Flavor Physics: old problems and recent hopes

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[*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]

European Research Council
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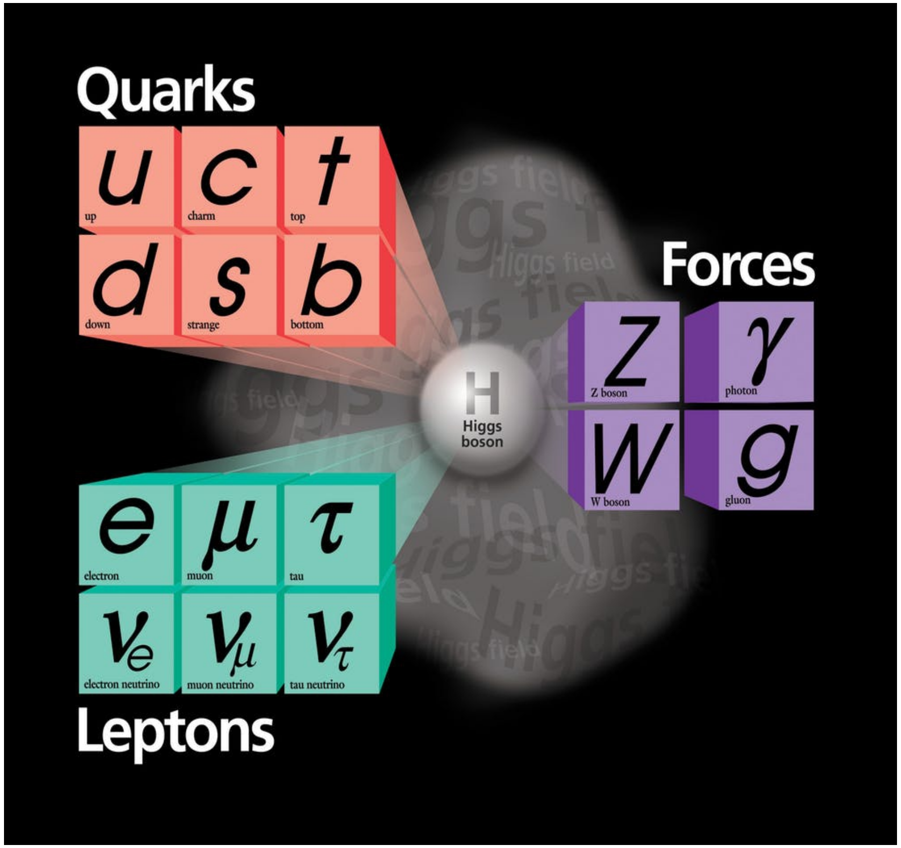
▶ Introduction

The Standard Model (SM) is a remarkably simple Quantum Field Theory (QFT) that describes well (*almost...*) all microscopic phenomena that we observe in Nature

$$\mathscr{L}_{SM} = \mathscr{L}_{gauge}(\psi_i, A_a) \quad + \quad \mathscr{L}_{Higgs}(H, A_a, \psi_i)$$



