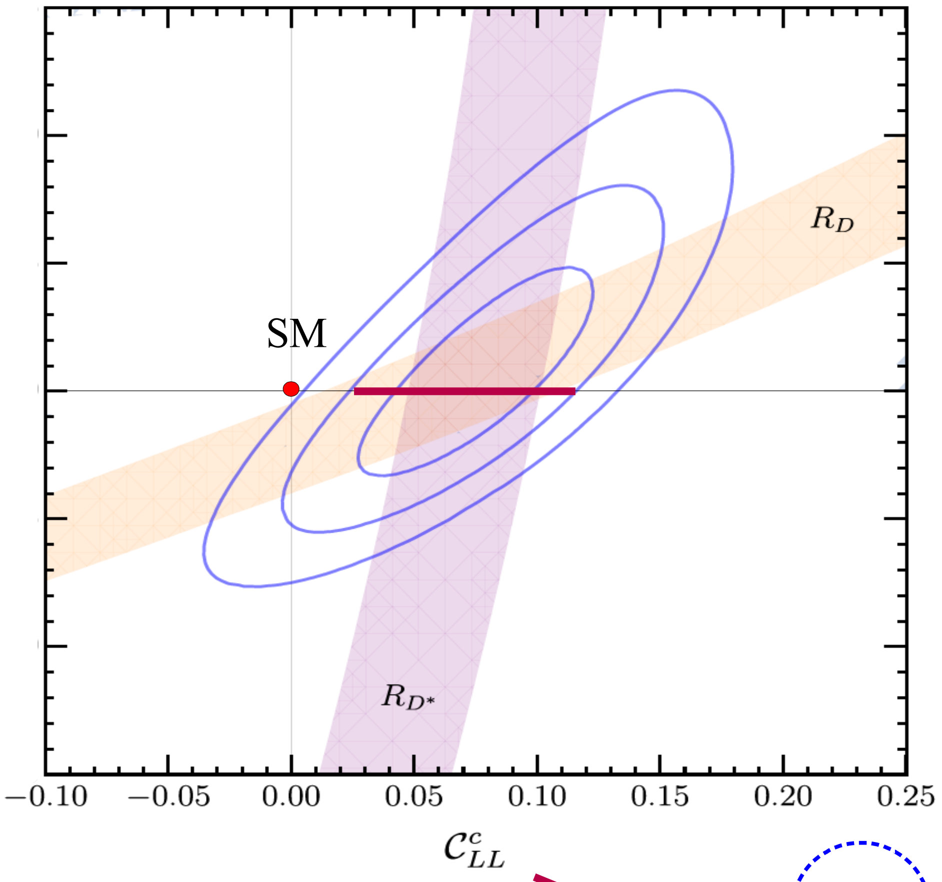
- Consistent results by three different exps. ~ 3.1σ excess over SM (*D and D* combined*)

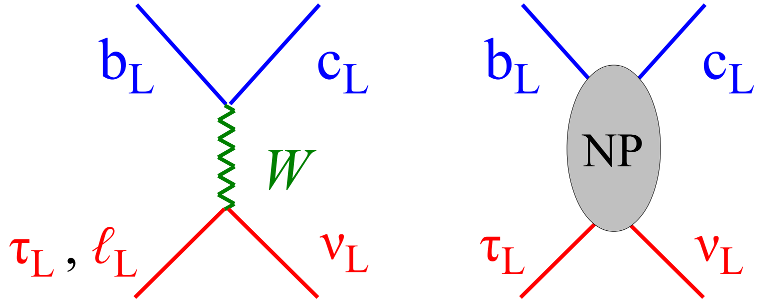
- SM predictions quite "clean": hadronic uncertainties cancel (*to large extent*) in the ratios

A closer look to B-physics 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

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

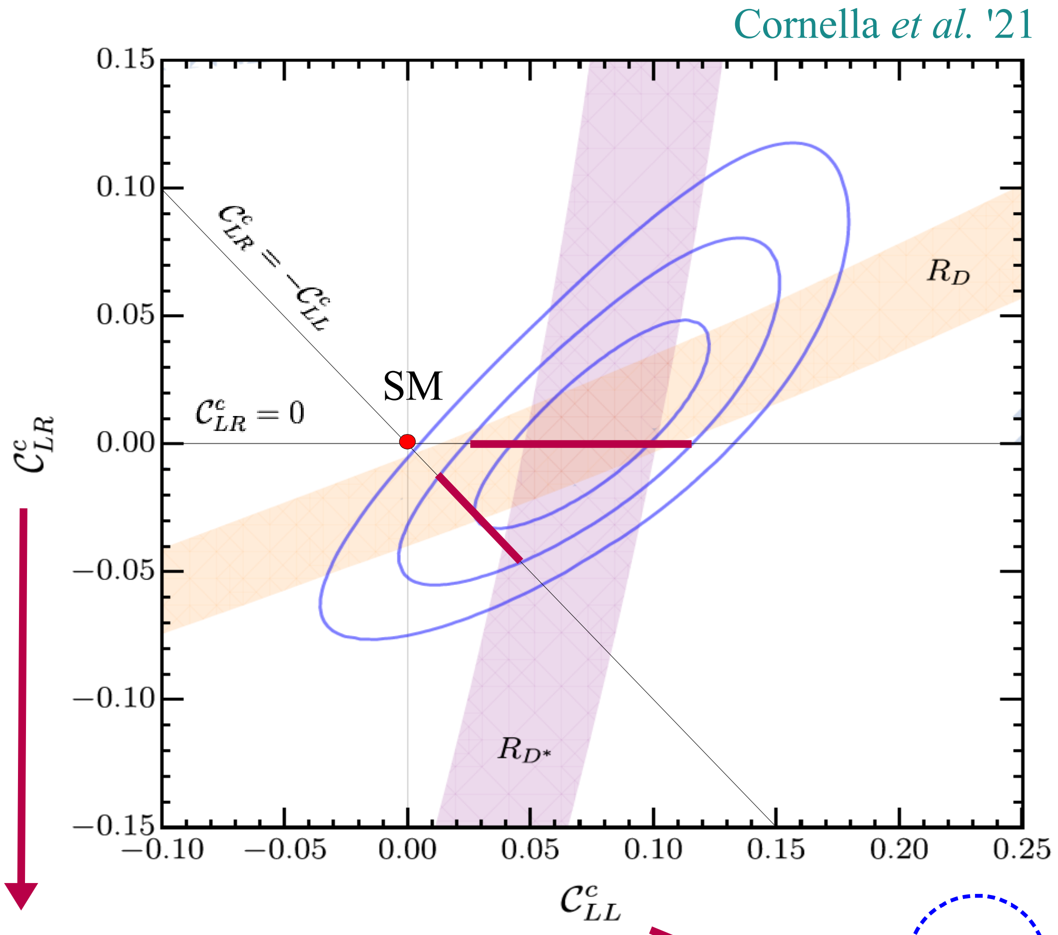
Same operator contributing to b → s *ll*

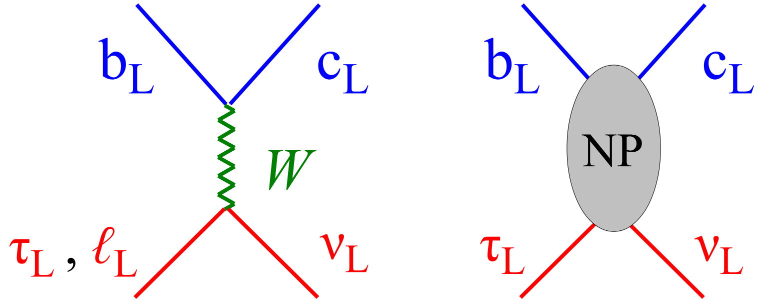
all 3rd gen. (contribute via CKM rotation)

A closer look to B-physics data

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

Cornella *et al.* '21





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But other options (*RH currents*) possible

$b_R \to c_L\, \tau_R\, \nu_L$

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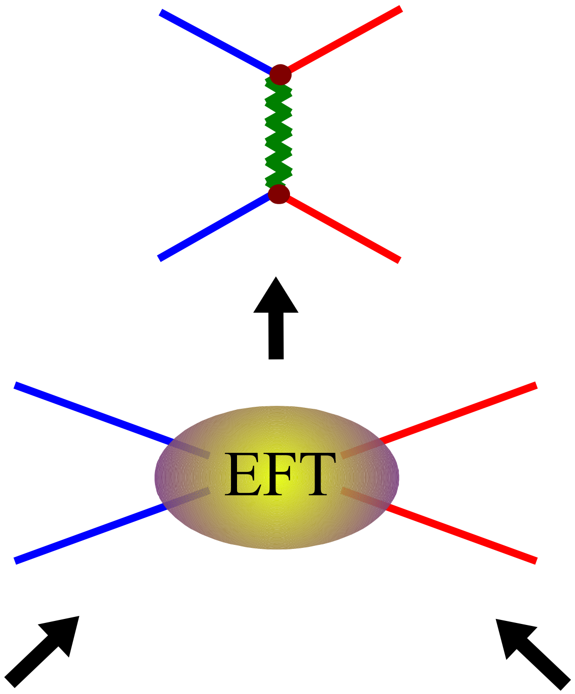
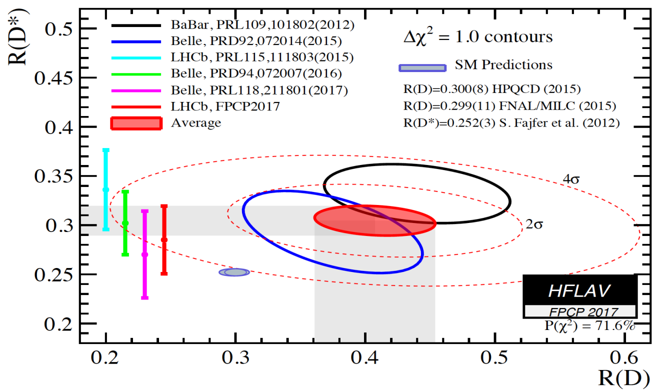
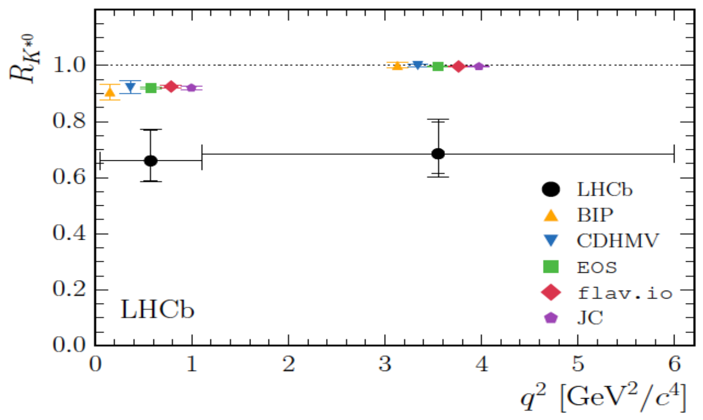
From EFT to simplified models

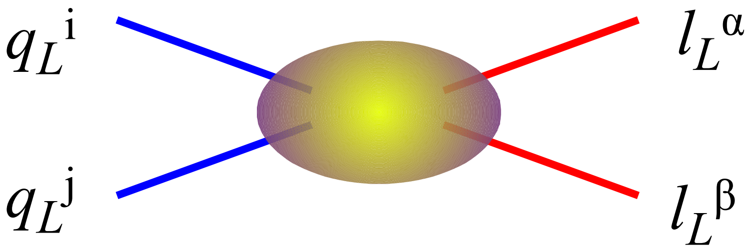






EFT considerations

- 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...)

