Theoretical interpretations of the B-physics anomalies

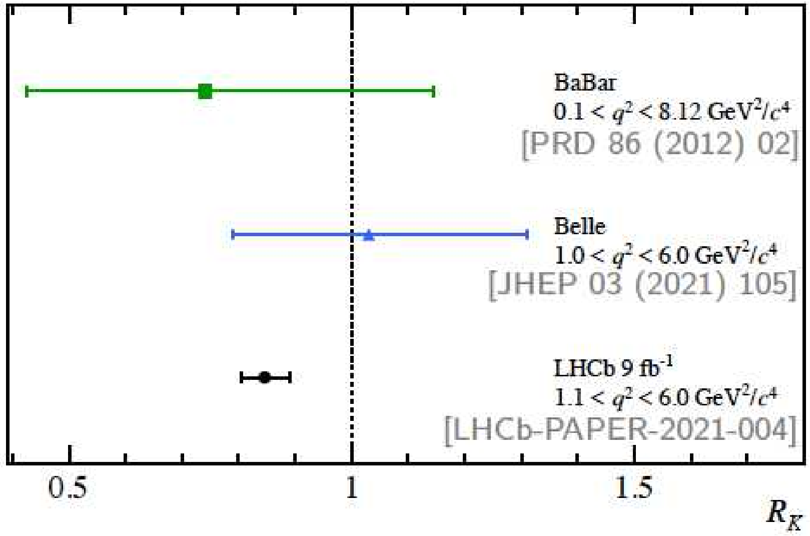
Gino Isidori
[*University of Zürich*]

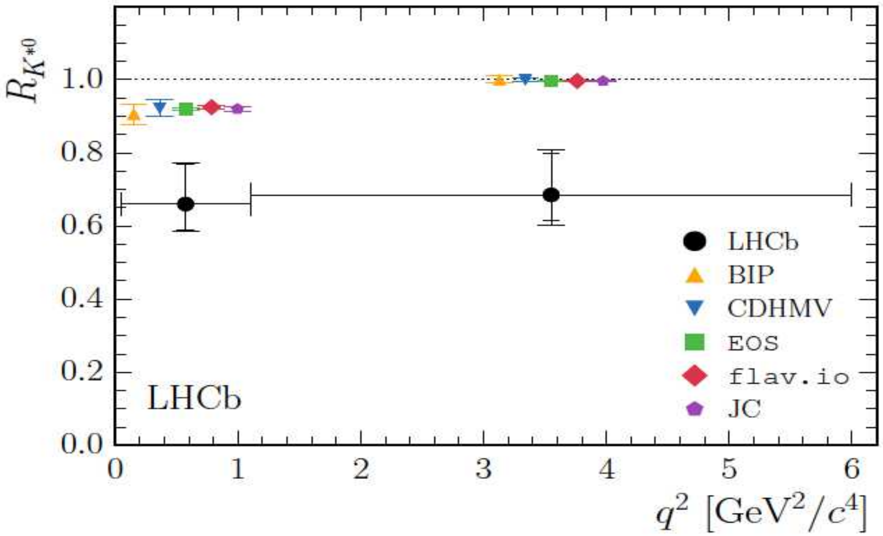
- *A closer look to the data*
- *EFT interpretations*
- *From EFT to simplified models*
- *Speculations on UV completions*
- *Conclusions*

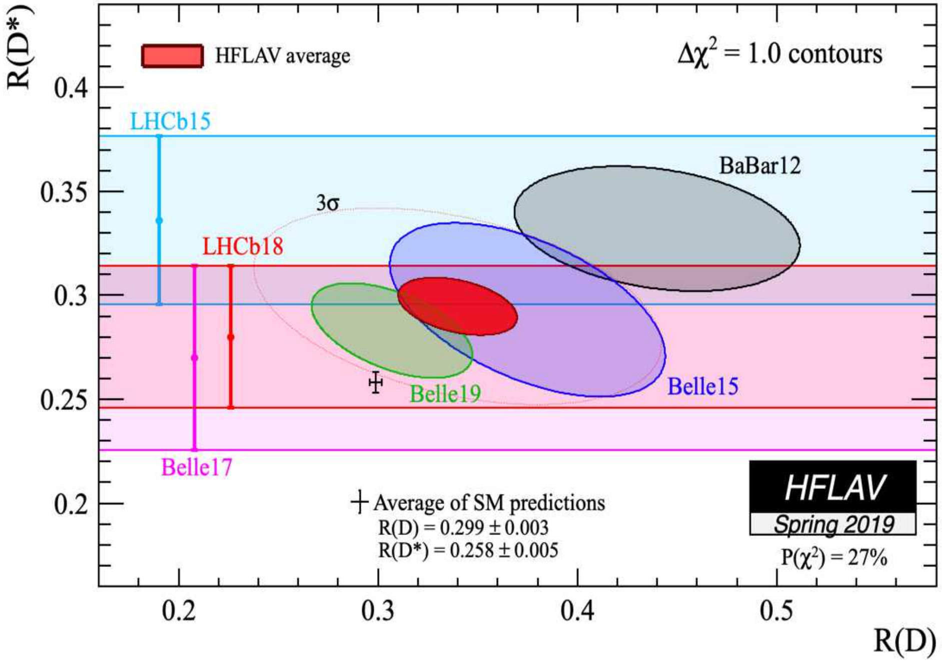
University of Zurich^UZH

erc
European Research Council
Established by the European Commission

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)

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)

N.B: LFU is an accidental symmetry of the SM Lagrangian in the limit where we neglect the lepton Yukawa couplings.

LFU is badly broken in the Yukawa sector, but all the lepton Yukawa couplings are small within the SM ($y_\tau \sim 0.01$), giving rise to the (*approximate*) universality of decay amplitudes which differ only by the different lepton species involved.

As for all accidental symmetries → ideal “tool” to look for BSM effects...

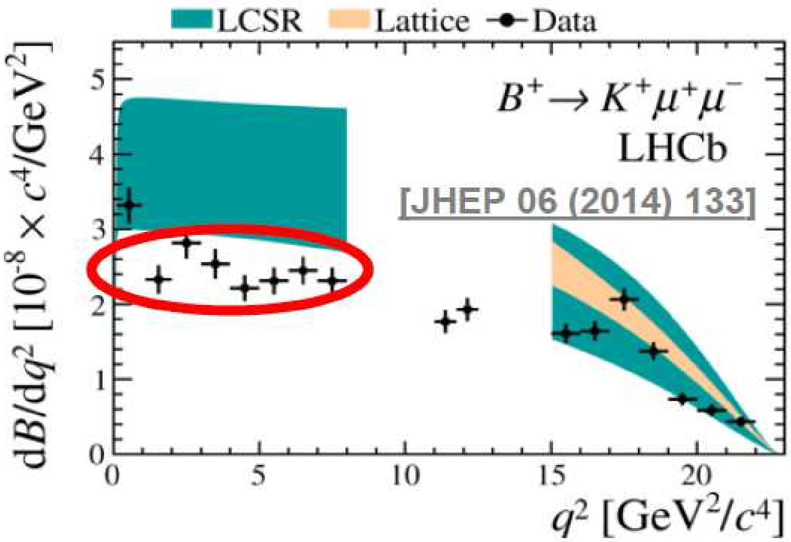
A closer look to the data

- b → s l^+l^- (neutral currents)

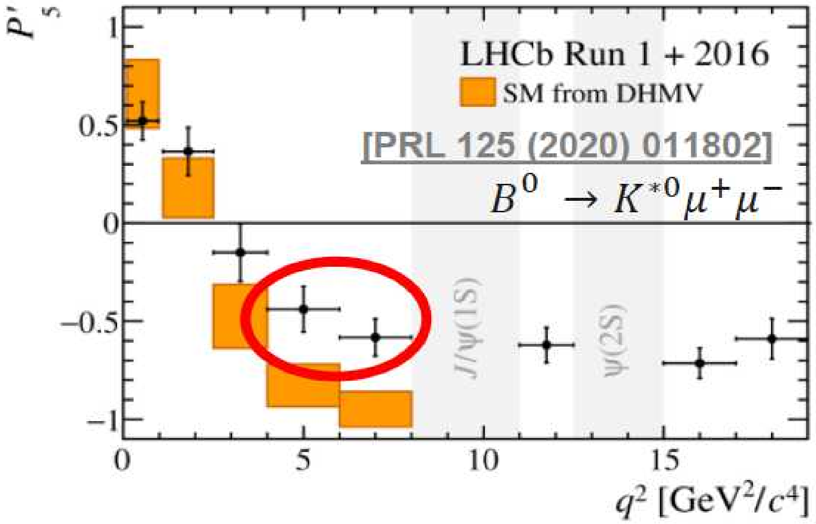
List of the observables:

- 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



[JHEP 06 (2014) 133]



[PRL 125 (2020) 011802]

A closer look to the data

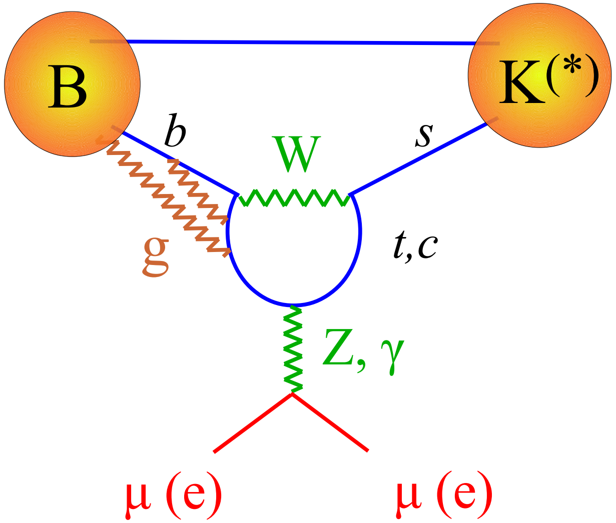
- $b \to s\, l^+ l^-$ (neutral currents)

List of the observables:

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

● 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

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

FCNC operators:

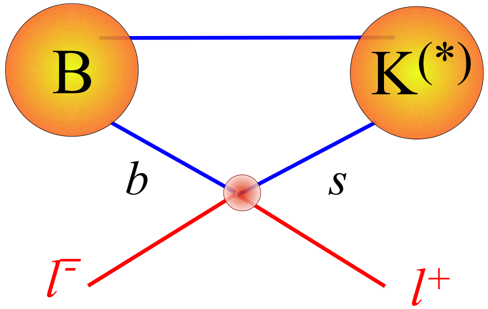
$$\mathcal{O}_{10}^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

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

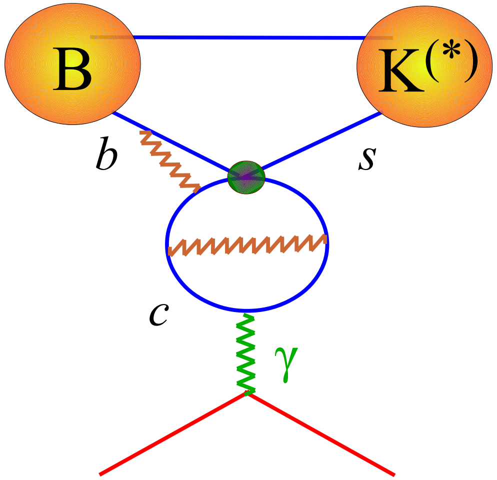
Four-quark operators:

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

$$\vdots$$



"easy" & "clean"



"difficult"

↓

induces ΔC_9^{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

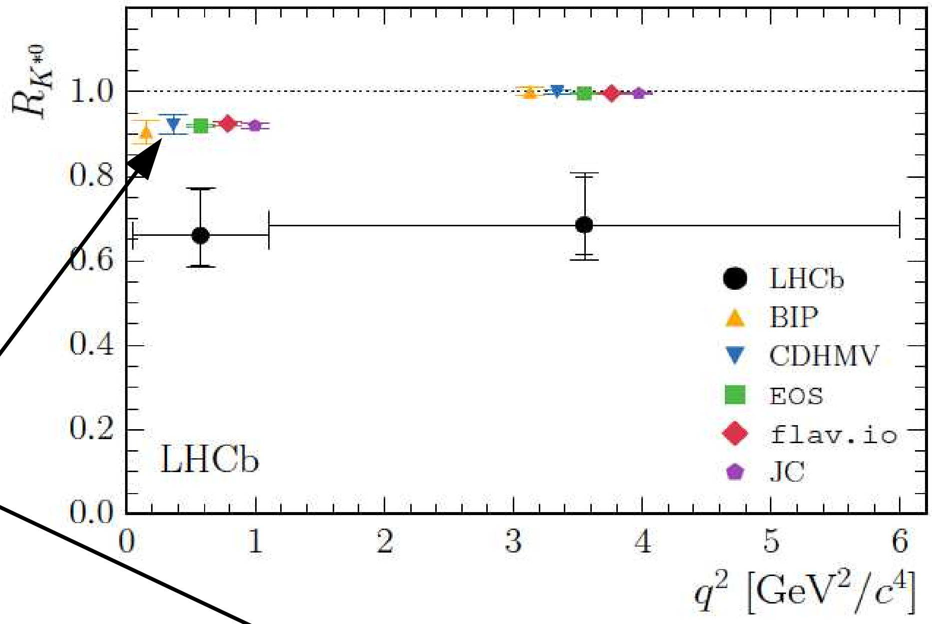
The LFU ratios:

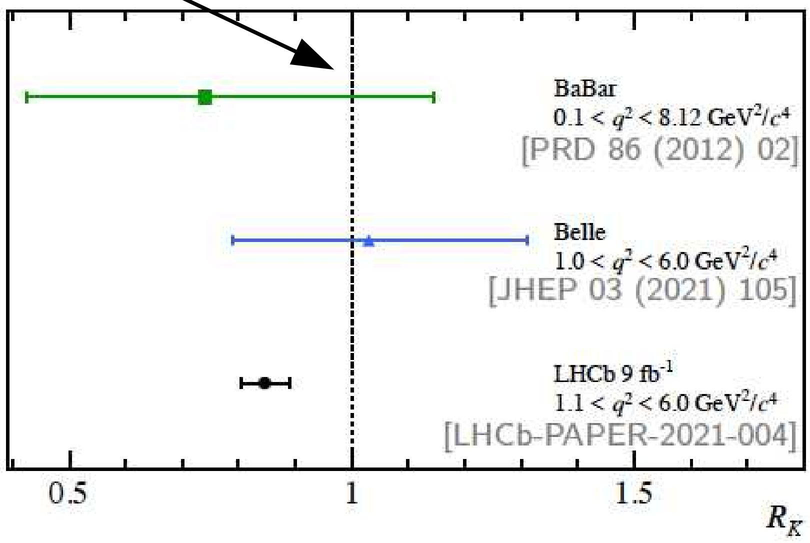
$$R_H = \frac{\int d\Gamma(B \to H\,\mu\mu)}{\int d\Gamma(B \to H\,ee)} \qquad (H = K, K^*)$$

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 $\boxed{2.2\sigma}$ to $\boxed{3.1\sigma}$ in each of the 3 bins measured by LHCb





A closer look to the data

The LFU ratios:

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

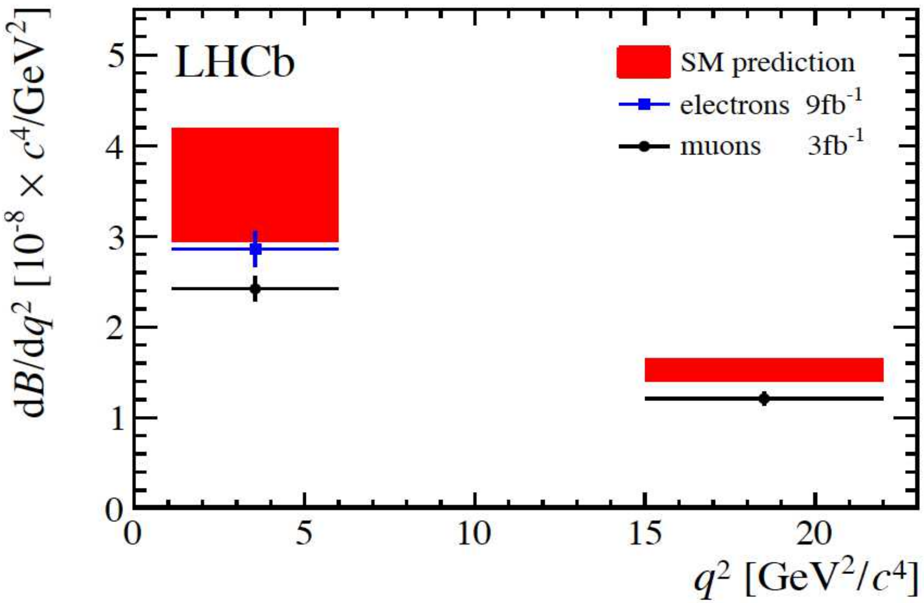
SM prediction very robust: $(R_H) = 1$
[*up tiny QED and lepton mass effects*]

