

Flavor Physics: Old problems and recent hopes

Gino Isidori

[*University of Zürich*]

- ▶ Introduction [*The flavor problem(s)*]
- ▶ The LFU anomalies
- ▶ EFT considerations on the anomalies
- ▶ Model-building considerations
- ▶ Speculations on UV completions
- ▶ Conclusions



University of
Zurich ^{UZH}

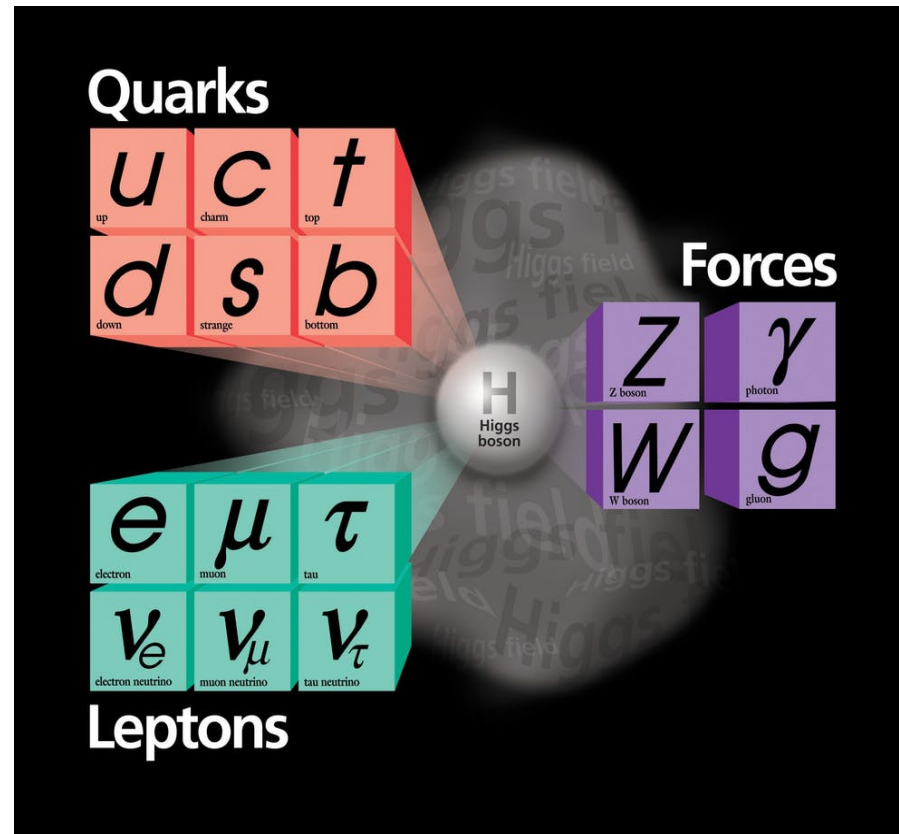


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► Introduction

(Almost...) all microscopic phenomena we observe in Nature seems to be well described by a remarkably simple Theory, the so-called “Standard Model” (**SM**) (that we continue to call “model” only for historical reasons...):

$$\mathcal{L}_{\text{Standard Model}} = \mathcal{L}_{\text{gauge}}(\Psi_i, A_a) + \mathcal{L}_{\text{Higgs}}(H, A_a, \Psi_i)$$



► Introduction

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



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

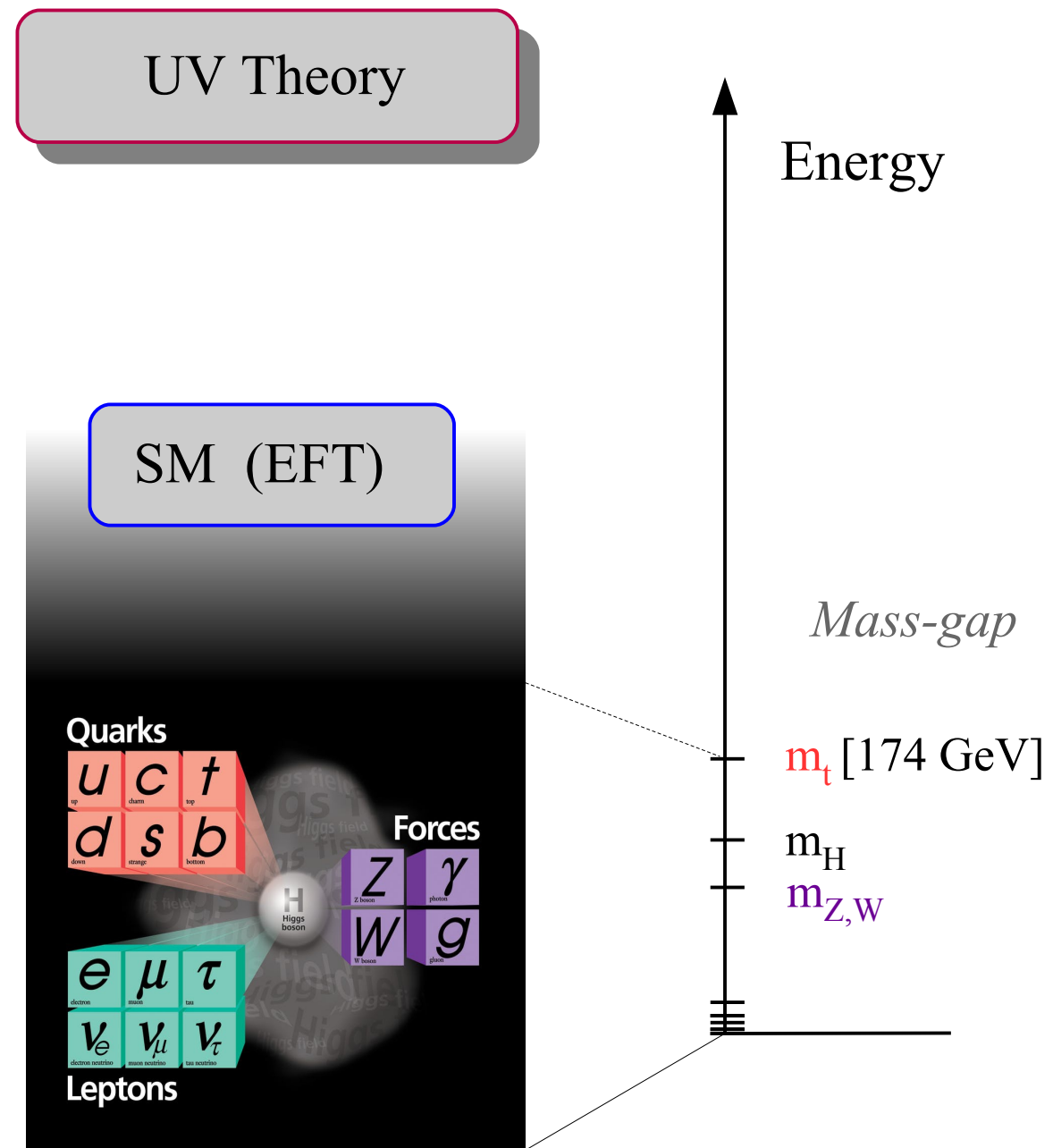
i.e. the **limit** (*in the range of energies and effective couplings so far probed*)
of a more fundamental theory
with new degrees of freedom

$$\mathcal{L}_{\text{SM-EFT}} = \underbrace{\mathcal{L}_{\text{gauge}}(\psi_i, A_a) + \mathcal{L}_{\text{Higgs}}(H, A_a, \psi_i)}_{\text{What we used to call the SM...}} + \dots$$

► 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



► Introduction

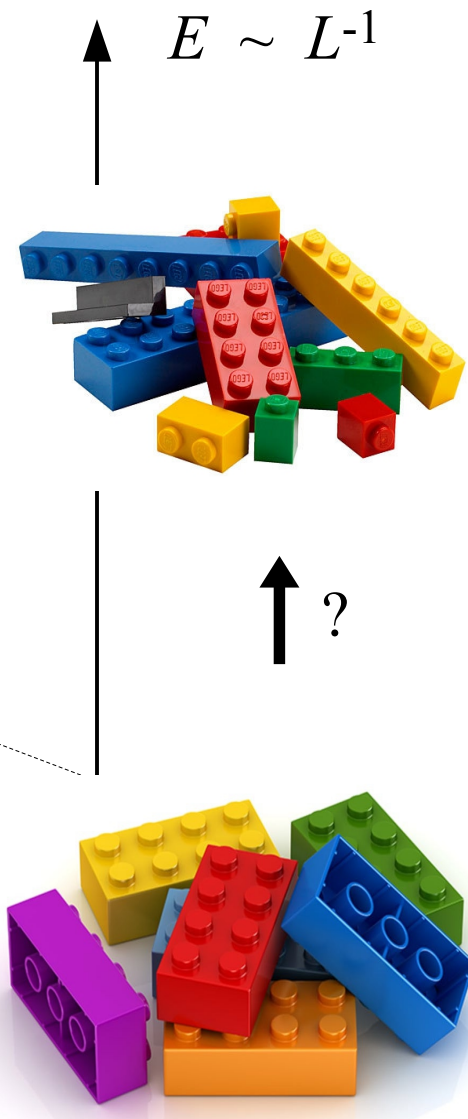
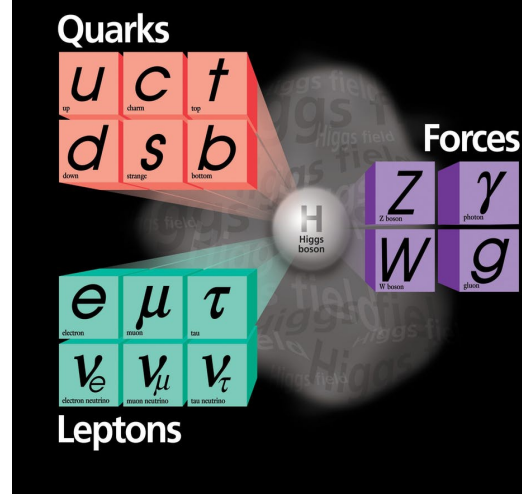
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We identified the “light” (“large”) pieces of our “construction game” & their long-range interactions

UV Theory

SM (EFT)



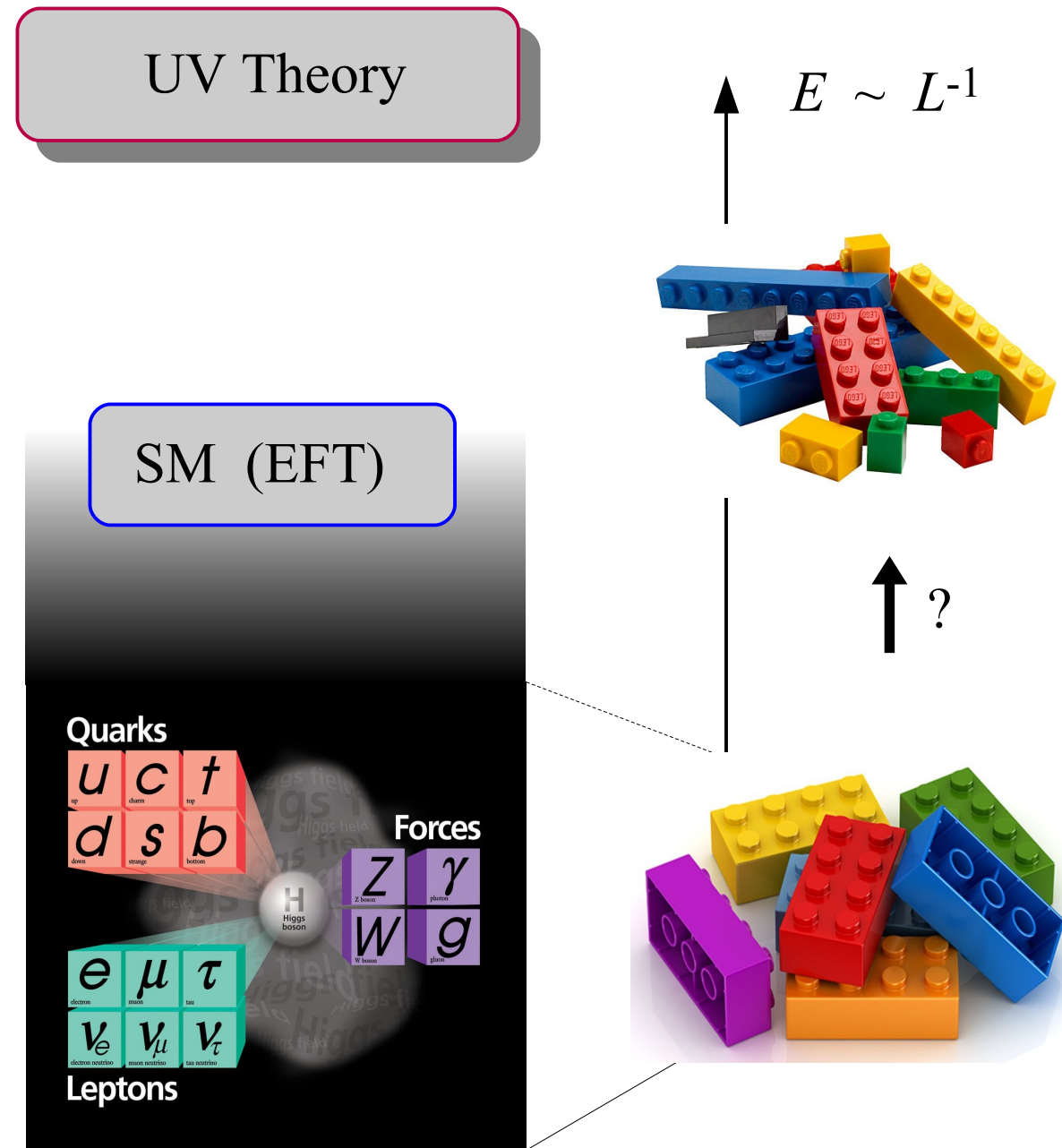
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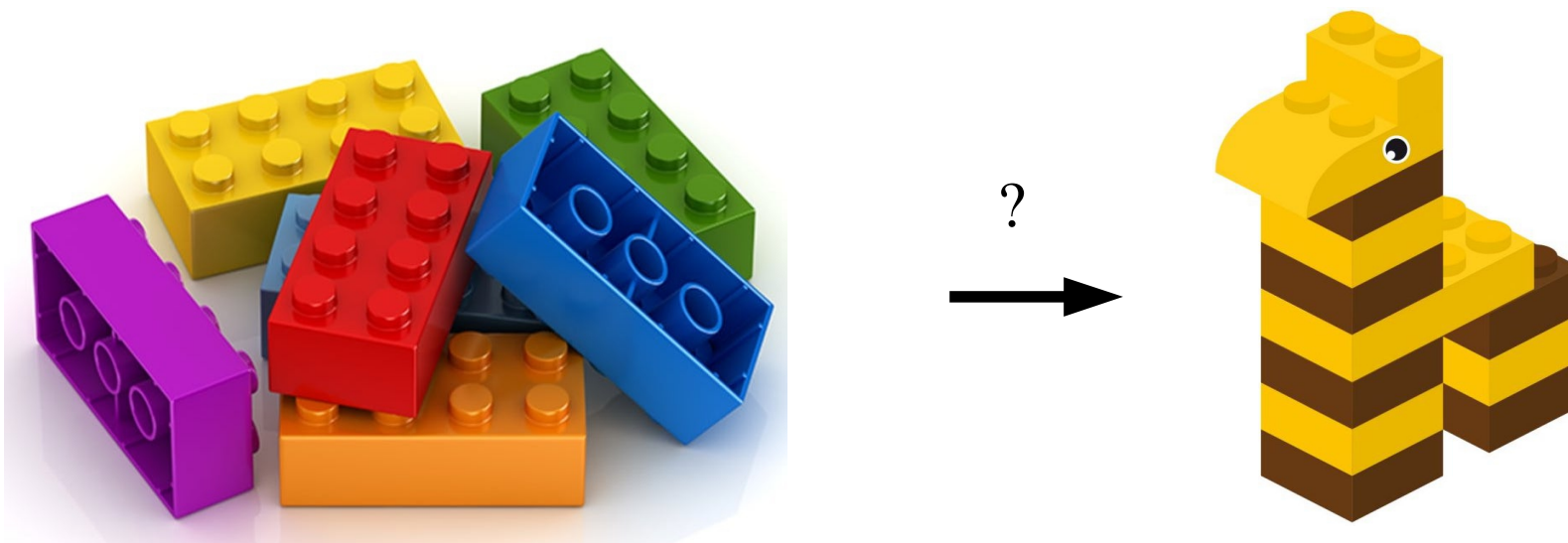
Reconstructing the UV theory from its low-energy limit is a very difficult problem with no unique solution

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



► Introduction

In the absence of direct signals of the new (heavy) degrees of freedom, the most interesting hints toward UV dynamics come from possible *un-natural features* of the EFT.



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Flavour physics plays a key role in this respect, and is likely to play an even more important role in the near future...

The Flavor Problem(s)



Isidor Issac Rabi
(1898—1988)



► The Flavor Problem(s)

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

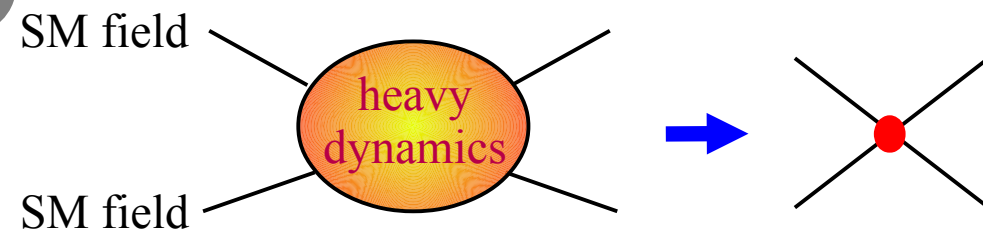
\mathcal{L}_{SM} Interactions surviving @ large distances
(operators with $d \leq 4$)

Local contact interactions
(operators with $d > 4$)

Long-range forces
of the SM particles

Higgs sector
to describe
their masses

“Remnant” of the heavy
dynamics at low energies



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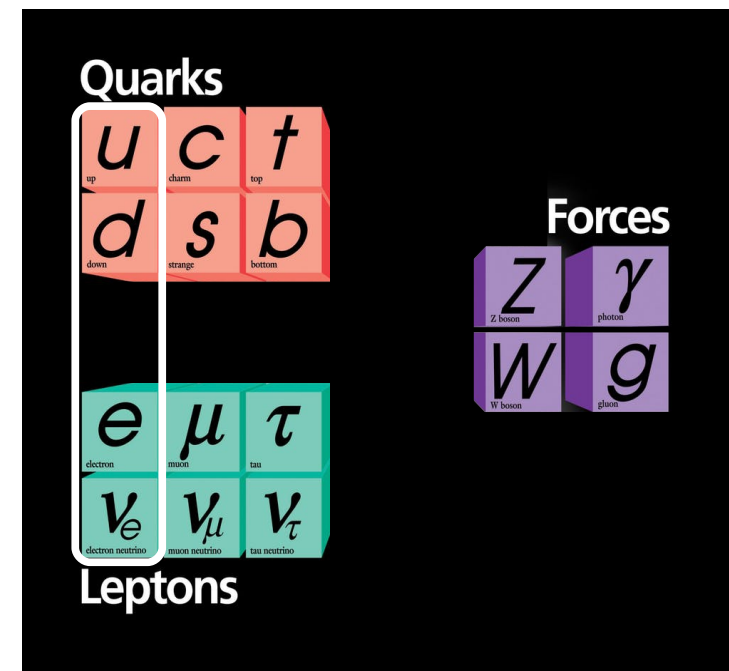
Long-range forces
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Structure fully dictated by

- Number of light fields
- Their charges under long-range interactions

It contains only “natural” $O(1)$ couplings

Three identical replica of the basic fermion family
⇒ huge flavor-degeneracy [$U(3)^5$ symmetry]



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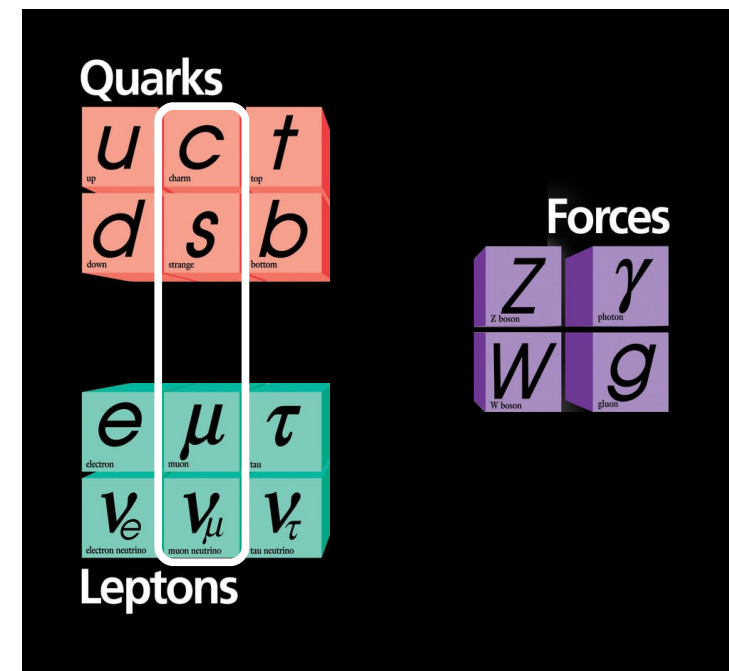
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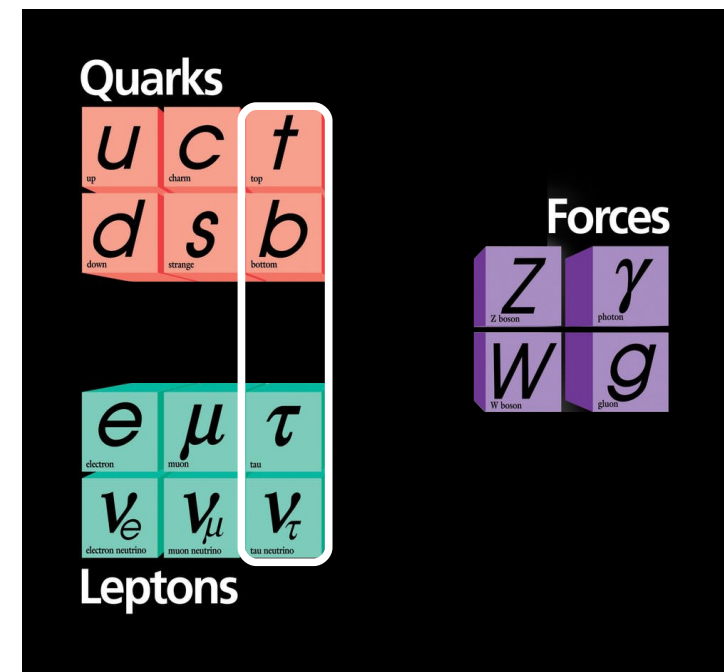
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▶ The Flavor Problem(s)