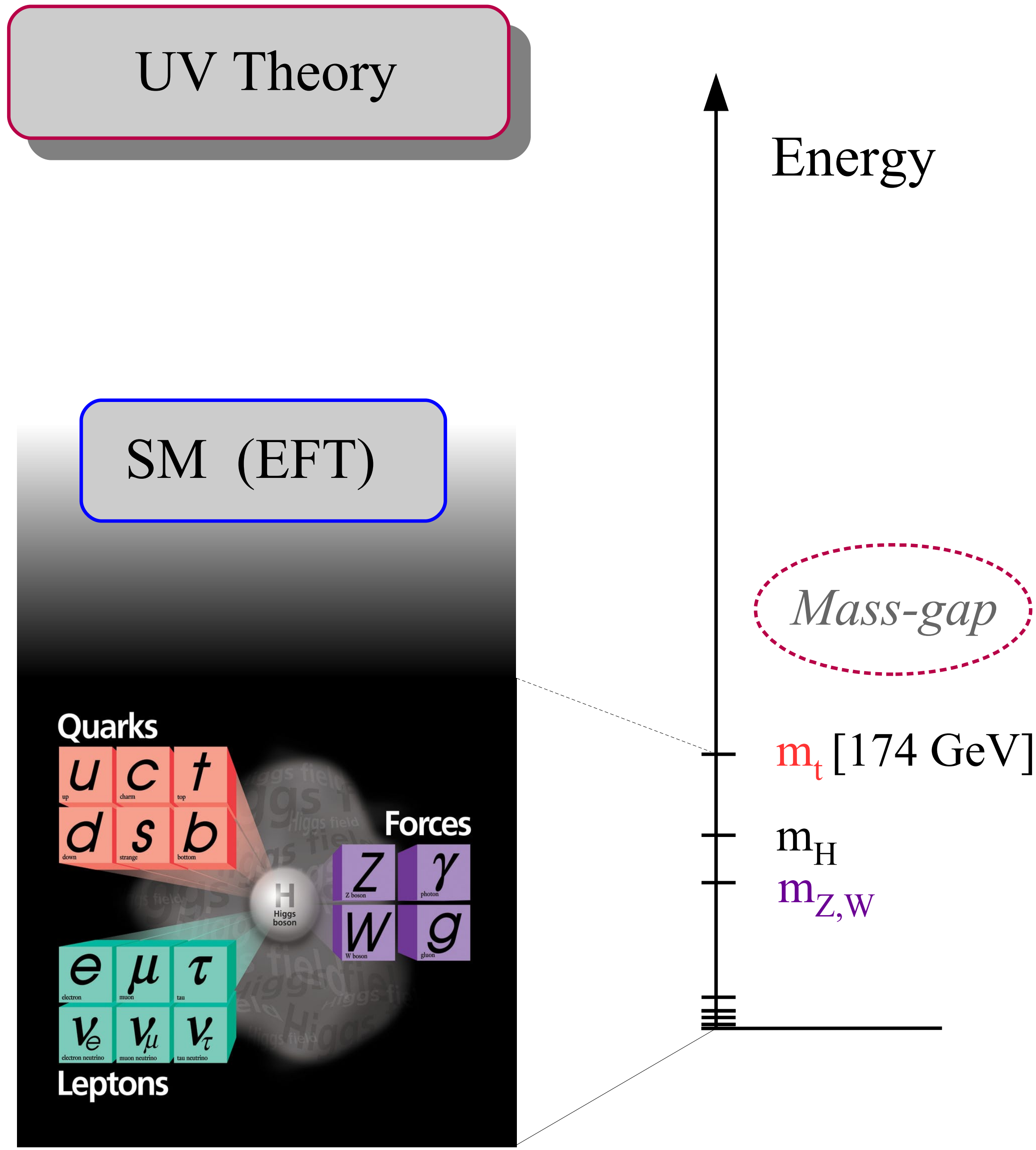
Introduction

As for any QFT, we believe the SM is only an Effective Field Theory (EFT), i.e. the low energy limit of a more complete theory with more degrees of fredom

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

We identified the *long-range* properties of this EFT, but we struggle to underatand

- *the nature of short-distance dynamics*
- *why such peculiar structure emerges at low-energies*



Introduction

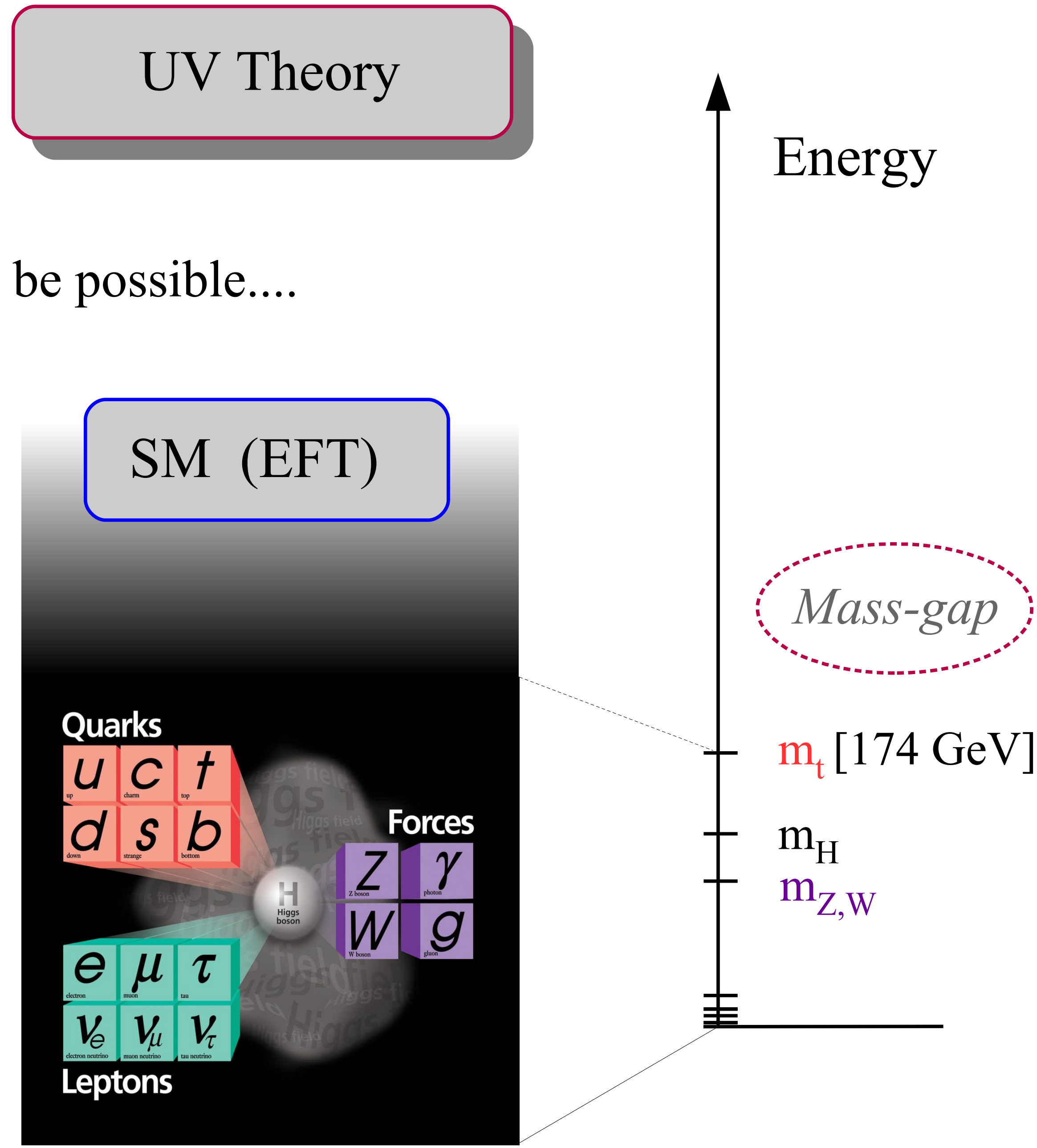
Ideally, we woul like to probe the UV *direclty,* via high-energy experiments

However, for > 30 years this will not be possible....

For the time being, we can only extract *indirect* UV infos exploring the low-energy limit of the EFT.

