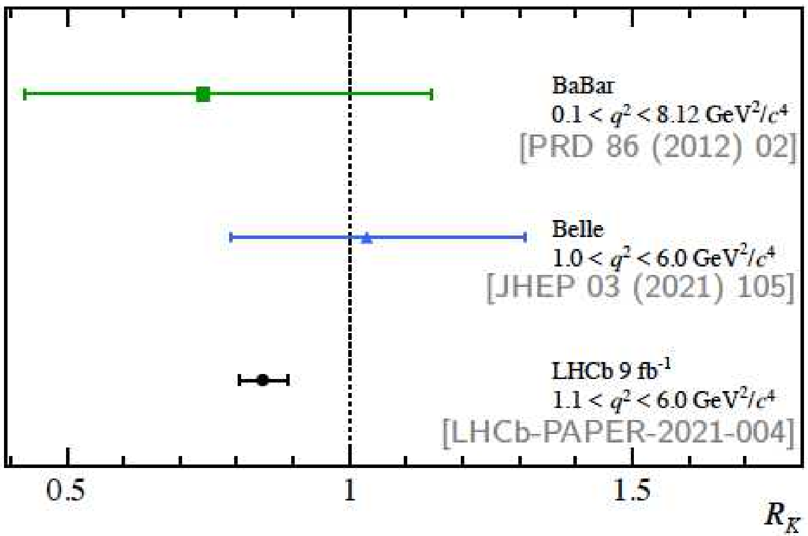
B-physics anomalies: *facts*, *hopes*, *dreams*, & *worries*

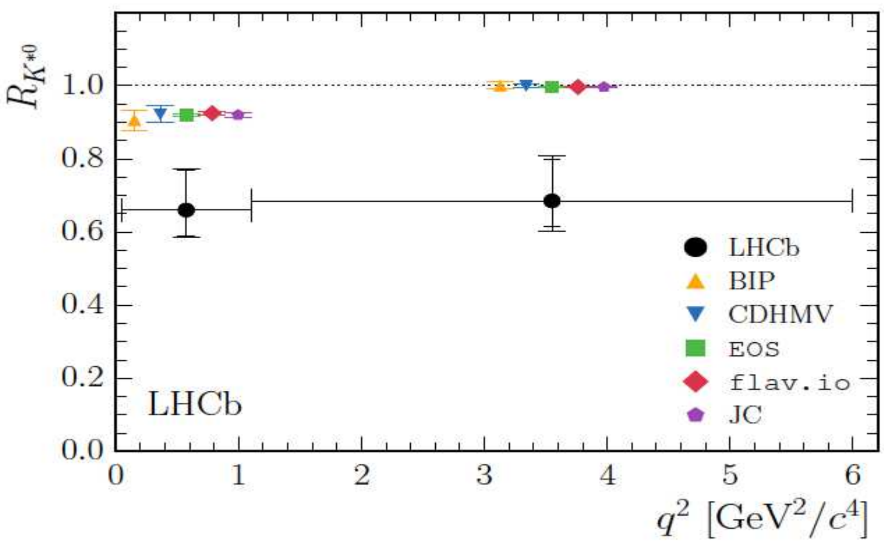
Gino Isidori
[*University of Zürich*]

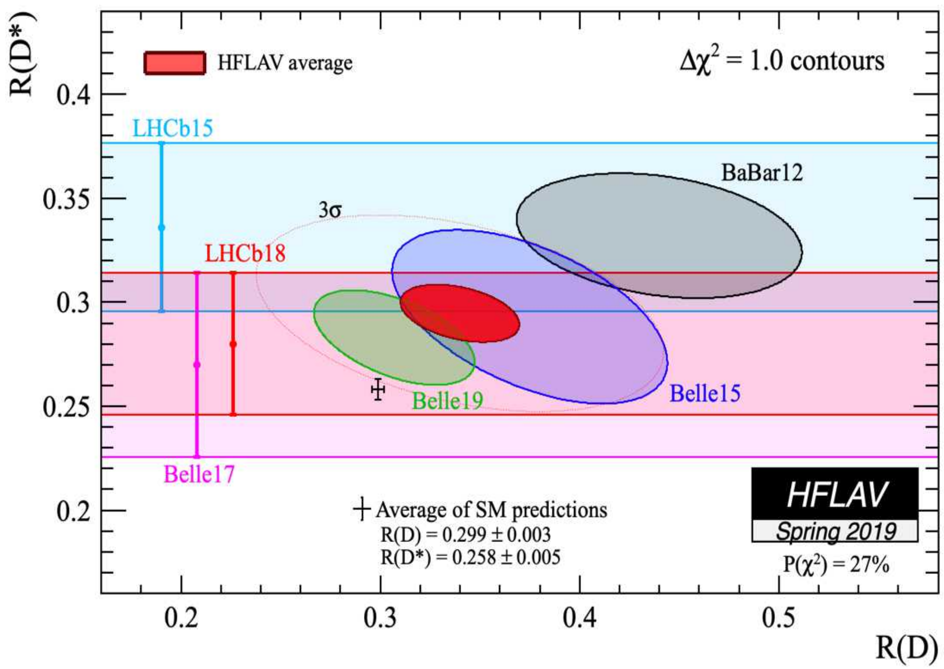
University of Zurich[UZH]

European Research Council
Established by the European Commission

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

3.1σ from single "clean" observable [R_K]

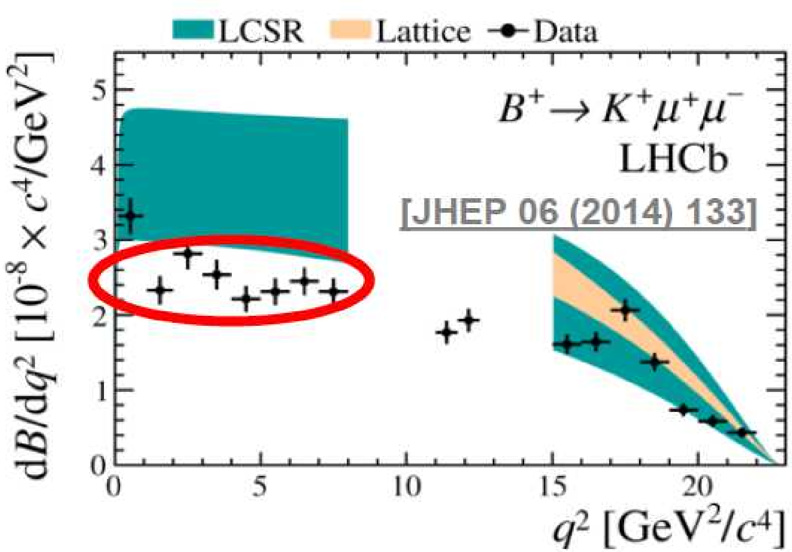
A closer look to the data

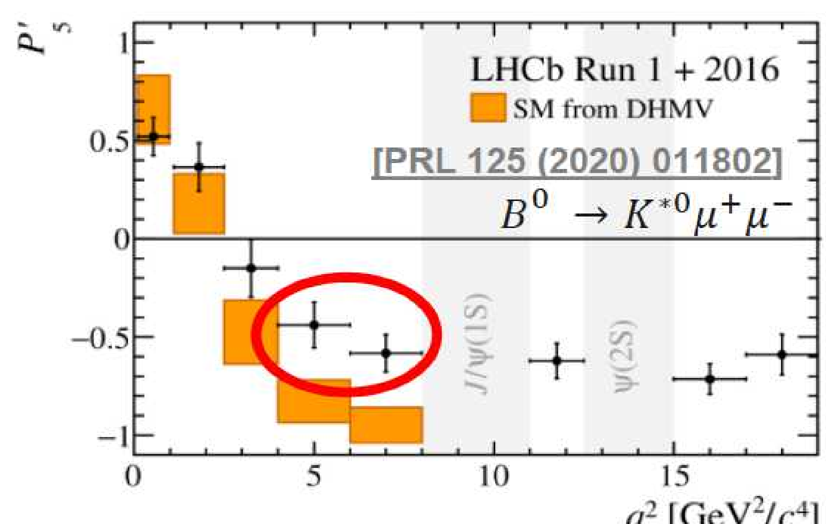
- $b \to s\, l^+ l^-$ (neutral currents)

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($B_s \to \mu\mu$)

chronological order





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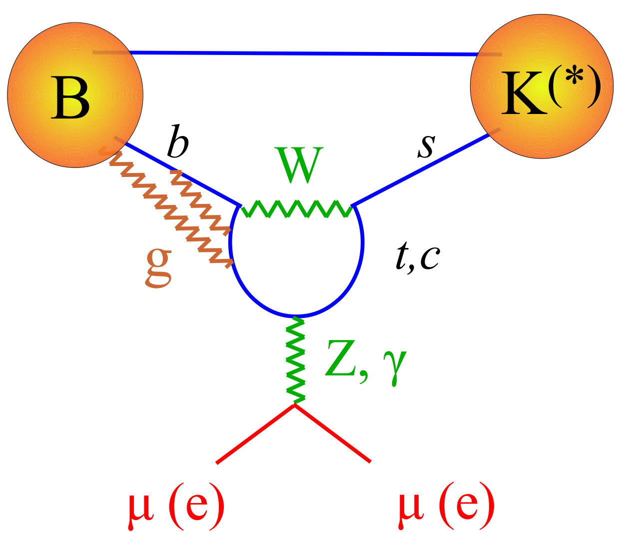
th. error <1%

th. error few %



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.

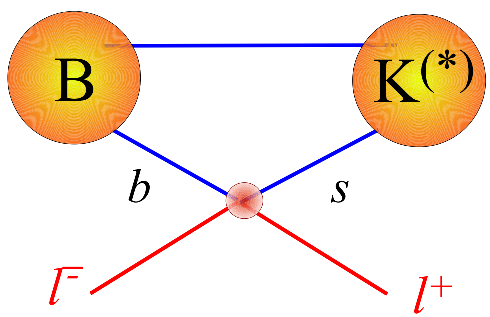
A closer look to the data

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:

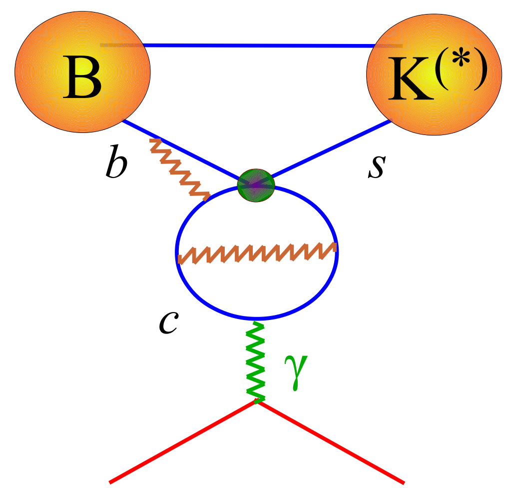
$$\mathcal{O}_{10}^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5 \ell)$$
$$\mathcal{O}_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$



"easy" & "clean"

Four-quark operators:

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



"difficult"

↓

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*

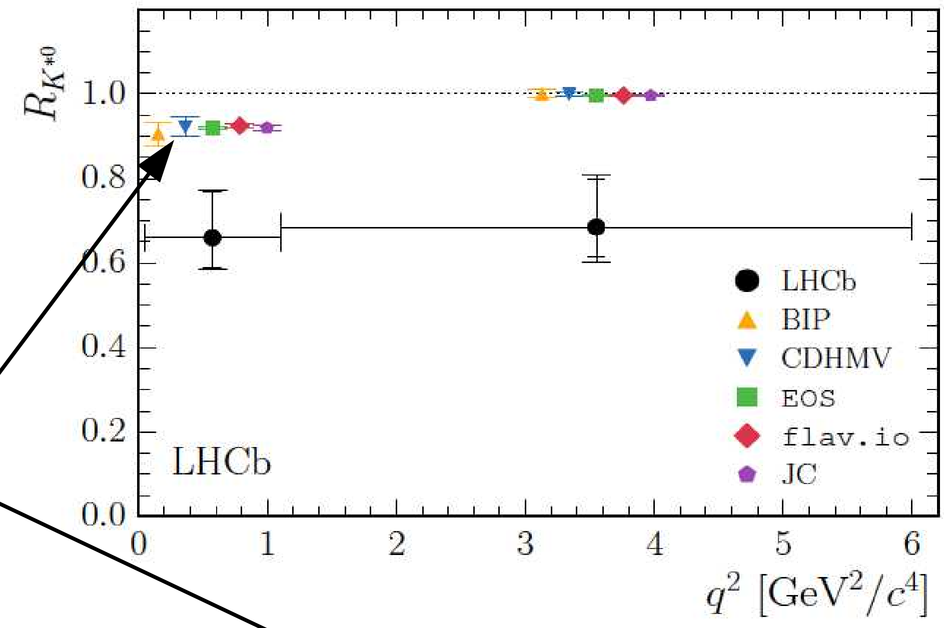
The LFU ratios:

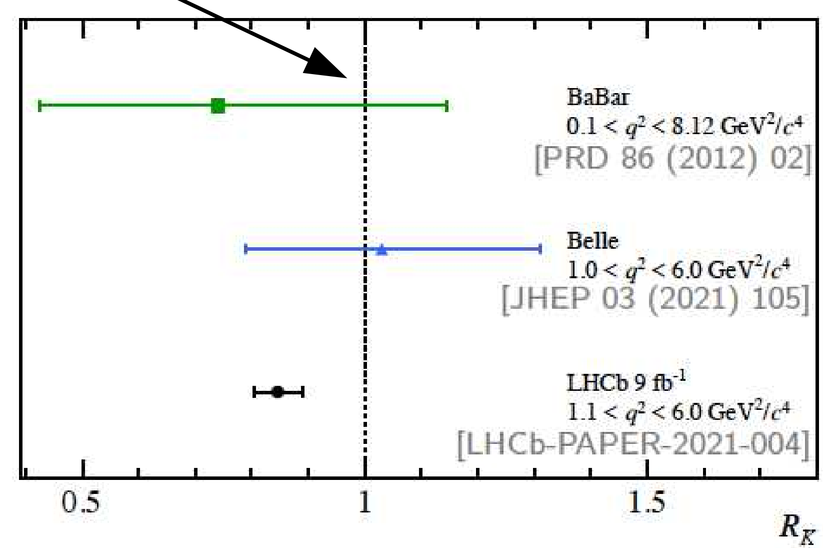
$$R_H = \frac{\int d\Gamma(B \to H\,\mu\mu)}{\int d\Gamma(B \to H\,ee)} \qquad (H = K, K^*)$$

SM prediction very robust: $(R_H) = 1$
[*up tiny QED and lepton mass effects*]

Bordone, GI, Pattori '16
GI, Nabeebascus, Zwicky '20

Deviations from the SM predictions ranging from 2.2σ to 3.1σ in each of the 3 bins measured by LHCb





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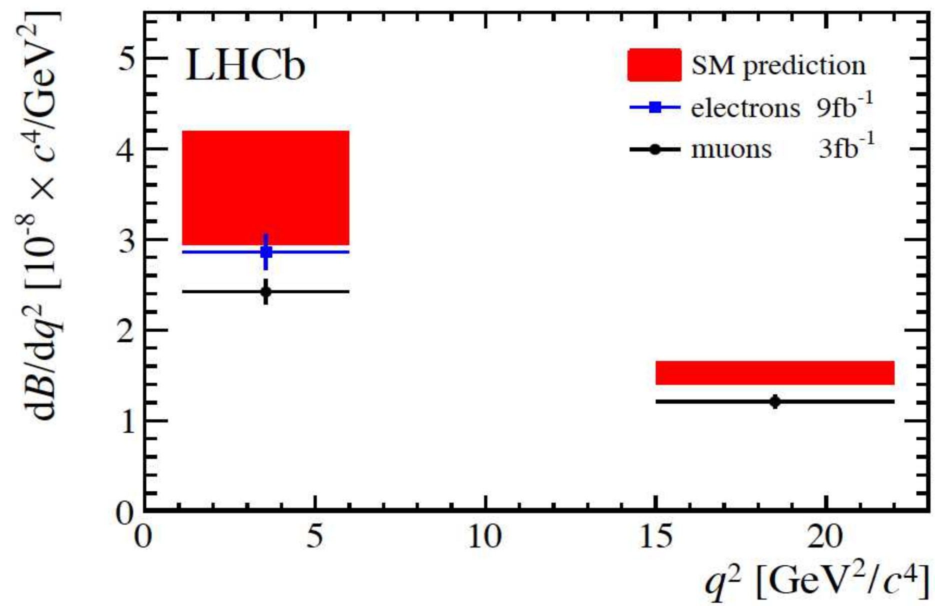
$B \to K\,ll$ LHCb '21



Deviations from the SM predictions ranging from 2.2σ to 3.1σ in each of the 3 bins measured by LHCb

According to our best estimates of the SM rates, what is observed is a (15-20)% *deficit of the muon modes*

$B_s \to \mu\mu$:

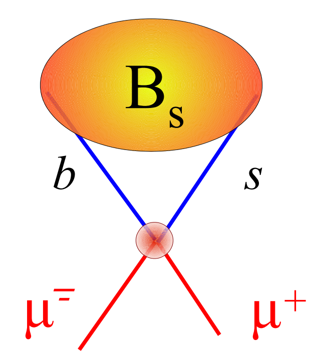
$$BR(B_s \to \mu\mu)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$

