

# *B-physics anomalies and the flavor problem*

Gino Isidori

[ *University of Zürich* ]

- ▶ Introduction
- ▶ A closer look to the data
- ▶ Effective Field Theory considerations
- ▶ From EFT to simplified models
- ▶ Speculations on ultraviolet completions
- ▶ Conclusions



University of  
Zurich <sup>UZH</sup>



European Research Council  
Established by the European Commission

## ► Introduction

(almost...) all microscopic phenomena we observe in Nature seem to be well described by the **SM**, a simple and elegant **Theory** that we continue to call “model” only for historical reasons...

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



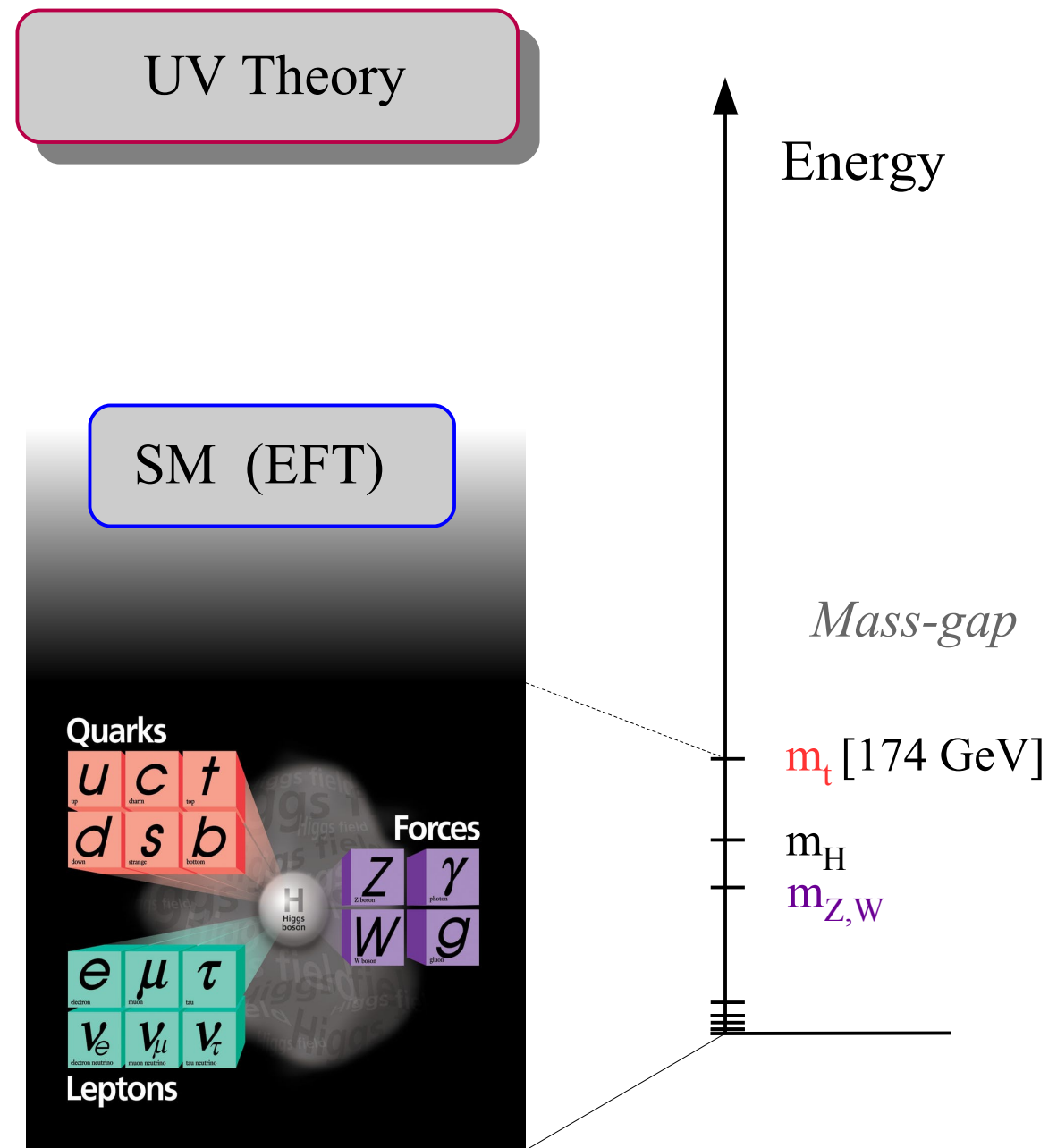
The Standard Model should be regarded as an Effective Field Theory (*EFT*)

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

What we know after the first phase of the LHC is that:

- The Higgs boson is SM-like and is “light” (*completion of the SM spectrum*)
- There is a mass-gap above the SM spectrum

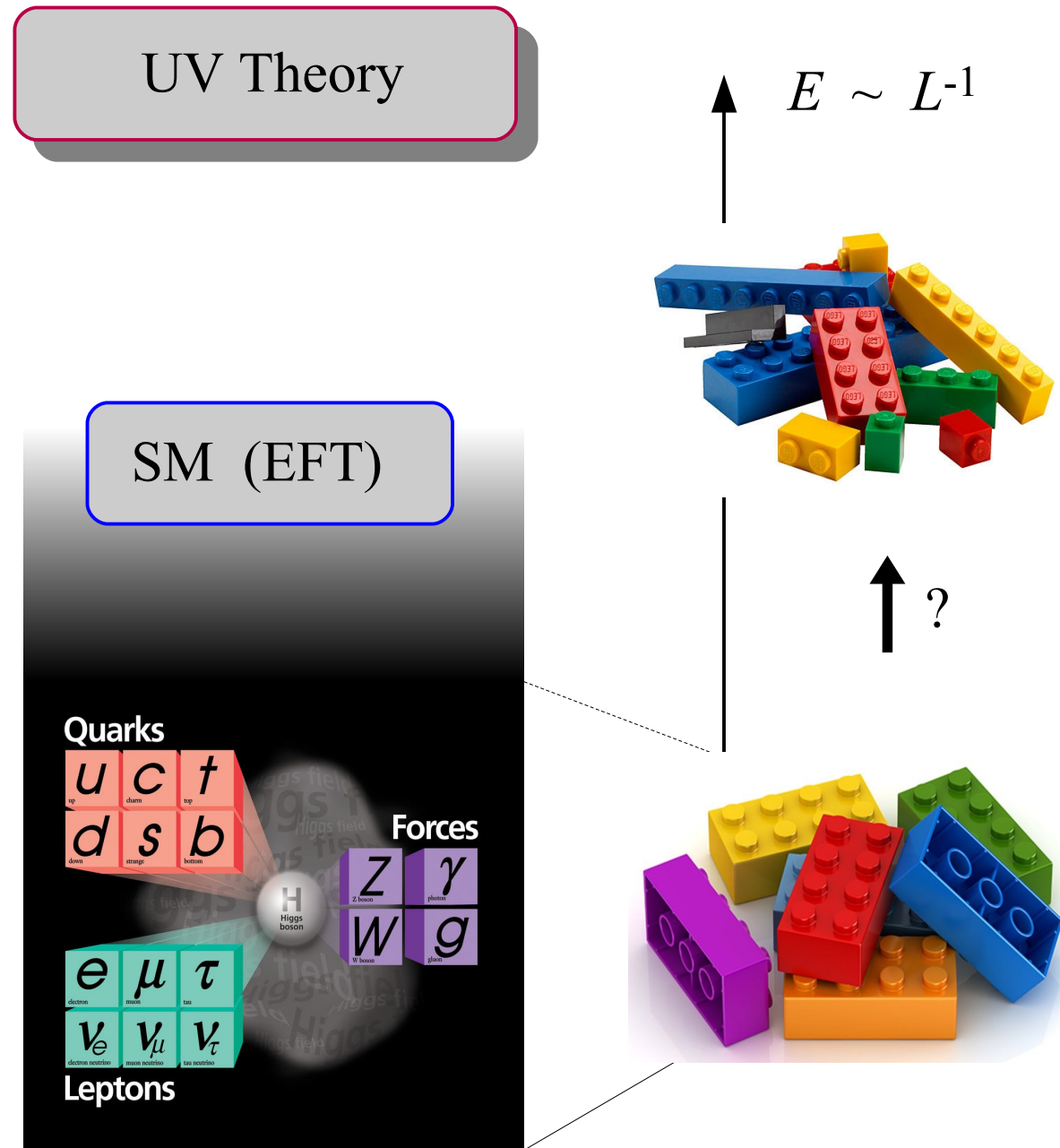


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We identified the “light” ↔ “large” pieces of our “construction game” & their long-range interactions



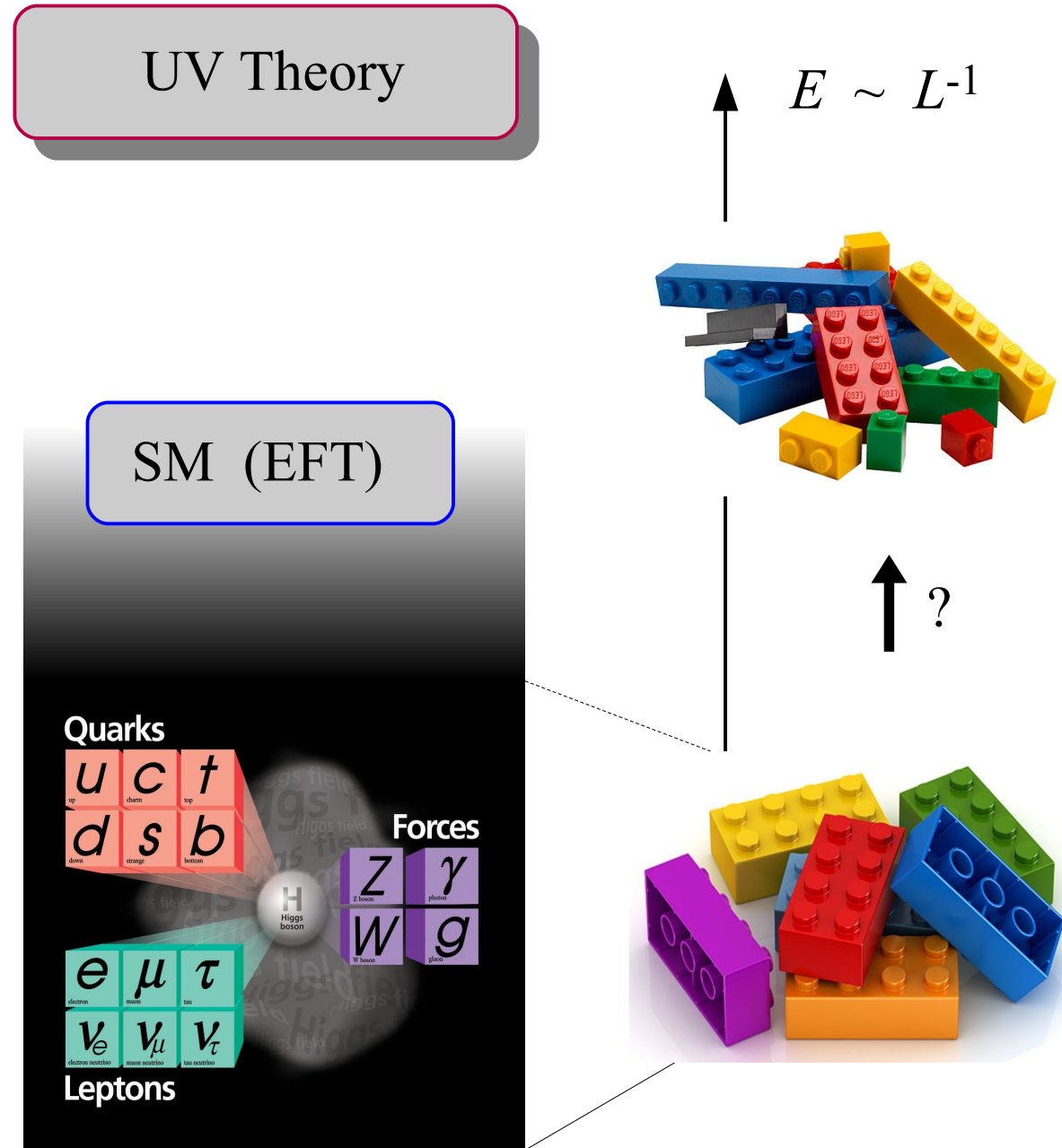
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Reconstructing the UV theory from its low-energy limit is a very difficult problem with no unique solution

*[It took more than 35 years to go from the Fermi Theory to the SM...]*



## ► Introduction

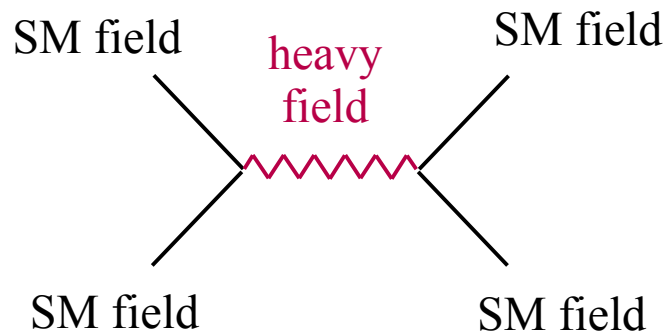
low-energy “projection”

*“integrate out”  
the heavy  
degrees of freedom*

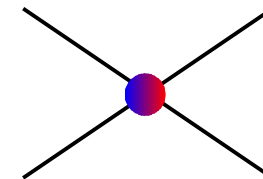
UV Theory



SM (EFT)



*“easy”  
(at least in principle...)*



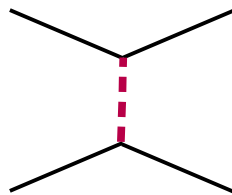
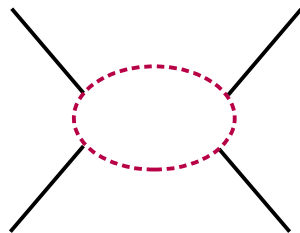
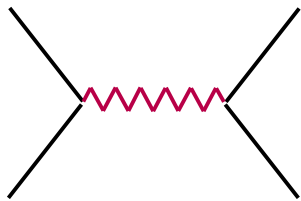
## ► Introduction

low-energy “projection”

*loss of information about nature & properties of the high-energy modes*

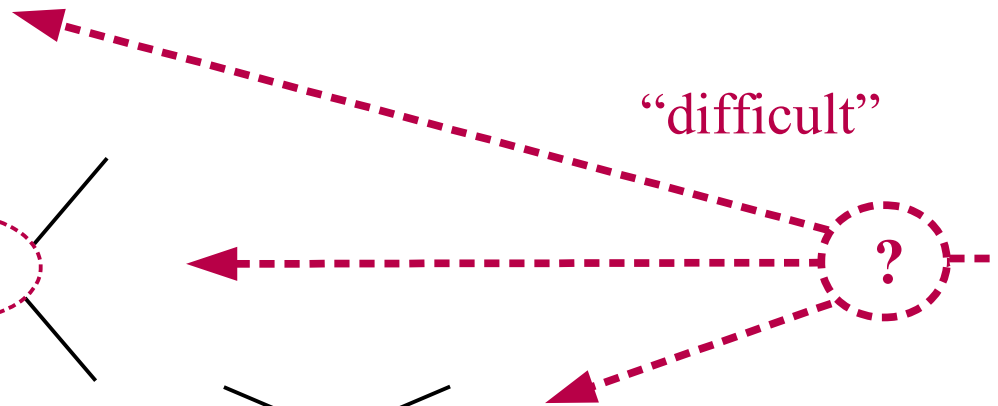
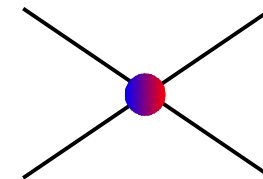
UV Theory

SM (EFT)



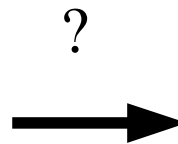
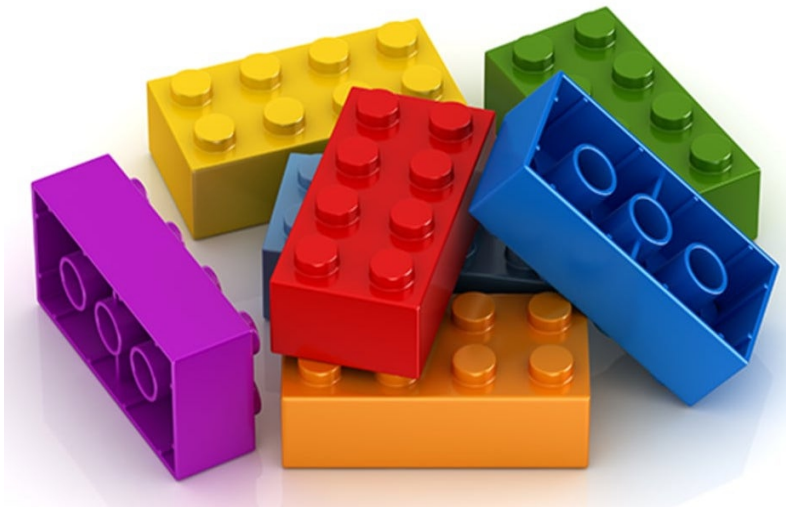
“difficult”

?



## ► Introduction

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





## ► Introduction

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

Two types of effects in QFT:

$$\mathcal{L}_{\text{SM-EFT}} = \underbrace{\mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}}_{\text{Un-natural aspects of low-energy couplings}} + \underbrace{\sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} \mathcal{O}_i^{d \geq 5}}_{\text{Violations of accidental symmetries}}$$

Un-natural aspects of  
low-energy couplings

*qualitative*  
UV imprint

Violations of  
accidental symmetries

*quantitative*  
UV imprint

UV Theory

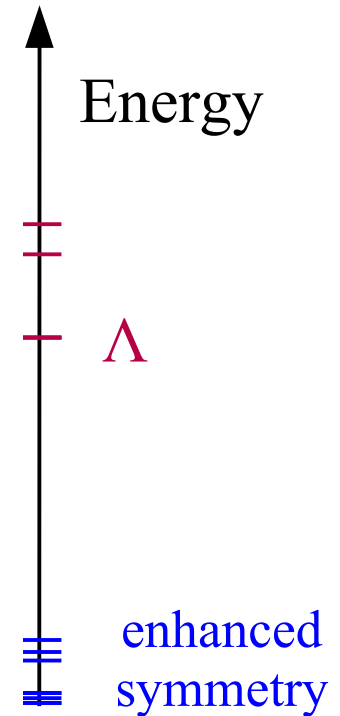
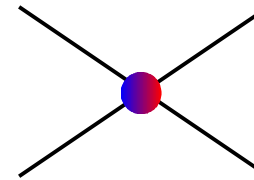
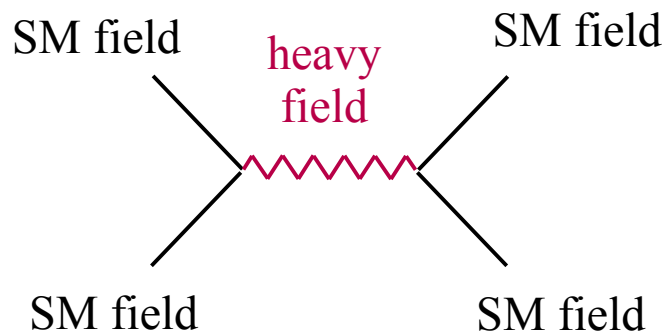


SM (EFT)

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



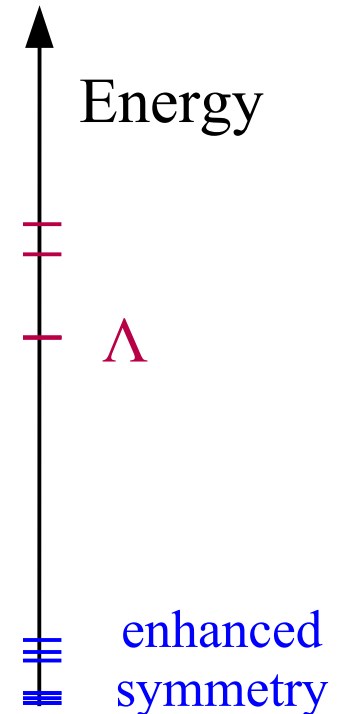
At large distances, not enough “variables” to describe the violation of the symmetry  
 [  $\sim$  multipole expansion ]

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Violations of accidental symmetries



Well-known examples from the past...