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}}$$

Higgs sector
to describe
particle masses

Within the SM, the flavor-degeneracy is broken only by the **Yukawa** interaction:

$$y_{ij} \psi_i \psi_j H \rightarrow m_{ij} \psi_i \psi_j$$

The Yukawa couplings have a peculiar hierarchical structure which does not appear to be accidental:

E.g.:

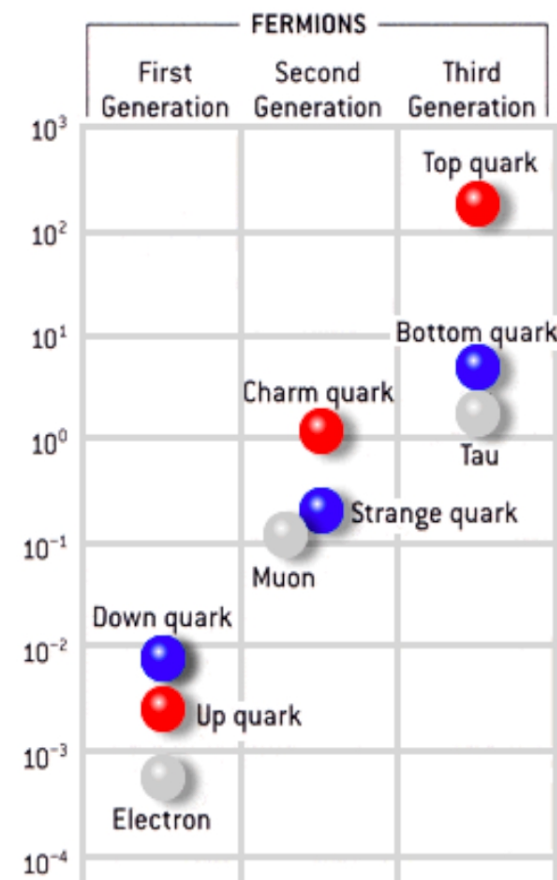
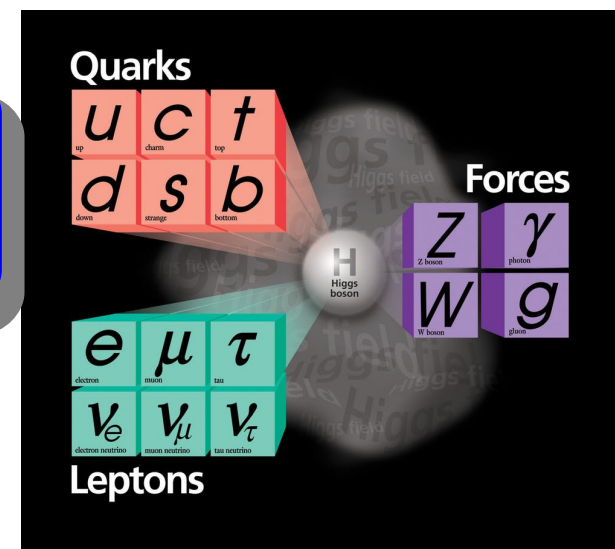
$$Y_U \sim \begin{pmatrix} \square & \square & \square \\ \square & \square & \square \\ \square & \square & \blacksquare \end{pmatrix}$$

$V_{ts} \approx 0.04$

$y_t = \frac{\sqrt{2} m_t}{\langle H \rangle} \approx 1$

$y_c \approx 0.005$

The SM Flavor problem



► The Flavor Problem(s)

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Large flavor symmetry

Flavor-degeneracy broken by the Yukawa interaction

Three identical replica of the basic fermion family
[$U(3)^5$ symmetry]

$$y_{ij} \psi_L^i \psi_R^j H \rightarrow m_{ij} \psi_L^i \psi_R^j$$

“Peculiar” breaking structure

Exact & approximate (*accidental* ?) symmetries

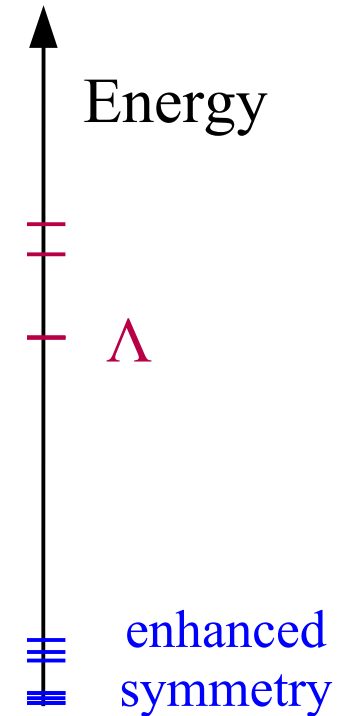
- Eg:
- $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} =$ (individual) Lepton Flavor [*exact symmetry*]
 - $m_u \approx m_d \approx 0 \rightarrow$ Isospin symmetry [*approximate symmetry*]

► The Flavor Problem(s)

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

(long-distance interactions)
(local contact interact.)

“**Accidental symmetries**” are symmetries which are not fundamental properties of the theory, but emerge accidentally at low energies / large distances → **not enough “variables”** to describe the violation of the symmetry [*~ multipole expansion*]



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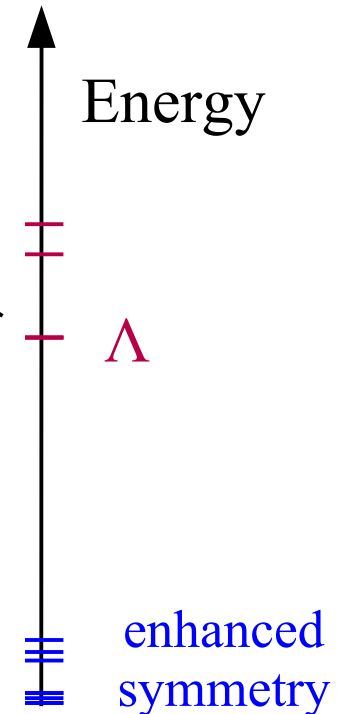
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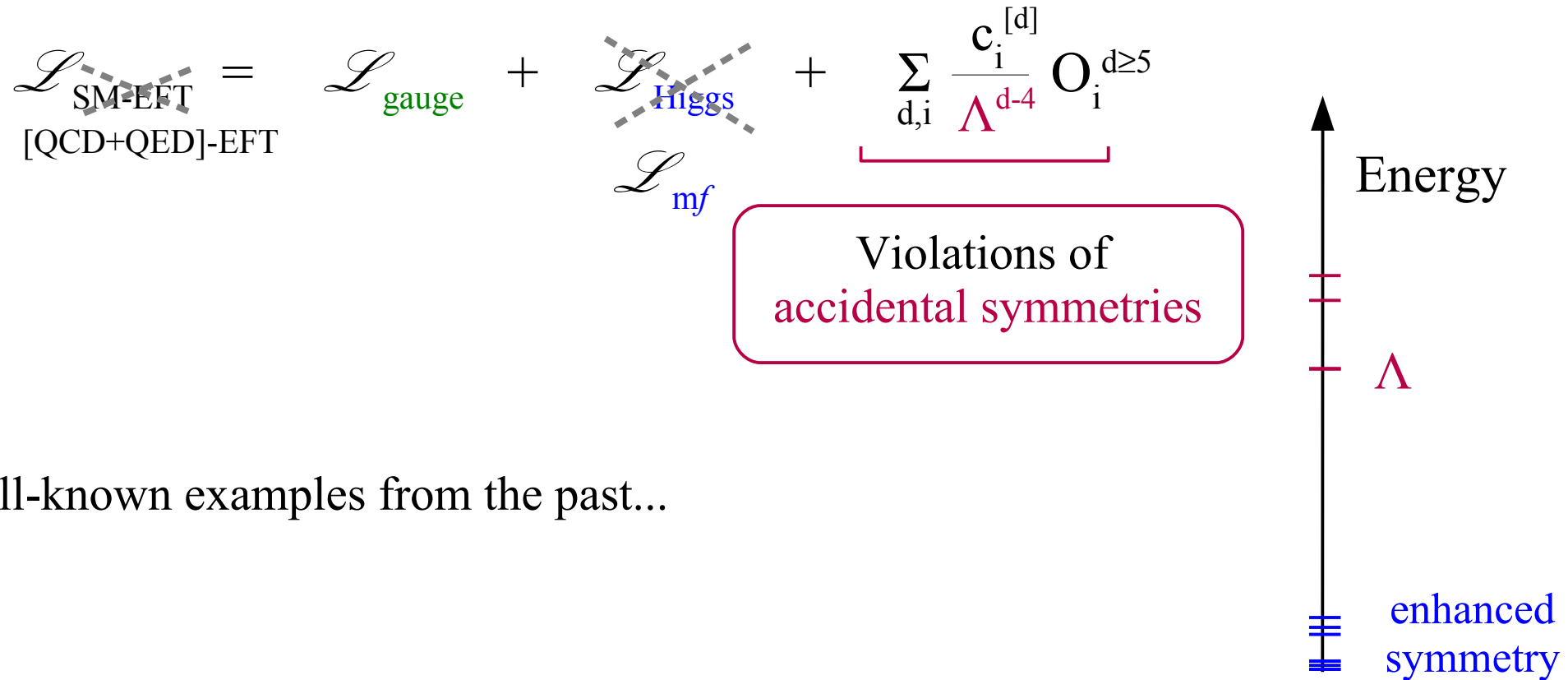
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If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

Violations of accidental symmetries



► The Flavor Problem(s)



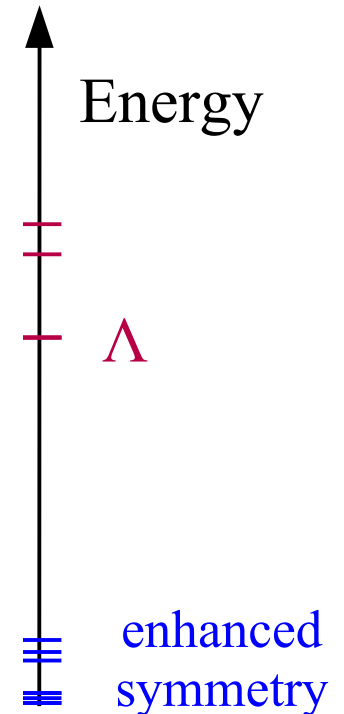
Well-known examples from the past...

Eg: *Low-energy theory:* QED + QCD
Accidental symm.: Flavor [U(1)^{n_f}]
Violated by: Weak interactions → G_F ~ (250 GeV)⁻²

► The Flavor Problem(s)

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

Violations of
accidental symmetries



Well-known examples from the past...

...the violations of **L**epton **F**lavor **U**niversality
recently reported by experiments (B-physics *anomalies*)
belong to this category

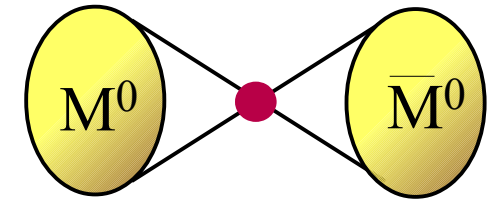
→ more later

► The Flavor Problem(s)

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In principle, we could expect many violations of the accidental symmetries from the heavy dynamics \rightarrow *new flavor violating effects*

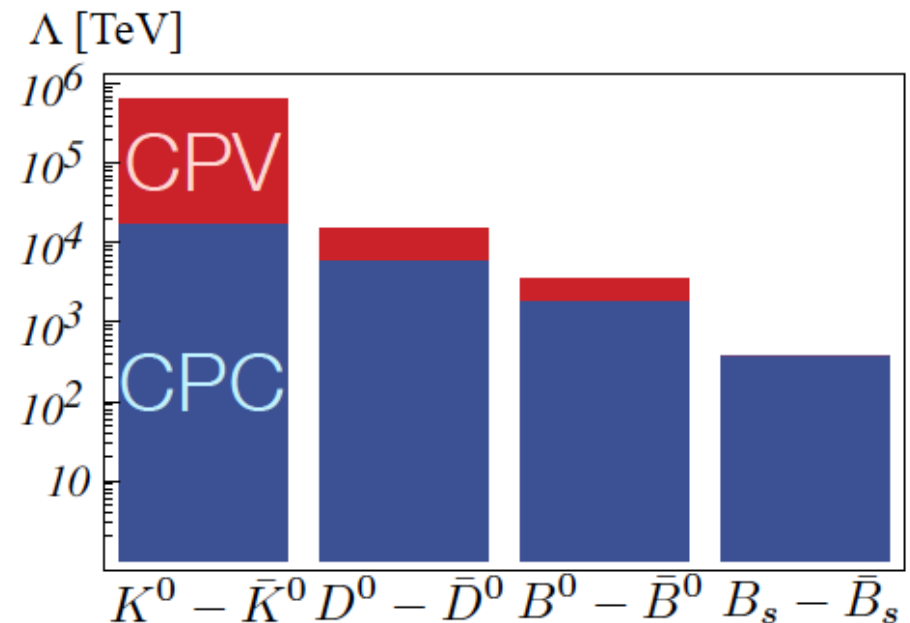
E.g.: $\frac{1}{\Lambda^2} (\psi_i \psi_j)^2$



However, beside the B-physics anomalies we observe none

Stringent bounds on the scale of possible new flavor non-universal interactions

The NP Flavor problem



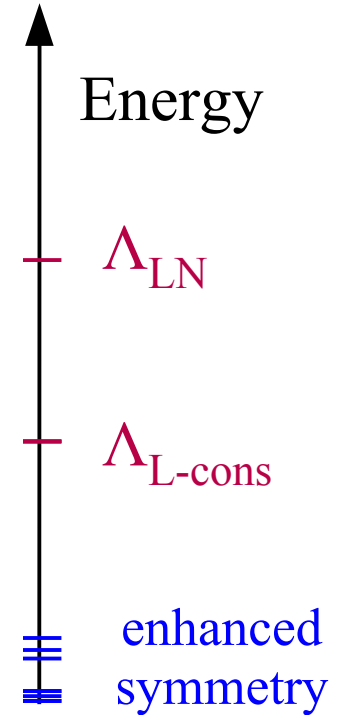
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Accidental symmetries allow us to separate different sectors of the EFT \leftrightarrow stable scale separation

Eg: *Total Lepton Number & neutrino masses*

$$\frac{g_v^{ij}}{\Lambda_{\text{LN}}} (L_L^T H)(L_L H^T) \longrightarrow (m_\nu)^{ij} = \frac{g_v^{ij} \langle H \rangle^2}{\Lambda_{\text{LN}}} \simeq 0.1 \text{ eV}$$



Consistent to assume $d=6$ ops preserving LN characterized by $\Lambda_{\text{L-cons}} \ll \Lambda_{\text{LN}}$

N.B.: The same is true for flavor-violating terms

(with minor technical differences related to approximate vs. exact symmetries)

► The Flavor Problem(s)

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Flavor-degeneracy:
 $U(3)^5$ symmetry

$U(3)^5$ symmetry
broken by
Yukawa couplings

Stringent bounds
on generic
flavor-violating ops.

The big questions in flavor physics:

- Are all the the accidental flavor symmetries of the SM broken in the other sectors of the SM-EFT ?
- Can we make sense of the tight NP bounds from flavor-violating processes and still hope to see NP signals somewhere?
And in case where?

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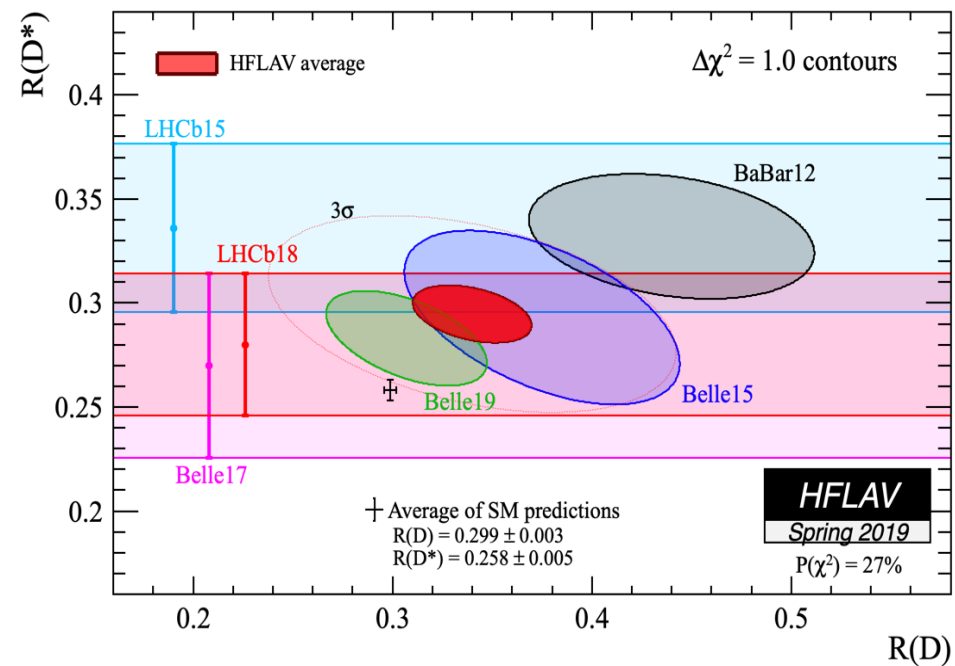
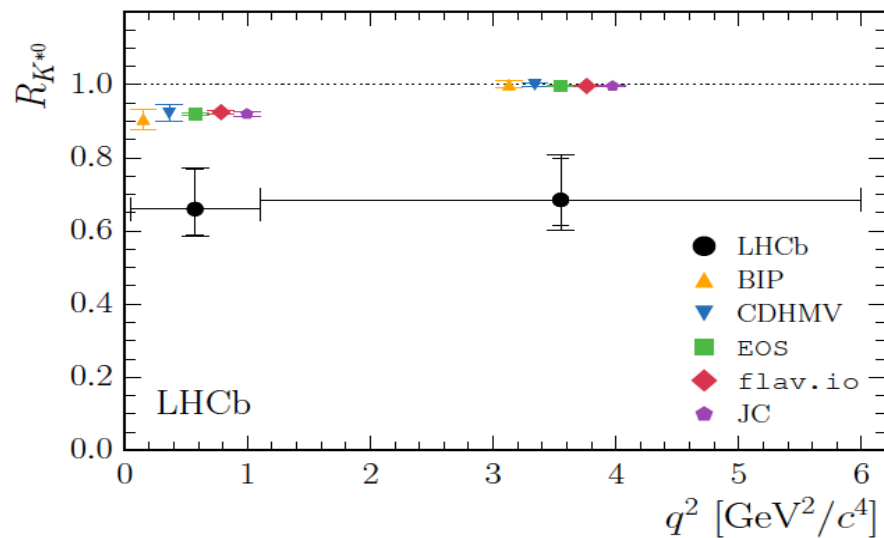
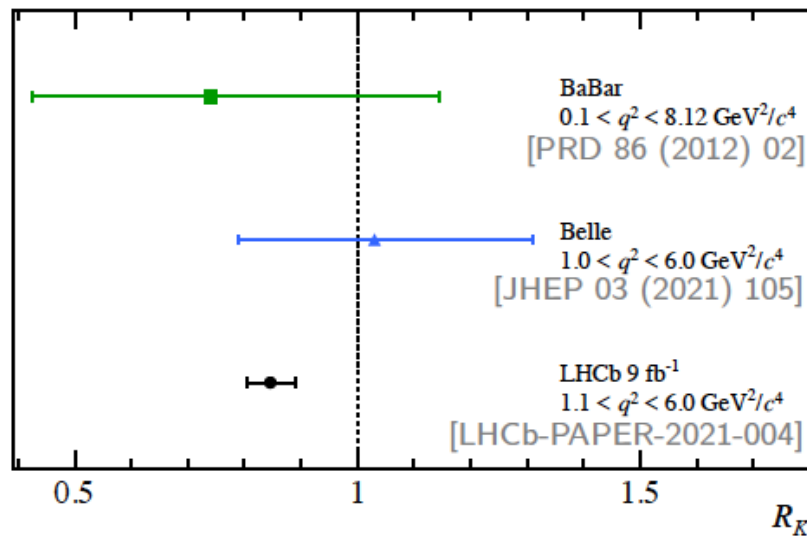
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Recent data start to provide some answers...

The LFU anomalies



► The LFU anomalies

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): μ vs. e
- $b \rightarrow c l \nu$ (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.