Beneke *et al.* '19

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

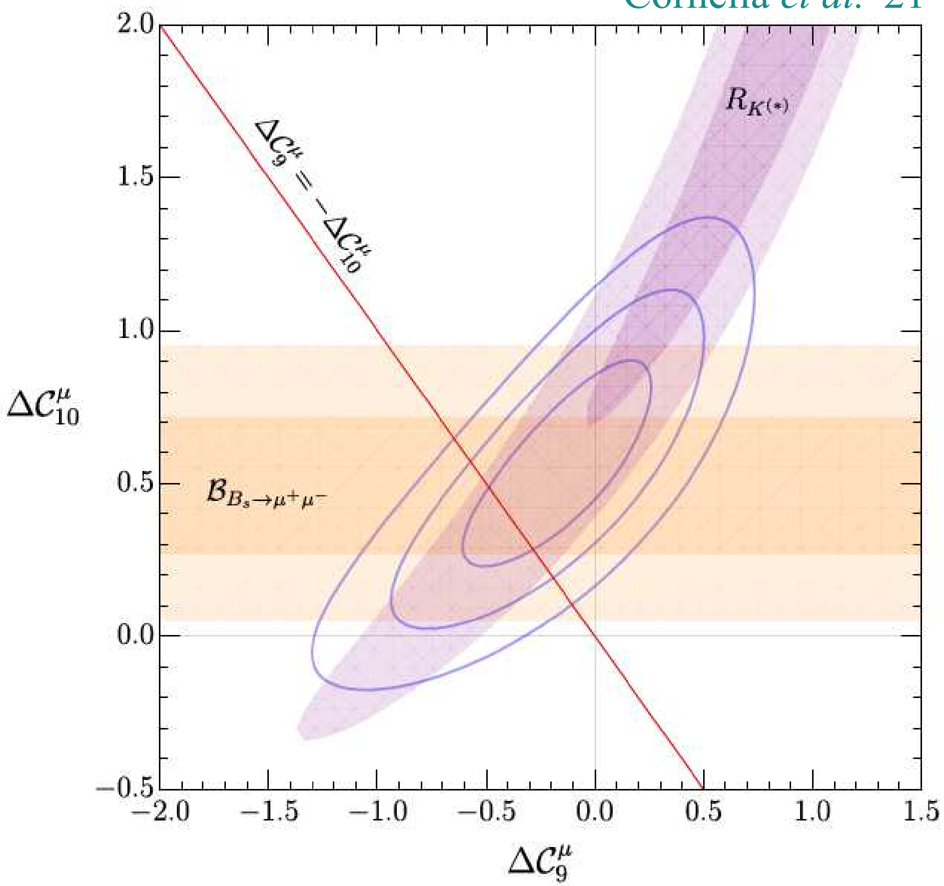
ATLAS+CMS+LHCb '21

2.3σ



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

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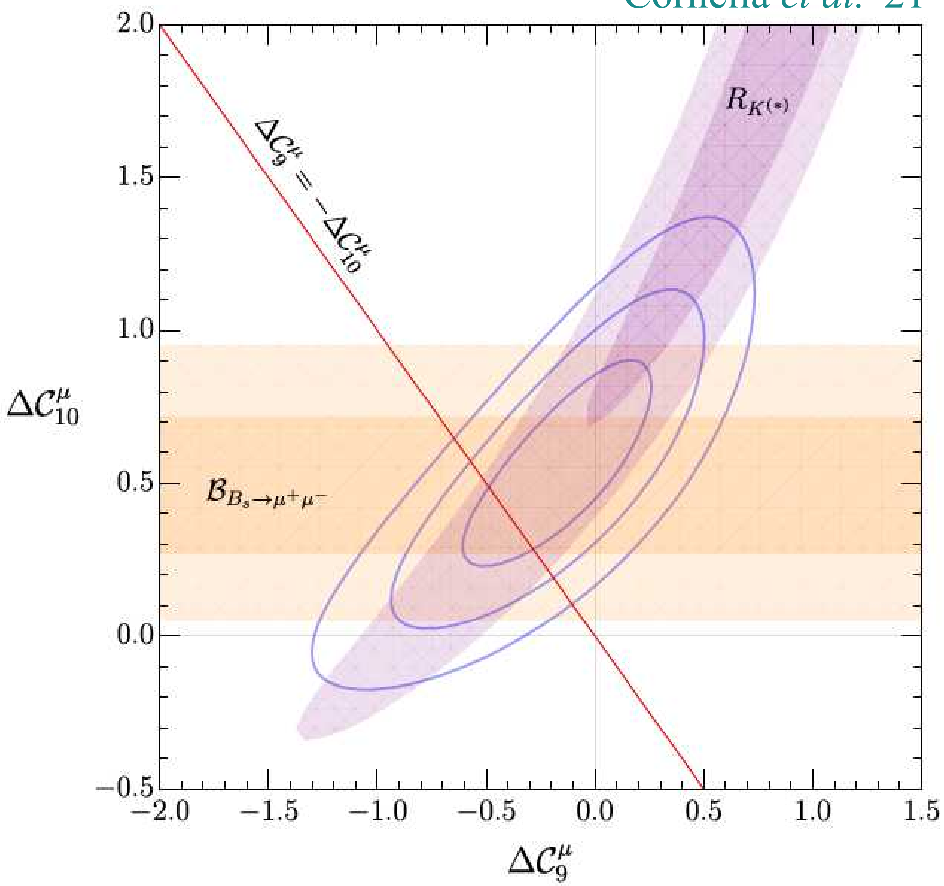

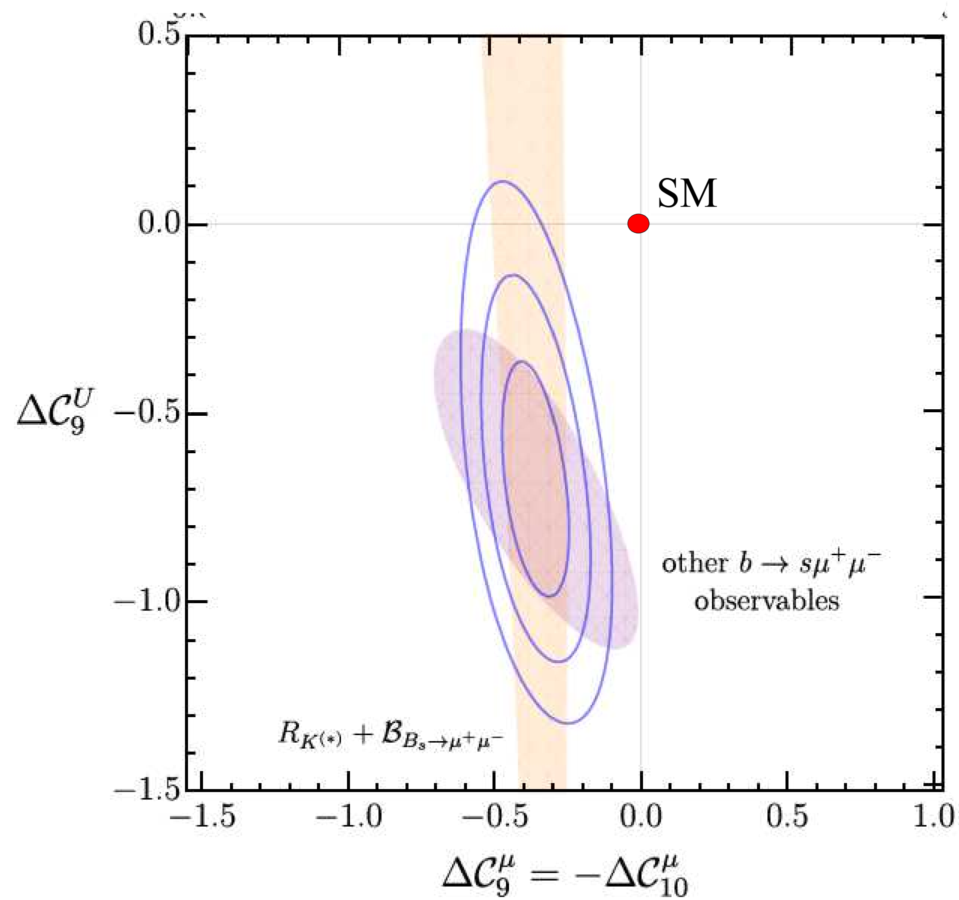

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>> 5σ with current best estimate of charm contrib

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

A closer look to the data

N.B.: the "nσ" quoted by various theory groups 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* → *no 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 $P(\Delta\chi^2 > \Delta\chi^2_{obs})$

Lancierini, GI, Owen, Serra, '21

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

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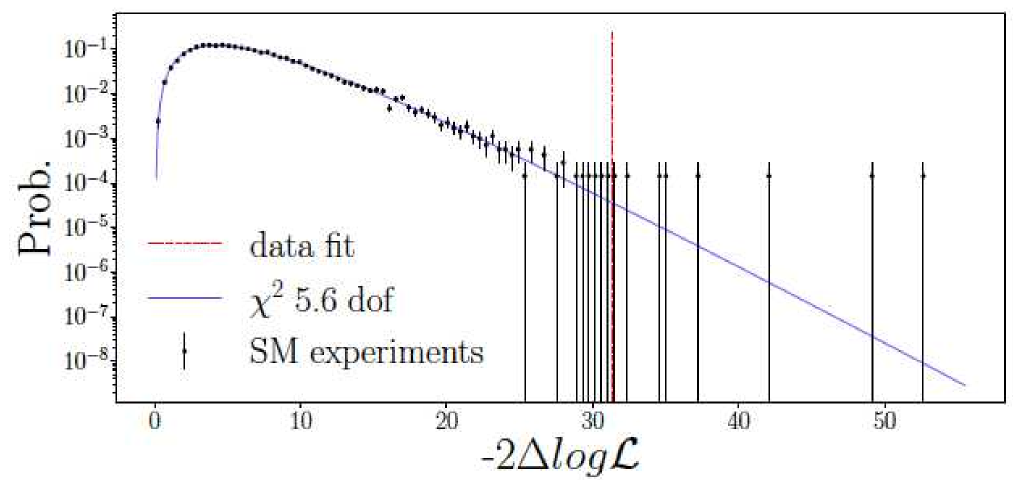
3.9σ *global significance* with respect to any form of heavy NP

Lancierini, GI, Owen, Serra, '21



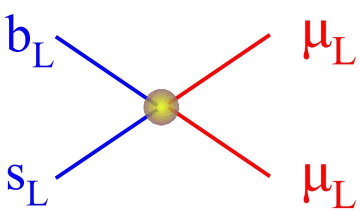
Remarkably high !

[*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

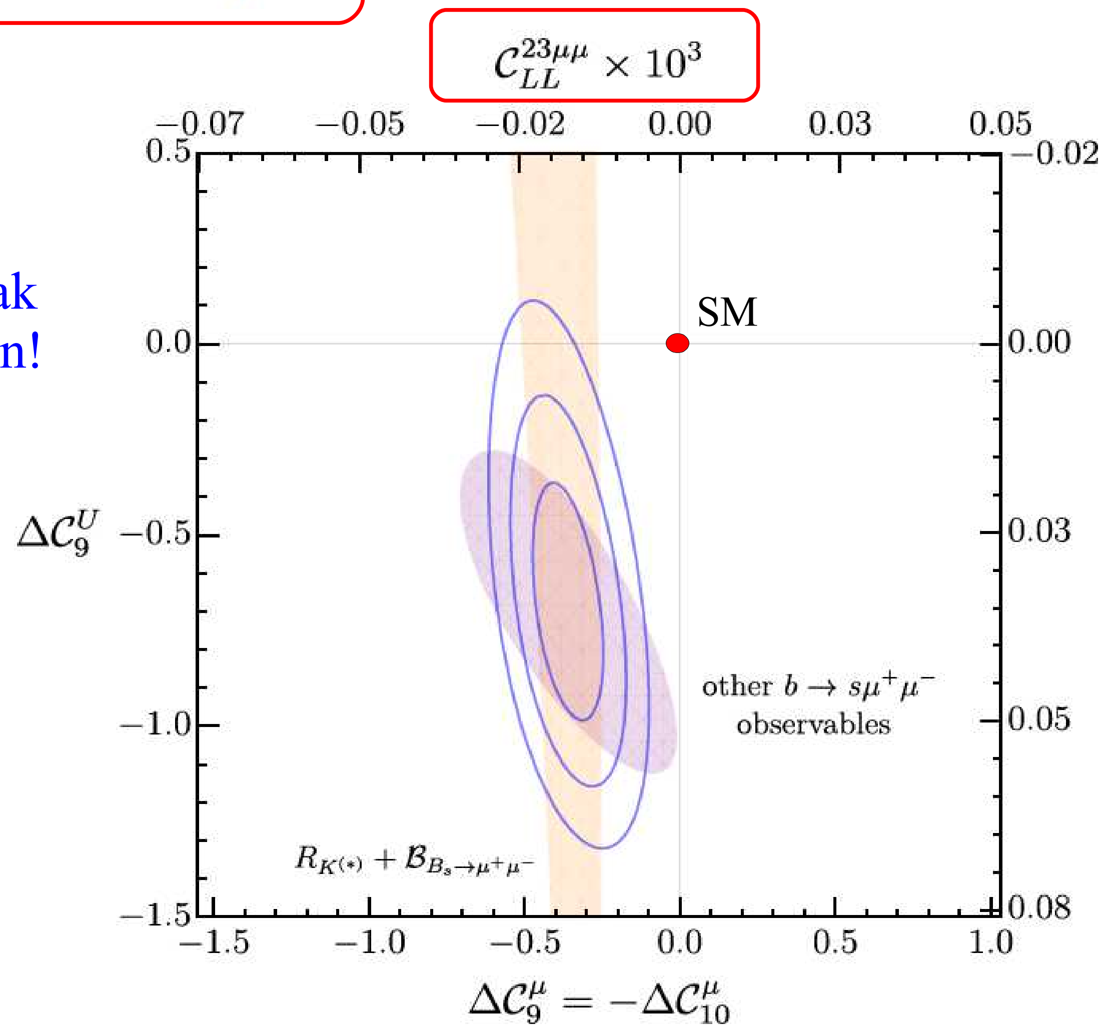
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j) \;\; = \frac{1}{2}\left[\mathcal{O}_{\ell q}^{(1)} + \mathcal{O}_{\ell q}^{(3)}\right]^{ij\alpha\beta}$$



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

super-weak interaction!

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



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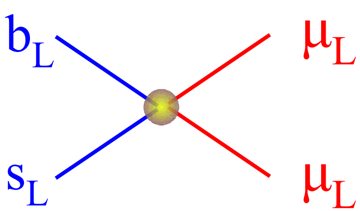

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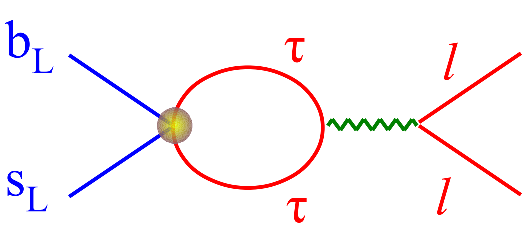
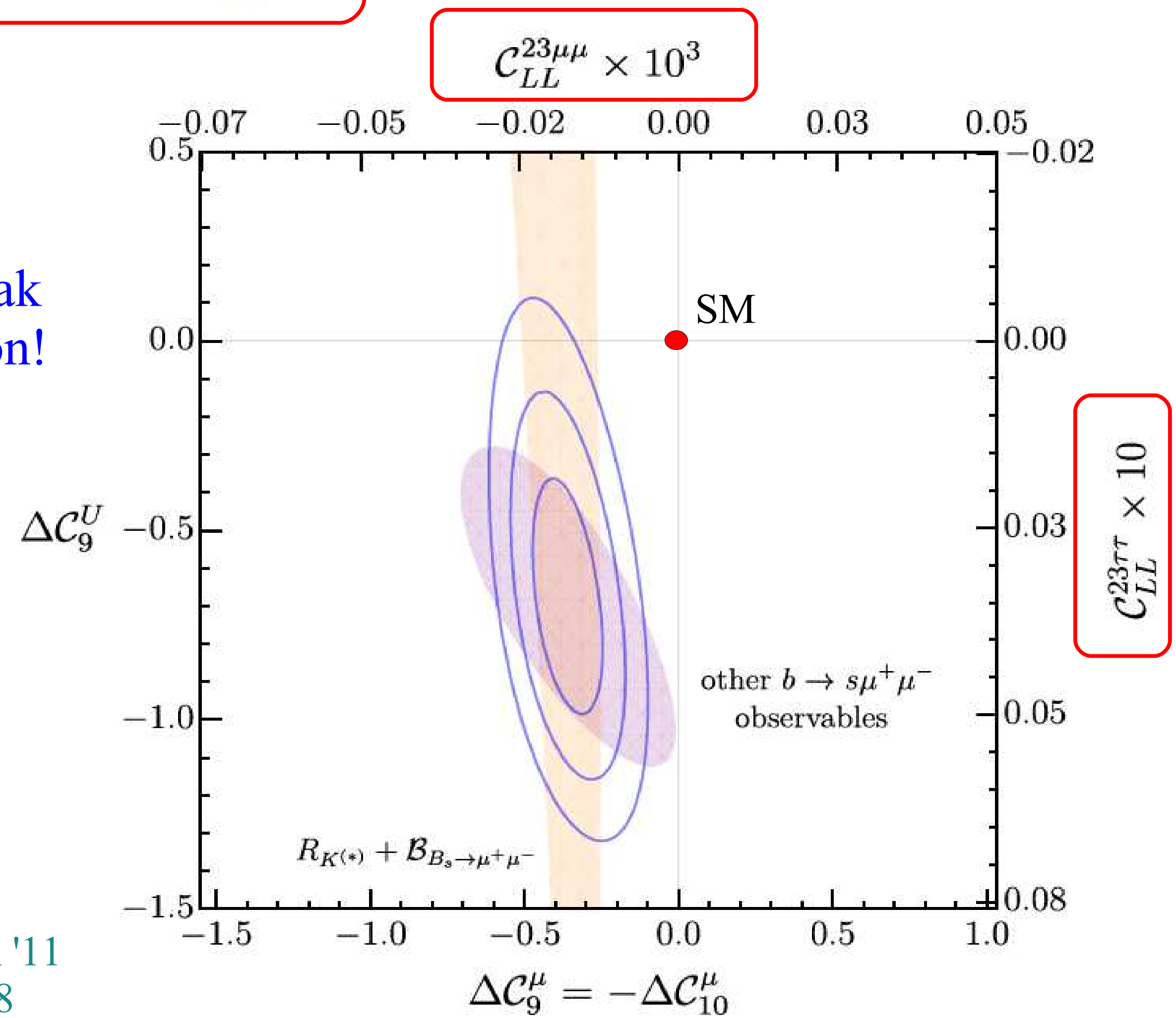
$C_{LL}^{23\mu\mu} \rightarrow \Delta C_9^\mu = -\Delta C_{10}^\mu$