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

Deviations from the SM predictions ranging from $\boxed{2.2\sigma}$ to $\boxed{3.1\sigma}$ in each of the 3 bins measured by LHCb

$B \to K\,ll$

LHCb '21



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

$B_s \to \mu\mu$:

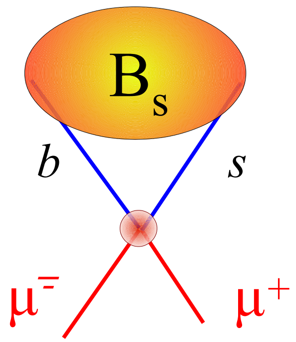
$$BR(B_s \to \mu\mu)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$

Beneke *et al.* '19

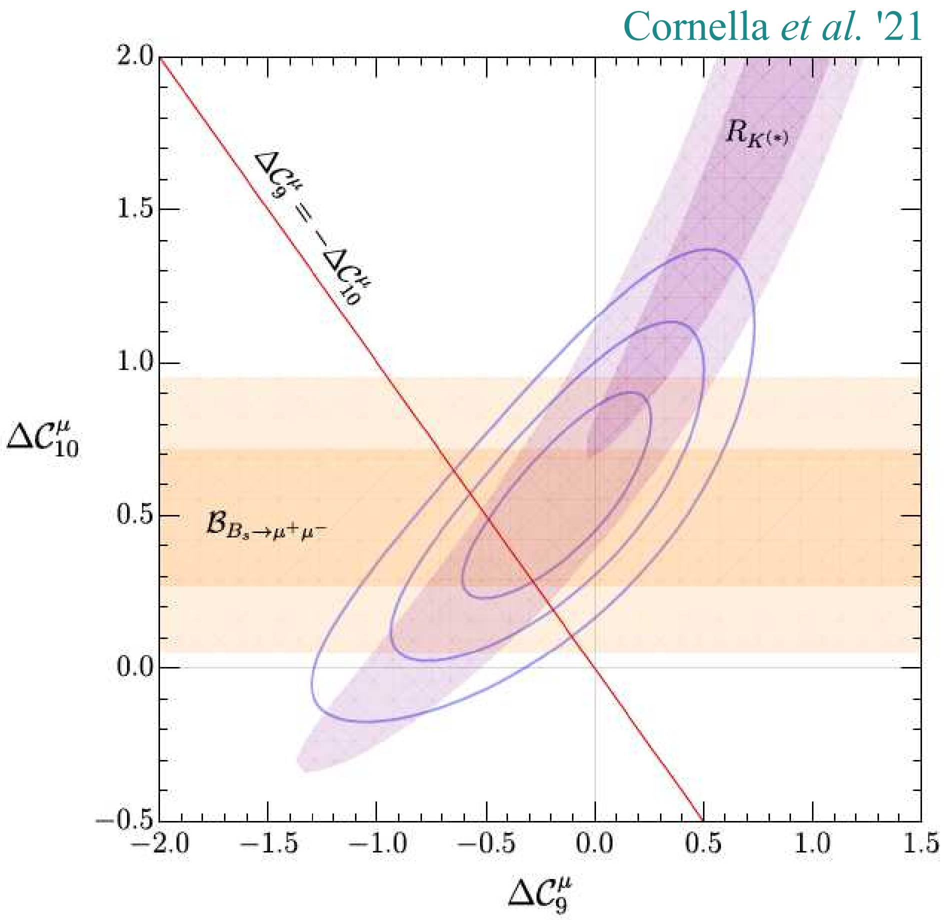
$$BR(B_s \to \mu\mu)_{exp} = (2.85 \pm 0.32) \times 10^{-9}$$

$\boxed{2.3\sigma}$

ATLAS+CMS+LHCb '21



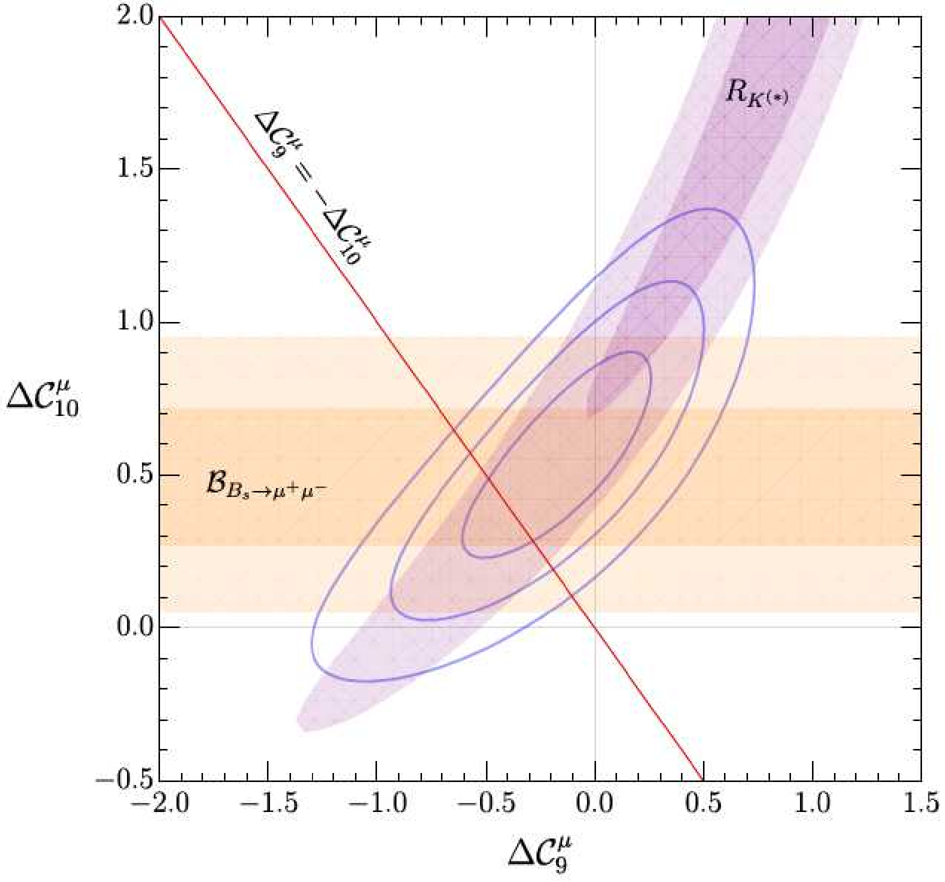
A closer look to the data

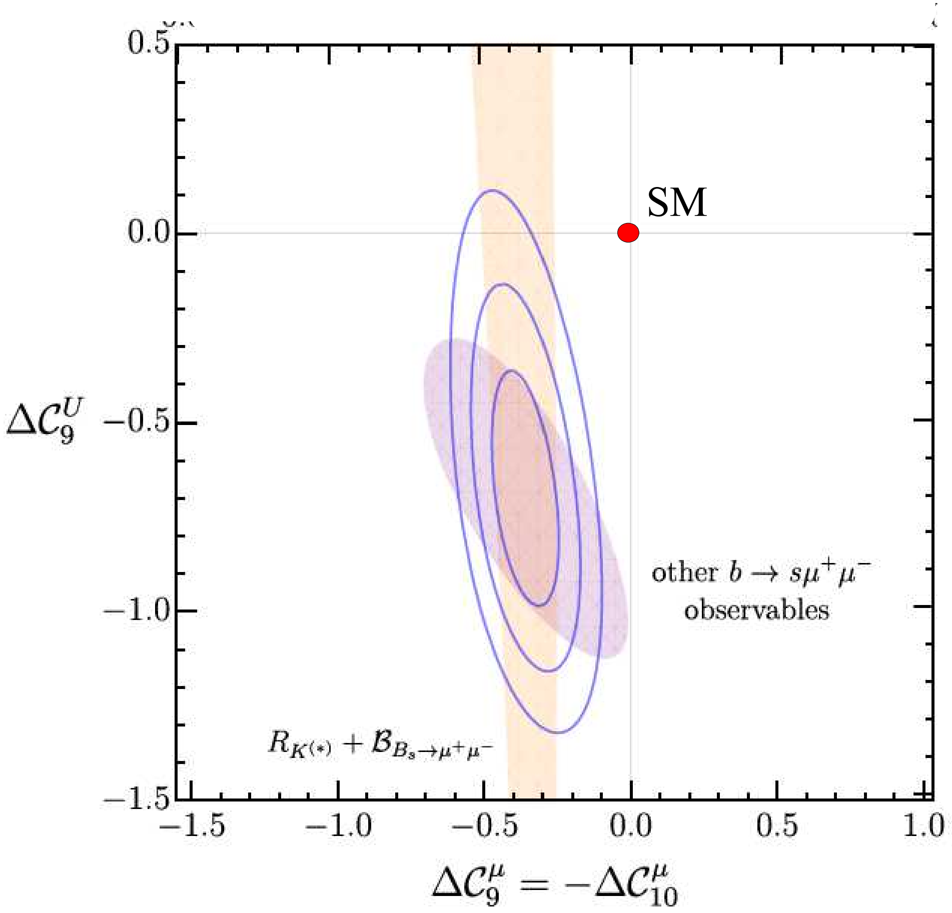


Conservative fit using "clean obs." only [$\Delta C_i^\mu = C_i^\mu - C_i^e$]:

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

A closer look to the data


Cornella *et al.* '21



Conservative fit using “clean obs.” only [$\Delta C_i^{\mu} = C_i^{\mu} - C_i^{e}$]:

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

$>> 5\sigma$ 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

A closer look to the data

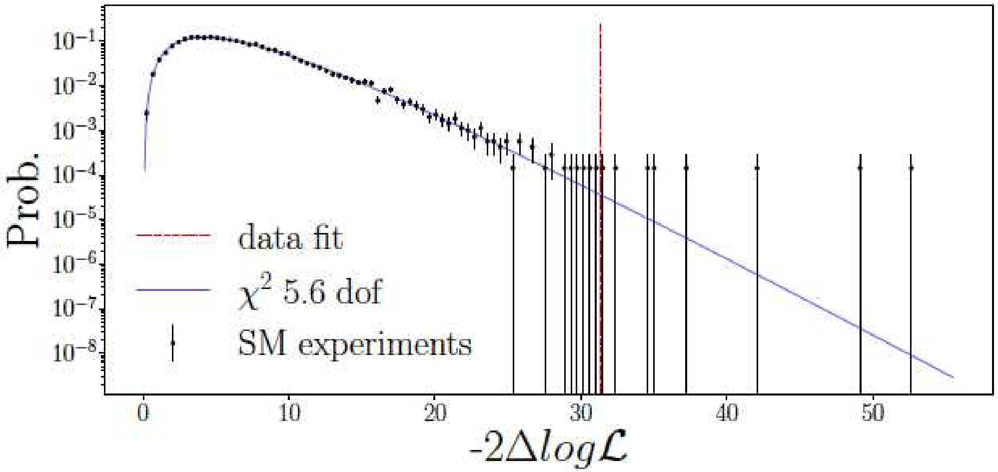
N.B.: the "nσ" quoted by various theory groups holds for specific NP hypotheses, motivated, but made *a posteriori* (*after looking at the data*) → *local significance*

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 $P(\Delta\chi^2 > \Delta\chi^2_{obs})$

$\boxed{3.9\sigma}$ *global significance* with respect to any form of heavy NP

Lancierini, GI, Owen, Serra, '21



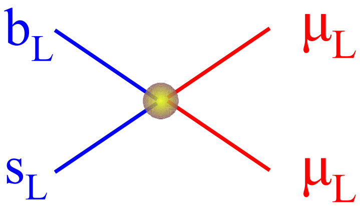
Remarkably high !

[*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

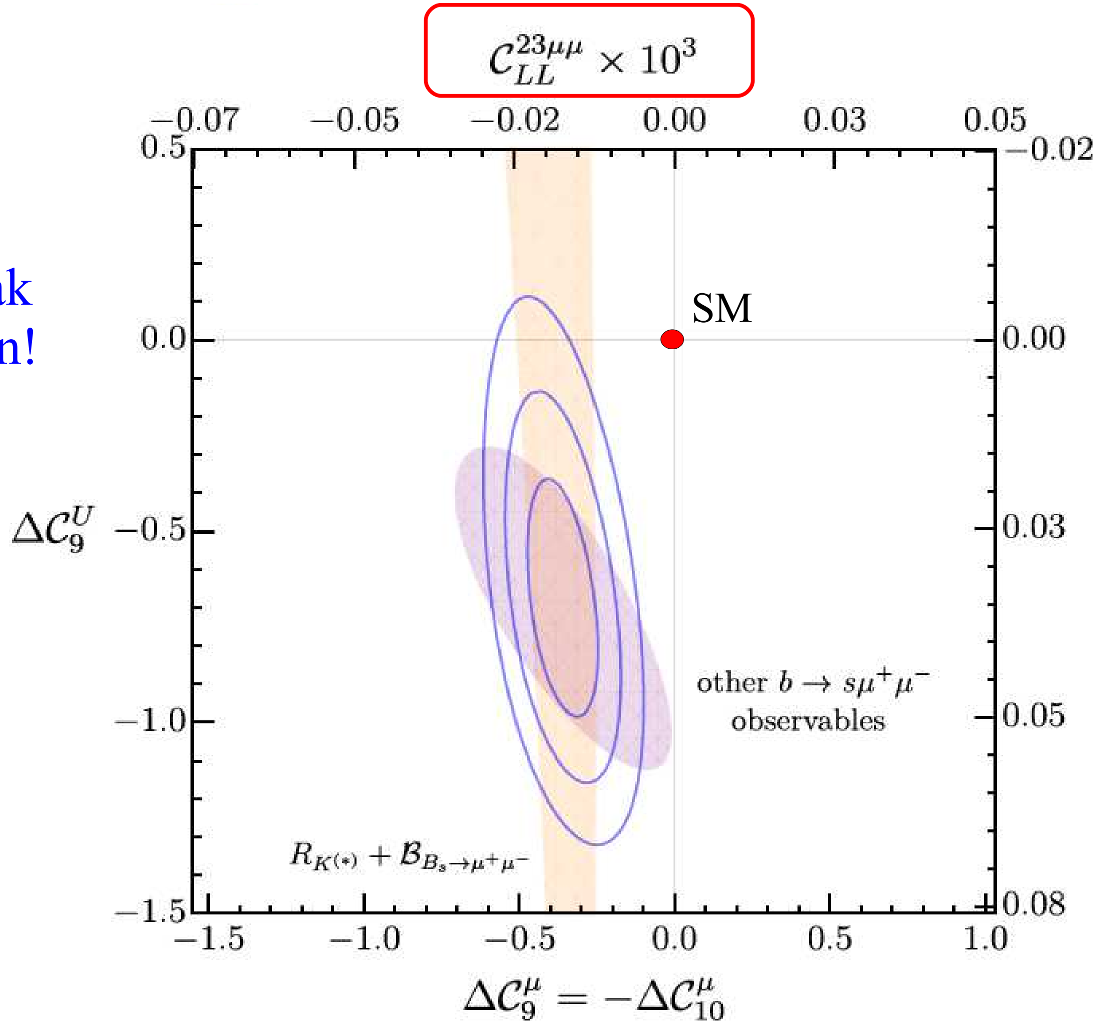
$$\boxed{\mathcal{O}^{ij\alpha\beta}_{LL} = (\bar{q}^i_L \gamma_\mu \ell^\alpha_L)(\bar{\ell}^\beta_L \gamma_\mu q^j_L)}$$



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

super-weak interaction!