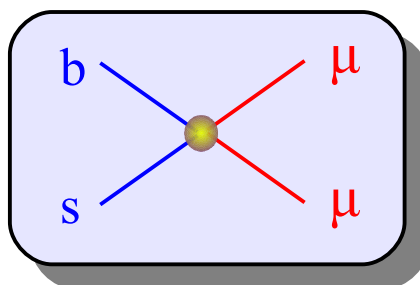
LFU is badly broken in the Yukawa sector: $y_e \sim 3 \times 10^{-6}$, $y_\mu \sim 3 \times 10^{-4}$, $y_\tau \sim 10^{-2}$

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

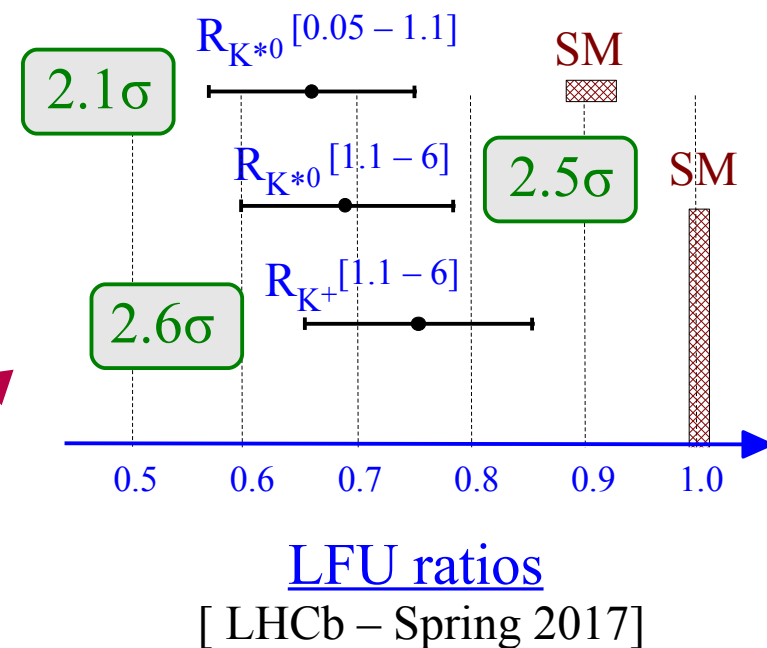
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- $b \rightarrow s l^+ l^-$ (neutral currents): μ vs. e

High significance: several observables pointing to the same coherent picture [several new results in 2021]



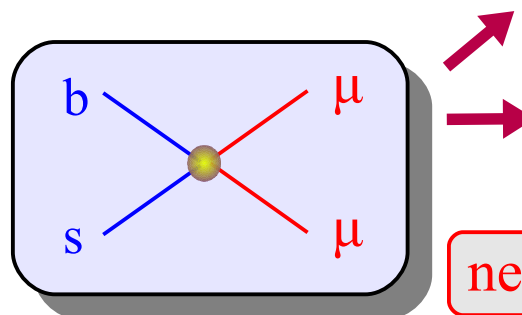
$$\Gamma(H_b \rightarrow H_s \mu\mu) / \Gamma(H_b \rightarrow H_s ee)$$



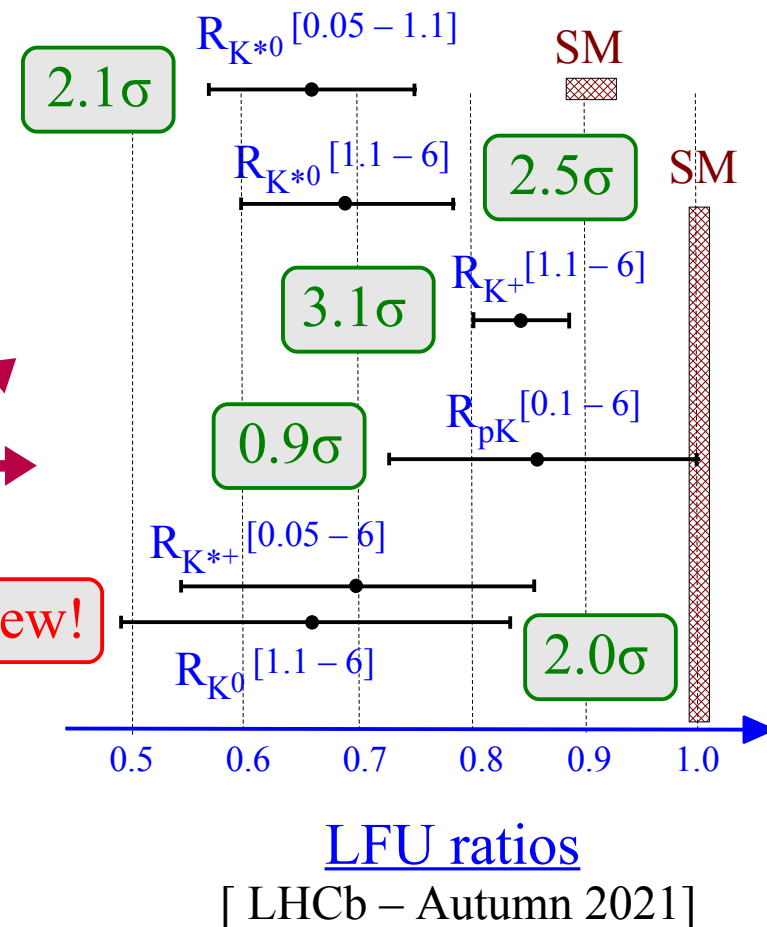
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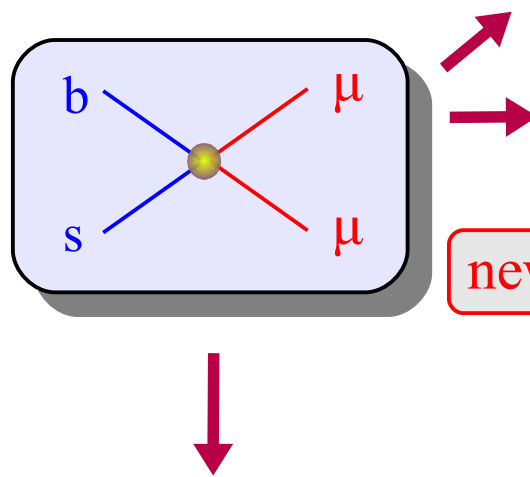
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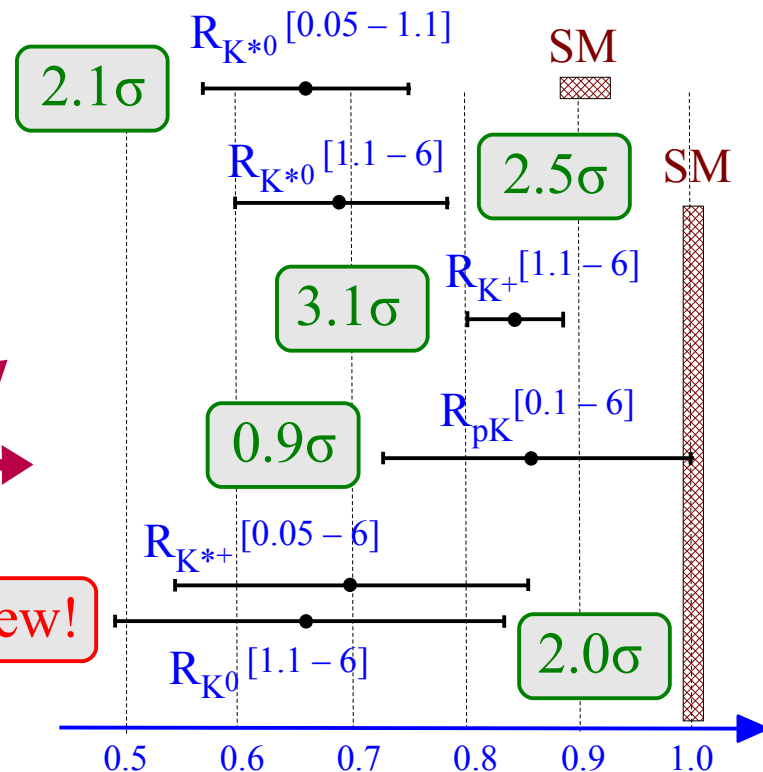
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$$BR(B_s \rightarrow \mu\mu)$$

$$BR_{\text{exp}} = (2.85 \pm 0.32) \times 10^{-9} \quad \text{ATLAS+CMS+LHCb '21}$$

$$BR_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

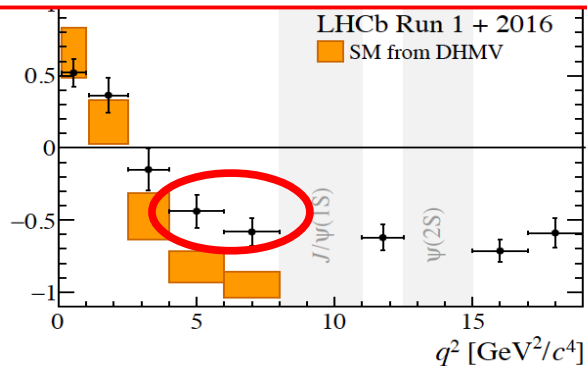
2.3σ

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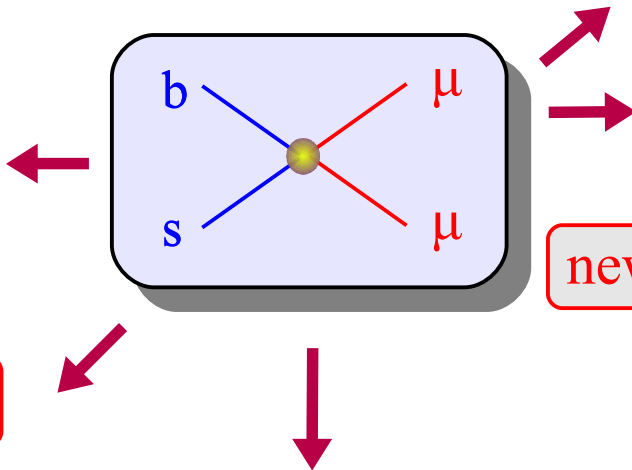
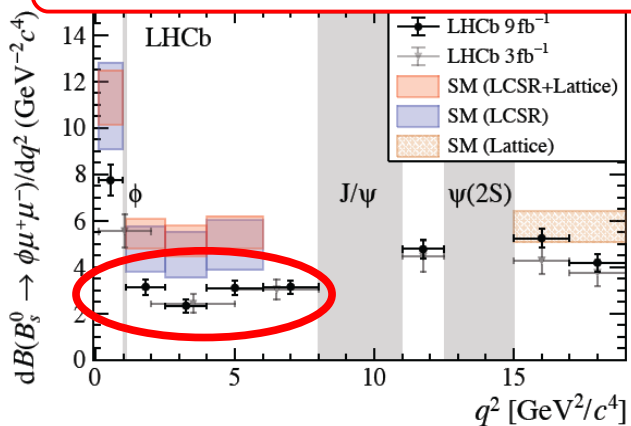
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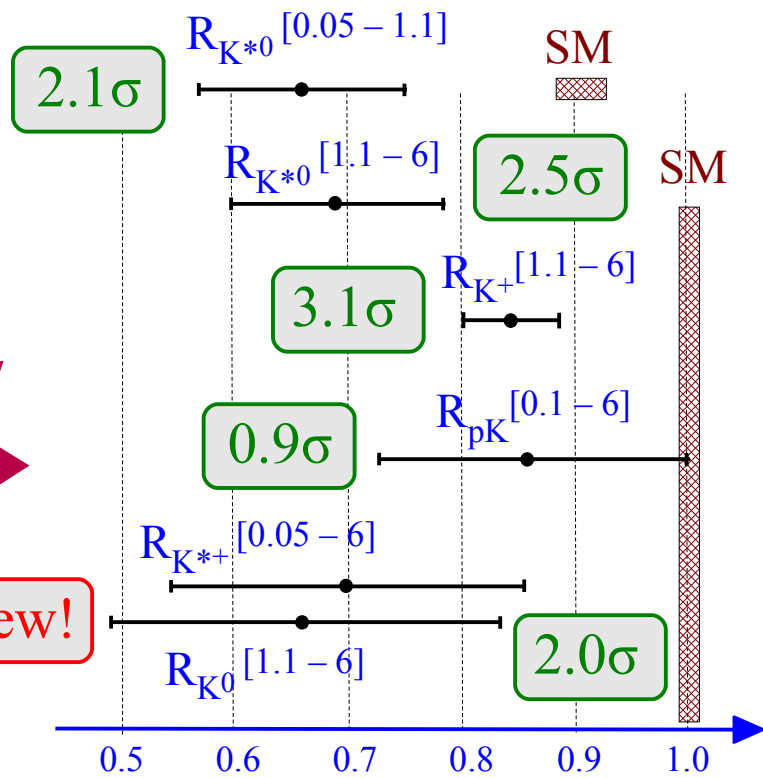
$B \rightarrow K^* \mu\mu$ angular distribution



$B \rightarrow H \mu\mu$ branching ratios



$\Gamma(H_b \rightarrow H_s \mu\mu) / \Gamma(H_b \rightarrow H_s ee)$



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► The LFU anomalies

• $b \rightarrow s l^+ l^-$ (neutral currents): μ vs. e

To describe $b \rightarrow s l l$ decays we

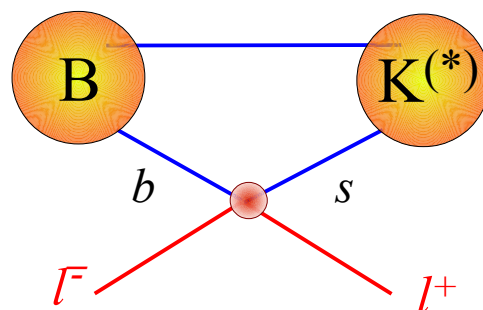
- build an EFT Lagrangian
- evolve it down to $\mu \sim m_b$
- evaluate hadronic matrix elements

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

FCNC operators:

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

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

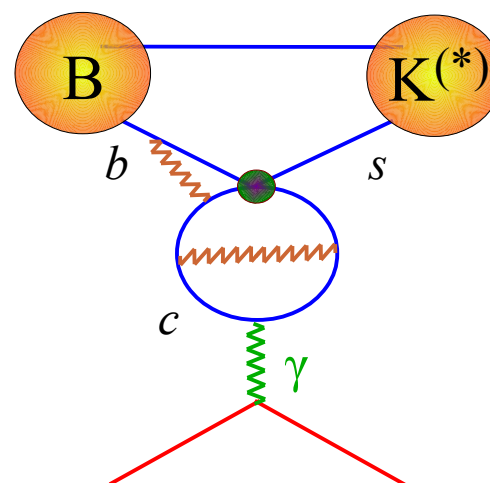


“easy” & “clean”

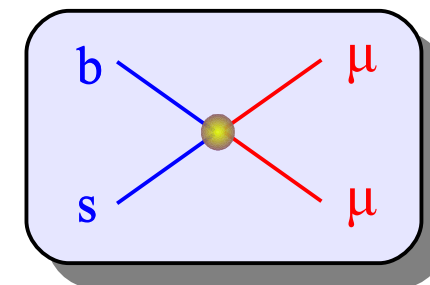
Four-quark operators:

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

⋮



“difficult” → induces ΔC_9^{Univ}



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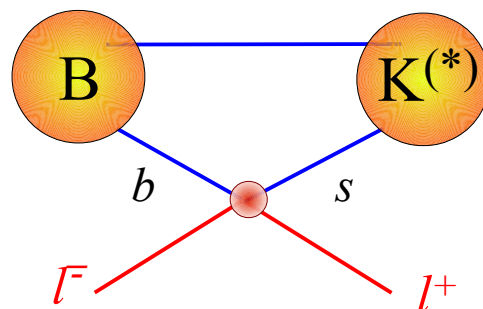
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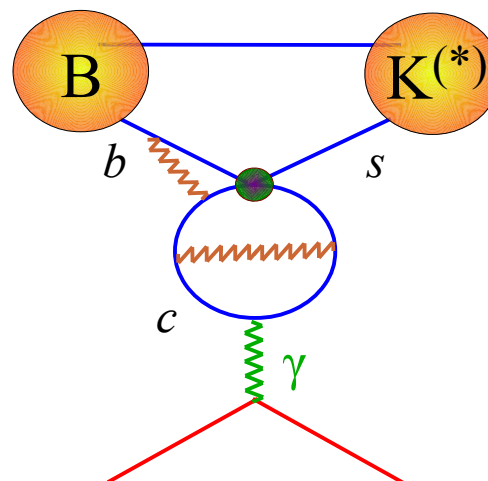


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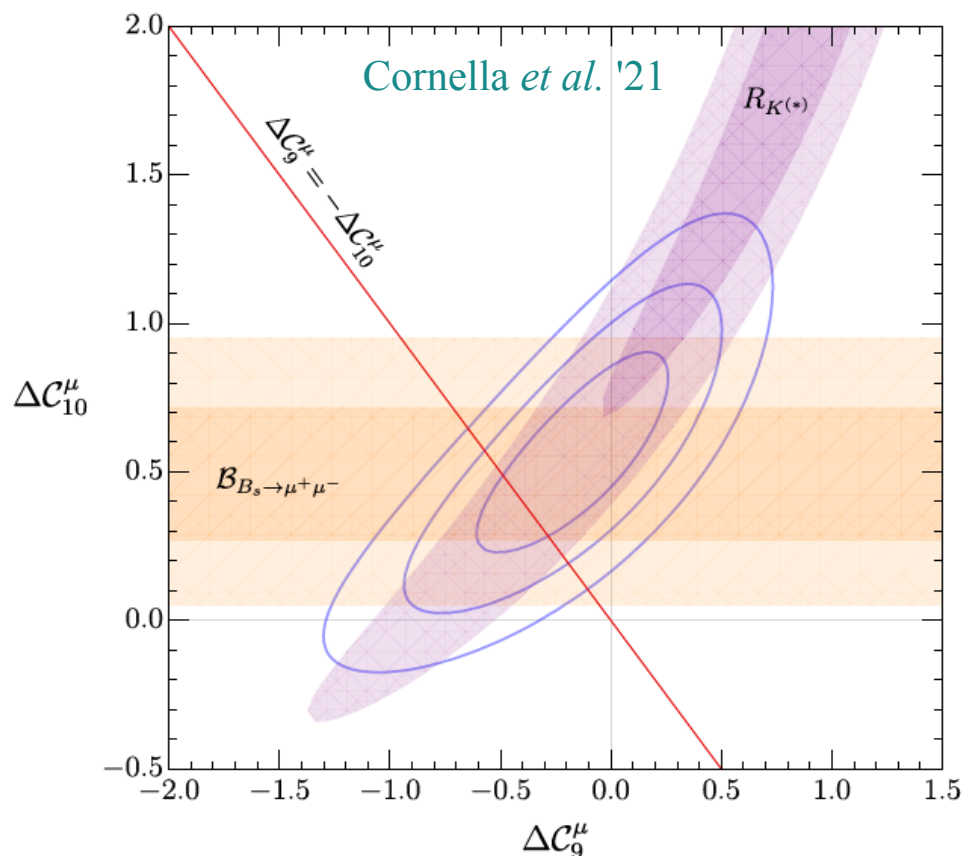


“difficult” → induces ΔC_9^{Univ}

Long-distance effect
cannot induce
LFU violations
(→ LFU ratios “clean”)
and cannot induce
axial-current ops.
(→ $B_s \rightarrow \mu\mu$ “clean”)

► The LFU anomalies

• $b \rightarrow s l^+ l^-$ (neutral currents): μ vs. e



FCNC operators:

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

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

“clean” short-distance effect of BSM origin [$\Delta C_i^\mu = C_i^\mu - C_i^e$]:

Conservative fit using “clean obs.” only

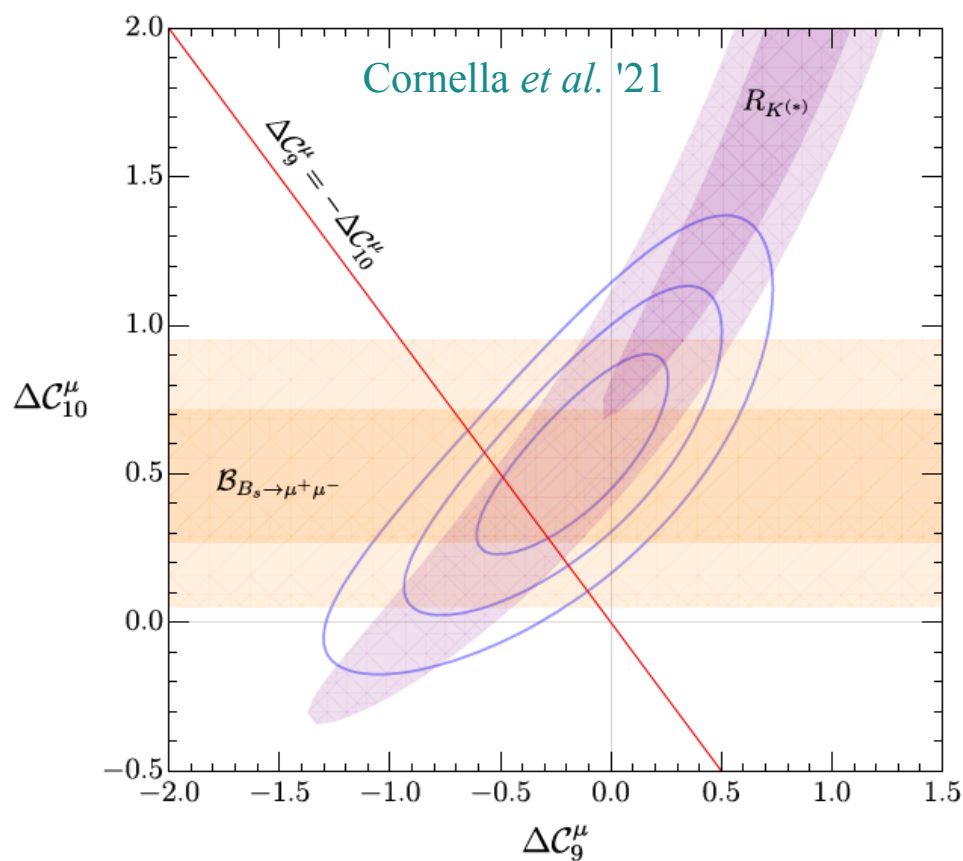
5.0 σ

significance of NP hypothesis

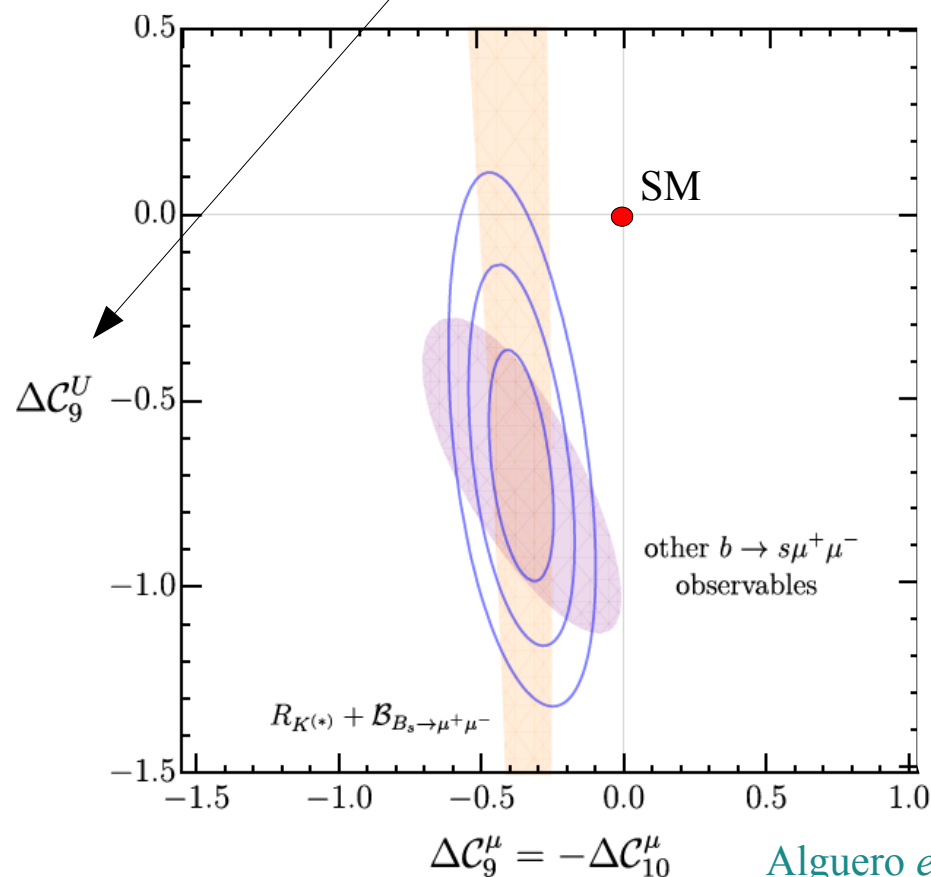
$$\Delta C_9^\mu = -\Delta C_{10}^\mu \text{ vs. SM}$$