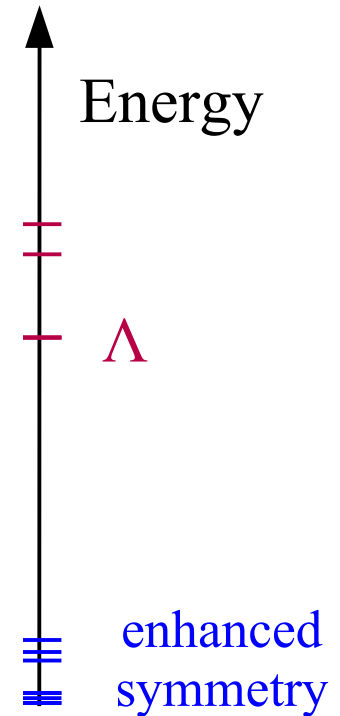
**Eg:** *Low-energy theory:* QED + QCD  
*Accidental symm.:* Flavor [ U(1)<sup>n<sub>f</sub></sup> ]  
*Violated by:* Weak interactions → G<sub>F</sub> ~ (250 GeV)<sup>-2</sup>

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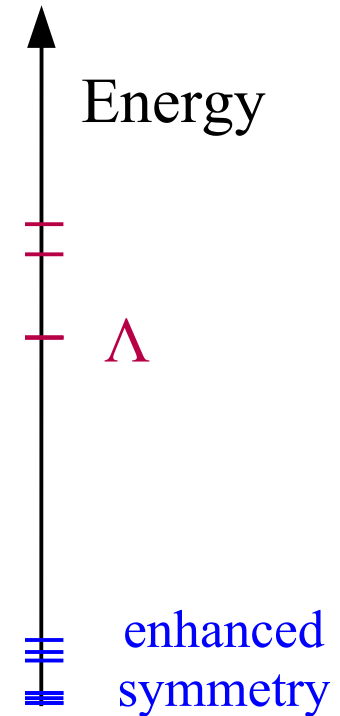
**Eg:** *Low-energy theory:* SM, 2 generations  
*Accidental symm.:* CP  
*Violated by:* “Super-weak” interactions →  $\frac{(G_F m_t V_{ts} V_{td})^2}{4\pi^2} \sim (10^4 \text{ TeV})^{-2}$

## ► Introduction

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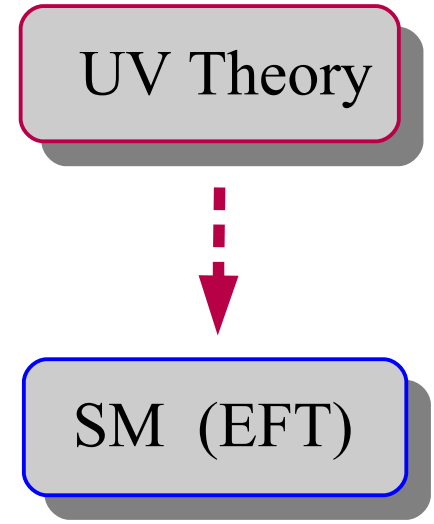
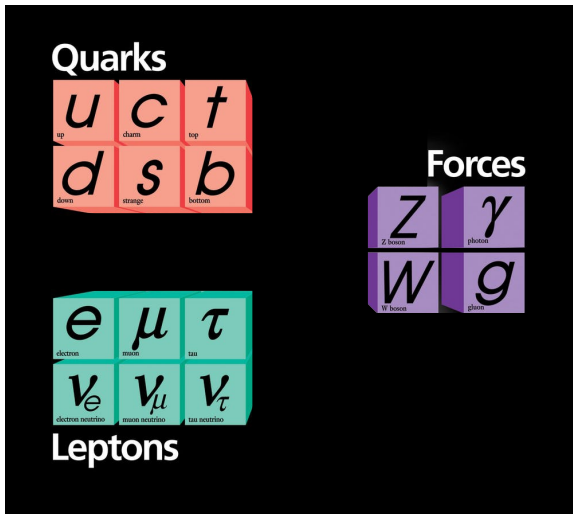
...the violations of **L**epton **F**lavor **U**niversality recently reported by experiments belong to this category

► Introduction

$$\mathcal{L}_{\text{SM-EFT}} = \underbrace{\mathcal{L}_{\text{gauge}}}_{\text{Natural}} + \mathcal{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} \mathcal{O}_i^{d \geq 5}$$

Natural  
(fully dictated by gauge symmetry)

Un-natural aspects of the SM couplings



► Introduction

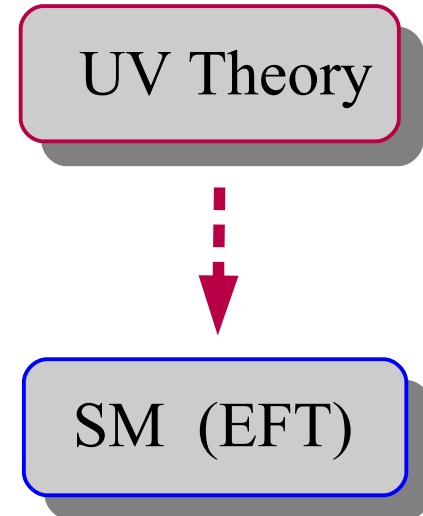
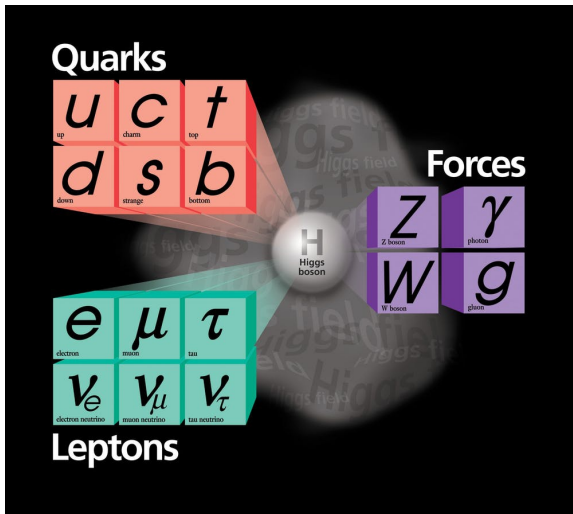
$$\mathcal{L}_{\text{SM-EFT}} = \underbrace{\mathcal{L}_{\text{gauge}}}_{\text{Natural}} + \underbrace{\mathcal{L}_{\text{Higgs}}}_{\text{Non-trivial UV imprints}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} \mathcal{O}_i^{d \geq 5}$$

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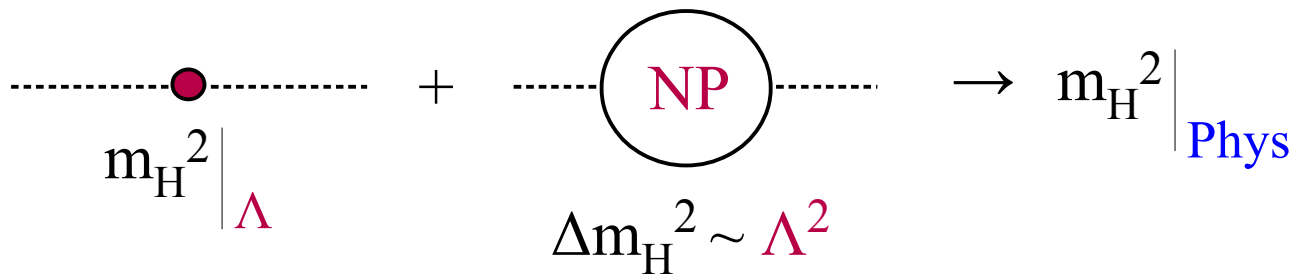
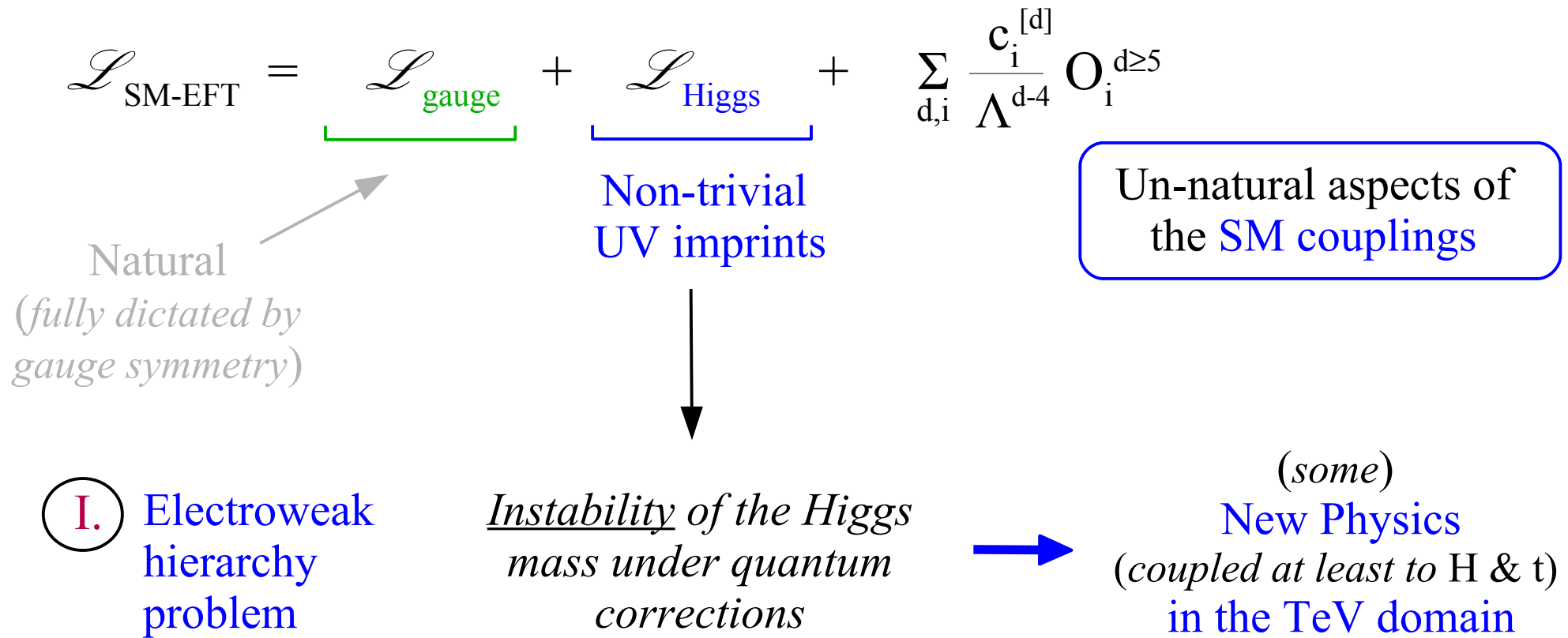
Non-trivial UV imprints

Un-natural aspects of the SM couplings

- I  $m_H^2 H^2$
- II  $y_{ij} \psi_i \psi_j H$



► Introduction





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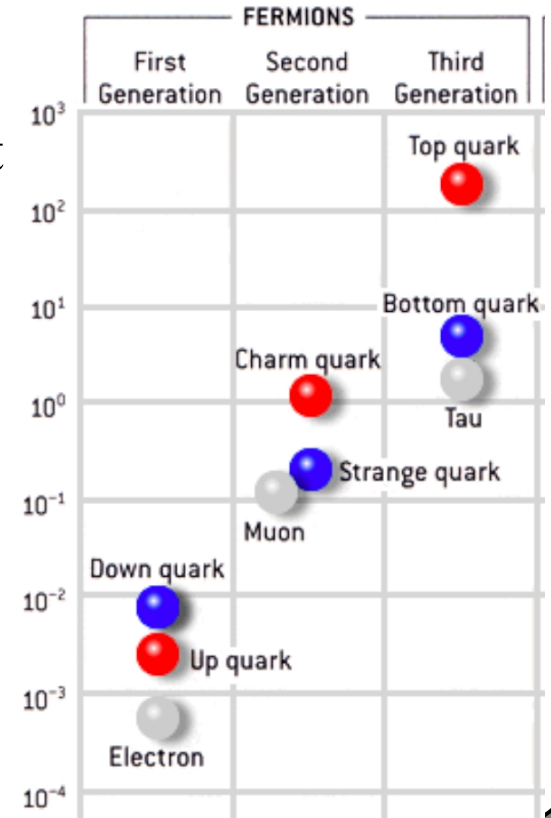
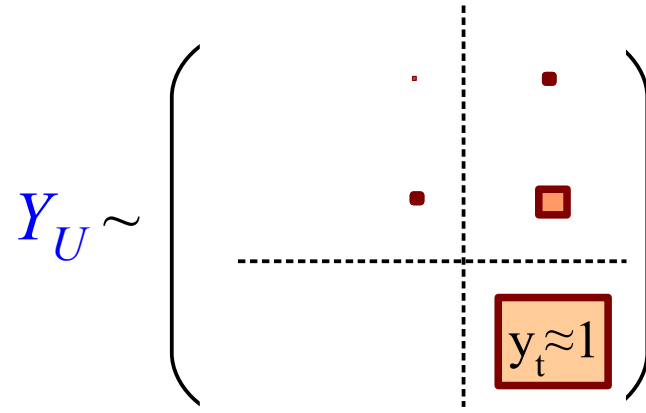
Non-trivial  
UV imprints

Un-natural aspects of the SM couplings

I. Electroweak hierarchy problem

II. Flavor problem

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



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Un-natural aspects of the SM couplings

I. Electroweak hierarchy problem

*Instability of the Higgs mass under quantum corrections*



(some) New Physics in the TeV domain

II. Flavor problem

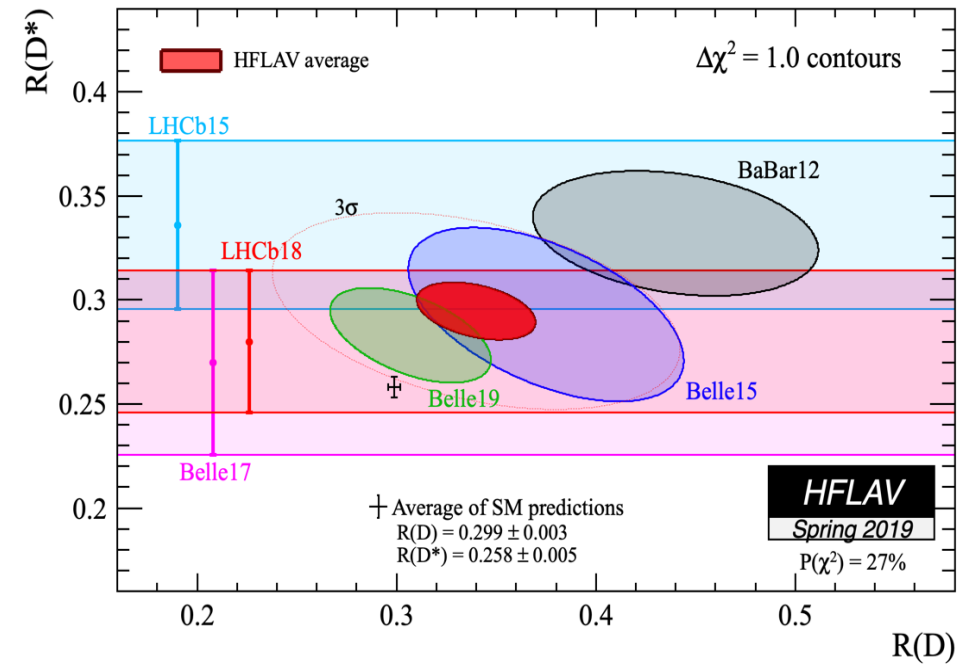
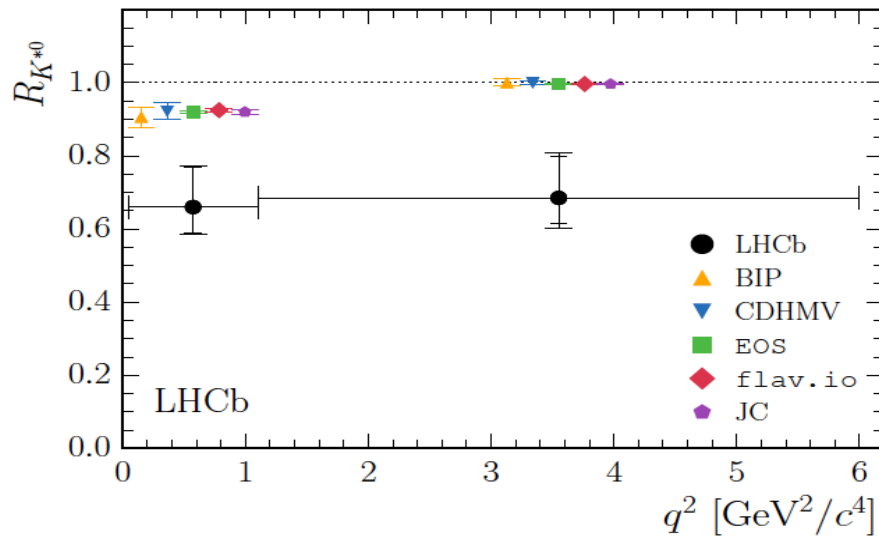
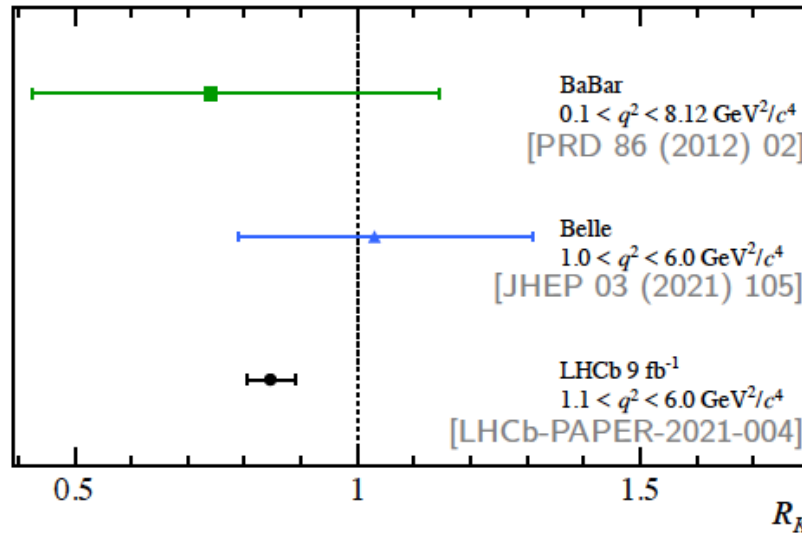
*Un-natural hierarchies in the couplings describing fermion masses*



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*)

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 **L**epton **F**lavor **U**niversality

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

- $b \rightarrow s l^+ l^-$  (neutral currents):  $\mu$  vs.  $e$
- $b \rightarrow c l \nu$  (charged currents):  $\tau$  vs. light leptons ( $\mu, e$ )

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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:

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} \Big|_{y_l = 0} \longrightarrow \text{accidental global symmetry: } 3 \times 3 \text{ (unitary) transformations of lepton fields in flavor space}$$

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

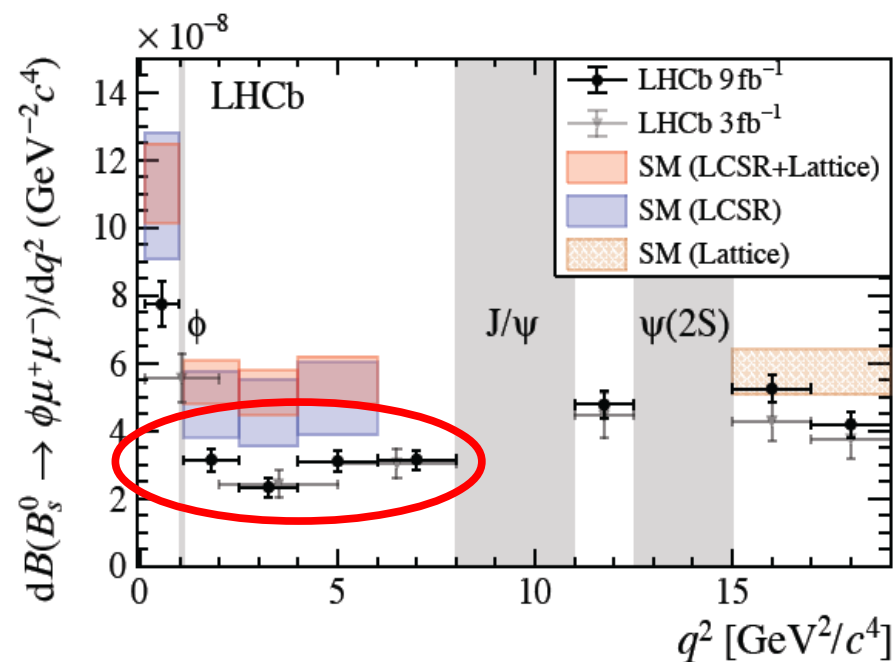
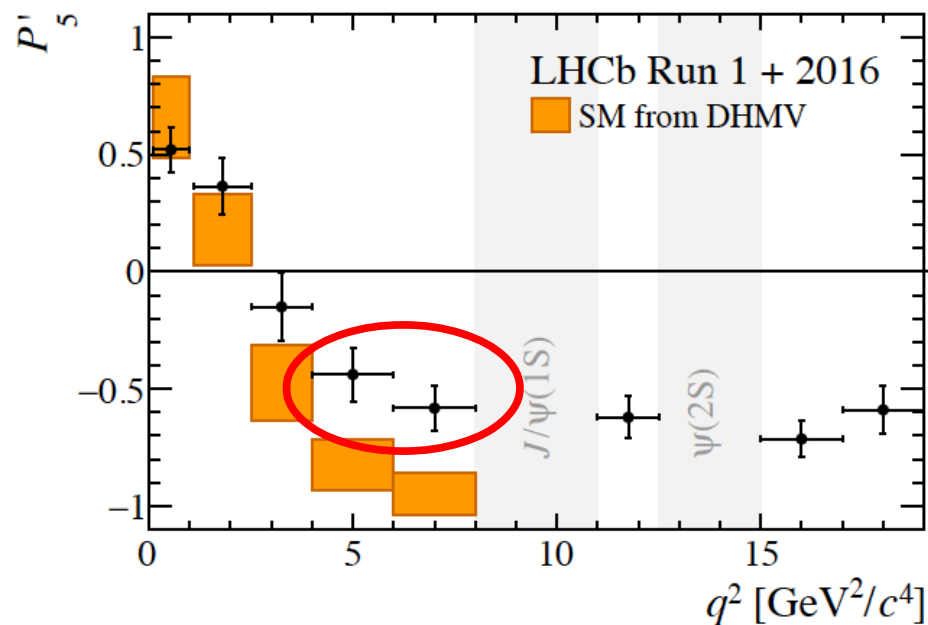
but all the lepton Yukawa couplings are small compared to SM gauge couplings, giving rise to the (*approximate*) universality of decay amplitudes which differ only by the different lepton species involved

## ► A closer look to the data

### • $b \rightarrow s l^+ l^-$ (neutral currents)

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

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

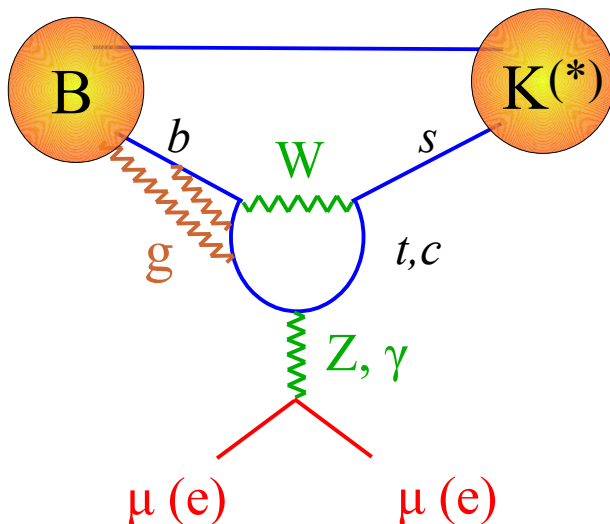


## ► A closer look to the data

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- LFU ratios ( $\mu$  vs.  $e$ ) in  $B \rightarrow K^* \ell\ell$  &  $B \rightarrow K \ell\ell$  😊 th. error <1%
- Smallness of  $\text{BR}(B_s \rightarrow \mu\mu)$  😊 th. error few %



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

$$\text{The recent result } R_K \approx \frac{\Gamma(B \rightarrow K \mu\mu)}{\Gamma(B \rightarrow K ee)} \approx 0.85 \pm 0.05$$

LHCb '21

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



► A closer look to the data

To describe  $b \rightarrow sll$  decays we

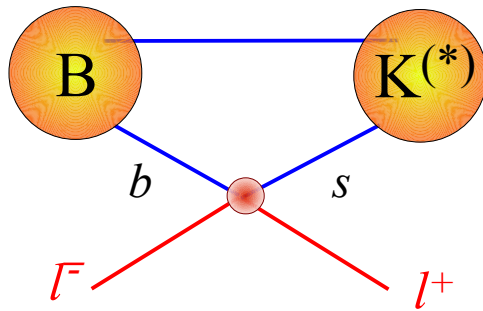
- build an EFT Lagrangian
- evolve it down to  $\mu \sim m_b$
- evaluate hadronic matrix elements