Many infos, with 2 clear messages:

- *sevral tuned* (SM) *couplings*
- *several* *accidental* (*approximate*) *symmetries*



Introduction

A closer look to the "SM-EFT":

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

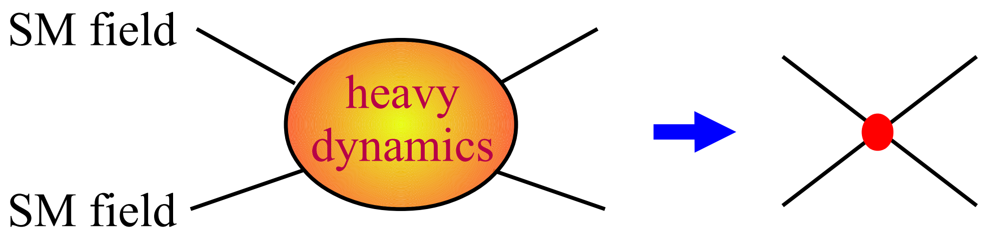
SM (EFT)

Interactions surving @ large distances
(operators with $d \leq 4$)

Long-range forces
of the SM particles
+
ground state (Higgs)

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

"Remnant" of the heavy dynamics at low energies



Introduction

The (indirect) imprints of the UV dynamics manifest themselves in two distict ways:

UV Theory

SM (EFT)

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

Un-natural/tuned values of low-energy couplings

qualitative UV imprint

Evidence of higher-dim. operators (↔ violations of accidental symmetries)

quantitative UV imprint

Introduction

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UV Theory

↓

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Un-natural/tuned values of low-energy couplings

qualitative UV imprint

Notable case: *instability of the Higgs mass term under quantum corrections* [electroweak hierarchy problem]:

$$m_H^2\big|_{\Lambda} + \text{NP} \;\; \Delta m_H^2 \sim \Lambda^2 \;\rightarrow\; m_H^2\big|_{\text{Phys}}$$

(*some*) New Physics (*coupled at least to* Higgs & top) in the TeV domain

Introduction

The (indirect) imprints of the UV dynamics manifest themselves in two distict ways:

UV Theory

SM (EFT)

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Un-natural/tuned values of low-energy couplings

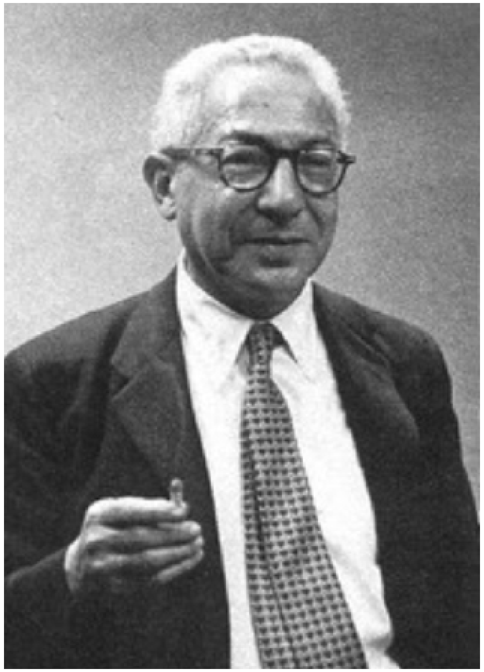
Evidence of higher-dim. operators (↔ violations of accidental symmetries)

<u>*qualitative*</u>
UV imprint

<u>*quantitative*</u>
UV imprint

Flavour physics
is telling us <u>much more on both these aspects !</u>
(*and might tell us even more in the near future...*)

The Flavor Problem(s)



Isidor Issac Rabi

(1898—1988)

The Flavor Problem(s)

$$\mathscr{L}_{\text{SM-EFT}} = \boxed{\mathscr{L}_{\text{gauge}}} + \mathscr{L}_{\text{Higgs}} + \ldots$$

UV Theory

"trivial" projection from the UV

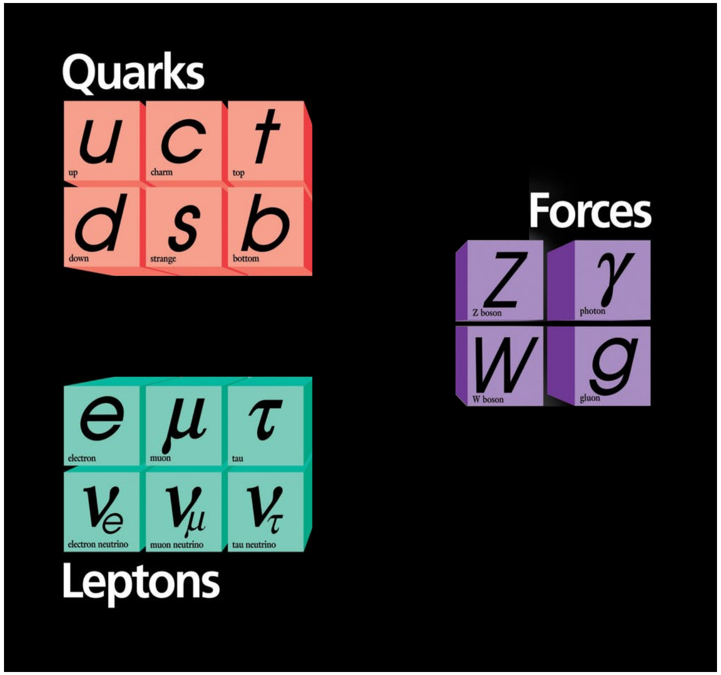
Long-range forces of the SM particles

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]



The Flavor Problem(s)

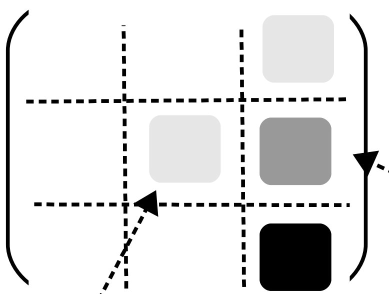
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \boxed{\mathscr{L}_{\text{Higgs}}} + \ldots$$

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 <u>does not appear to be accidental</u>:

E.g.:

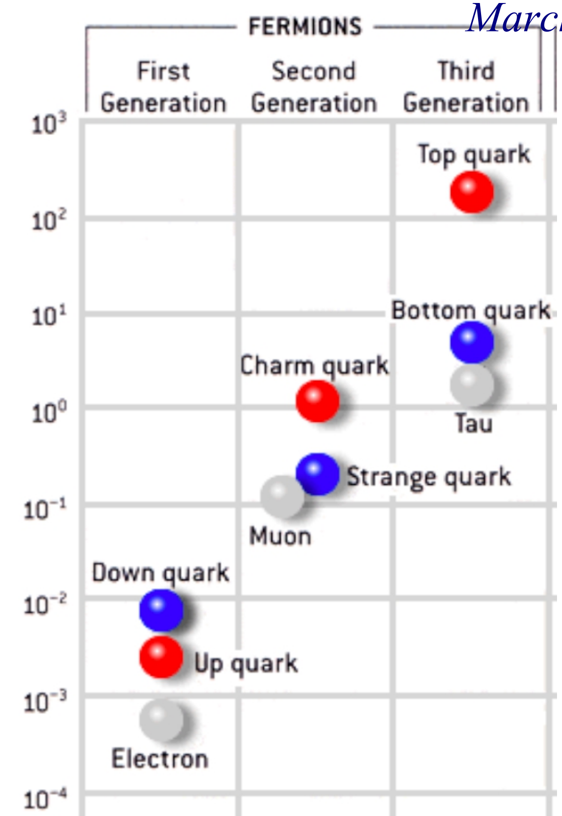
$Y_U \sim$ 

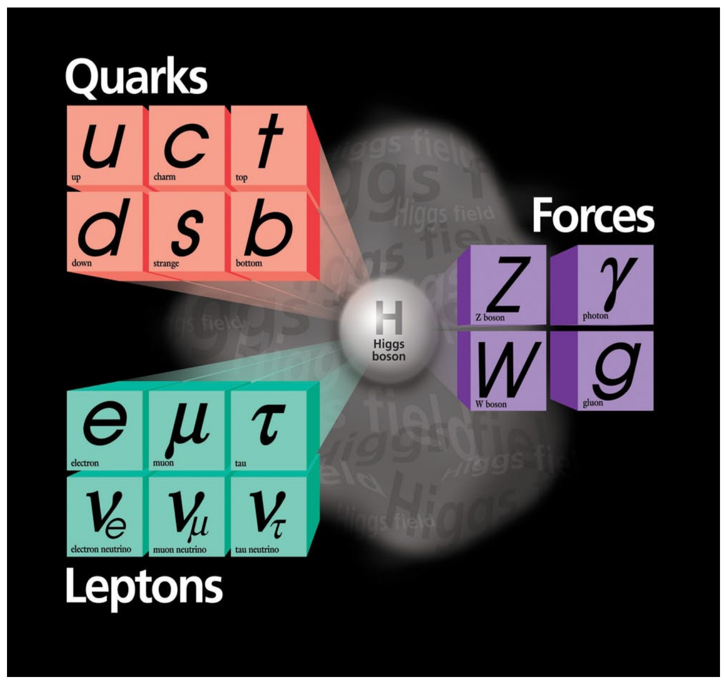
$V_{ts} \approx 0.04$

$y_c \approx 0.005$

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

The SM Flavor problem





The Flavor Problem(s)

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

Large flavor symmetry

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

Flavor-degeneracy broken by the Yukawa interaction

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

"Peculiar" breaking structure

Exact & approximate (*accidental* ?) symmetries

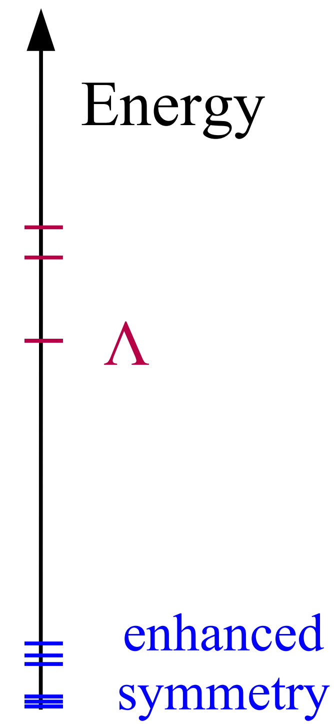
Eg:

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

▶ *The Flavor Problem(s)* [*a brief detour…*]

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

(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*]

The Flavor Problem(s) [*a brief detour…*]

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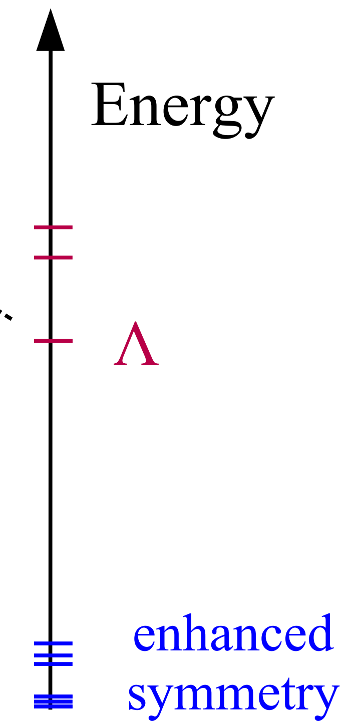

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If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

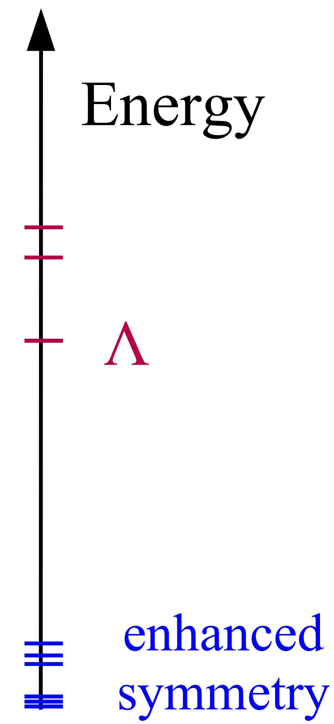
Violations of
accidental symmetries

▶ *The Flavor Problem(s)* [*a brief detour...*]

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

[QCD+QED]-EFT $\qquad \mathcal{L}_{mf}$

Violations of
accidental symmetries



Well-known examples from the past...