► The LFU anomalies

● $b \rightarrow s l^+ l^-$ (neutral currents): μ vs. e



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



Conservative fit using “clean obs.” only

5.0 σ

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

$\gg 5\sigma$ best estimate of charm contribution

4.3 σ global significance of NP
(very conserv. estimate)

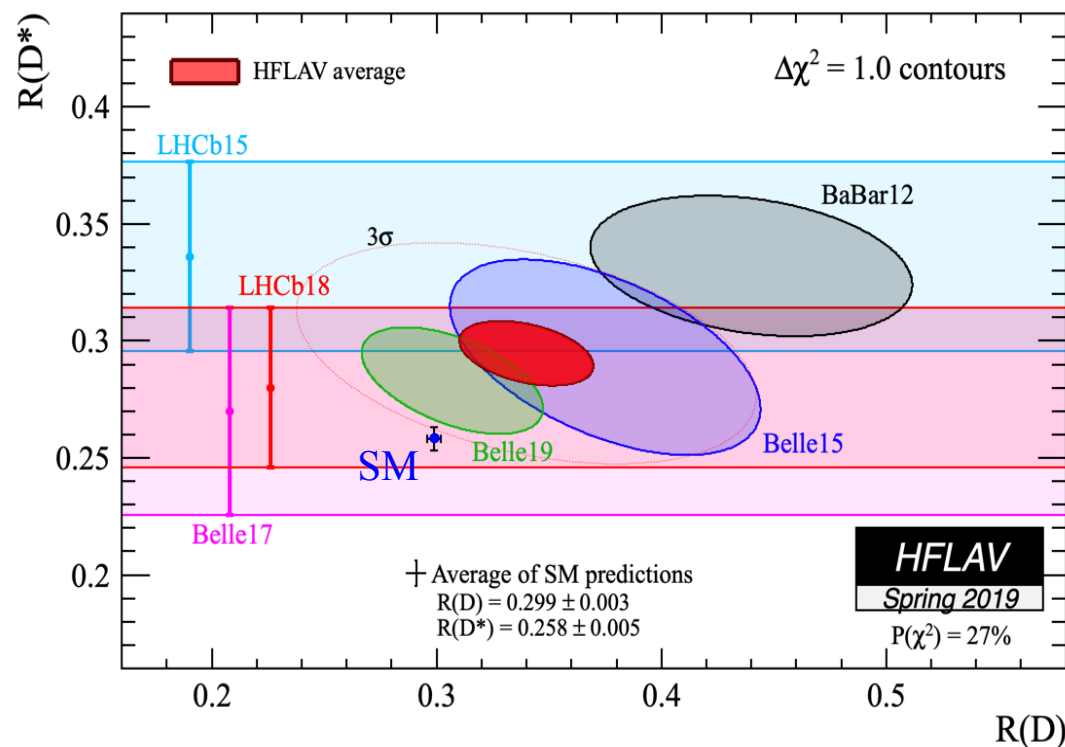
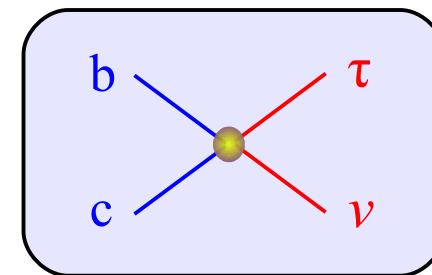
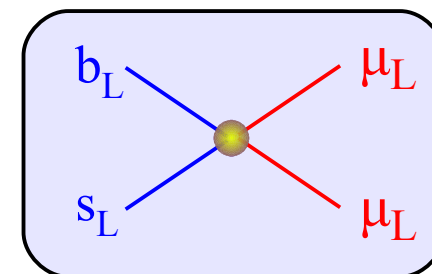
Alguero et al. '19
Ciuchini et al. '20
Li-Sheng et al. '21
Altmanshofer & Stangl '21

GI, Lancierini
Owen, Serra '21

► The LFU anomalies

• $b \rightarrow s l^+ l^-$ (neutral currents): μ vs. e

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



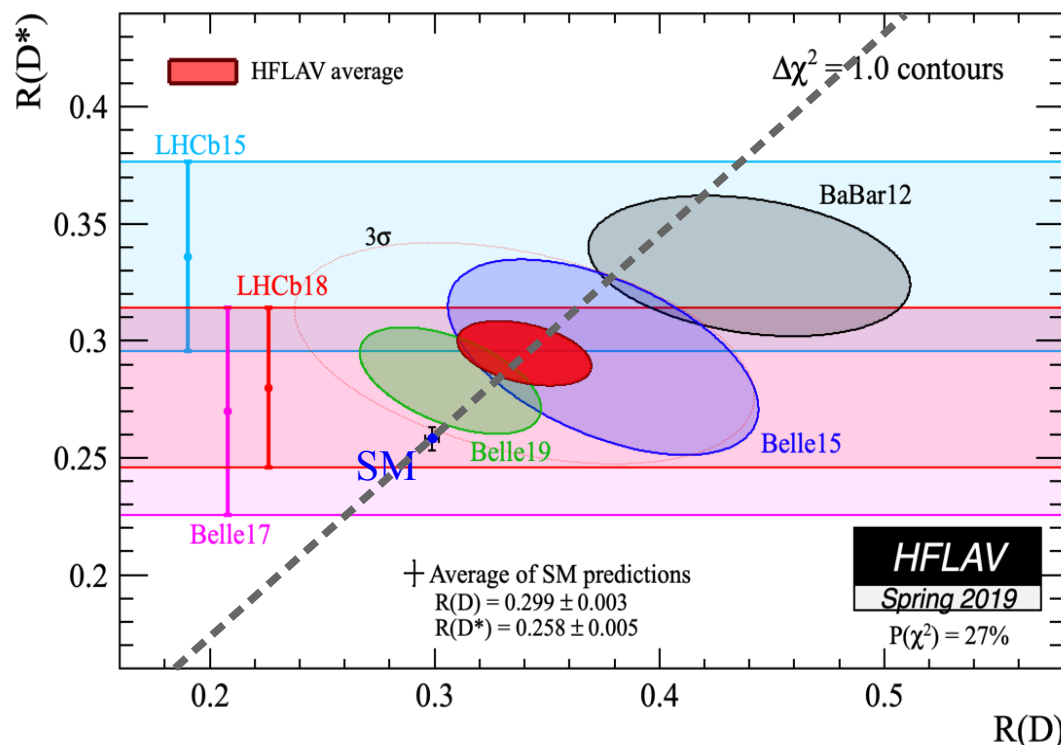
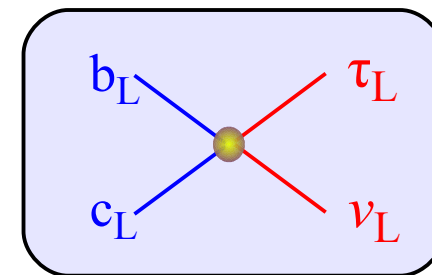
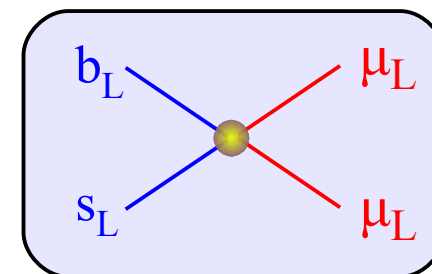
$$R(X) = \frac{\Gamma(B \rightarrow X \tau \nu)}{\Gamma(B \rightarrow X l \nu)} \quad X = D \text{ or } D^*$$

- Clean SM predictions (*uncertainties cancel in the ratios*)
- Consistent results by 3 different exp.ts: **3.1 σ** excess over SM
- Slower progress

► The LFU anomalies

• $b \rightarrow s l^+ l^-$ (neutral currents): μ vs. e

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



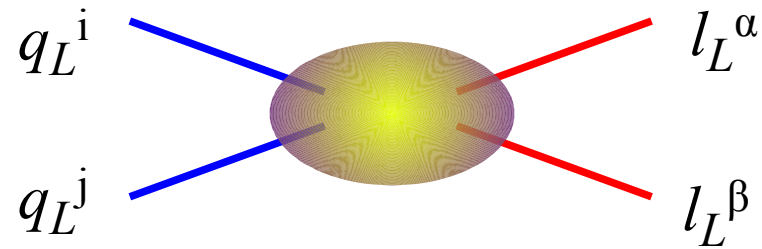
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- Clean SM predictions (*uncertainties cancel in the ratios*)
- Consistent results by 3 different exp.ts: **3.1 σ** excess over SM
- Slower progress

→ Large NP effect competing with tree-level SM amplitude

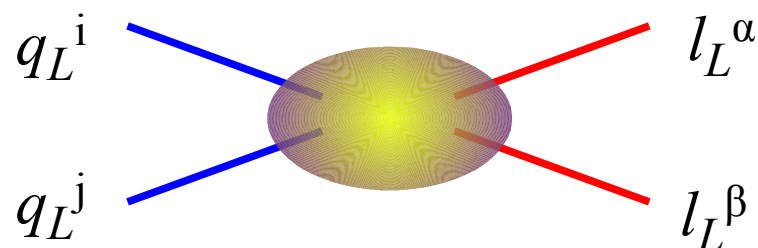
→ Left-handed NP amplitude describe well data (*but other options still possible*)

EFT considerations on the LFU anomalies



► 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 coupl. [*compete with SM tree-level*] in $b(3^{\text{rd}}) \ c(2^{\text{nd}}) \rightarrow \tau(3^{\text{rd}}) \ \nu_\tau(3^{\text{rd}})$
- Small coupl. [*compete with SM loop-level*] in $b(3^{\text{rd}}) \ s(2^{\text{nd}}) \rightarrow \mu(2^{\text{rd}}) \ \mu(2^{\text{rd}})$



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

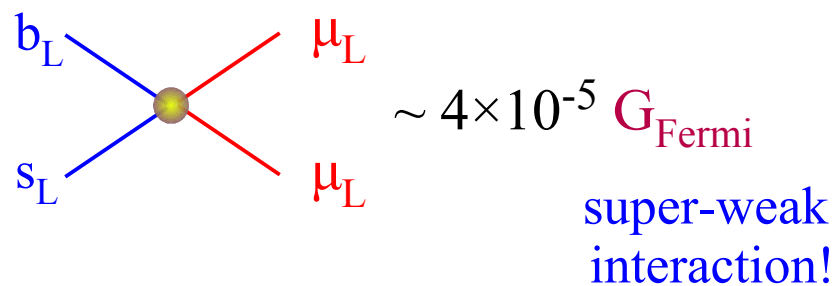


*Link to pattern
 of the Yukawa
 couplings !*

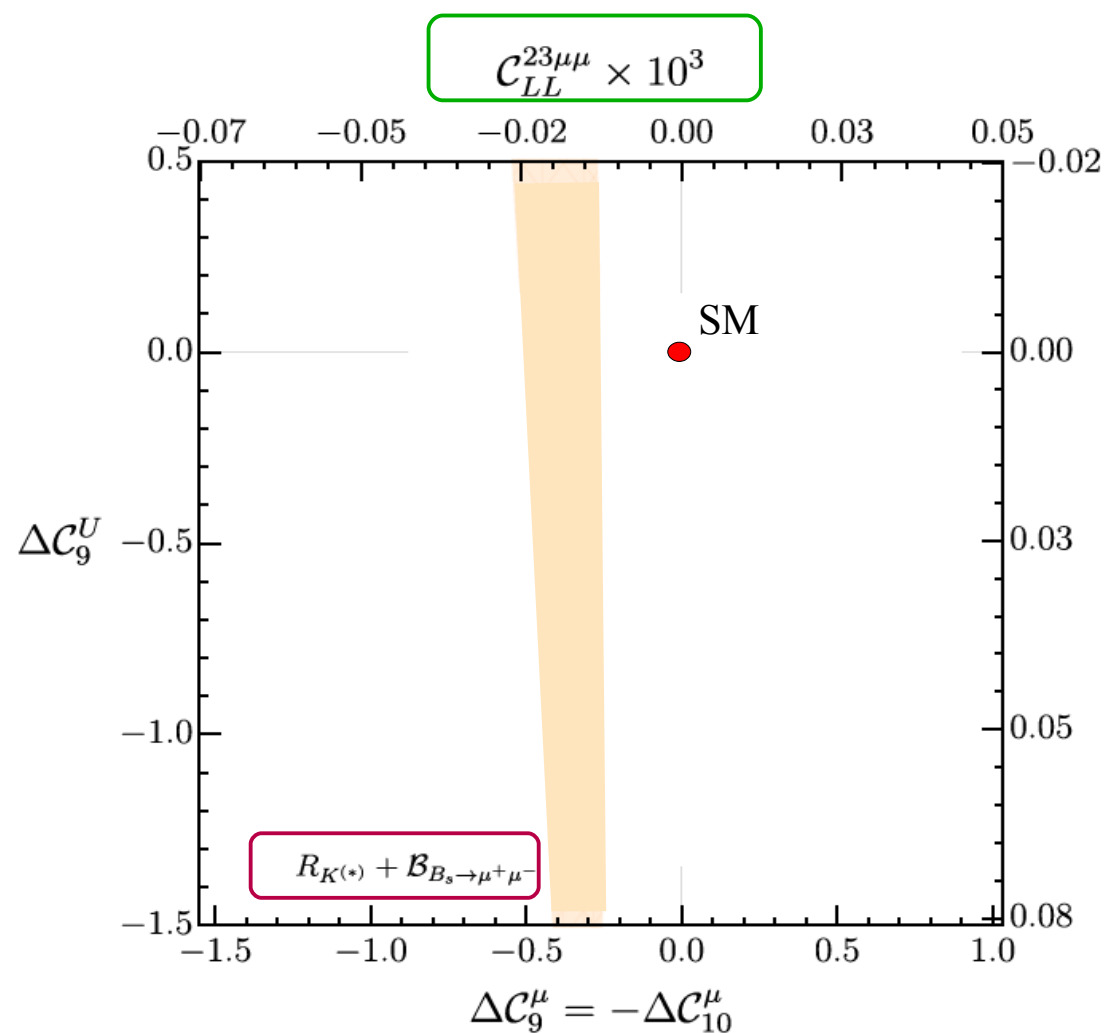
► EFT considerations

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

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



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

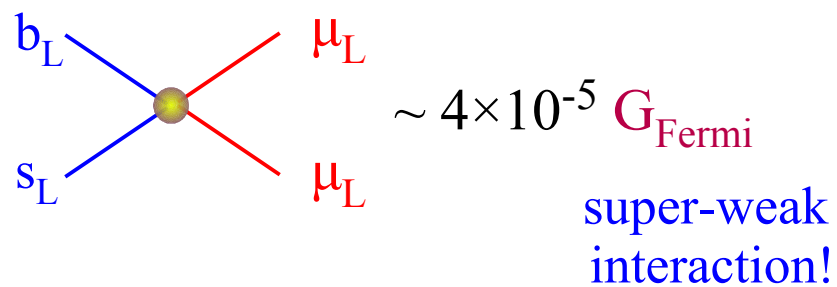


► EFT considerations

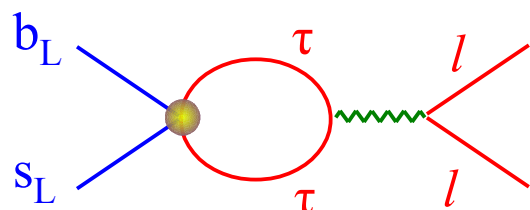
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✓ $O(10^{-1})$ suppress. for each 2nd gen. l_L

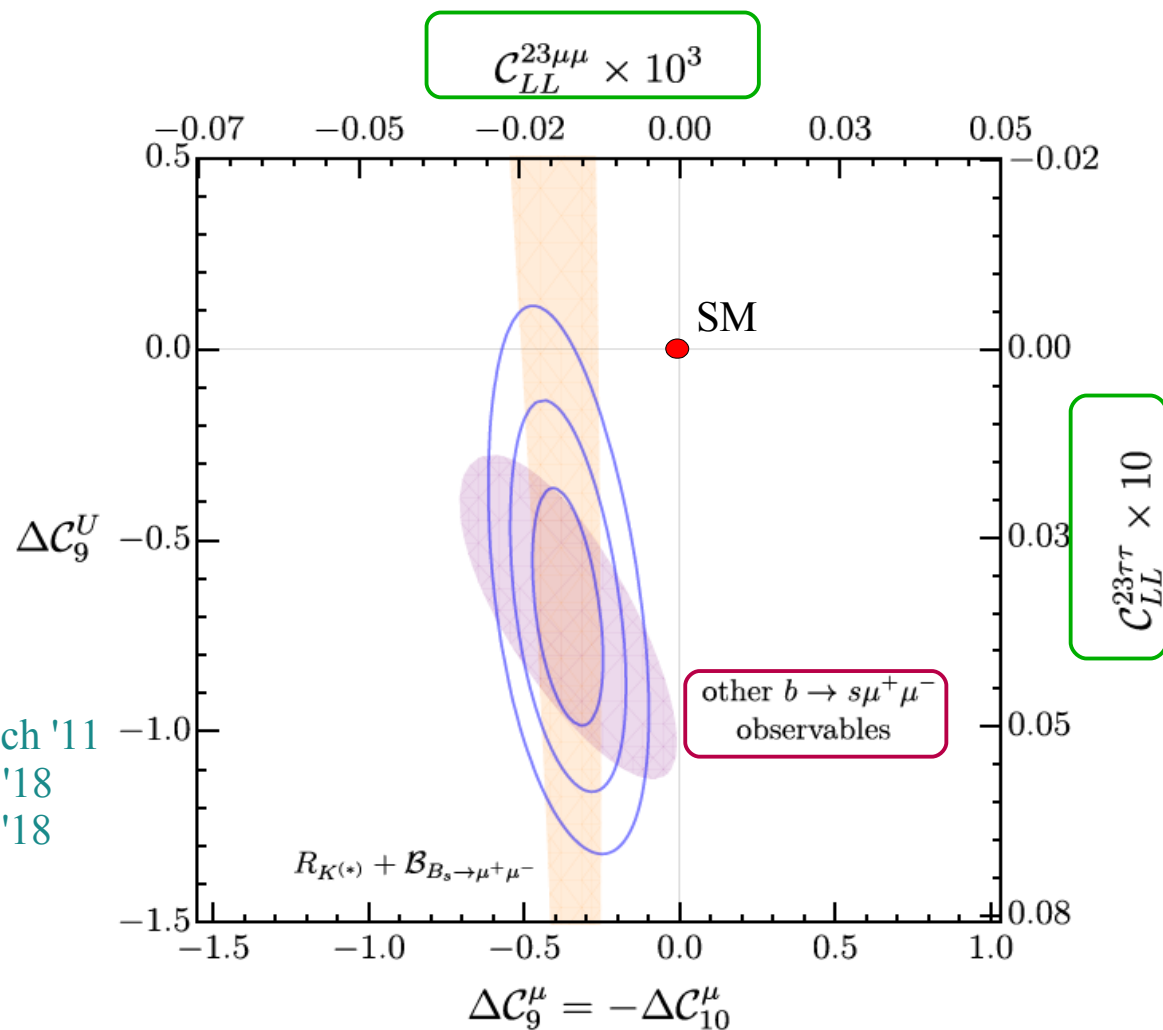


$$C_{LL}^{23\mu\mu} \rightarrow \Delta C_9^\mu = -\Delta C_{10}^\mu$$



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

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

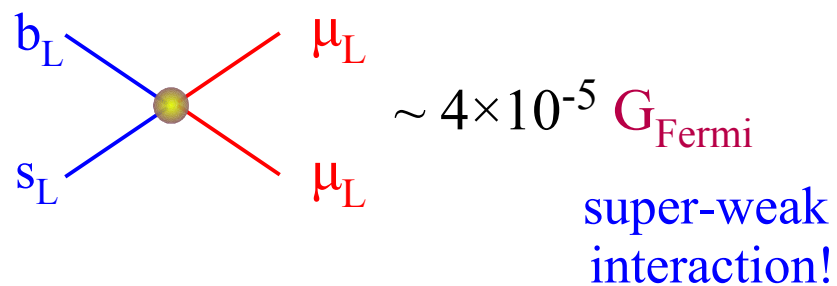


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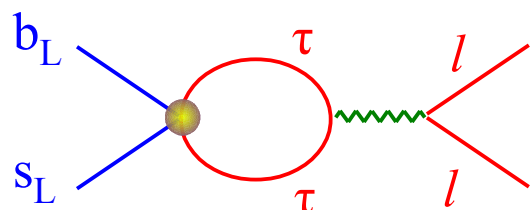
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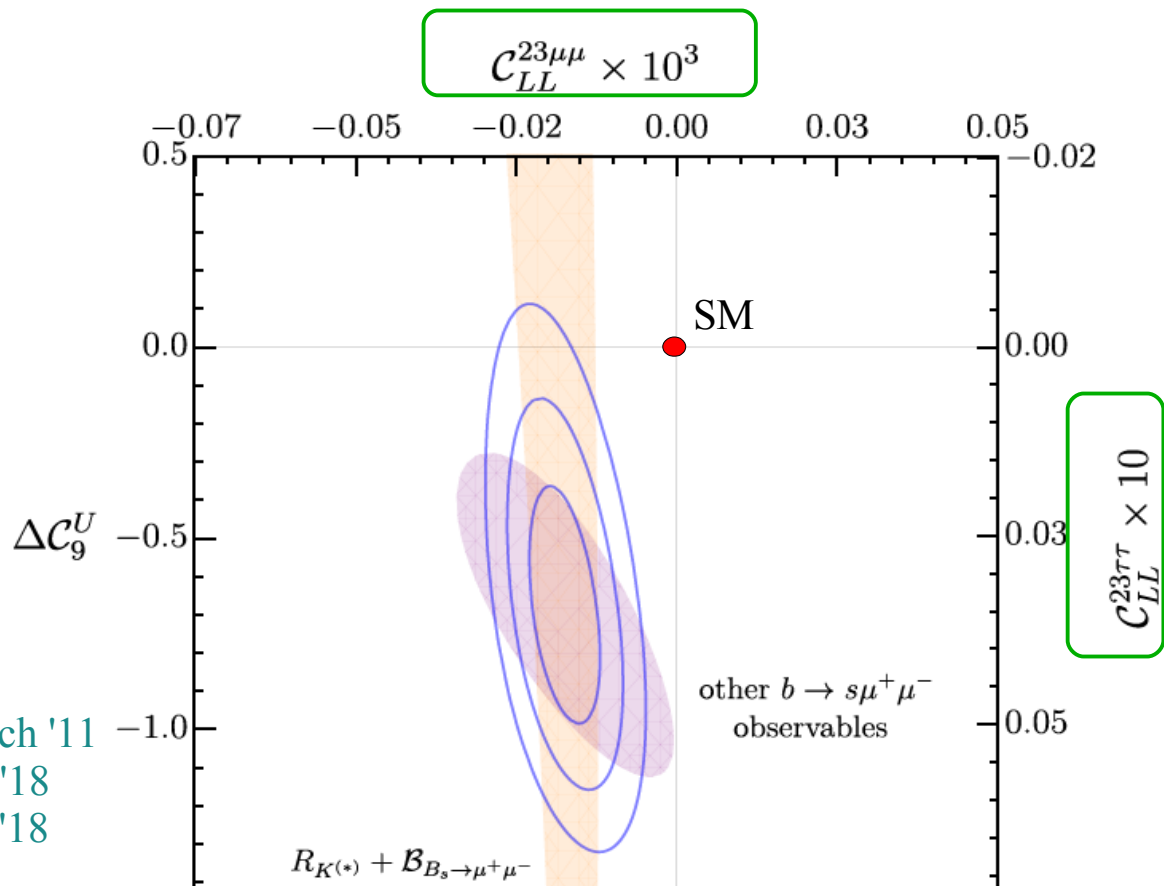
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Bobeth & Haisch '11
Crivellin *et al.* '18
Alguero *et al.* '18