$C_{LL}^{23\tau\tau} \rightarrow \Delta C_9^{\rm Univ}$

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



▶ *A closer look to the data*

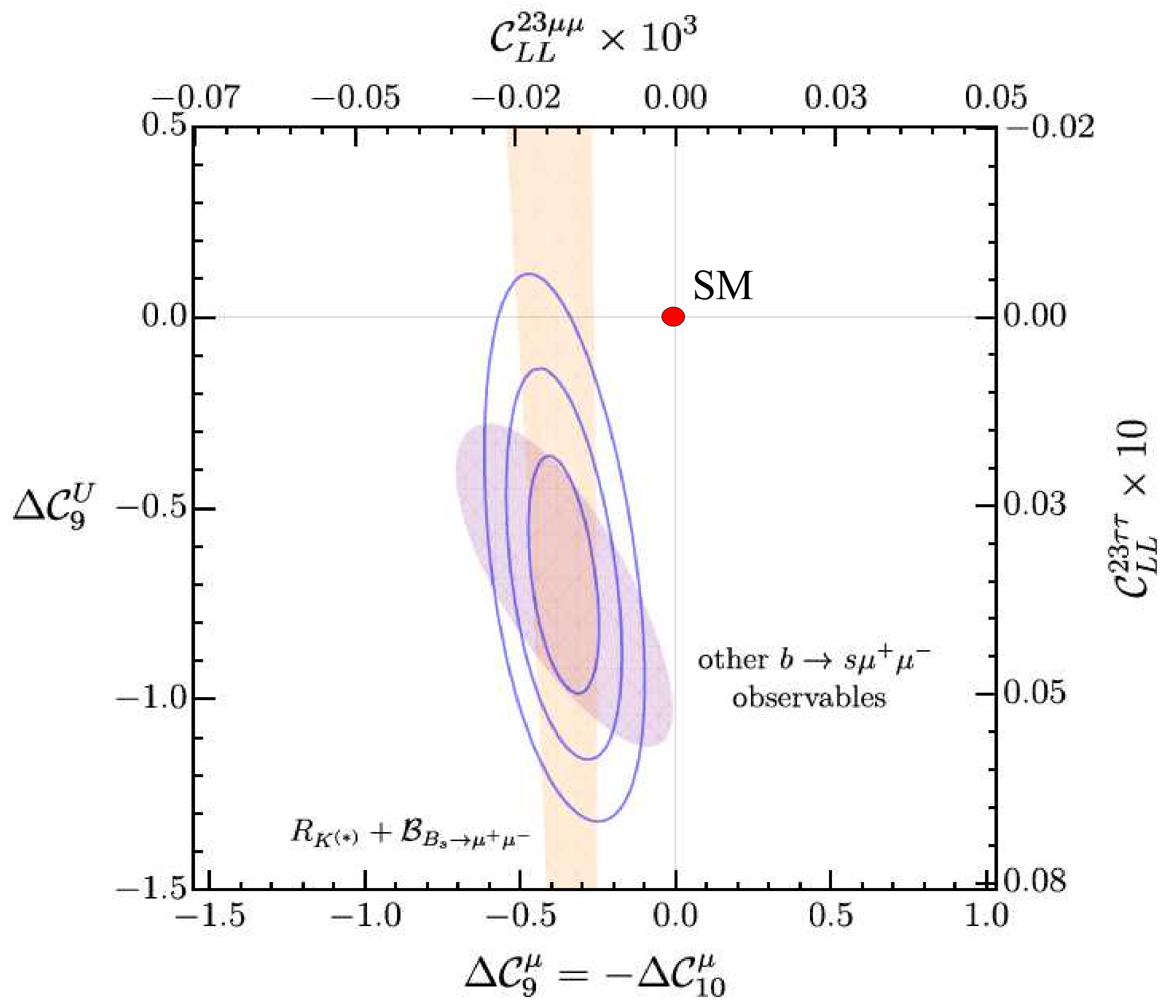
Some *historical* remarks,
on how we arrived here:

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

2013 P_5' [$B \to K^* \mu\mu$] $\to$ $C_9 \neq C_9^{SM}$ Descotes-Genon, Matias, Virto '13

2014 hypothesis $\Delta C_9^\mu = -\Delta C_{10}^\mu$
==> $R_{K^*} \sim R_K$ & $B(B_s \to \mu\mu) < B_{SM}$

Hiller & Schmaltz '14



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==> $R_{K^*} \sim R_K$ & $B(B_s \to \mu\mu) < B_{SM}$ 2017-19

Hiller & Schmaltz '14

2015 U(2) hypothesis for b→s & b→c combined ==> $C^{23\tau\tau} \sim O(10^2) \times C^{23\mu\mu}$

Barbieri, GI, Pattori, Senia '15 [+ *others...*]

2017 High-pT and EWPO

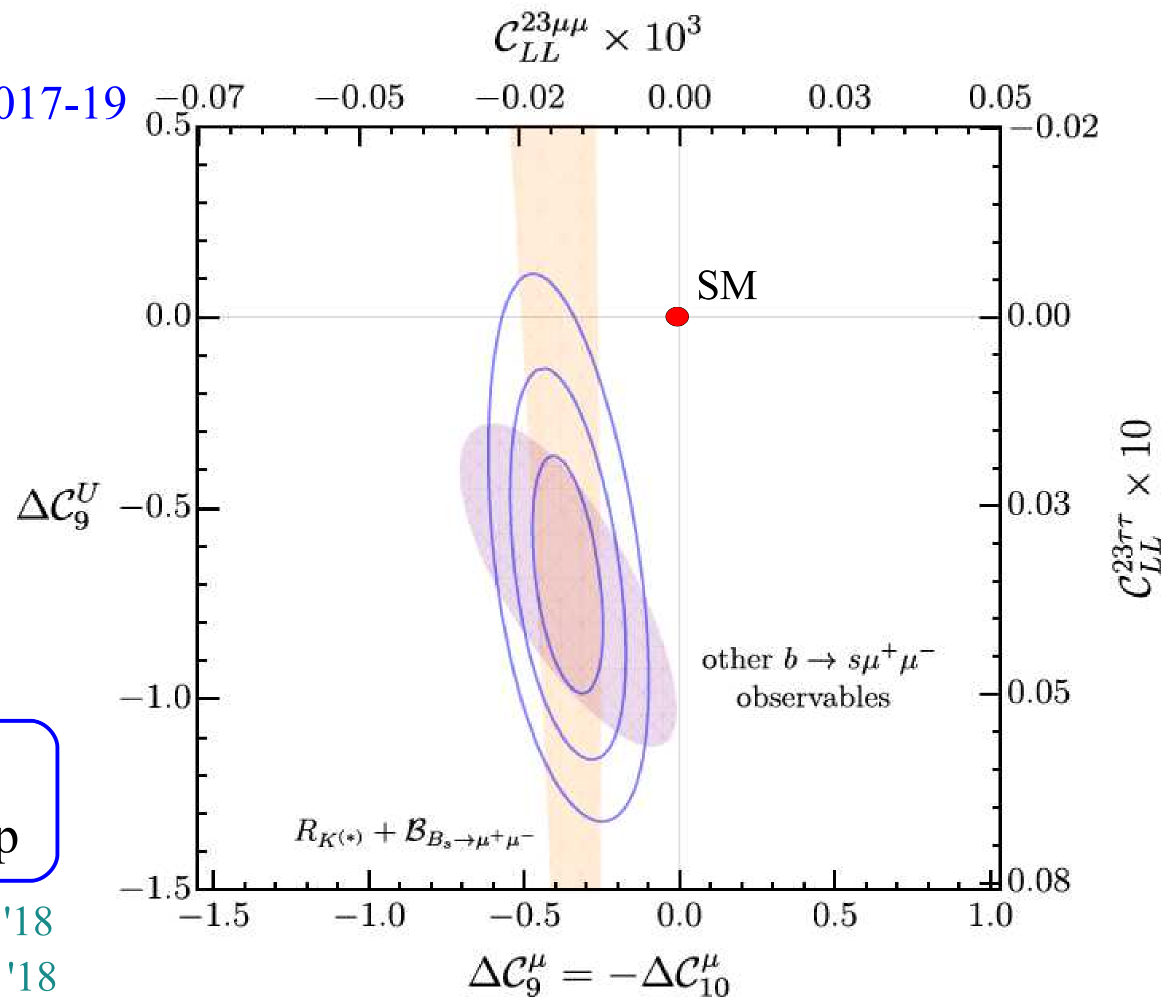
==> $C^{23\tau\tau}$ needed to explain b→c

Buttazzo, Greljo, GI, Marzocca '17

2018 - 2021 evidence of ΔC_9^U from global fits of correct size from $C^{23\tau\tau}$ @ 1-loop

Crivellin, Greub, Muller, Saturnino '18

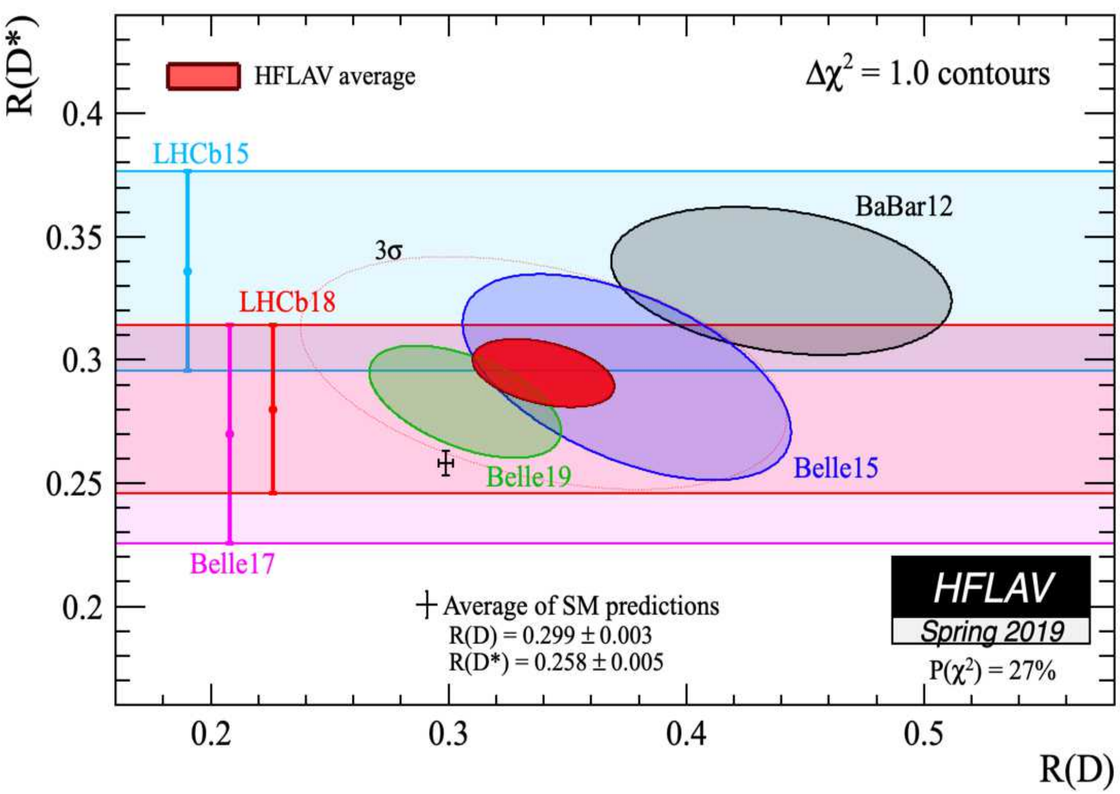
Alguero *et al.* '18

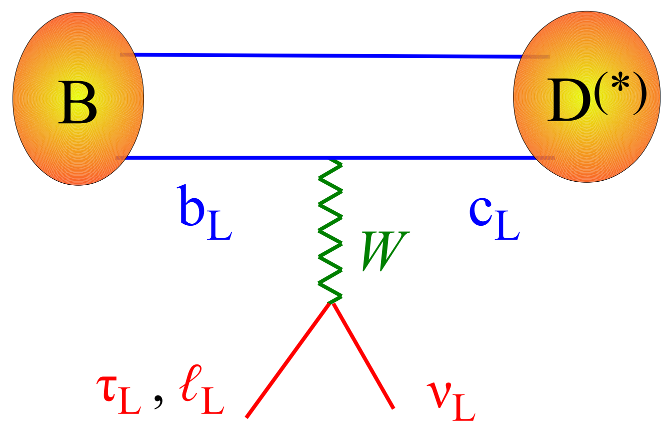


A closer look to the data

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

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



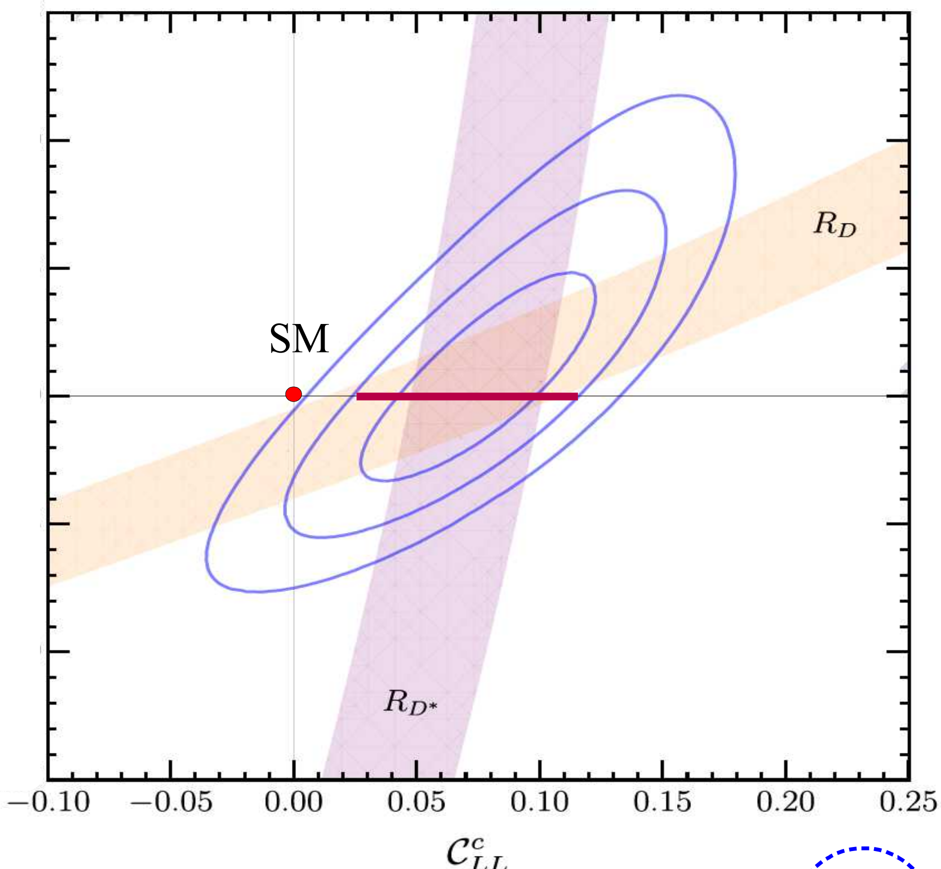


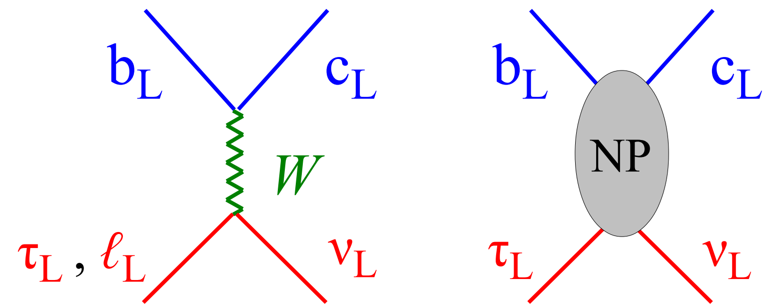
- Consistent results by three different exps. ~ 3.1σ excess over SM (*D and D* combined*)
- SM predictions quite "clean": hadronic uncertainties cancel (*to large extent*) in the ratios