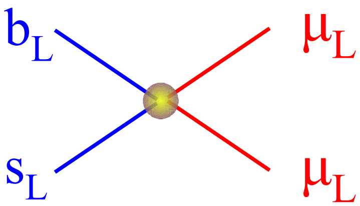
$C^{23\mu\mu}_{LL} \rightarrow \Delta C_9^\mu = -\Delta C_{10}^\mu$



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

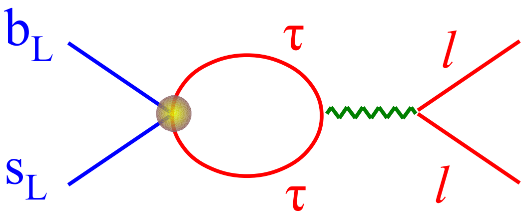
$$\boxed{\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)}$$



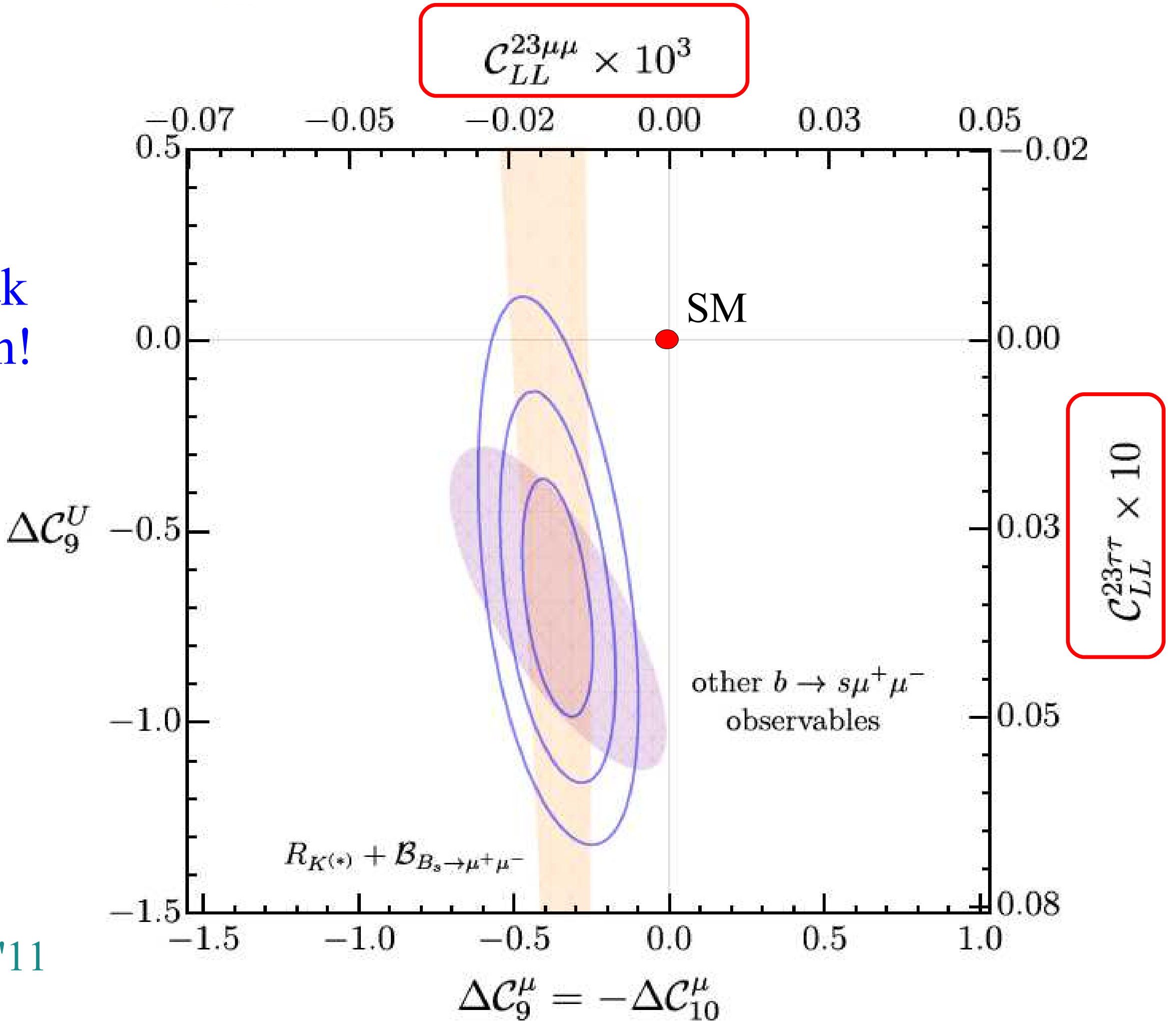
$\sim 2\times10^{-5}\, G_{\rm Fermi}$

super-weak interaction!

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



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



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

▶ *A closer look to the data*

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

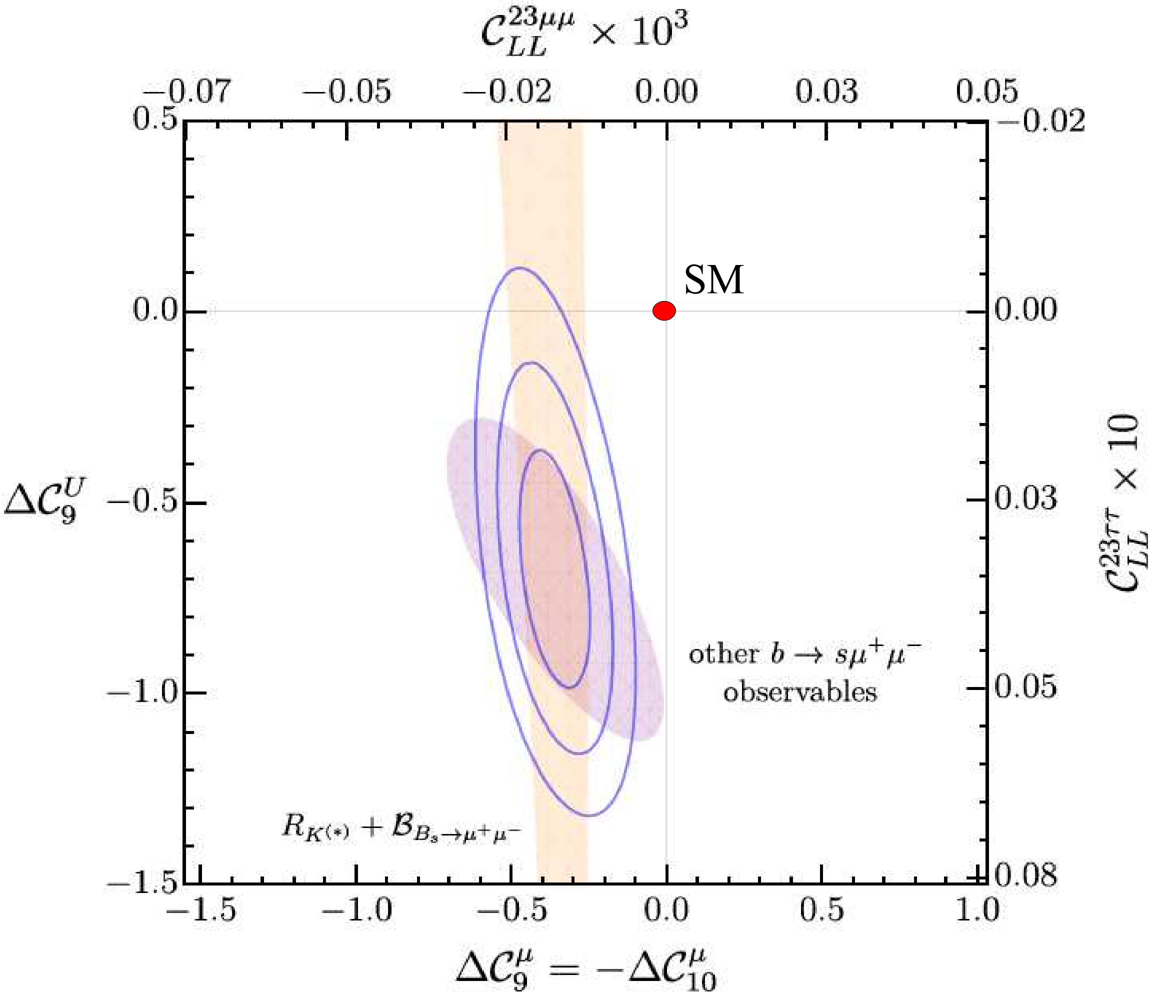
Some *historical* remarks, on how we arrived here:

2013 P_5' [$B \to K^* \mu\mu$] → $C_9 \neq C_9^{SM}$ 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



▶ *A closer look to the data*

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

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

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

2014 hypothesis $\Delta C_9^\mu = -\Delta C_{10}^\mu$
==> $\boxed{R_{K^*} \sim R_K \;\&\; B(B_s \to \mu\mu) < B_{SM}}$ 2017-19

Hiller & Schmaltz '14

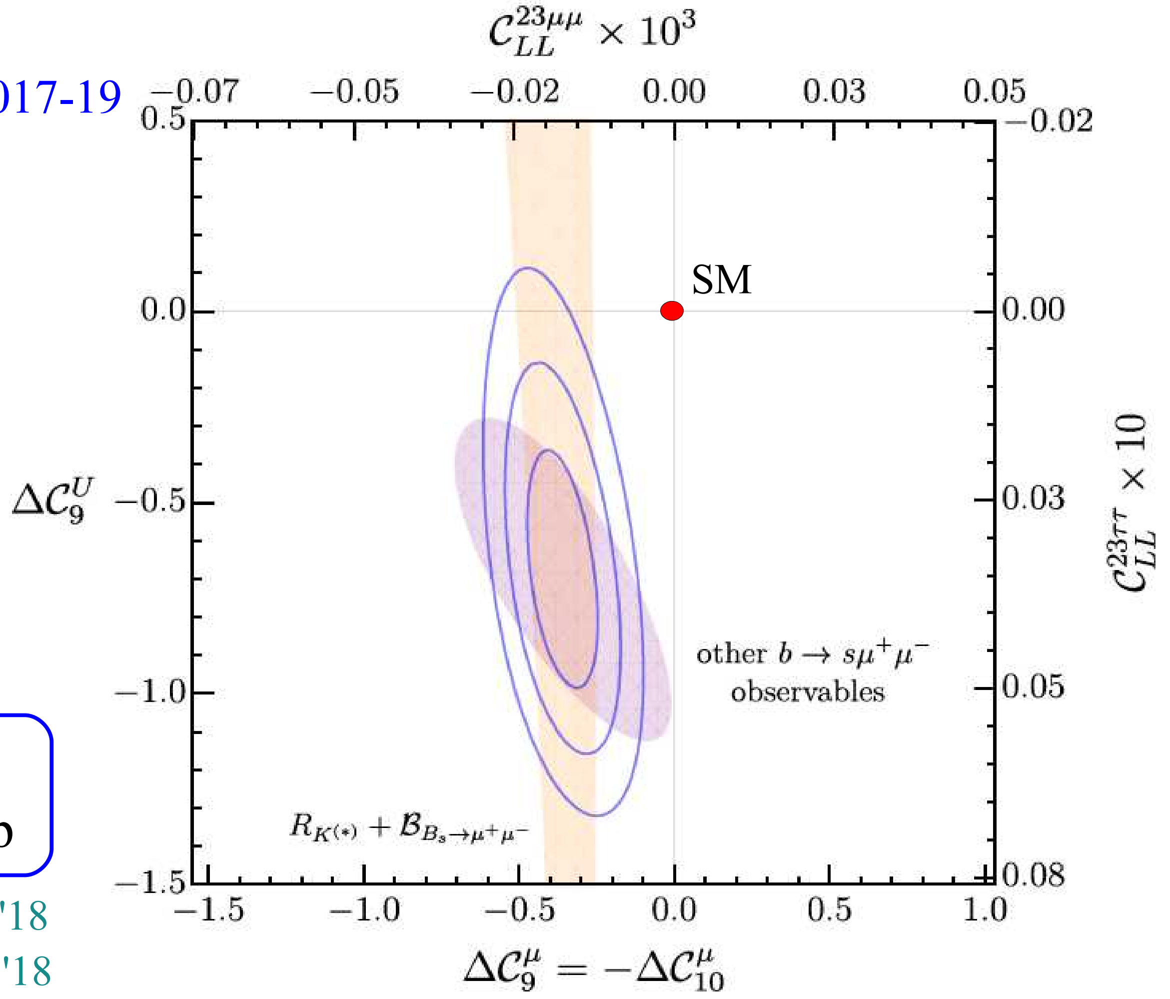
2015 U(2) hypothesis for b→s & b→c combined ==> $C^{23\tau\tau} \sim O(10^2) \times C^{23\mu\mu}$

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 $\boxed{\text{evidence of } \Delta C_9^U \text{ from global fits of correct size from } C^{23\tau\tau} \text{ @ 1-loop}}$