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

Link to CC anomaly



Size (and need) of $C^{23\tau\tau}$ pre-dicted from CC before this effect was observed in NC Greljo *et al.* '17

► EFT considerations

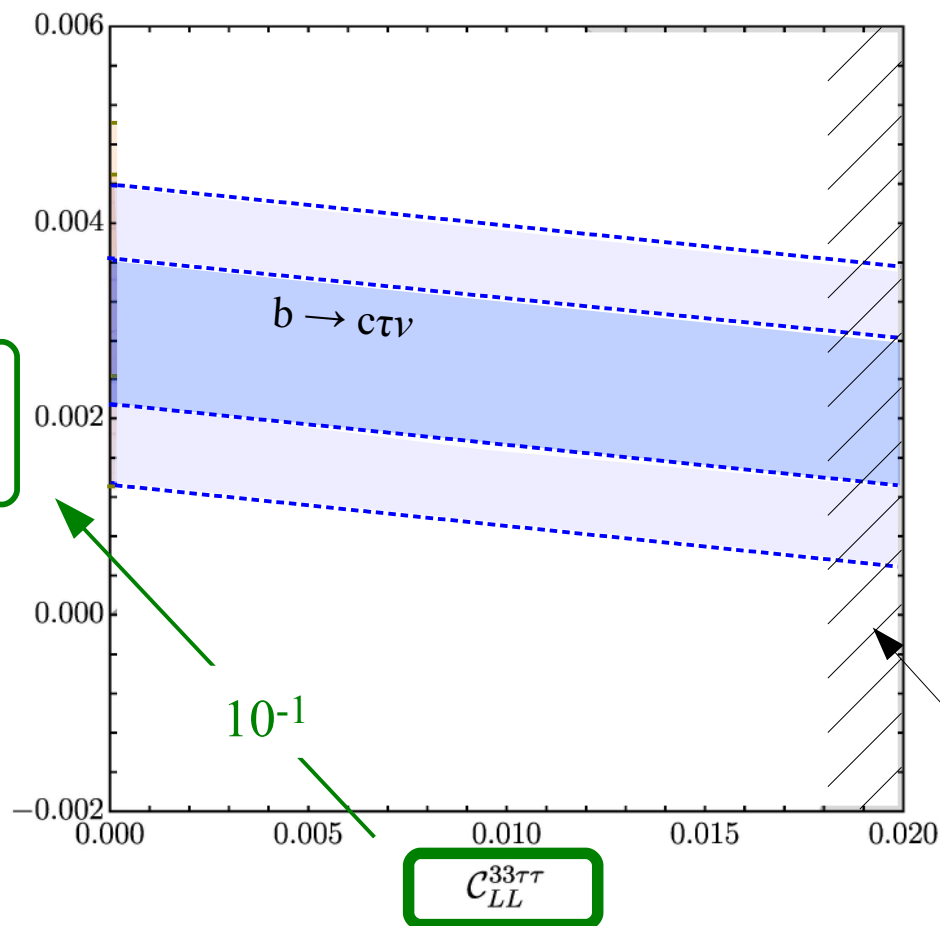
Data point to (short-distance) NP effects in operators of the type

- ✓ $O(10^{-1})$ suppress. for each 2nd gen. q_L or l_L

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

charged-currents:

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



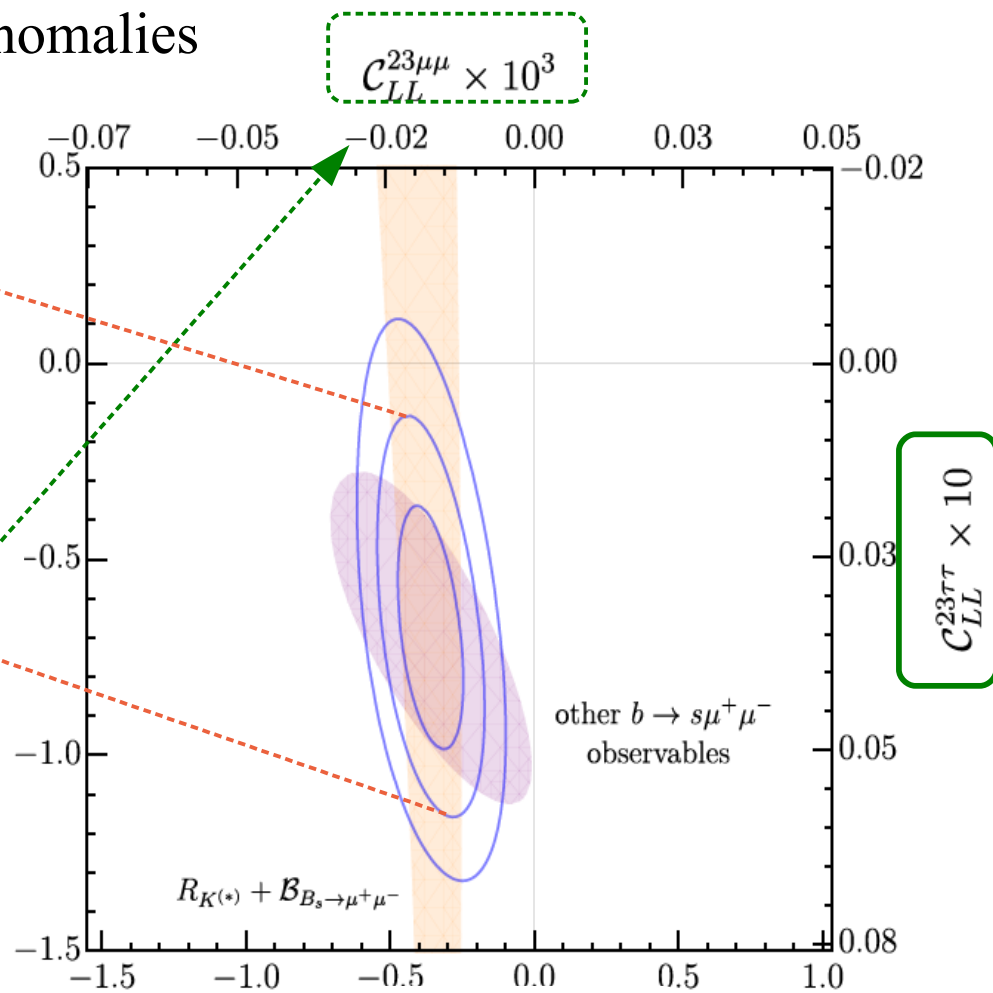
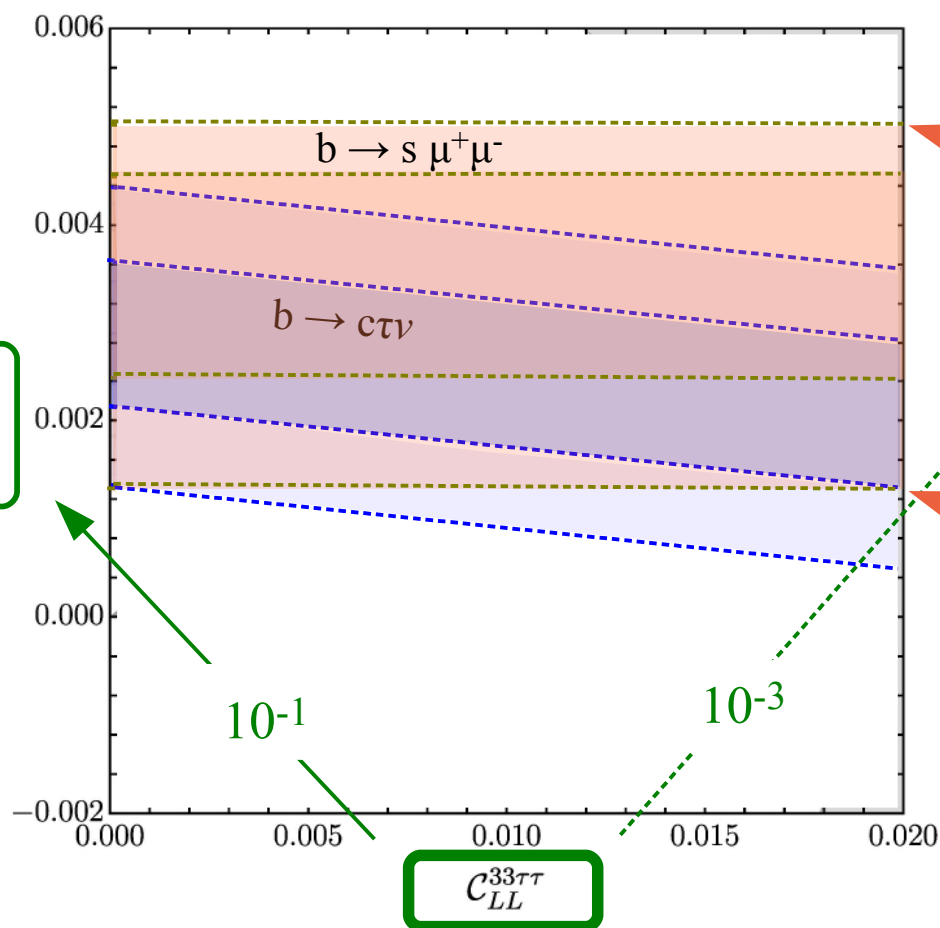
bounds from high-pT searches

► EFT considerations

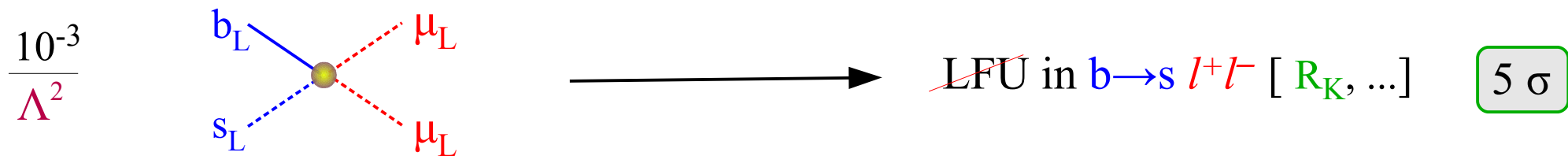
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- ✓ Nice consistency among the 2 sets of anomalies



► EFT considerations

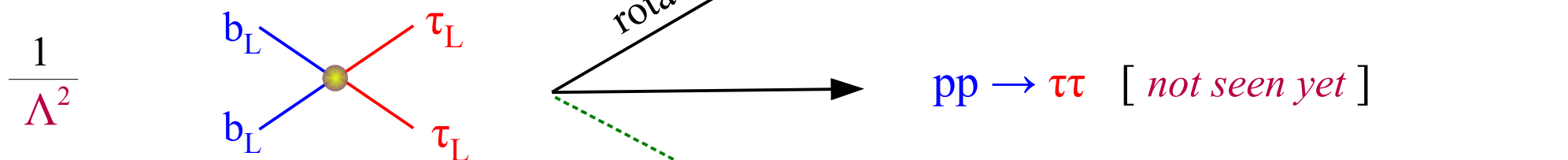
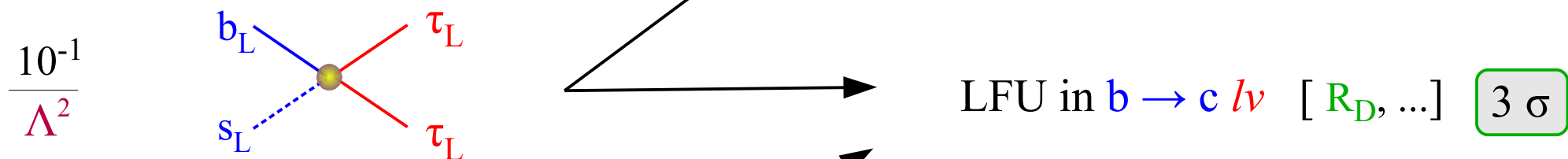
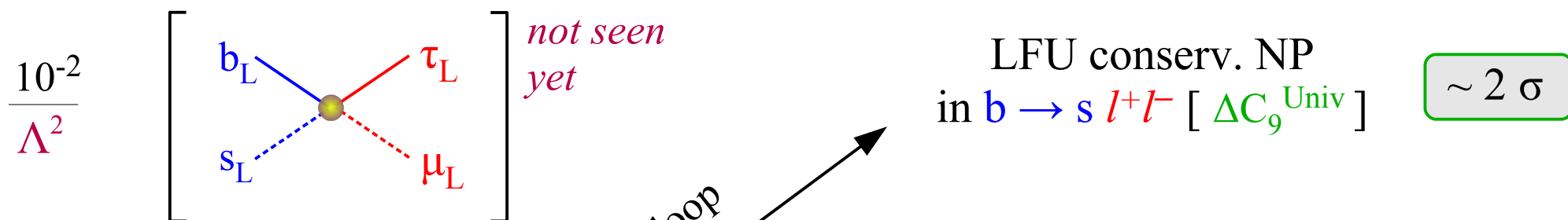
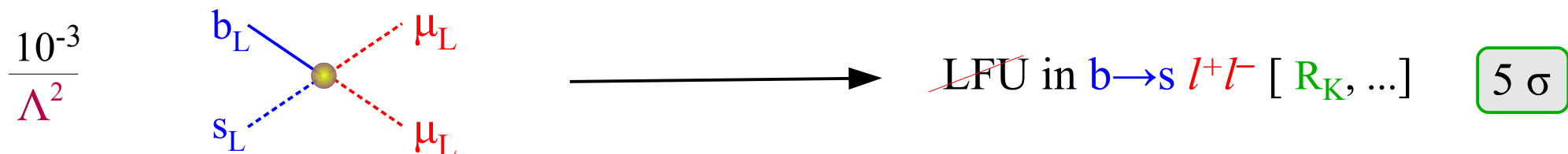


“natural”
connection

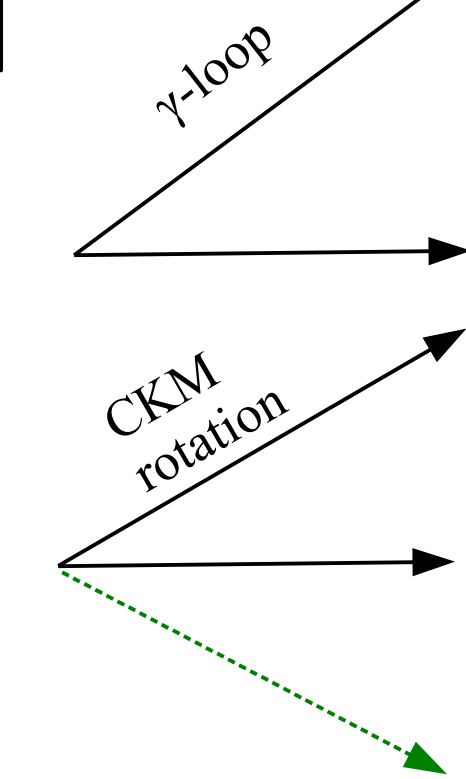


$\Lambda \approx 1.5 \text{ TeV}$

► EFT considerations



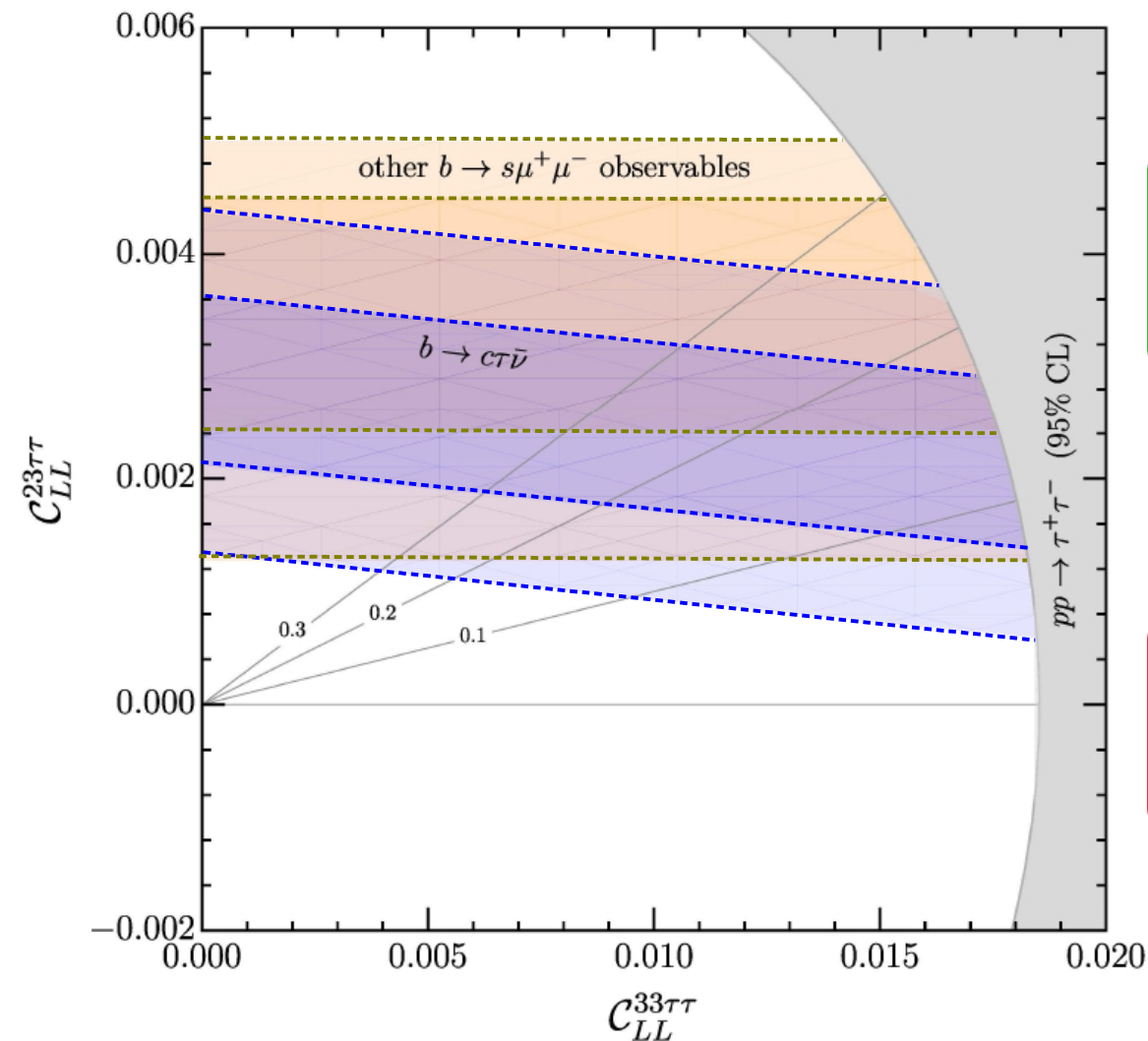
$\Lambda \approx 1.5 \text{ TeV}$



NP stabilizing the Higgs sector [*still a hope...*]

► 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:

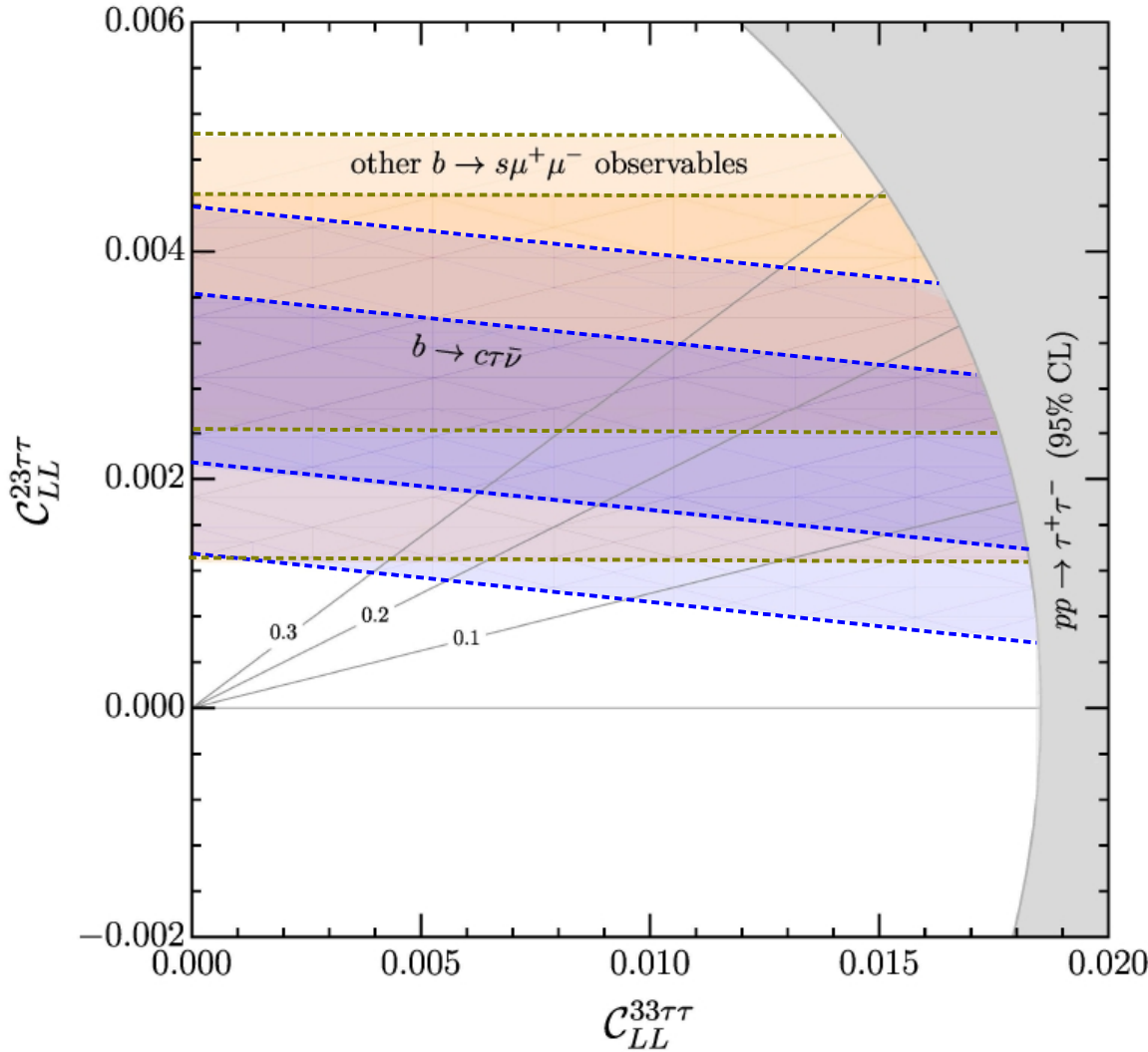
- ✓ $O(10^{-1})$ for each 2nd gen. q_L or l_L
- ✓ Nice consistency among the two sets of anomalies

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

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

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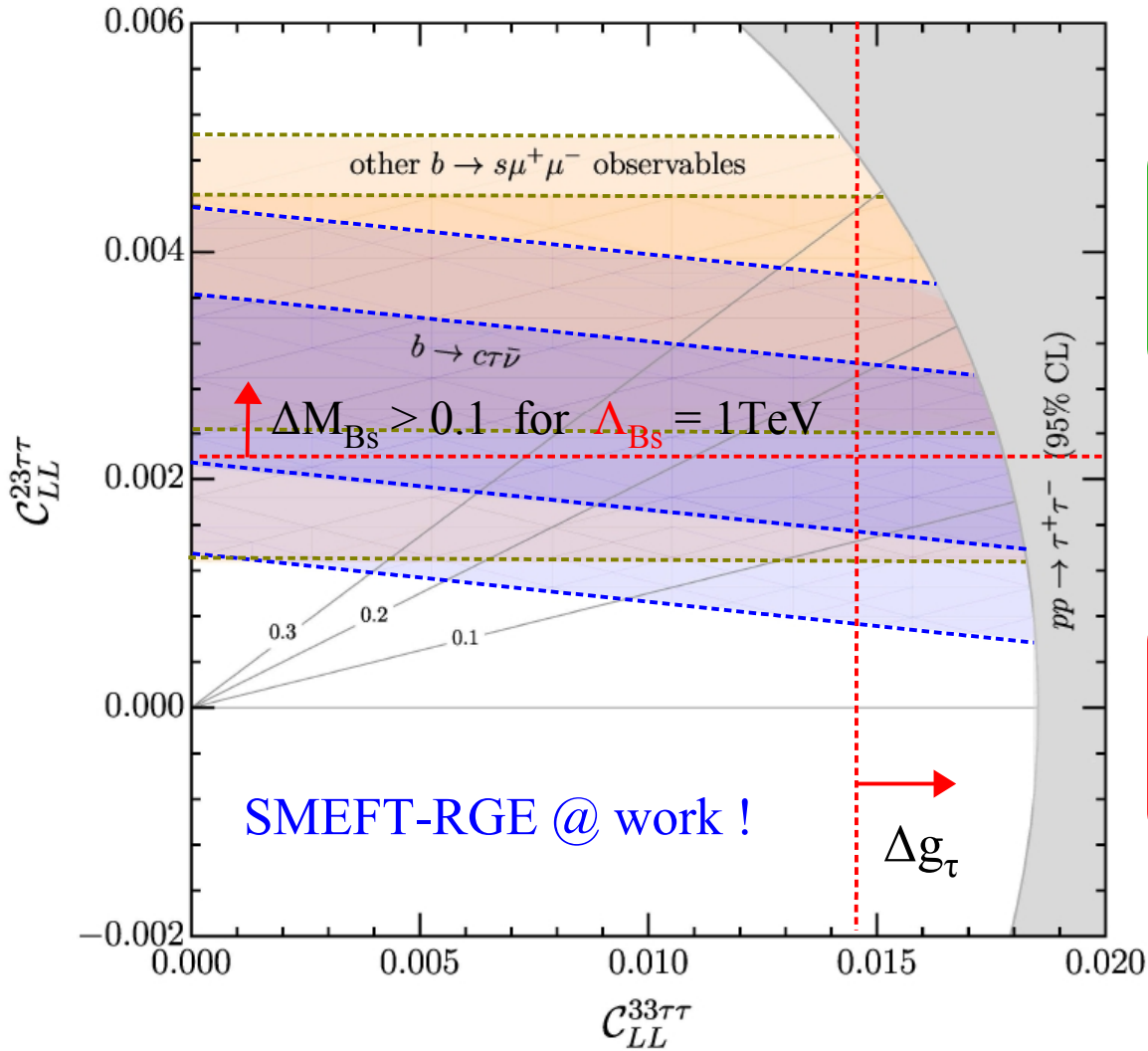


Leptoquarks

as tree-level mediators of the LFU anomalies

► EFT considerations

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

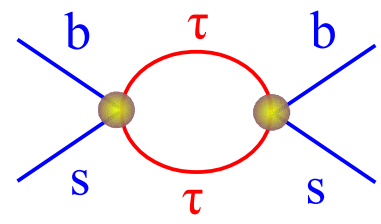


Pattern emerging from data:

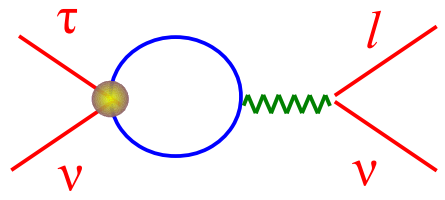
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$$\Delta M_{B_s} \sim (C^{23\tau\tau})^2 \Lambda_{B_s}^2$$



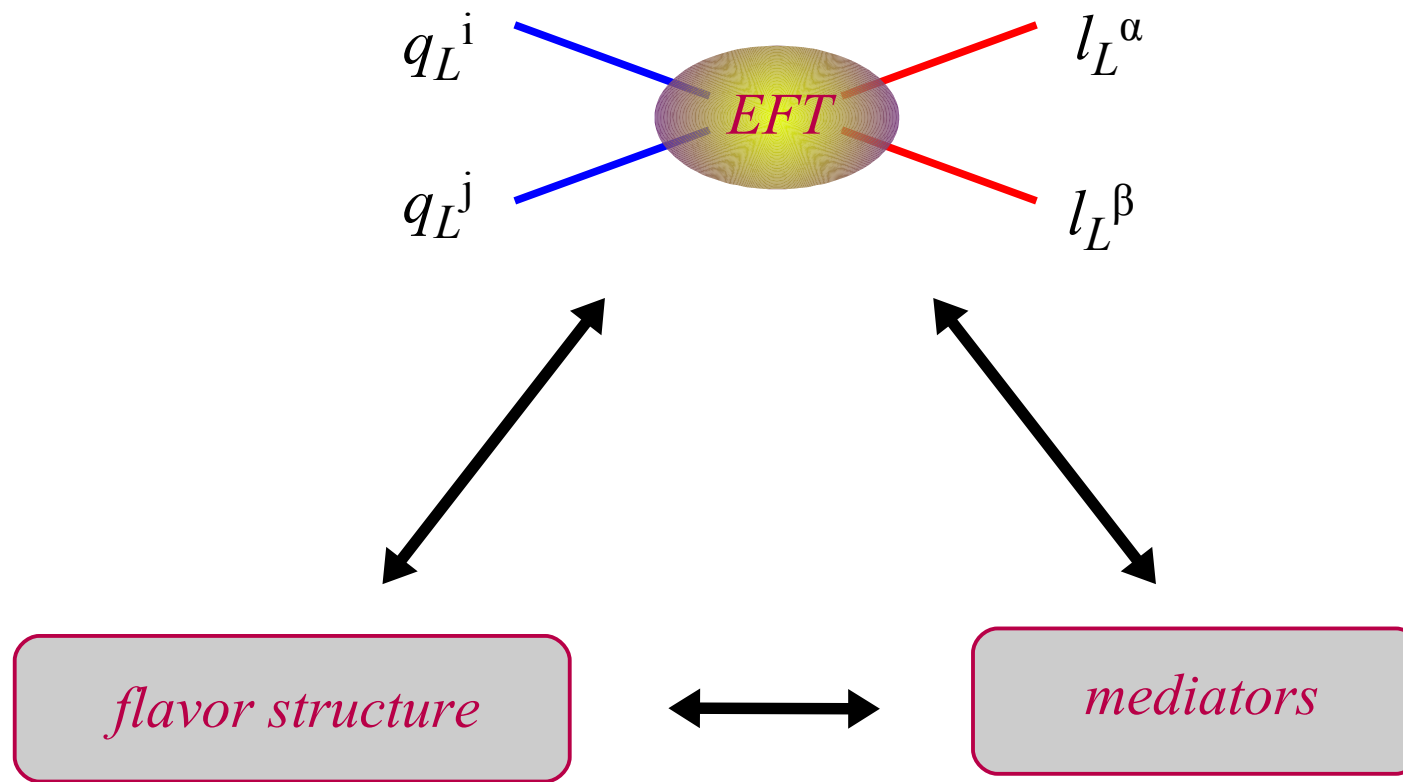
$$\Delta g_\tau \sim (C^{33\tau\tau}) \log(\Lambda/m_l)$$

Model-building considerations



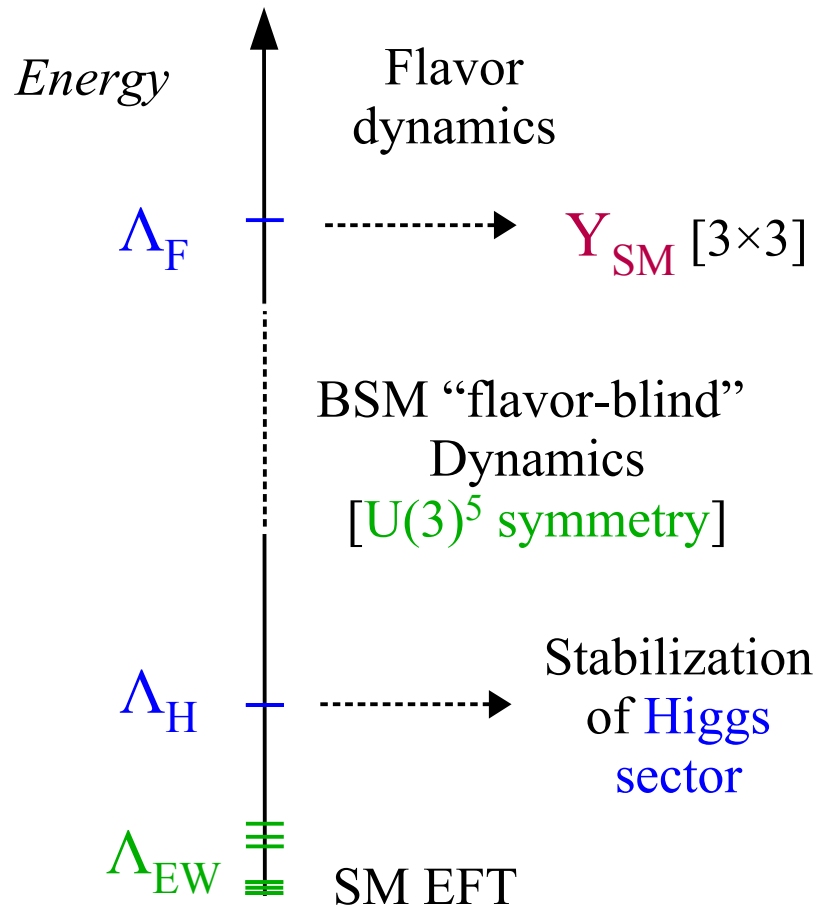
► Model-building considerations

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*



► Model-building considerations

The old (MFV) paradigm:



Main idea:

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

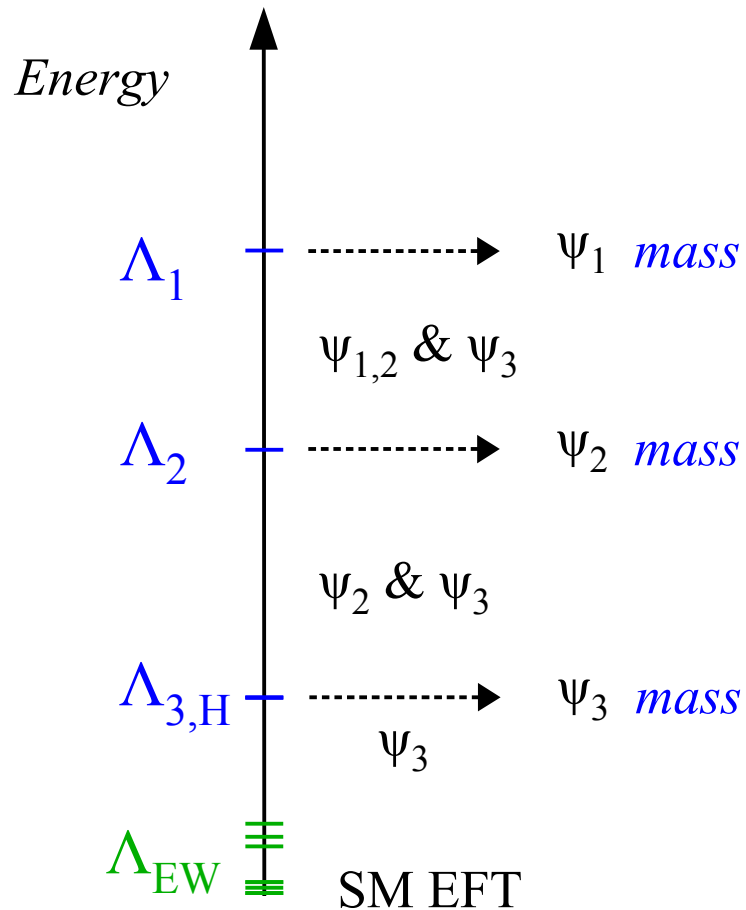


3 gen. = "identical copies"
up to high energies

► Model-building considerations

~~The old (MEV) paradigm~~

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

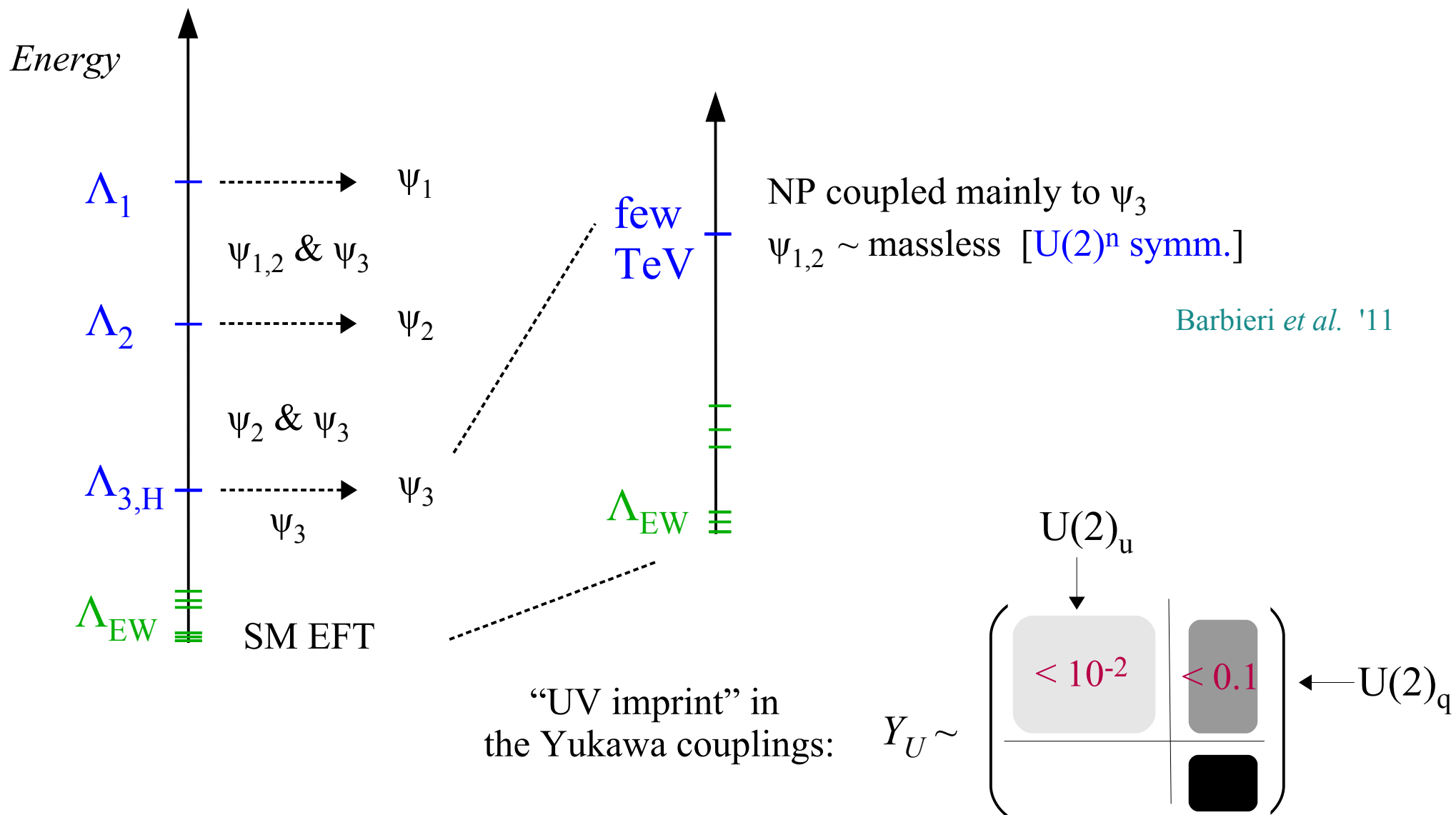


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► Model-building considerations

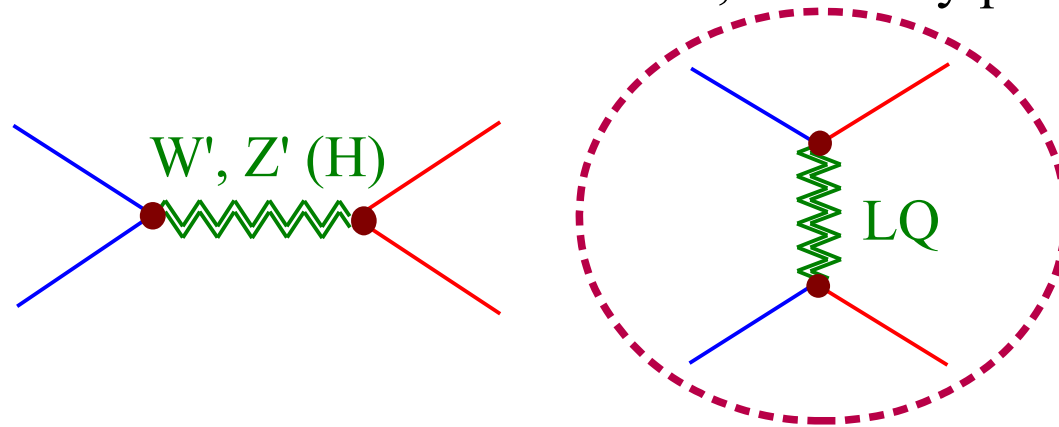
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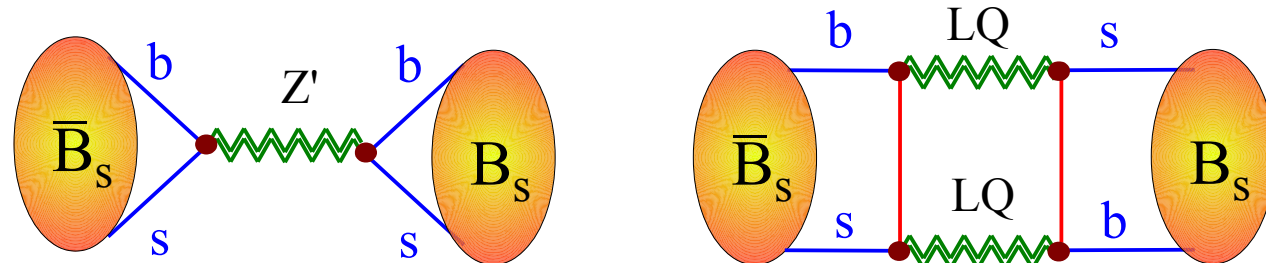
► Model-building considerations

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

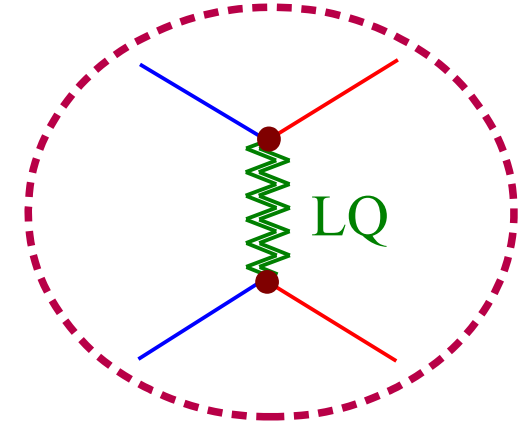


II. Direct searches:

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

► Model-building considerations

“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 & \mathcal{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**

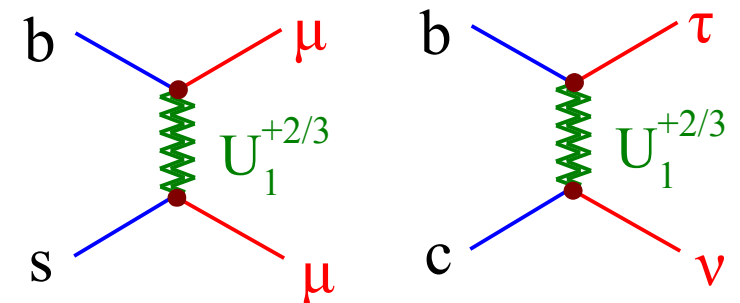
Assad *et al.* '17
Di Luzio *et al.* '17
Bordone *et al.* '17
Heeck & Teresi '18
+ ...
- **Vector LQ as techni-fermion resonances**
Barbieri *et al.* '15; Buttazzo *et al.* '16,
Barbieri, Murphy, Senia, '17 + ...
- **LQ as Kaluza-Klein excit.**
Megias, Quiros, Salas '17
Megias, Panico, Pujolas, Quiros '17
Blanke, Crivellin, '18 + ...