A closer look to the data

- $b \to c\, l\nu$ (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 $b \to s\, ll$

all 3rd gen. (contribute via CKM rotation)

A closer look to the data

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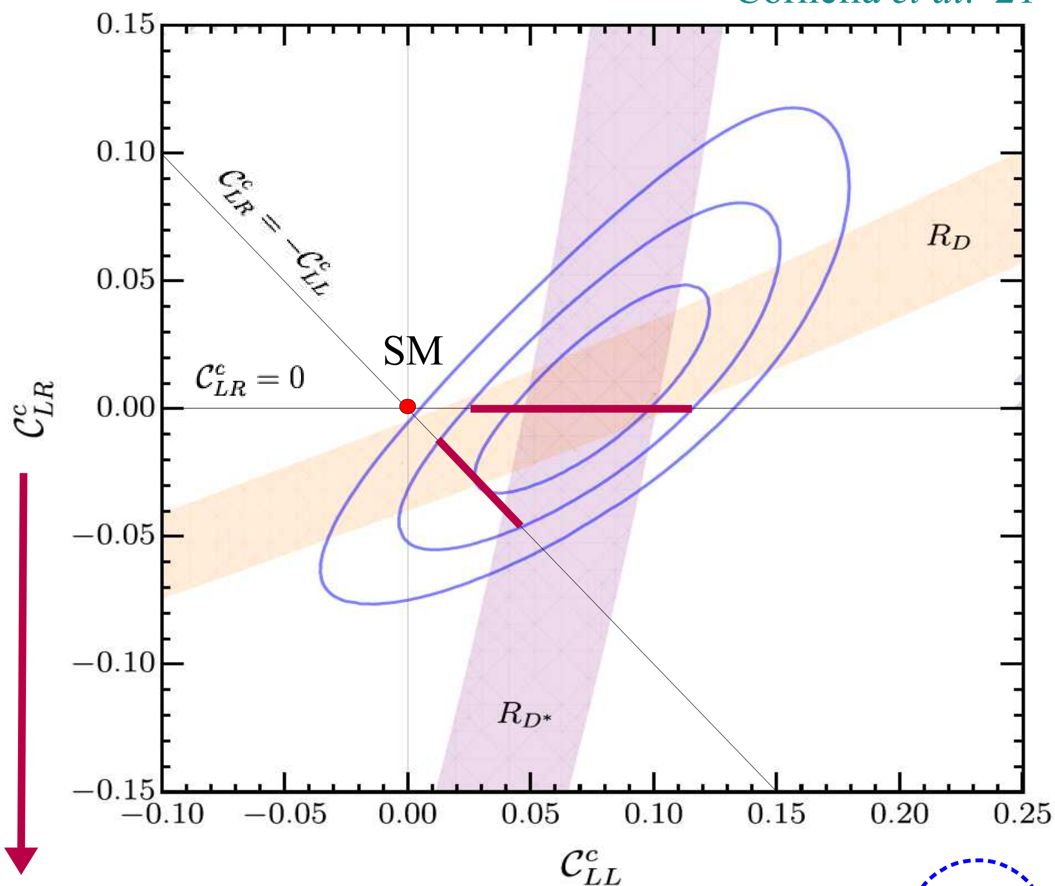
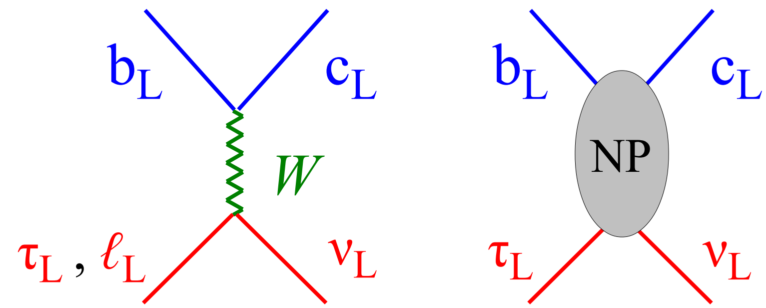
Cornella *et al.* '21





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}

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

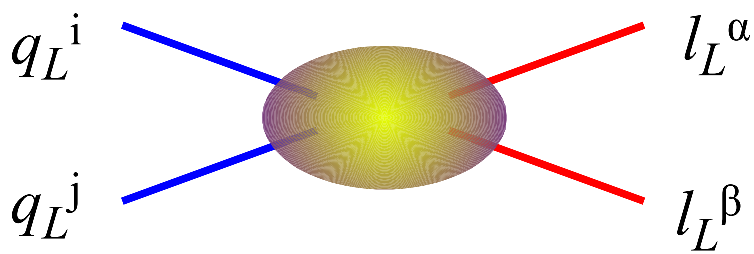
Same operator contributing to $b \to s\, ll$

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



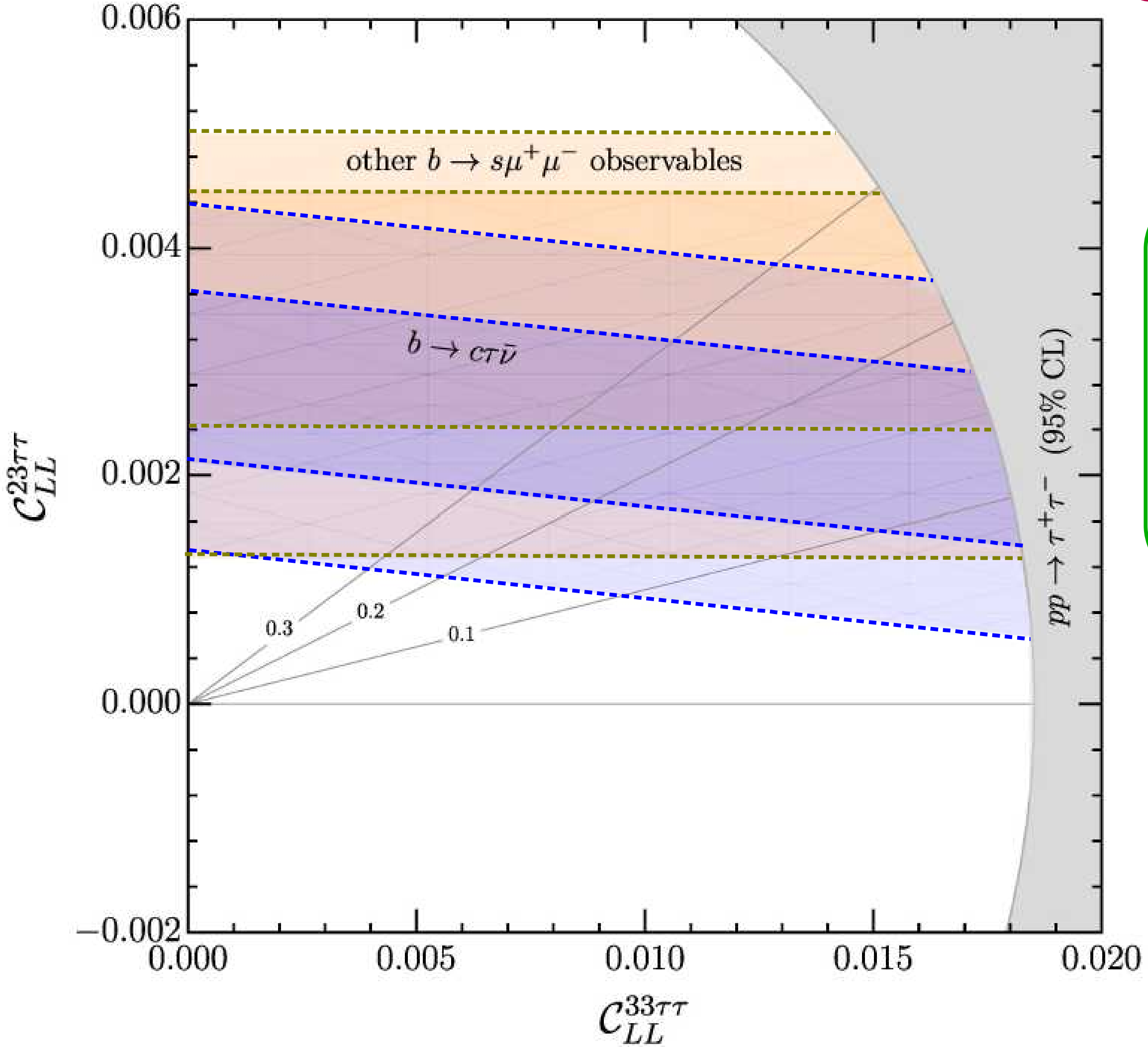
Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

- 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



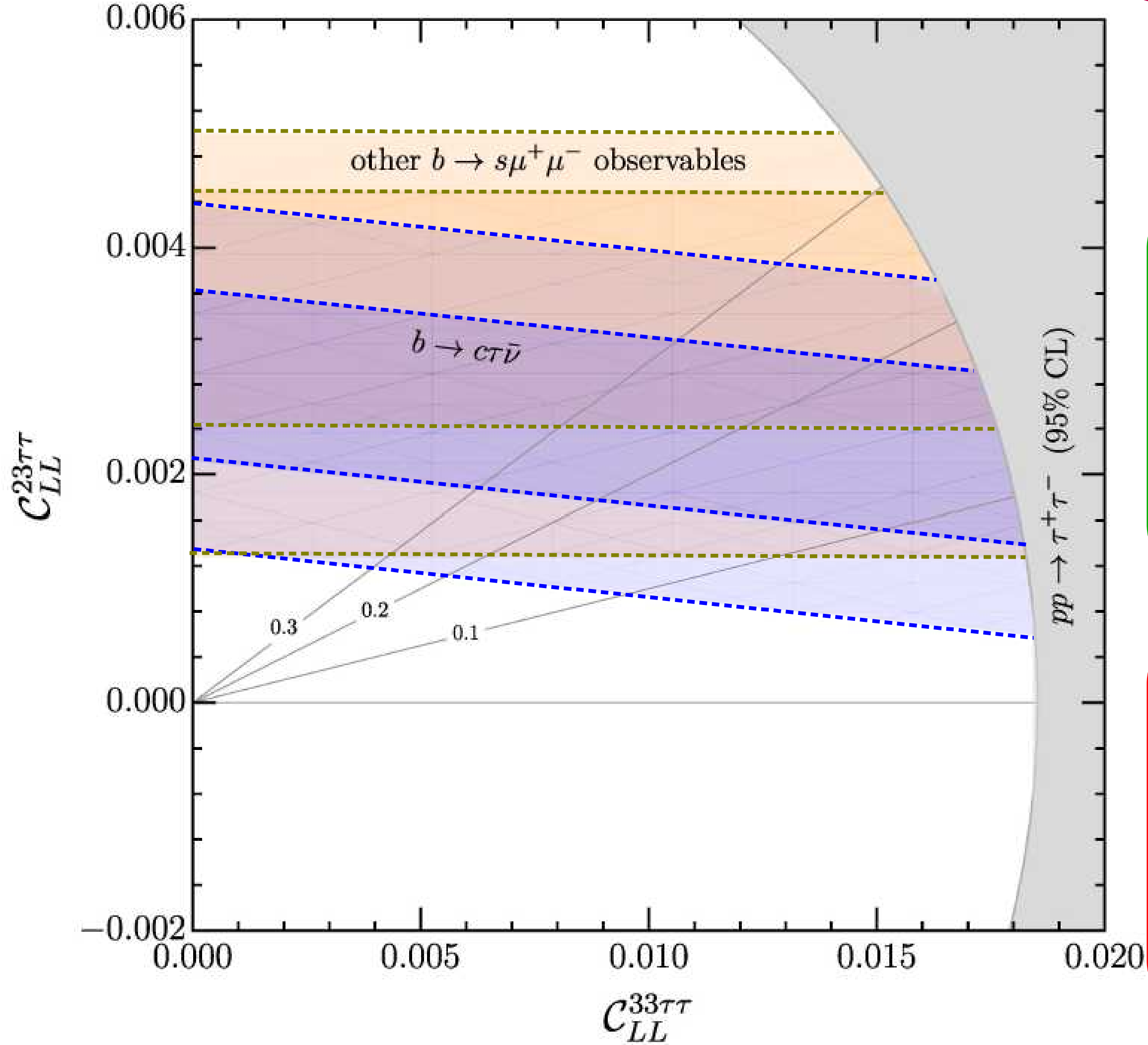
$$(\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j) = \frac{1}{2}\left[\mathcal{O}_{\ell q}^{(1)} + \mathcal{O}_{\ell q}^{(3)}\right]^{ij\alpha\beta}$$

Pattern emerging from data in $2 \leftrightarrow 3$ sector:

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

Link to pattern of the Yukawa couplings !

EFT considerations



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Pattern emerging from data in 2 ↔ 3 sector:

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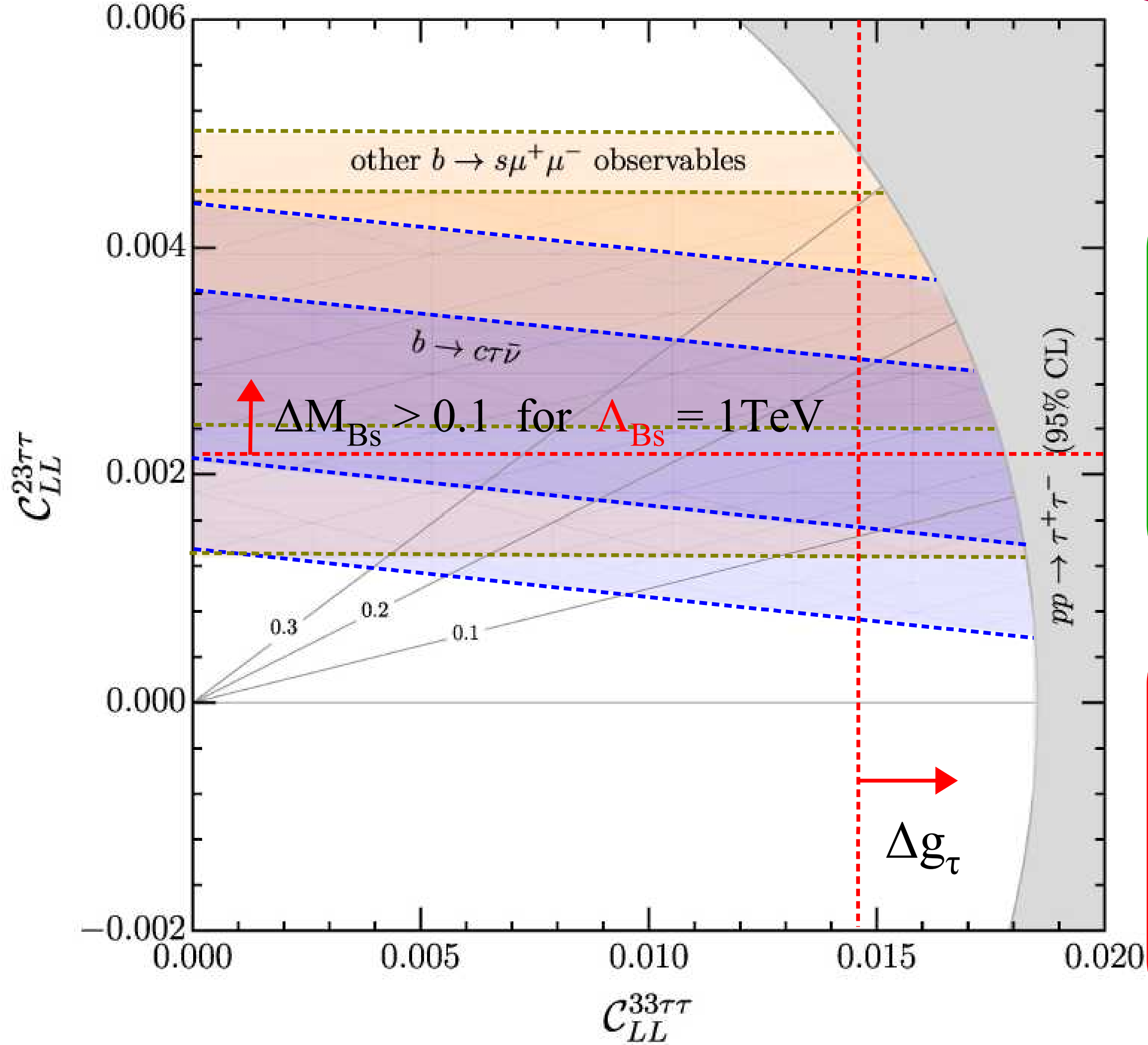
Additional ~10^{-2} (~loop) suppression for

- ✖ Four-quarks (ΔF=2)
- ✖ Four-leptons ($\tau\to\mu\nu\nu$)
- ✖ Semi-leptonic $O^{(1\text{-}3)}$ ($b\to s\nu\nu$)

► EFT considerations

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



Pattern emerging from data in 2 ↔ 3 sector:

- ✔ ~ 10^{-1} for each 2nd gen. q_L or l_L
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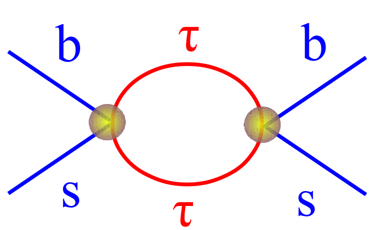
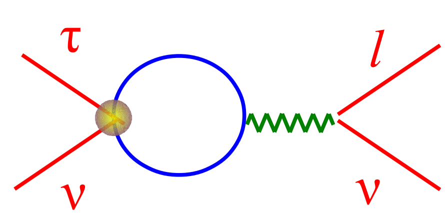
- ✖ Four-leptons ($\tau \to \mu\nu\nu$)
- ✖ Semi-leptonic $O^{(1\text{-}3)}$ ($b \to s\nu\nu$)