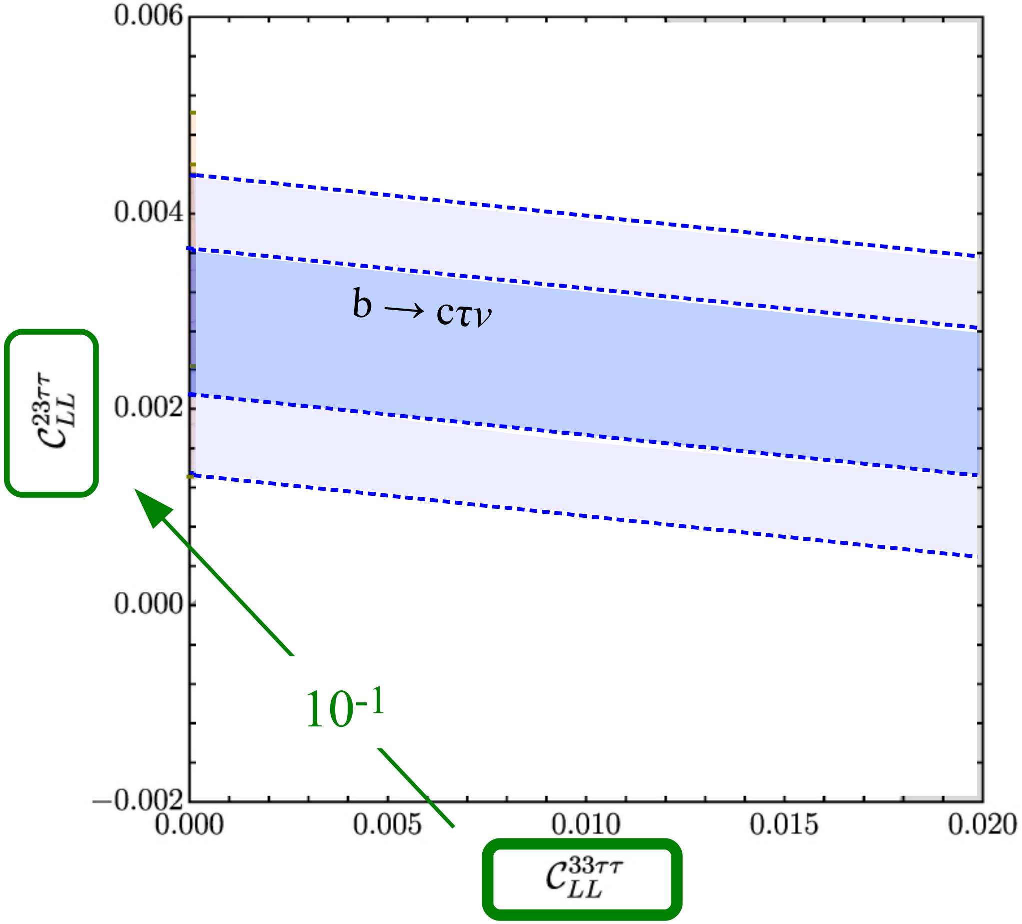
- Large coupling [*competing with SM tree-level*] in bc → $l_3\,\nu_3$ [R_D, R_{D^*}]
- Small coupling [*competing with SM loop-level*] in bs → $l_2\,\,l_2$ [R_K, R_{K^*}, ...]

↓

$C_{ij\alpha\beta}$ = large for 3rd generation fields + small terms for 2nd (& 1st) generations →

Link to pattern of the Yukawa couplings !

EFT considerations



charged-currents only:

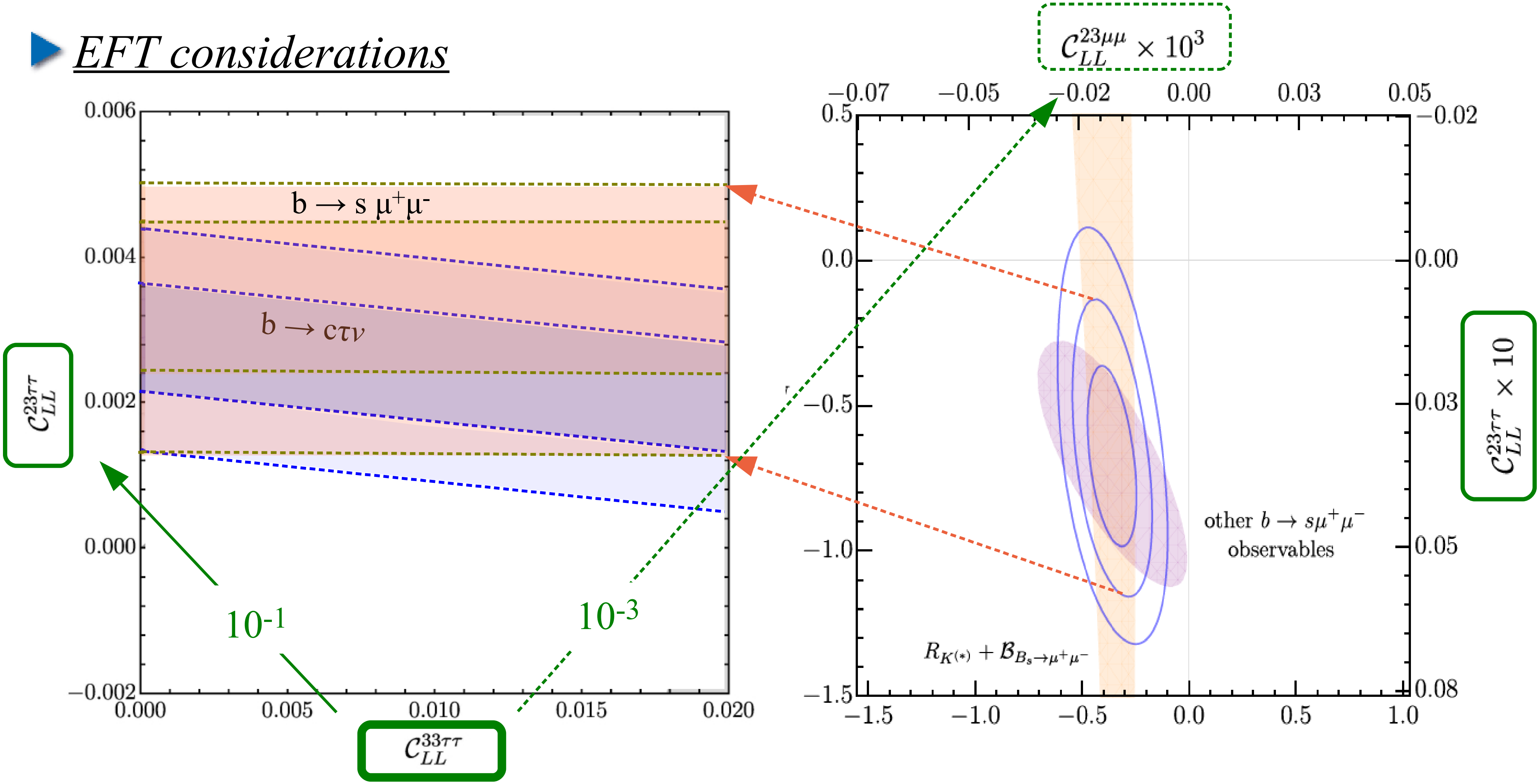
$$\frac{V_{cb}\,\mathcal{C}^{33\tau\tau}_{LL} + V_{cs}\,\mathcal{C}^{23\tau\tau}_{LL}}{V_{cb}}$$

Pattern emerging from data:

$$\boxed{\mathcal{O}^{ij\alpha\beta}_{LL} = (\bar{q}^i_L \gamma_\mu \ell^\alpha_L)(\bar{\ell}^\beta_L \gamma_\mu q^j_L)}$$

- ✓ O(10^{-1}) suppress. for each 2nd gen. q_L or l_L [*recall* $|V_{ts}| \sim 0.4\times10^{-1}$]

EFT considerations



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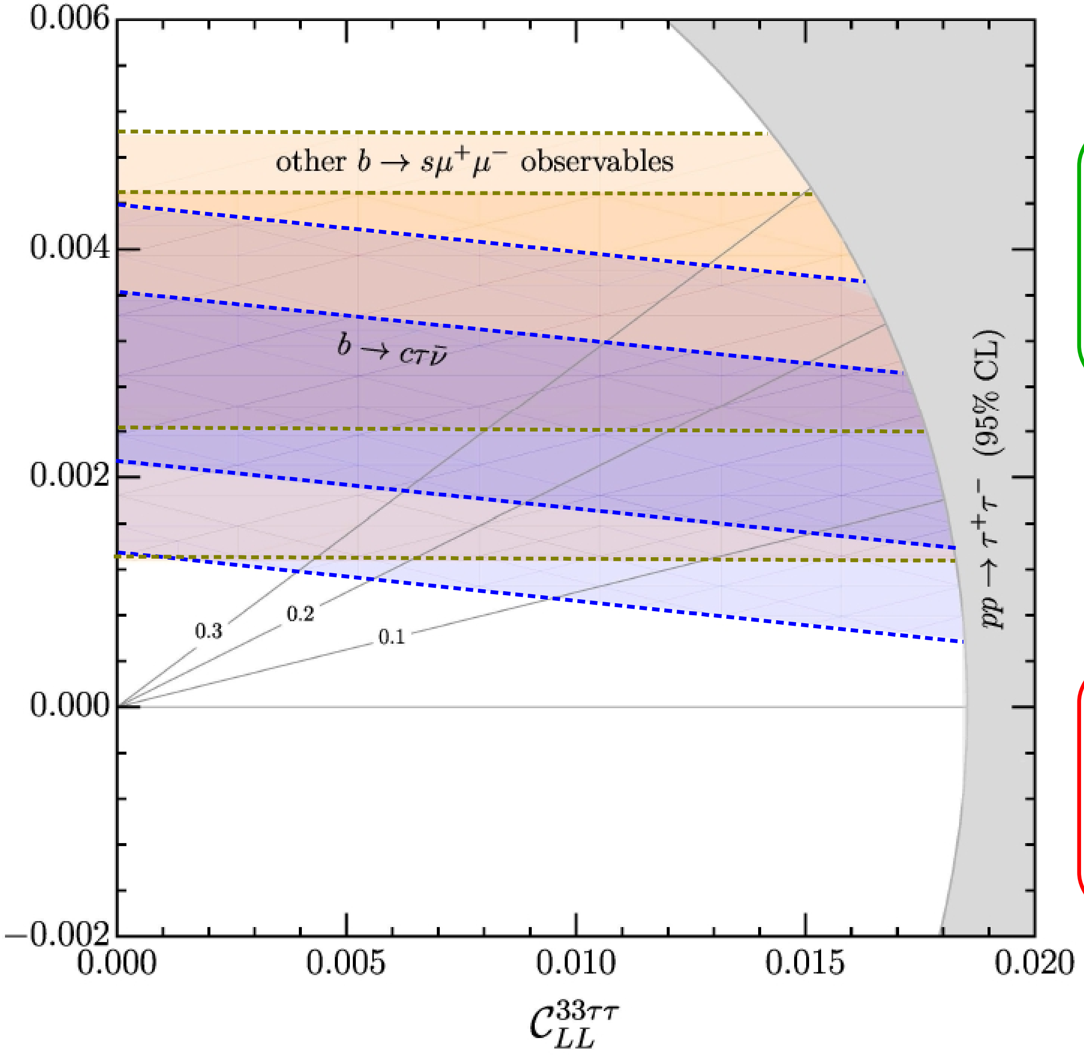
- ✓ Nice consistency among the 2 sets of anomalies

EFT considerations

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



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What we do not see (*seem to call for an additional ~ loop suppression*):