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

*FCNC operators:*

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

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

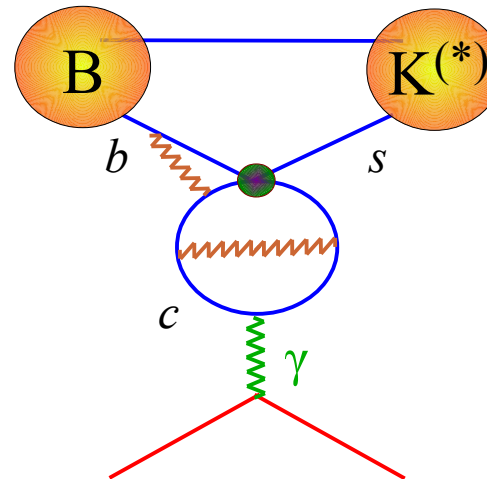


“easy” & “clean”

*Four-quark operators:*

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

⋮



“difficult”



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

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

► A closer look to the data

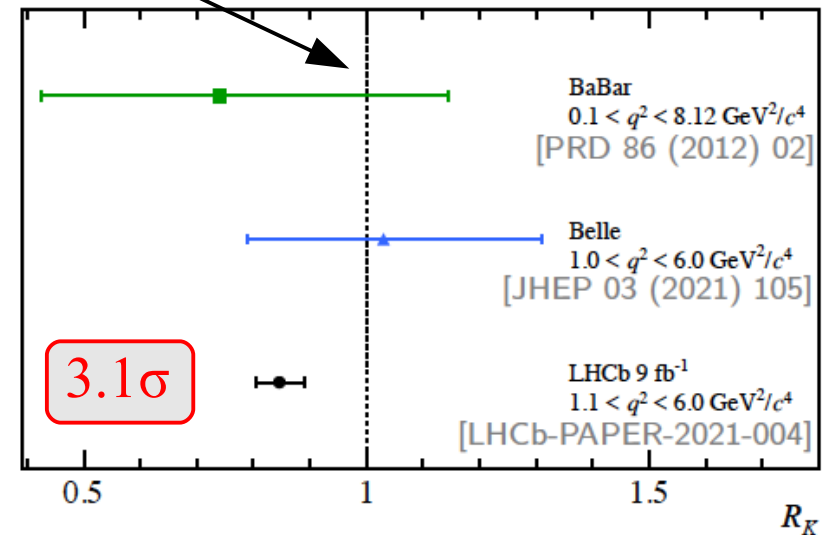
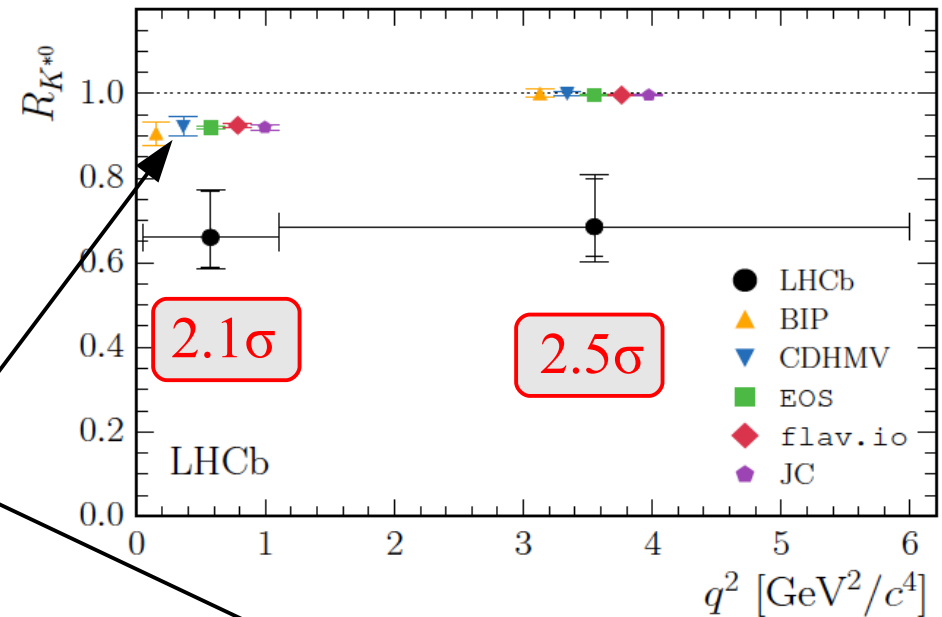
The LFU ratios:

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

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

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

Deviations from the SM predictions ranging from  $2.1\sigma$  to  $3.1\sigma$  in each of the 3 bins measured by LHCb



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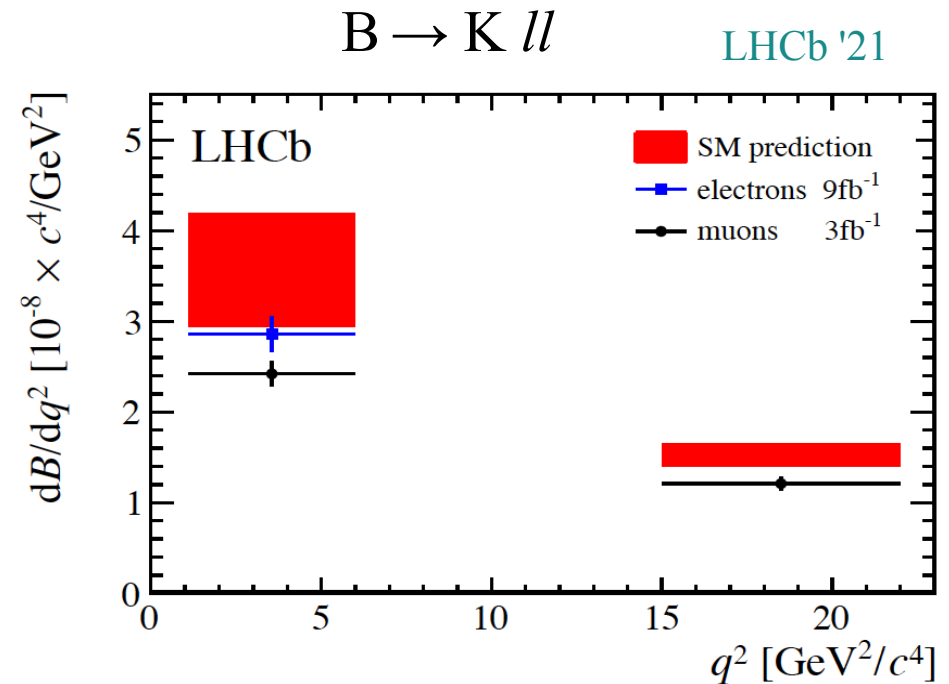
$B_s \rightarrow \mu\mu$ :

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

Beneke *et al.* '19

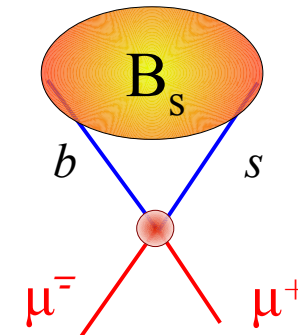
$$BR(B_s \rightarrow \mu\mu)_{exp} = (2.85 \pm 0.32) \times 10^{-9}$$

ATLAS+CMS+LHCb '21

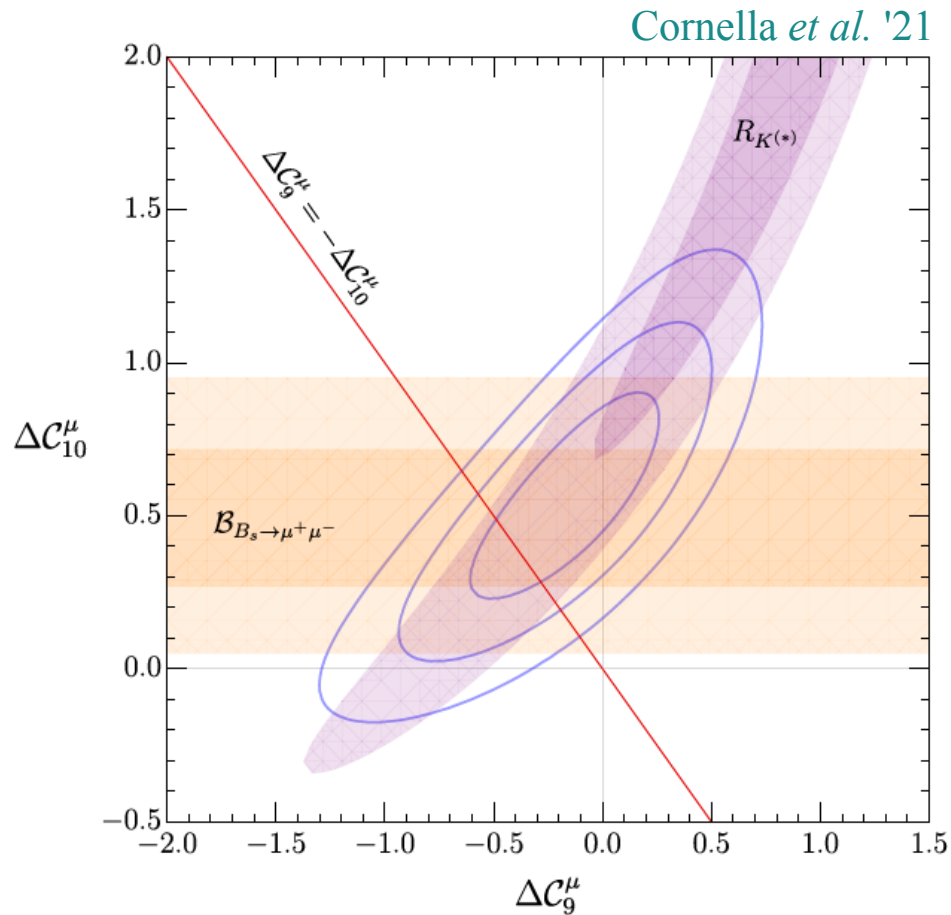


According to our best estimates of the SM rates, what is observed is a (15-20)% deficit of the muon modes

$2.3\sigma$



► A closer look to the data



Conservative fit using “clean obs.”

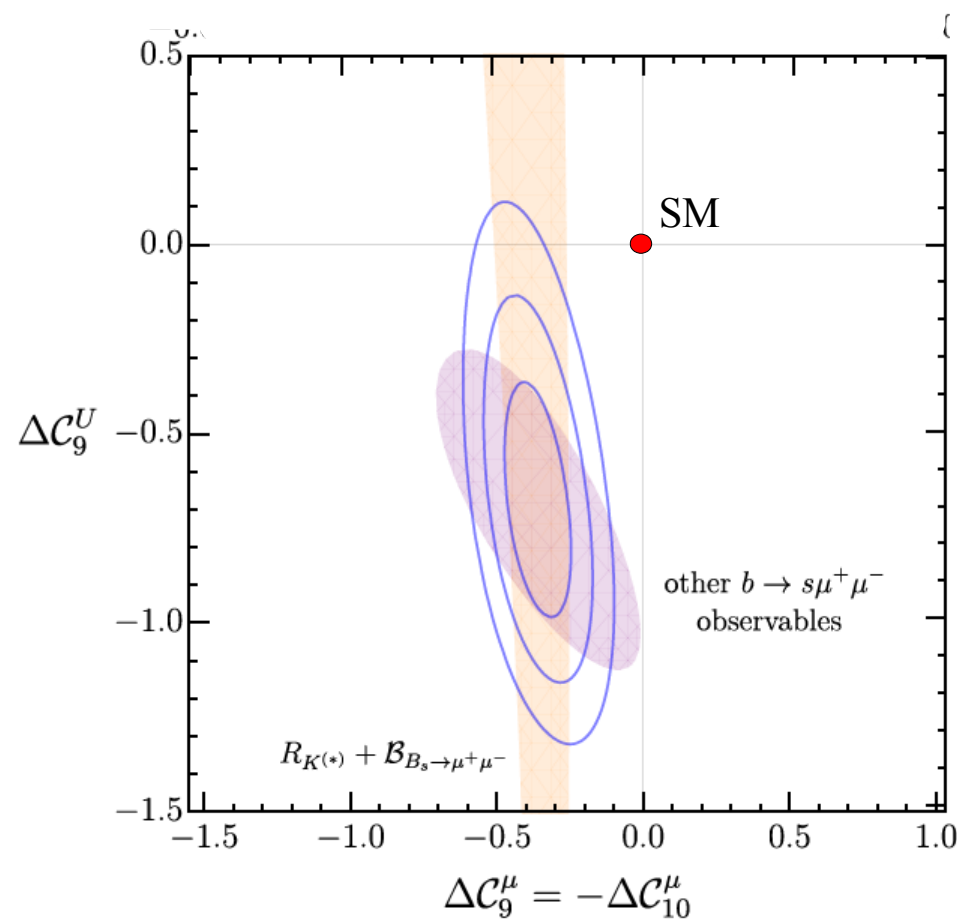
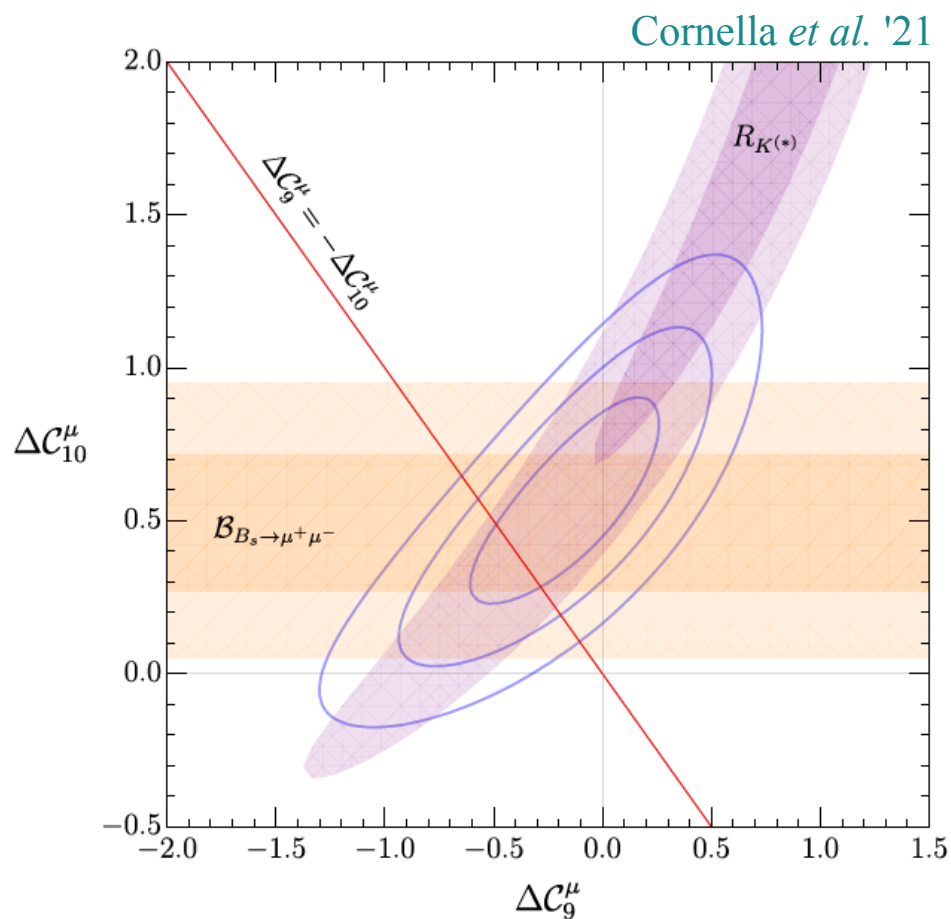
only [  $\Delta C_i^{\mu} = C_i^{\mu} - C_i^e$  ]:

4.6 $\sigma$

significance of NP hypothesis

$$\Delta C_9^{\mu} = -\Delta C_{10}^{\mu} \text{ vs. SM}$$

► A closer look to the data



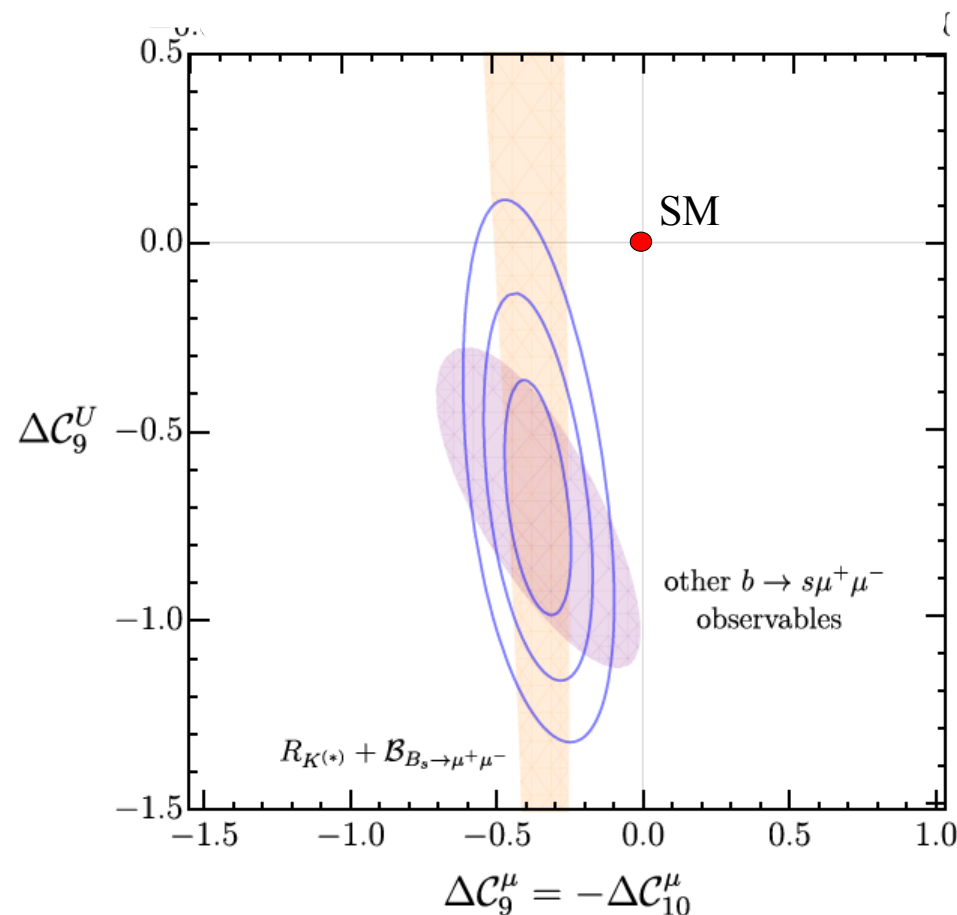
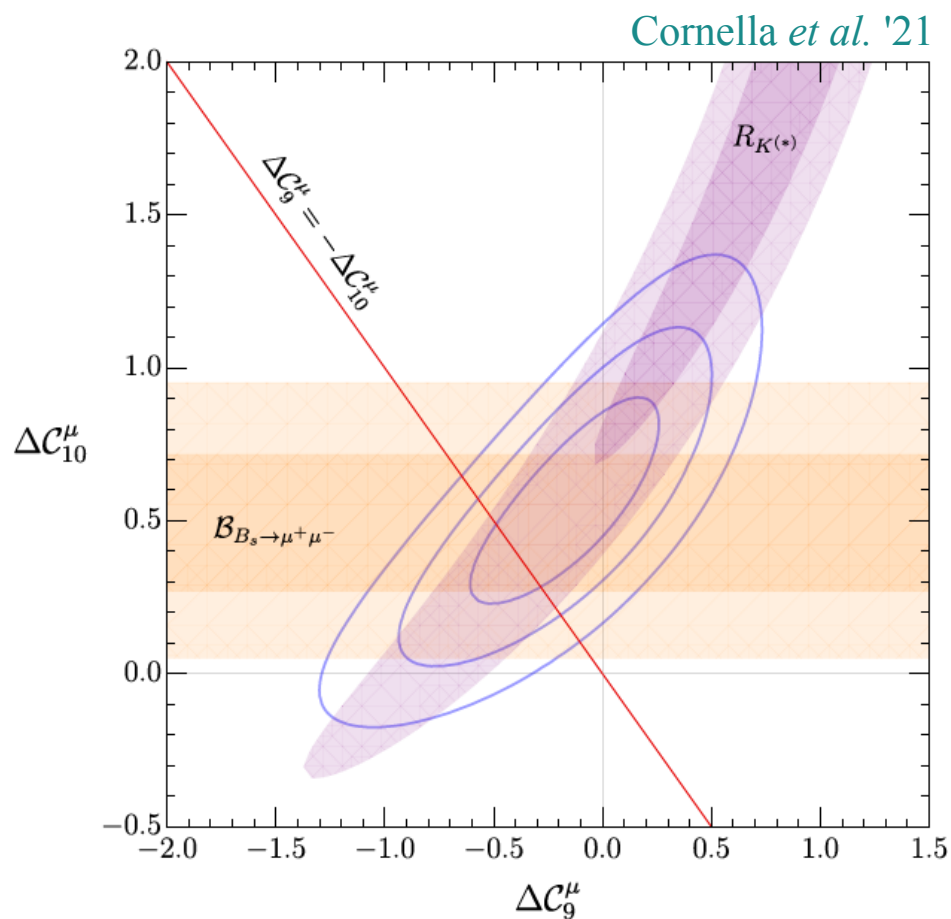
**Conservative fit** using “clean obs.”  
only [  $\Delta C_i^\mu = C_i^\mu - C_i^e$  ]:

**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



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

**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

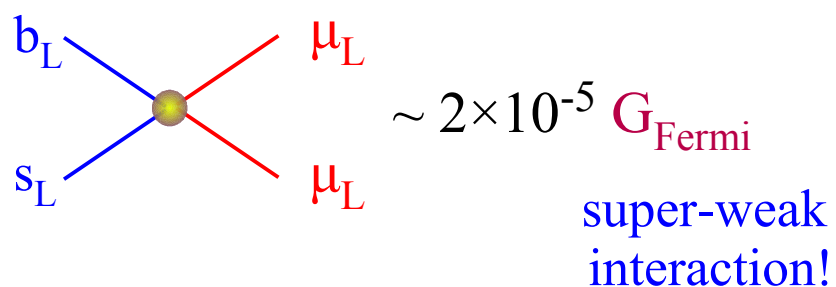
**3.9 $\sigma$**  global significance of NP  
(very conserv. estimate)