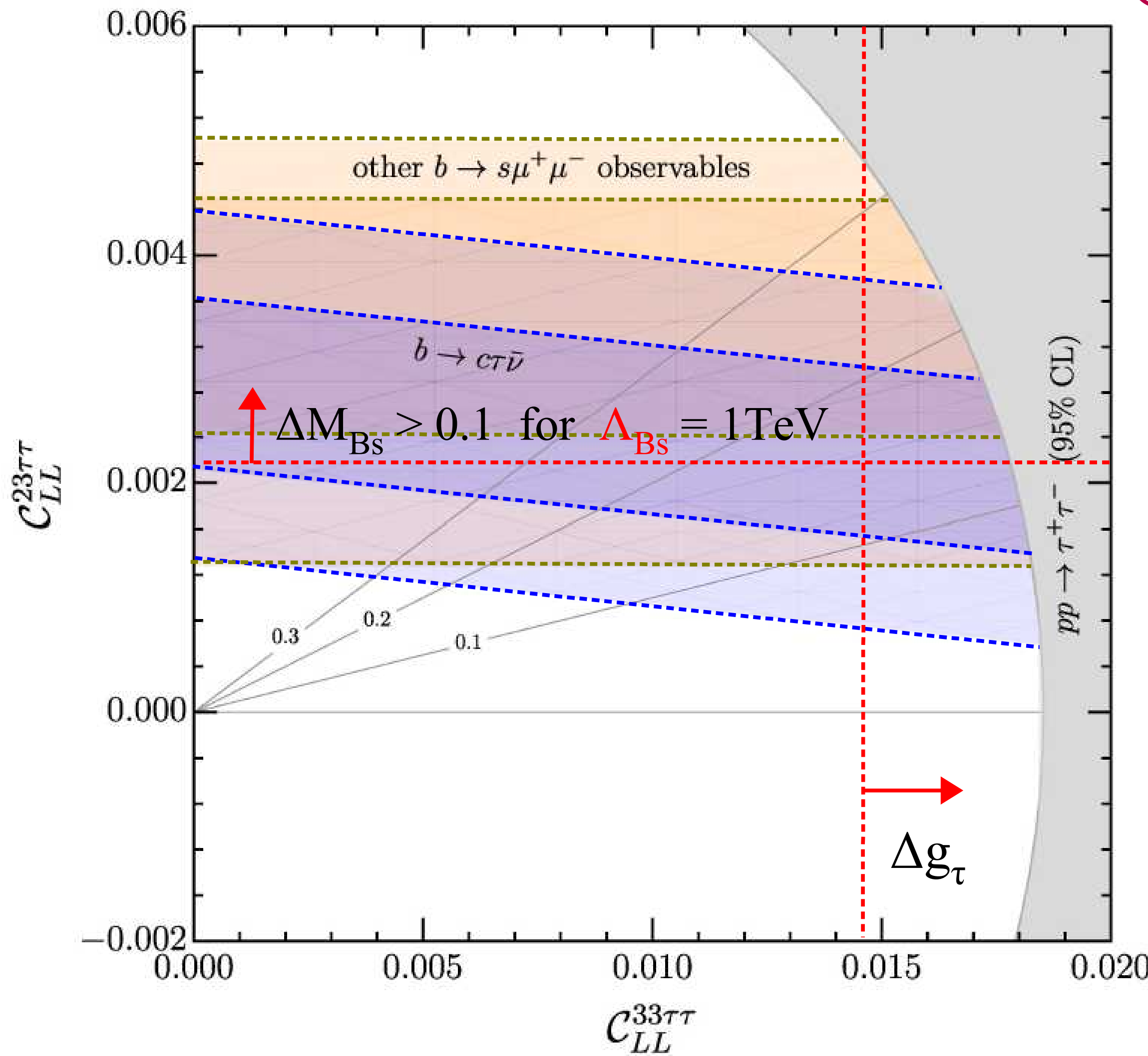
$\Delta M_{Bs} \sim (C^{23\tau\tau})^2\, \Lambda_{Bs}^{\;2}$



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

▶ EFT considerations

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



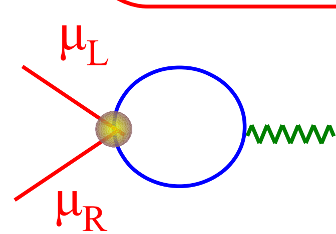
Pattern emerging from data in 2 ↔ 3 sector:

- ✔ ~ 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

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

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

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

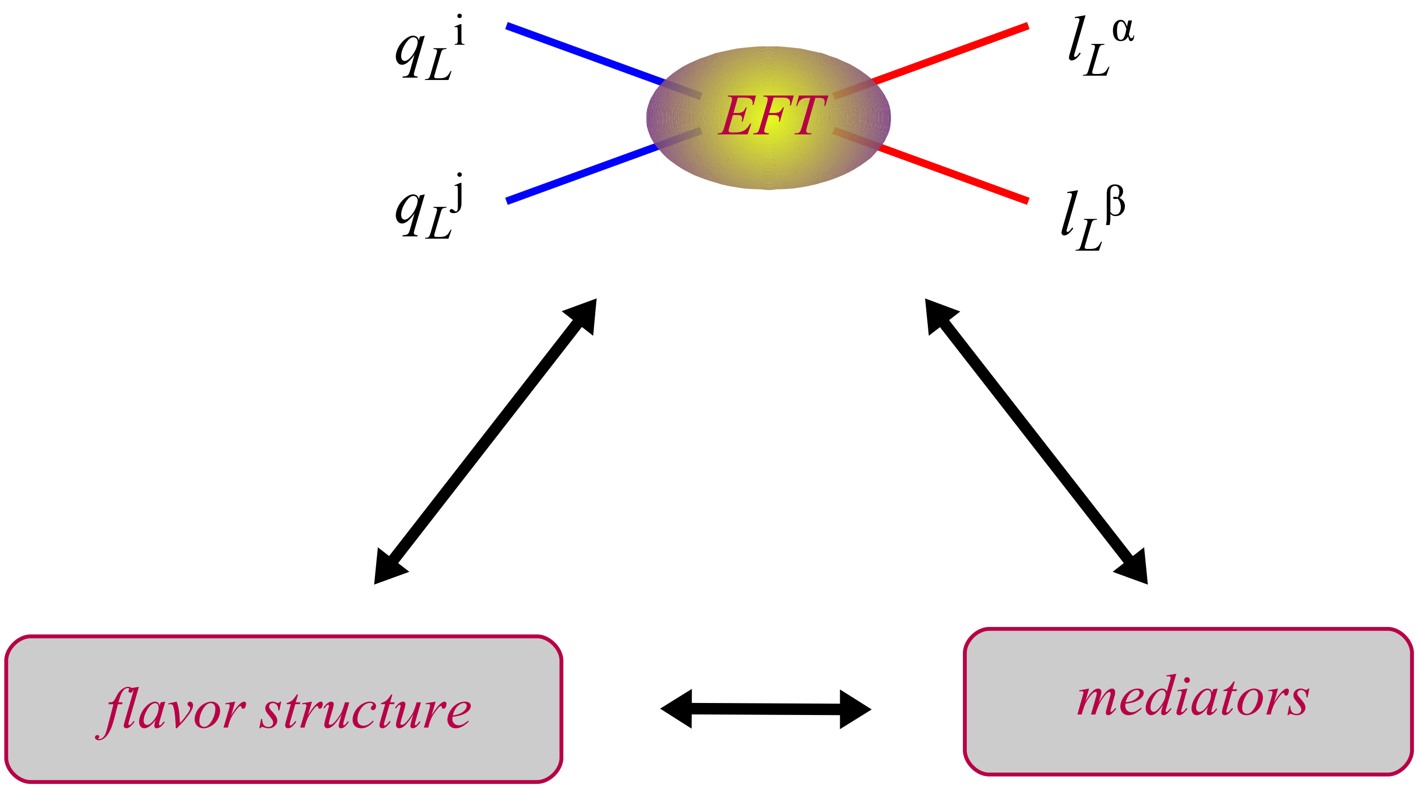


$\Delta a_\mu << a_\mu^{SM-EW}$

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

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*



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

So far, the vast majority of model-building attempts to extend the SM was based on the following two (*implicit*) hypotheses:

- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavor problem ➡ The 3 gen. as “identical” copies (*but for Yukawa-type interactions*)

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

So far, the vast majority of model-building attempts to extend the SM was based on the following two (*implicit*) hypotheses:

- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavor problem → ~~The 3 gen. as "identical" copies (*but for Yukawa-type interactions*)~~

The recent flavor anomalies seem to suggest a new avenue in BSM approaches:

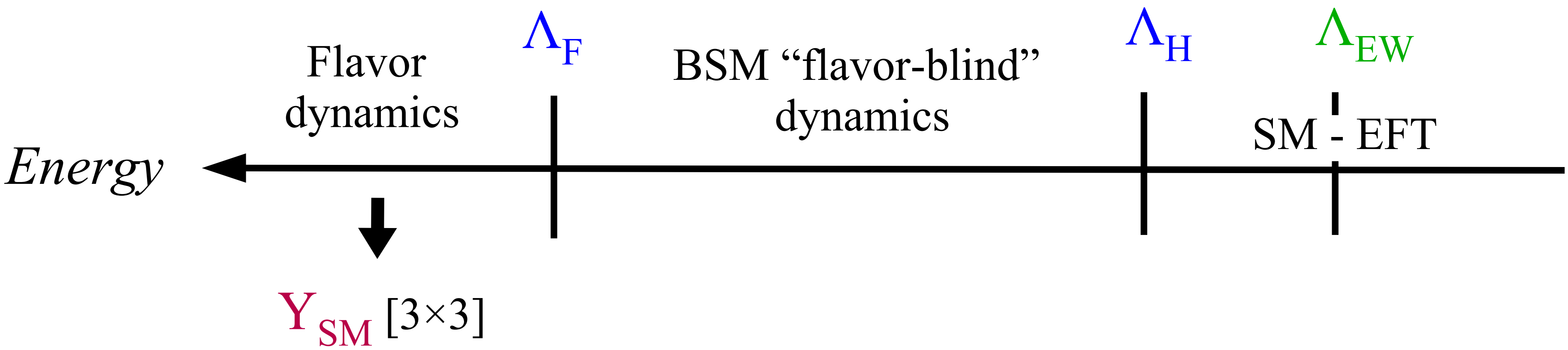
The universality of SM gauge interactions is only a low-energy property

↓

- We should not ignore the flavor problem
  New TeV-scale interactions distinguishing the different families

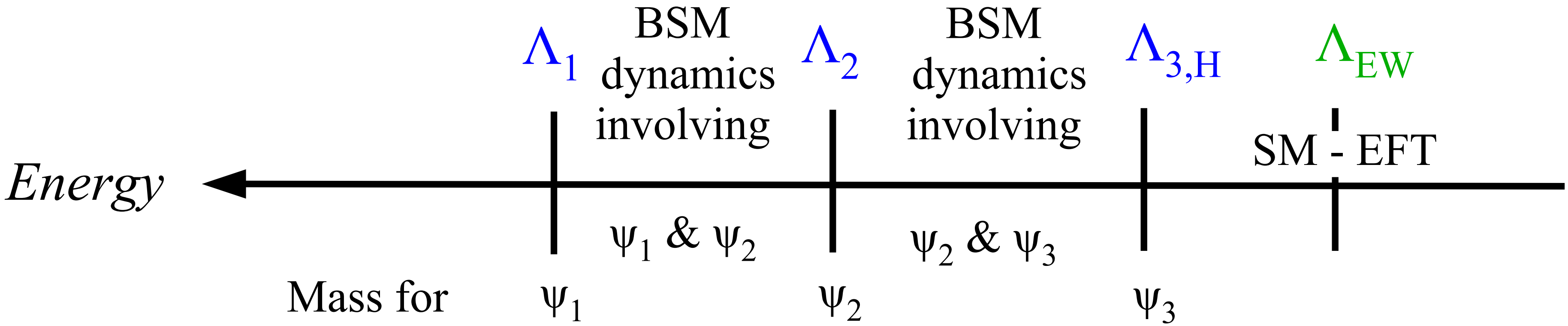
From EFT to simplified models [*the flavor structure*]

The MFV paradigm:



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

~~*The MFV paradigm*~~   *Multi-scale picture @ origin of flavor:*



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

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

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

Non-trivial UV imprints

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

From the EFT point fo view, the generic consequence of a construction of this type is that the nearby dynamics ($E \sim \Lambda_3$) is characterized by a an approximate $U(2)^n$ flavor symmetry:

$$\psi = \left[\begin{array}{c} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \\ \hline \psi_3 \end{array} \right]$$

← light generations (*flavor doublet*)

← 3rd generation (*flavor singlet*)

↑ SM fermion (e.g. q_L)

with suitable (small) symmetry-breaking terms, related to the SM Yukawa couplings [*largest breaking:* $3_L \to 2_L$ controlled by $|V_{ts}| \sim 0.04$]

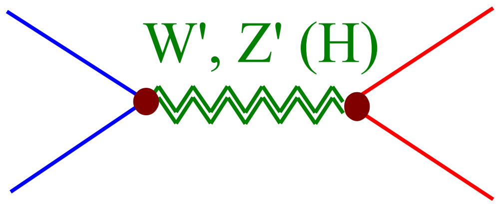
Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

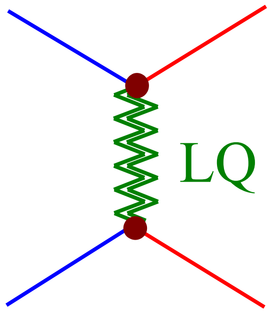
NB: In the 3-scale picture this flavor symmetry is an "accidental" symmetry, resulting from the (flavor) non-universal structure of BSM interactions

N.B.: this symmetry (& symmetry-breaking pattern) was proposed well-before the anomalies appeared...

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...





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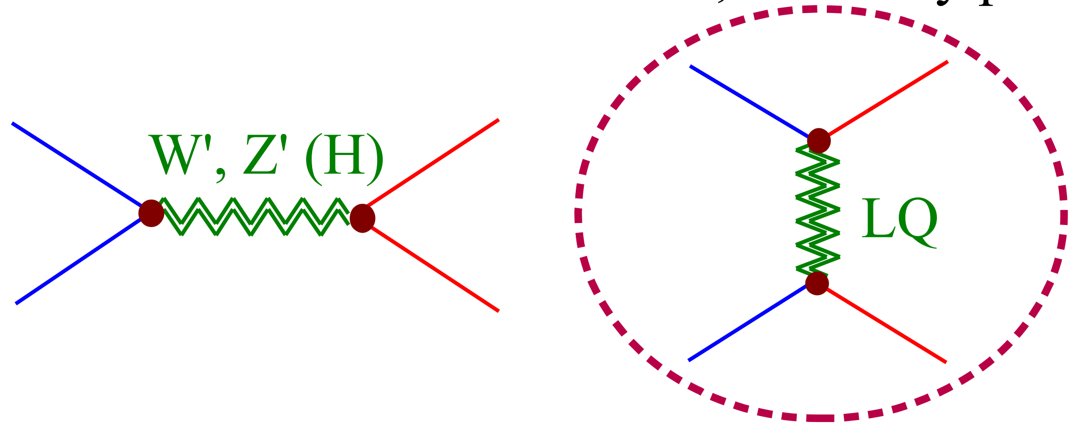
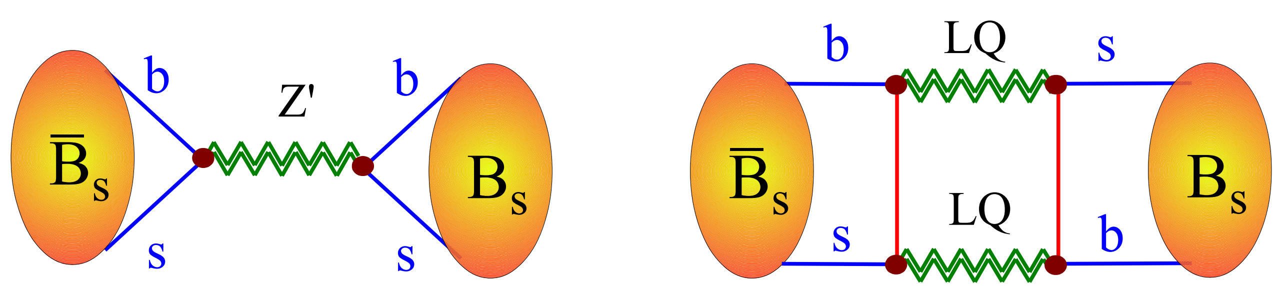


LQ (both scalar and vectors) have two general strong advantages with respect to the other mediators:

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* [*the possible mediators*]

"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
  + ...