Crivellin, Greub, Muller, Saturnino '18
Alguero *et al.* '18

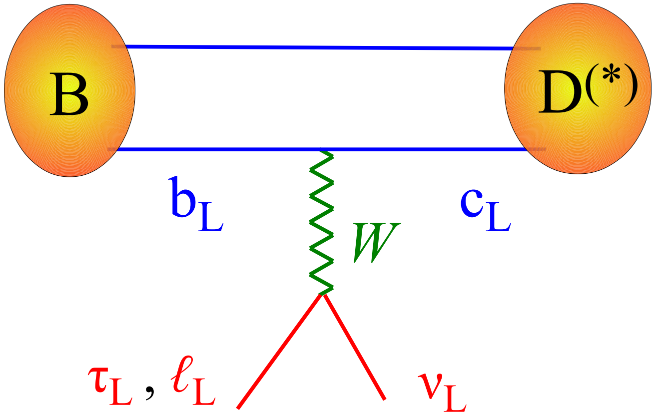


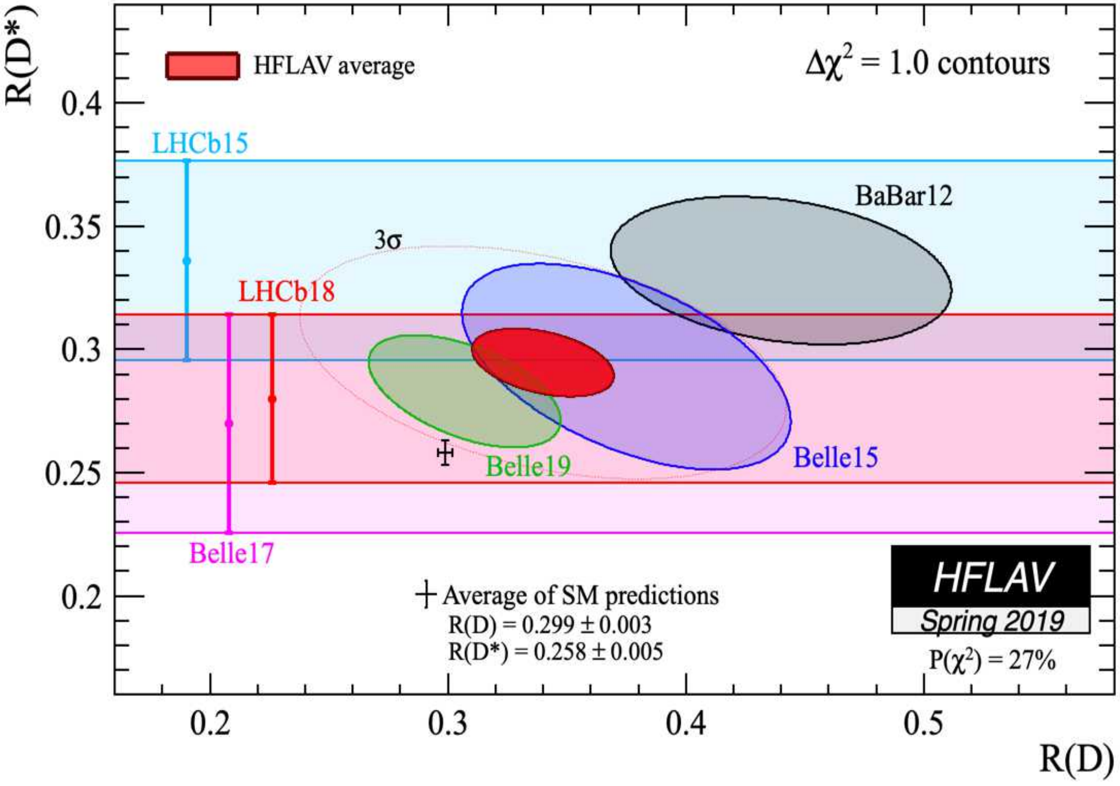
A closer look to the data

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

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$

X = D or D*



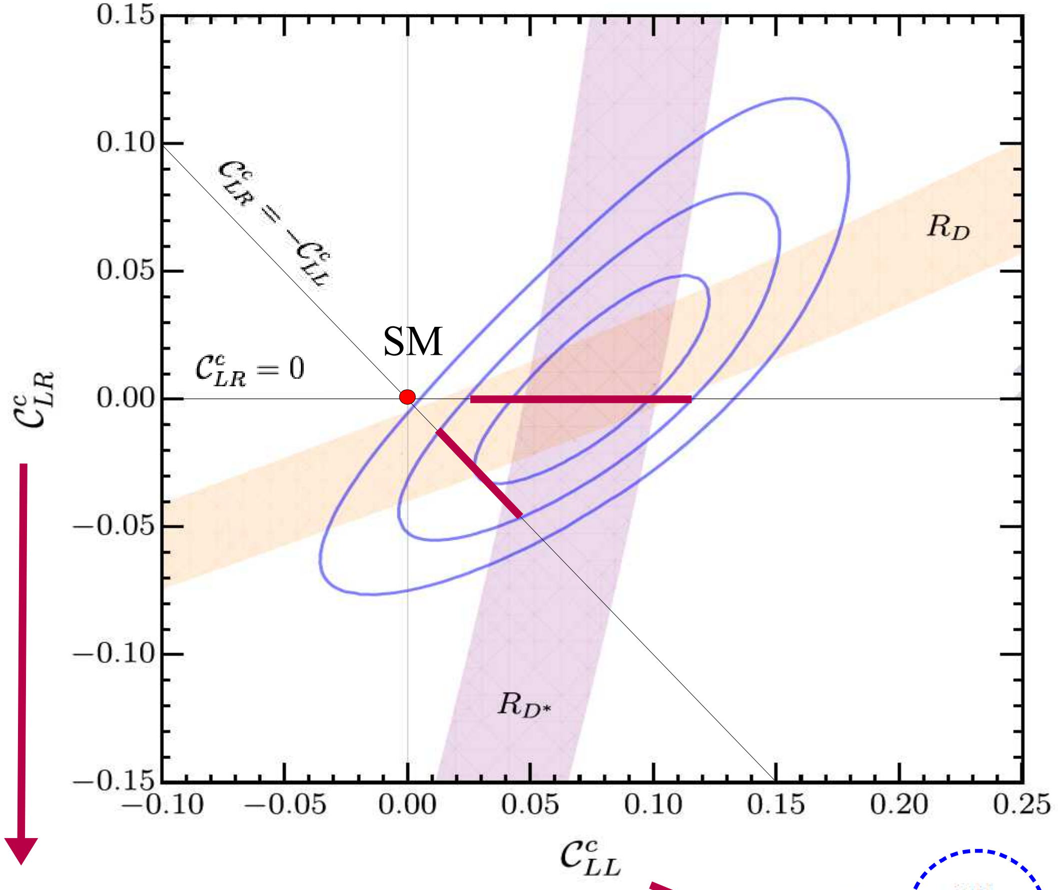


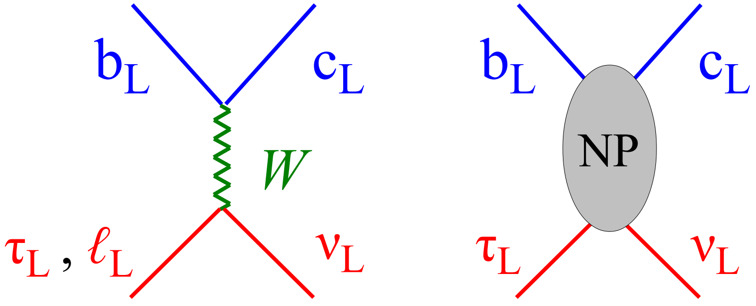
- Consistent results by three different exps. ~ 3.1σ excess over SM (*D and D* combined*)
- SM predictions quite "clean": hadronic uncertainties cancel (*to large extent*) in the ratios

A closer look to the data

- b → c *l*ν (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

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

Same operator contributing to b → s *ll*

all 3rd gen. (contribute via CKM rotation)

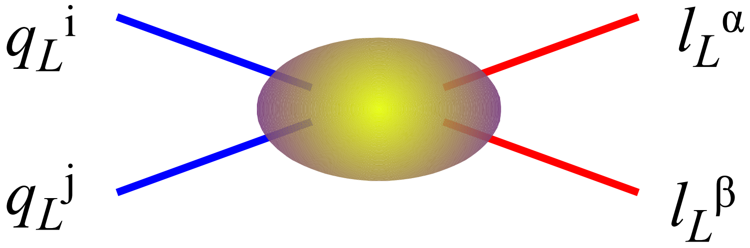
$(\bar{q}^i_L \gamma_\mu \tau_L)(\bar{\tau}_R \gamma_\mu b_R)$

CKM “weighted mix” as for $\mathcal{C}^c_{LL}$

EFT 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



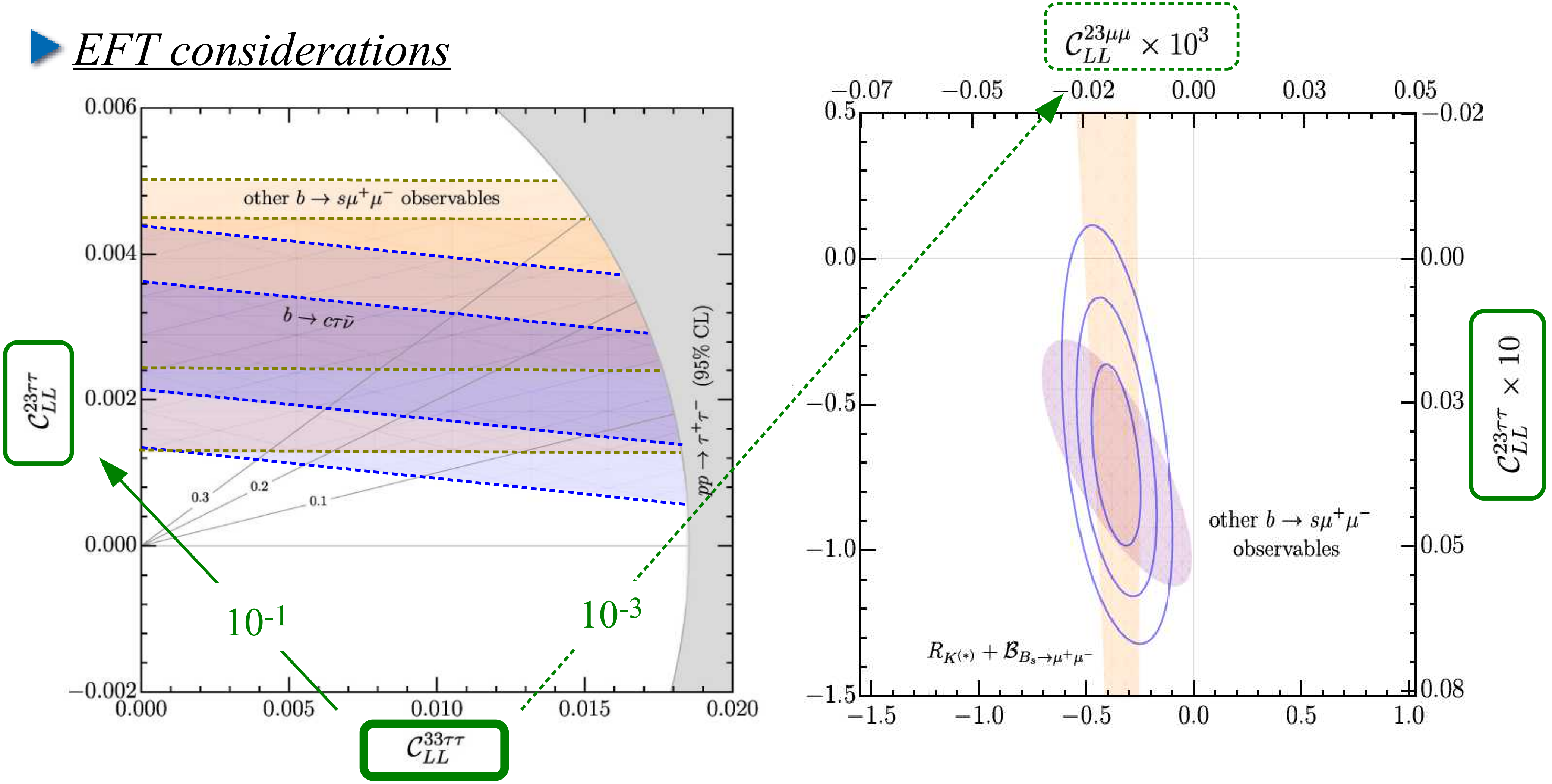
Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

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

↓

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

EFT considerations



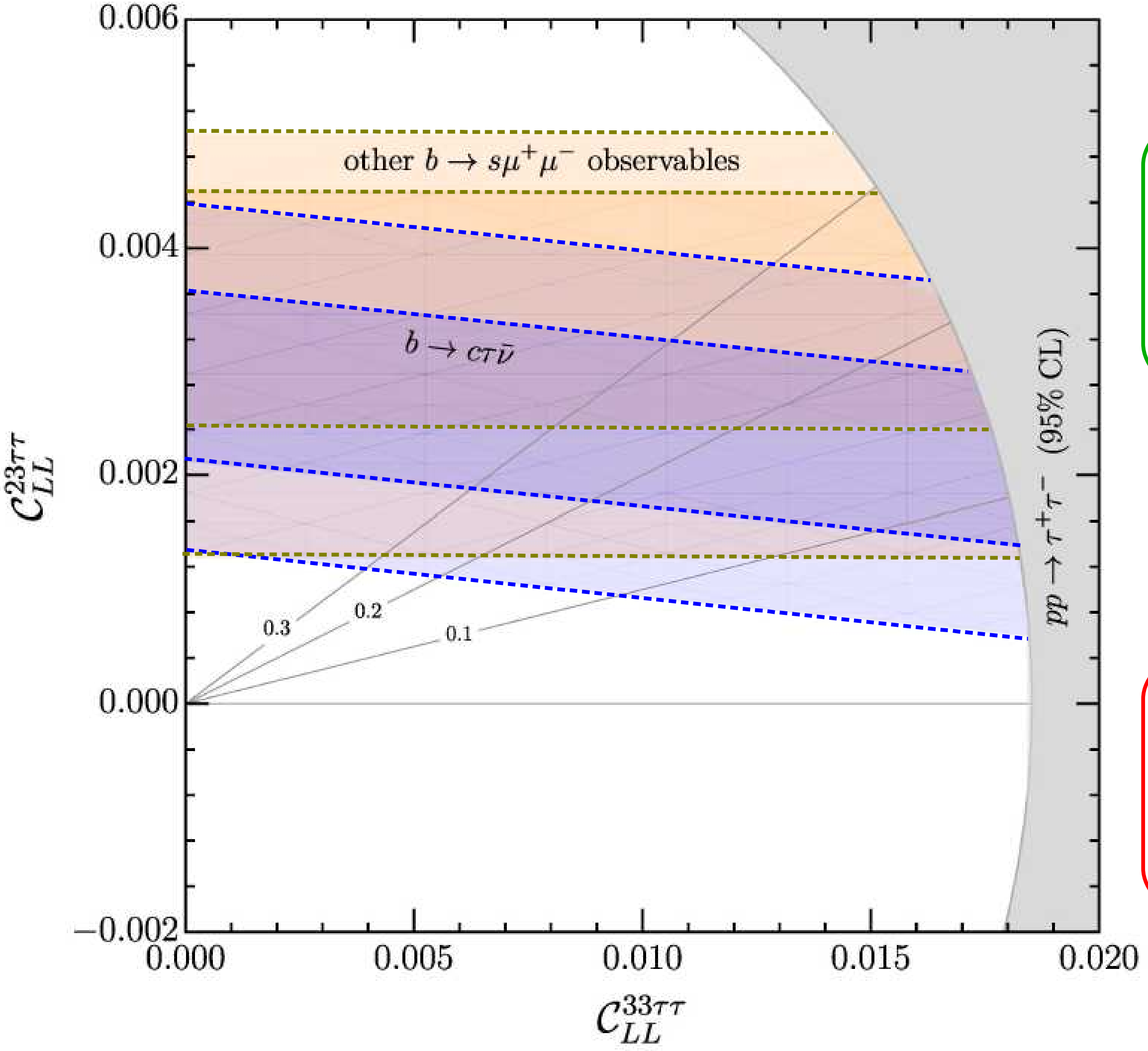
Pattern emerging from data:

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

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

▶ *EFT considerations*

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



Pattern emerging from data:

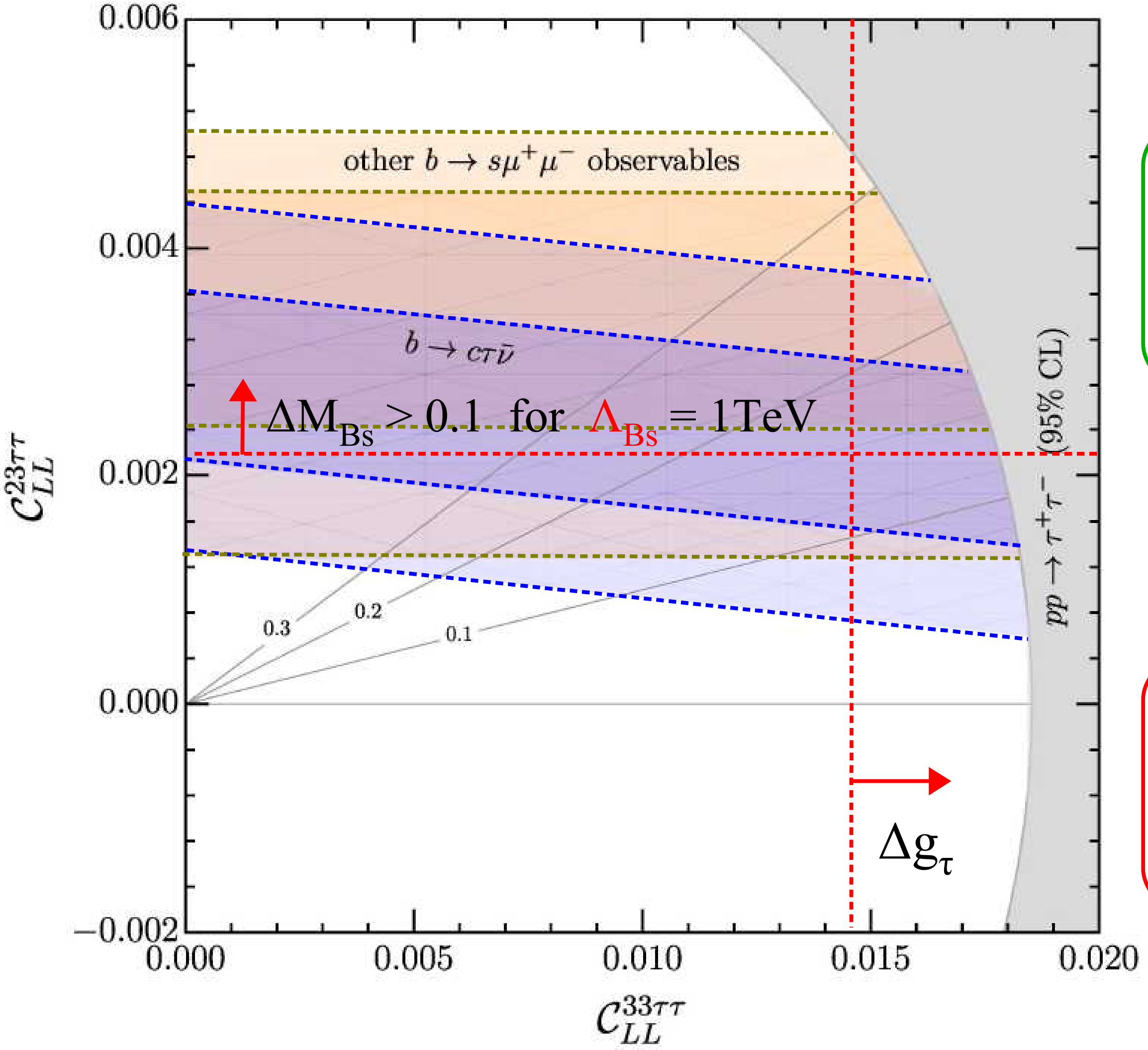
- ✓ O(10^{-1}) for each 2nd gen. q_L or l_L
- ✓ Nice consistency among the two sets of anomalies