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

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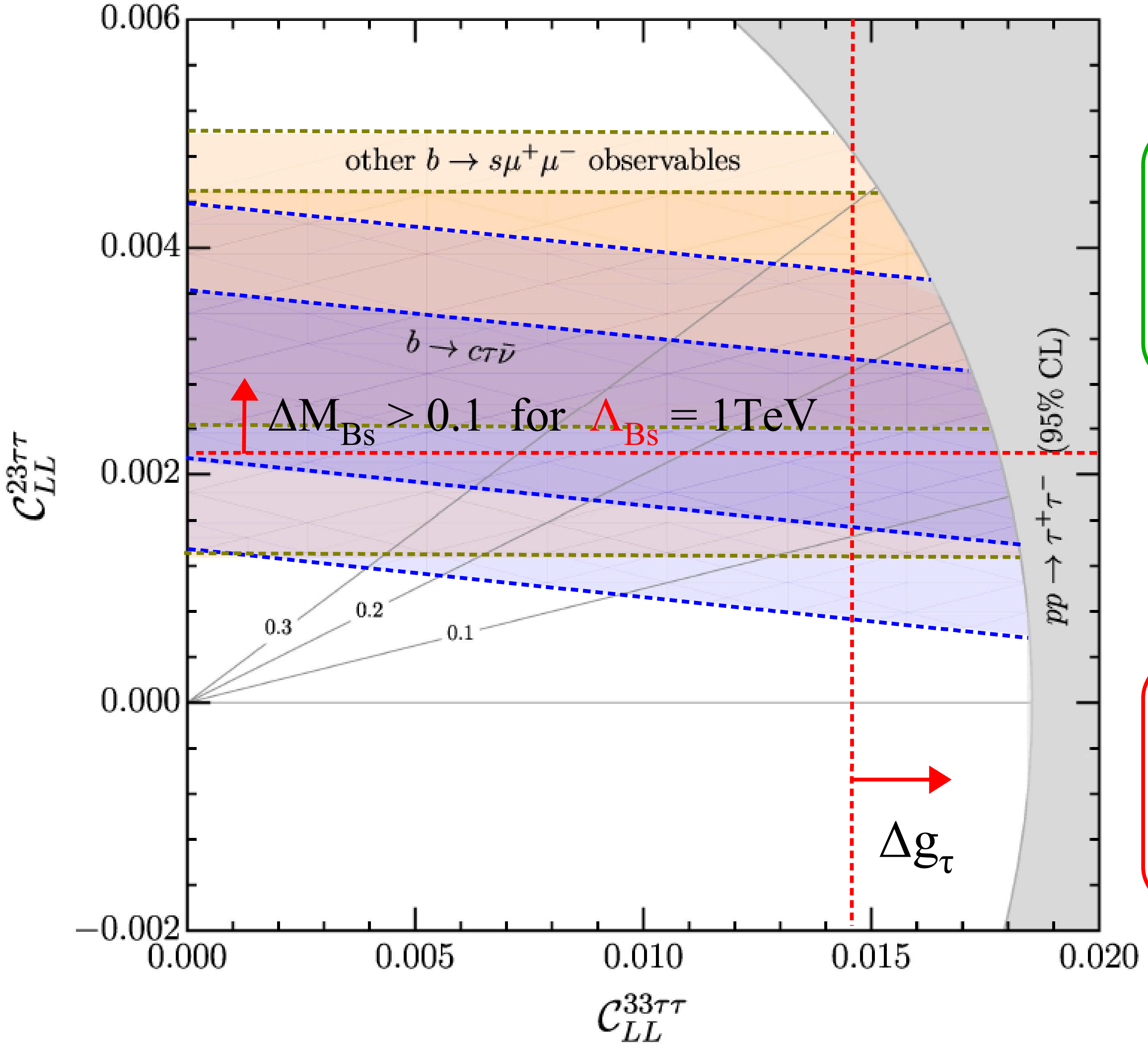

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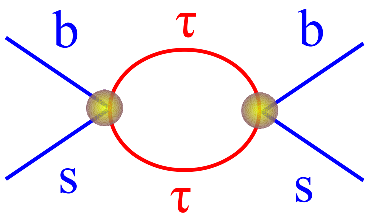
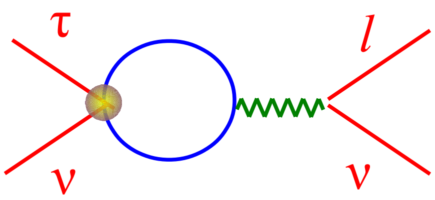


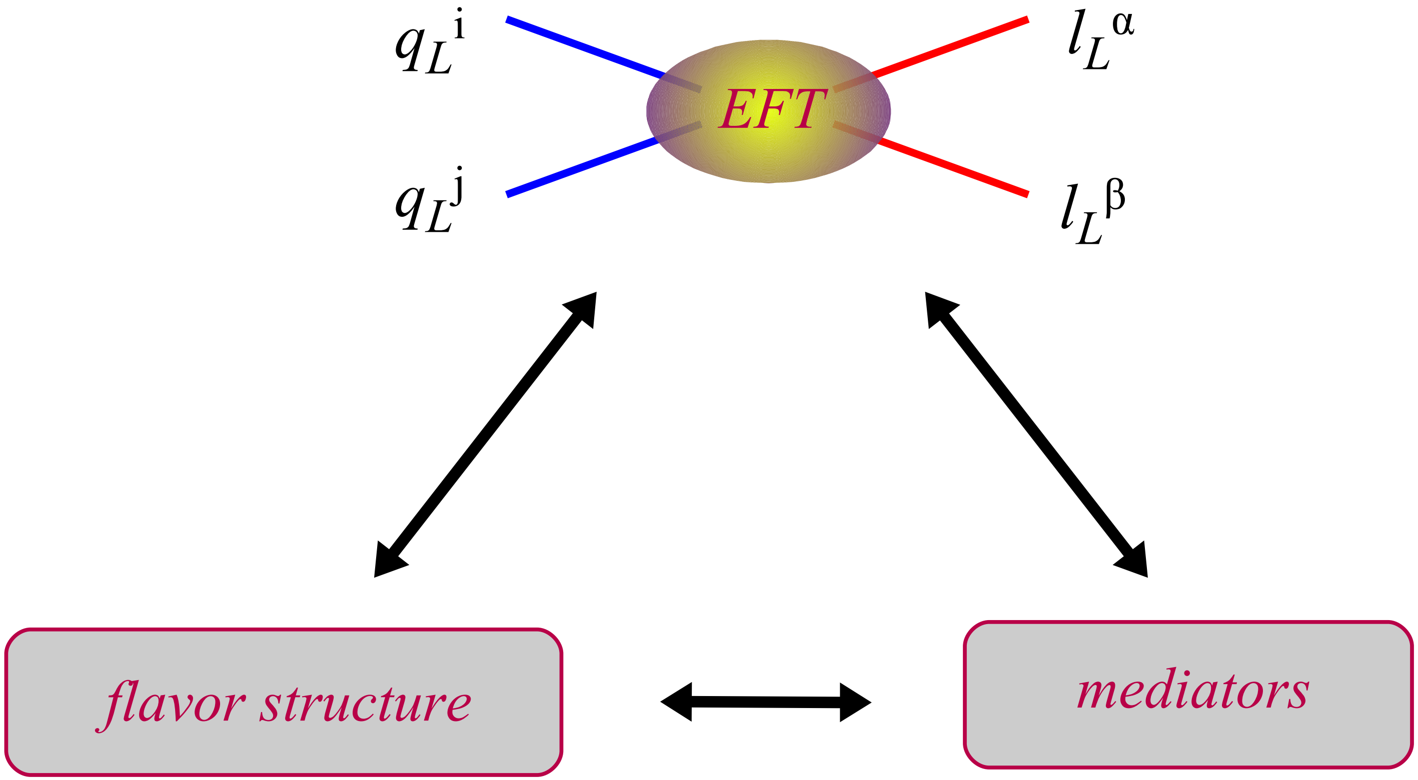
$\Delta M_{Bs} \sim (C^{23\tau\tau})^2 \, \Lambda_{Bs}{}^2$



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

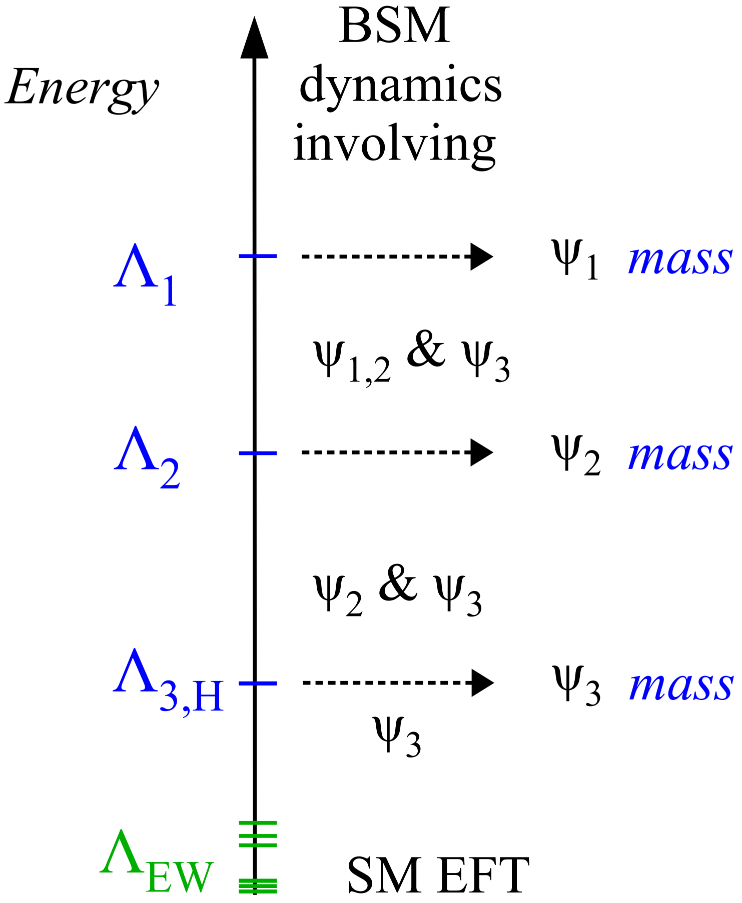
From EFT to simplified models

To move from the EFT toward more complete/ambitious models, we need to address two general aspects: the *flavor structure* of the underlying theory, and the nature of the possible *mediators*



<u>*From EFT to simplified models*</u> [*the flavor structure*]

Multi-scale picture @ origin of flavor:



Energy

BSM dynamics involving

Λ_1 → ψ_1 *mass*

$\psi_{1,2}$ & ψ_3

Λ_2 → ψ_2 *mass*

ψ_2 & ψ_3

$\Lambda_{3,H}$ → ψ_3 *mass*

ψ_3

Λ_{EW} SM EFT

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

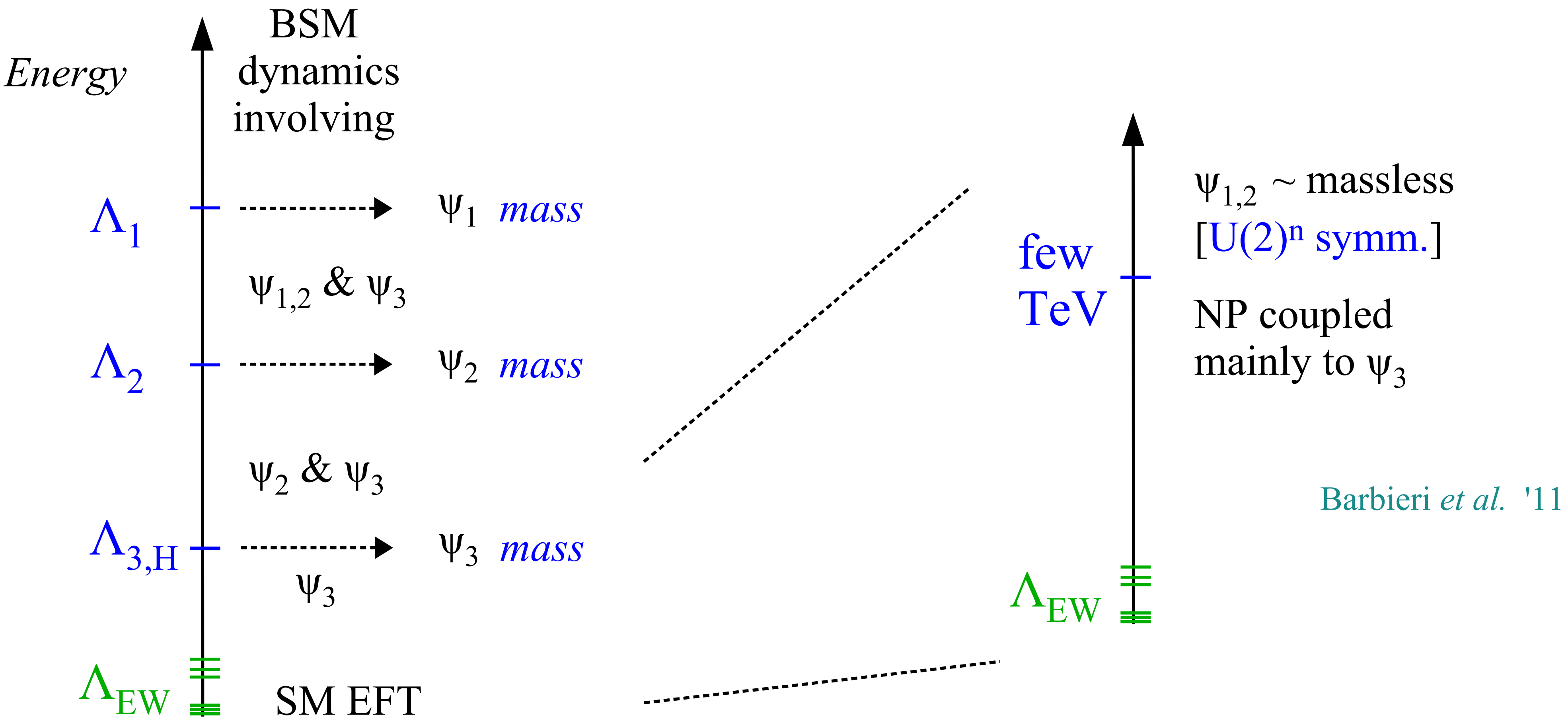
Main idea:

- Flavor non-universal interactions already at the TeV scale:
- 1st & 2nd gen. have small masses because they are coupled to NP at heavier scales

~~3 gen. = "identical copies"~~
~~up to high energies~~

▶ *From EFT to simplified models* [*the flavor structure*]

Multi-scale picture @ origin of flavor:



Energy

BSM dynamics involving

Λ_1 ··········› ψ_1 *mass*

$\psi_{1,2}$ & ψ_3

Λ_2 ··········› ψ_2 *mass*

ψ_2 & ψ_3

$\Lambda_{3,H}$ ··········› ψ_3 *mass*

ψ_3

Λ_{EW} SM EFT

few TeV

$\psi_{1,2}$ ~ massless [$U(2)^n$ symm.]

