B-physics anomalies and flavor hierarchies: a natural link

Gino Isidori
[*University of Zürich*]

- Introduction
- The anomalies
- Effective Field Theory considerations
- From EFT to simplified models
- Speculations on ultraviolet completions
- Conclusions

University of Zurich[UZH]

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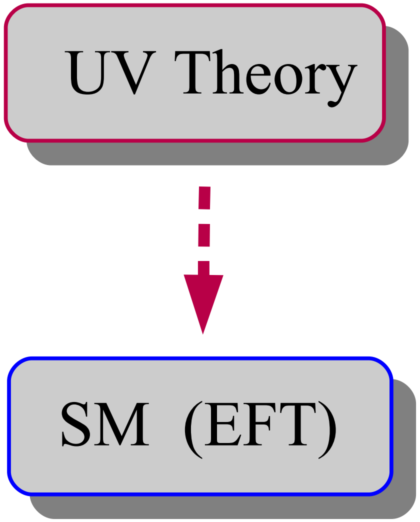
Introduction

Despite all its phenomenological successes, the SM has some deep unsolved problems (*hierarchy problem*, *flavor problem*, *neutrino masses, dark-matter, dark energy, inflation*…)

The Standard Model should be regarded as an *Effective Field Theory* (*EFT*), i.e. the limit (*in the range of energies and effective couplings so far probed*) of a more fundamental theory with new degrees of freedom



Introduction

The most interesting hints toward UV dynamics come from possible *un-natural features* of the EFT.

UV Theory

SM (EFT)

Two types of effects in QFT:

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

Un-natural aspects of low-energy couplings

Violations of accidental symmetries

qualitative UV imprint

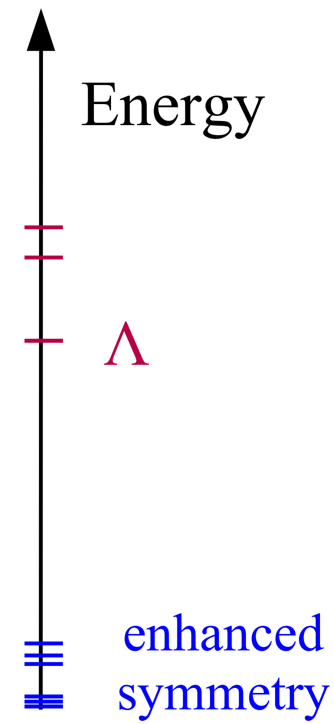
quantitative UV imprint

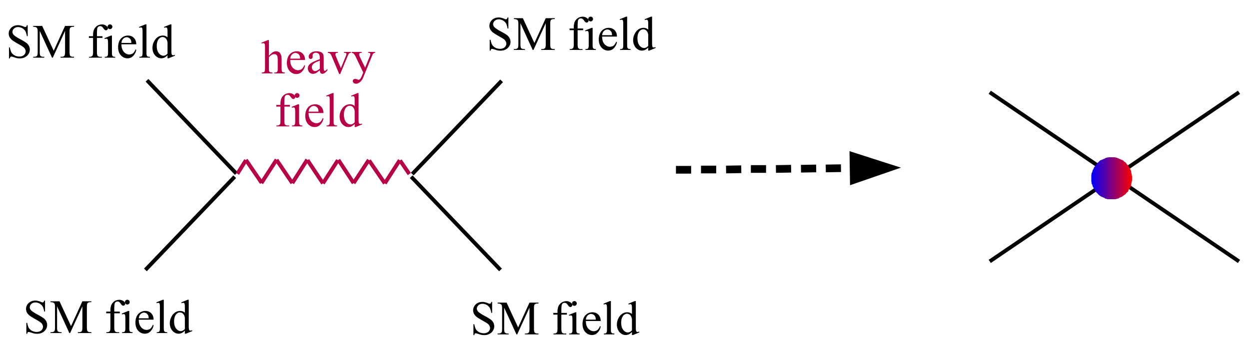
Introduction

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

If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

Violations of accidental symmetries





At large distances, not enough "variables" to describe the violation of the symmetry [~ *multipole expansion*]

The violations of Lepton Flavor Universality recently reported by experiments belong to this category

Introduction

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Natural
(*fully dictated by gauge symmetry*)

Non-trivial
UV imprints

I $m_H^2 H^2$

II $y_{ij}\, \psi_i \psi_j H$

UV Theory

SM (EFT)

Un-natural aspects of
the SM couplings

Introduction

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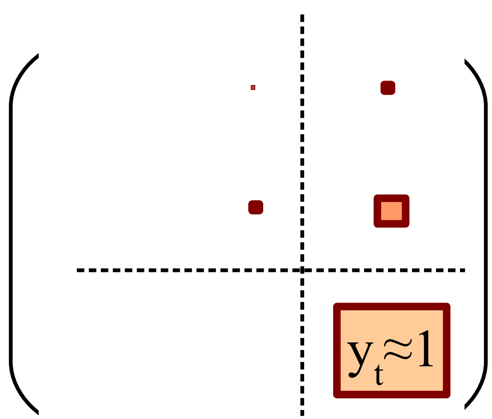
Natural *(fully dictated by gauge symmetry)*

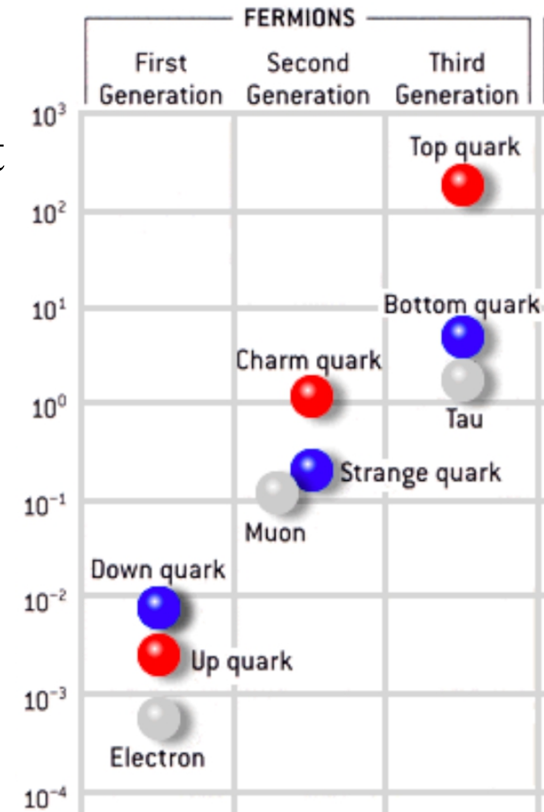
Non-trivial UV imprints

II. Flavor problem

The entries of the Yukawa couplings span 5 orders of magnitude & do not appear at all accidental:

$Y_U \sim$





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Natural (*fully dictated by gauge symmetry*)

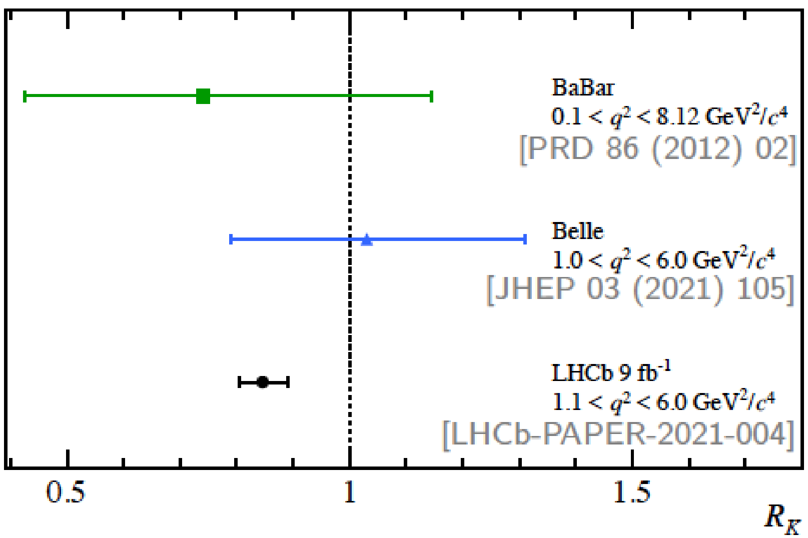
Non-trivial UV imprints

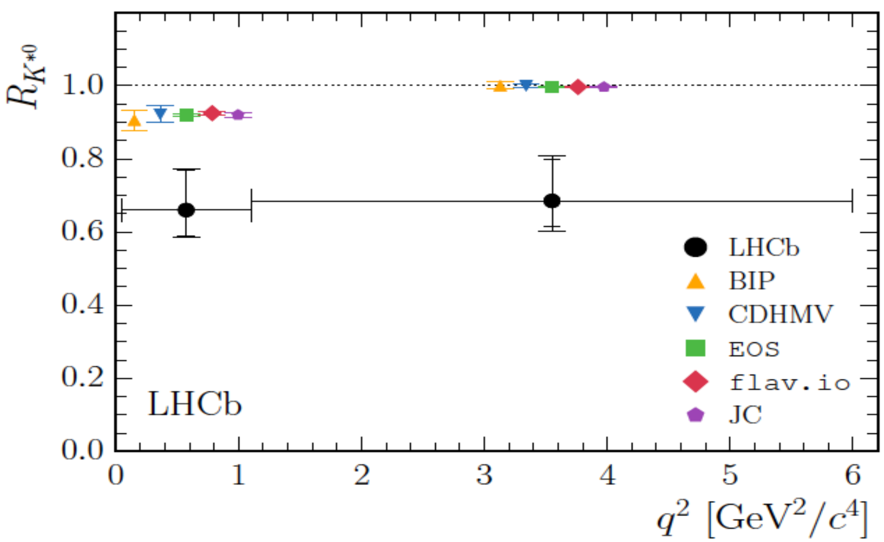
I. Electroweak hierarchy problem — *Instability of the Higgs mass under quantum corrections* → (*some*) New Physics in the TeV domain

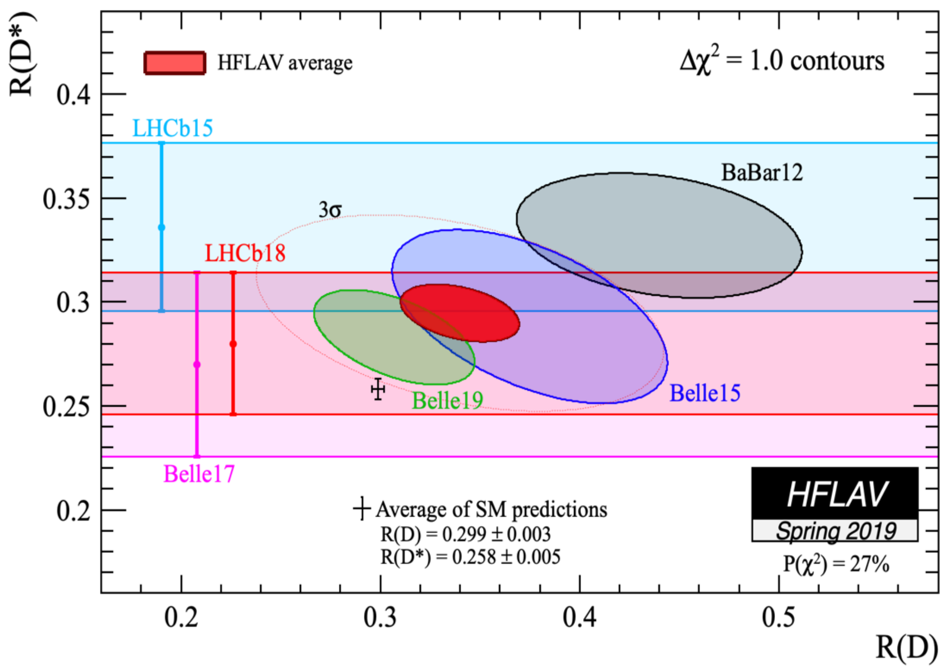
II. Flavor problem — *Un-natural hierarchies in the couplings describing fermion masses* → flavor non-universal dynamics (*at some energy scale*)

As I will argue in the rest of this talk, the violations of LFU suggest to "attack" these two problems together, and not one at a time (*as often done in the past*)

The anomalies







▶ *The anomalies*

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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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: $y_e \sim 3\times10^{-6}$, $y_\mu \sim 3\times10^{-4}$, $y_\tau \sim 10^{-2}$

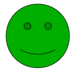
but all the lepton Yukawa couplings are small compared to SM gauge couplings, giving rise to the (*approximate*) universality of decay amplitudes which differ only by the different lepton species involved

The anomalies

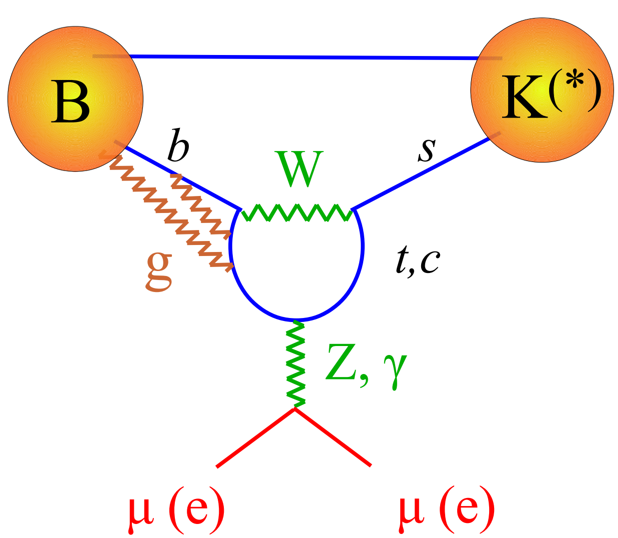
- $b \to s\, l^+ l^-$ (neutral currents)

List of the observables exhibiting anomalies (= *deviations from SM*):

- 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($B_s \to \mu\mu$)

 th. error <1%

 th. error few %



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

The recent result $R_K \approx \dfrac{\Gamma(B \to K\, \mu\mu)}{\Gamma(B \to K\, ee)} \approx 0.85 \pm 0.05$

LHCb '21

strengths the consistency of a picture which was already very coherent and points to New Physics of short-distance origin.