Eg: *Low-energy theory:* QED + QCD

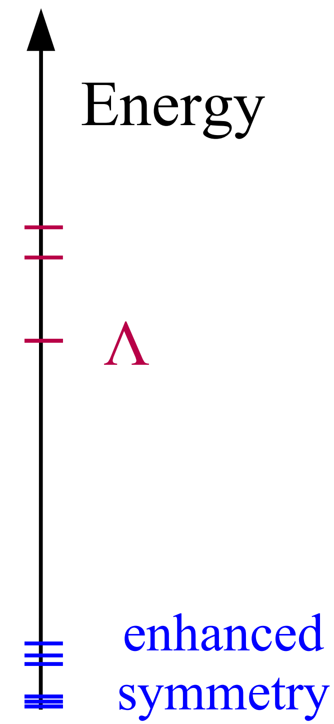
Accidental symm.: Flavor [$U(1)^{n_f}$]

Violated by: <u>Weak interactions</u> $\rightarrow G_F \sim (250\ \text{GeV})^{-2}$

The Flavor Problem(s) [*a brief detour…*]

$$\mathcal{L}_{\cancel{\text{SM-EFT}}\atop [\text{SM-2]-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \underbrace{\sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}}$$

Violations of accidental symmetries



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Accidental symm.: Flavor [$U(1)^{n_f}$]

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Eg: *Low-energy theory:* SM, 2 generations

Accidental symm.: CP

Violated by: "Super-weak" interaction [L. Wolfenstein]:

$$\frac{e^{i\delta}}{\Lambda^2}\,(\bar{s}\,\Gamma\, d)^2 \qquad\qquad \frac{1}{\Lambda^2} \sim (10^4\ \text{TeV})^{-2} \sim \frac{(G_F\, m_t V_{ts} V_{td})^2}{4\pi^2}$$

The Flavor Problem(s) [*a brief detour...*]

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

Violations of
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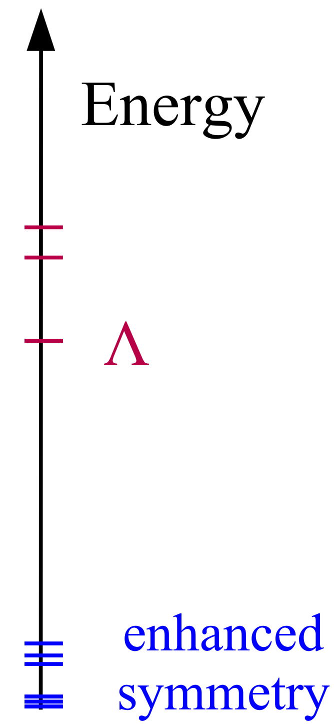


Well-known examples from the past...

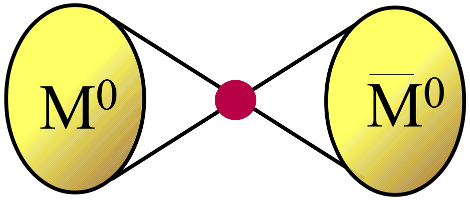
...the violations of Lepton Flavor Universality
recently reported by experiments (B-physics *anomalies*)
belong to this category

The Flavor Problem(s)

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

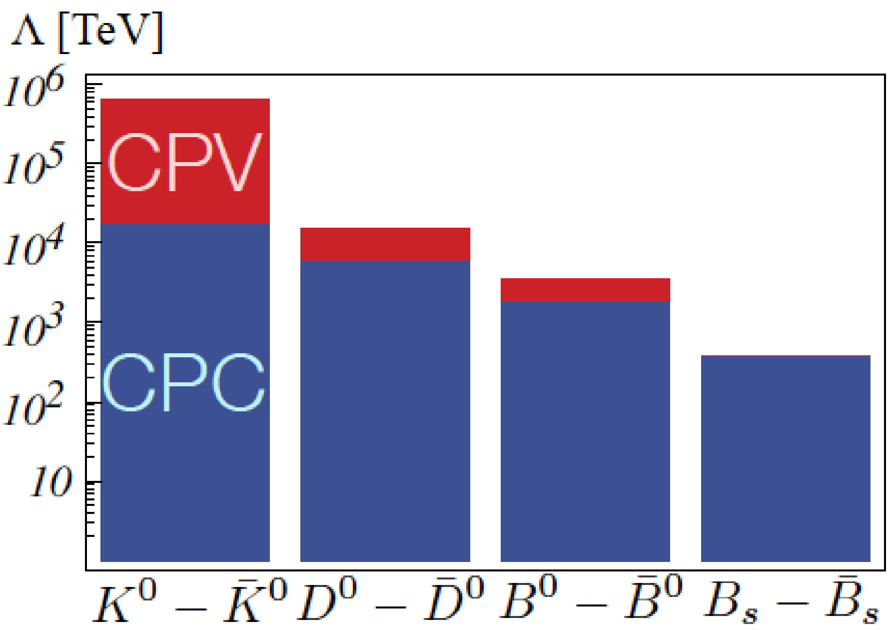
In principle, we could expect many violations of the accidental symmetries from the heavy dynamics → *new flavor violating effects*

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

The Flavor Problem(s)