Lancierini, GI,  
Owen, Serra, '21

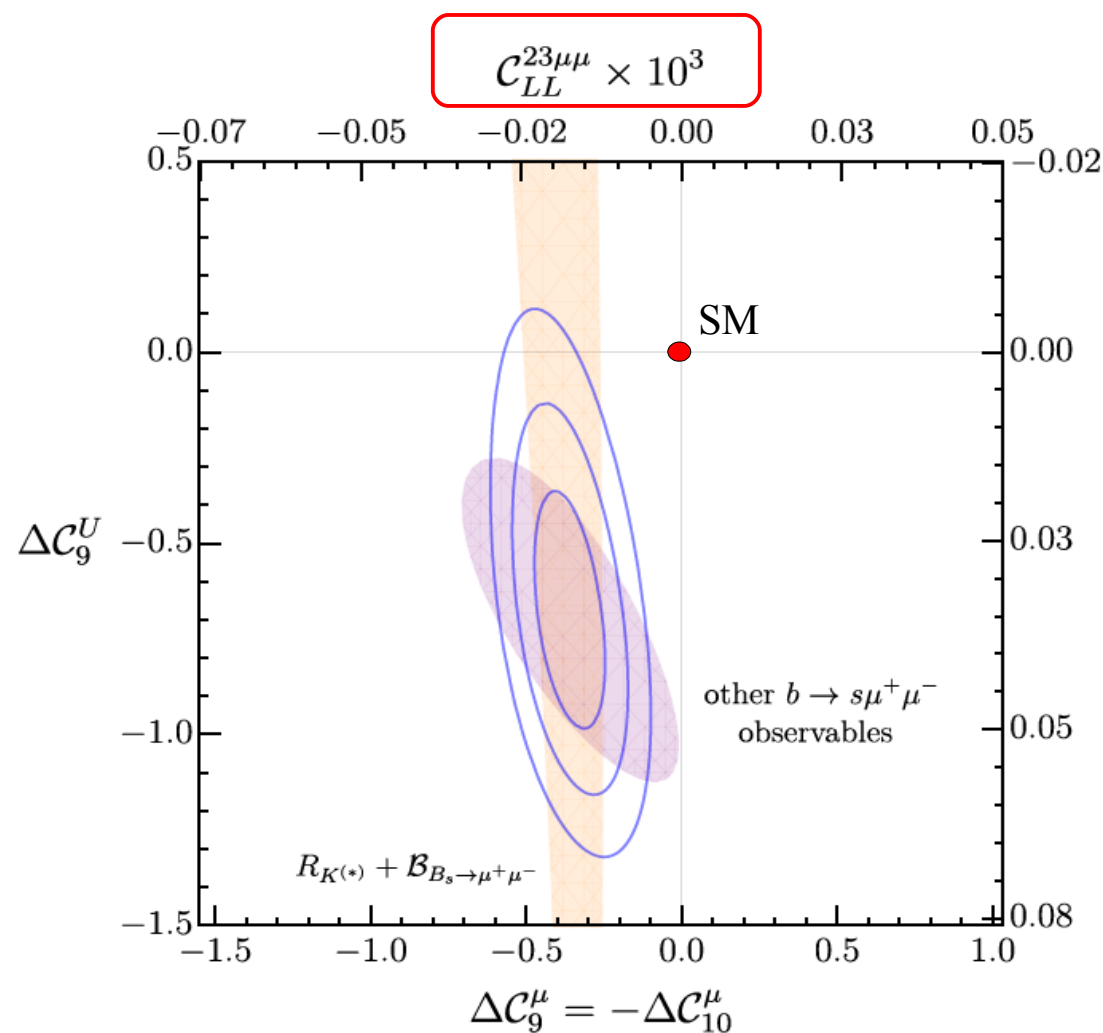
► A closer look to the data

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

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



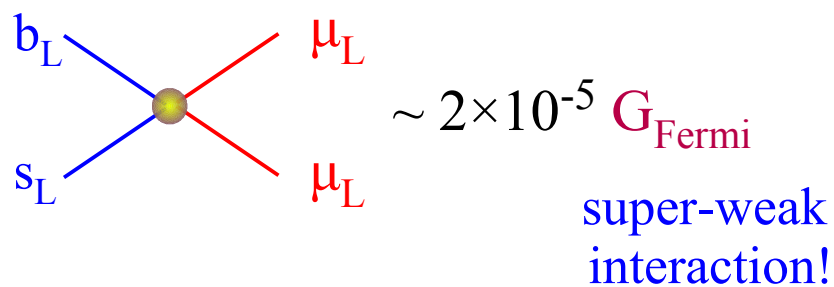
$$C_{LL}^{23\mu\mu} \rightarrow \Delta C_9^\mu = -\Delta C_{10}^\mu$$



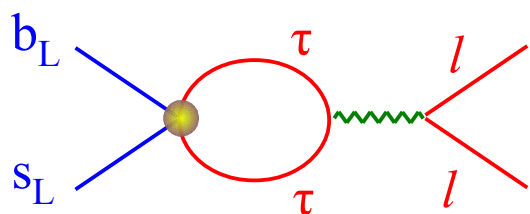
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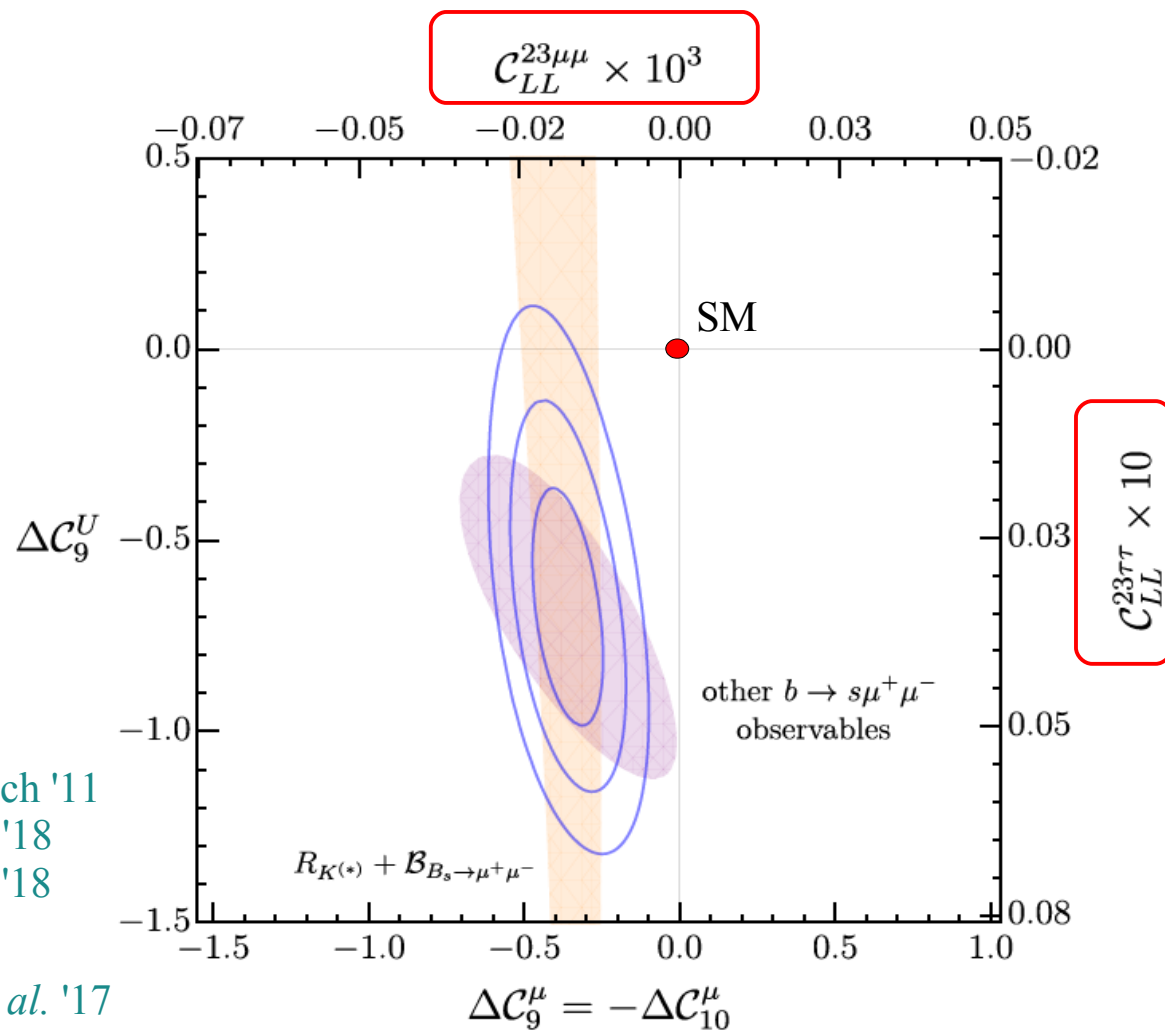
$$C_{LL}^{23\mu\mu} \rightarrow \Delta C_9^\mu = -\Delta C_{10}^\mu$$



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

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

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

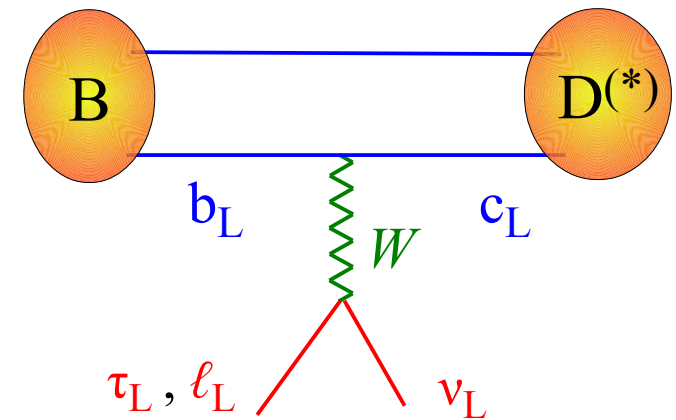
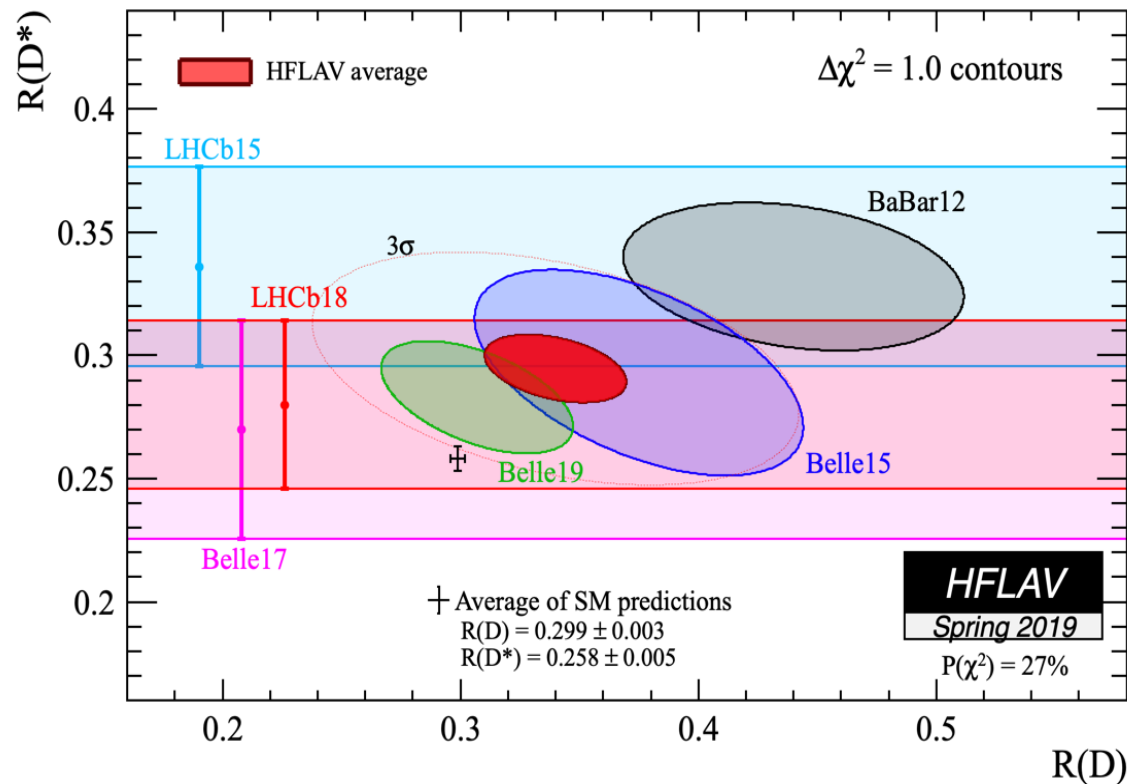




► A closer look to the data

- $b \rightarrow c \ell \bar{\nu}$  (charged currents):  $\tau$  vs. light leptons ( $\mu, e$ )

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

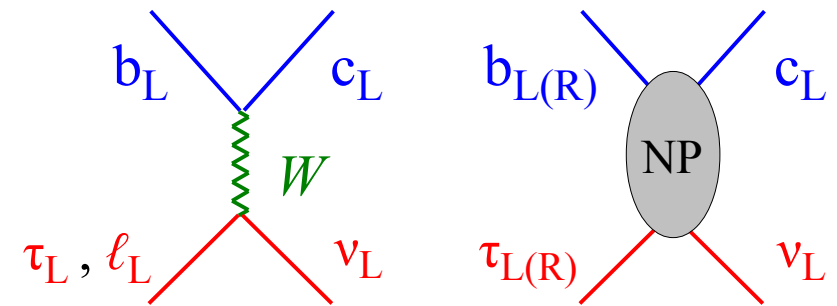
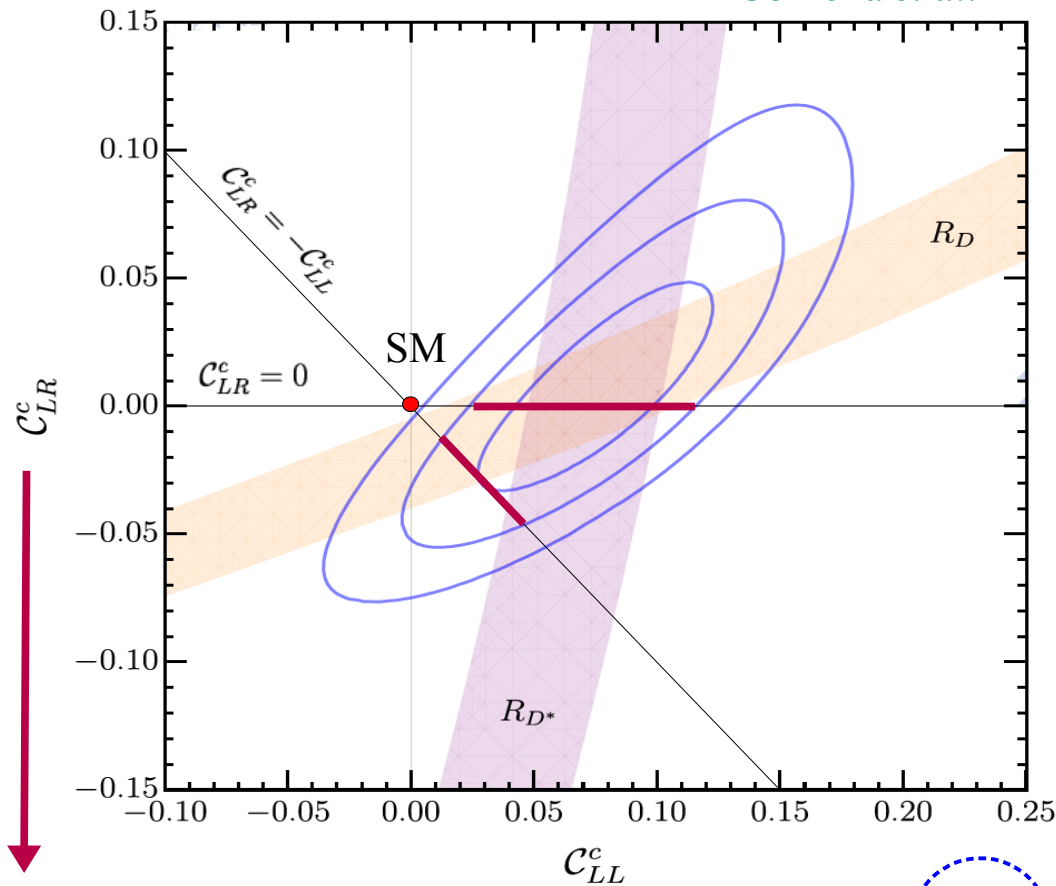


- Consistent results by three different exs.  $\sim 3.1\sigma$  excess over SM ( $D$  and  $D^*$  combined)
- SM predictions quite “clean”: hadronic uncertainties cancel (to large extent) in the ratios

► A closer look to the data

- $b \rightarrow c \ell \nu$  (charged currents):  $\tau$  vs. light leptons ( $\mu, e$ )

Cornella et al. '21



Data consistent with a universal enhancement (10-20%) of  $\tau$  modes

But other options (*RH currents*) possible

Same operator contributing to  $b \rightarrow s \ell \ell$

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

CKM “weighted mix” as for  $C_{LL}^c$

$$\frac{V_{cb} C_{LL}^{33\tau\tau} + V_{cs} C_{LL}^{23\tau\tau}}{V_{cb}}$$

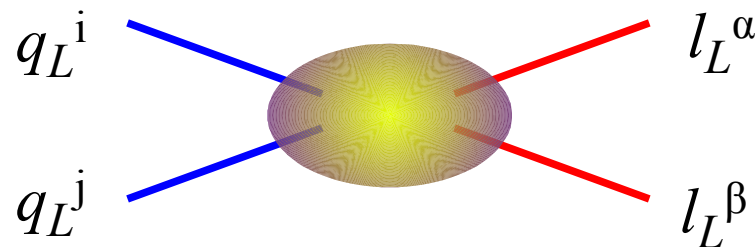
all 3<sup>rd</sup> gen. (contribute via CKM rotation)

## 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** →  $l_3 \nu_3$  [ $\mathbf{R}_D, \mathbf{R}_{D^*}$ ]
- Small coupling [*competing with SM loop-level*] in **bs** →  $l_2 l_2$  [ $\mathbf{R}_K, \mathbf{R}_{K^*}, \dots$ ]

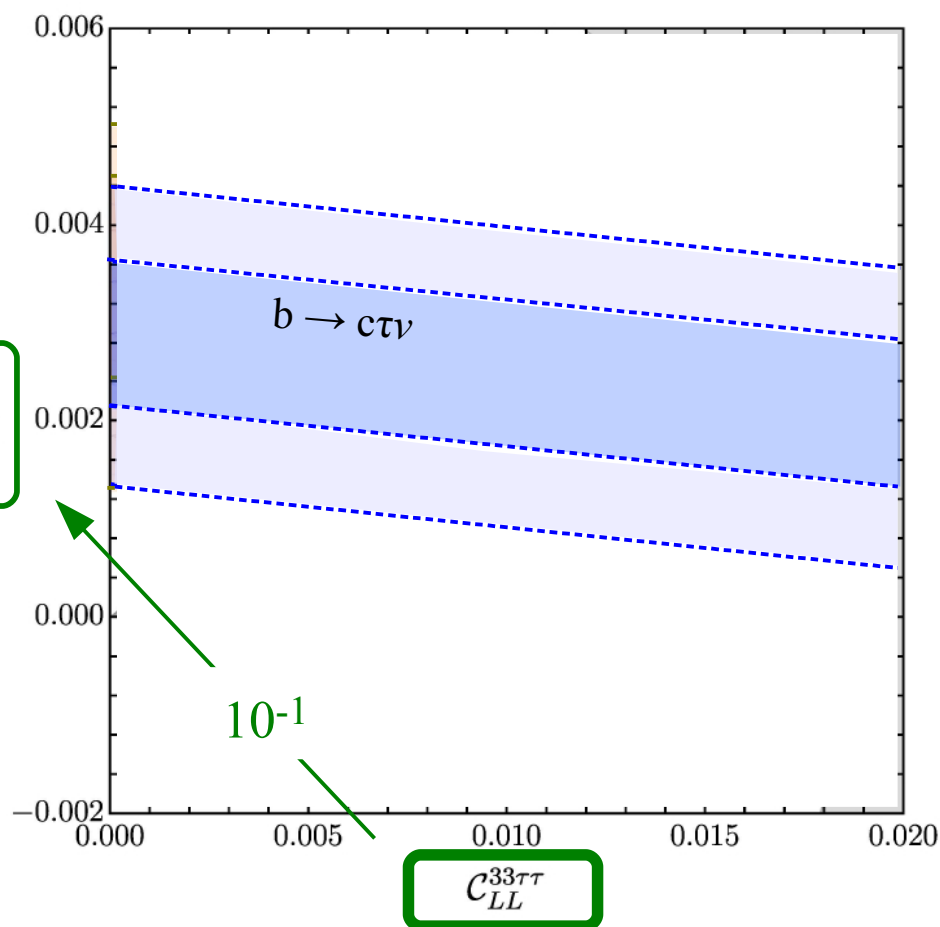


$$C_{ij\alpha\beta} = \begin{array}{l} \text{large for} \\ 3^{\text{rd}} \text{ generation} \\ \text{fields} \end{array} + \begin{array}{l} \text{small terms} \\ \text{for } 2^{\text{nd}} \text{ (\& } 1^{\text{st}}) \\ \text{generations} \end{array}$$



*Link to pattern  
of the Yukawa  
couplings !*

► EFT considerations



*charged-currents only:*

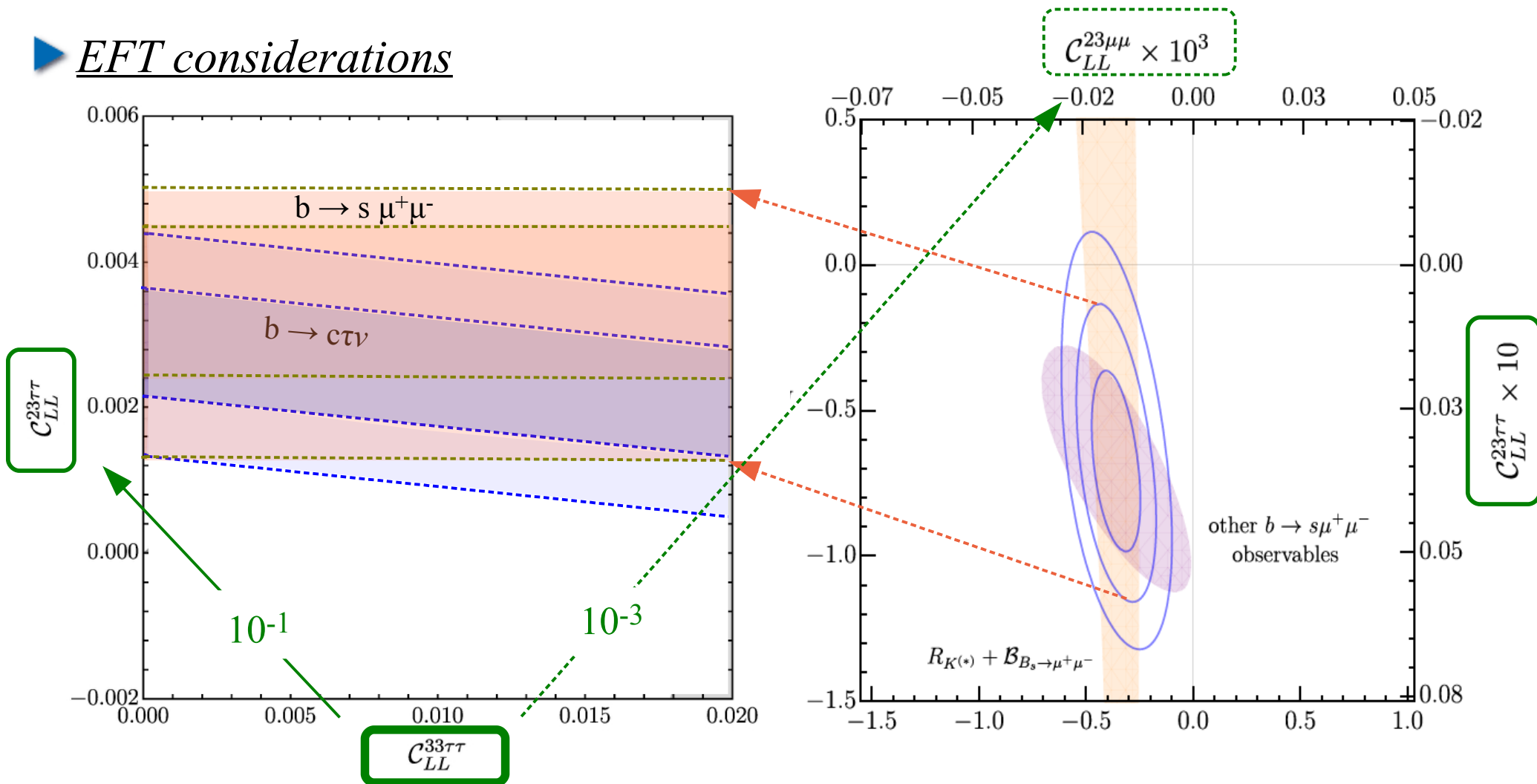
$$\frac{V_{cb} C_{LL}^{33\tau\tau} + V_{cs} C_{LL}^{23\tau\tau}}{V_{cb}}$$