The anomalies

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

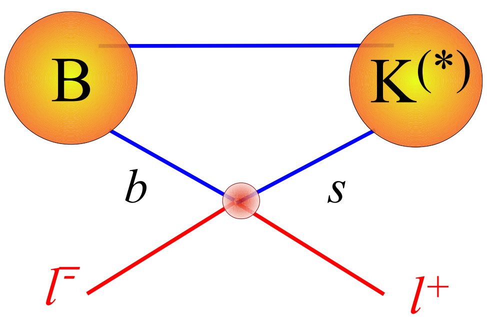
$$\mathcal{L}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \sum_i \mathcal{C}_i \mathcal{O}_i$$

FCNC operators:

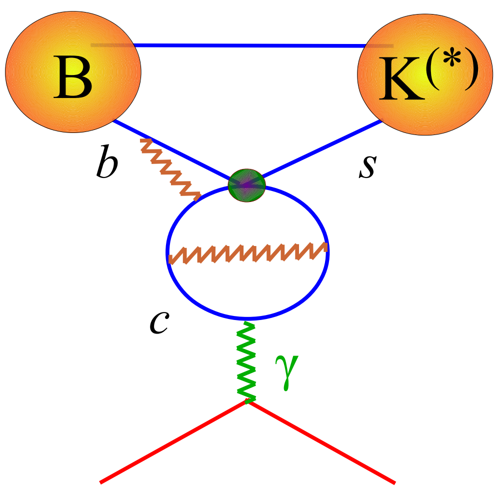
$$\mathcal{O}_{10}^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$
$$\mathcal{O}_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

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 $\Delta C_9^{\rm Univ}$

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"*)

▶ *The anomalies*

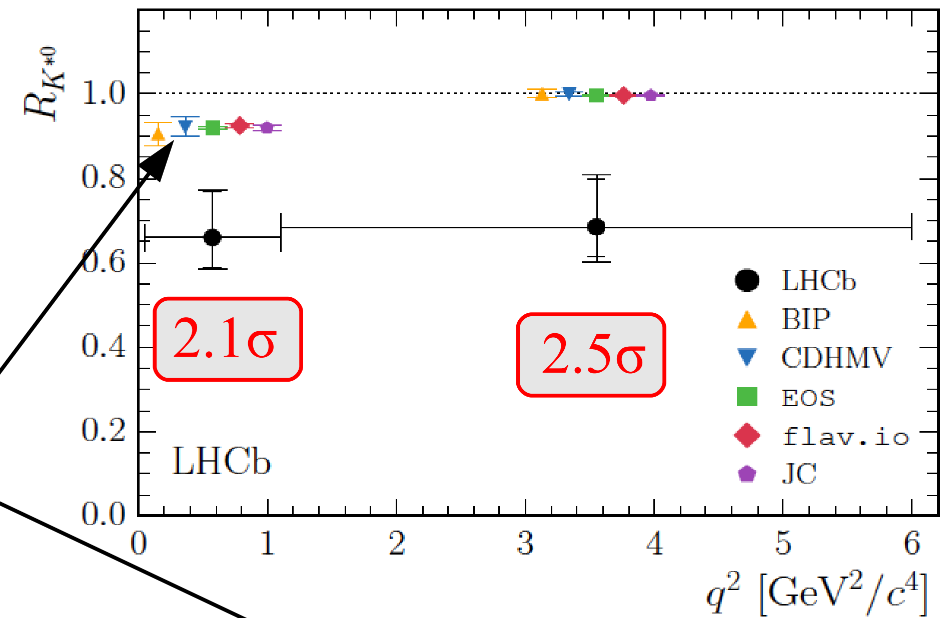
The LFU ratios:

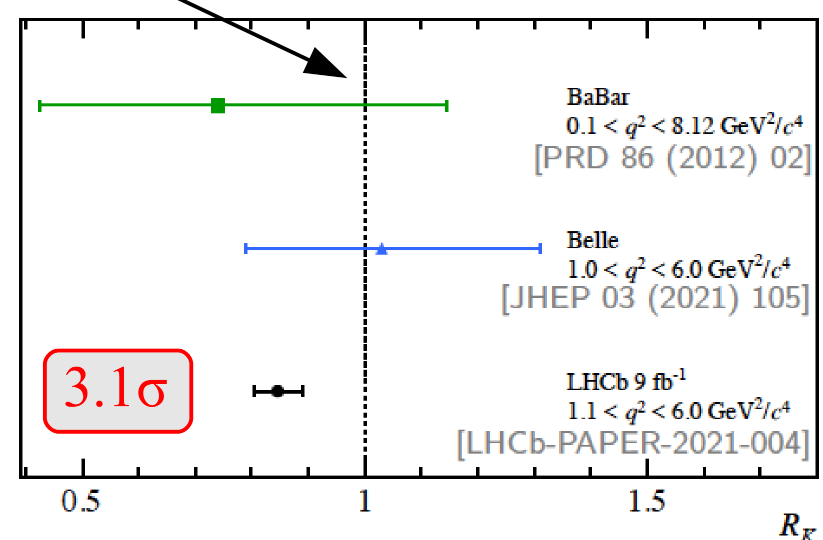
$$R_H = \frac{\int d\Gamma(B \to H\, \mu\mu)}{\int d\Gamma(B \to H\, ee)} \qquad (H = K, K^*)$$

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 2.1σ to 3.1σ in each of the 3 bins measured by LHCb





$B_s \to \mu\mu$:

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

Beneke *et al.* '19

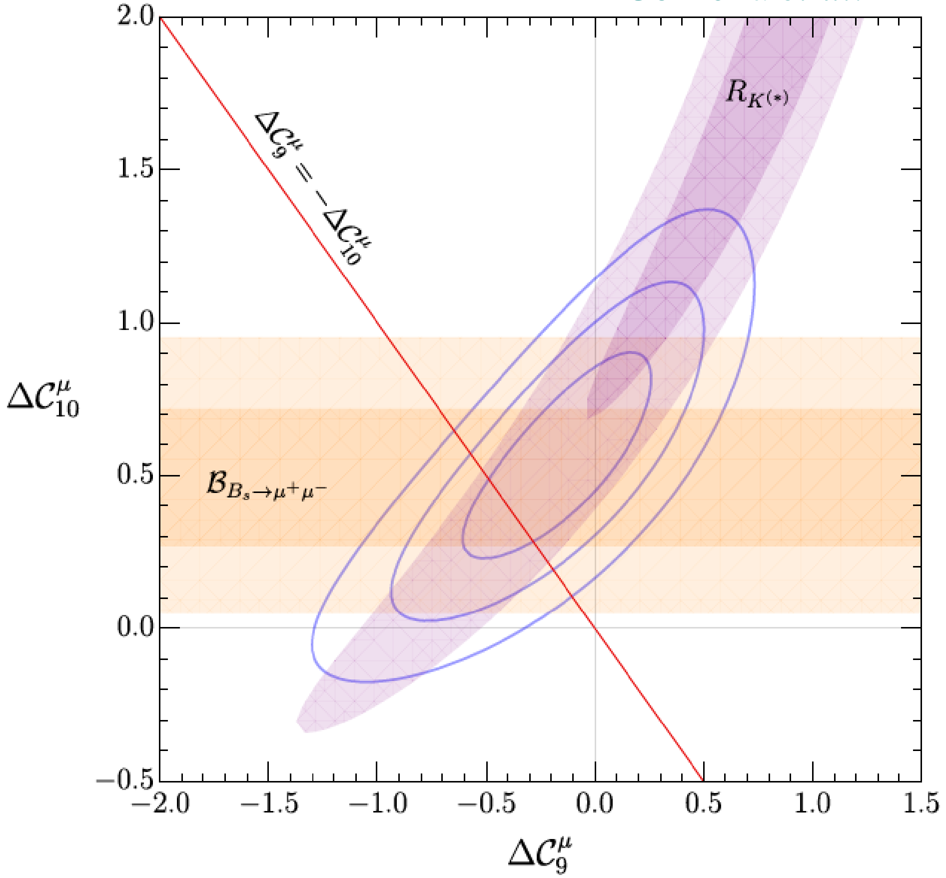
$$BR(B_s \to \mu\mu)_{exp} = (2.85 \pm 0.32) \times 10^{-9}$$

ATLAS+CMS+LHCb '21

2.3σ

The anomalies

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

The anomalies

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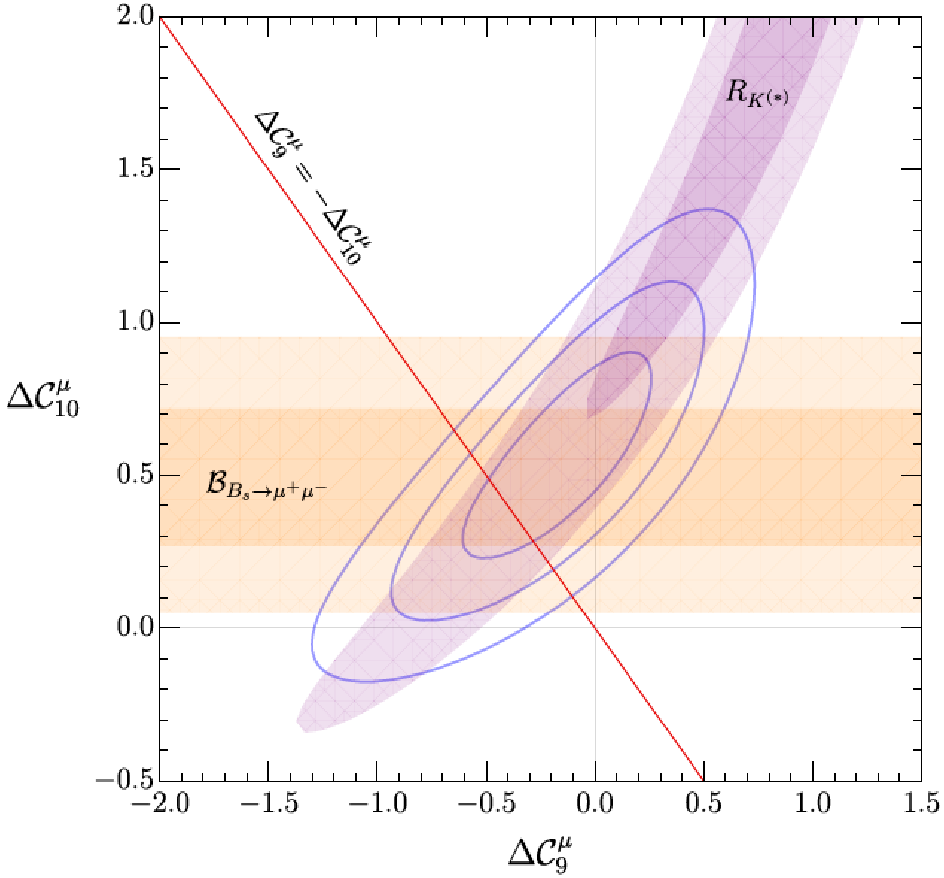
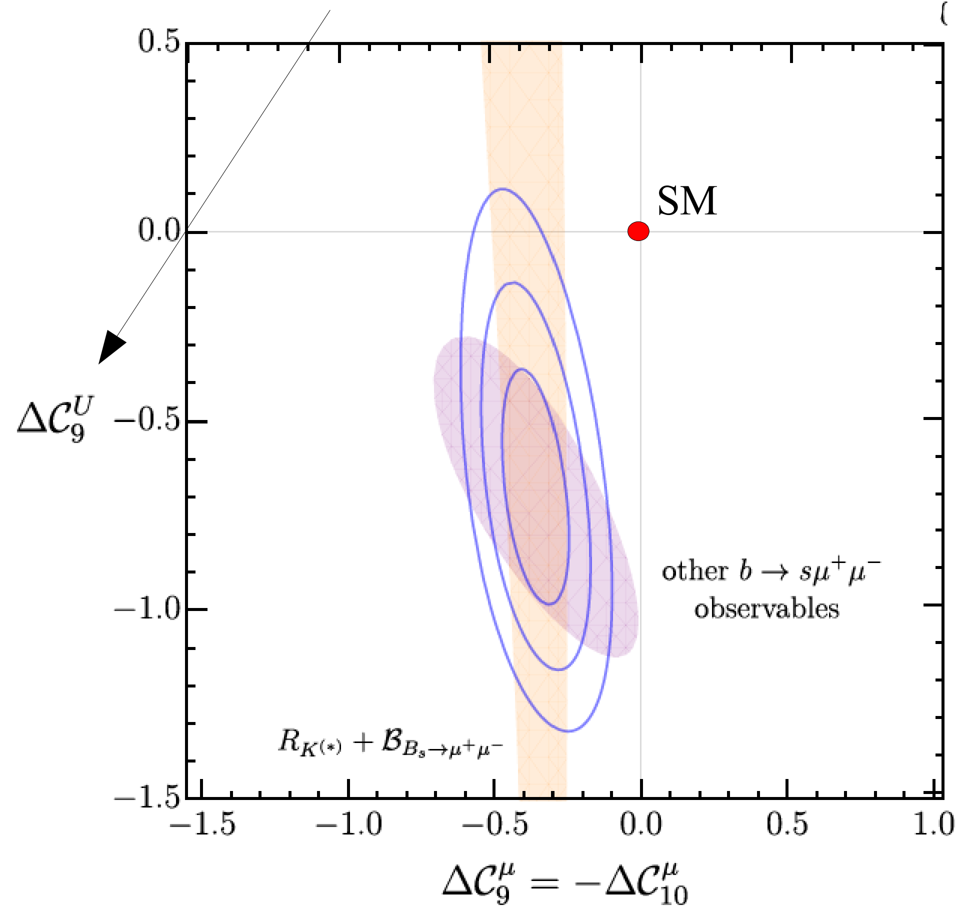


Lepton-universal shift to C_9
(*sensitive to charm re-scattering*)



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

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

>> 5σ with current best estimate of charm contrib

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

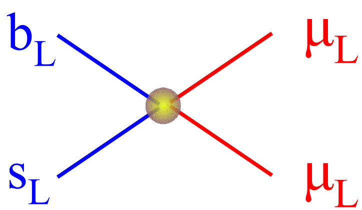
4σ *global significance* of NP (*very conserv. estimate*)