NP coupled mainly to ψ_3

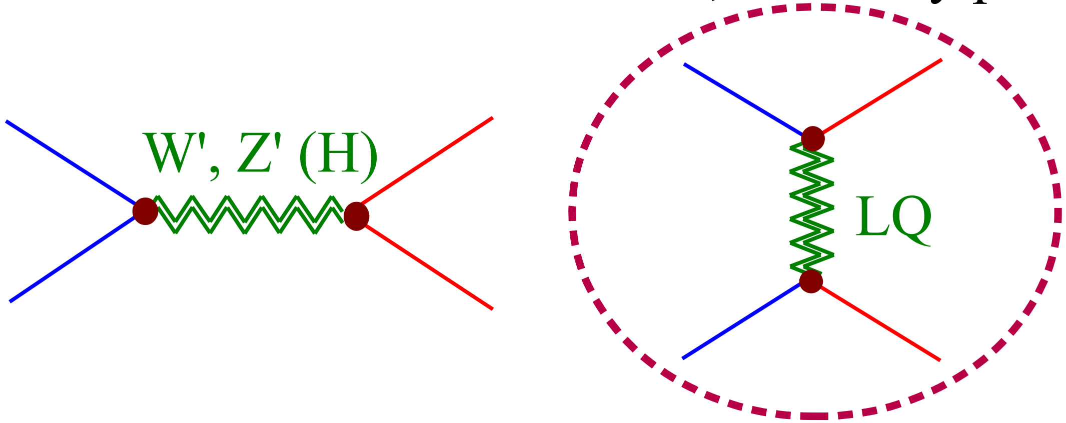
Λ_{EW}

Barbieri *et al.* '11

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \underbrace{\mathscr{L}_{\text{Higgs}} + \mathscr{L}_{Y} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}}_{\text{Non-trivial UV imprints}}$$

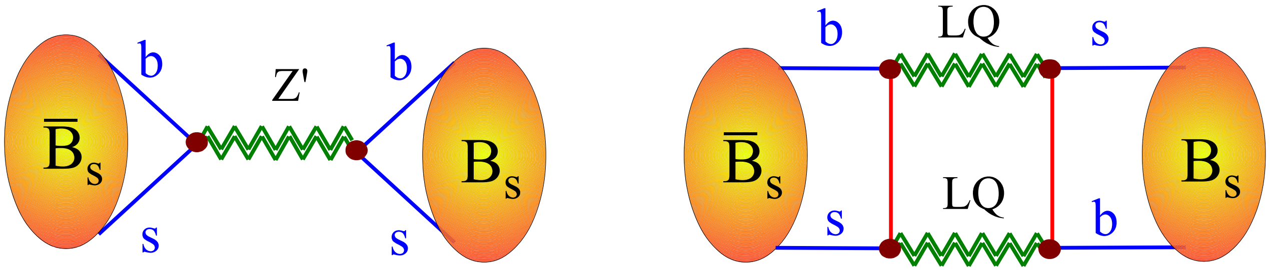
▶ *From EFT to simplified models* [*the possible mediators*]

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...



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

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

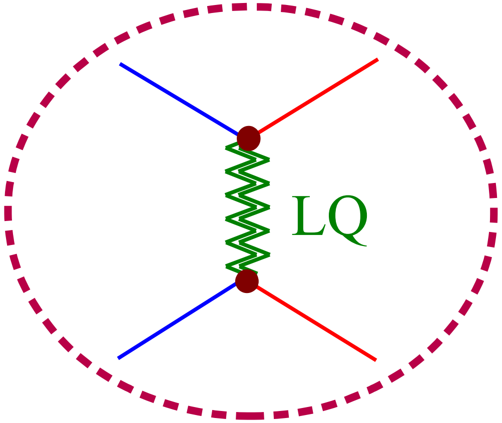


II. Direct searches: 3rd gen. LQ are also in better shape as far as direct searches are concerned (*contrary to Z'*...).

From EFT to simplified models [*the possible mediators*]

Leptoquarks suffered of an (*undeserved*) "bad reputation" for two main reasons:

- Could mediate proton decay → not a general feature of the LQ: it depends on the model...! [*e.g. not the case in the Pati-Salam model*]



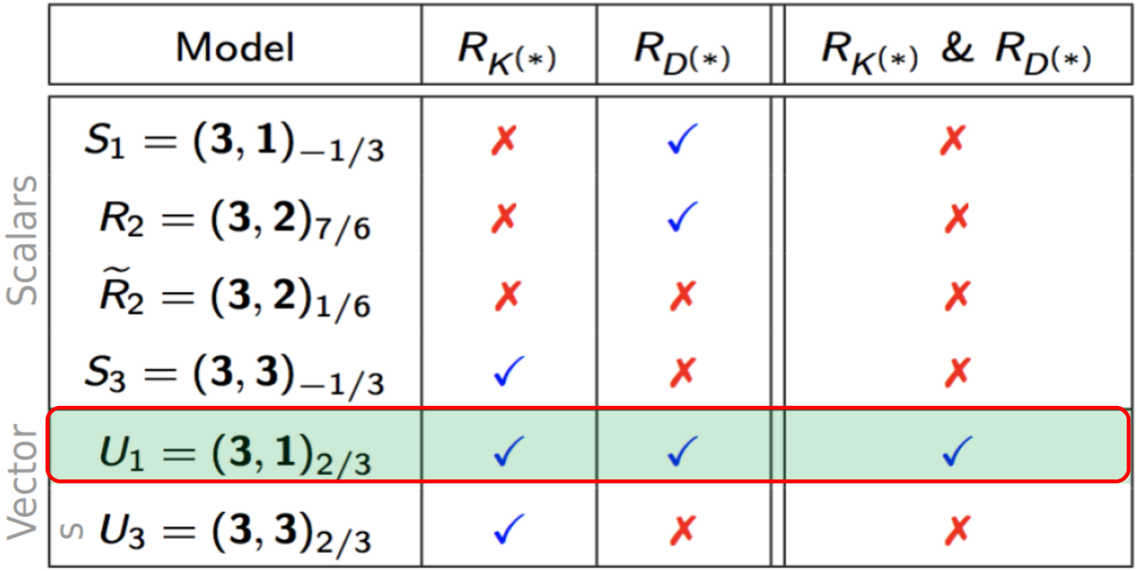
- Severe bounds from processes involving μ & e (such as $K_L \to \mu e$) → avoided with non-trivial flavor structure [*e.g. non-univ. interactions*]

On the other hand, they are a "natural" feature in many SM extensions → "Renaissance" of LQ models (*to explain the anomalies, but not only...*):

- Scalar LQ as PNG
  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
  Marzocca '18
- Vector LQ as techni-fermion resonances
  Barbieri *et al.* '15; Buttazzo *et al.* '16, Barbieri, Murphy, Senia, '17 + ...
- Scalar LQ from GUTs & $\not{R}$ 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 + ...
- LQ as Kaluza-Klein excit.
  Megias, Quiros, Salas '17
  Megias, Panico, Pujolas, Quiros '17
  Blanke, Crivellin, '18 + ...
- Vector LQ in GUT gauge models
  Assad *et al.* '17
  Di Luzio *et al.* '17
  Bordone et *al.* '17
  Heeck & Teresi '18
  + ...

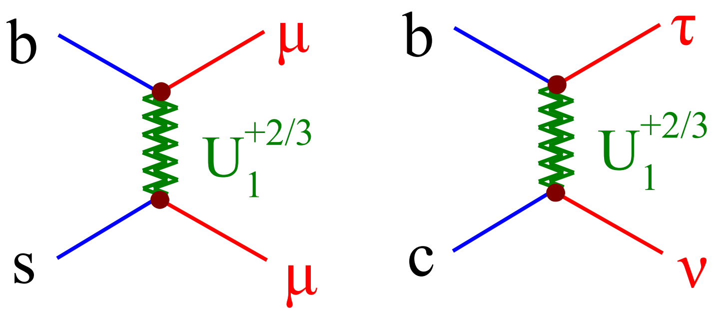
From EFT to simplified models [*the possible mediators*]

Which LQ explains which anomaly?



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

Angelescu, Becirevic, DAF, Sumensari [1808.08179]



Barbieri, GI, Pattori, Senia '15

- mediator: U_1
- flavor structure: $U(2)^n$

(approx. flavor symmetry resulting from the multi-scale picture)

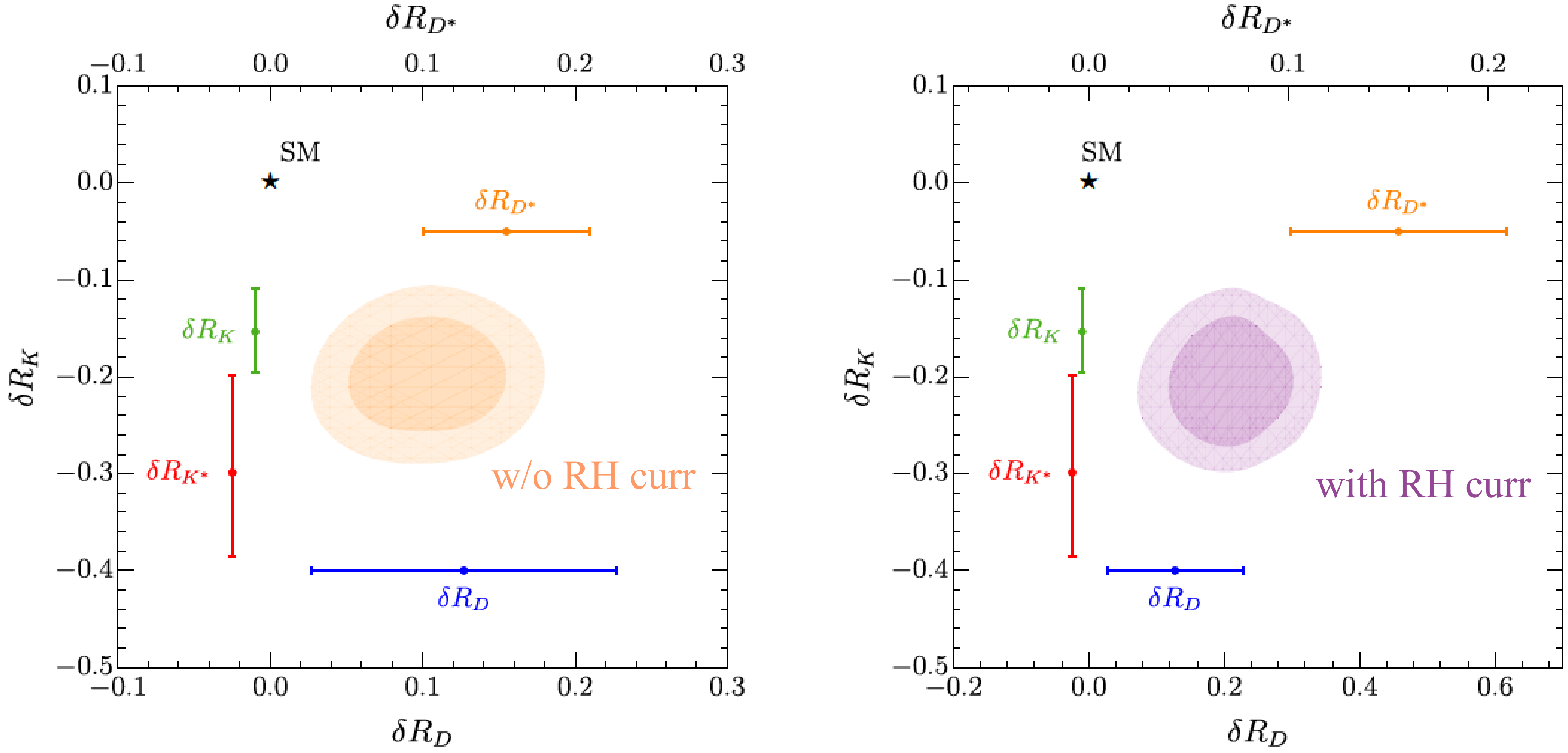
LQ of the Pati-Salam gauge group:
$SU(4) \times SU(2)_L \times SU(2)_R$