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 2<sup>nd</sup> gen.  $q_L$  or  $l_L$  [ recall  $|V_{ts}| \sim 0.4 \times 10^{-1}$  ]

► EFT considerations



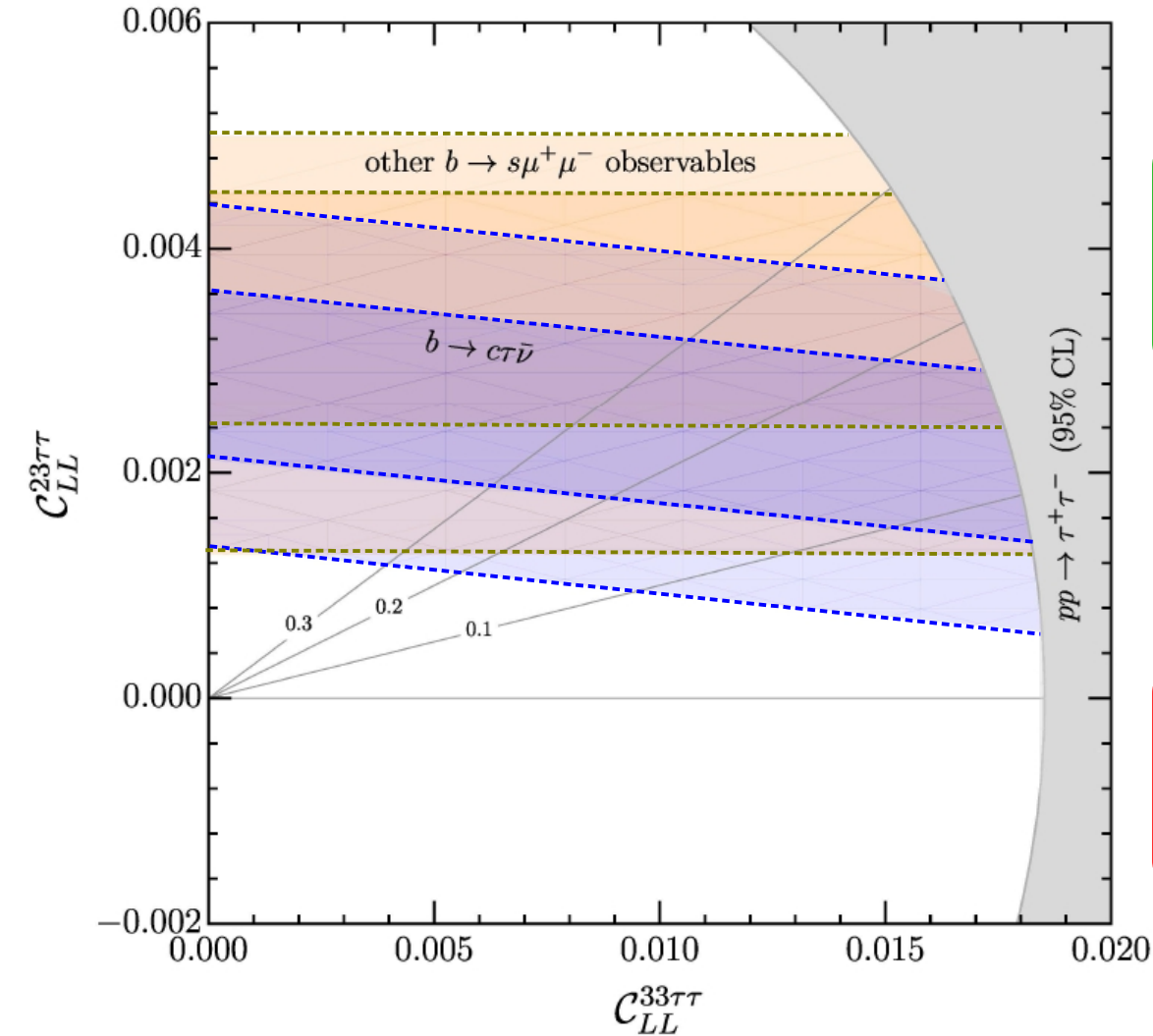
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- ✓ Nice consistency among the 2 sets of anomalies

► EFT considerations

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



Pattern emerging from data:

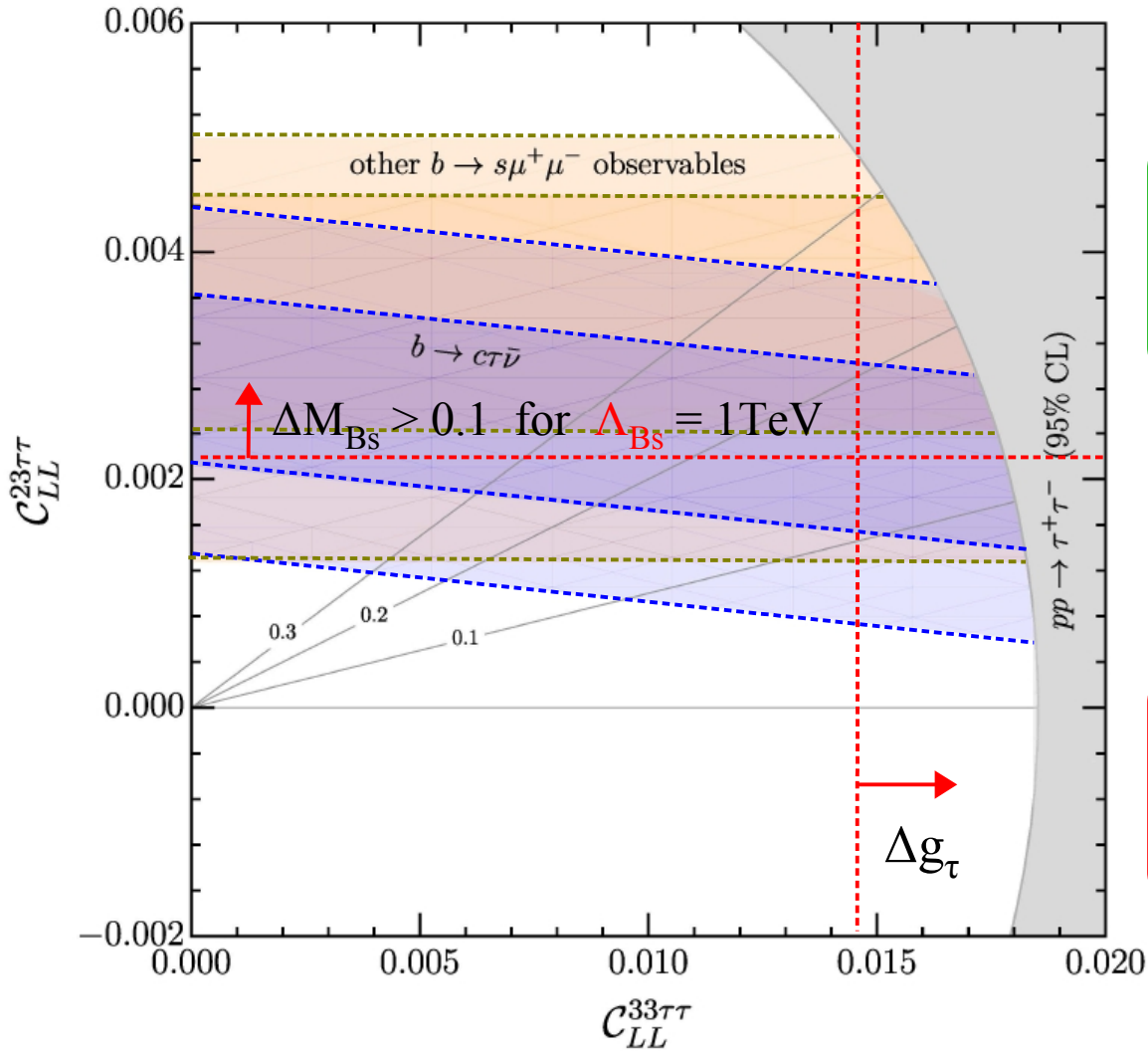
- ✓  $O(10^{-1})$  for each 2<sup>nd</sup> gen.  $q_L$  or  $l_L$
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What we do not see (*seem to call for an additional  $\sim$  loop suppression*):

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

► EFT considerations

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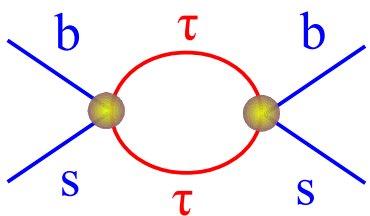


Pattern emerging from data:

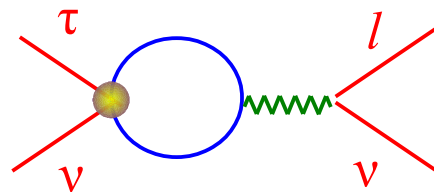
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$$\Delta M_{B_s} \sim (C^{23\tau\tau})^2 \Lambda_{B_s}^2$$



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

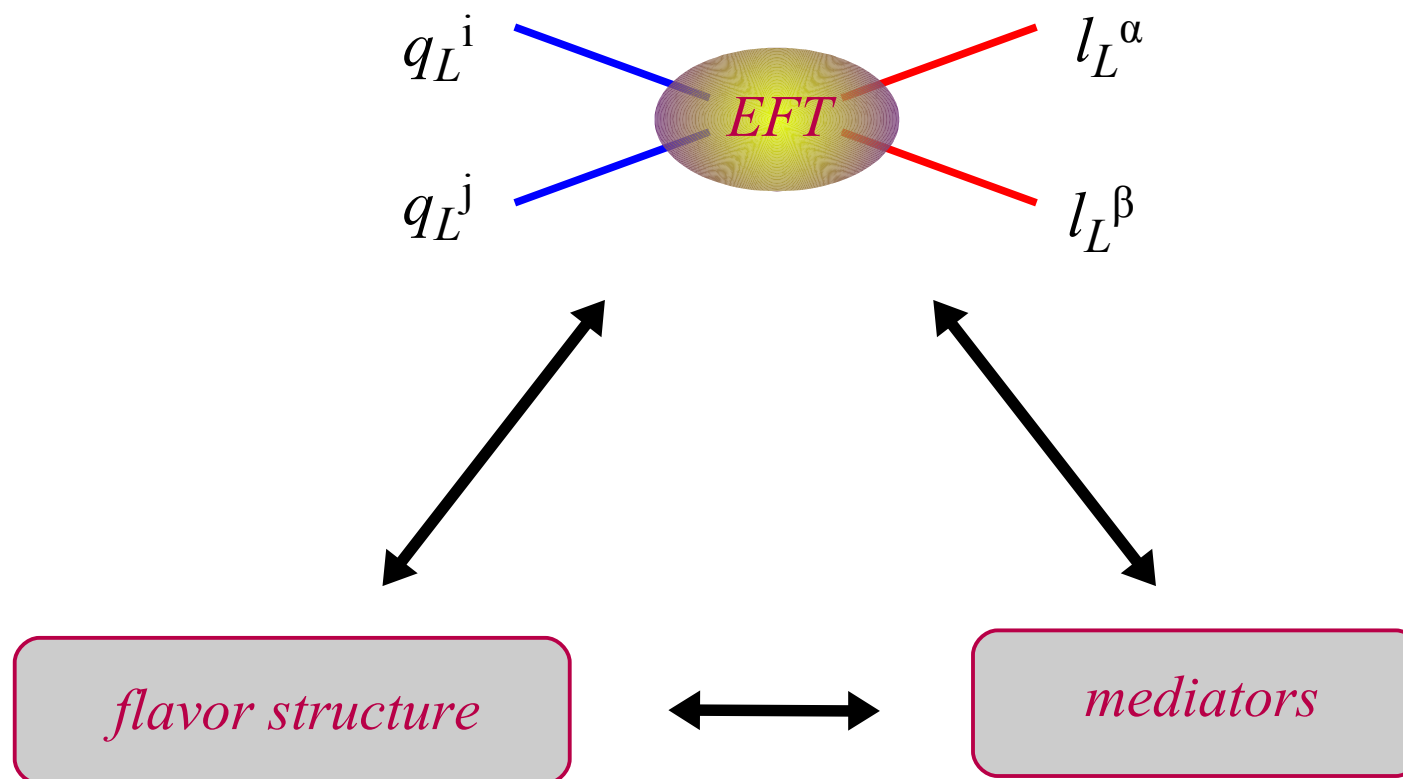


## From EFT to simplified models



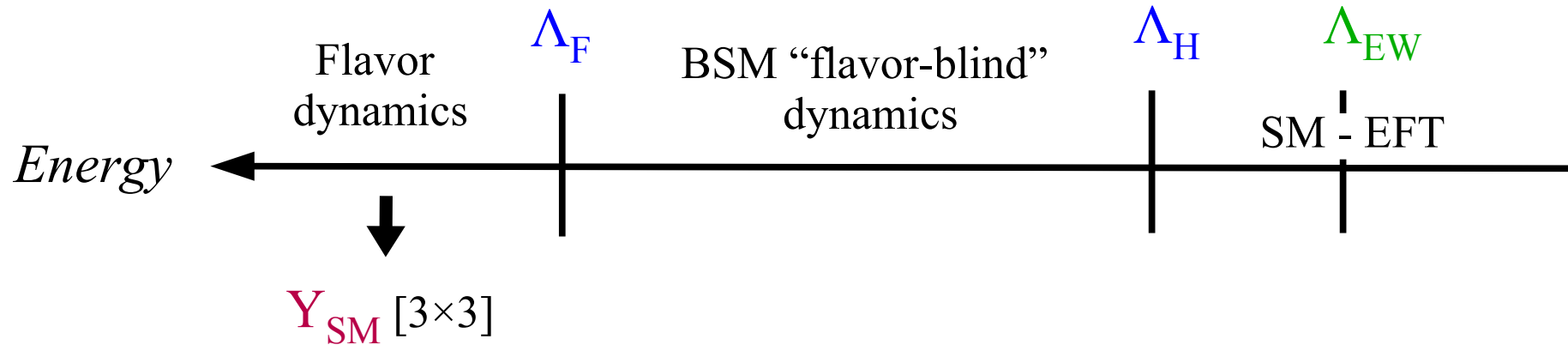
► *From EFT to simplified models*

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*



► From EFT to simplified models [the flavor structure]

*The MFV paradigm:*



*Main idea:*

- Concentrate on the **Higgs hierarchy problem**
- Postpone (*ignore*) **the flavor problem**

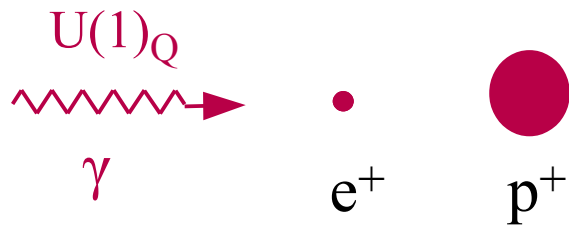


3 gen. = "identical copies"  
up to high energies

► From EFT to simplified models [the flavor structure]

To better appreciate the change of perspective we need: let's consider the following analogy:

*Suppose we could test matter only with long wave-length photons:*

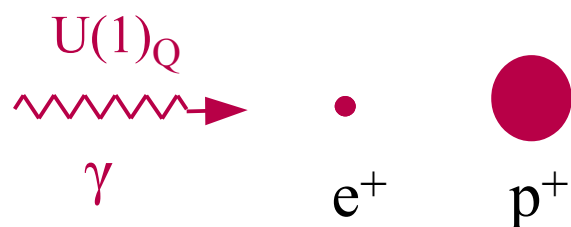


we would conclude that these two particles are “identical copies” but for their mass ...

► From EFT to simplified models [the flavor structure]

To better appreciate the change of perspective we need: let's consider the following analogy:

*Suppose we could test matter only with long wave-length photons:*



we would conclude that these two particles are “identical copies” but for their mass ...

This is exactly the same (*potentially misleading*) argument we use to infer flavor universality in the SM...



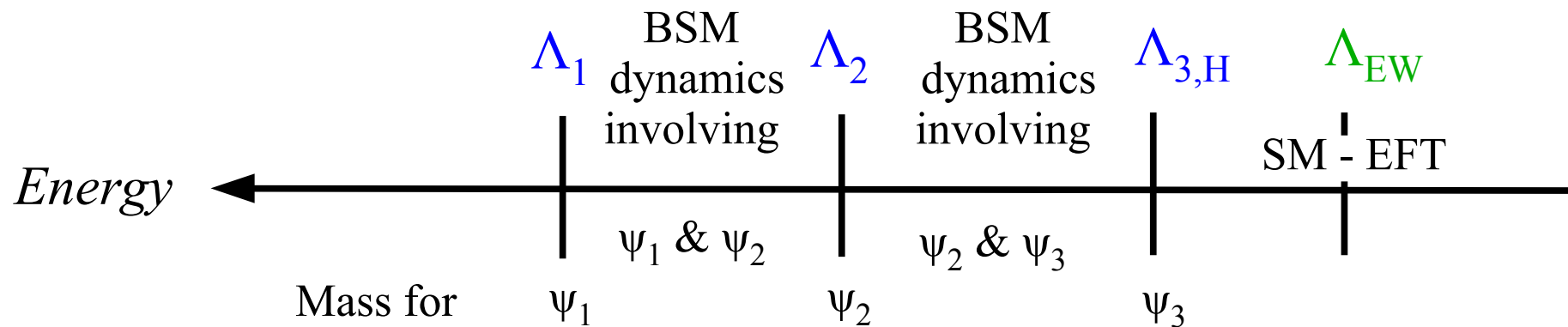
These three (families) of particles seems to be “identical copies” but for their mass ...

The SM quantum numbers of the three families could be an “accidental” low-energy property: the different families may well have a very different behavior at high energies, as signaled by their different mass

► From EFT to simplified models [the flavor structure]

~~The MEV paradigm:~~

*Multi-scale picture @ origin of flavor:*



*Main idea:*

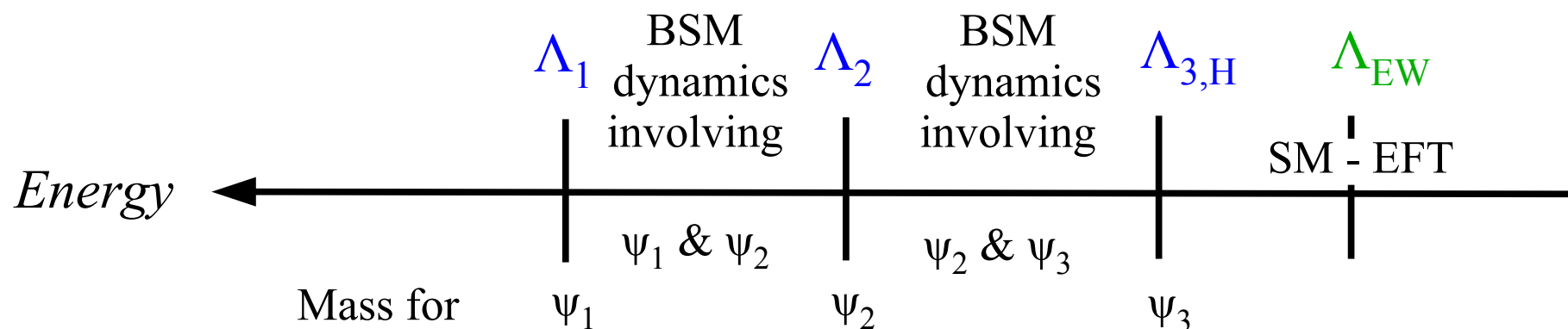
- Flavor **non-universal interactions** already at the **TeV scale**:
- **1<sup>st</sup> & 2<sup>nd</sup> gen.** have small masses because they are coupled to **NP at heavier scales**

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

► From EFT to simplified models [the flavor structure]

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Multi-scale picture @ origin of flavor:



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

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

Non-trivial UV imprints

► From EFT to simplified models [the flavor structure]

From the EFT point of view, the generic consequence of the multi-scale construction I advocate is that the nearby dynamics ( $E \sim \Lambda_3$ ) is characterized by an approximate (*accidental*)  $U(2)^n$  flavor symmetry:

$$\begin{array}{c} \Psi \\ \uparrow \\ \text{SM fermion (e.g. } q_L) \end{array} = \begin{array}{c} \left[ \begin{array}{c} \Psi_1 \\ \Psi_2 \\ \dots \\ \Psi_3 \end{array} \right] \end{array} \begin{array}{l} \leftarrow \text{light generations (flavor doublet)} \\ \leftarrow 3^{\text{rd}} \text{ generation (flavor singlet)} \end{array}$$

with suitable (small) symmetry-breaking terms, related to the SM Yukawa couplings  
[ $3_L \rightarrow 2_L$  controlled by  $\varepsilon \sim |V_{ts}| \sim 10^{-1}$ ]

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

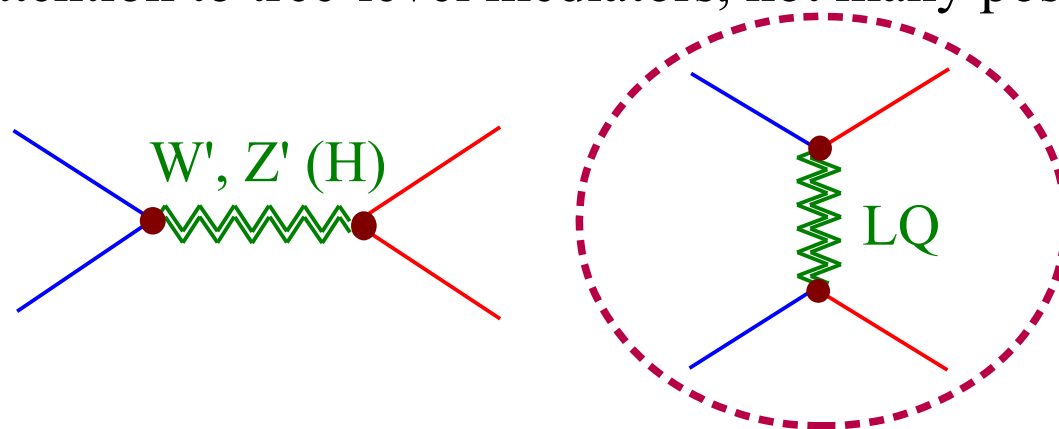
$$Y_U \sim \left( \begin{array}{c|c} O(\varepsilon^2) & \varepsilon \uparrow \\ \hline & \boxed{y_t \approx 1} \end{array} \right)$$

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



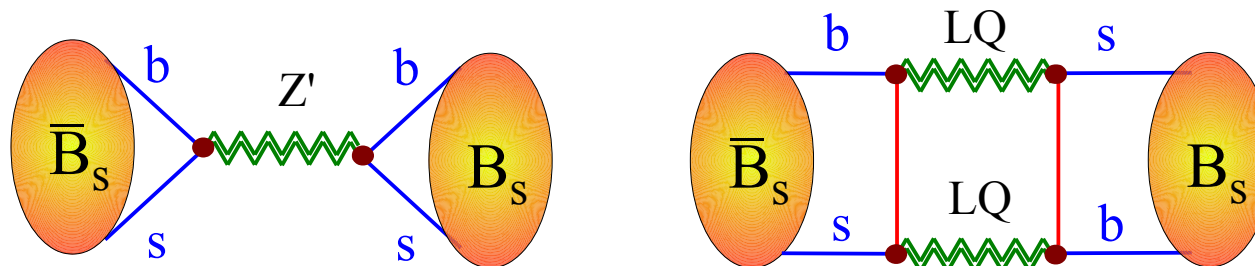
► From EFT to simplified models [the possible mediators]

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.  $\Delta F=2$  &  
 $\tau \rightarrow l\nu\nu$



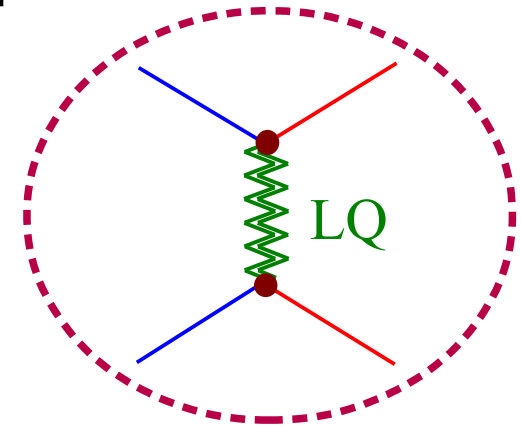
II. Direct searches:

3<sup>rd</sup> gen. LQ are also in better shape as far as direct searches are concerned (*contrary to Z'...*).