Lancierini, GI, Owen, Serra, '21

▶ *The anomalies*

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

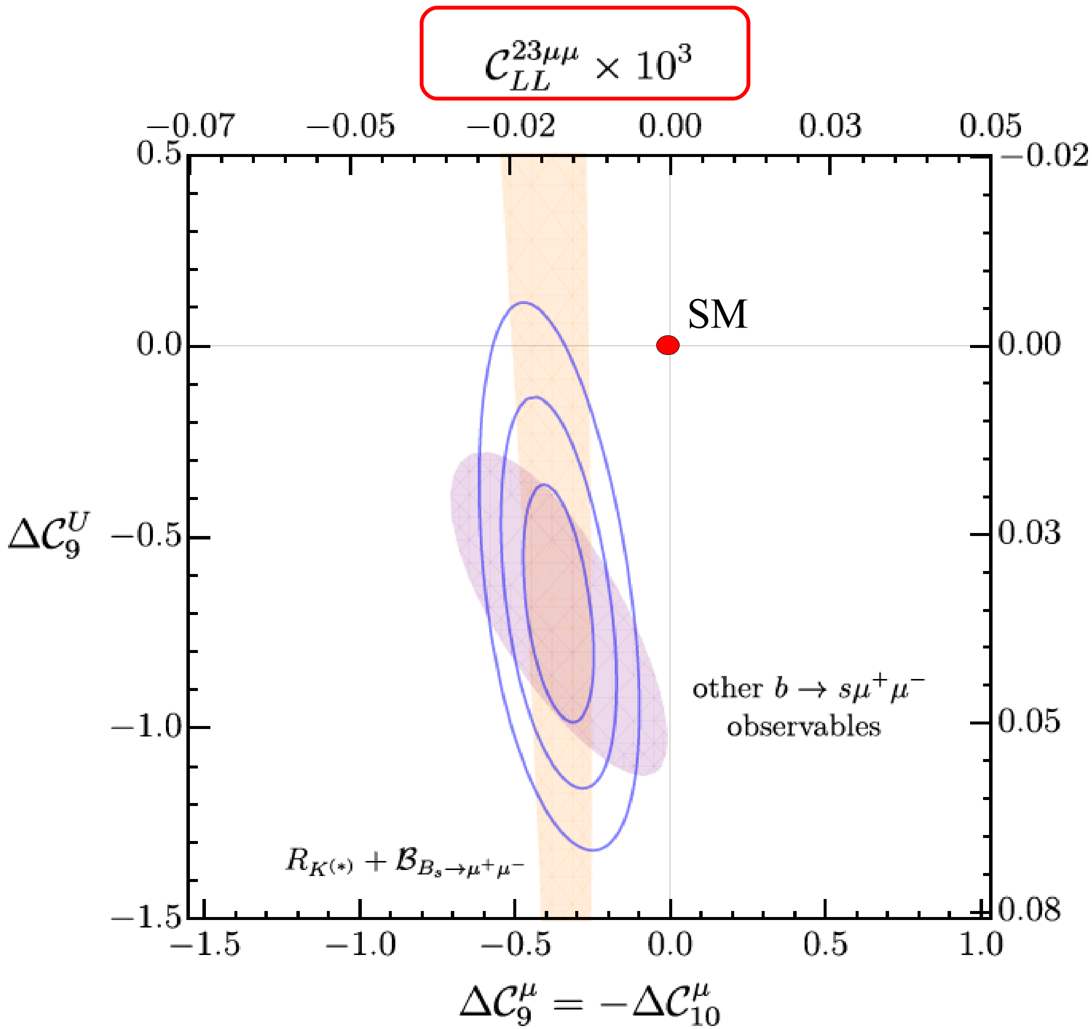
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)$$



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

super-weak interaction!

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



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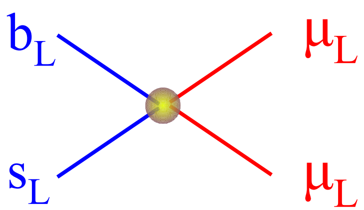

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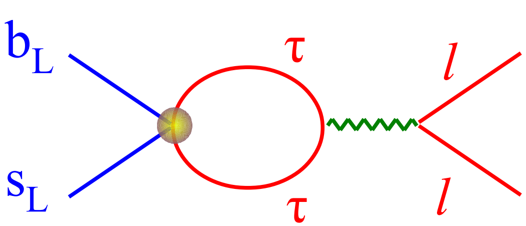
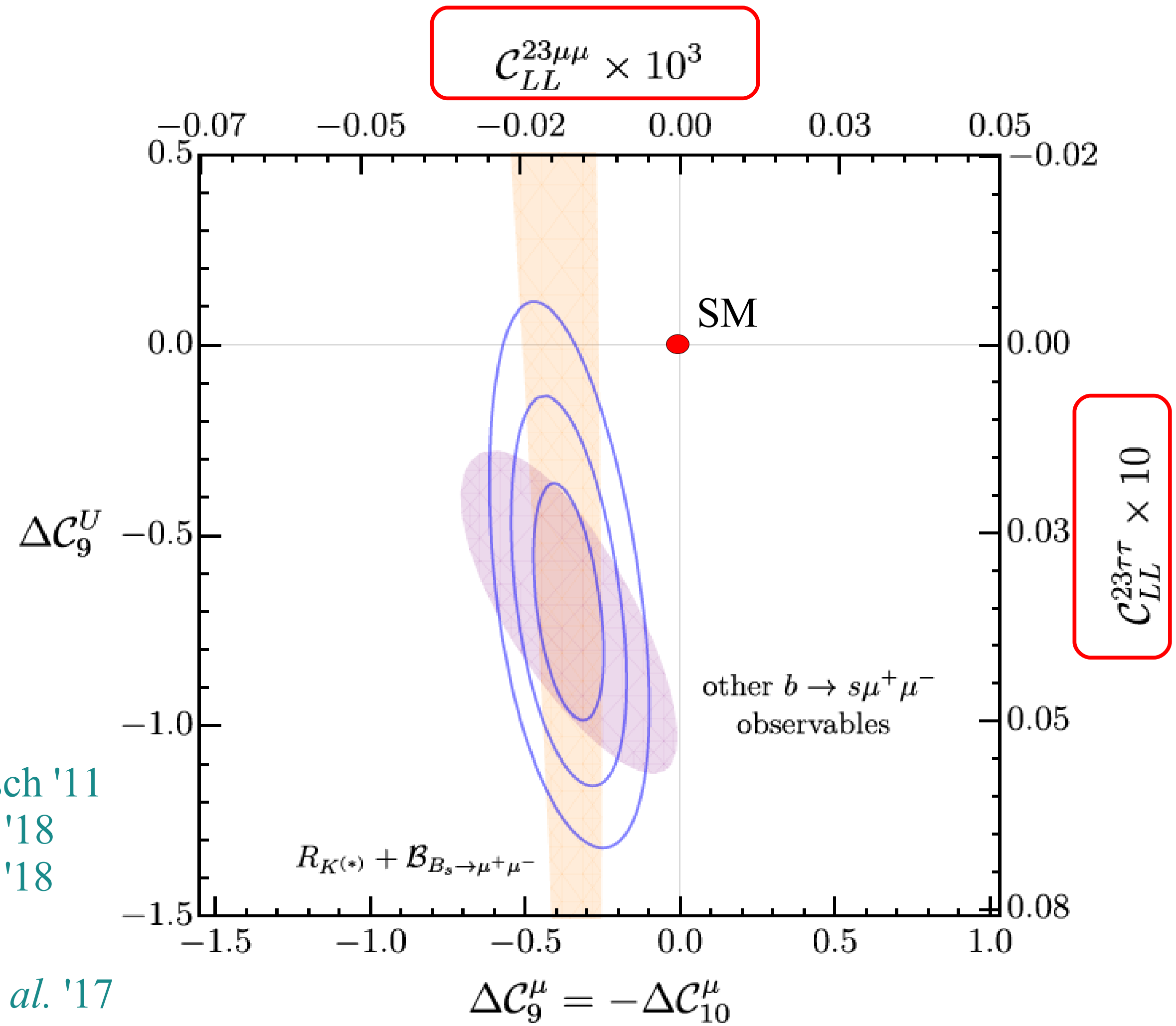
$C_{LL}^{23\mu\mu} \rightarrow \Delta C_9^\mu = -\Delta C_{10}^\mu$



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

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

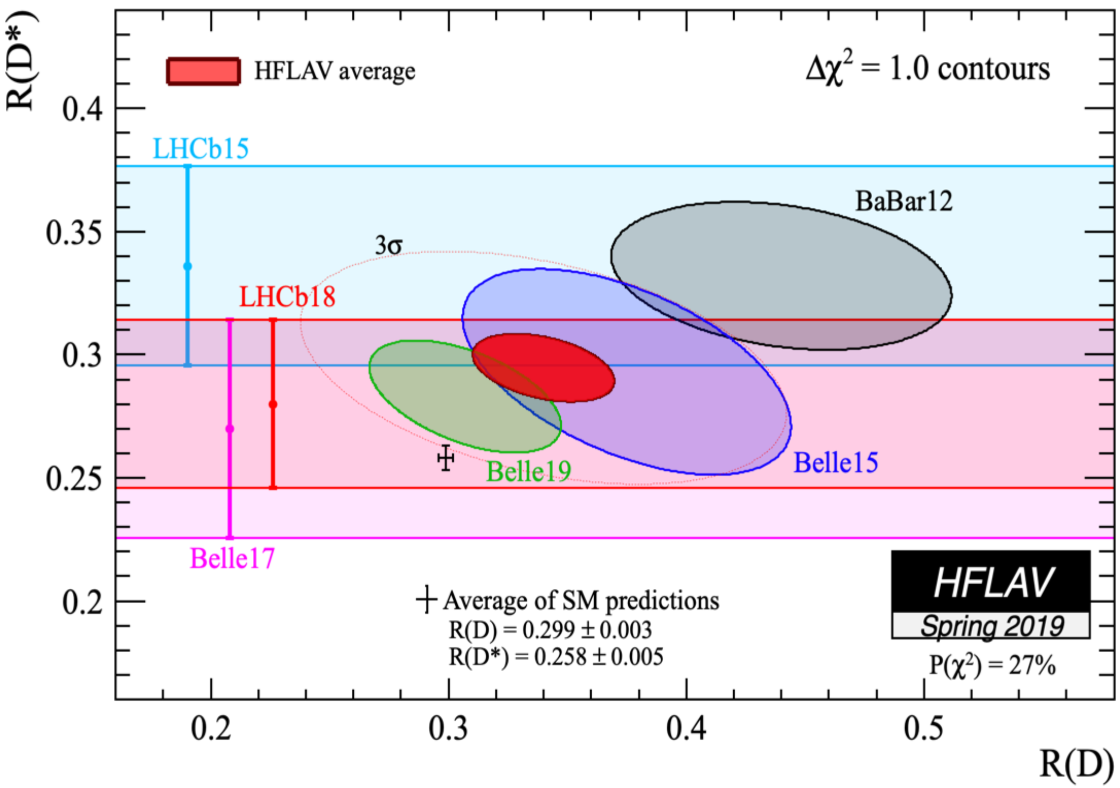
→ Link to CC anomaly Greljo *et al.* '17

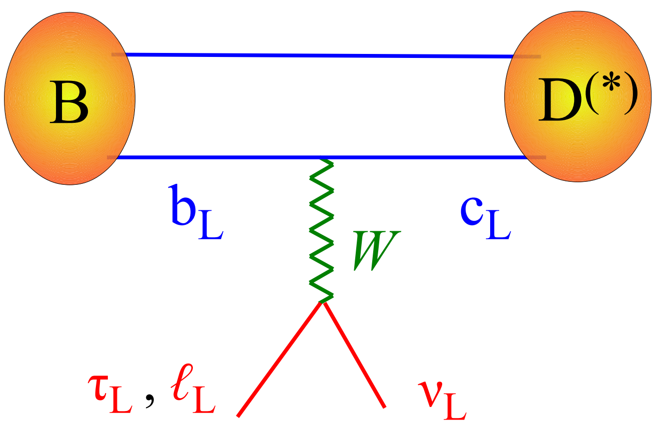


The anomalies

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

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



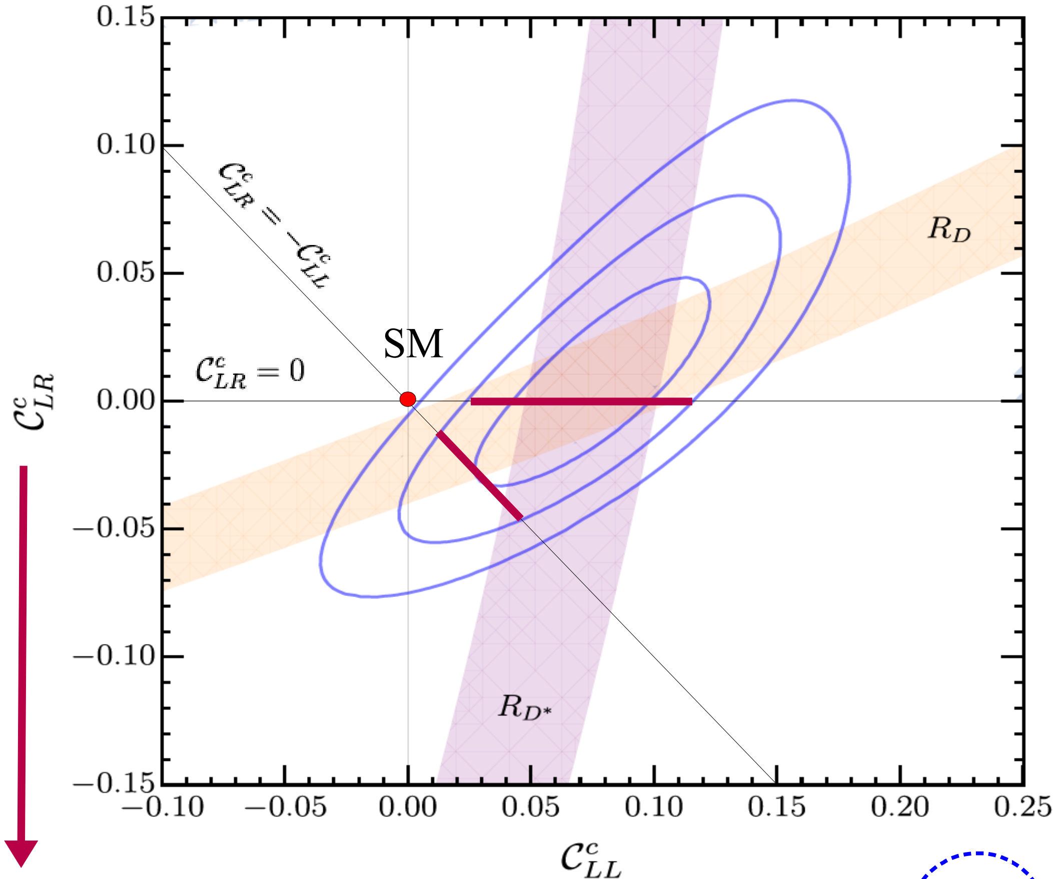


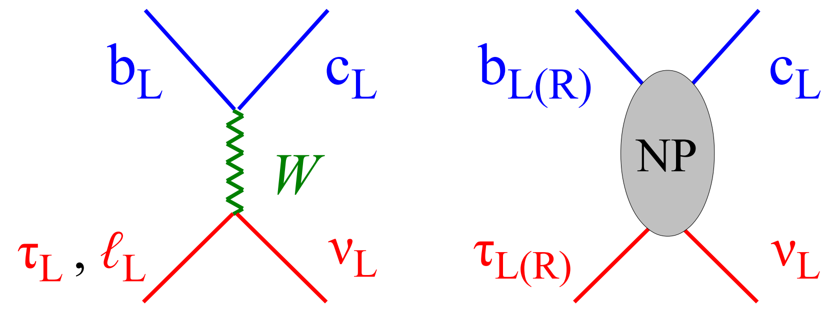
- Consistent results by three different exps. ~ 3.1σ excess over SM (*D and D* combined*)
- SM predictions quite "clean": hadronic uncertainties cancel (*to large extent*) in the ratios