▶ *From EFT to simplified models* [*the possible mediators*]

Considering the U_1 only

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

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



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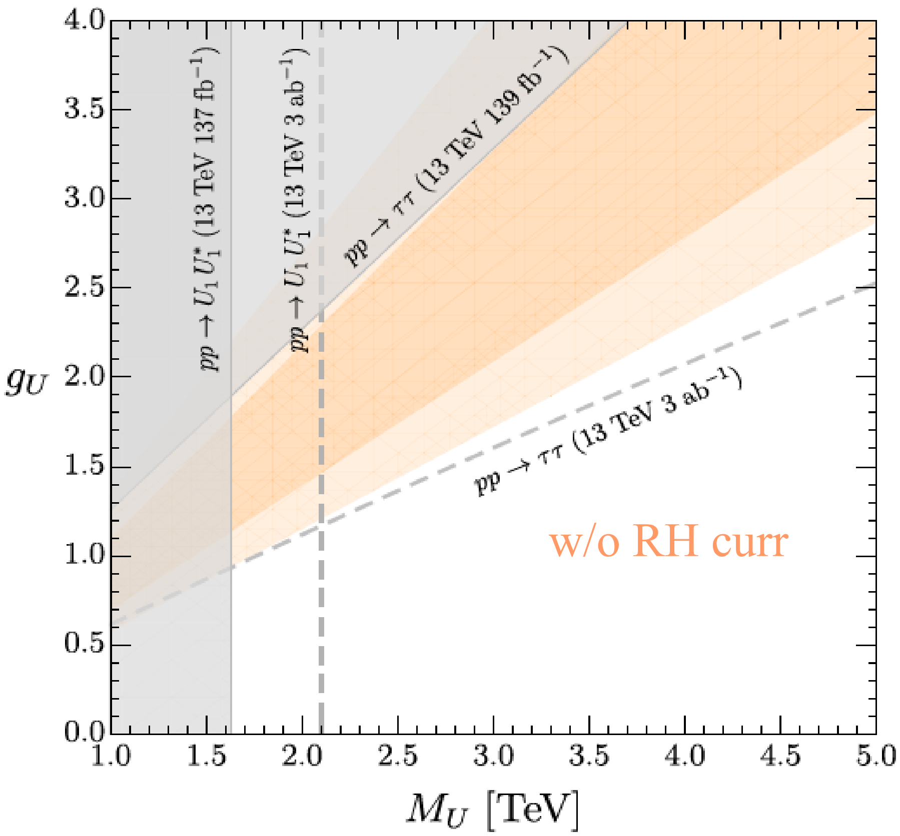

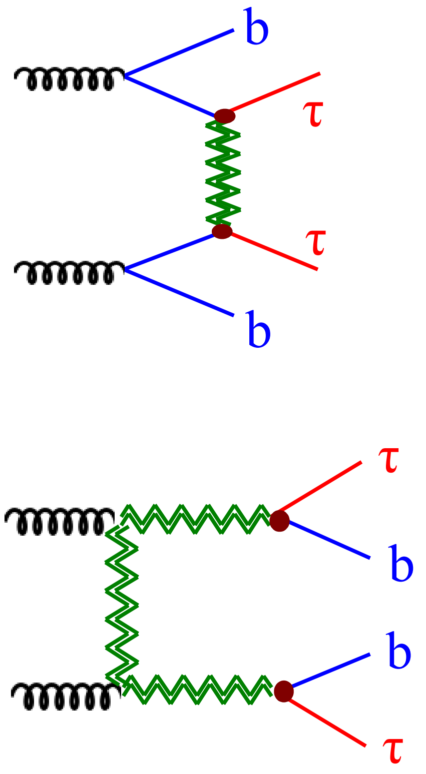

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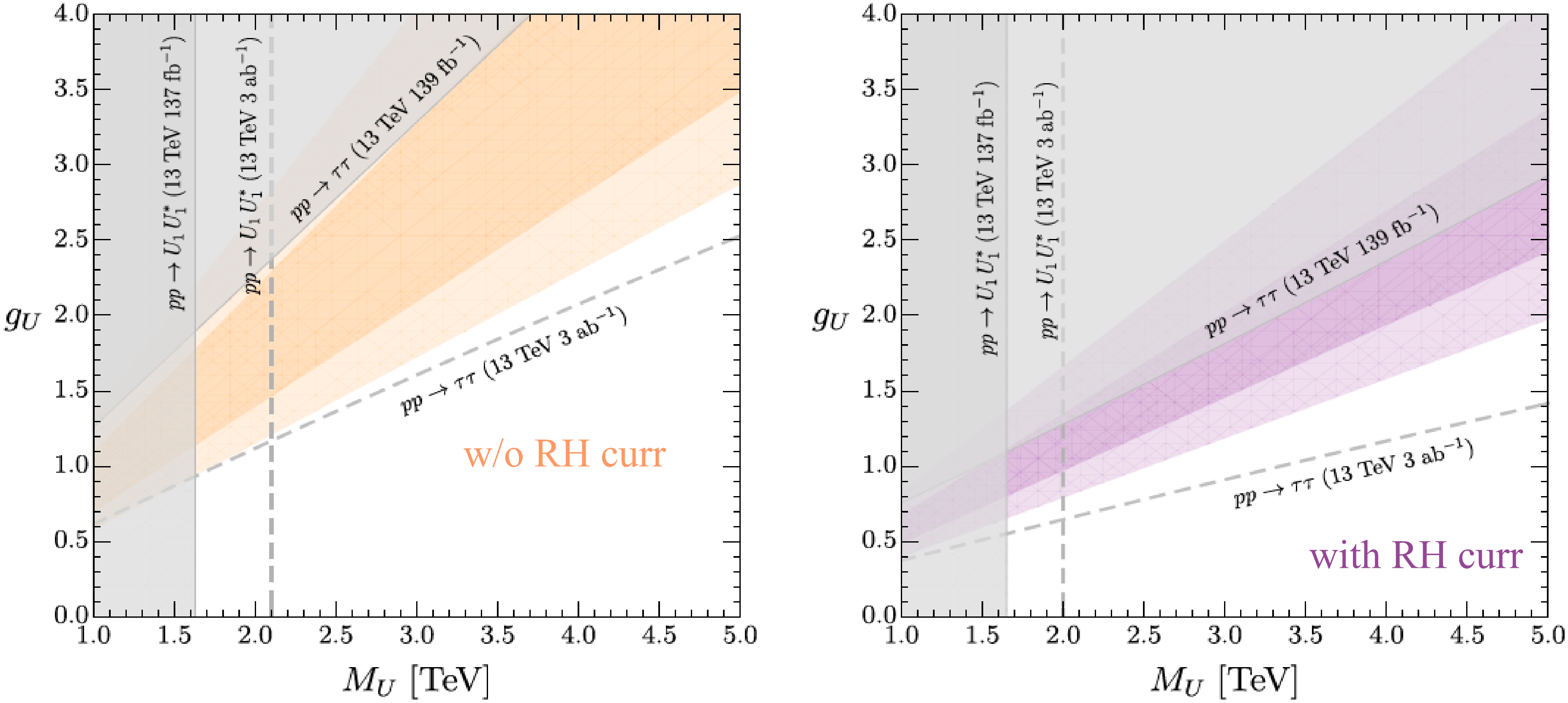
Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21



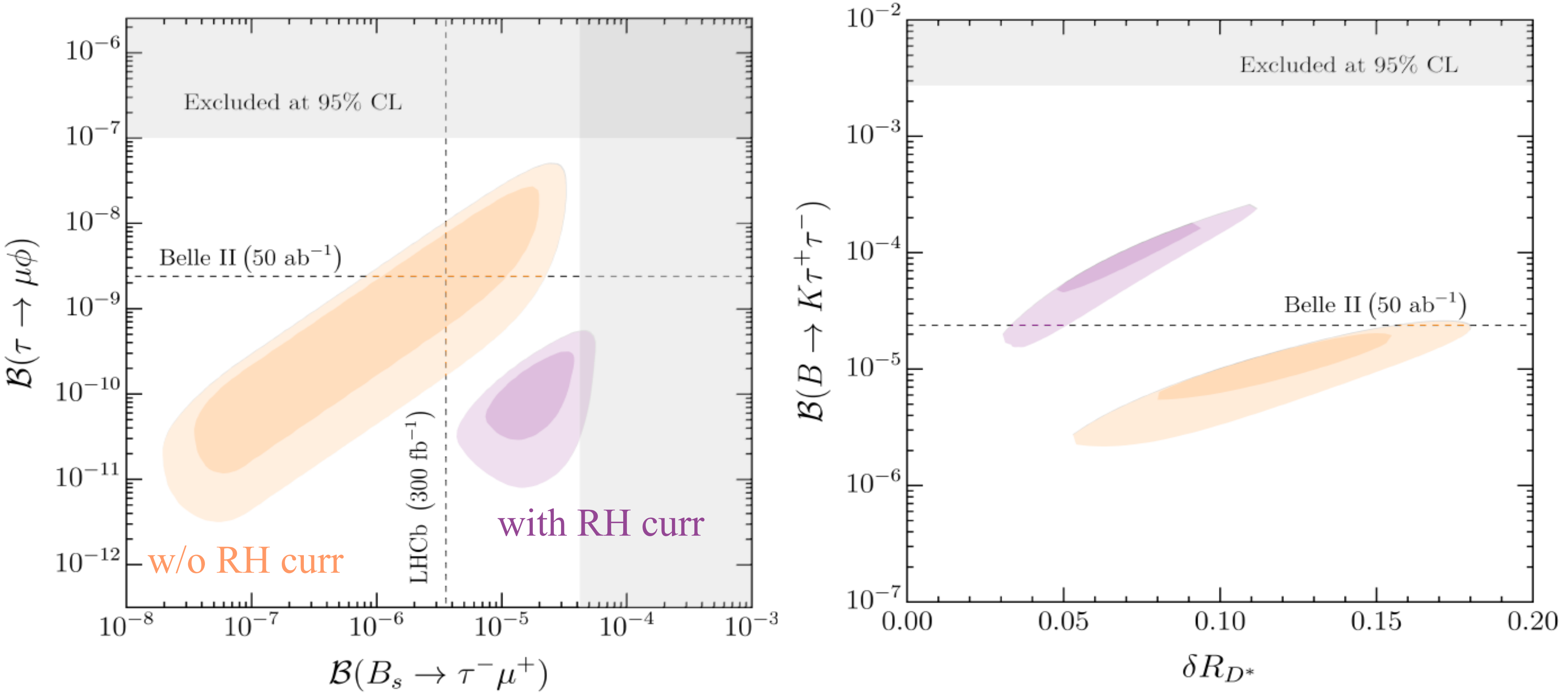
▶ <u>From EFT to simplified models</u> [*the possible mediators*]