► From EFT to simplified models [the possible mediators]

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

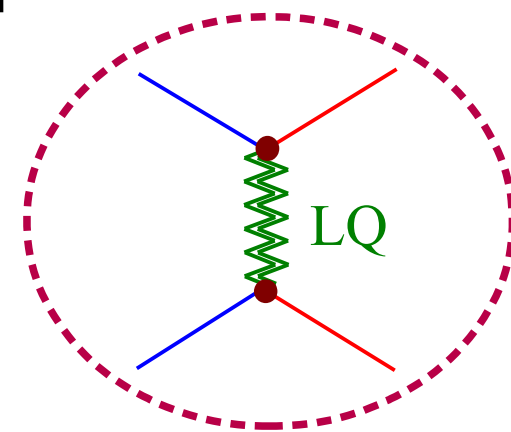
- Could mediate proton decay → **not a general feature of the LQ: it depends on the model...!**  
[*e.g. not the case in the Pati-Salam model*]
- Severe bounds from processes involving  $\mu$  &  $e$  (such as  $K_L \rightarrow \mu e$ )  
→ **avoided with non-trivial flavor structure** [*e.g. non-univ. interactions*]



► From EFT to simplified models [the possible mediators]

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



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

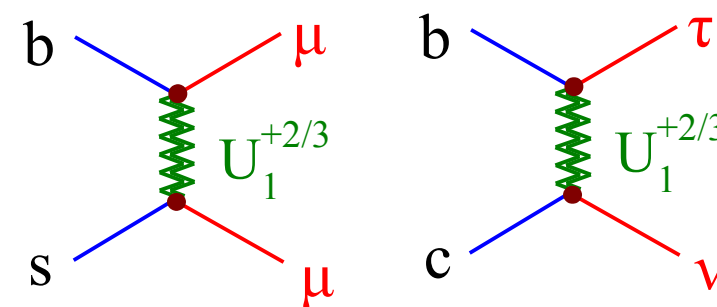
- |  |  |   |
|--|--|---|
| <ul style="list-style-type: none"> <li>• <b>Scalar LQ as PNG</b><br/>Gripaios, '10<br/>Gripaios, Nardecchia, Renner, '14<br/>Marzocca '18</li> </ul>   | <ul style="list-style-type: none"> <li>• <b>Scalar LQ from GUTs &amp; <math>\mathcal{R}</math> SUSY</b><br/>Hiller &amp; Schmaltz, '14; Becirevic <i>et al.</i> '16,<br/>Fajfer <i>et al.</i> '15-'17; Dorsner <i>et al.</i> '17;<br/>Crivellin <i>et al.</i> '17; Altmannshofer <i>et al.</i> '17<br/>Trifinopoulos '18, Becirevic <i>et al.</i> '18 + ...</li> </ul> | <ul style="list-style-type: none"> <li>• <b>Vector LQ in GUT gauge models</b><br/><br/>Assad <i>et al.</i> '17<br/>Di Luzio <i>et al.</i> '17<br/>Bordone <i>et al.</i> '17<br/>Heeck &amp; Teresi '18<br/>+ ...</li> </ul> |
| <ul style="list-style-type: none"> <li>• <b>Vector LQ as techni-fermion resonances</b><br/>Barbieri <i>et al.</i> '15; Buttazzo <i>et al.</i> '16,<br/>Barbieri, Murphy, Senia, '17 + ...</li> </ul> | <ul style="list-style-type: none"> <li>• <b>LQ as Kaluza-Klein excit.</b><br/>Megias, Quiros, Salas '17<br/>Megias, Panico, Pujolas, Quiros '17<br/>Blanke, Crivellin, '18 + ...</li> </ul>  |   |

► From EFT to simplified models [the possible mediators]

*Which LQ explains which anomaly?*

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

Angelescu, Becirevic, DAF, Sumensari [1808.08179]



LQ of the Pati-Salam gauge group:

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

Barbieri, GI, Patteri, Senia '15

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

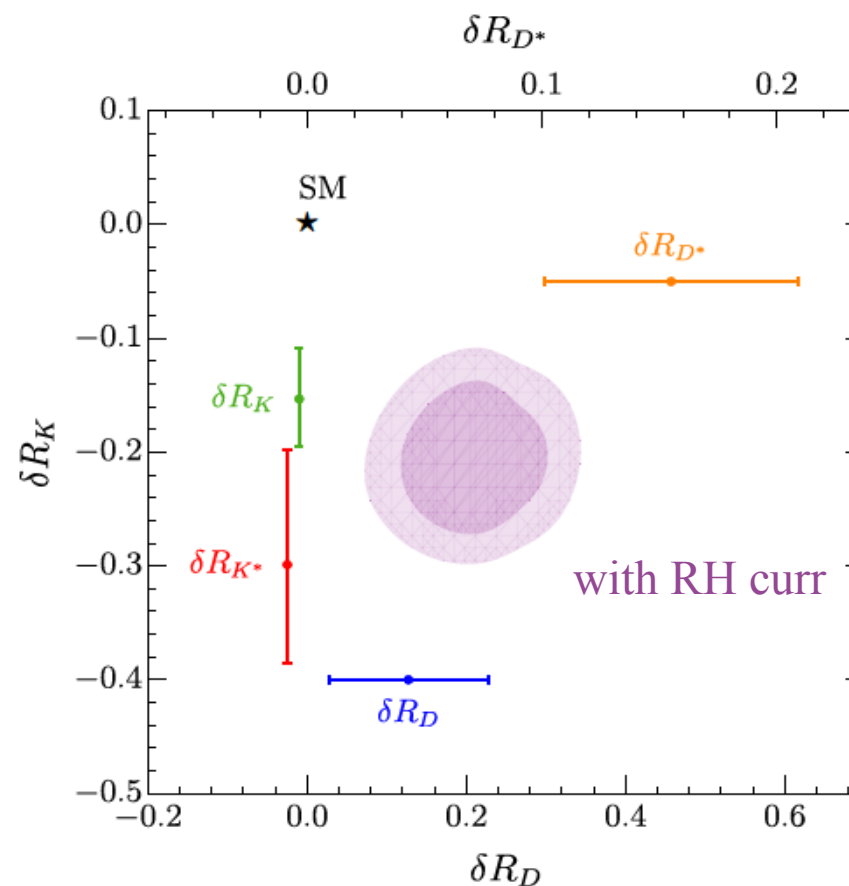
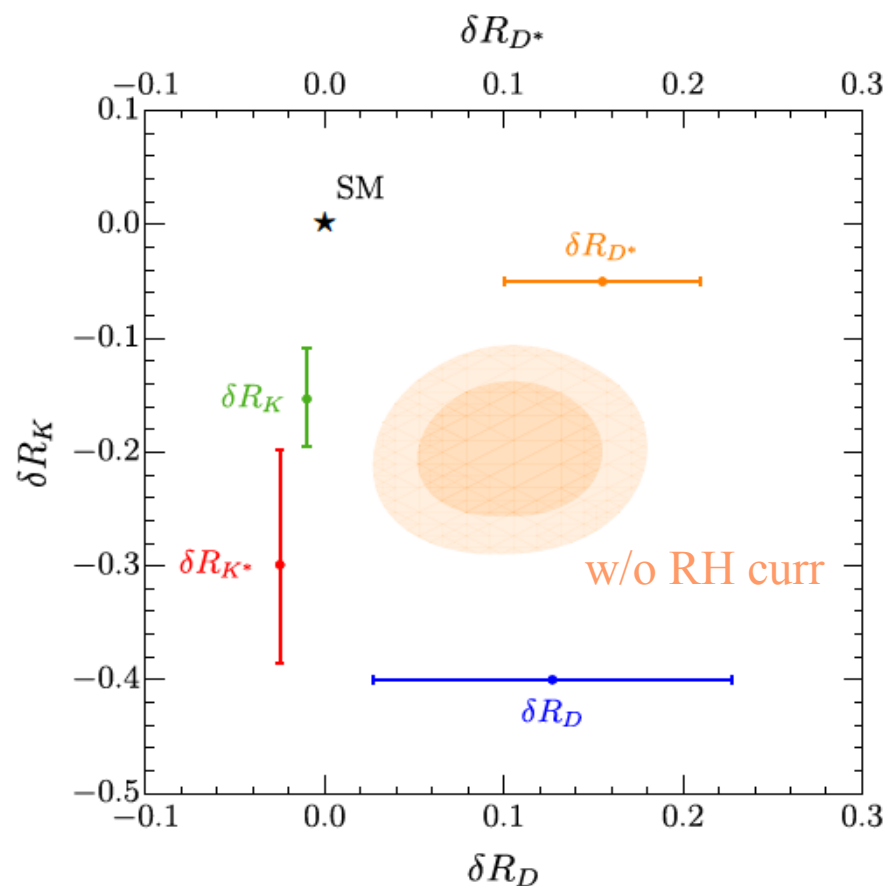
( approx. flavor symmetry ensuring a CKM-like mixing  $3^{\text{rd}} \rightarrow 1^{\text{st}}, 2^{\text{nd}}$  gen. )

► From EFT to simplified models [the possible mediators]

Considering the  $U_1$  only

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

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

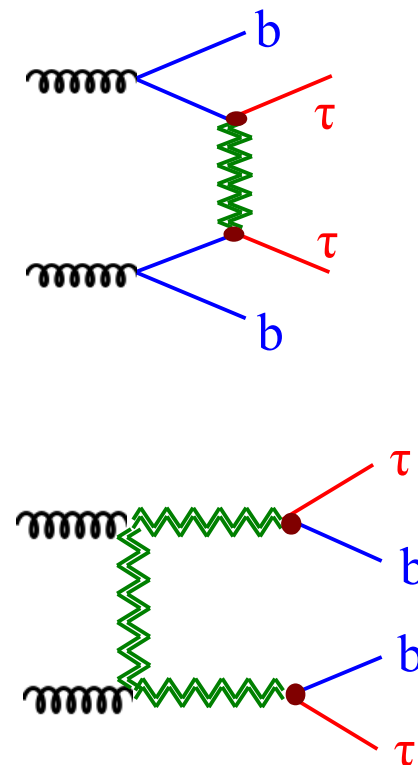
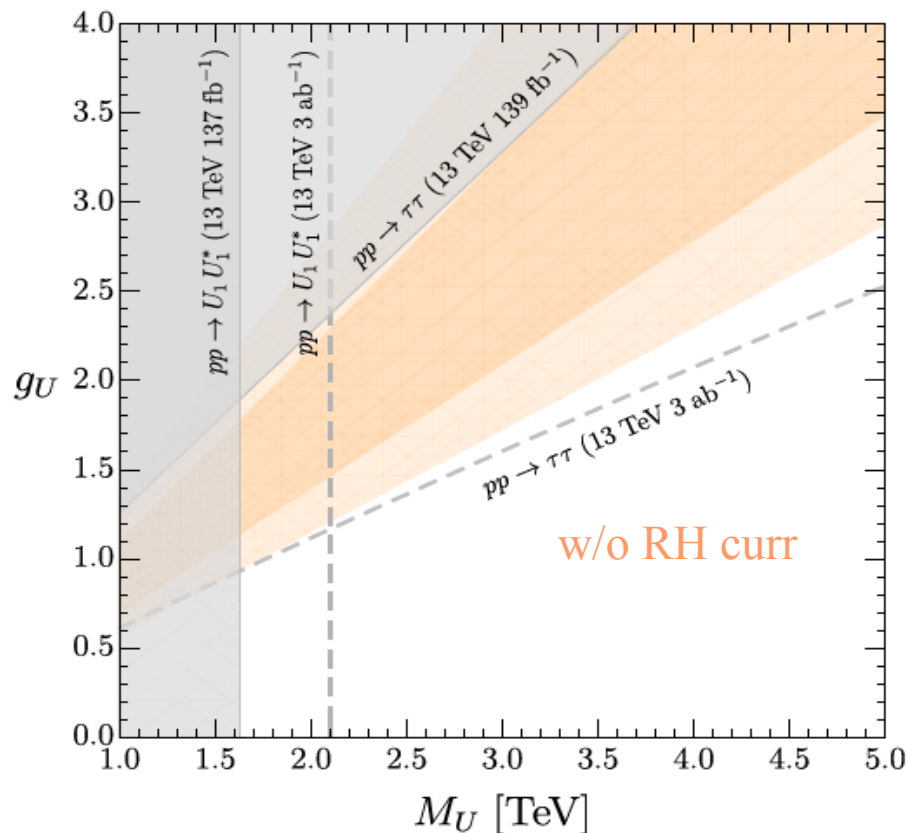


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and fitting all low-energy data leads to an excellent description of present data which is fully consistent with high-pT searches [*within the reach of HL-LHC*]:



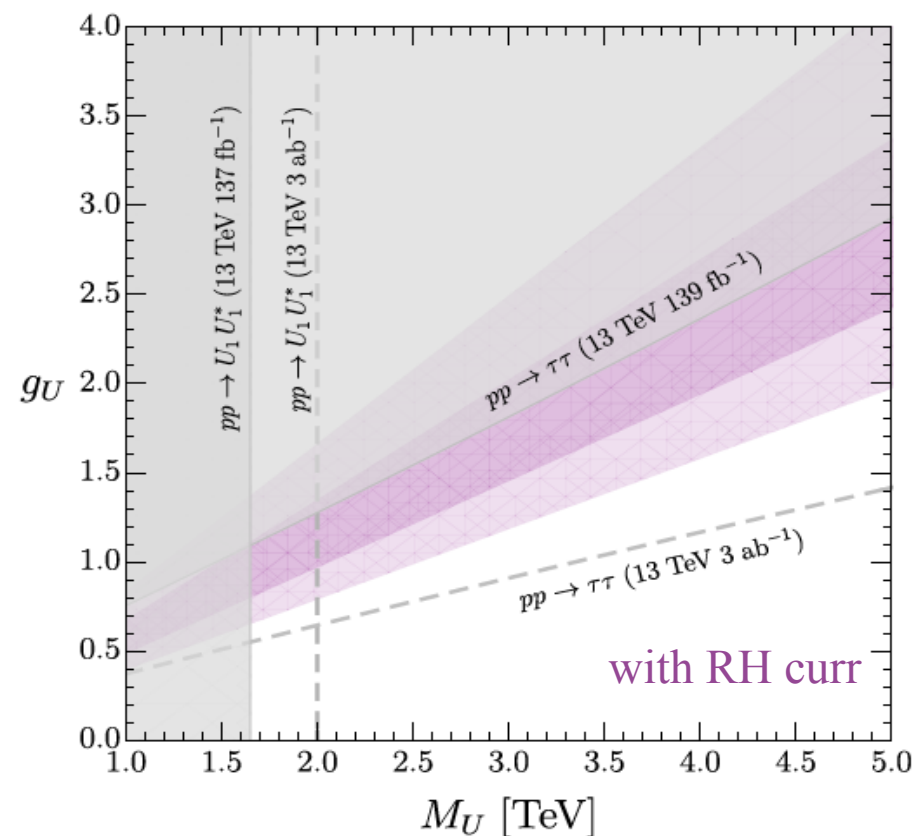
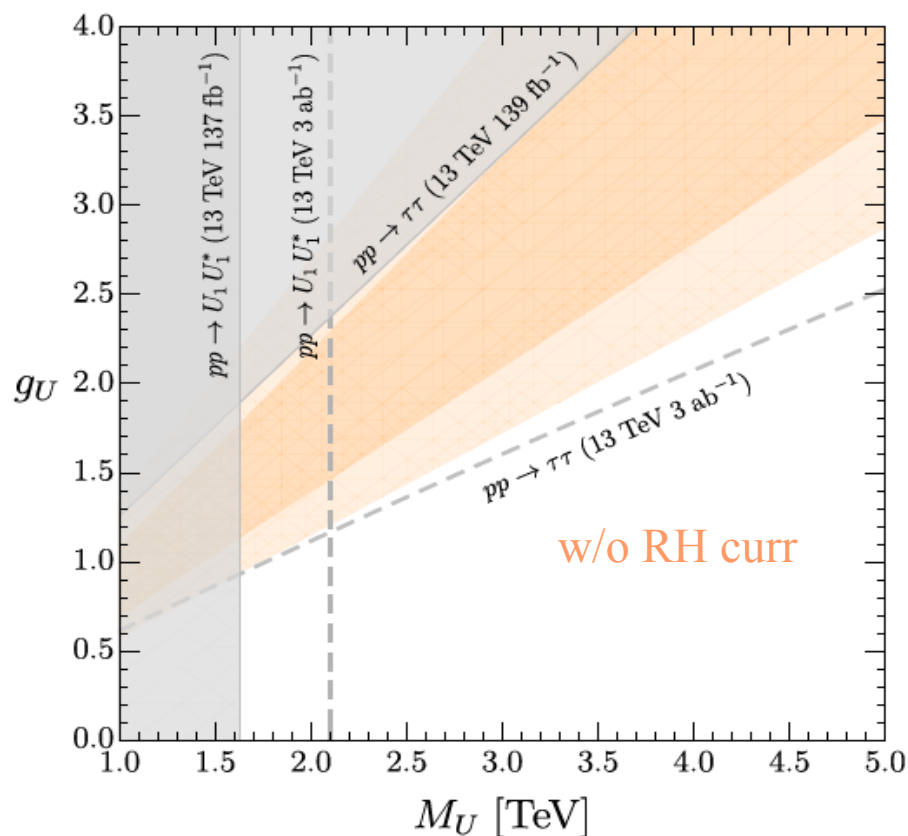
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Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21



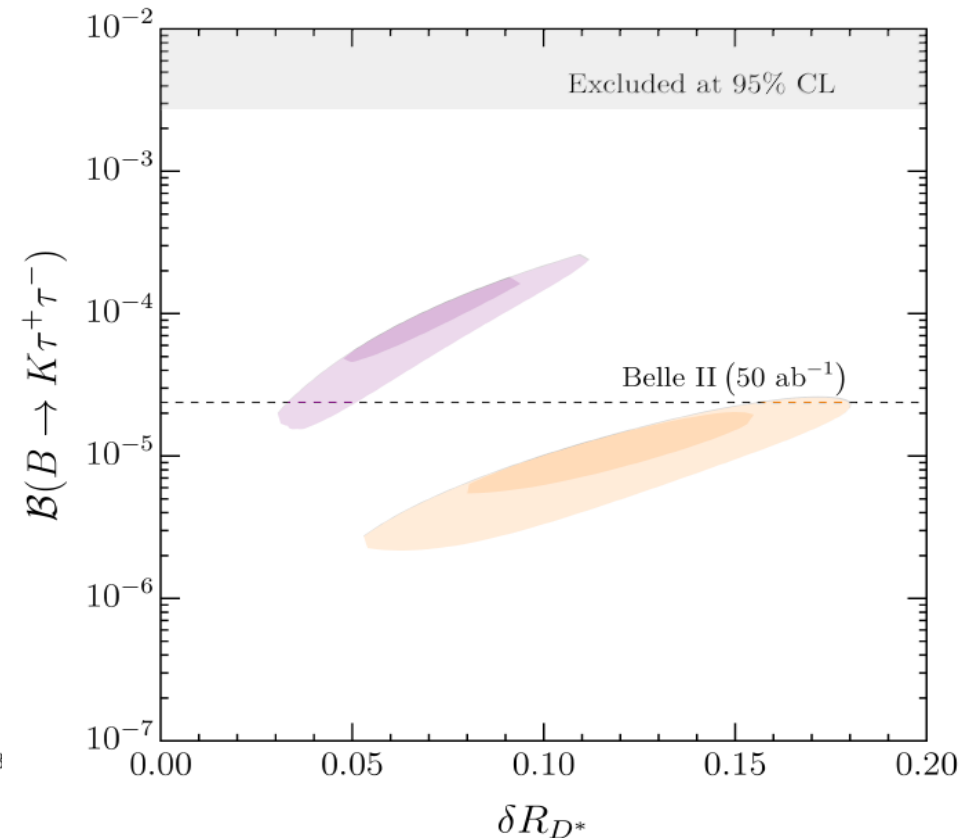
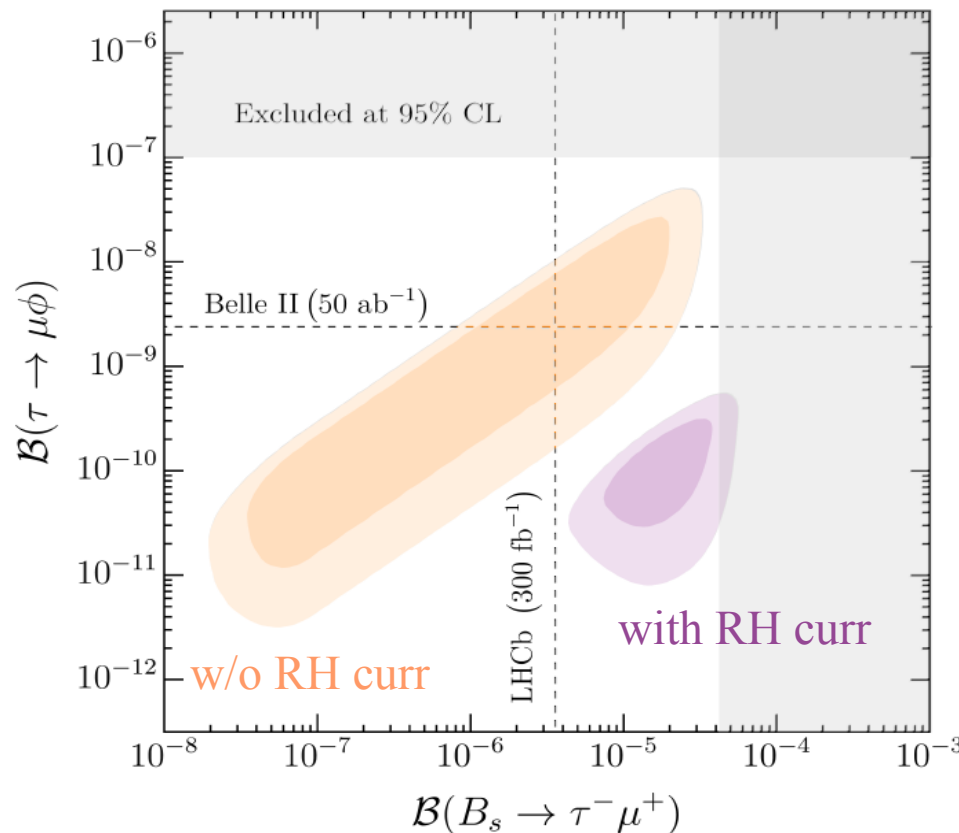
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Considering the  $U_1$  only