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

Flavor-degeneracy:
U(3)^5 symmetry

U(3)^5 symmetry
broken by
Yukawa couplings

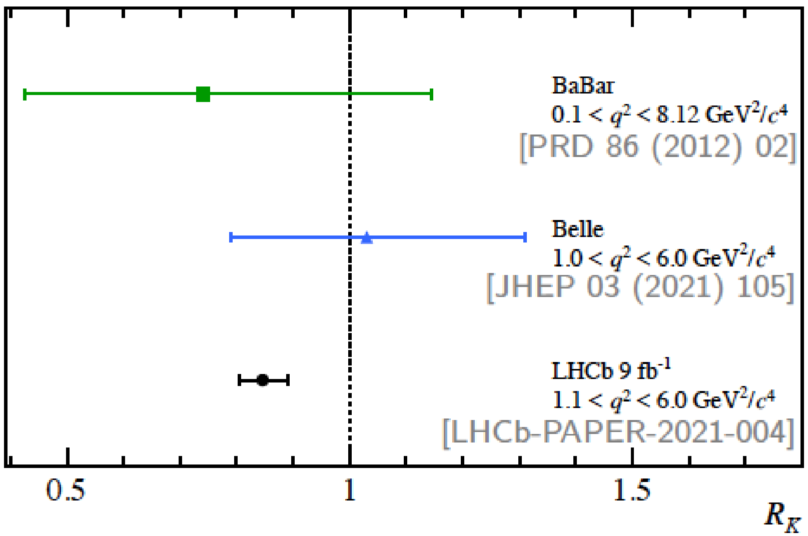
Stringent bounds
on generic
flavor-violating ops.

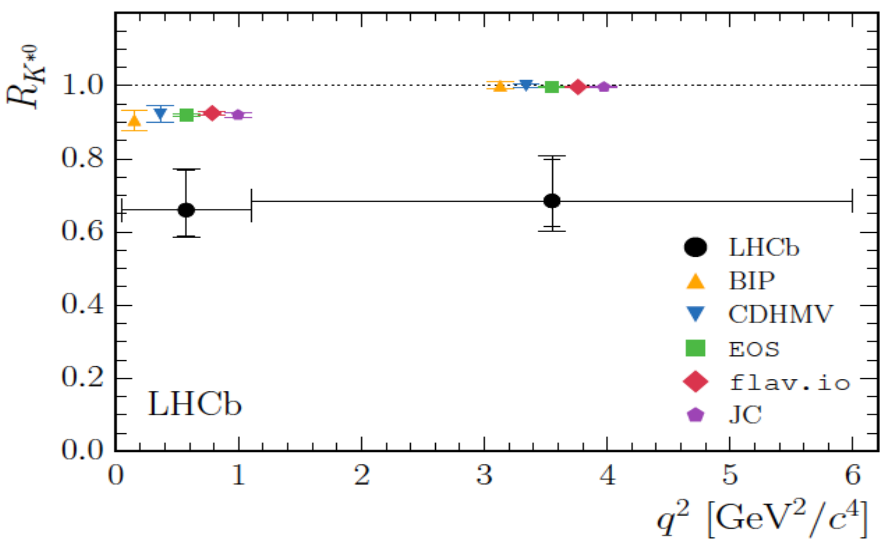
The big questions in flavor physics:

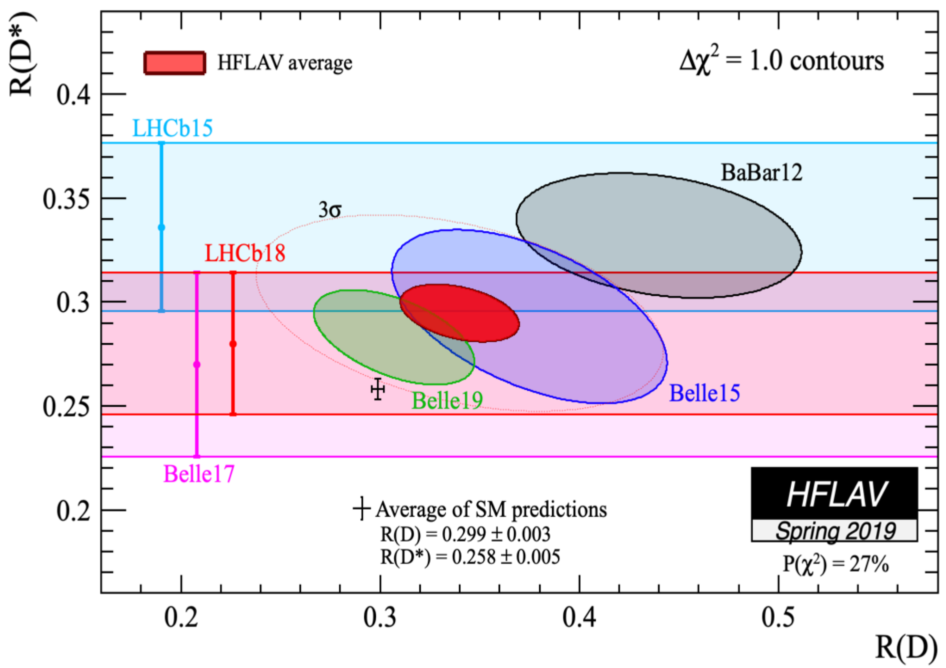
- Are <u>all</u> the the accidental flavor symmetries of the SM broken in the other sectors of the SM-EFT ?
- Can we make sense of the tight NP bounds from flavor-violating processes and still hope to see NP signals somwhere? And in case where?

Recent data start to provide some aswers...