The anomalies

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

Cornella *et al.* '21





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

But other options (*RH currents*) possible

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

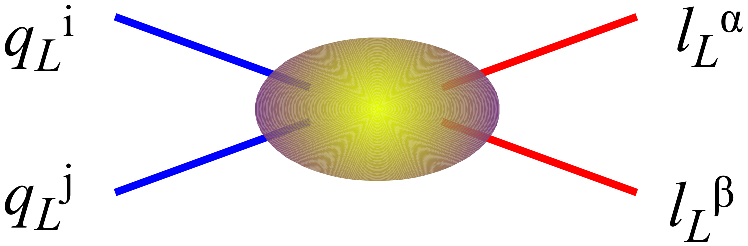
CKM "weighted mix" as for $\mathcal{C}^c_{LL}$

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

Same operator contributing to b → s ll

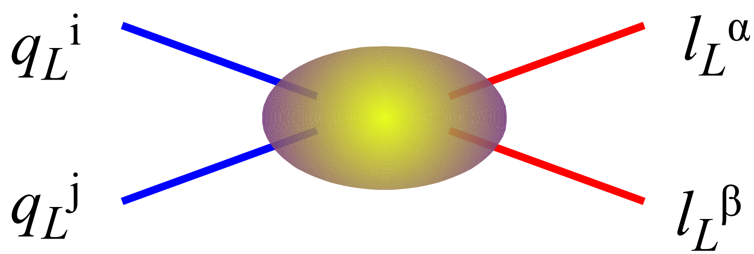
all 3rd gen. (contribute via CKM rotation)

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



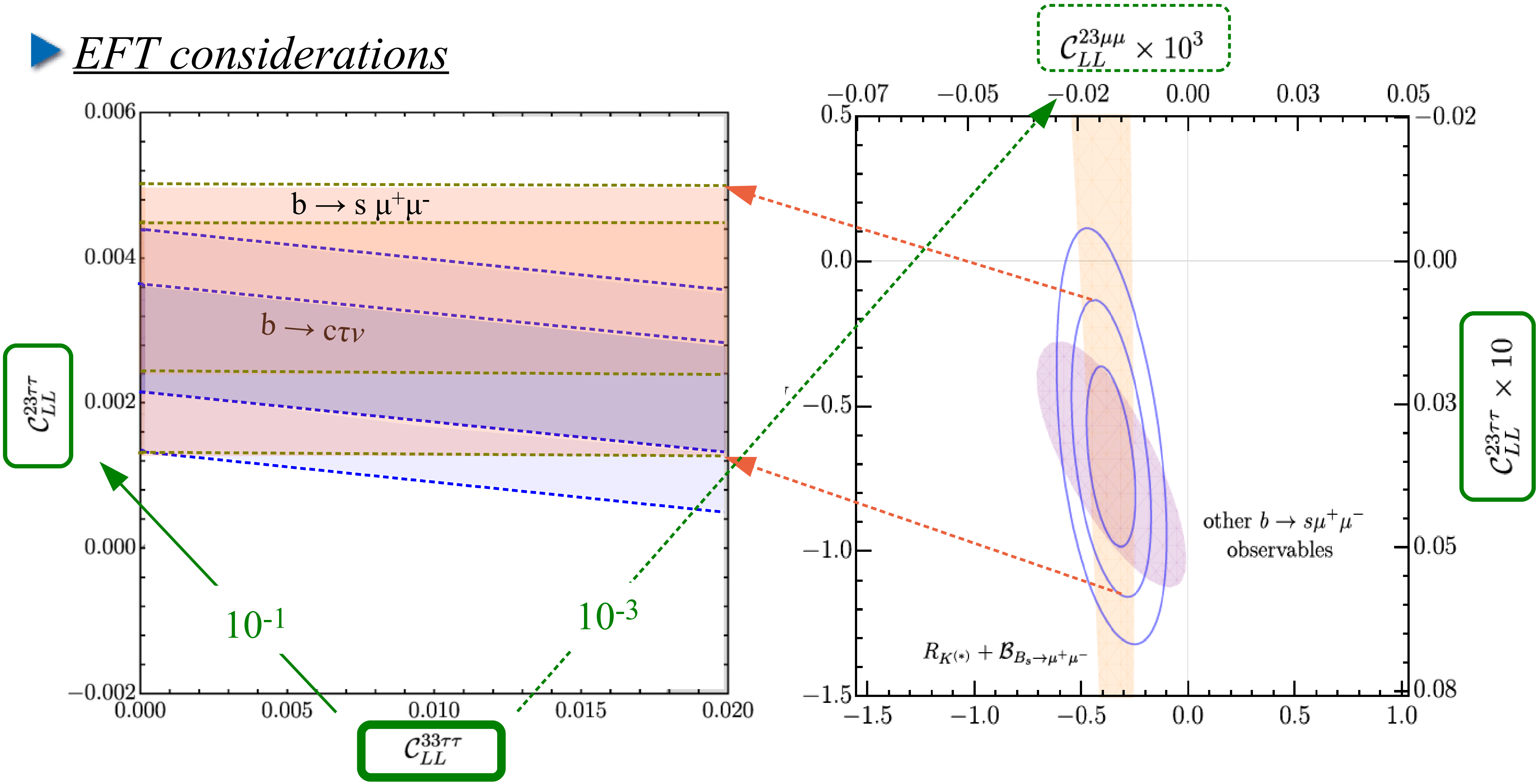
Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

- 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*}, ...]

↓

$C_{ij\alpha\beta}$ = large for 3rd generation fields + small terms for 2nd (& 1st) generations → *Link to pattern of the Yukawa couplings !*

EFT considerations



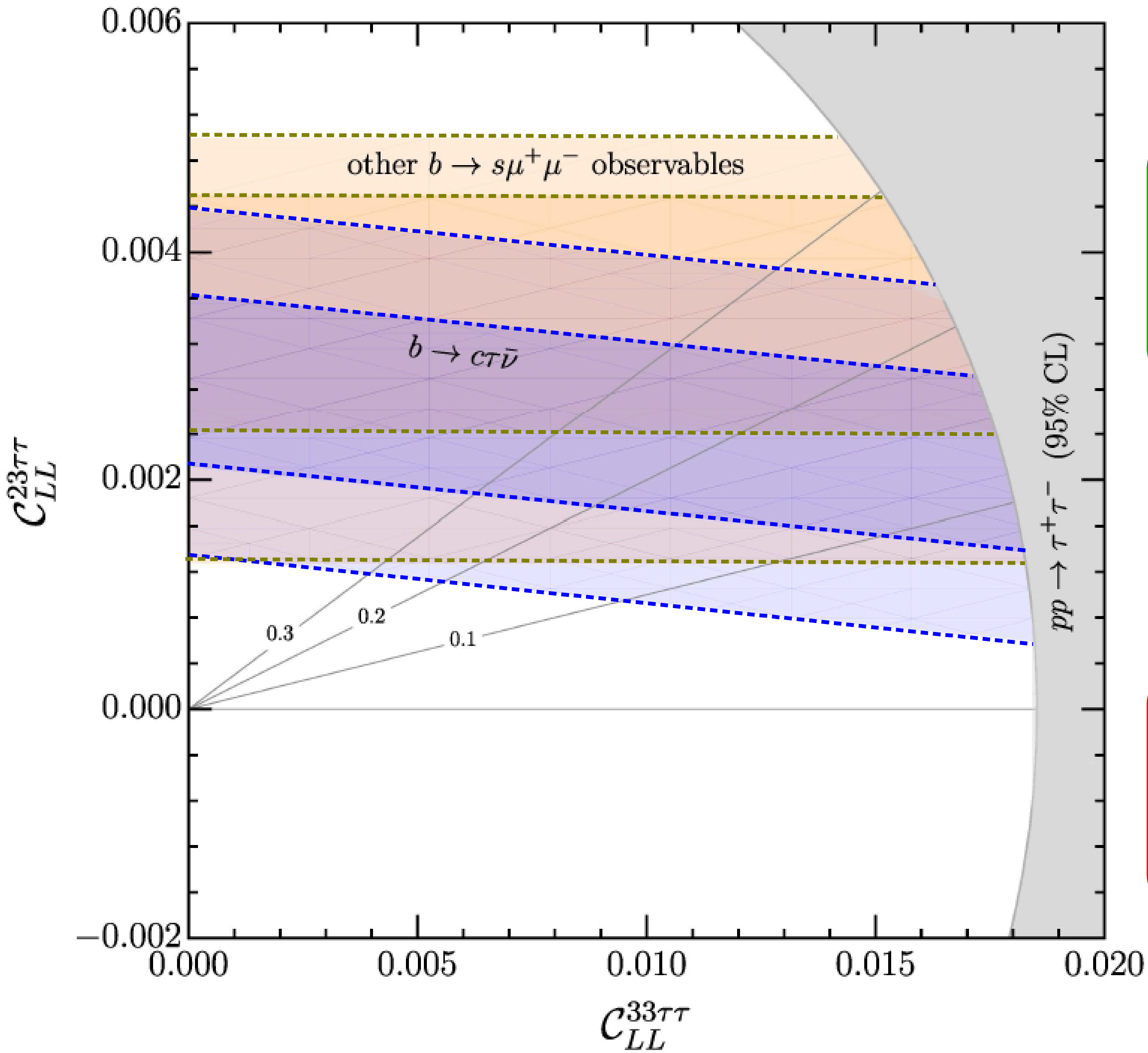
Pattern emerging from data:

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

- ✔ $O(10^{-1})$ 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

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



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

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

▶ EFT considerations

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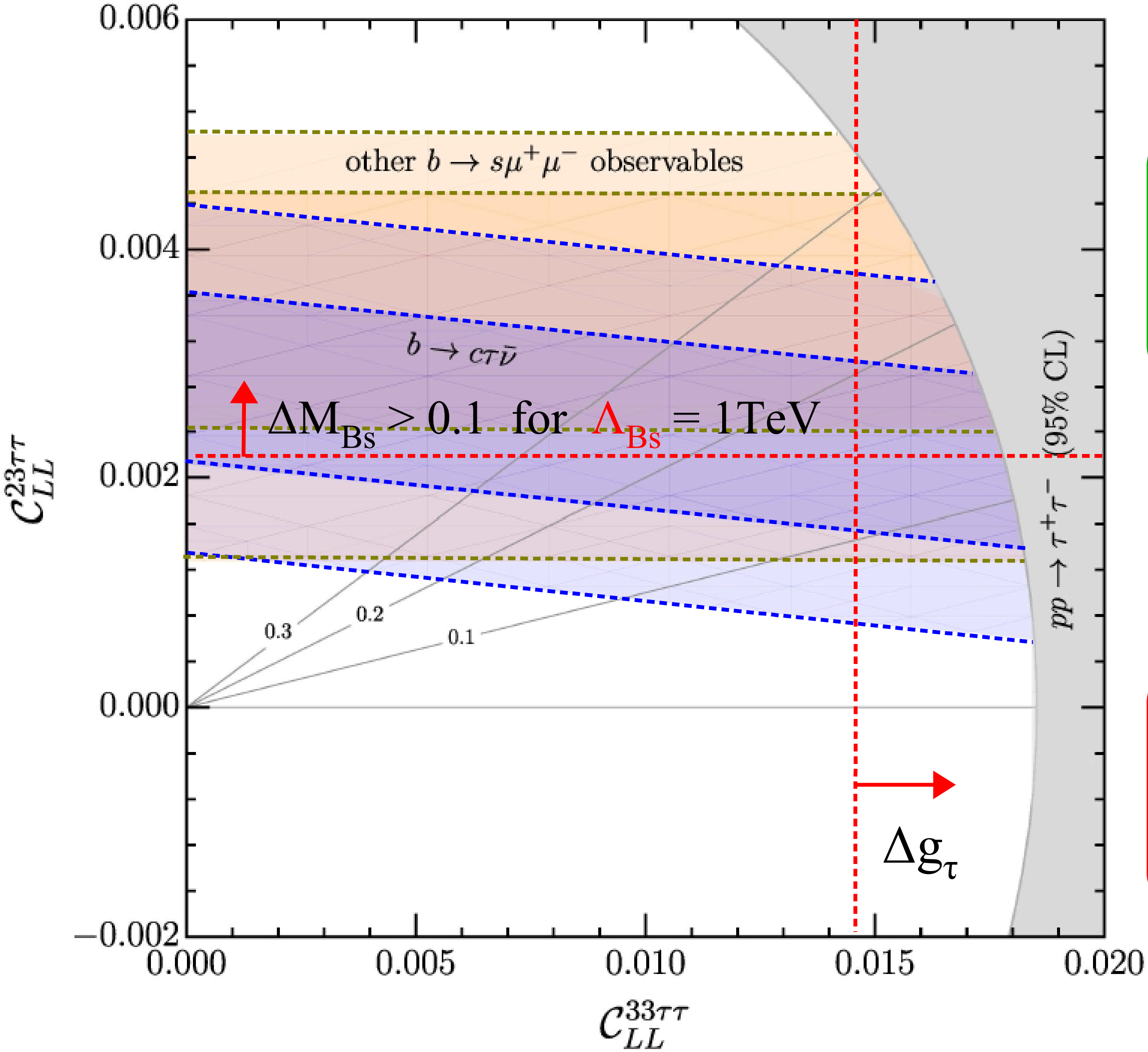