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)

EFT considerations

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

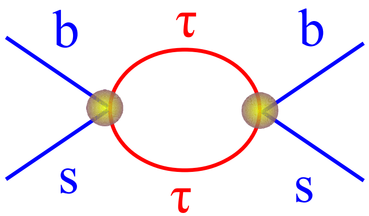


Pattern emerging from data:

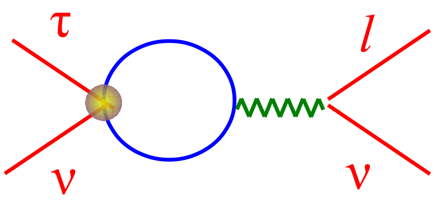
- ✓ $O(10^{-1})$ for each 2nd gen. q_L or l_L
- ✓ Nice consistency among the two sets of anomalies

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

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



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

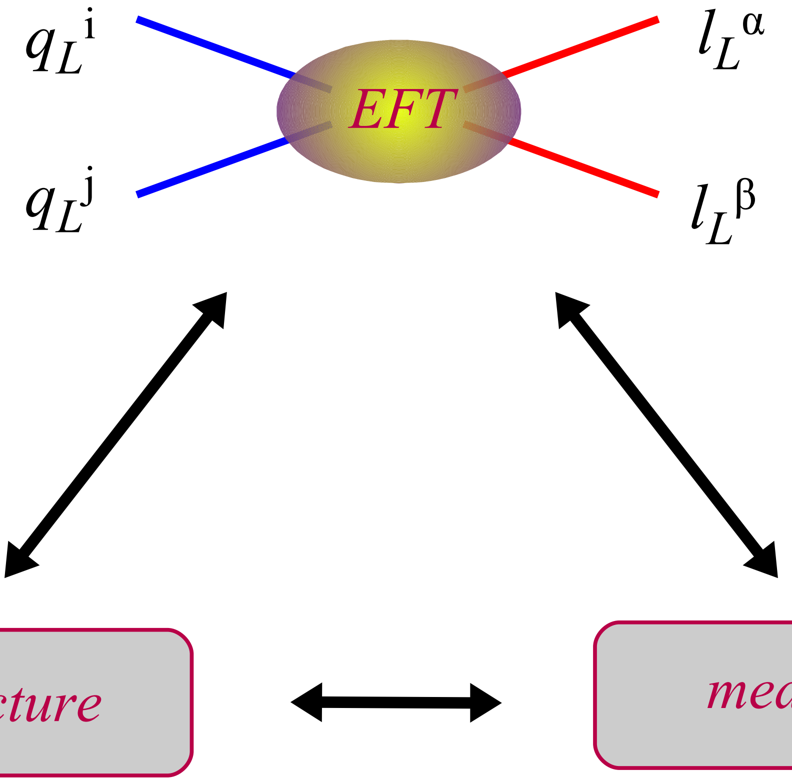


$\Delta g_\tau \sim (C^{33\tau\tau})\log(\Lambda/m_t)$

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*

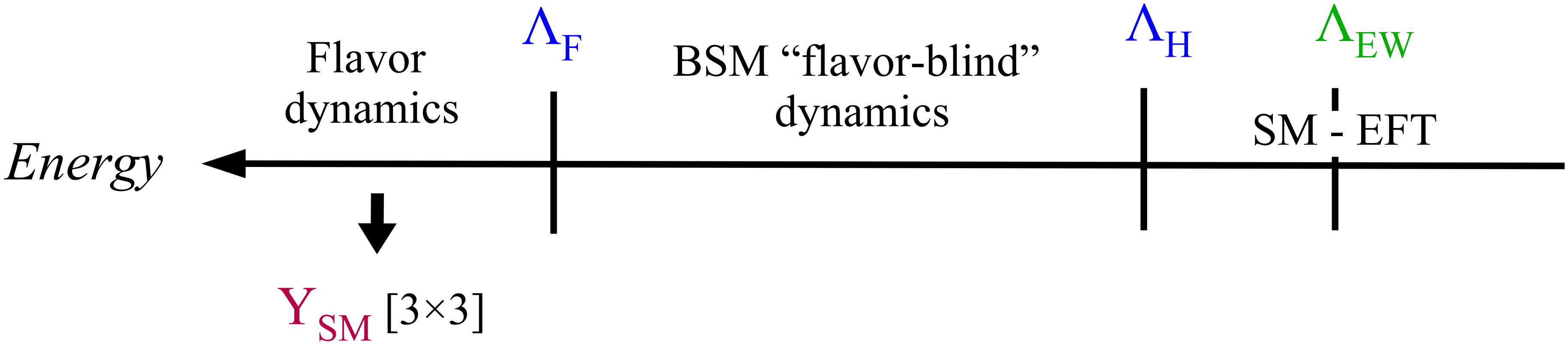


flavor structure

mediators

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

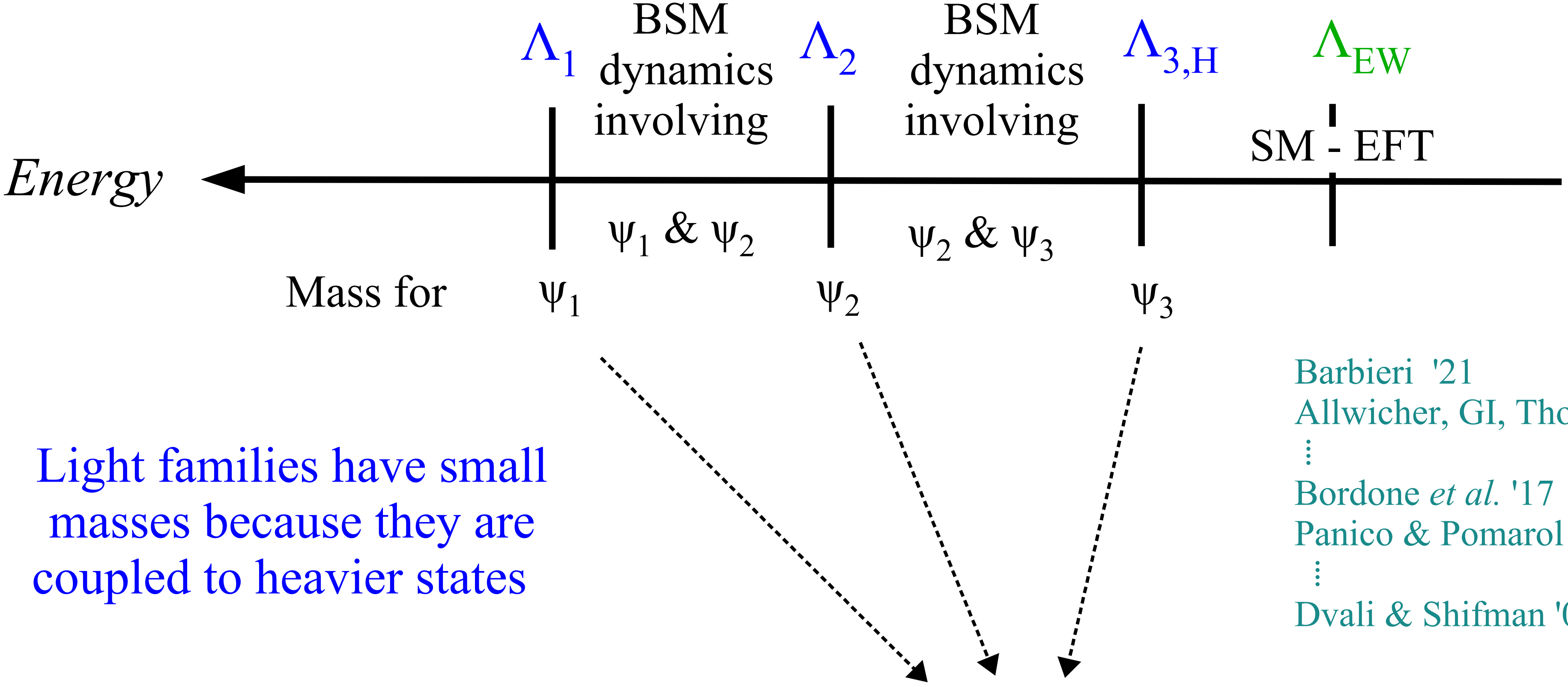
The MFV paradigm:



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

~~*The MFV paradigm*~~

Multi-scale picture @ origin of flavor:



Λ_1 BSM dynamics involving ψ_1 & ψ_2 Λ_2 BSM dynamics involving ψ_2 & ψ_3 $\Lambda_{3,H}$ Λ_{EW}

SM - EFT

Energy

Mass for ψ_1 ψ_2 ψ_3

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

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

From EFT to simplified models [*the 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:

$$\psi = \left[\begin{array}{c} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \\ \hdashline \psi_3 \end{array} \right] \quad \begin{array}{l} \longleftarrow \text{ light generations (\textit{flavor doublet})} \\ \\ \longleftarrow \text{ } 3^{rd} \text{ generation (\textit{flavor singlet})} \end{array}$$

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 $|V_{ts}| \sim 0.04$]

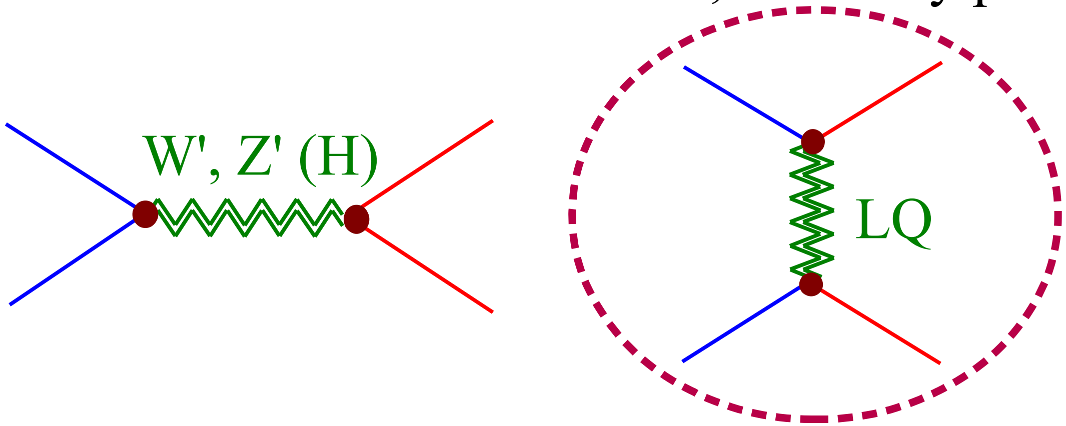
Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

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...

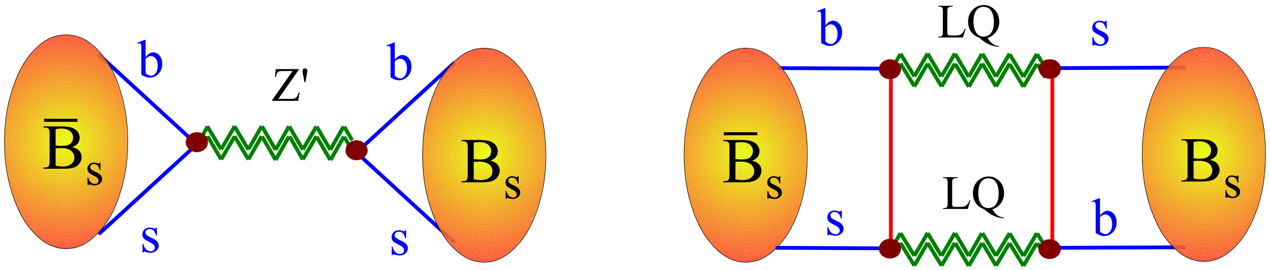
▶ *From EFT to simplified models* [*the possible mediators*]

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...



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

I. ΔF=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*]

"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 & $\not{R}$ 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 + ...

- Vector LQ in GUT gauge models
  Assad *et al.* '17
  Di Luzio *et al.* '17
  Bordone et *al.* '17
  Heeck & Teresi '18
  + ...

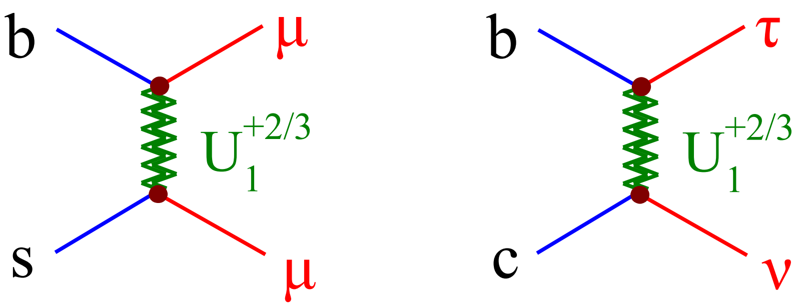
- Vector LQ as techni-fermion resonances
  Barbieri *et al.* '15; Buttazzo *et al.* '16, Barbieri, Murphy, Senia, '17 + ...

- 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]

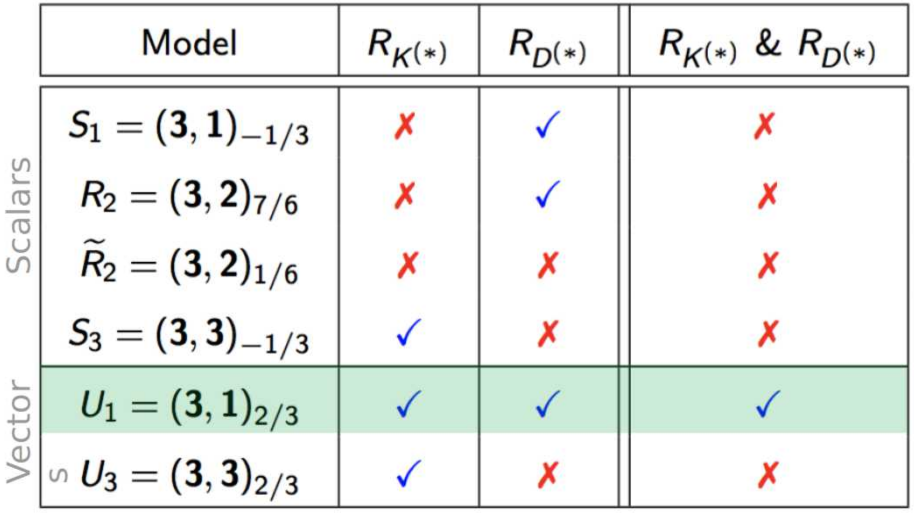


From EFT to simplified models [*the possible mediators*]

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

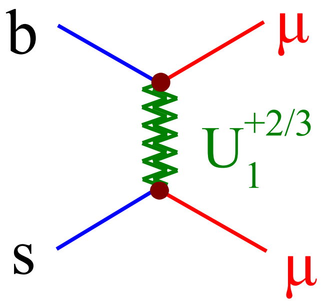
- Scalar LQ as PNG
  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
  Marzocca '18
- Scalar LQ from GUTs & $\not{R}$ SUSY
  Hiller & Schmaltz, '14; Becirevic *et al.* '16, Fajfer *et al.* '15-'17; Dorsner *et al.* '17; Crivellin *et al.* '17; Altmannshofer *et al.* '17 Trifinopoulos '18, Becirevic *et al.* '18 + ...
- 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 + ...