► Model-building considerations

Which LQ explains which anomaly?

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

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

► Model-building considerations

Considering the U_1 only

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

assuming a minimally-broken $U(2)^n$ structure for the couplings

$$\beta_L \sim \begin{pmatrix} & & \square \\ & \square & \blacksquare \\ \square & \blacksquare & \bullet \end{pmatrix} \quad \beta_R \sim \begin{pmatrix} & \square \\ \square & \blacksquare \end{pmatrix}$$

we can attempt a global fit of all low-energy data (anomalies + EWPO + flavor), taking into account all the RG effects

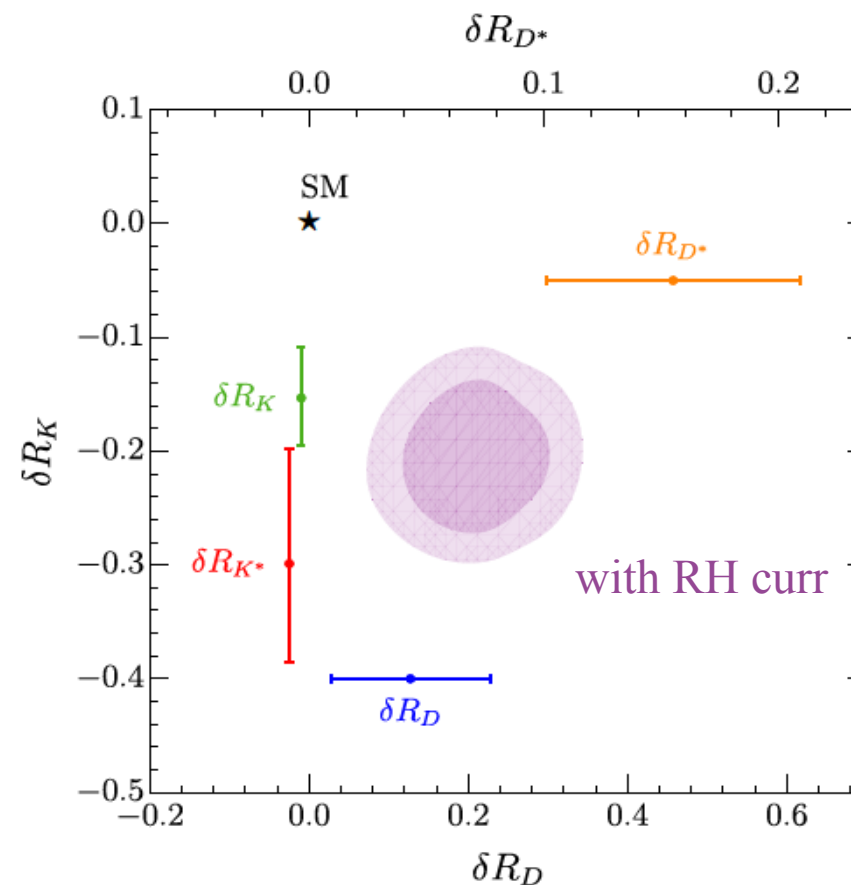
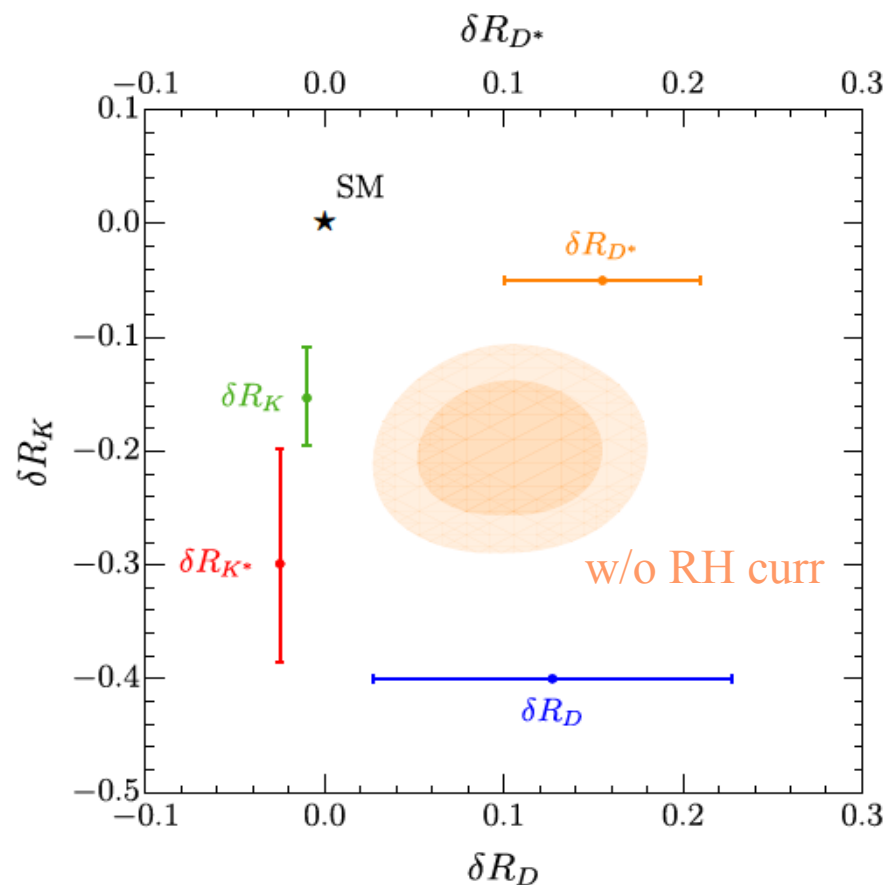
$$M_U \rightarrow \text{EW scale [[SMEFT-RGE @ work](#)]}$$

► Model-building considerations

Considering the U_1 only

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

→ excellent description of all available low-energy data:



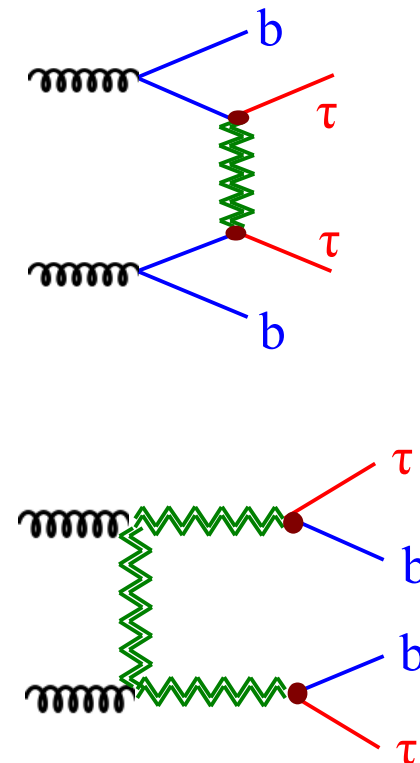
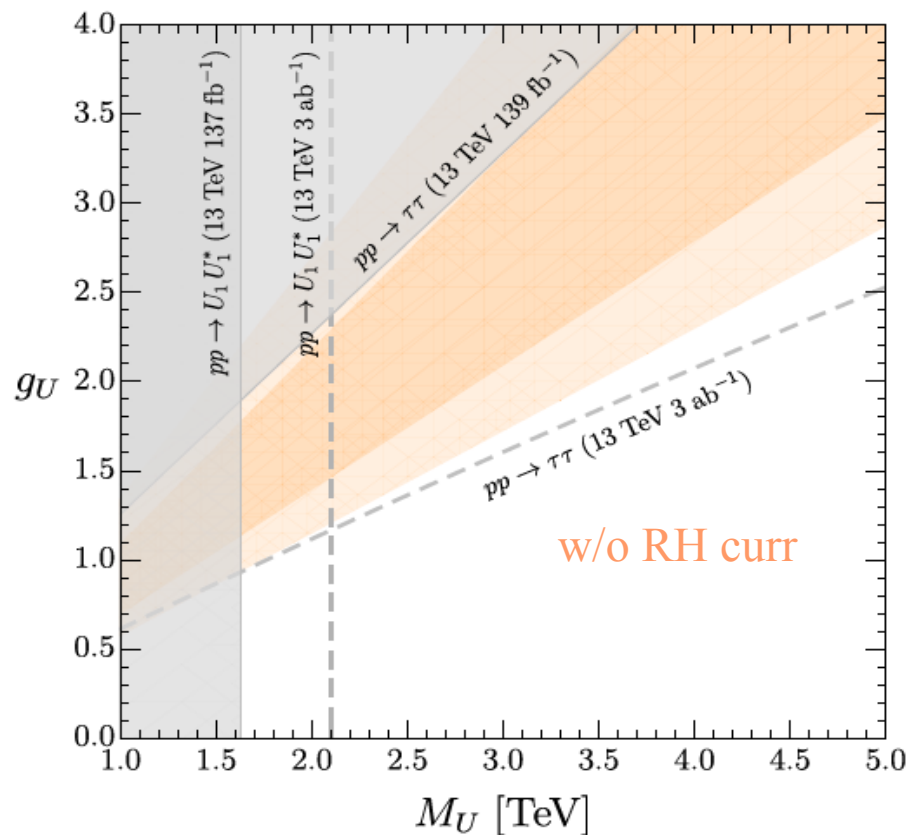
► Model-building considerations

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

→ excellent description of all available low-energy data

→ consistent with present high-energy data → *signals within the reach of HL-LHC:*



► Model-building considerations

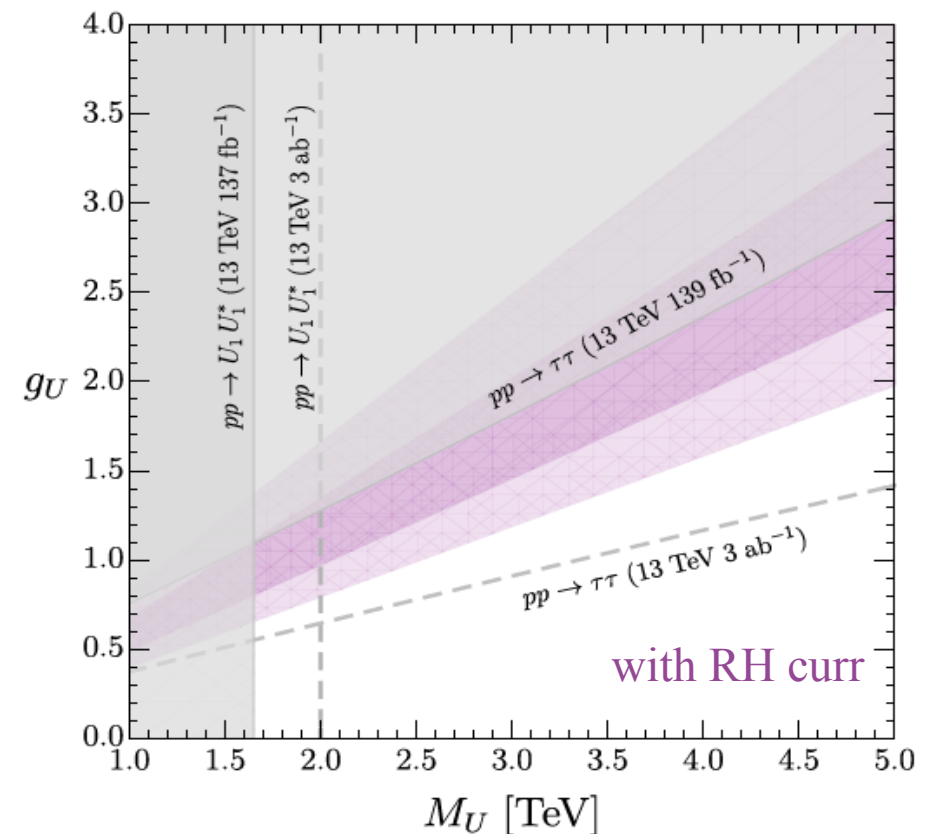
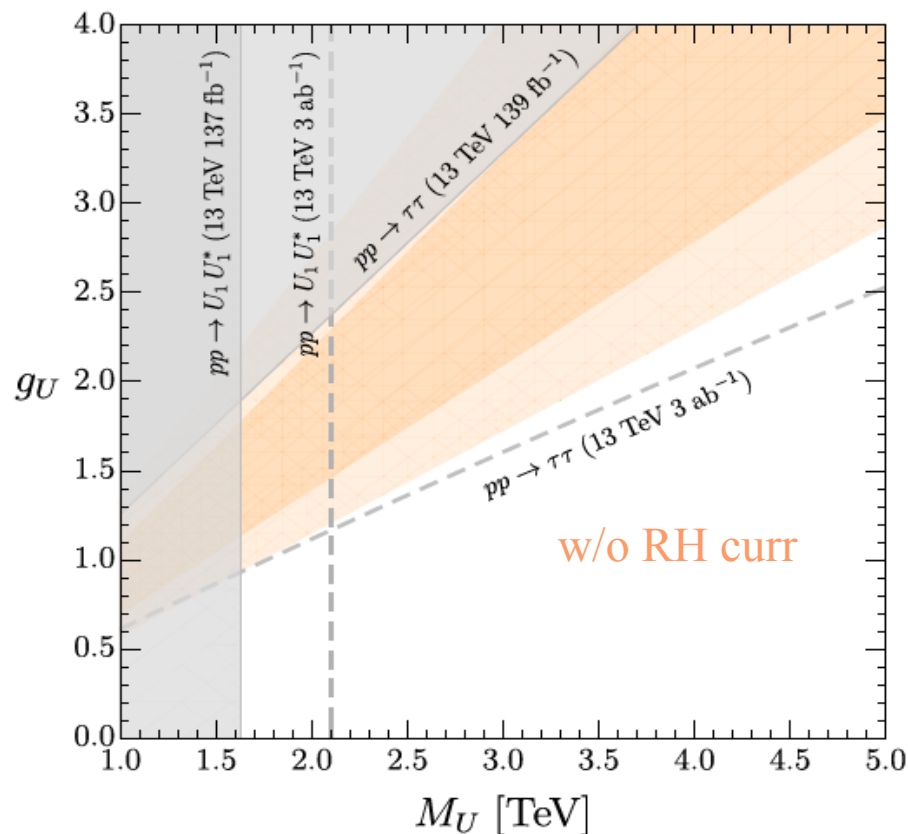
Considering the U_1 only

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

→ excellent description of all available low-energy data

→ consistent with present high-energy data → *signals within the reach of HL-LHC*:

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

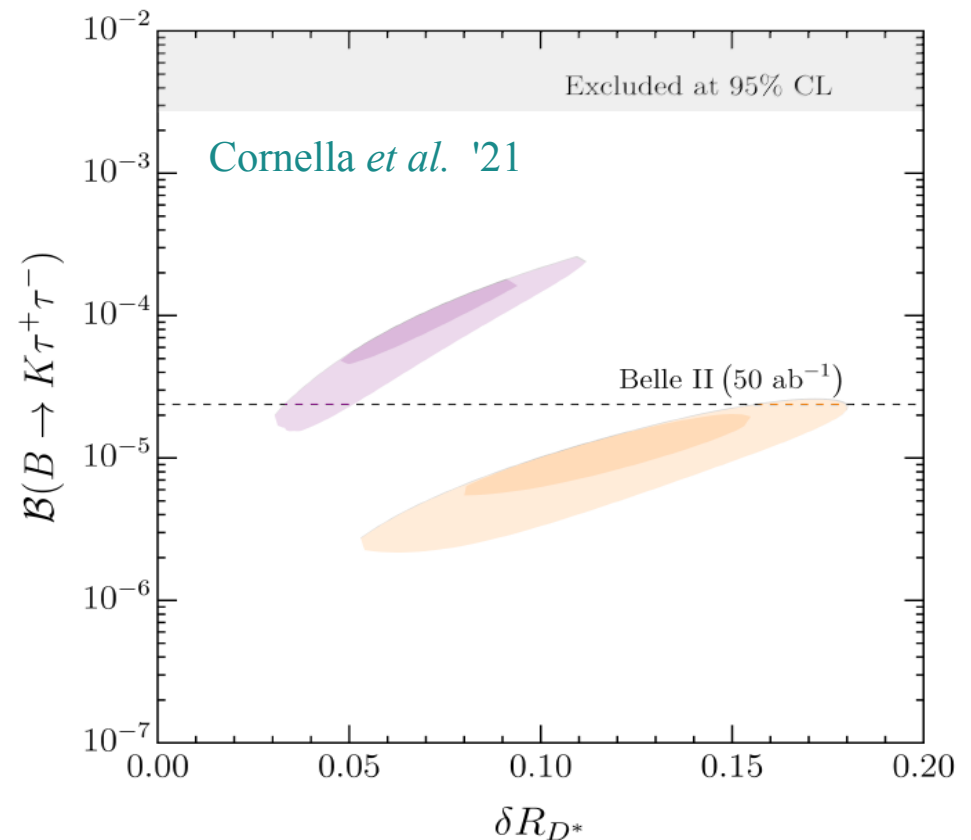
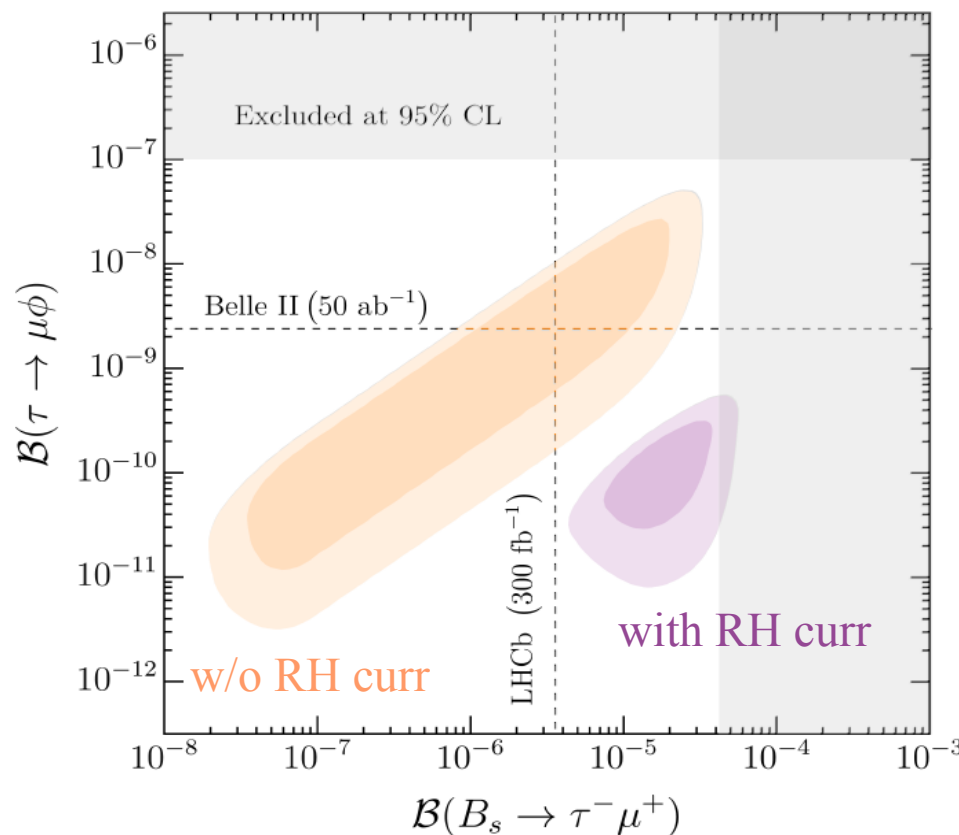