Considering the U_1 only

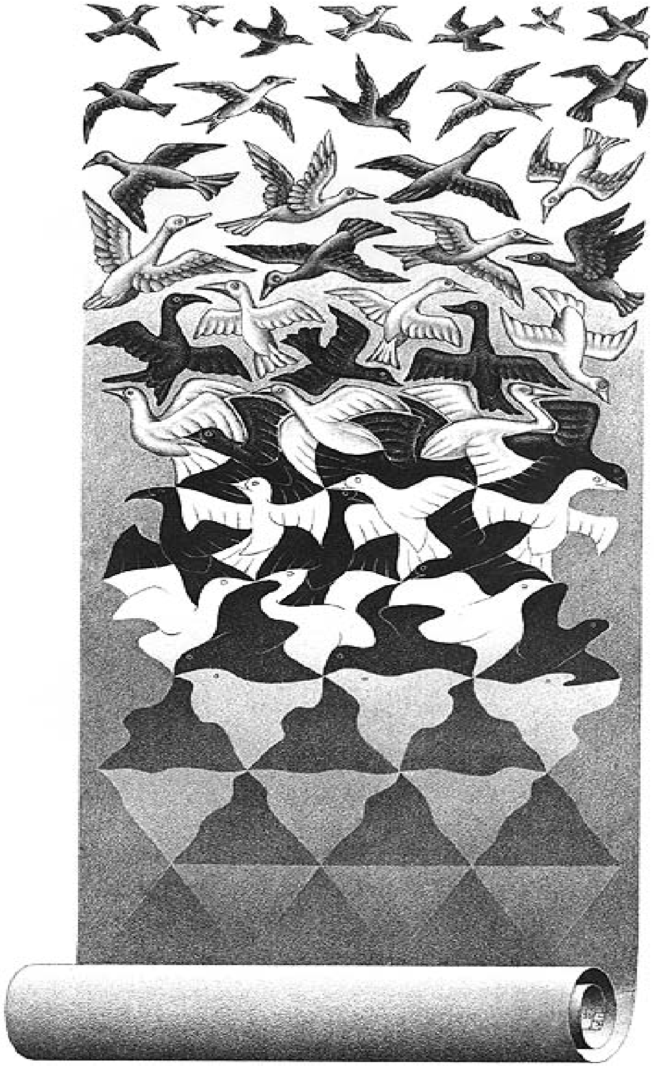
$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}}\, U_1^\mu \left[\beta^L_{i\alpha}\,(\bar q^i_L \gamma_\mu \ell^\alpha_L) - \beta^R_{i\alpha}\,(\bar d^i_R \gamma_\mu e^\alpha_R)\right] + \mathrm{h.c.}$$

and fitting <u>all low-energy data</u> leads to an excellent description of present data which is fully <u>consistent with high-pT searches</u>, and has interesting implications for future low-energy searches:

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



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 $SU(4) \to SU(3)_C\times U(1)_{B-L}$

$$SU(4) \sim \left[\begin{array}{c:c} SU(3)_C & 0 \\ \hdashline 0 & 0 \end{array}\right] \quad \left[\begin{array}{c:c} 0 & LQ \\ \hdashline LQ & \end{array}\right] \quad \left[\begin{array}{c:c} \frac{1}{3} & 0 \\ \hdashline 0 & -1 \end{array}\right]$$

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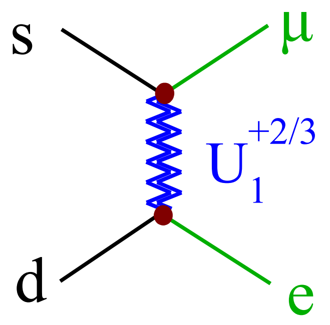
The problem of the "original PS model" are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \to \mu e$]

Attempts to solve this problem simply adding extra fermions or scalars

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



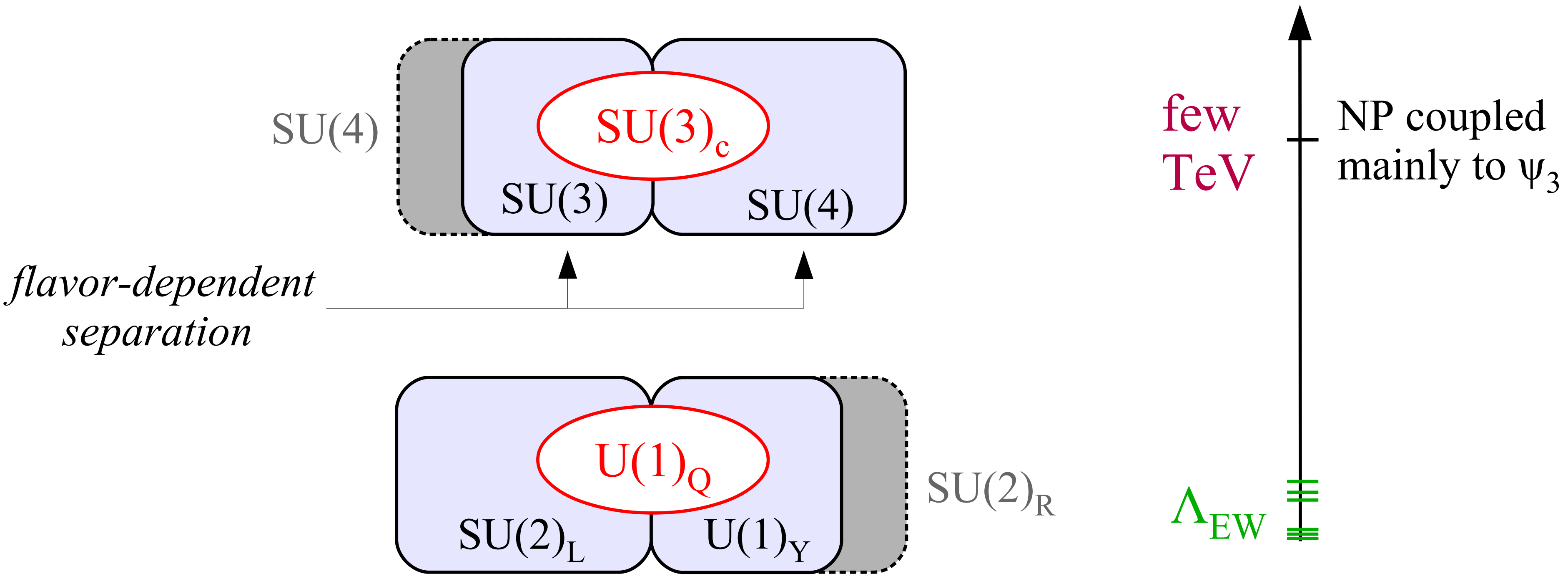
Speculations on UV completions

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*

$$\downarrow$$

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



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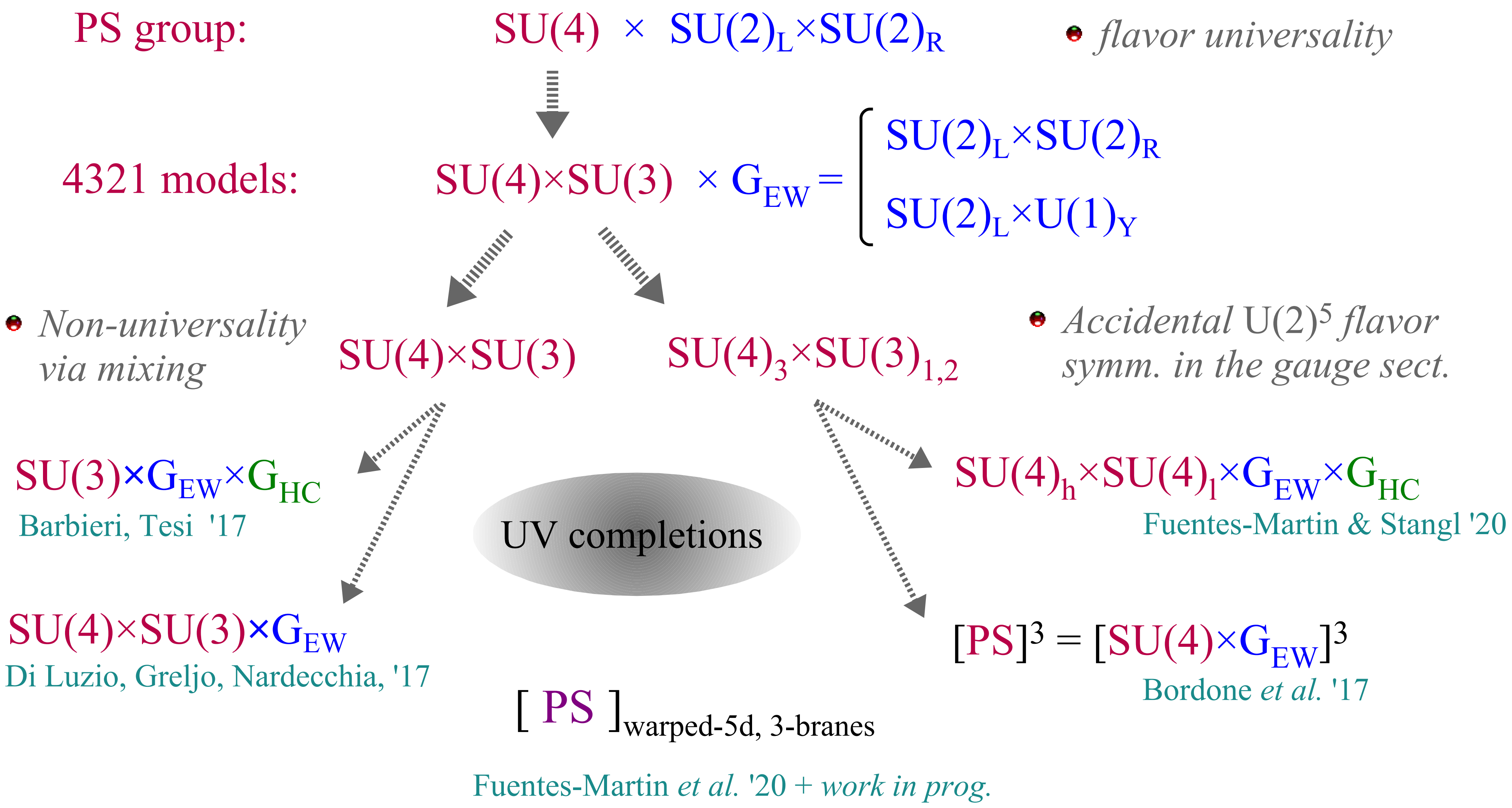


PS group: $SU(4) \times SU(2)_L \times SU(2)_R$

- *flavor universality*

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

- *Non-universality via mixing*

$SU(4) \times SU(3)$

$SU(4)_3 \times SU(3)_{1,2}$

- *Accidental* U(2)^5 *flavor symm. in the gauge sect.*

$SU(3) \times G_{EW} \times G_{HC}$

Barbieri, Tesi '17

$SU(4) \times SU(3) \times G_{EW}$

Di Luzio, Greljo, Nardecchia, '17

UV completions

$SU(4)_h \times SU(4)_l \times G_{EW} \times G_{HC}$

Fuentes-Martin & Stangl '20

$[PS]^3 = [SU(4) \times G_{EW}]^3$

Bordone *et al.* '17

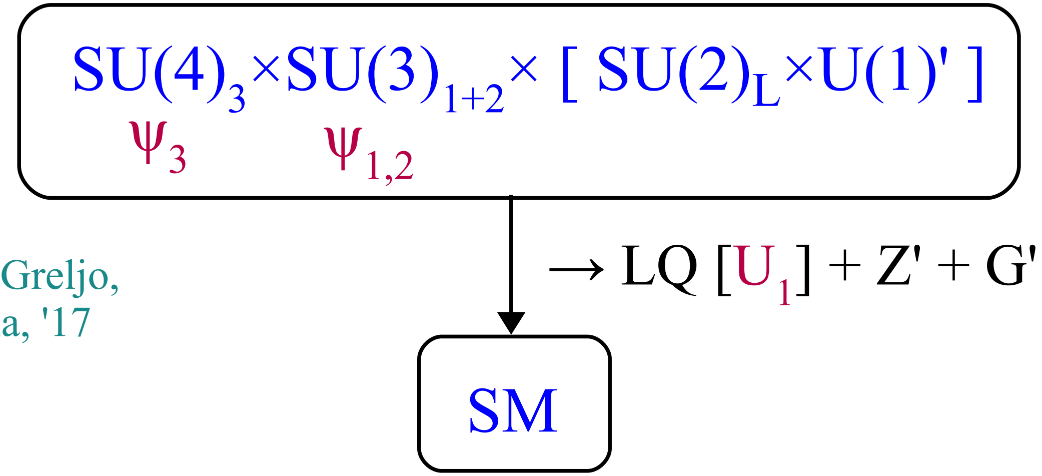
$[\ PS\ ]_{\text{warped-5d, 3-branes}}$

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

Speculations on UV completions

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 $\psi_{1,2}$

$\rightarrow$ LQ $[U_1] + Z' + G'$

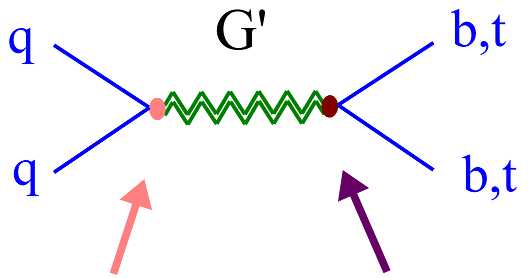
SM

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*)



small coupling to light quarks

large coupling to 3rd gen. quarks

Speculations on UV completions

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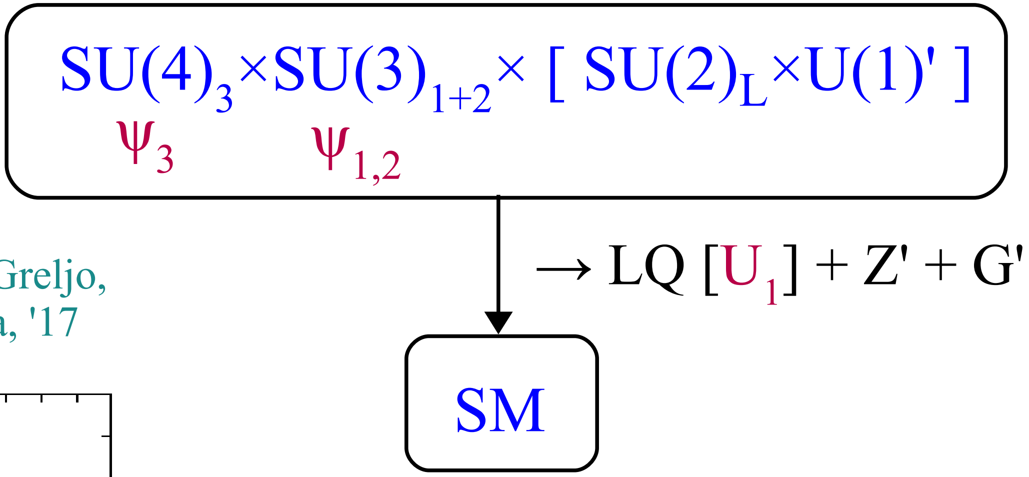