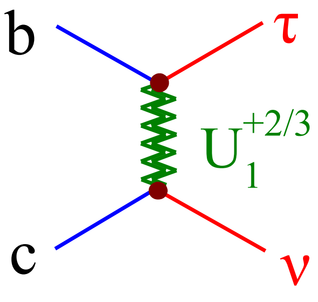
Which LQ explains which anomaly?



	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]





Barbieri, GI, Pattori, Senia '15

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

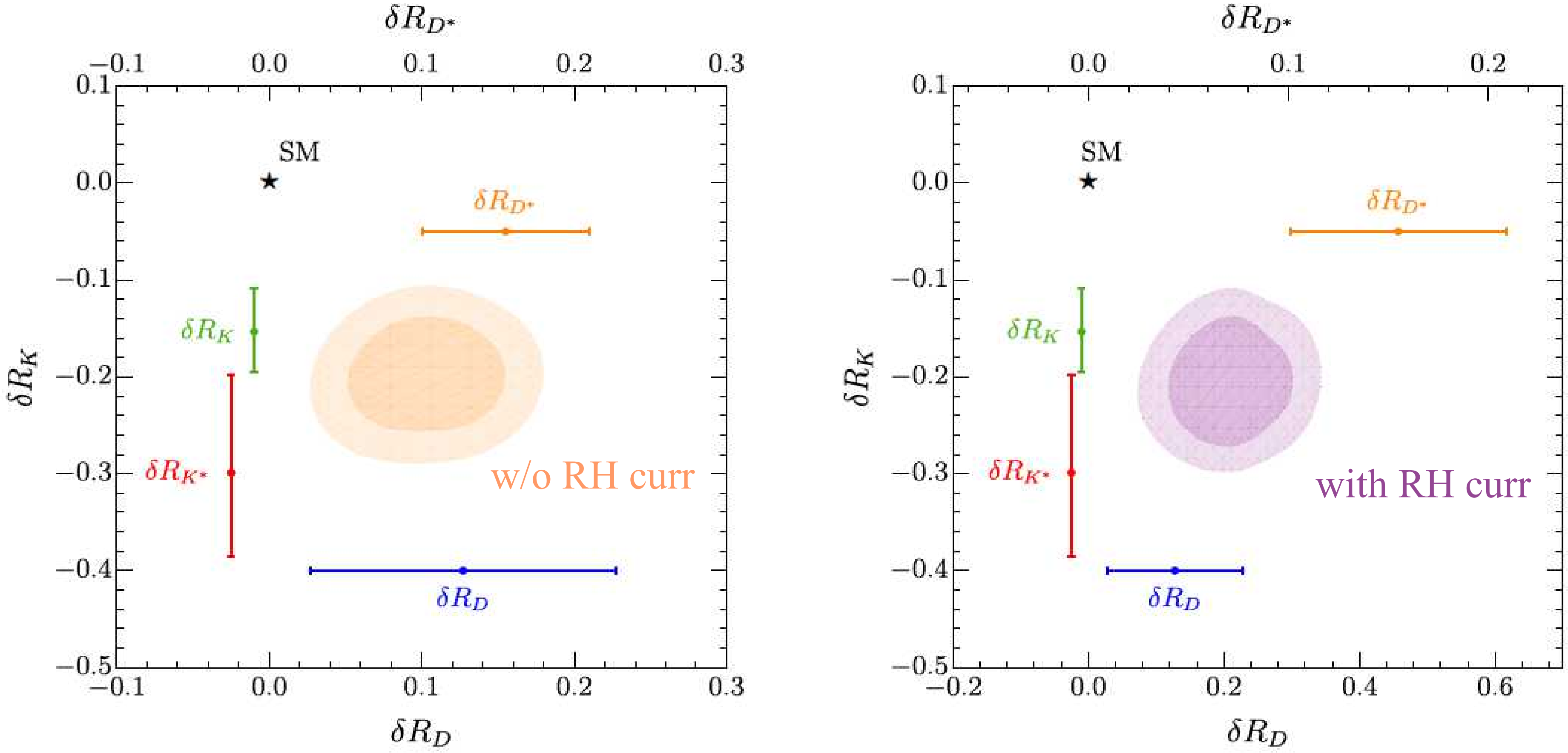
LQ of the Pati-Salam gauge group:
$\boxed{SU(4)}\times SU(2)_L\times SU(2)_R$

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

Considering the U_1 only

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

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



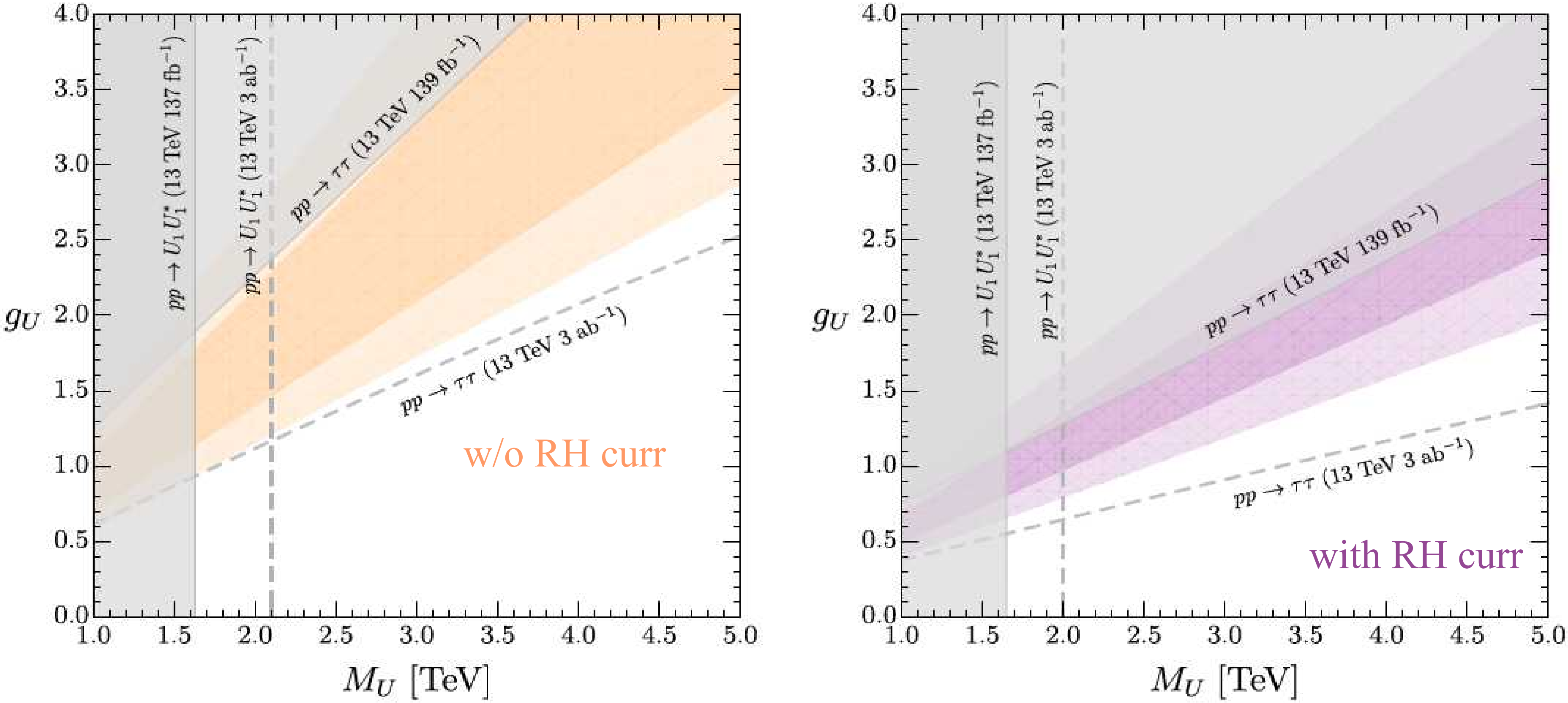
<u>From EFT to simplified models</u> [*the possible mediators*]

Considering the U_1 only

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

and fitting <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



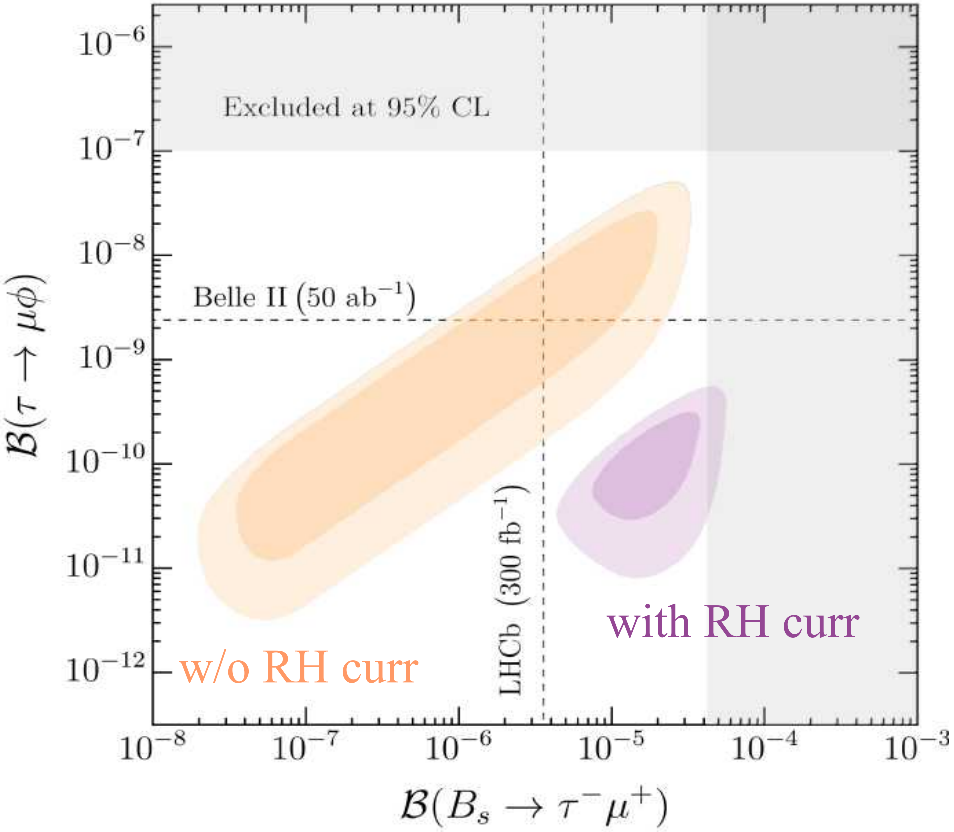
<u>*From EFT to simplified models*</u> [*the possible mediators*]

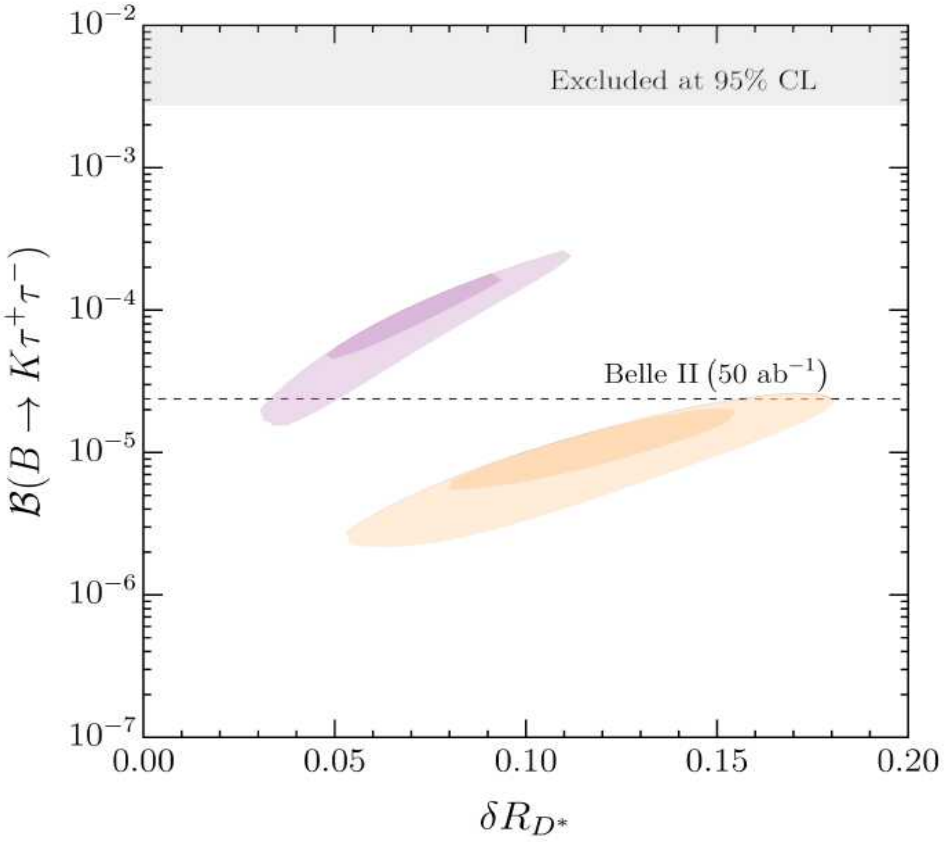
Considering the U_1 only

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

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> & 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 <u>only massive LQ</u> that is a good mediator for <u>both</u> anomalies:

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

Fermions in SU(4):

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

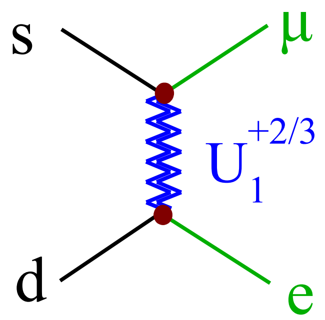
Main Pati-Salam idea:
Lepton number as "the 4th color"

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

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 $K_L \rightarrow \mu e$]

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

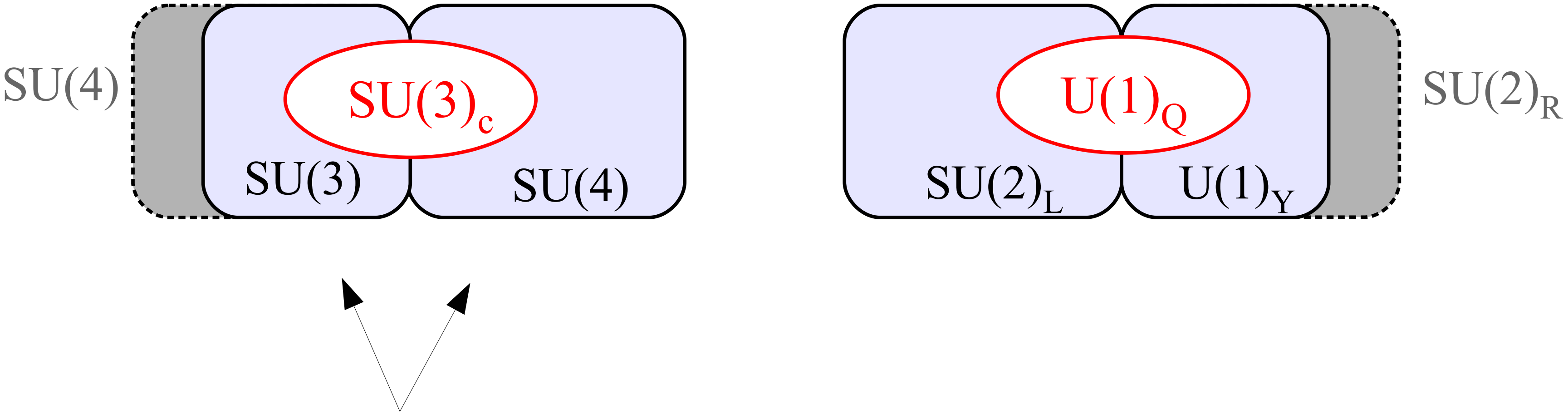
Second observation: we can "protect" the light families charging under SU(4) only the 3rd gen. or, more generally, "separating" the universal SU(3) component