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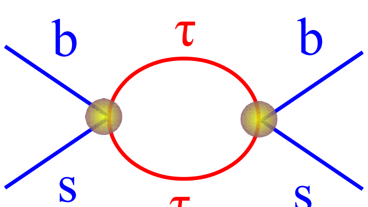
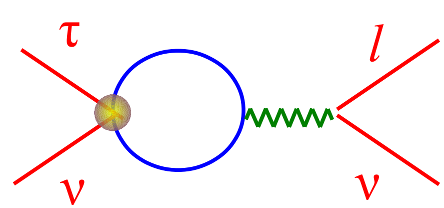
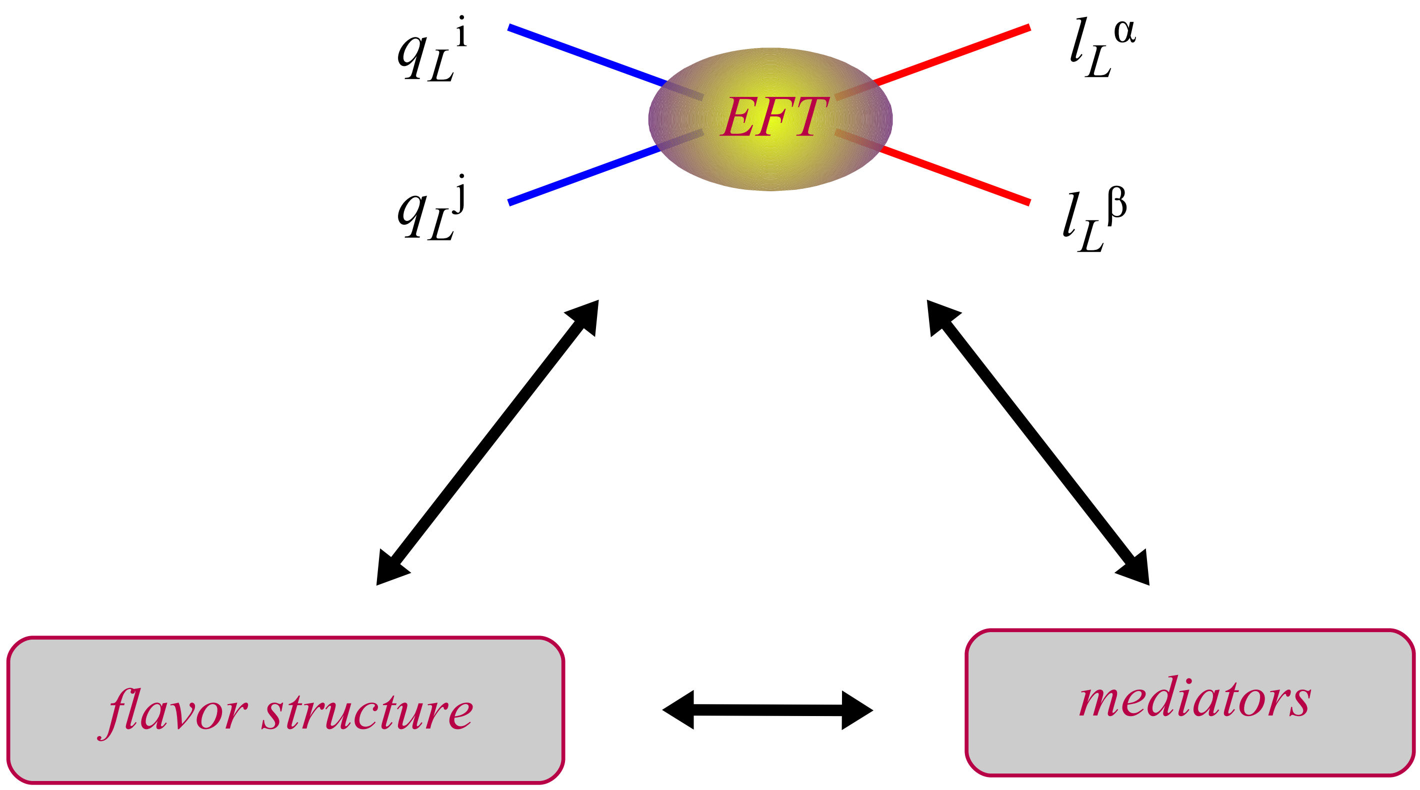


$\Delta M_{Bs} \sim (C^{23\tau\tau})^2\, \Lambda_{Bs}^{\ 2}$



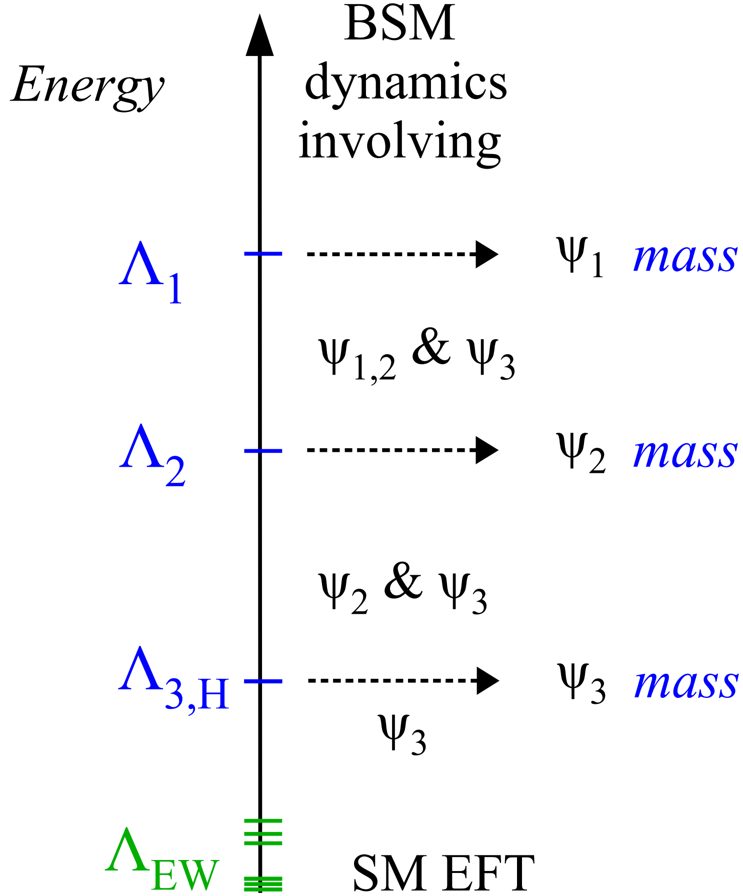
$\Delta g_\tau \sim (C^{33\tau\tau}) \log(\Lambda/m_t)$

From EFT to simplified models



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

Multi-scale picture @ origin of flavor:



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

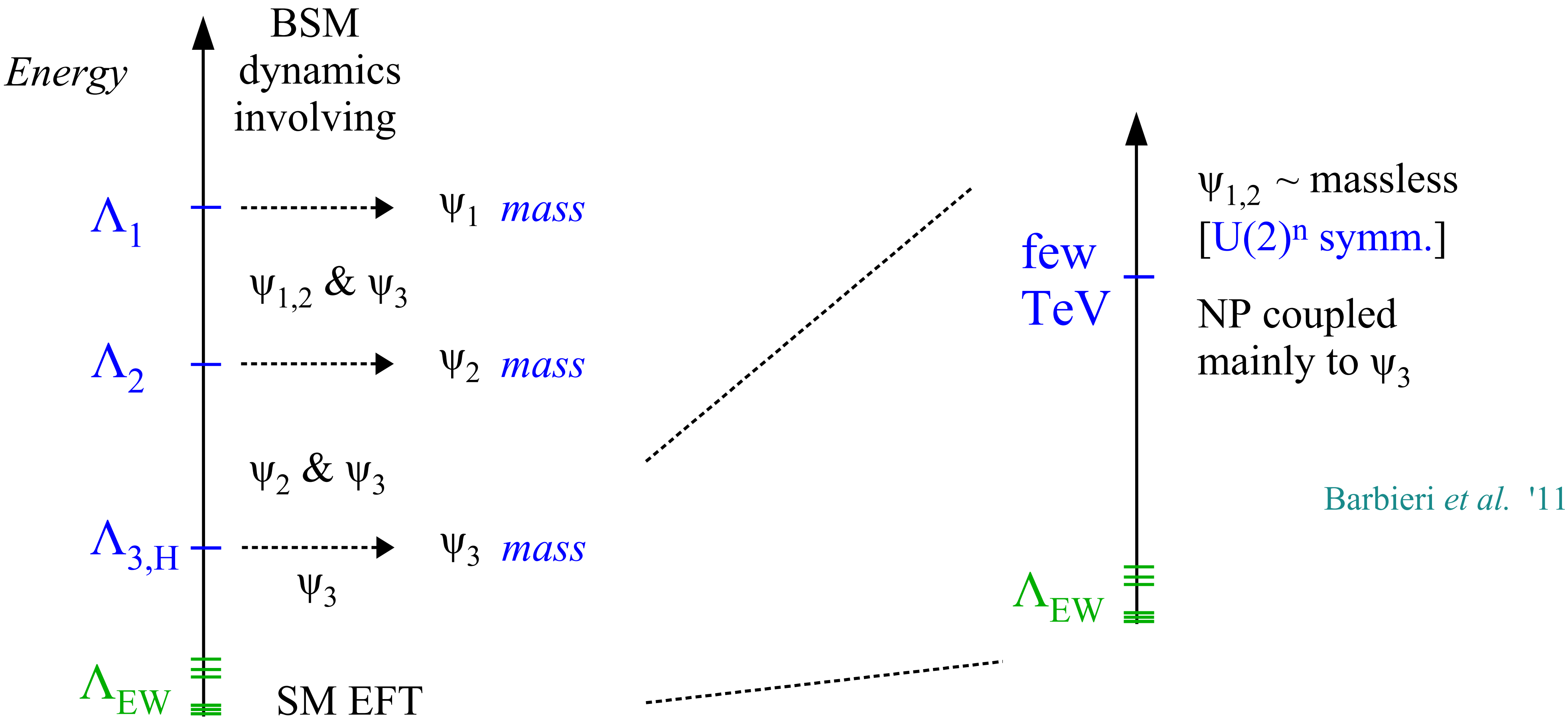
Main idea:

- 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:

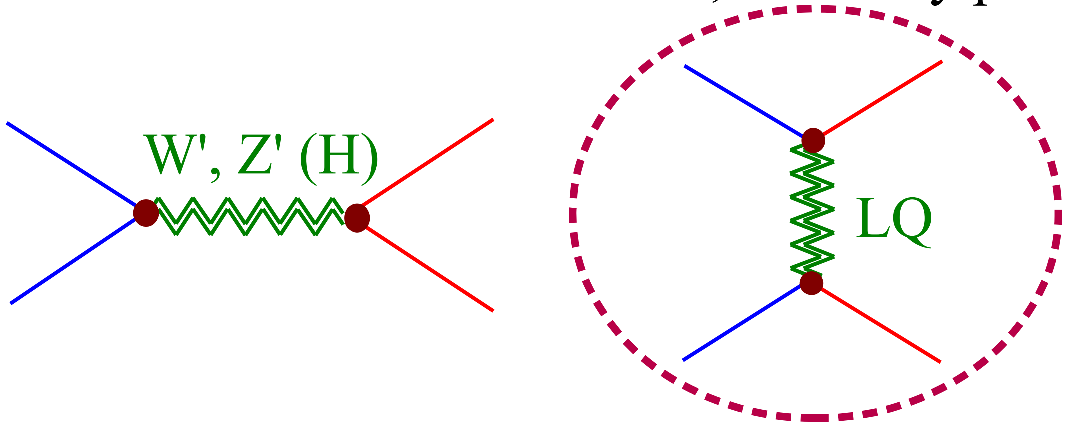


$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{Y} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

Non-trivial UV imprints

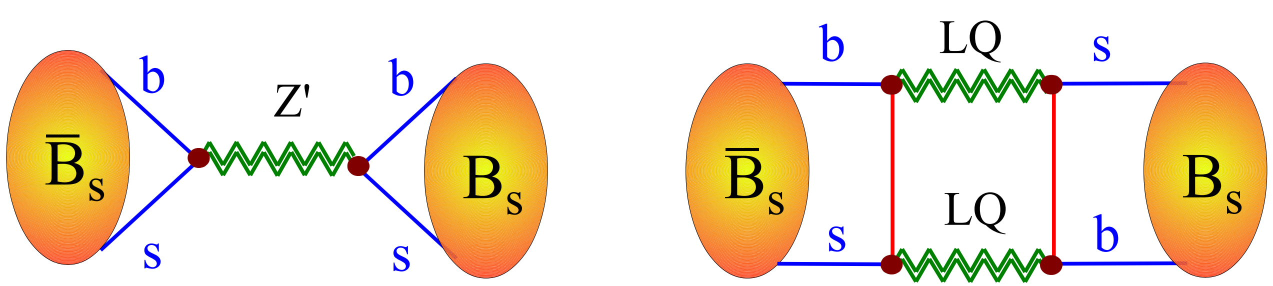
▶ *From EFT to simplified models* [*the possible mediators*]

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 & $\tau \to l\nu\nu$



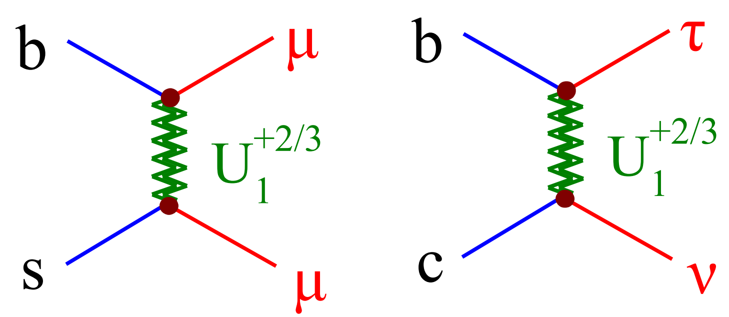
II. Direct searches: 3^{rd} gen. LQ are also in better shape as far as direct searches are concerned (*contrary to Z'*...).