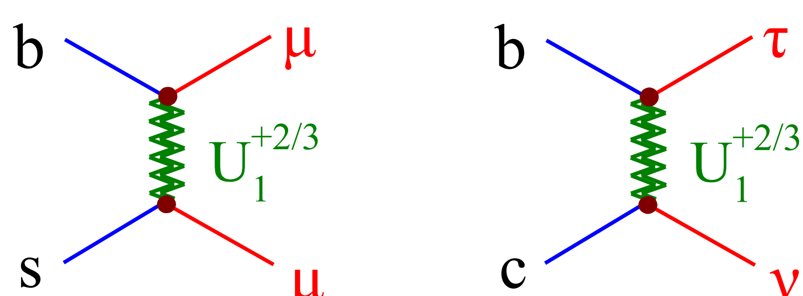
- Vector LQ as techni-fermion resonances
  Barbieri *et al.* '15; Buttazzo *et al.* '16, Barbieri, Murphy, Senia, '17 + ...

- 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]



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

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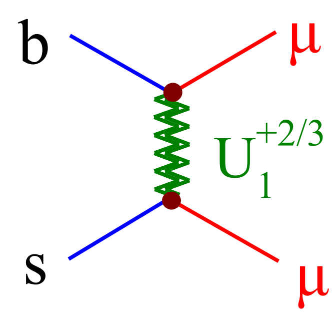
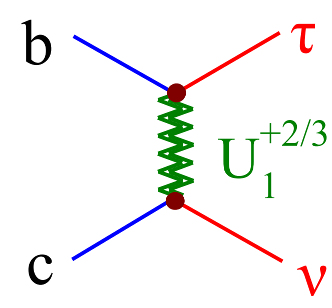




Barbieri, GI, Pattori, Senia '15

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

LQ of the Pati-Salam gauge group:

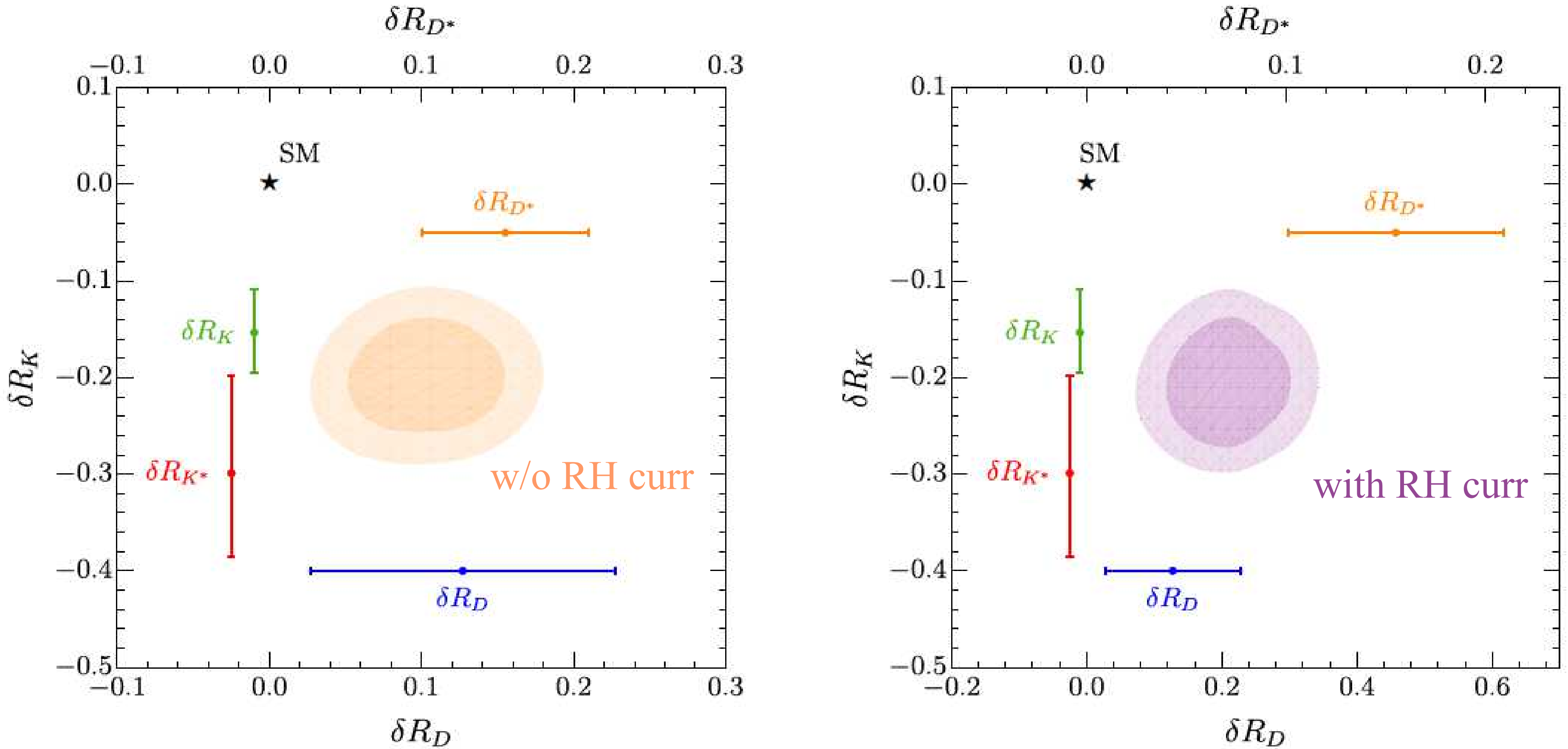
$SU(4) \times SU(2)_L \times SU(2)_R$

▶ From EFT to simplified models [the possible mediators]

Considering the U_1 only

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

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



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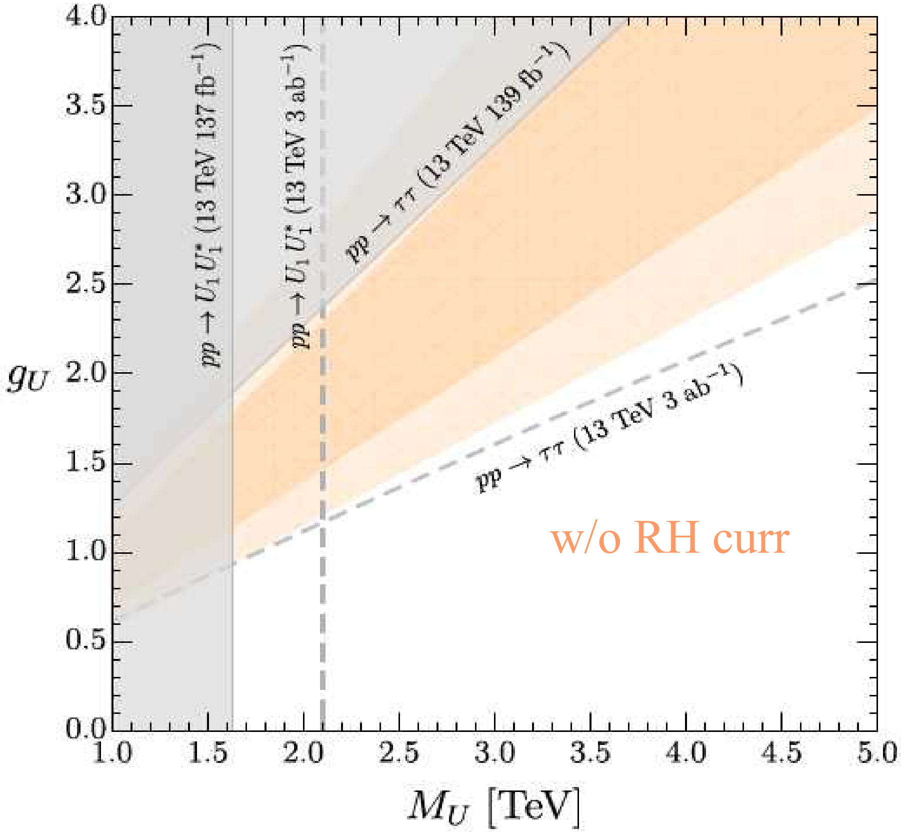
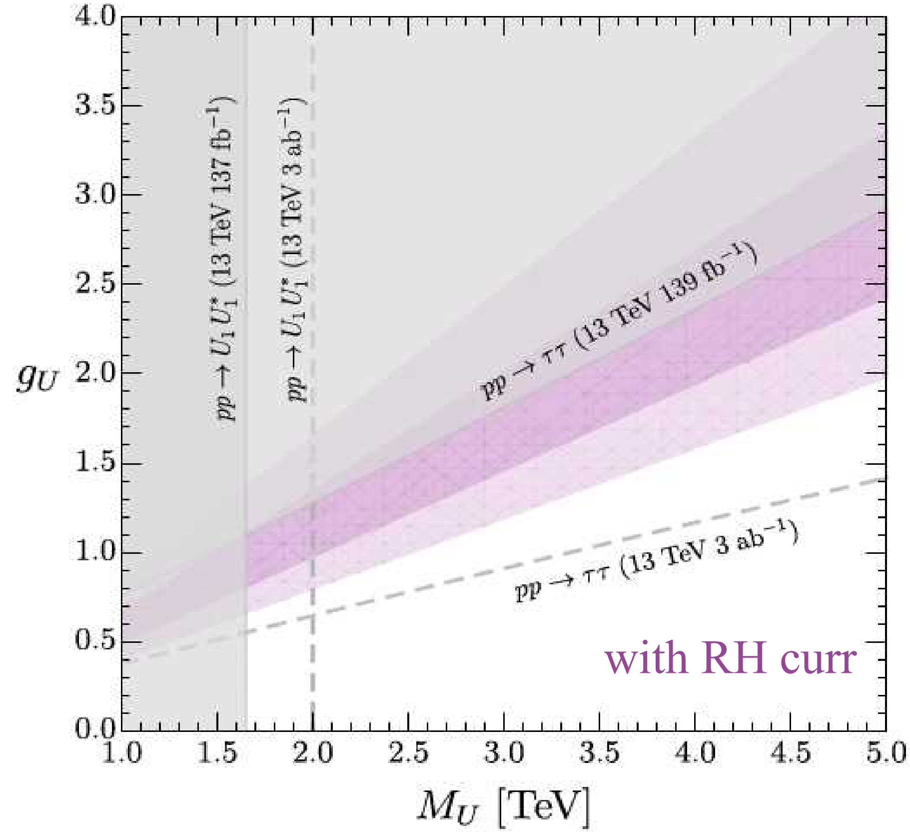
and fitting <u>all low-energy data</u> leads to an excellent description of present data which is fully <u>consistent with high-pT searches</u> [*within the reach of HL-LHC*]:

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





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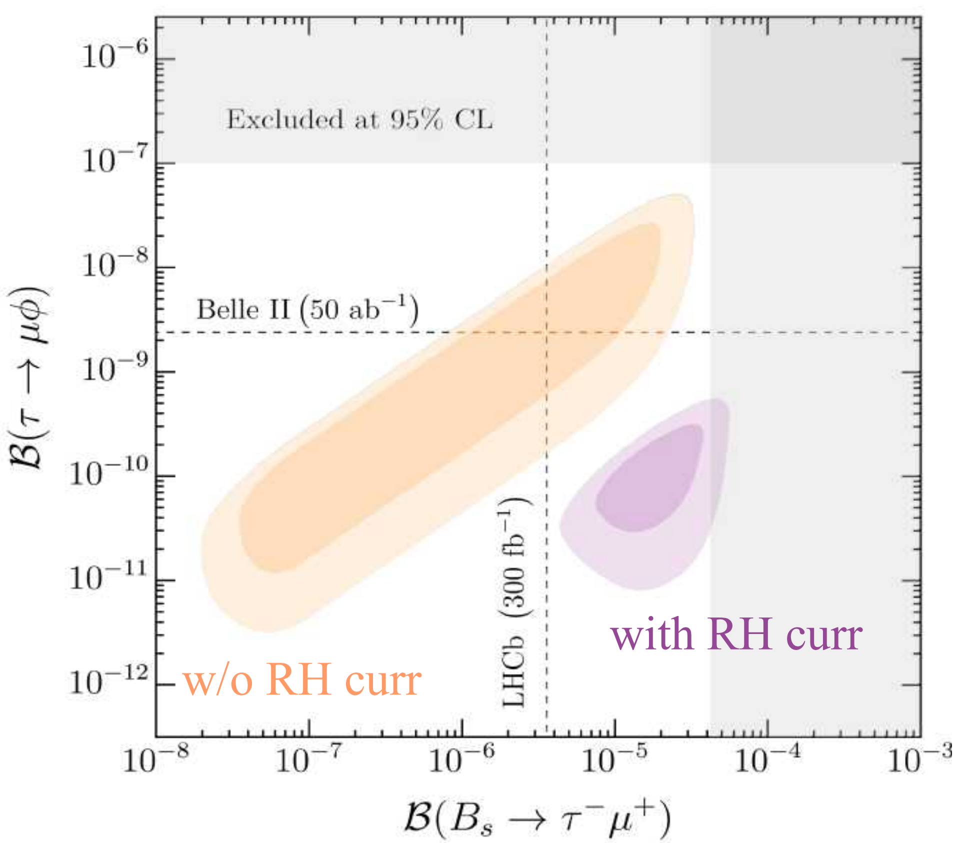
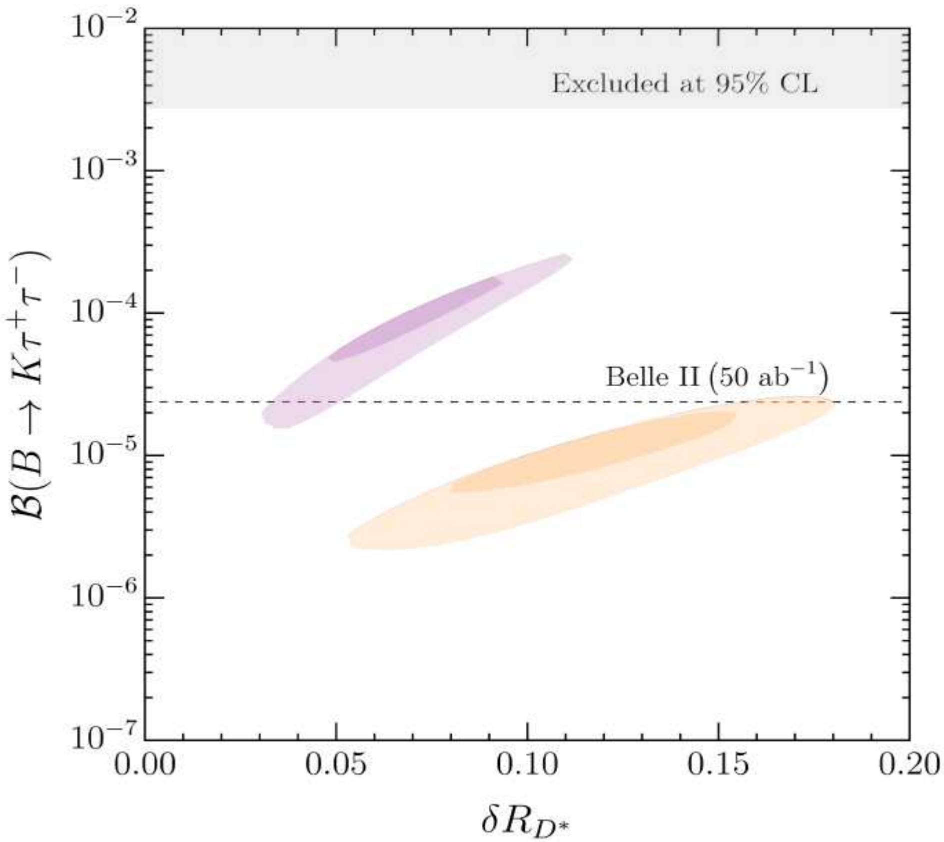
and fitting <u>all low-energy data</u> leads to an excellent description of present data which is fully <u>consistent with high-pT searches</u> & has interesting implications for future low-energy searches:

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):

$$\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix} \quad \begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$$

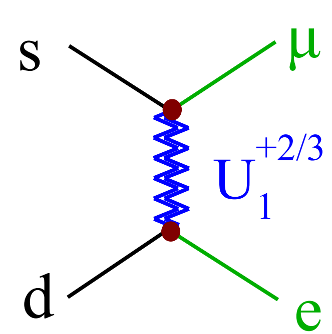
Main Pati-Salam idea:
Lepton number as "the 4th color"