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

- *flavor universality*

$$\downarrow$$

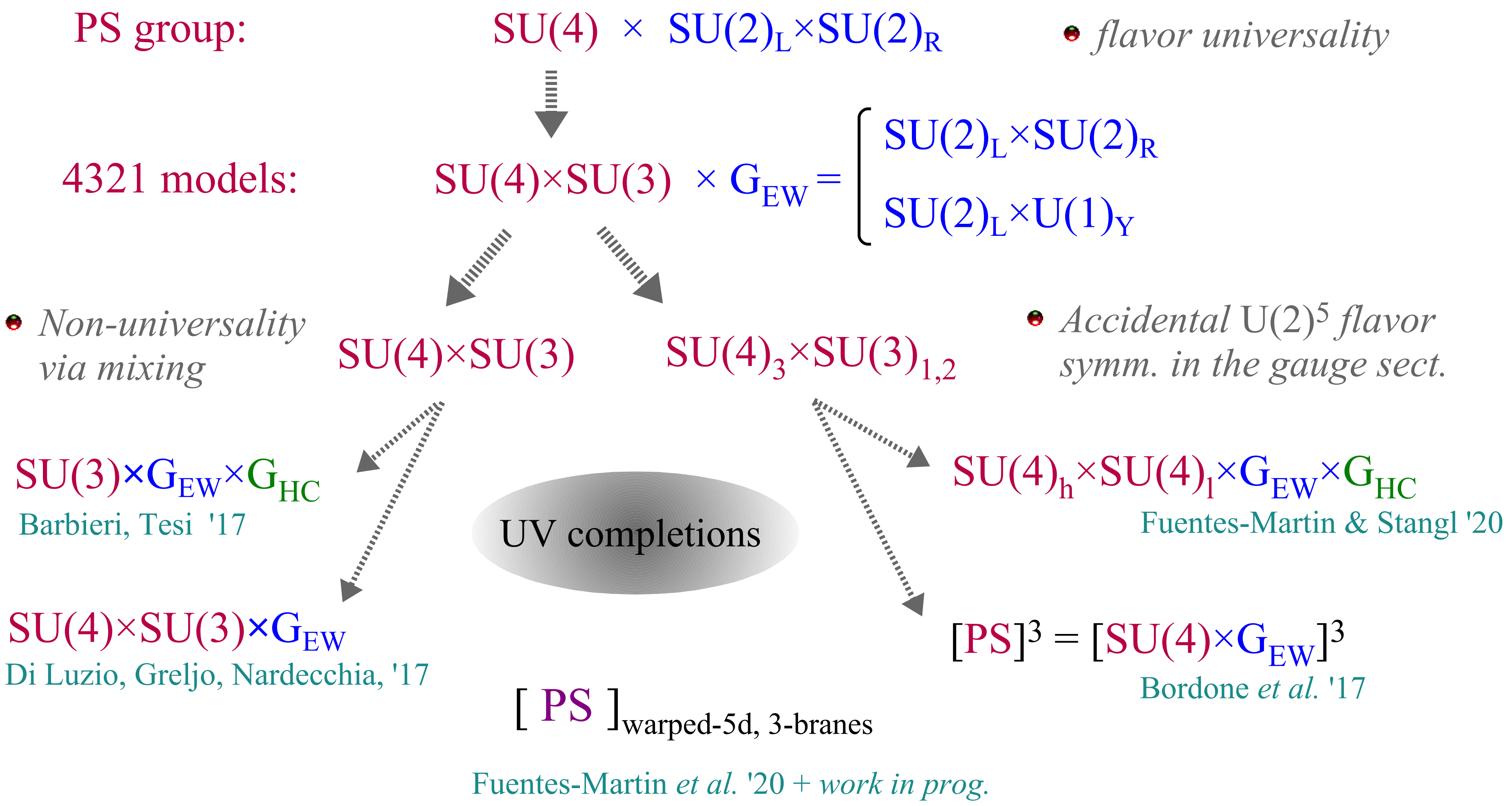
4321 models: $$SU(4)\times SU(3) \times G_{EW} = \begin{cases} SU(2)_L\times SU(2)_R \\ SU(2)_L\times U(1)_Y \end{cases}$$



This separation is not flavor blind

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

- *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

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

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

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

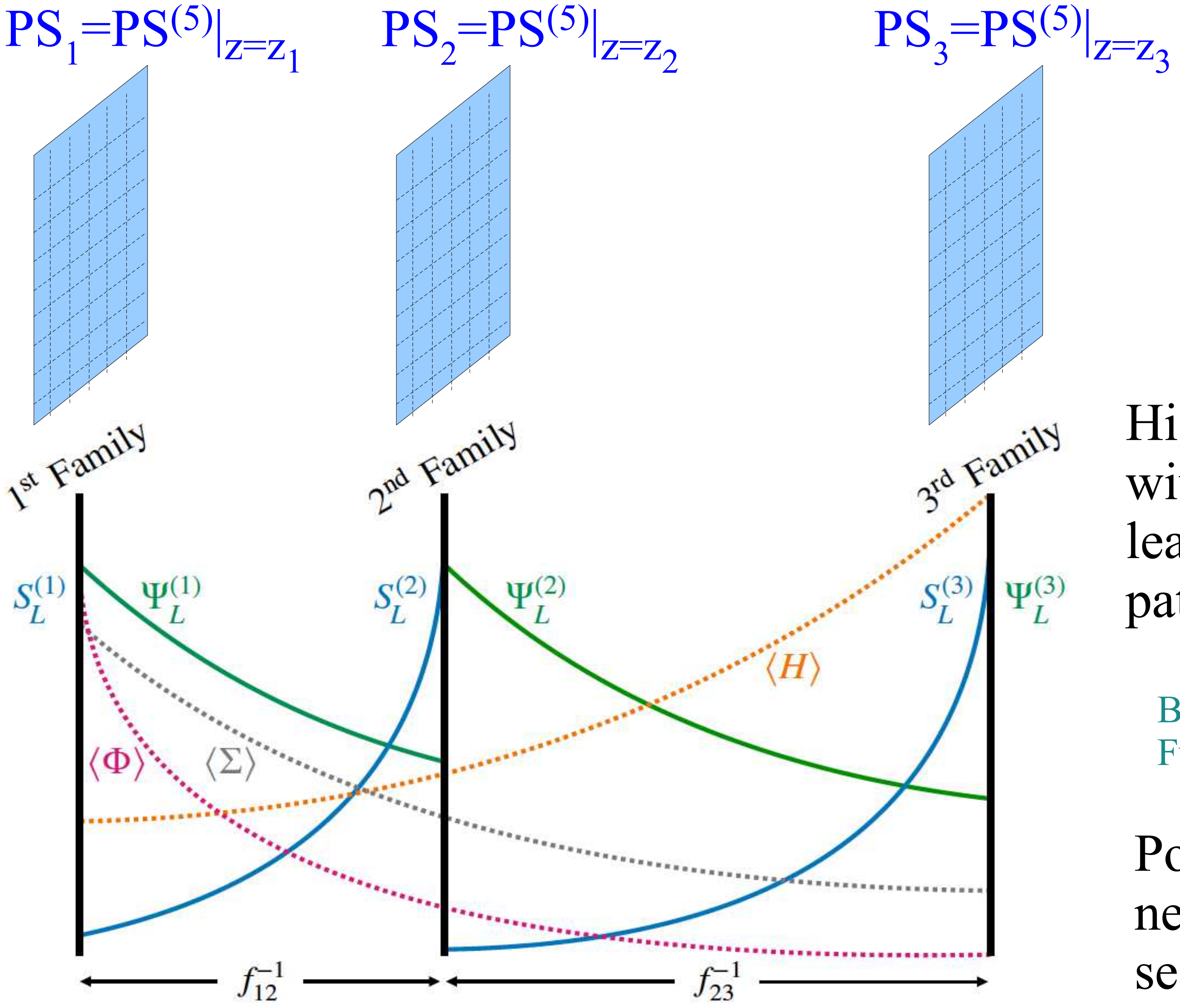
Fuentes-Martin & Stangl '20

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

Bordone *et al.* '17

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 $\psi_{1,2}$

→ LQ $[U_1]$ + Z' + G'

SM

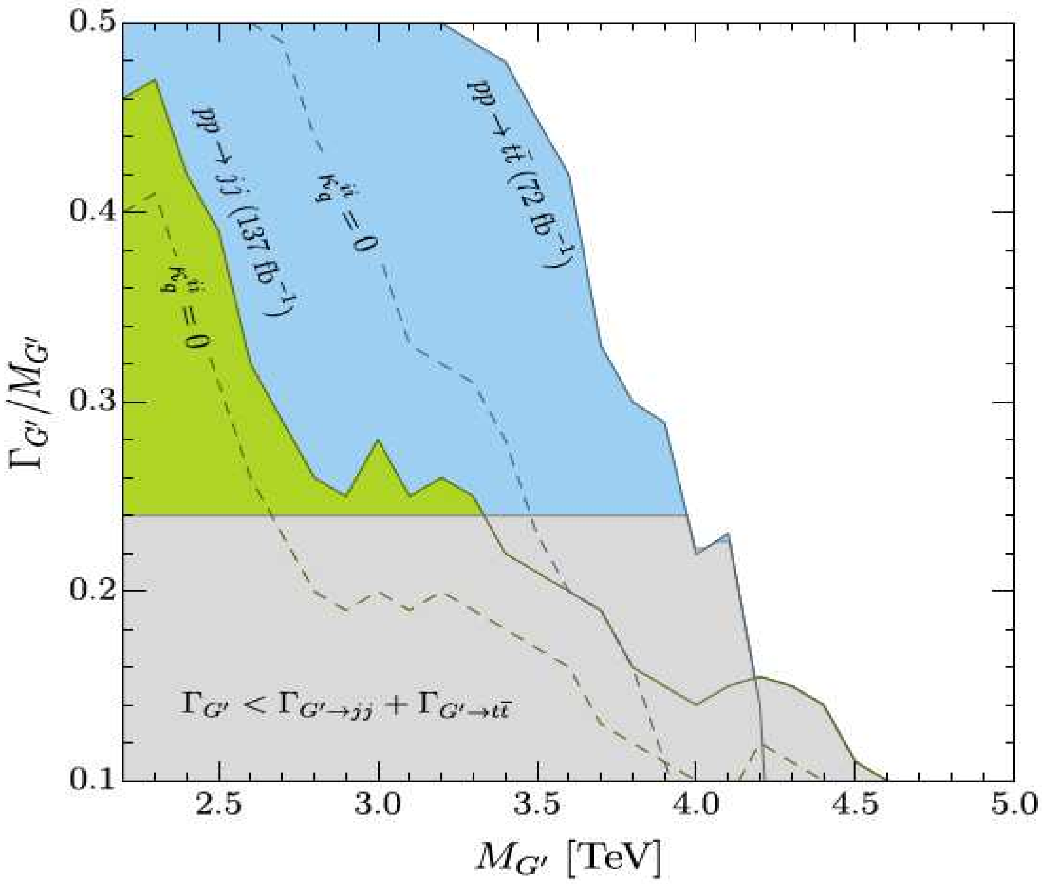
Despite the apparent complexity, the construction is highly constrained

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

consistent with present data !

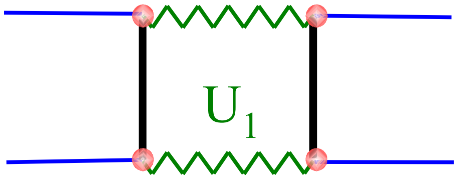
New striking collider signature:
G' (“*coloron*” = *heavy color octet*)

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

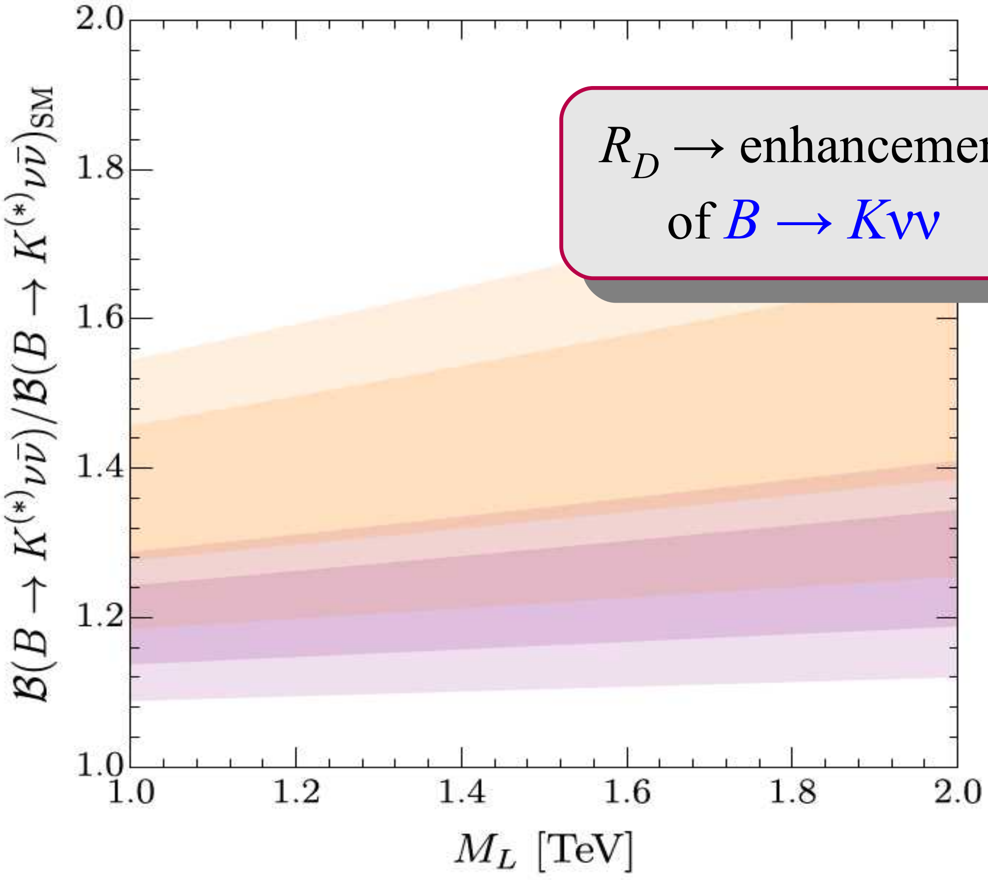


Speculations on UV completions

UV-sensitive observables in 4321 models

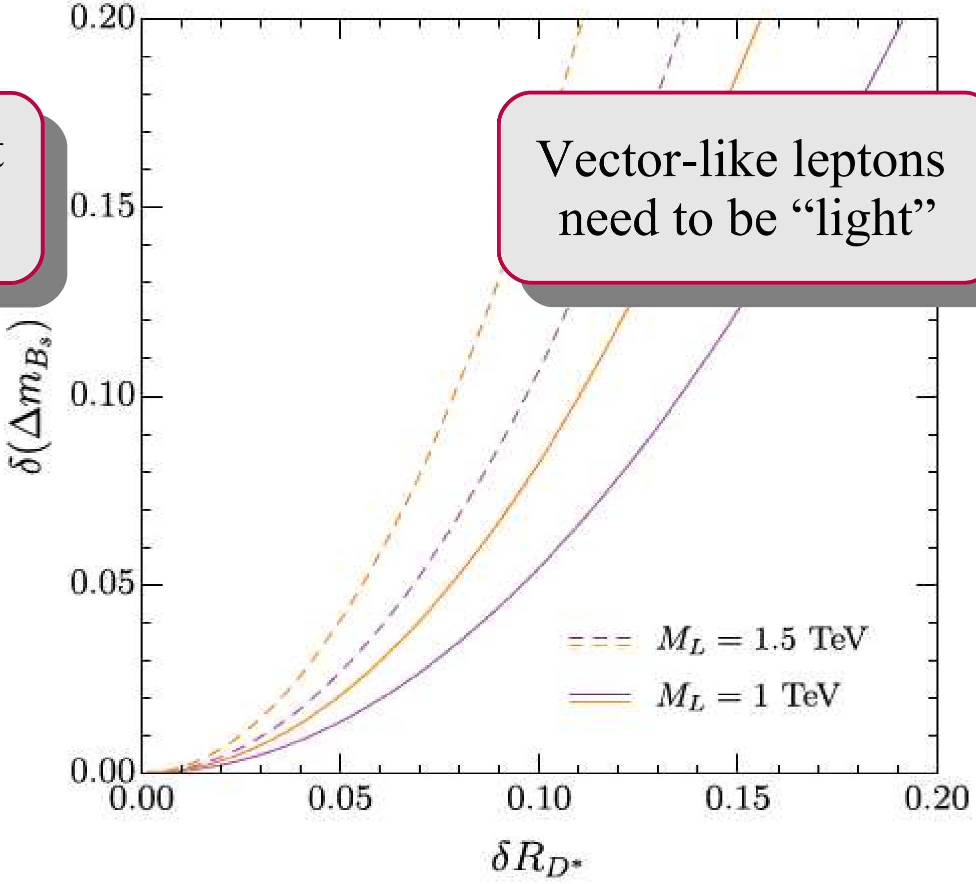


A) $B \to K\nu\nu$



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

B) B_s mixing [ΔF=2]