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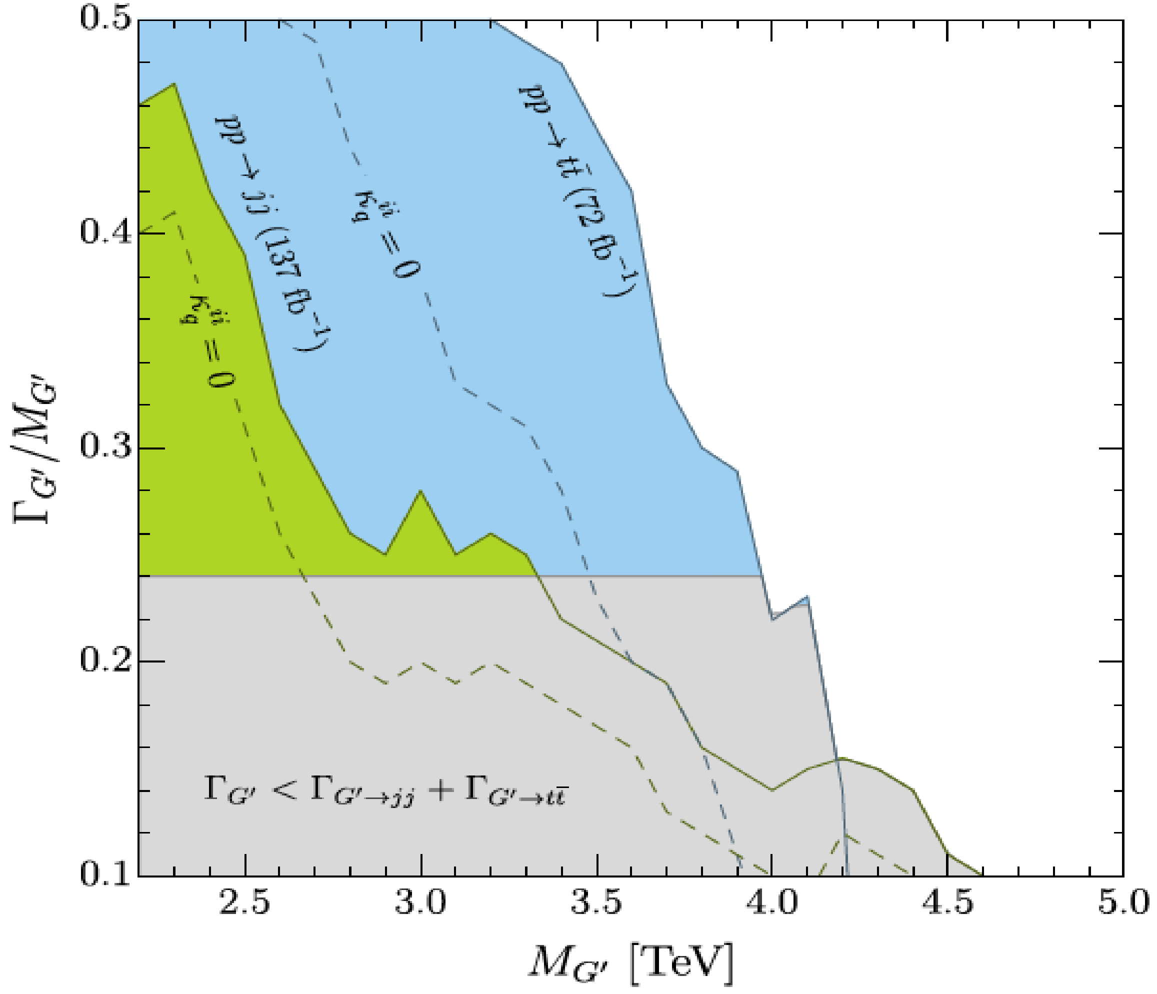
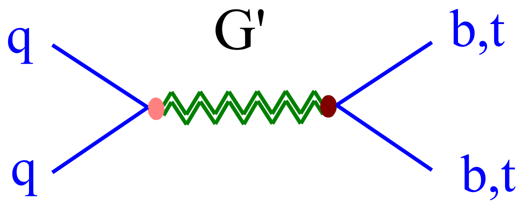


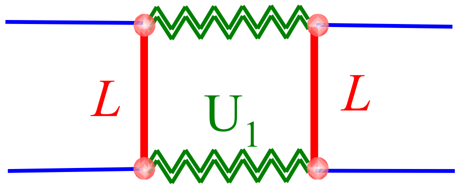


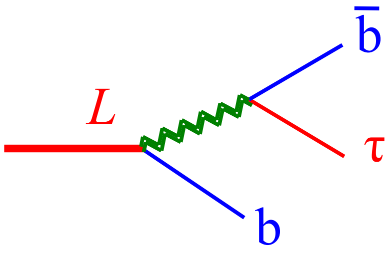
Presently, the strongest constraint on the energy scale of the model [from pp → $t\,\bar{t}$]

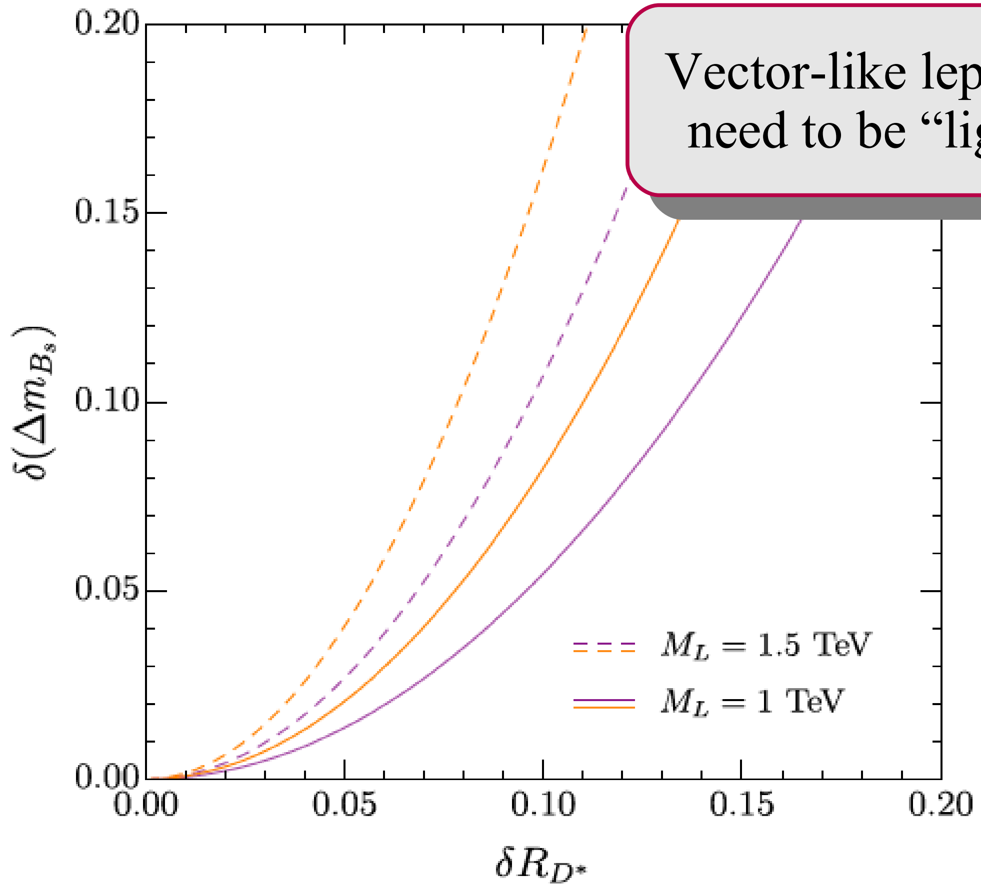
Speculations on UV completions

A second important ingredient of this class of UV models are vector-like quarks and vector-like leptons, which play a key role in both low- and high-energy observables

E.g.: B_s mixing [$\Delta F=2$]