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

and fitting all low-energy data leads to an excellent description of present data which is fully consistent with high-pT searches, 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 4<sup>th</sup> color”

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

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

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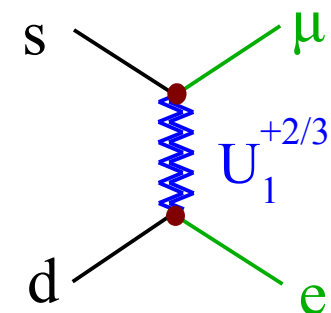
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The problem of the “original PS model” are the strong bounds on the LQ couplings to 1<sup>st</sup> & 2<sup>nd</sup> generations [e.g.  $M > 200 \text{ TeV}$  from  $K_L \rightarrow \mu e$ ]

*Attempts to solve this problem simply adding extra fermions or scalars*

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

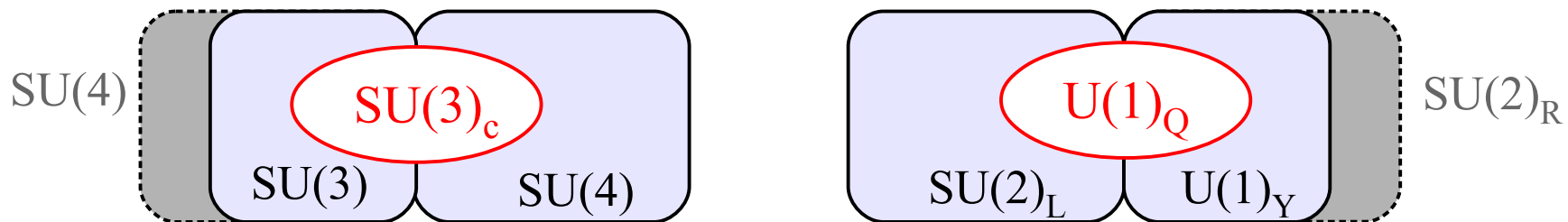


► Speculations on UV completions

**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*

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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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*

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

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

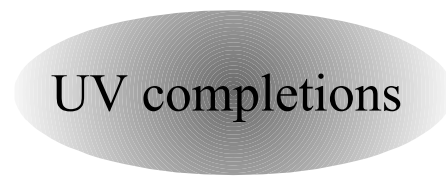
• *Accidental  $U(2)^5$  flavor symm. in the gauge sect.*

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

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

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

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

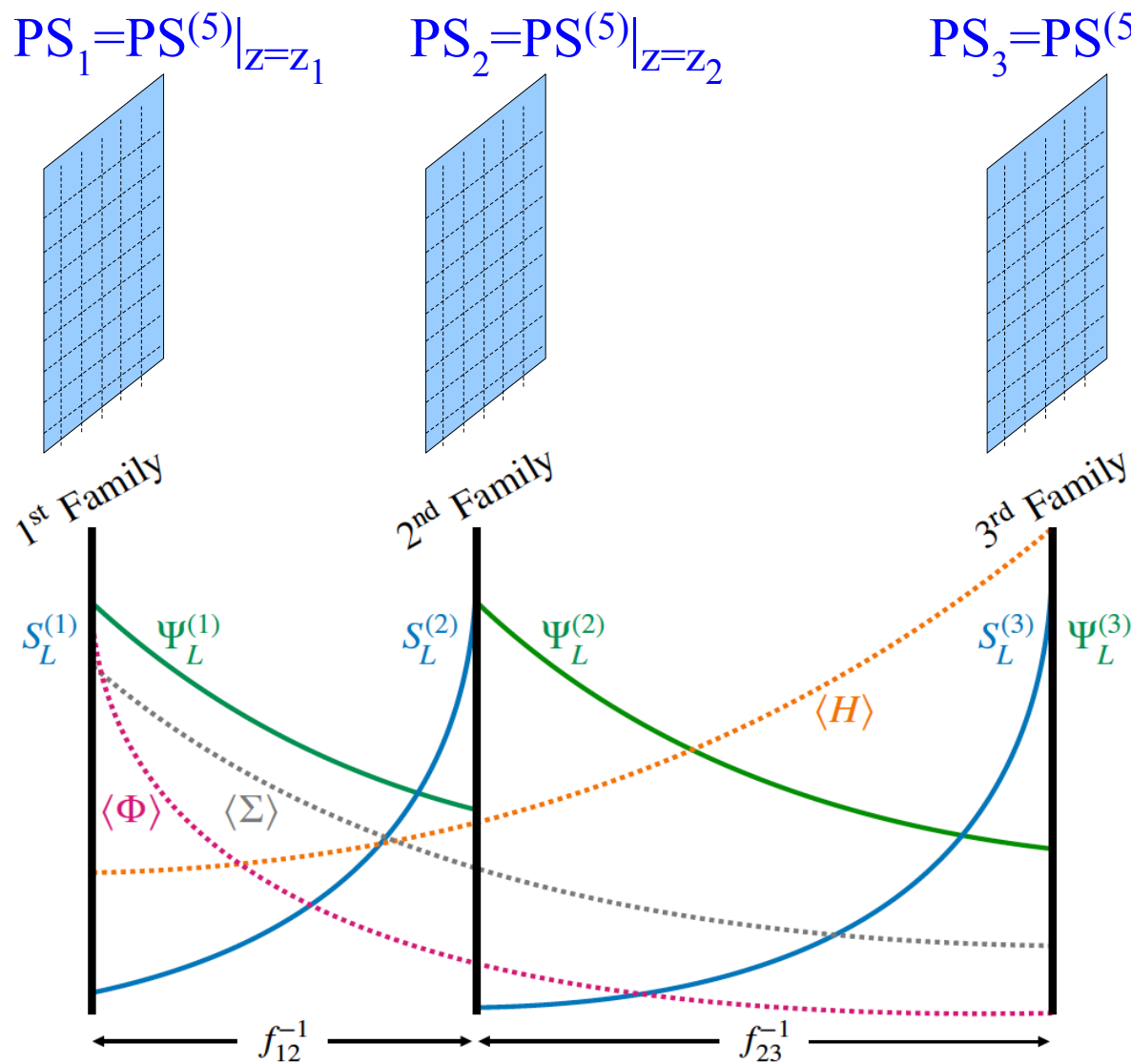


$[PS]_{\text{warped-5d, 3-branes}}$

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  $\leftrightarrow$  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

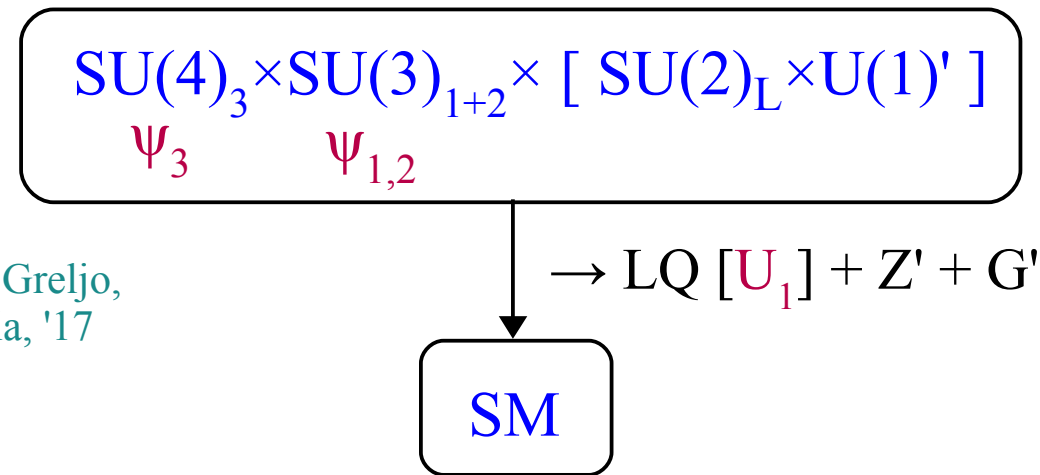
Bordone, Cornella, Fuentes-Martin, GI '17  
 Fuentes-Martin, GI, Pages, Stefanek '20

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

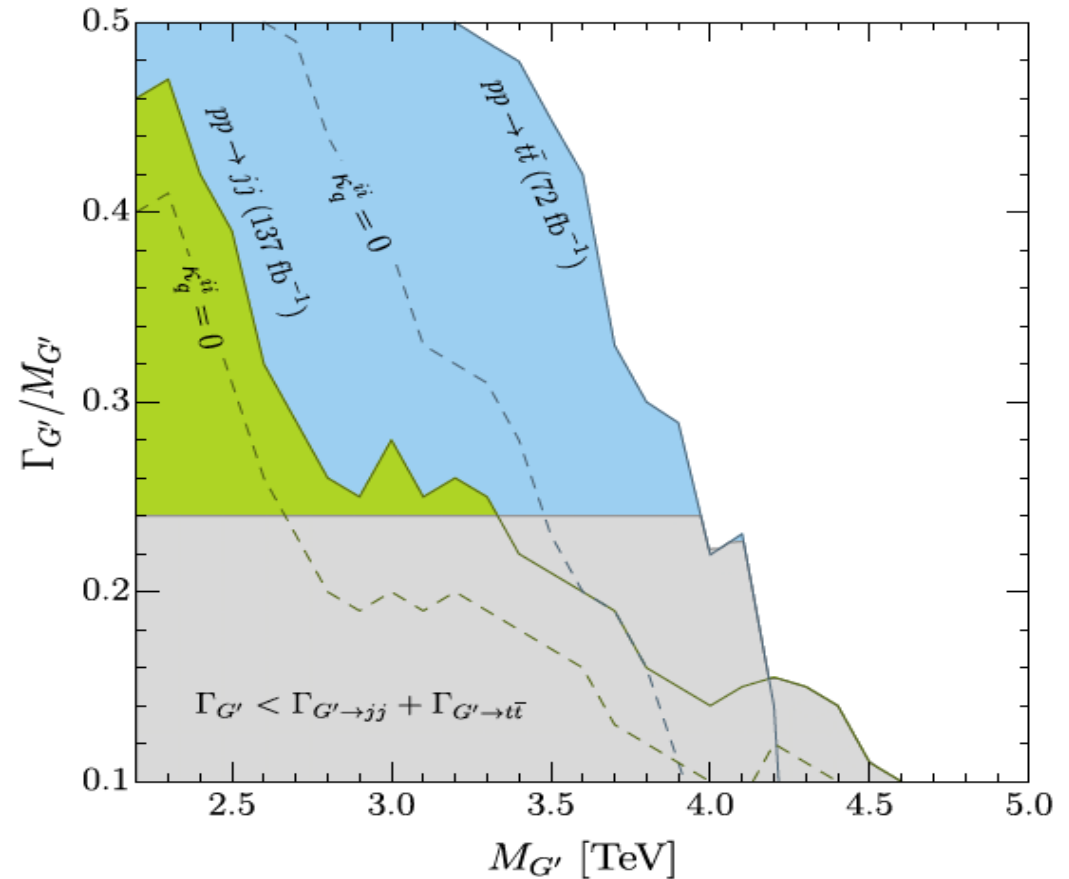


Despite the apparent complexity, the construction is highly constrained

- Positive features the EFT reproduced
  - Calculability of  $\Delta F=2$  processes
  - Precise predictions for **high-pT data**
- } *consistent with present data!*

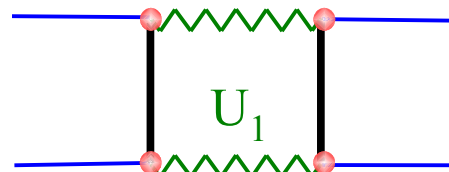
New striking collider signature:  $G'$  (“*coloron*” = *heavy color octet*)

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

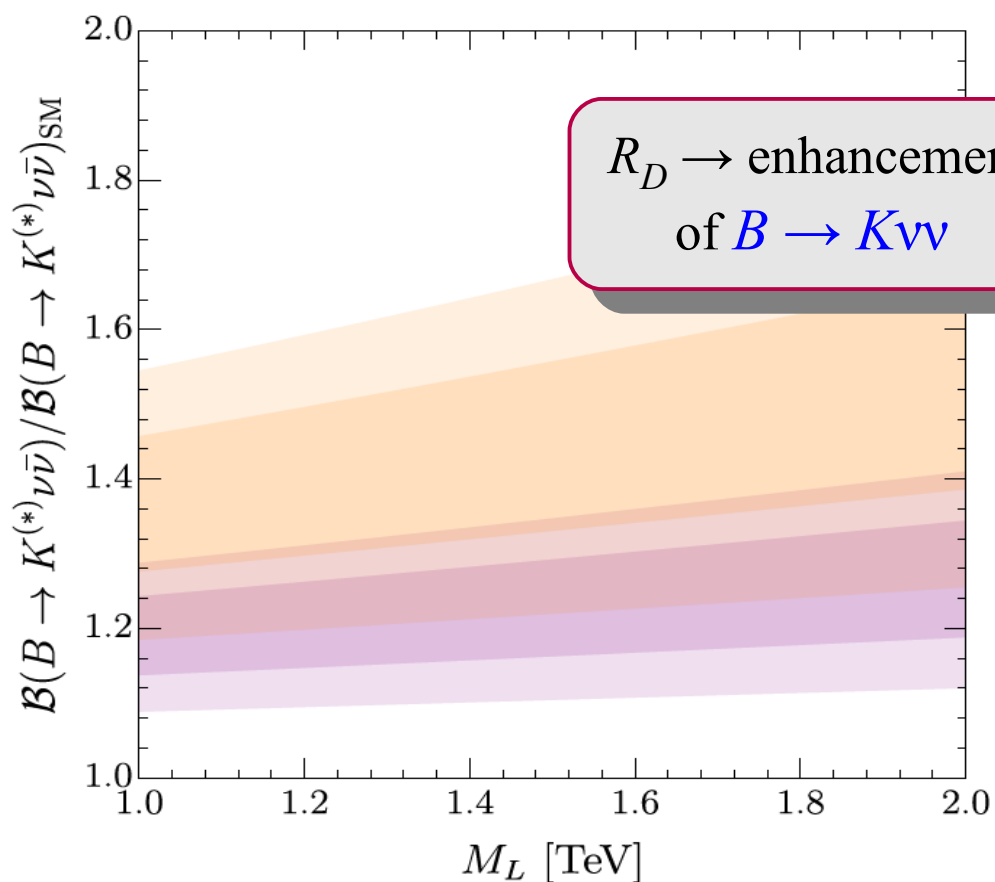


► Speculations on UV completions

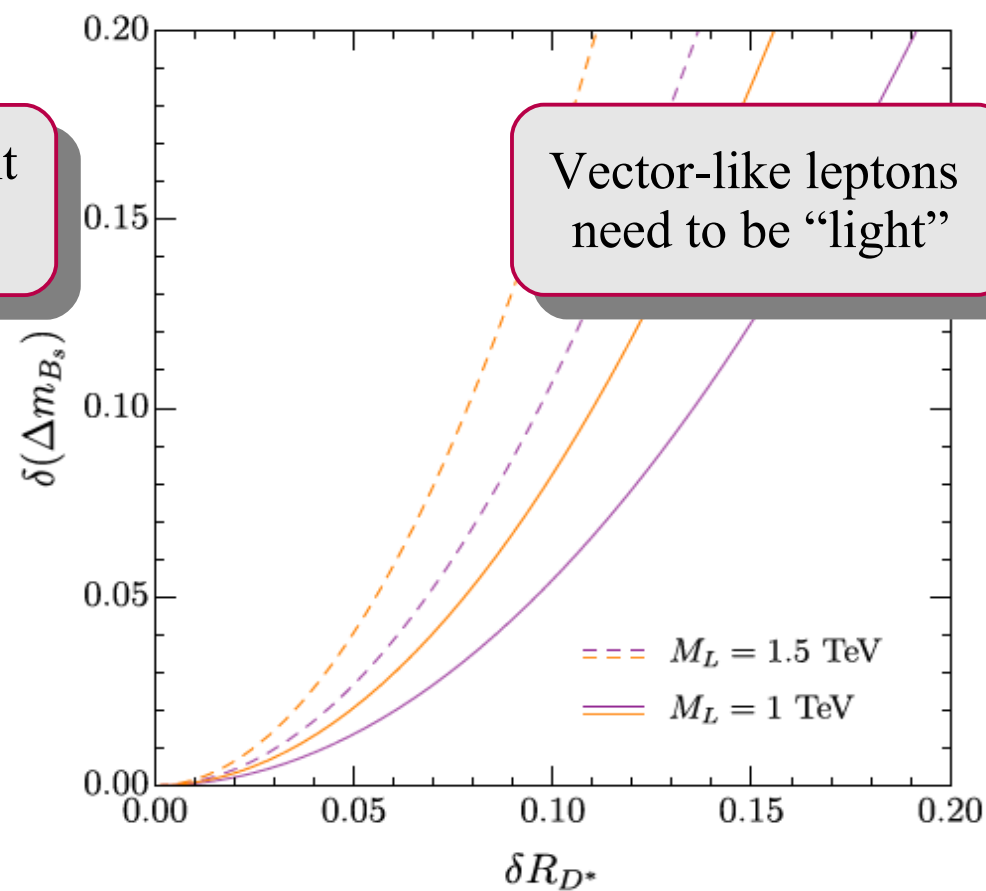
UV-sensitive observables in 4321 models



A)  $B \rightarrow K\nu\nu$



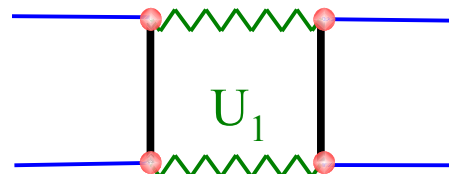
B)  $B_s$  mixing [ $\Delta F=2$ ]



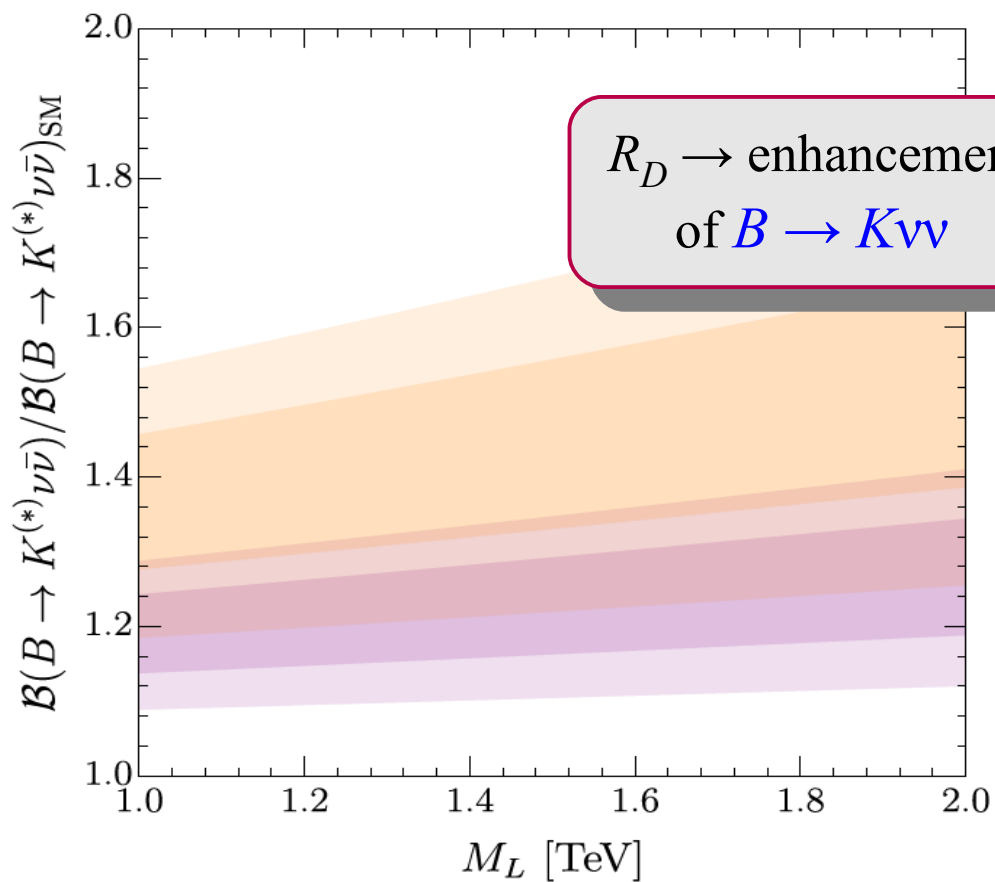


## ► Speculations on UV completions

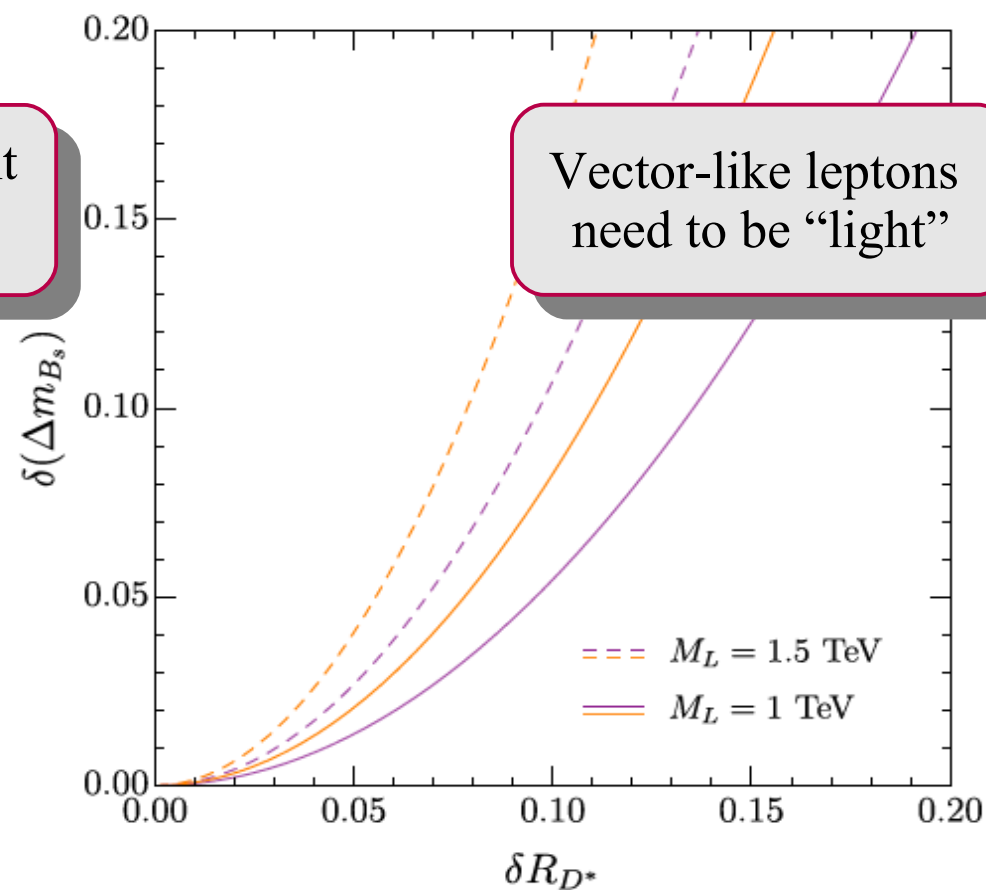
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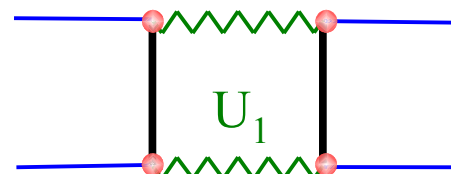