Vector-like leptons need to be “light”

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

Conclusions

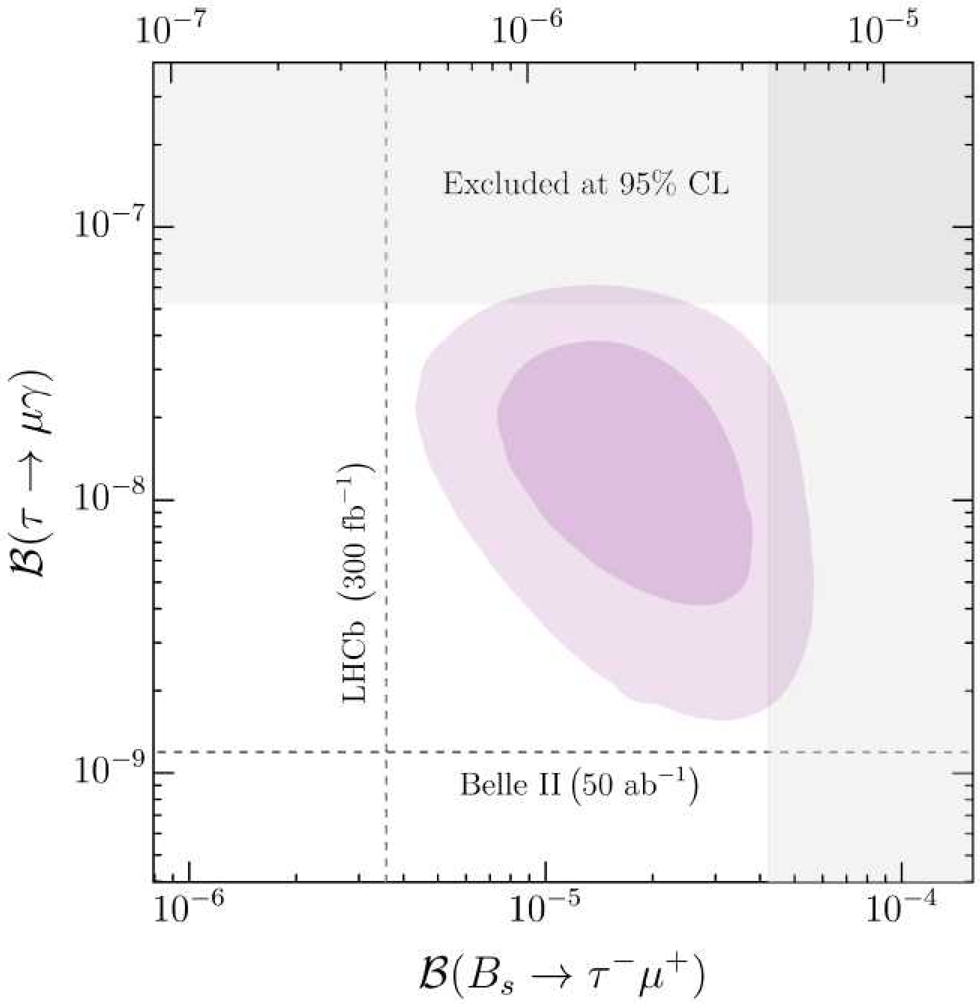
- The statistical significance of the LFU anomalies is growing: in the b→s*ll* system the chance this is a pure statistical fluctuation is marginal...
- If combined, the two sets of anomalies point to non-trivial flavor dynamics around the TeV scale, involving mainly the 3rd family → connection to the 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

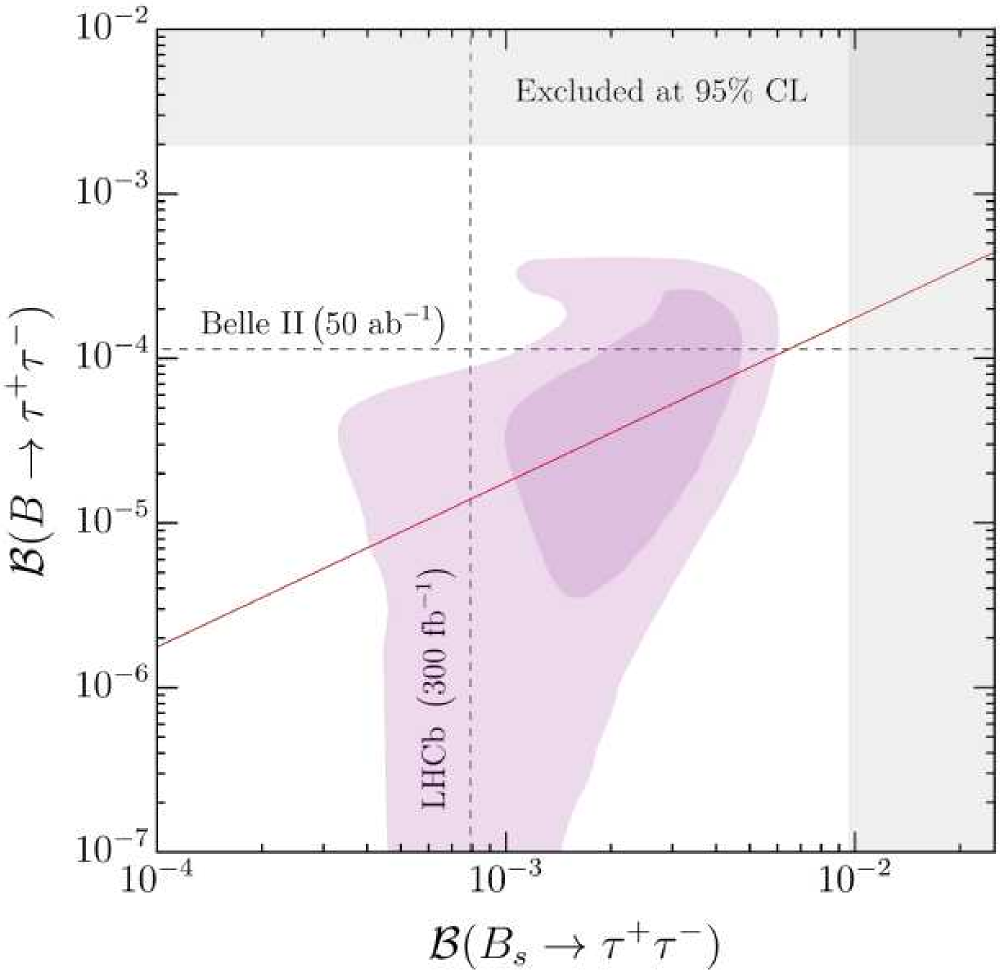
⬇

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


Backup

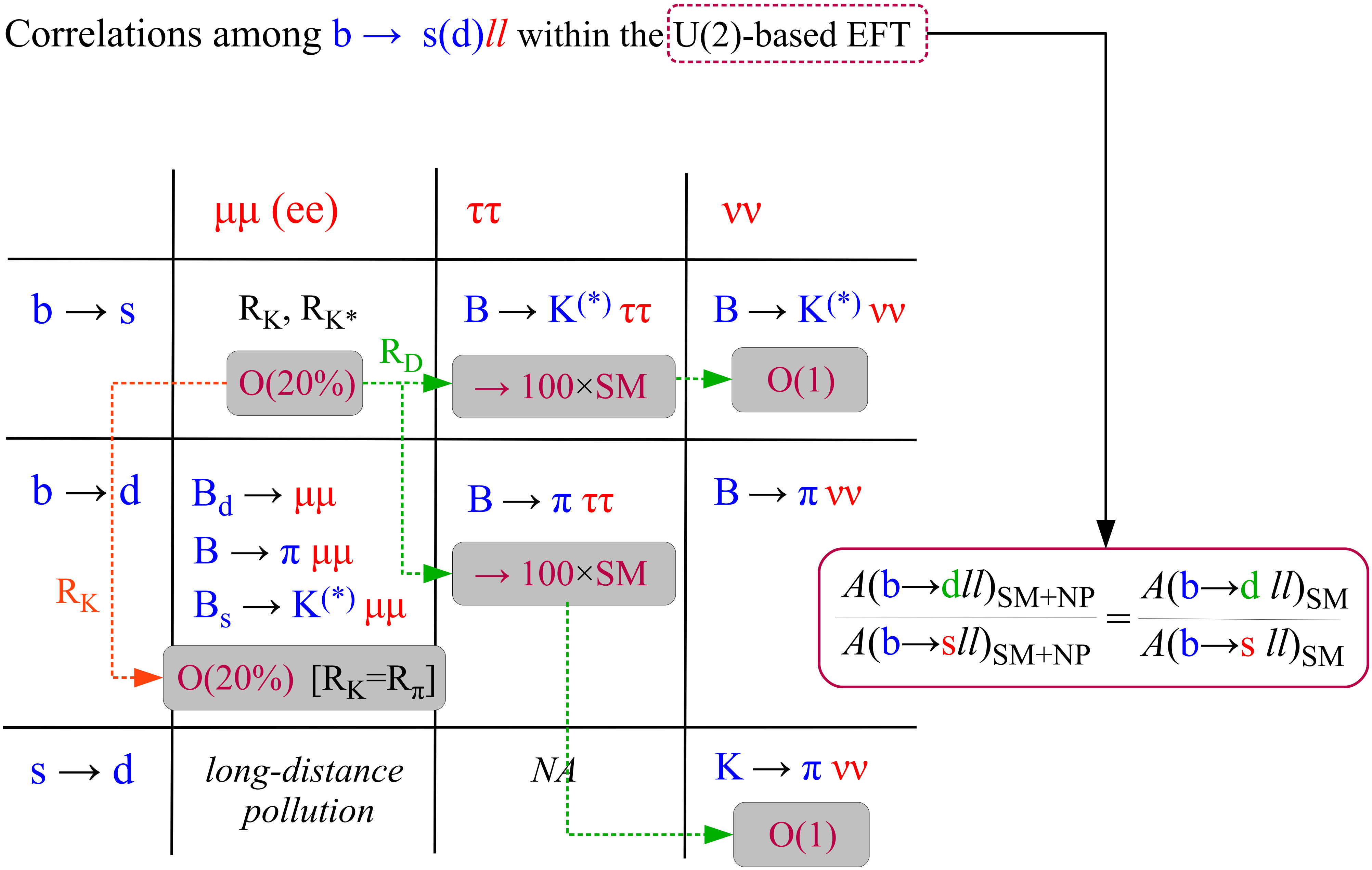
Other low-energy observables





▶ *Other low-energy observables*

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

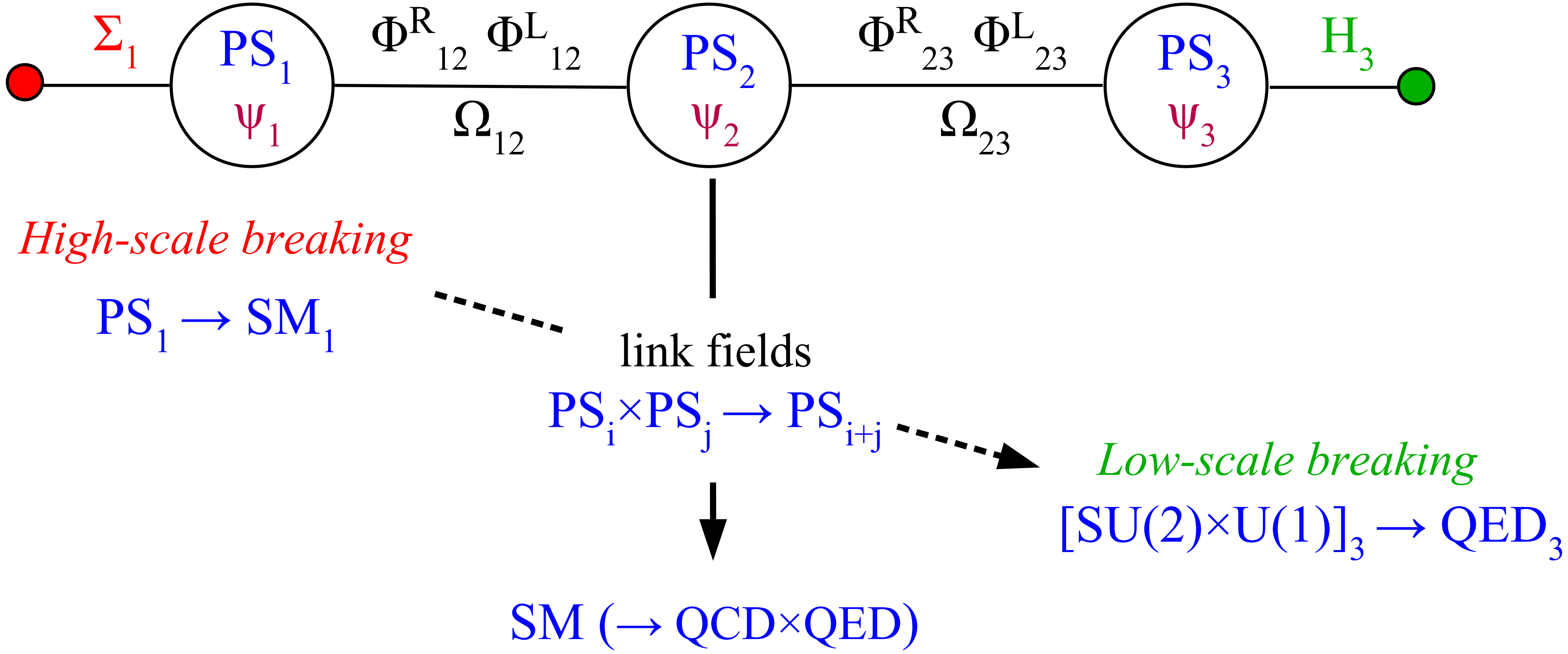


	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ $\to$ 100×SM	$B \to K^{(*)} \nu\nu$ O(1)
$b \to d$	$B_d \to \mu\mu$ $B \to \pi\, \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) $[R_K = R_\pi]$	$B \to \pi\, \tau\tau$ $\to$ 100×SM	$B \to \pi\, \nu\nu$
$s \to d$	*long-distance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

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

Speculations on UV completions

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



High-scale breaking

$PS_1 \rightarrow SM_1$

link fields

$PS_i \times PS_j \rightarrow PS_{i+j}$

Low-scale breaking

$[SU(2)\times U(1)]_3 \rightarrow QED_3$

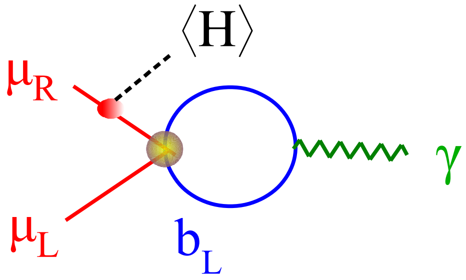
SM (→ QCD×QED)

- 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.

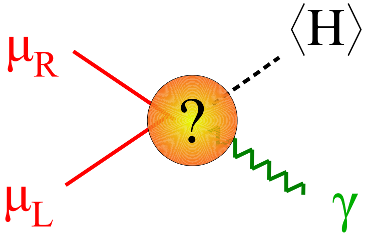
About g-2

It is not easy to reconcile the $(g\text{-}2)_\mu$ anomaly with both flavor anomalies and, more generally, with models with a "natural" flavor structure (↔ Y_{SM}).

We do find a non-standard contribution to $(g\text{-}2)_\mu$ in the set up I described, but is very small



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