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

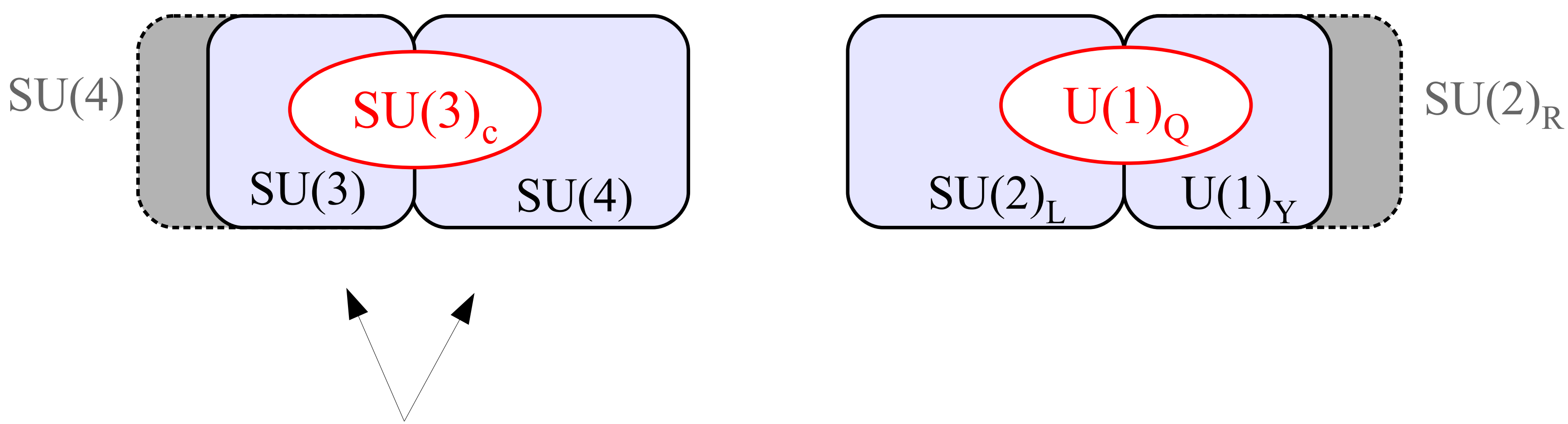


Speculations on UV completions

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*

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

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

- *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

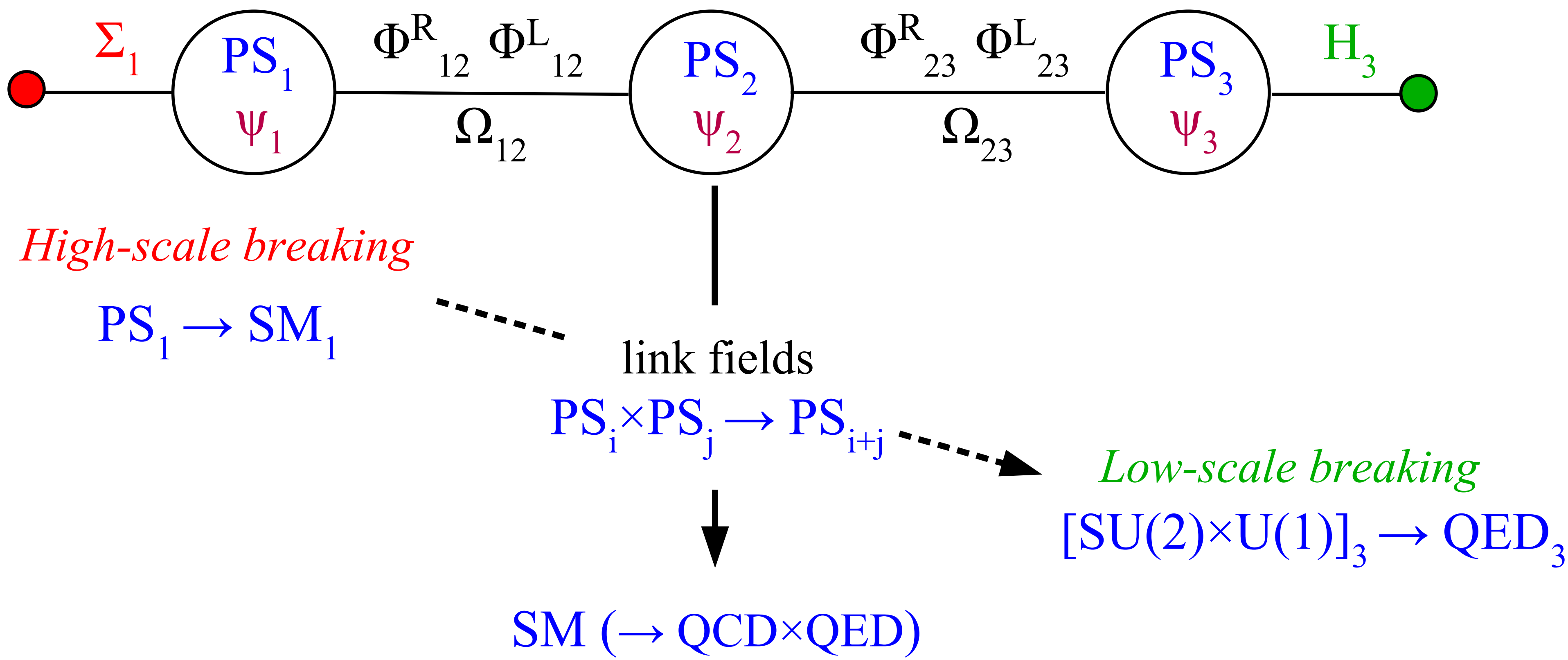
$[PS]^3 = [SU(4) \times G_{EW}]^3$
Bordone *et al.* '17

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

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

Speculations on UV completions

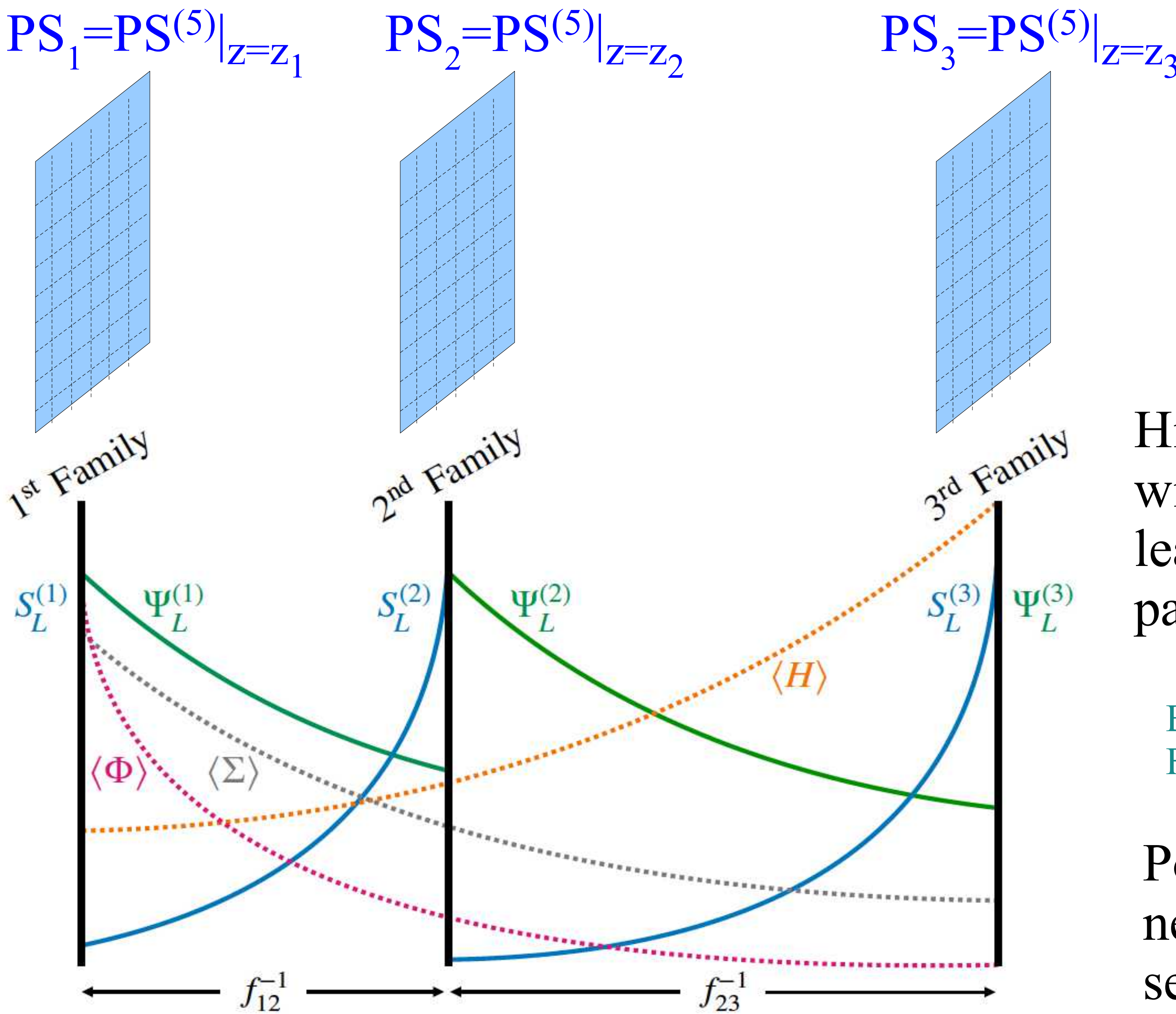
The PS^3 set-up...   Bordone, Cornella, Fuentes-Martin, GI, '17



- Unification of quarks and leptons [*natural explanation for* $U(1)_Y$ *charges*]
- De-unification (= *flavor deconstruction*) of the gauge symmetry
- Breaking to the diagonal SM group occurs via appropriate "link" fields, responsible also for the generation of the hierarchies in the Yukawa couplings.

Speculations on UV completions

… and its 5D embedding [ambitious attempt to construct a *full theory of flavor* via Pati-Salam embedding in a warped 5D space-time]



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 $\psi_{1,2}$

↓ → LQ [U_1] + Z' + G'

SM

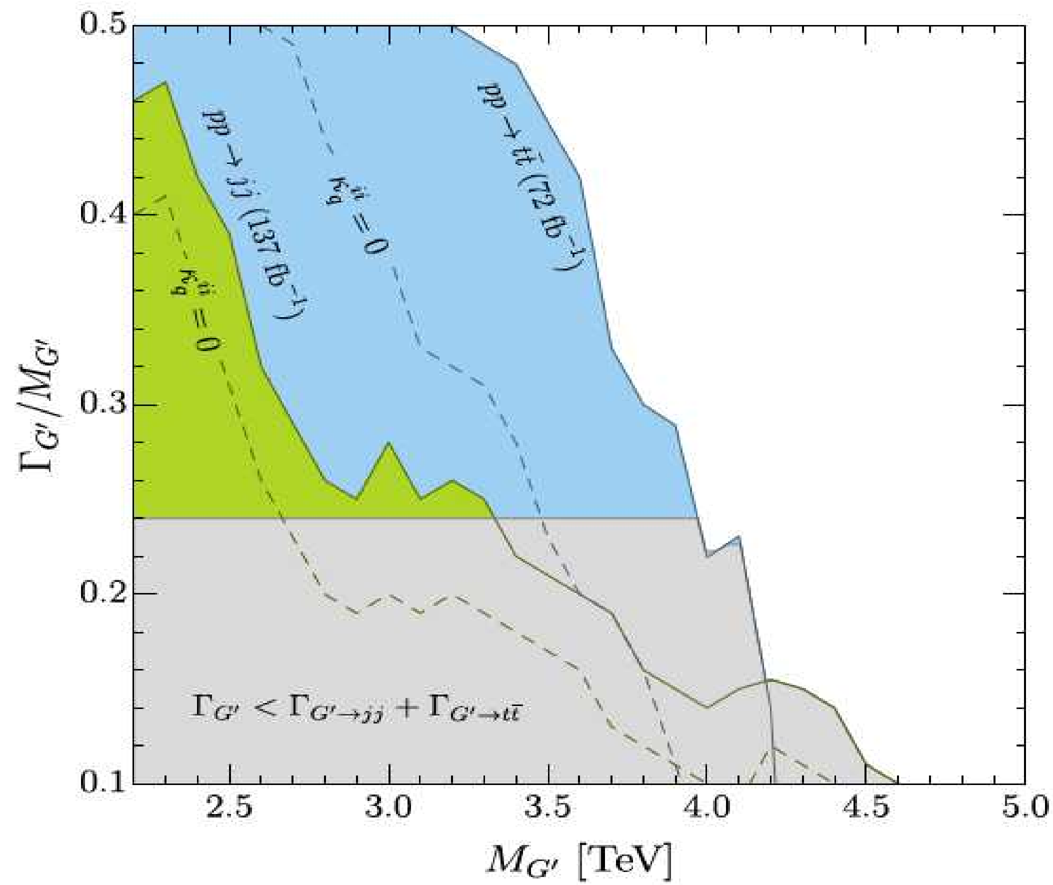
Despite the apparent complexity, the construction is highly constrained

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

} *consistent with present data !*

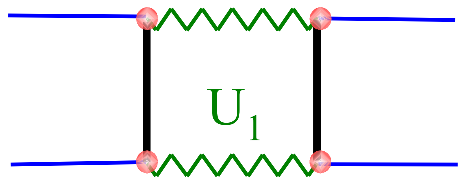
New striking collider signature:
G' (“*coloron*” = *heavy color octet*)

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



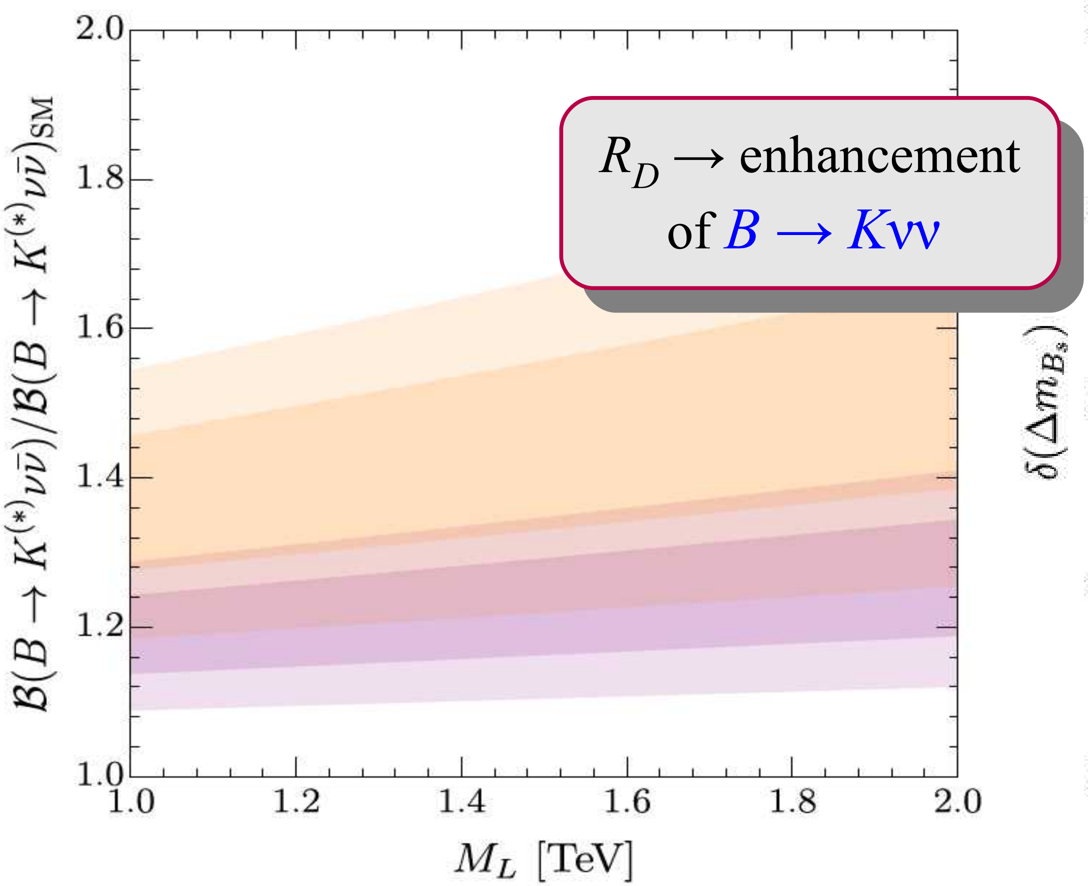
Speculations on UV completions

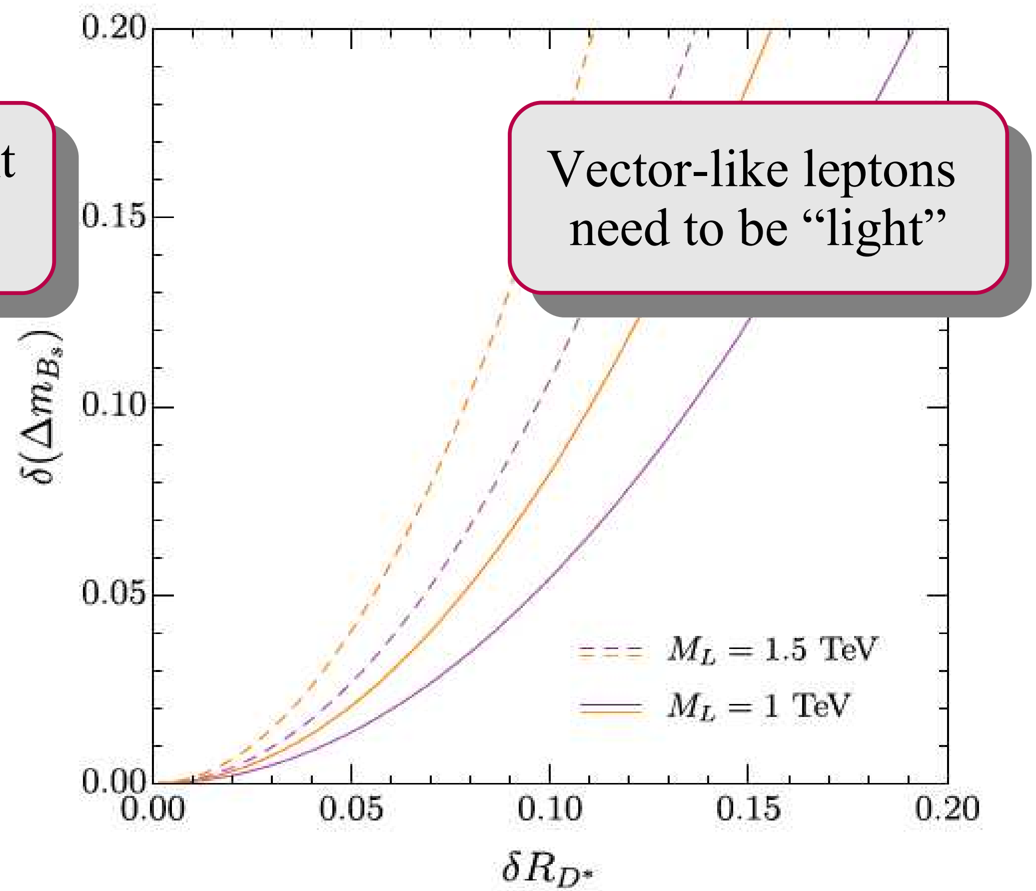
UV-sensitive observables in 4321 models



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

B) B_s mixing [ΔF=2]