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- excellent description of all available low-energy data
- consistent with present high-energy data → *signals within the reach of HL-LHC*
- *interesting implications also for future low-energy searches:*



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

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

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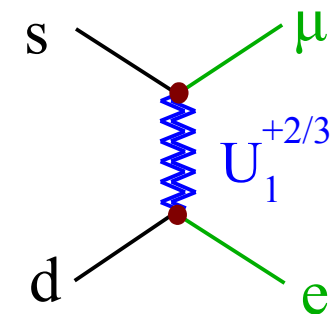
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The problem of the “original PS model” are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200 \text{ TeV}$ from $K_L \rightarrow \mu e$]

Attempts to solve this problem simply adding extra fermions or scalars

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

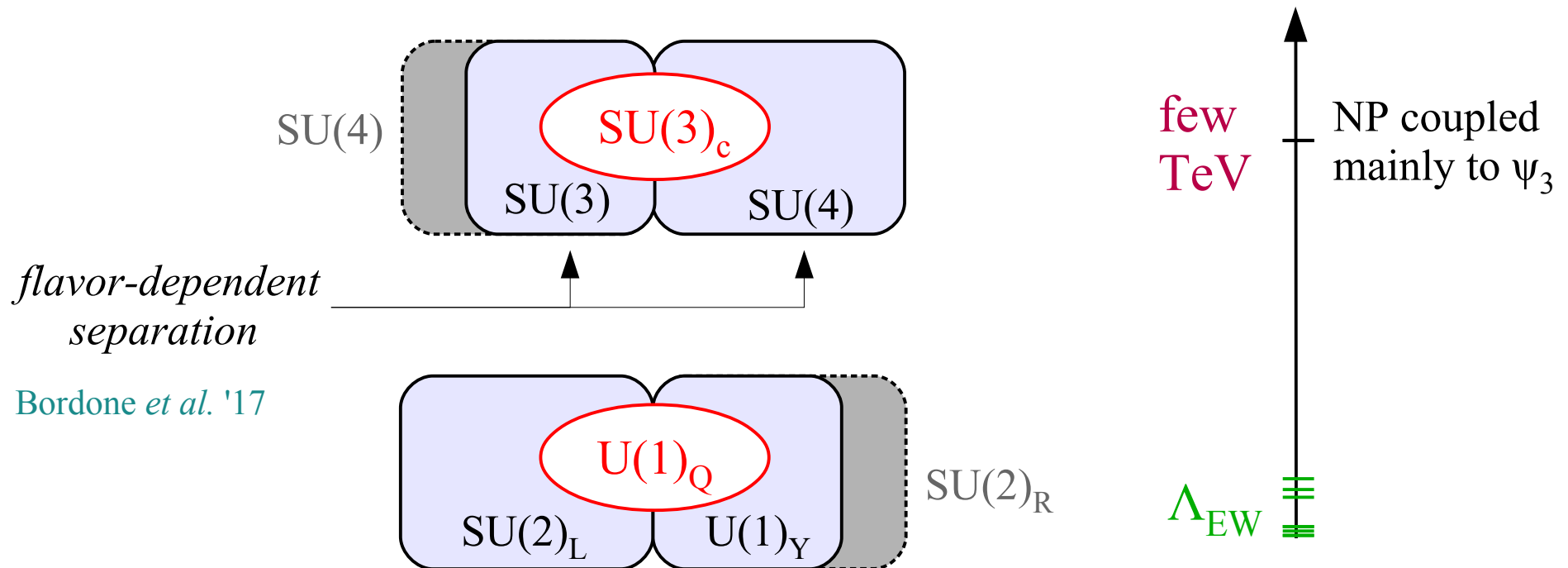


► Speculations on UV completions

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

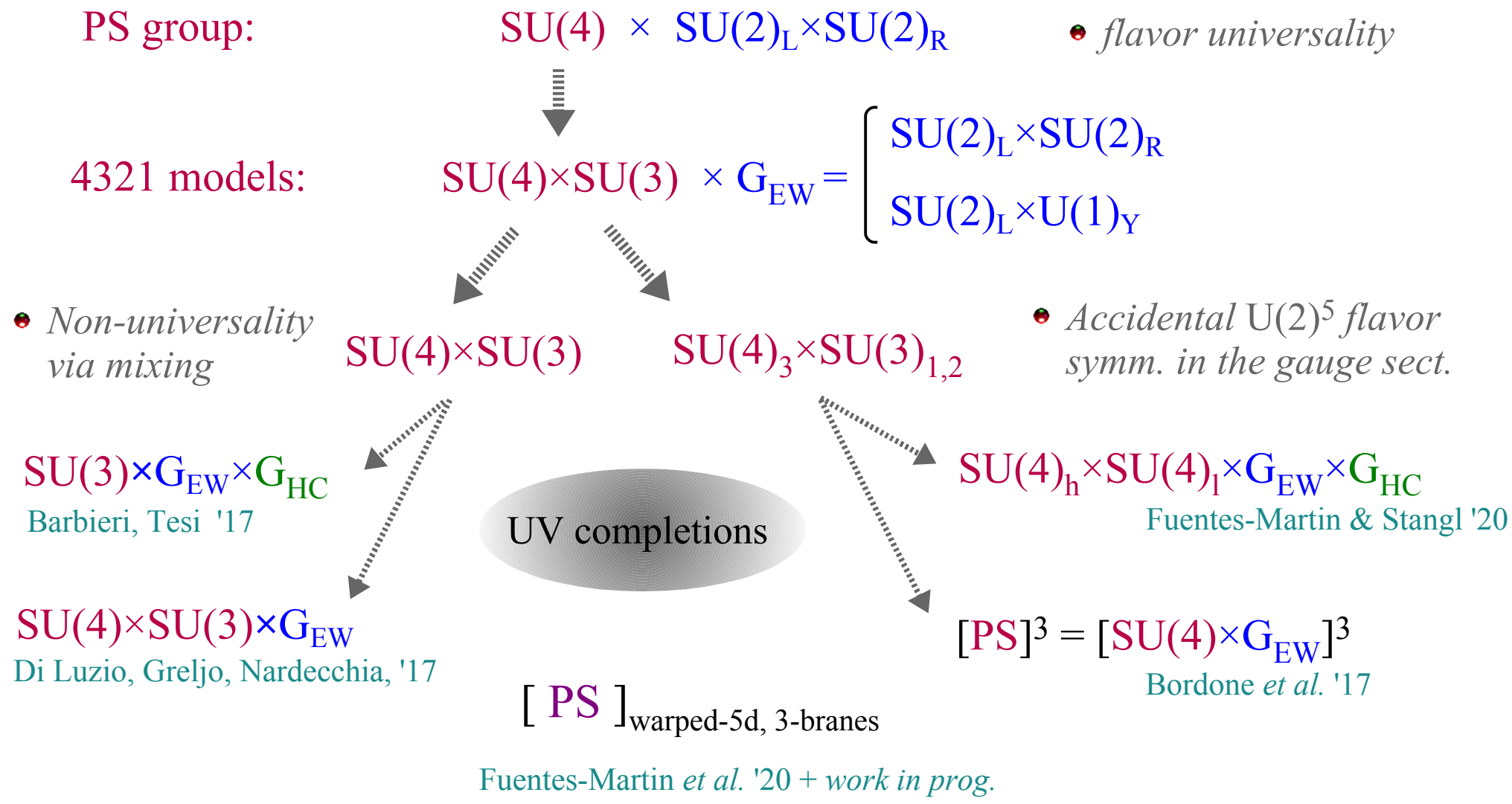
PS group: $SU(4) \times SU(2)_L \times SU(2)_R$ • *flavor universality*

4321 models: $SU(4) \times SU(3) \times G_{EW} = \begin{cases} SU(2)_L \times SU(2)_R \\ SU(2)_L \times U(1)_Y \end{cases}$ Di Luzio, Greljo, Nardecchia, '17



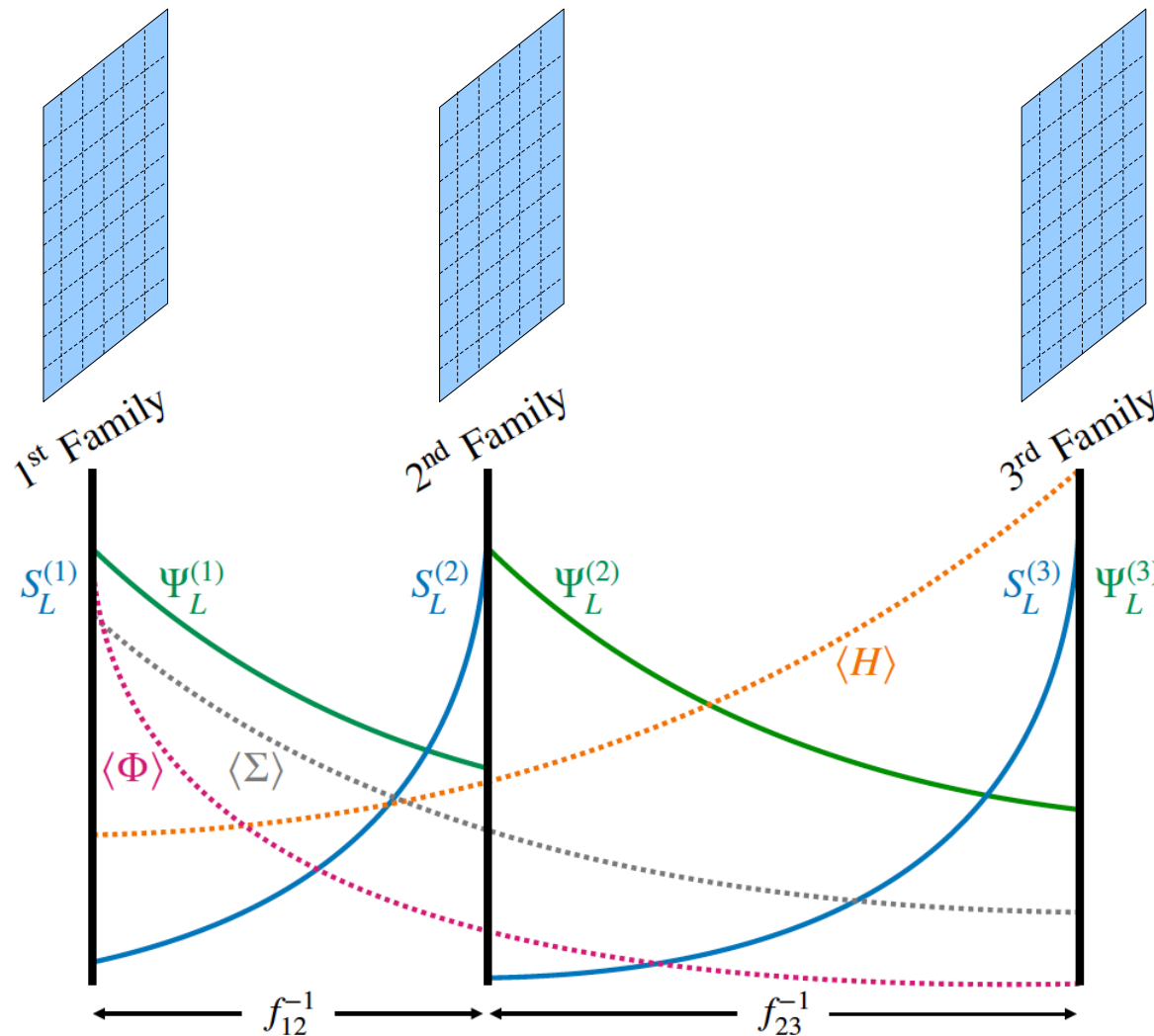
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► Speculations on UV completions

An ambitious attempt to construct a *full theory of flavor* has been obtained embedding the Pati-Salam gauge group (or variations) 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

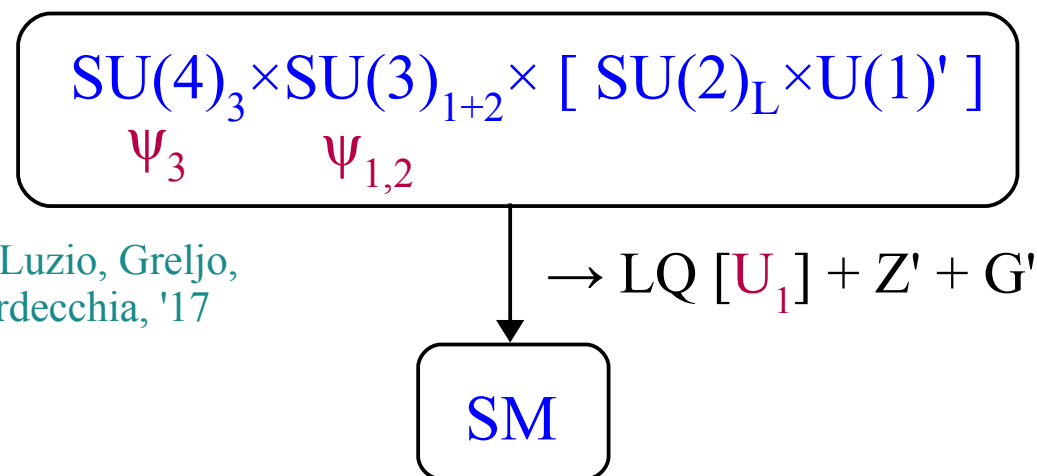
In most *PS-extended models* collider and low-energy pheno are controlled by the effective 4321 gauge group that rules TeV-scale dynamics

Despite the apparent complexity, the construction is highly constrained

Renormalizable structure achieved with vector-like fermions

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
q_L^i	1	3	2	1/6
u_R^i	1	3	1	2/3
d_R^i	1	3	1	-1/3
ℓ_L^i	1	1	2	-1/2
e_R^i	1	1	1	-1
ψ'_L	4	1	2	0
ψ'_u	4	1	1	1/2
ψ'_d	4	1	1	-1/2
χ^i_L	4	1	2	0
χ^i_R	4	1	2	0
H_1	1	1	2	1/2
H_{15}	15	1	2	1/2
Ω_1	$\bar{4}$	1	1	-1/2
Ω_3	$\bar{4}$	3	1	1/6
Ω_{15}	15	1	1	0

Di Luzio, Greljo, Nardecchia, '17



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

► Speculations on UV completions

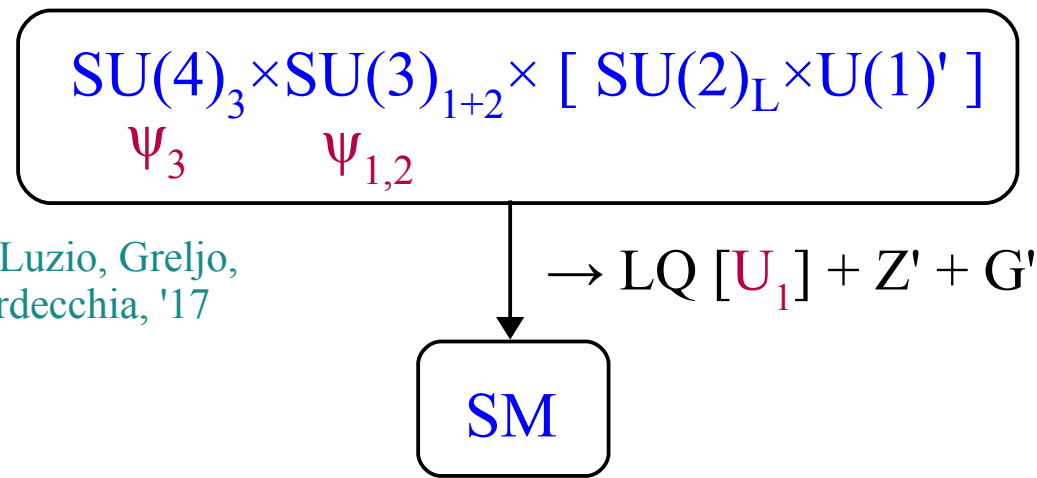
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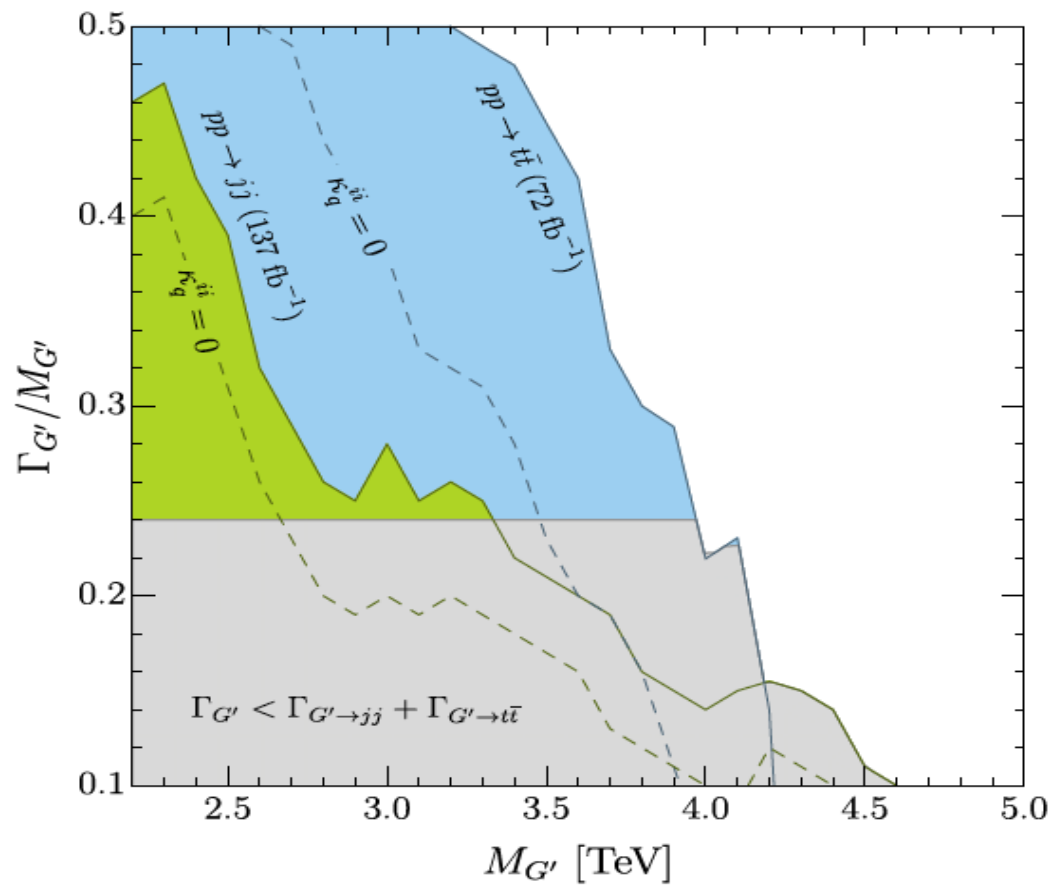
New striking collider signature:

G' (“coloron”) = heavy color octet, coupled mainly to 3rd generation quarks

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



Di Luzio, Greljo, Nardecchia, '17



Conclusions

- Flavor is an essential ingredient to understand the structure of the SMEFT. This statement, which we deduce already by the SM Yukawa structure, is reinforced by the recent anomalies
- 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 3rd 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

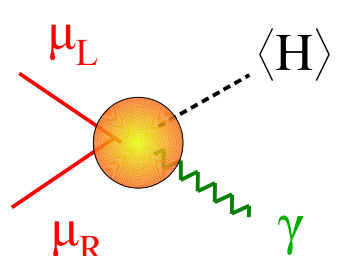


Very interesting (near-by!) future...
(both on the exp., the pheno,
and the model-building point of view)



► What about $g-2$?

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



A Feynman diagram showing a muon loop. Two red lines represent the muon legs, labeled μ_L and μ_R . A dashed line represents the Higgs boson, labeled $\langle H \rangle$. A wavy green line represents a photon, labeled γ . The loop is depicted as a yellow-orange sphere with internal lines.

$$\Delta a_\mu = (a_\mu^{\text{exp}} - a_\mu^{\text{SM}})$$

$$\approx (a_\mu^{\text{SM}})^{\text{EW}} \quad \rightarrow \quad \Lambda \sim \begin{cases} 100 \text{ GeV} & \text{(helicity suppression } \sim m_\mu \text{ as in SM)} \\ 10 \text{ TeV} & \text{(remove helicity suppression. } m_\mu \rightarrow m_t) \end{cases}$$

$\sim 4 \sigma$

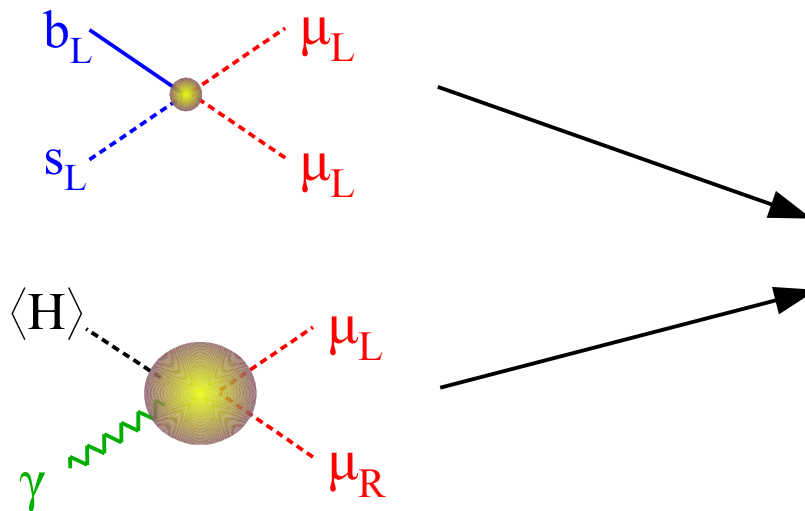
(more controversial...)

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

► What about $g-2$?

The situation might be different if the charged-current anomalies will go away...

A possible alternative “story”:



Possible unified description by means of a new interaction with special role for muons (and maybe tau's)

→ Z' is back !

Greljo, Stangl, Thomsen '21
 Baum *et al.* '21
 Davighi, '21
 Altmannshofer *et al.* '21
 + *many others...*

- Connections to origin of the Yukawa is lost
- Exact flavor symmetries needed to avoid $\mu \rightarrow e\gamma$
 (→ *different behavior of quarks & leptons*)