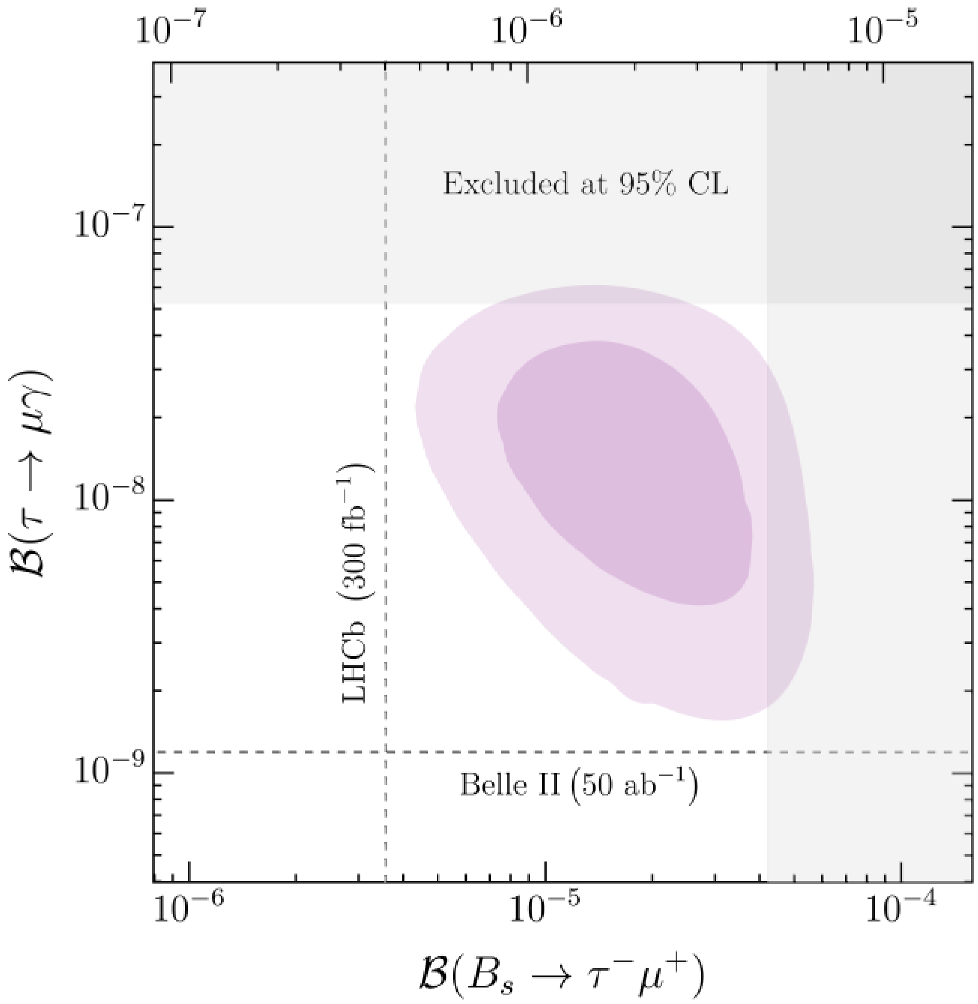


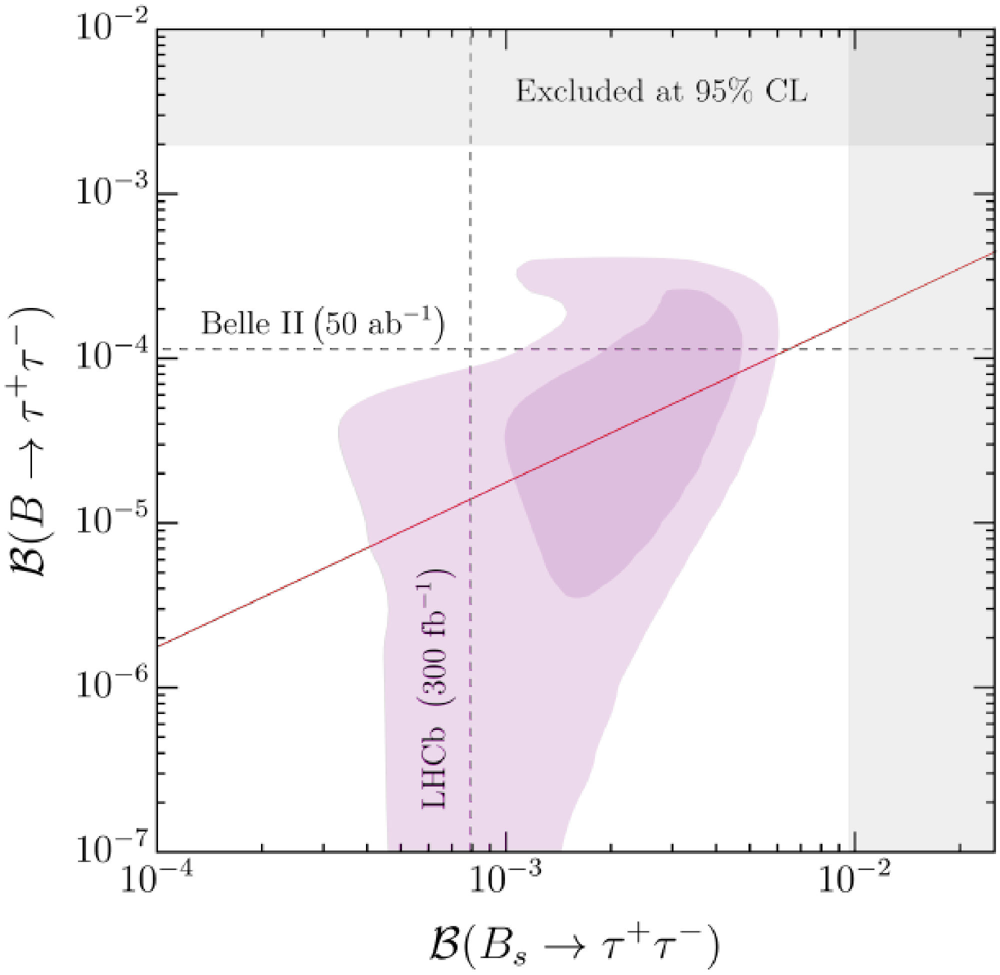
Vector-like leptons need to be "light"

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

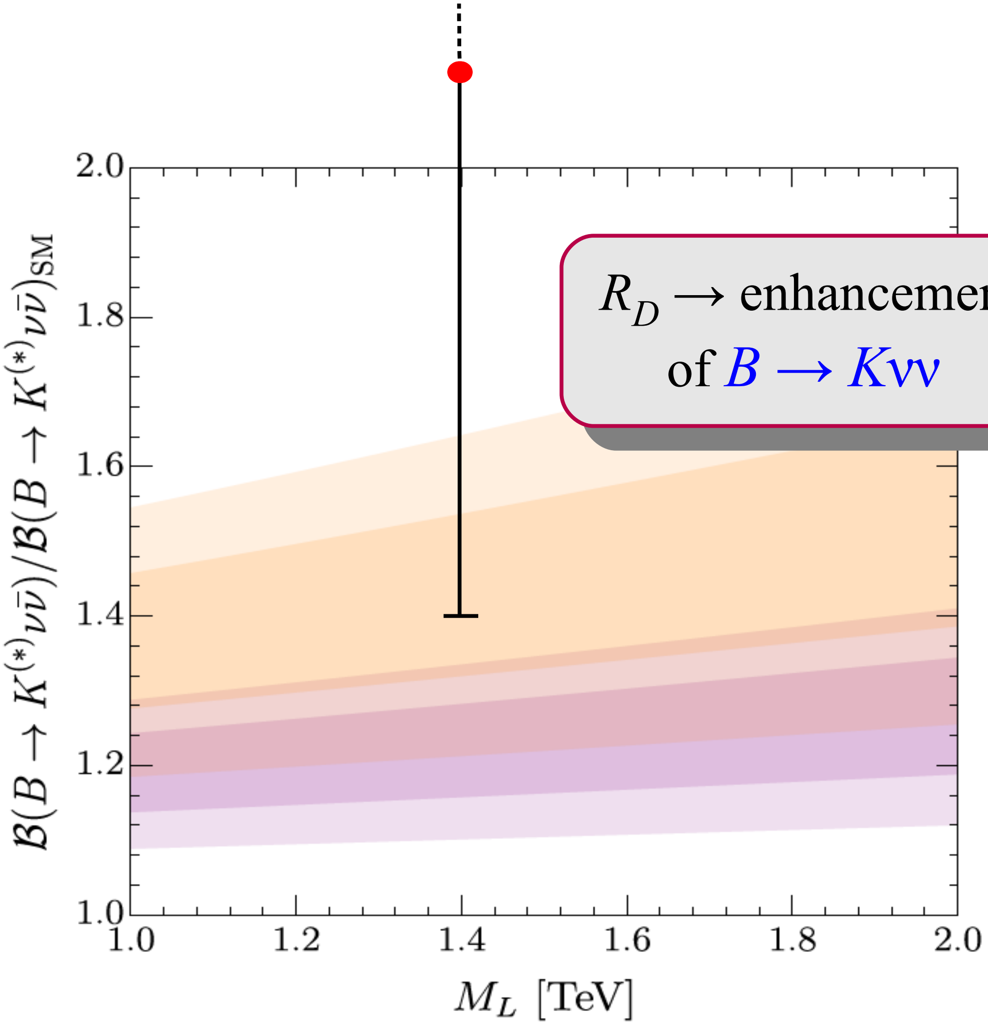

Backup

▶ *Other low-energy observables*

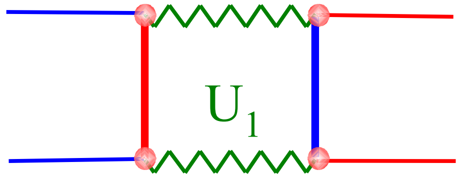


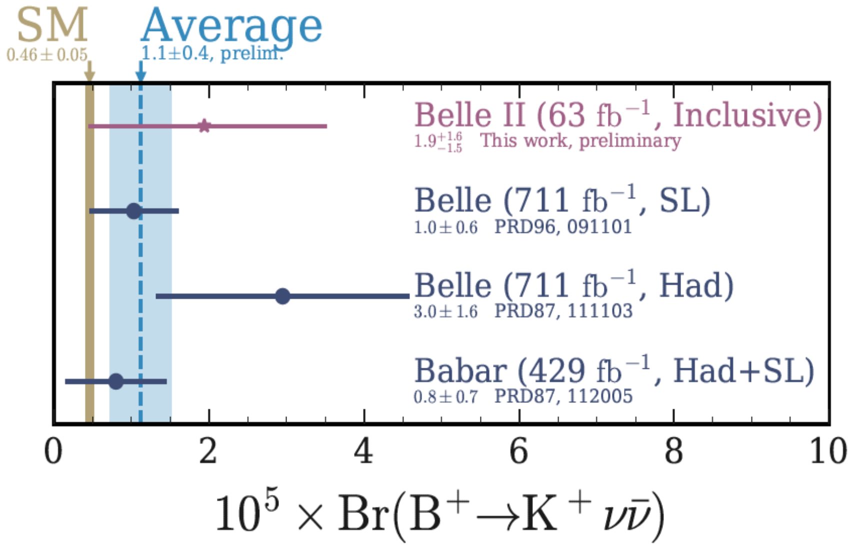


Other low-energy observables



$R_D \to$ enhancement of $B \to K\nu\nu$

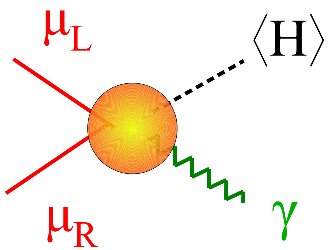




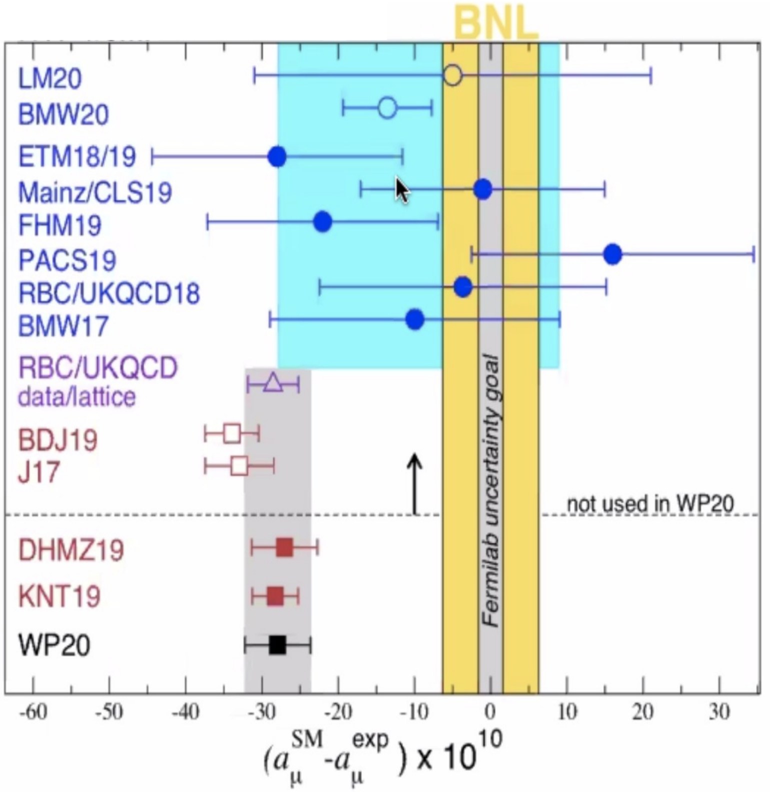
Fuentes-Martin, GI, Konig, Selimovic, '20
Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21

▶ *What about* $(g\text{-}2)_\mu$?

Not obvious how to reconcile the $(g\text{-}2)_\mu$ anomaly with both flavor anomalies and, more generally, with models with a “natural” flavor structure (↔ Y_{SM}).



$$\Delta a_\mu = (a_\mu^{exp} - a_\mu^{SM}) \approx (a_\mu^{SM})^{EW} \quad \longrightarrow \quad \Lambda \sim \left[\begin{array}{ll} 100\text{ GeV} & \text{(helicity suppression} \sim m_\mu \text{ as in SM)} \\ 10\text{ TeV} & \text{(remove helicity suppr. } m_\mu \to m_t) \end{array}\right.$$



A. El-Khadra '21

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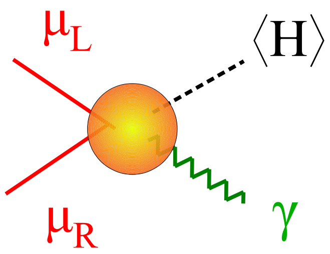

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Main difficulty: strong flavor alignment needed to avoid bounds from $\mu \to e\,\gamma$ (10^{-5} alignment in the 1 ↔ 2 sector) & $\tau \to \mu\,\gamma$ (10^{-1} alignment)

Example of recent *attempts to combine LFU anomalies & g-2*

- $a_\mu \oplus R_K$ 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

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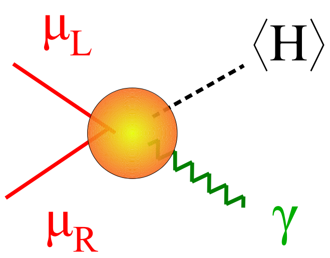

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However… $(g\text{-}2)_\mu$ is more "flexible" (*no generation change, necessary loop-level*)
→ could come from light NP. *No obvious connection to the flavor anomalies*