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 Lepton Flavor Universality

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

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

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

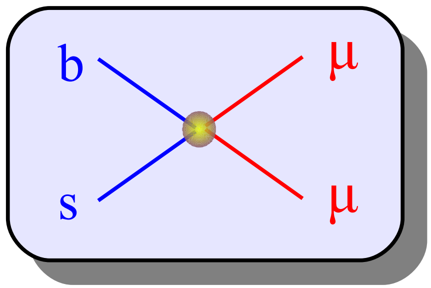
LFU is badly broken in the Yukawa sector: $y_e \sim 3\times10^{-6}$, $y_\mu \sim 3\times10^{-4}$, $y_\tau \sim 10^{-2}$

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

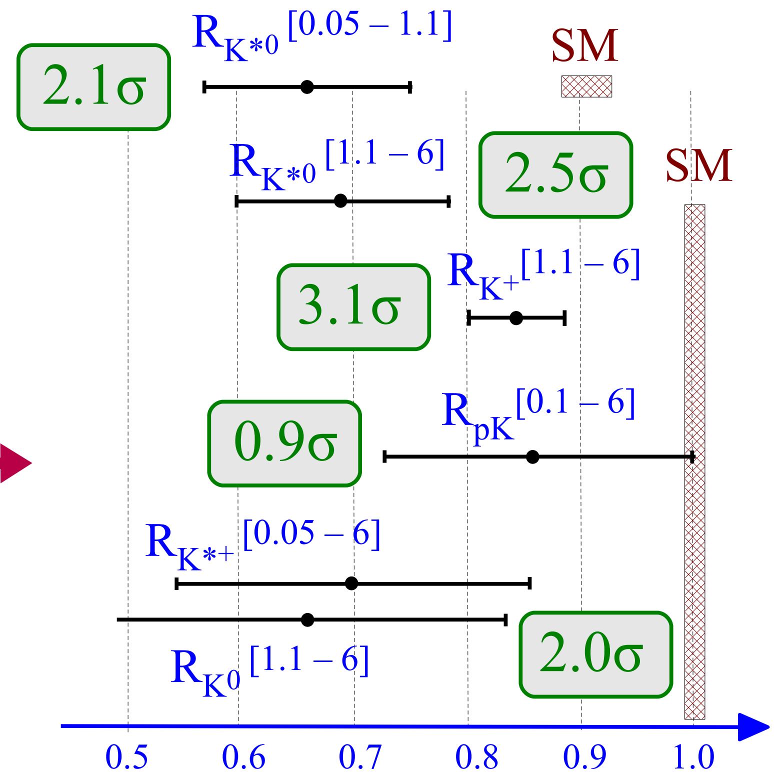
The LFU anomalies

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

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



$\Gamma(H_b \to H_s\, \mu\mu)/\Gamma(H_b \to H_s\, ee)$



LFU ratios

[LHCb – Autumn 2021]

▶ *The LFU anomalies*

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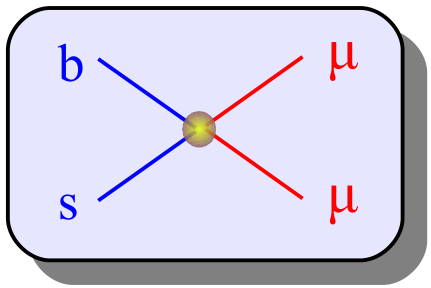
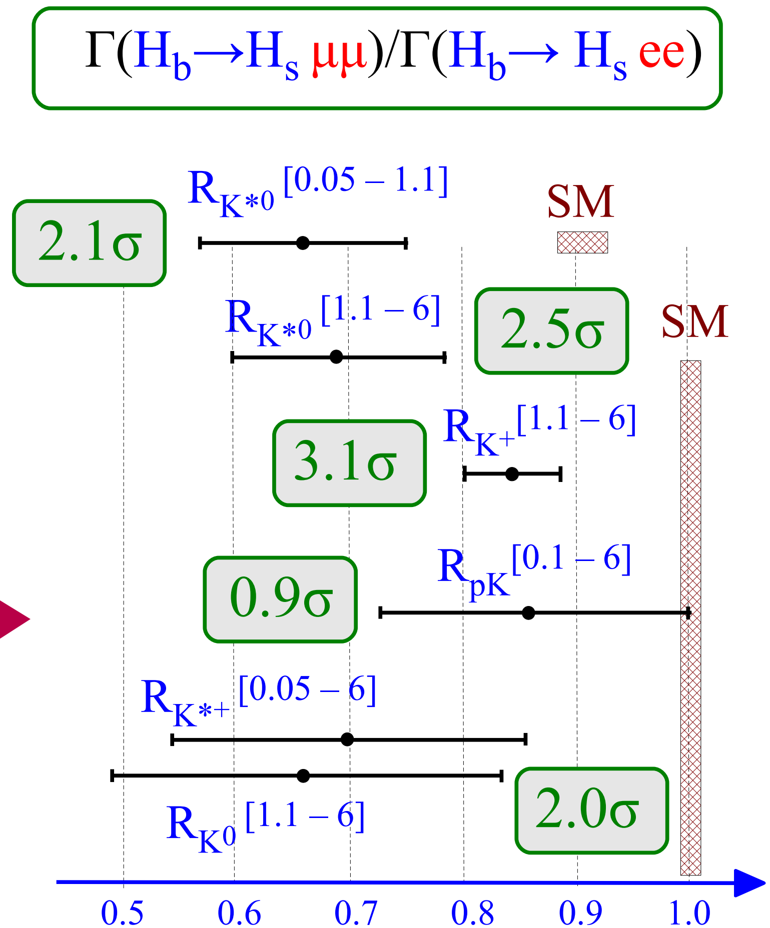




BR(B_s → μμ)