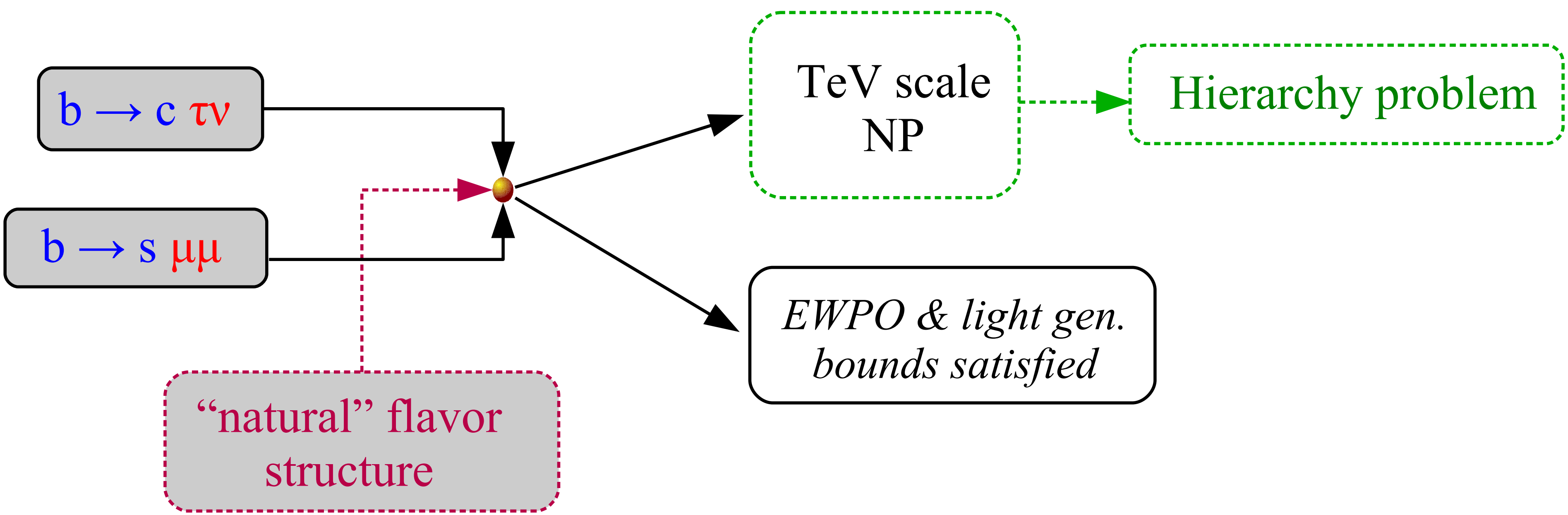
Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21
Fuentes-Martin, GI, Konig, Selimovic, '20

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?



Worries

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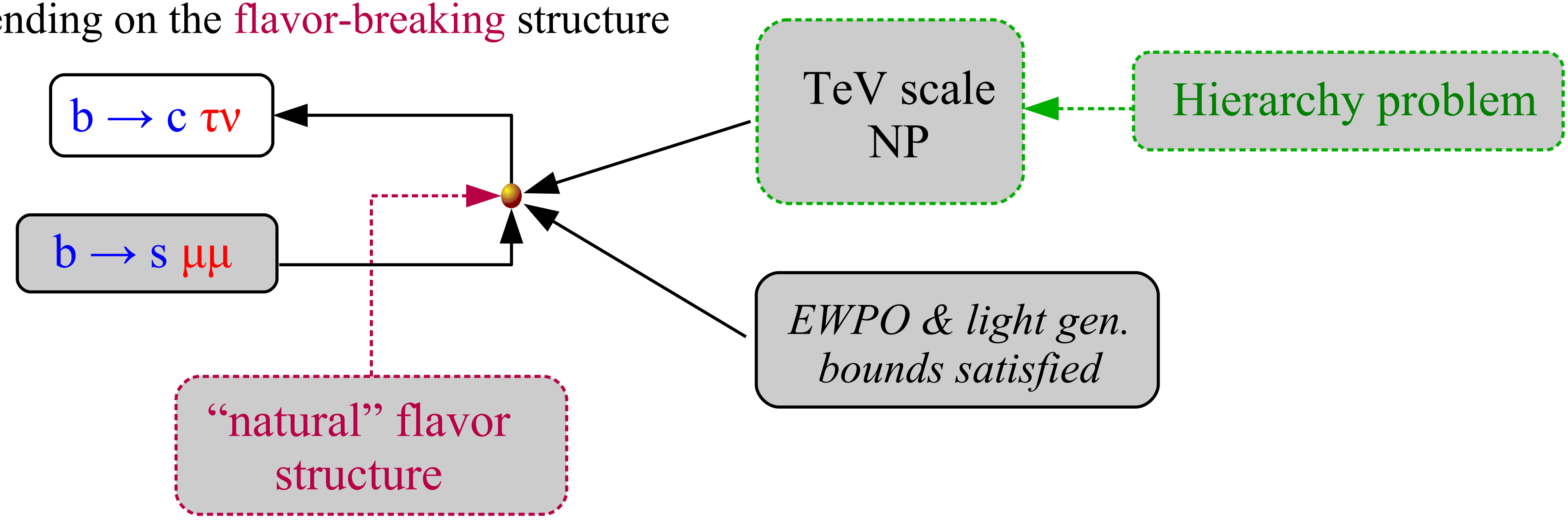
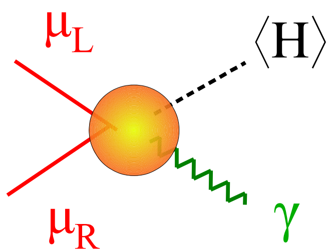
$\Delta R_D \sim (3\% - 30\%)$
depending on the flavor-breaking structure



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:

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



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

- $a_\mu \oplus R_K$ with special role of muons [$U(1)_{B\text{-}3L_\mu} \subset G$] 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... $(g\text{-}2)_\mu$ 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 $b \to s\ell\ell$ 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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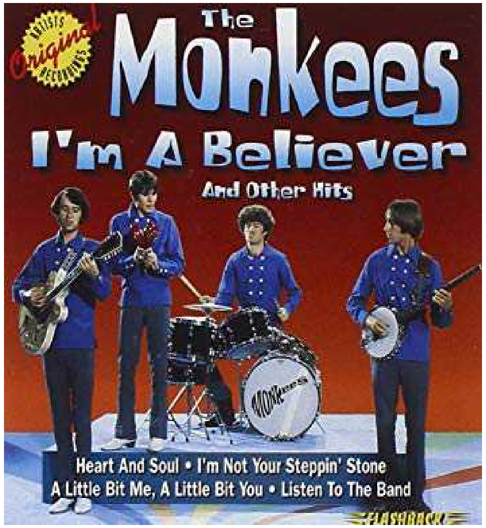
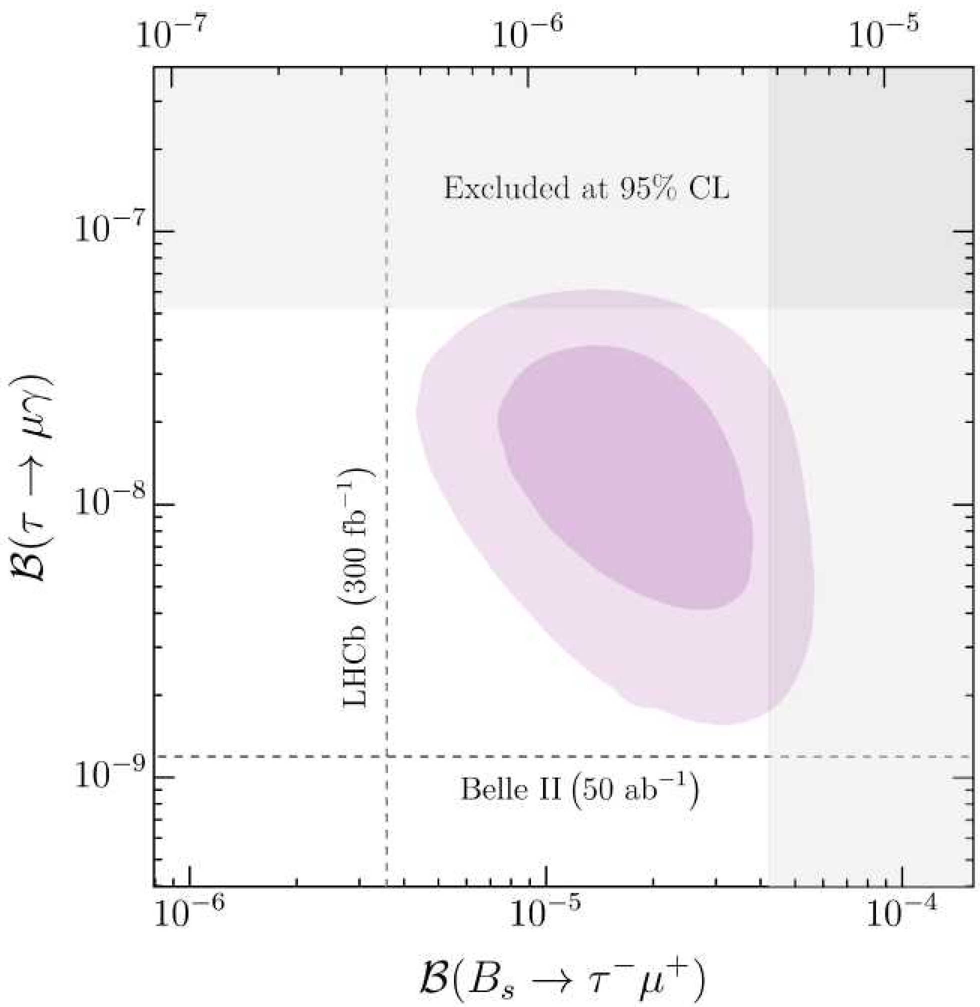
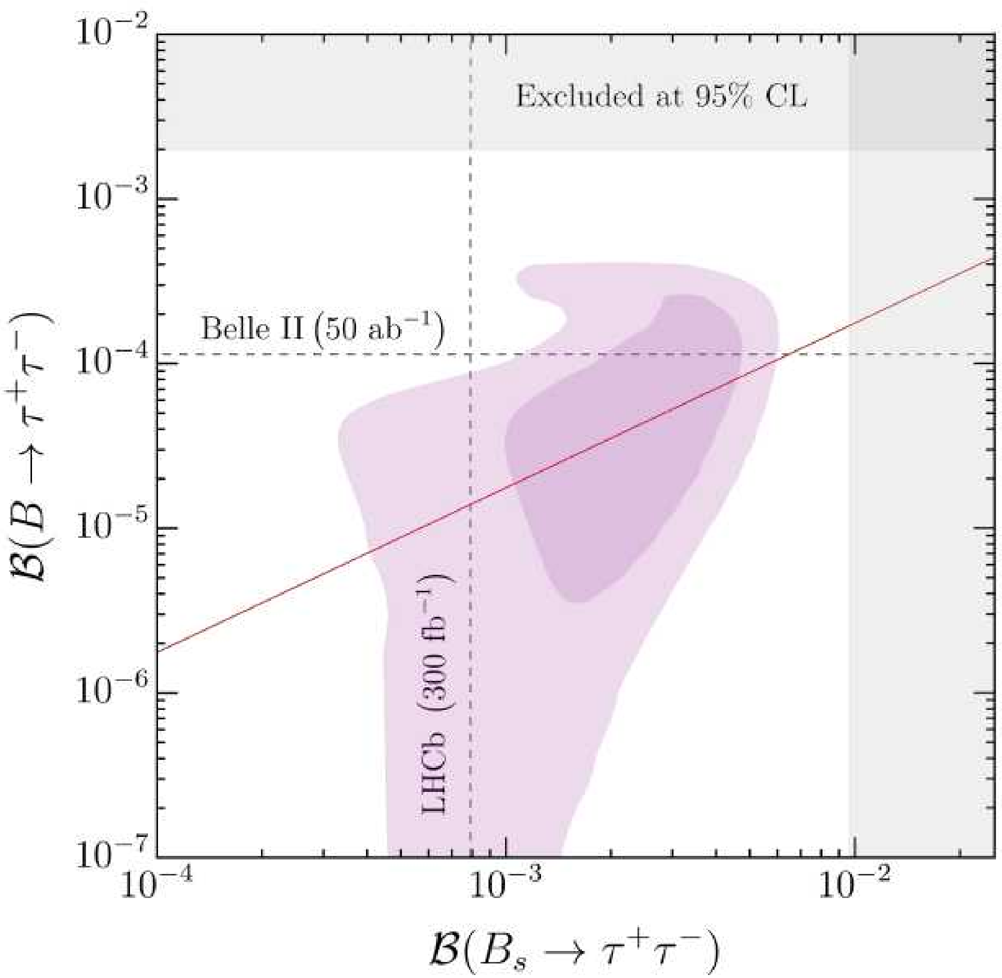


(*already since quite some time...*)


Backup

Other low-energy observables





Other low-energy observables

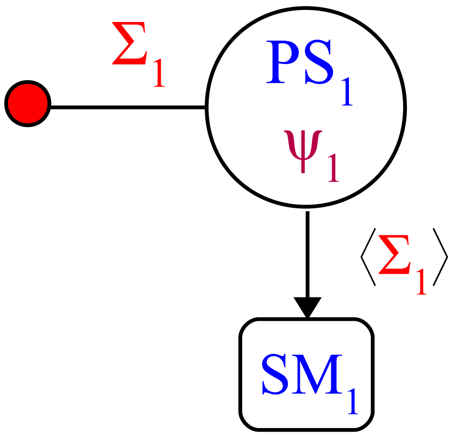
Correlations among $b \to s(d)\ell\ell$ within the U(2)-based EFT

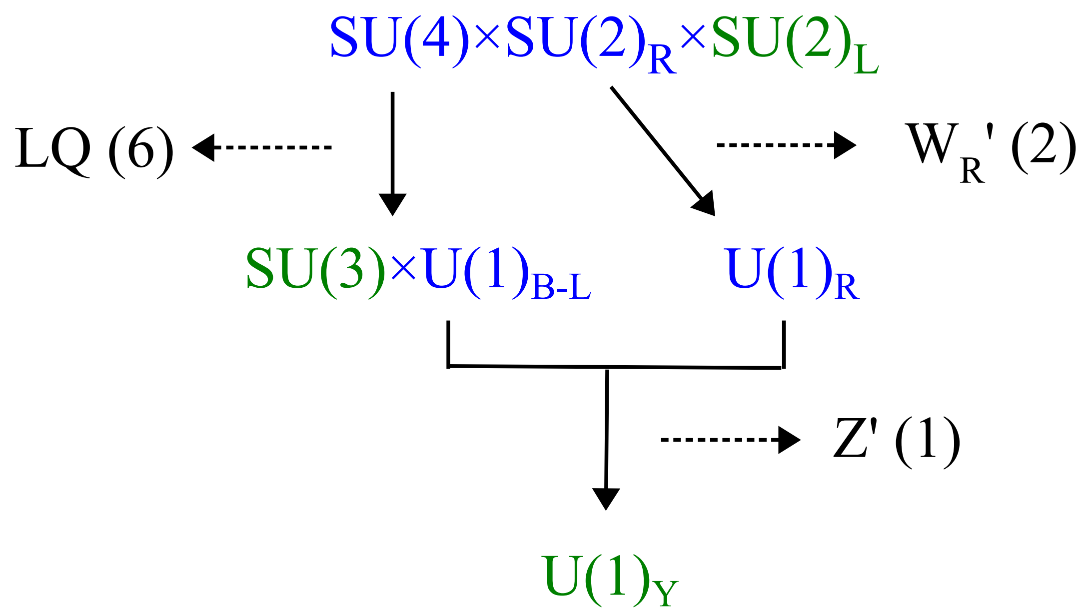
	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)}\tau\tau$ $\to$ 100×SM	$B \to K^{(*)}\nu\nu$ O(1)
$b \to d$	$B_d \to \mu\mu$ $B \to \pi\mu\mu$ $B_s \to K^{(*)}\mu\mu$ O(20%) [$R_K = R_\pi$]	$B \to \pi\tau\tau$ $\to$ 100×SM	$B \to \pi\nu\nu$
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi\nu\nu$ O(1)

R_D R_K

$$\frac{A(b \to d\ell\ell)_{SM+NP}}{A(b \to s\ell\ell)_{SM+NP}} = \frac{A(b \to d\,\ell\ell)_{SM}}{A(b \to s\,\ell\ell)_{SM}}$$

▸ *Symmetry breaking pattern in* PS^3





High-scale [~ 10^3 TeV]
"vertical" breaking [PS → SM]

PS_1 [$SU(4)_1\times SU(2)^R{}_1$]

↓

SM_1 [$SU(3)_1\times U(1)^Y{}_1$]

▶ Symmetry breaking pattern in PS^3