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

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 ensuring a CKM-like mixing $3^{rd} \rightarrow 1^{st}, 2^{nd}$ gen.)

LQ of the Pati-Salam gauge group:

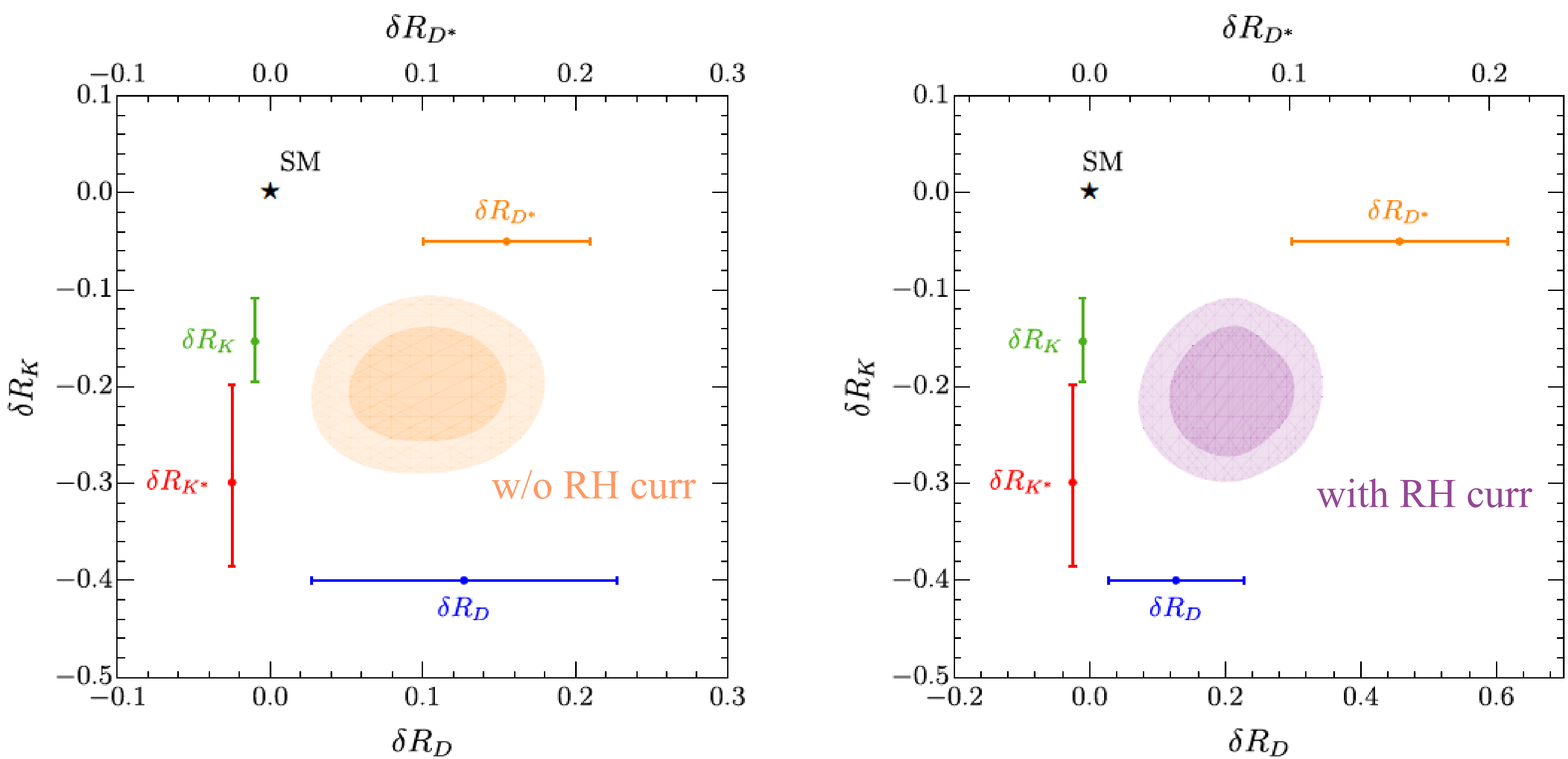
$SU(4) \times SU(2)_L \times SU(2)_R$

▶ <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:



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

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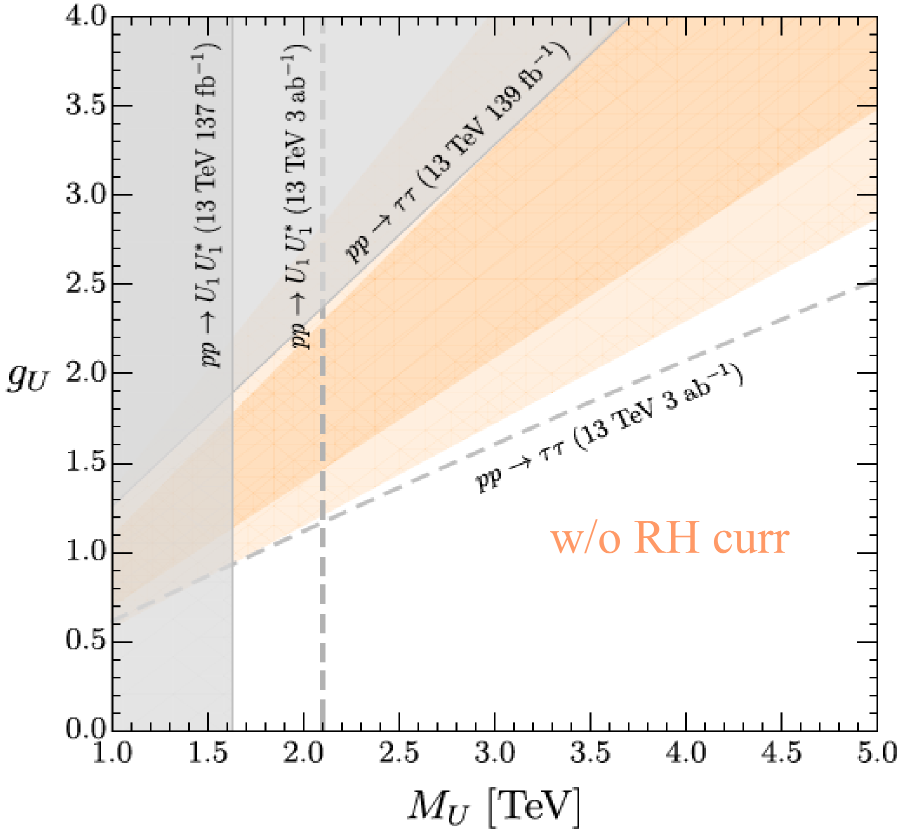
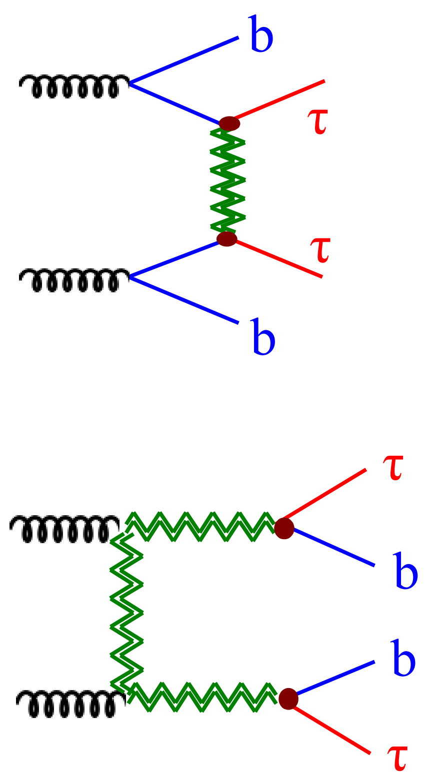
and fitting all low-energy data leads to an excellent description of present data which is fully consistent with high-pT searches [*within the reach of HL-LHC*]:





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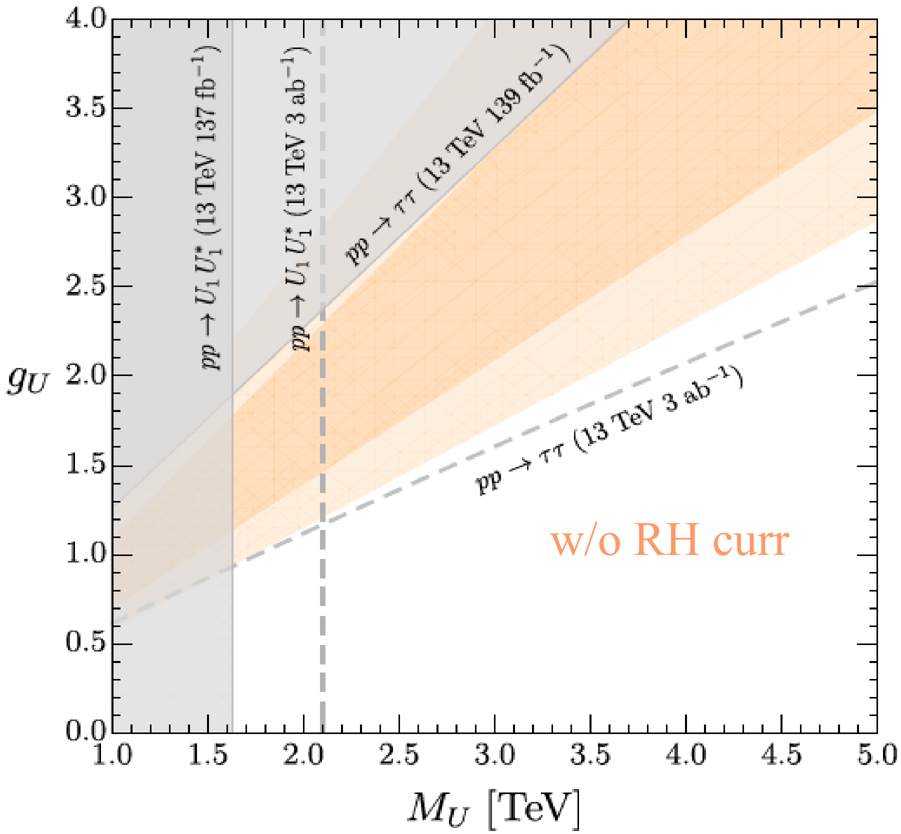
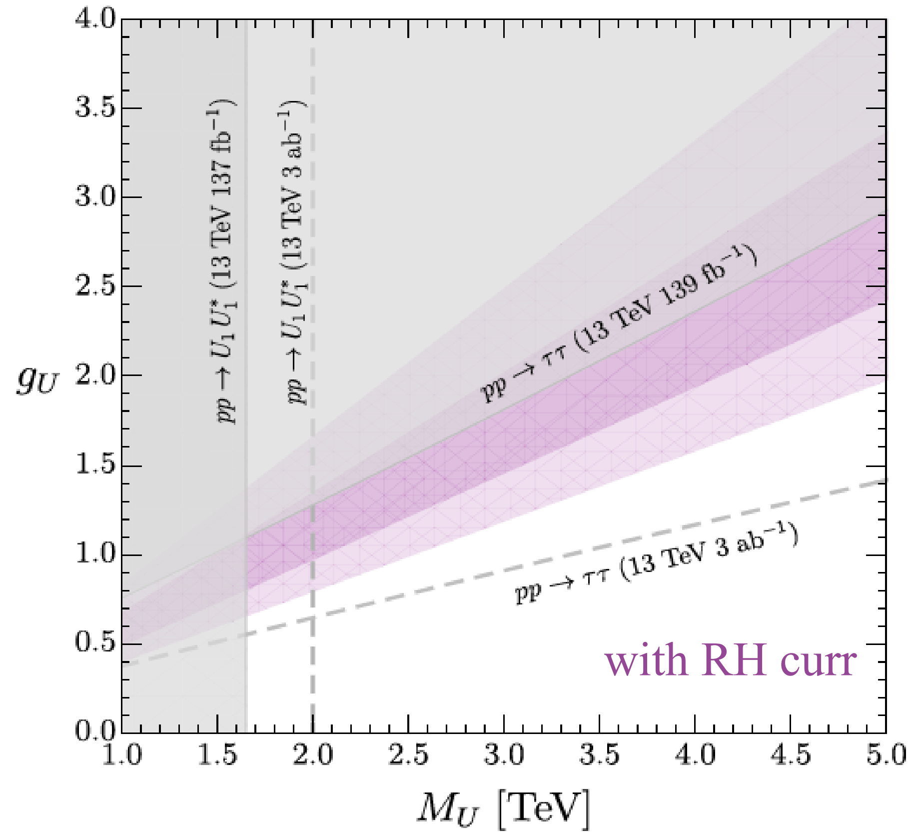
and fitting <u>all low-energy data</u> leads to an excellent description of present data which is fully <u>consistent with high-pT searches</u> [*within the reach of HL-LHC*]:

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





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Considering the U_1 only

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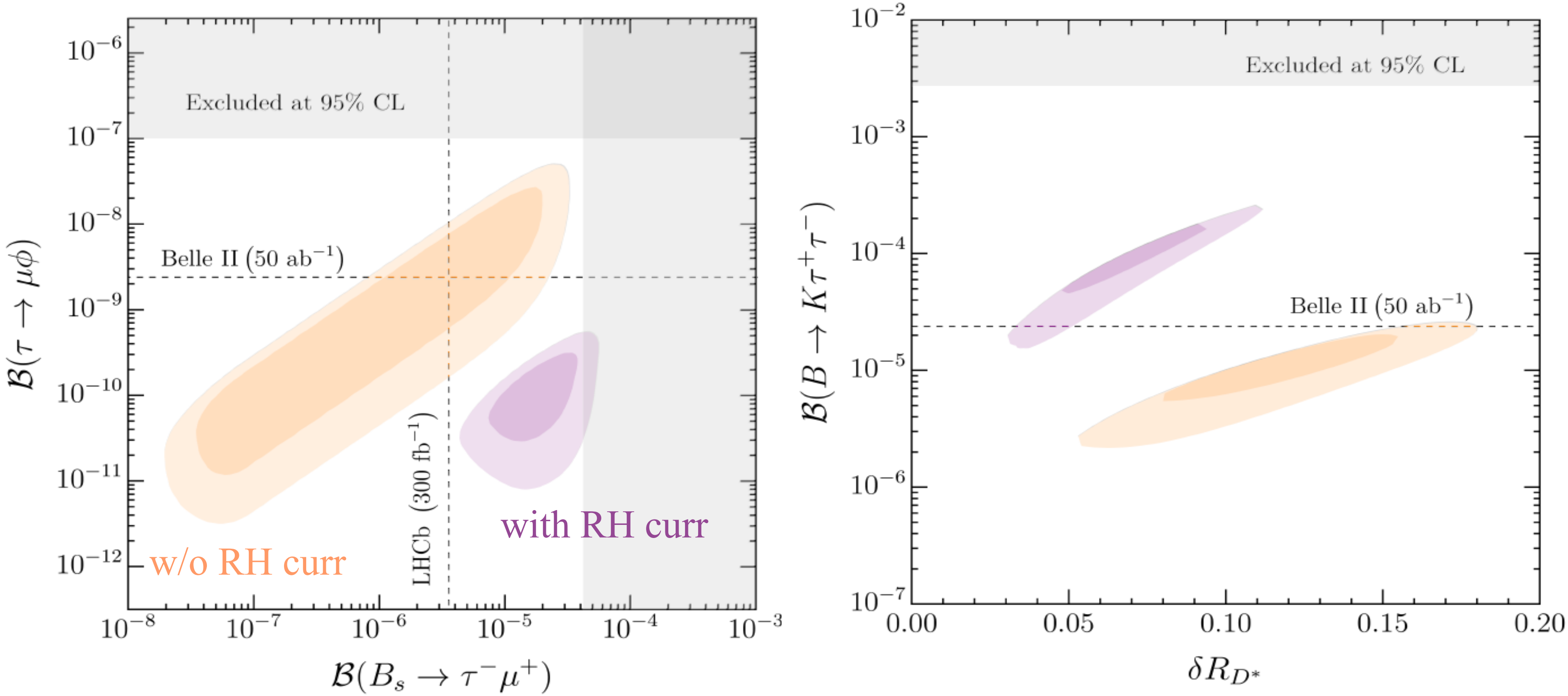
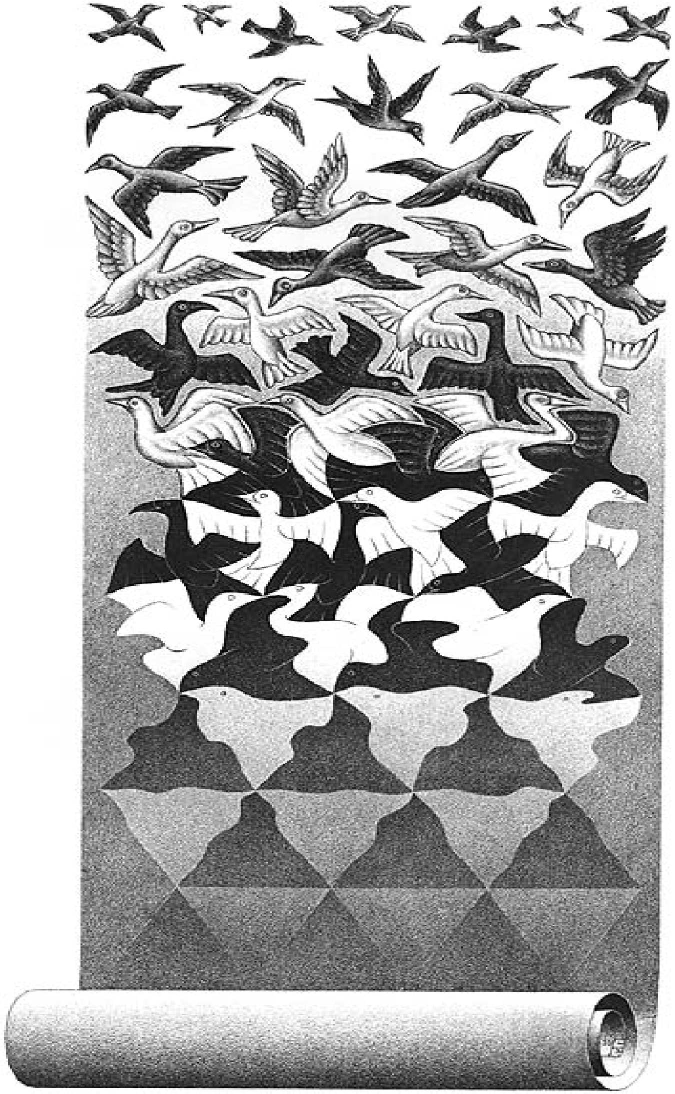
and fitting <u>all low-energy data</u> leads to an excellent description of present data which is fully <u>consistent with high-pT searches</u>, and has interesting implications for future low-energy searches:

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):

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

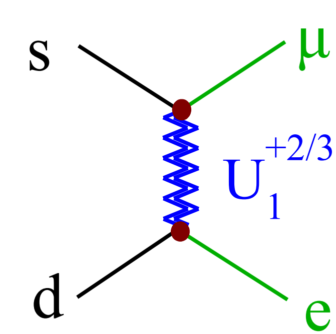
Main Pati-Salam idea:
Lepton number as "the 4th color"

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

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

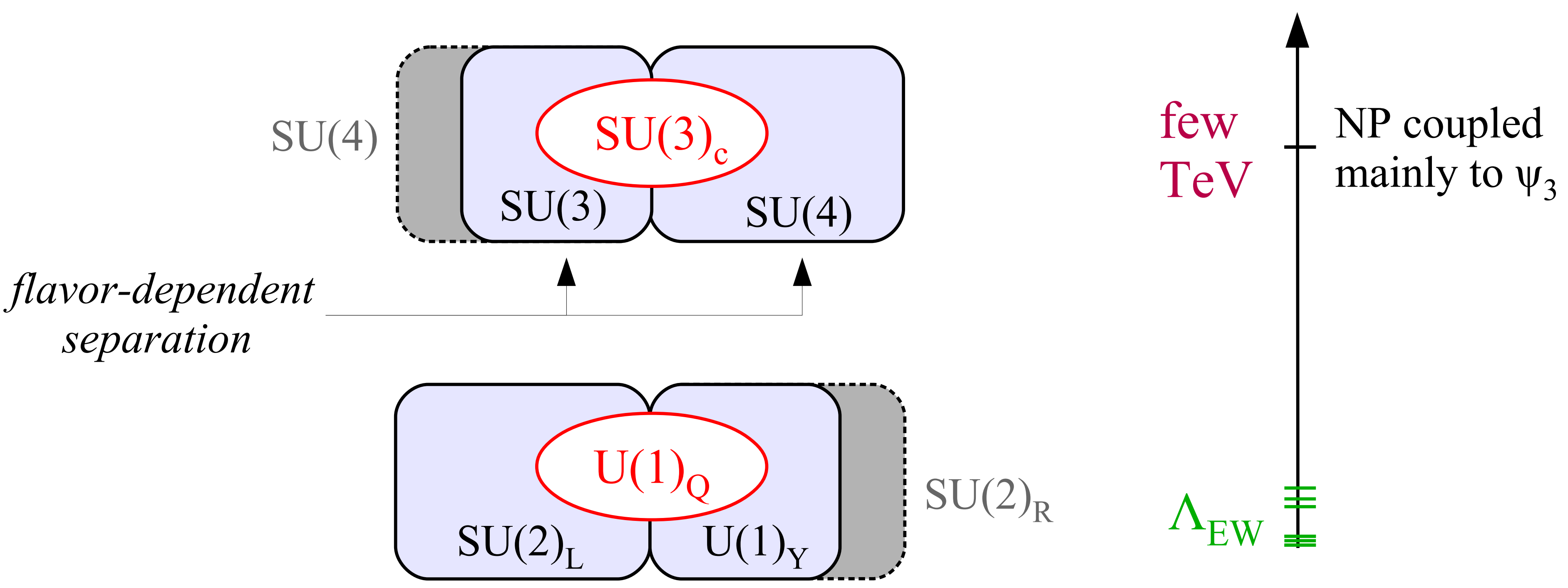


Speculations on UV completions

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



Speculations on UV completions

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

• *Non-universality via mixing*: $SU(4) \times SU(3)$

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

UV completions

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

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

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

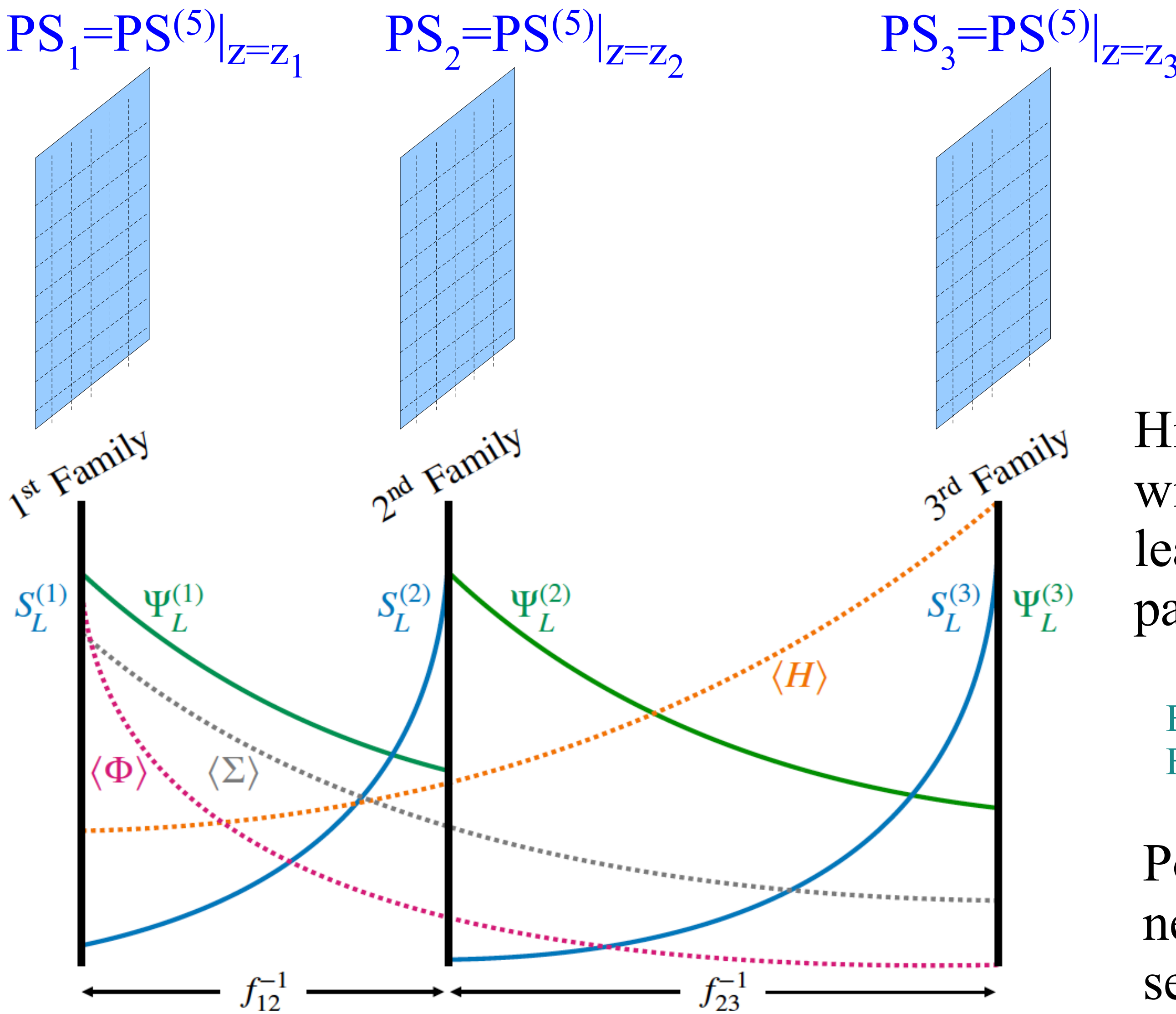
$[PS]^3 = [SU(4) \times G_{EW}]^3$ — Bordone *et al.* '17

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

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

Speculations on UV completions

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



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

Dvali & Shifman, '00

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

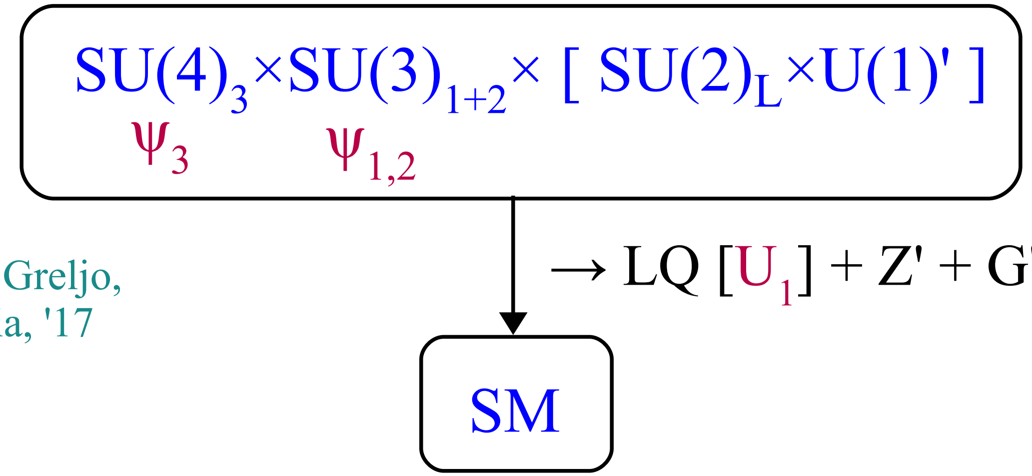
Bordone, Cornella, Fuentes-Martin, GI '17
Fuentes-Martin, GI, Pages, Stefanek '20