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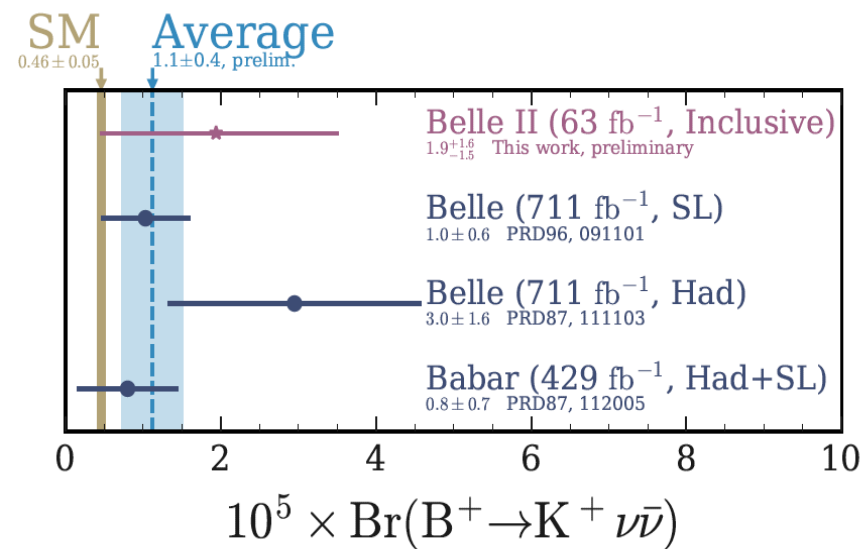
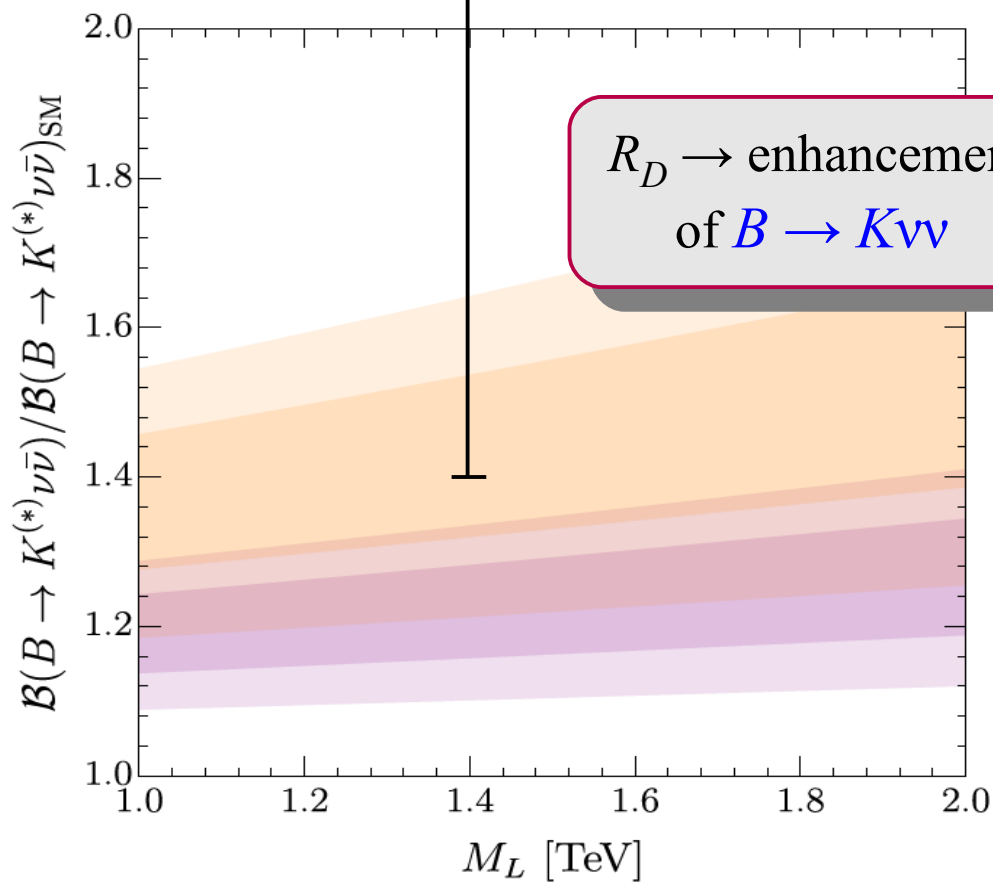


► Speculations on UV completions

UV-sensitive observables in 4321 models



A)  $B \rightarrow K\nu\nu$



## Conclusions

- The statistical significance of the **LFU anomalies is growing**: in the  $b \rightarrow sll$  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 3<sup>rd</sup> family  $\rightarrow$  **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)



► *A closer look to the data*

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

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

- Even concentrating only on the clean observables, or even only in the LFU ratios, there can be different correlations depending on the underlying NP → you must explore all possible NP directions → **L**ook **E**lsewhere **E**ffect (LEE)
- The choice of the operator basis is arbitrary: how can the significance depend on the basis choice?
- You cannot do cherry-picking in selecting the observables and only few exhibit deviations → small significance once you include them all



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

## ► A closer look to the data

The “ $n\sigma$ ” quoted by various th. groups (global fits) holds for specific NP hypotheses, motivated, but made *a posteriori* (after looking at the data) → *local significance*

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

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

Lancierini, GI,  
Owen, Serra, '21

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

## ► A closer look to the data

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3.9 $\sigma$

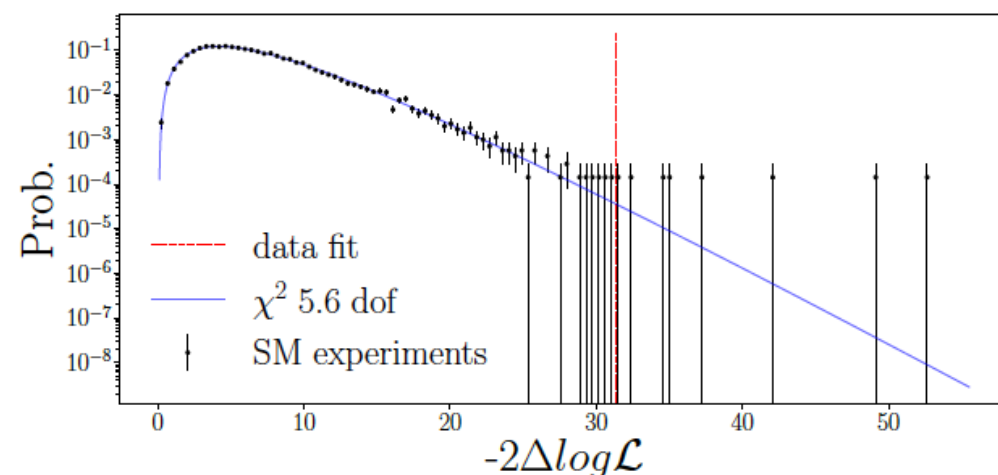
*global significance*

with respect to any form of heavy NP

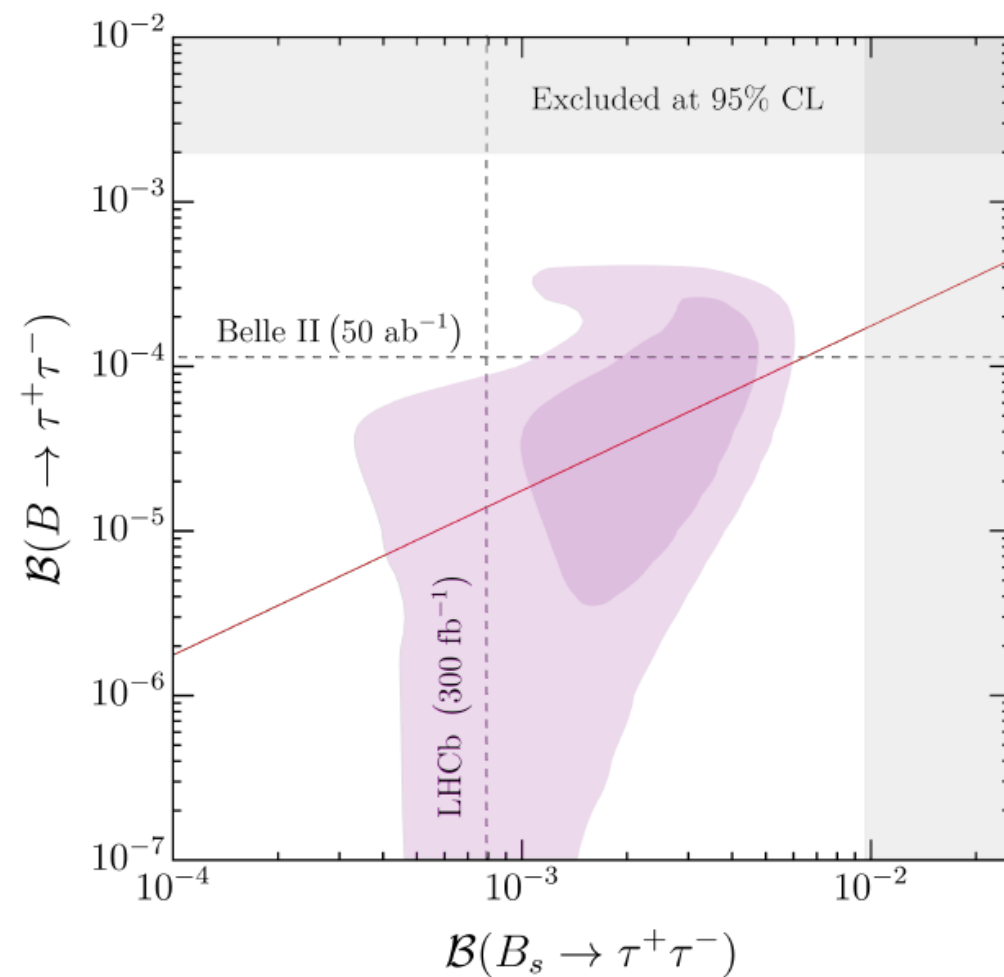
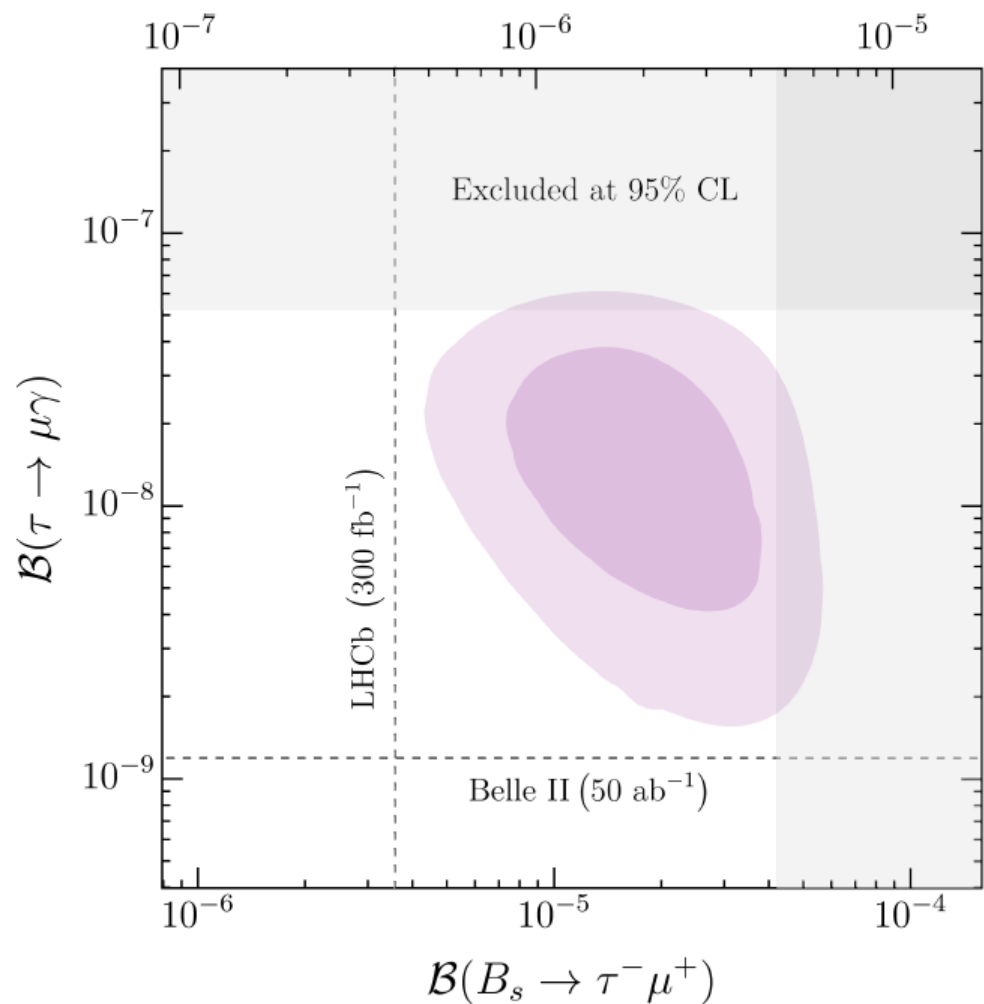
Lancierini, GI,  
Owen, Serra, '21

Remarkably high !

[despite being very conservative]



► Other low-energy observables

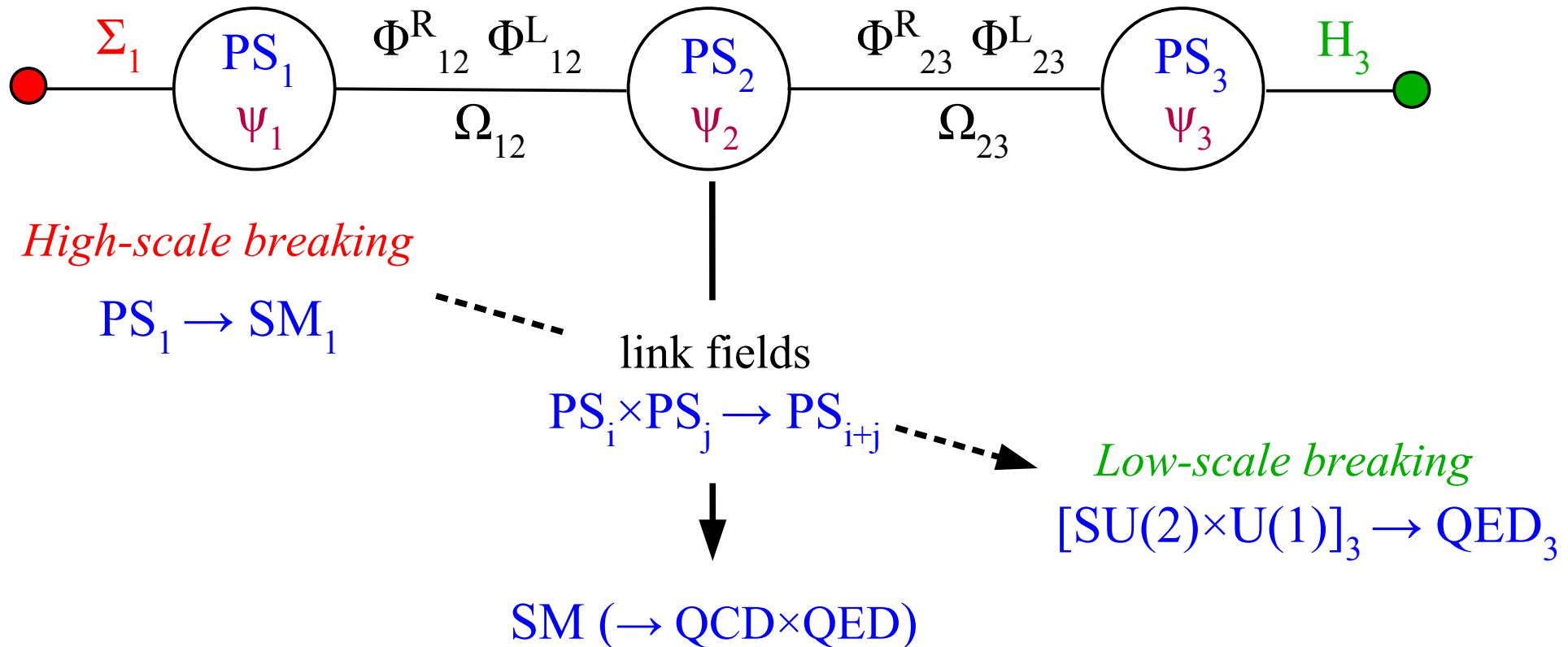




► Speculations on UV completions

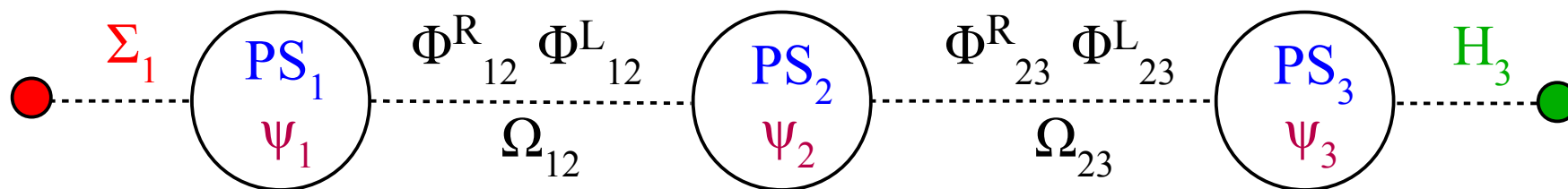
The  $PS^3$  set-up:

Bordone, Cornella, Fuentes-Martin, GI, '17

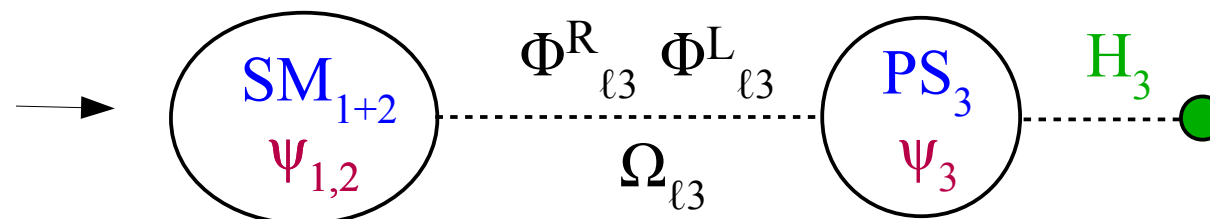


- ★ **Unification** of quarks and leptons [*natural explanation for  $U(1)_Y$  charges*]
- ★ **De-unification** (= *flavor deconstruction*) of the gauge symmetry
- ★ Breaking to the diagonal SM group occurs via appropriate “**link**” fields, responsible also for the **generation of the hierarchies in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

► Speculations on UV completions



Below  $\sim 100$  TeV  
Flavor-degeneracy  
of light quarks

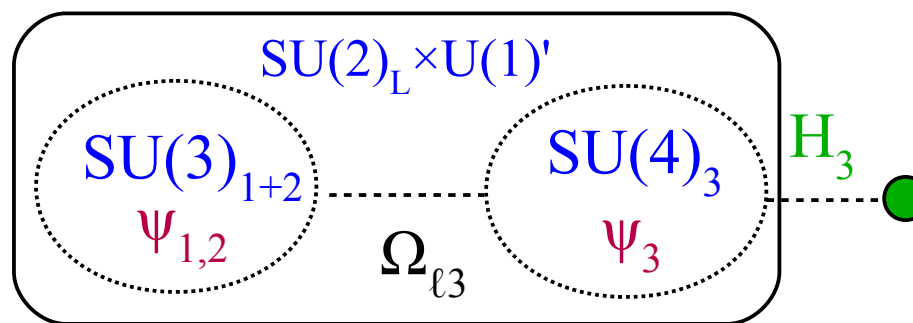


$\rightarrow W_L' + W_R'$  [ $\sim 5-10$  TeV]

*Sub-leading Yukawa terms  
from higher dim ops:*

$$Y_U = \begin{bmatrix} \Delta & V \\ \hline & y_t \end{bmatrix}$$

$$\frac{\langle \Phi_{\ell 3}^R \Phi_{\ell 3}^L \rangle}{(\Lambda_{23})^2} \qquad \frac{\langle \Omega_{\ell 3} \rangle}{\Lambda_{23}}$$



$\rightarrow LQ [U_1] + Z' + G'$  [ $\sim 2-3$  TeV]