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

Speculations on UV completions

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

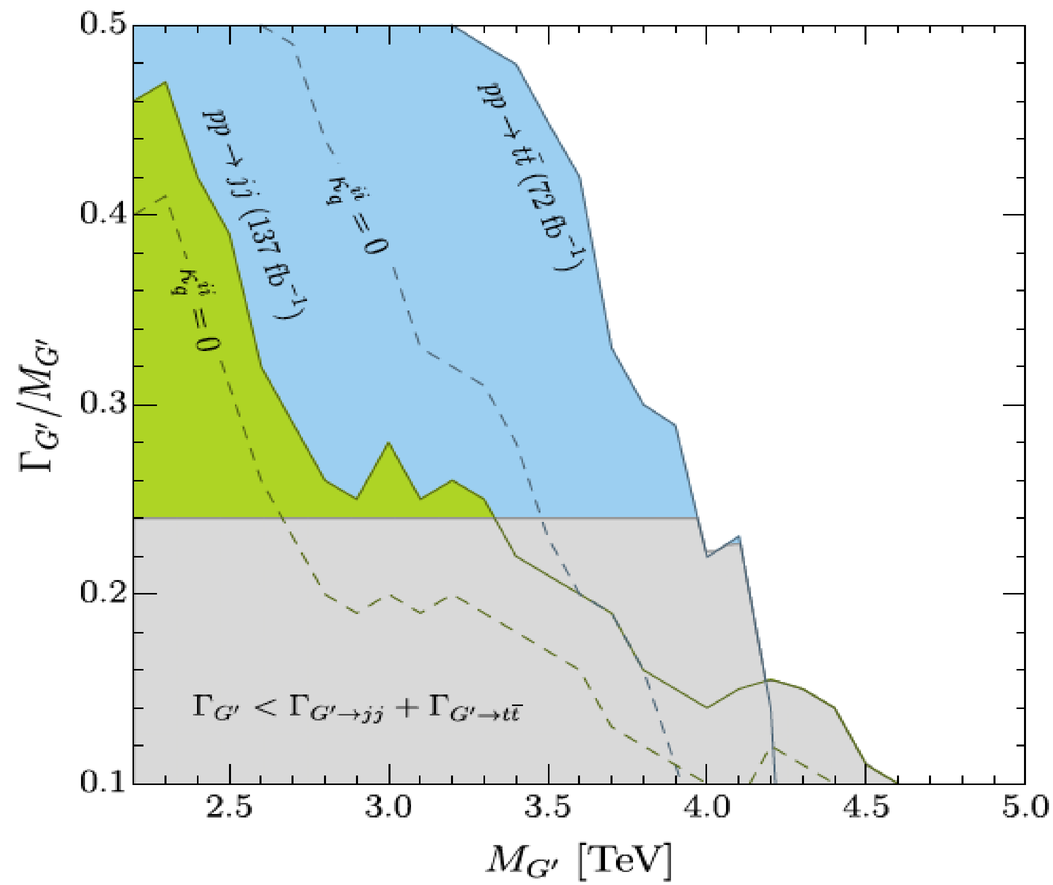
Di Luzio, Greljo, Nardecchia, '17



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*)

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

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

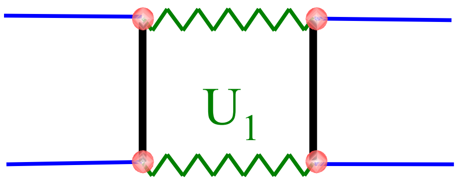
↓

Very interesting (near-by!) future...
(both on the exp., the pheno,
and the model-building point of view)

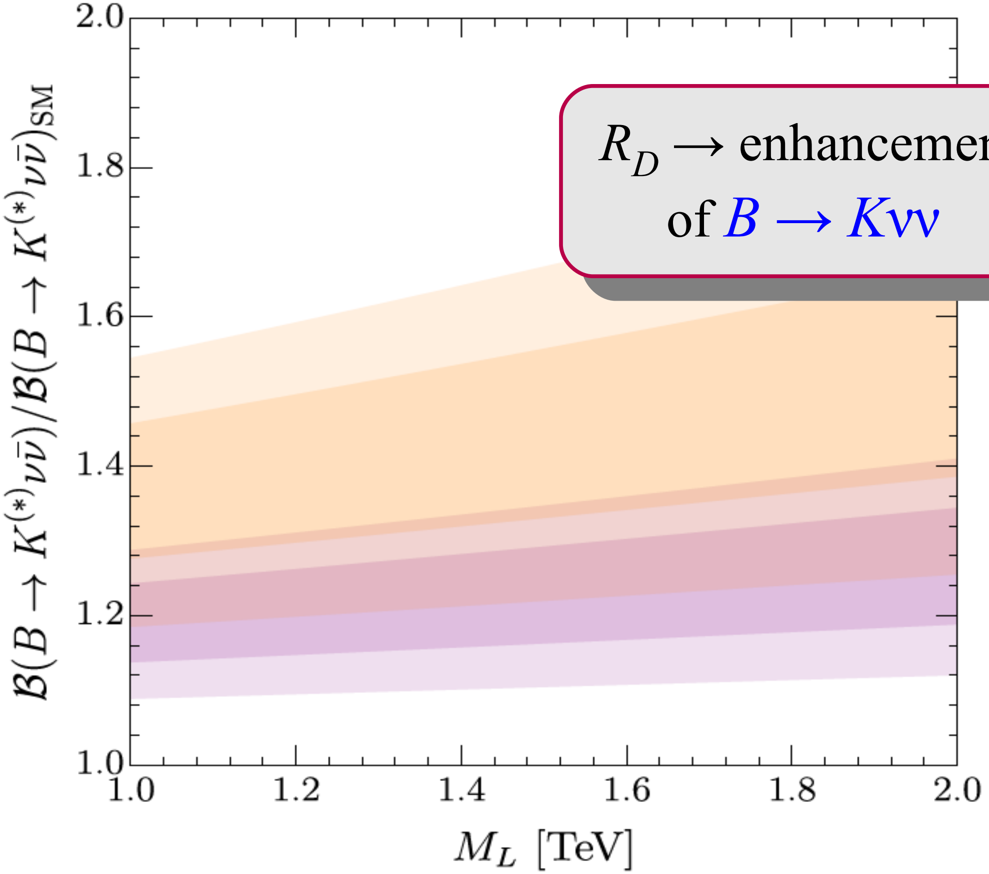

Backup

Speculations on UV completions

UV-sensitive observables in 4321 models

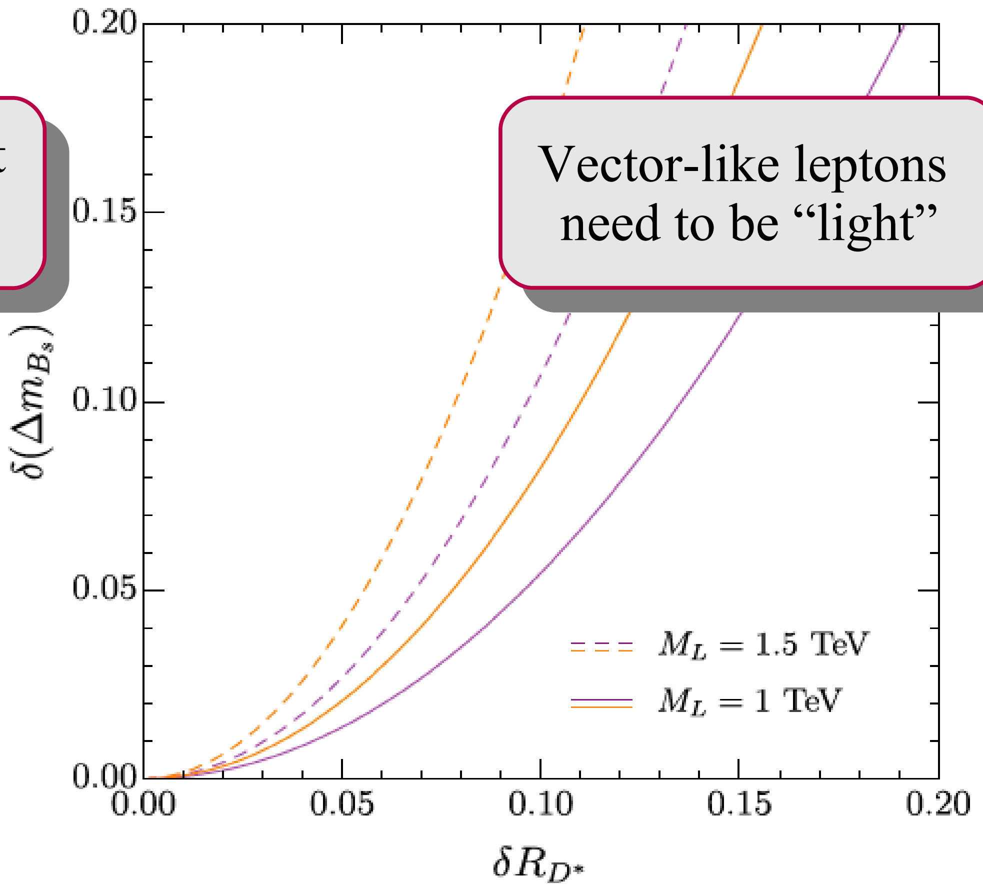


A) $B \to K\nu\nu$



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

B) B_s mixing [ΔF=2]

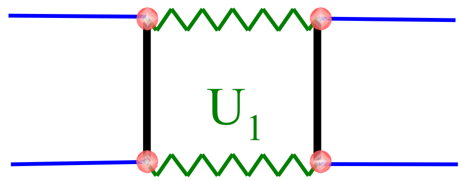


Vector-like leptons need to be "light"

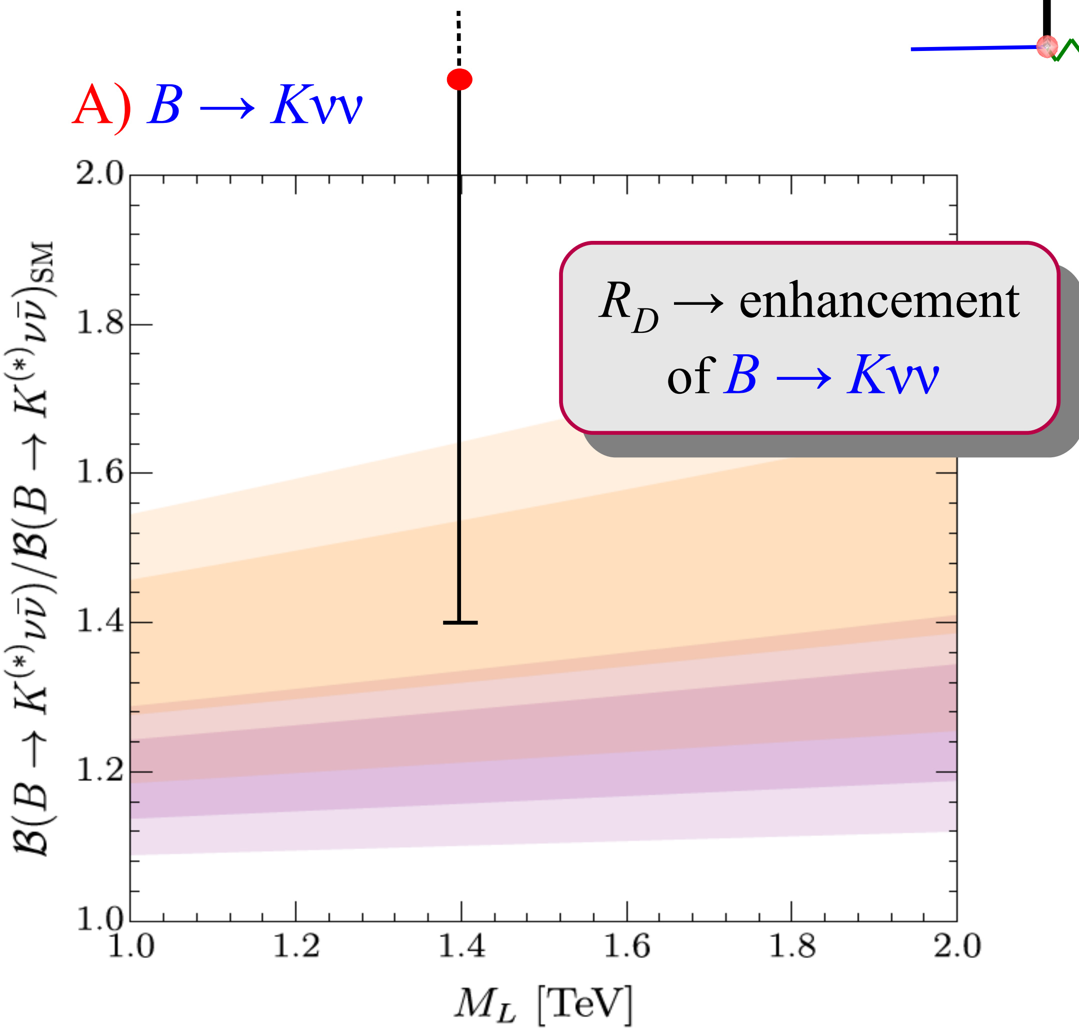
Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21
Fuentes-Martin, GI, Konig, Selimovic, '20

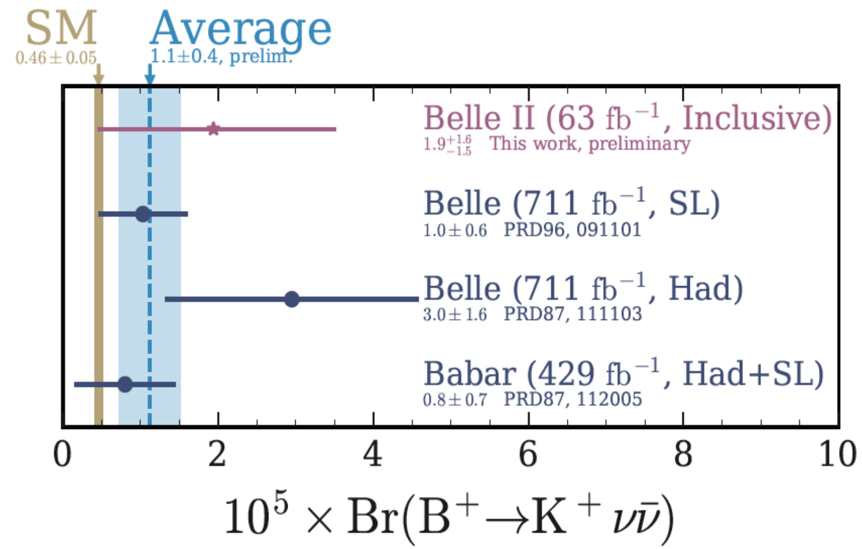
▶ Speculations on UV completions

UV-sensitive observables in 4321 models



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





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