$BR_{exp} = (2.85\pm0.32) \times 10^{-9}$ ATLAS+CMS+LHCb '21

$BR_{SM} = (3.66\pm0.14) \times 10^{-9}$ 2.3σ

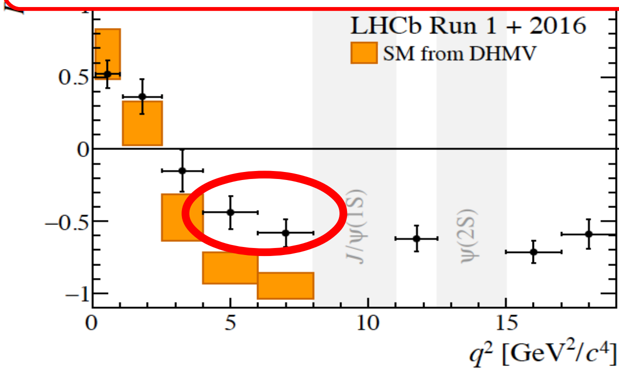
The LFU anomalies

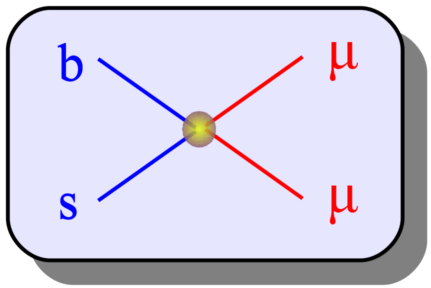
$\Gamma(H_b \to H_s\, \mu\mu)/\Gamma(H_b \to H_s\, ee)$

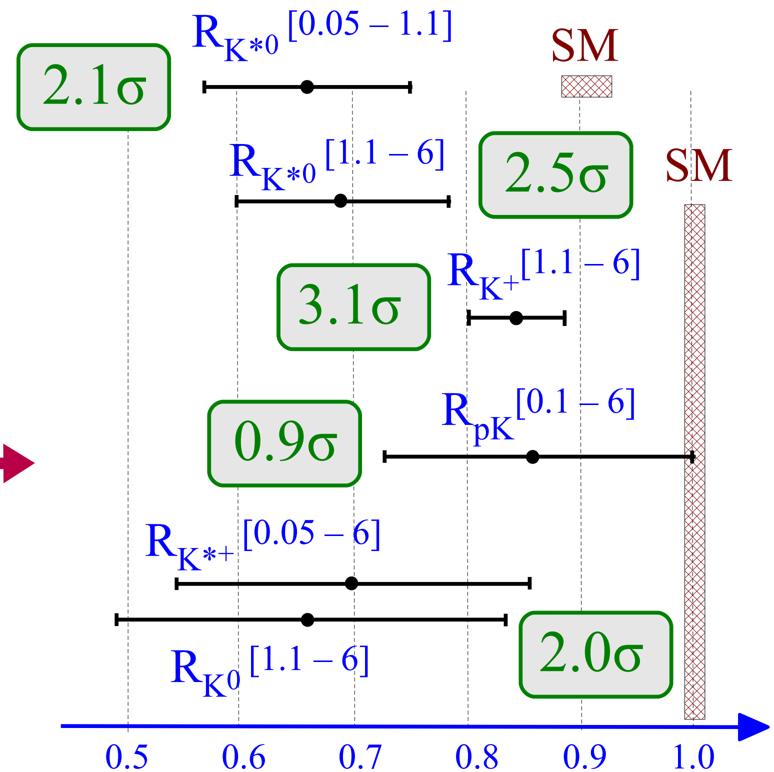
- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e

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

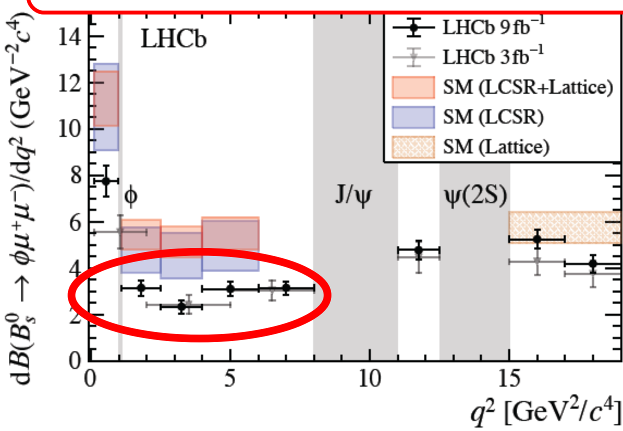
$B \to K^* \mu\mu$ angular distribution







$B \to H\, \mu\mu$ branching ratios



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2.3σ

The LFU anomalies

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

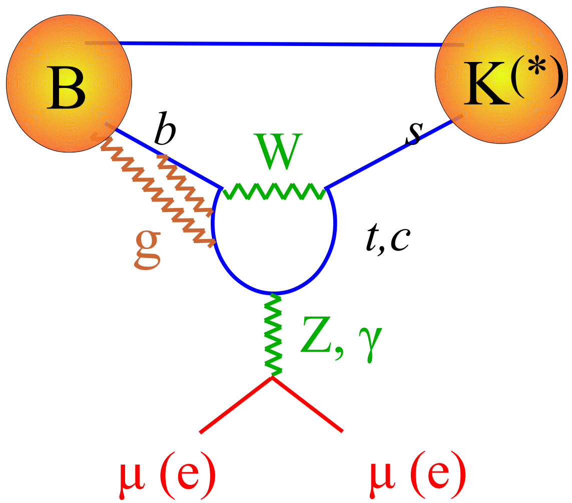
$b \to s\, l^+l^-$ transitions are forbidden at the tree level within the SM.

Depending on the $q^2 = m^2 ll$ range, they are dominated by

- short distance dynamics
  $\to$ *precisely calculable, more sensitive to NP*
- long-distance dynamics
  $\to$ *moderate/large theory erorrs, small/no sensitivity to NP*

N.B: long-distance dynamics is lepton-flavor universal

- <u>cannot</u> generate $C_i^{\mu} \neq C_i^{e}$
- <u>does not afect</u> $C_{10}^{\mu,e}$

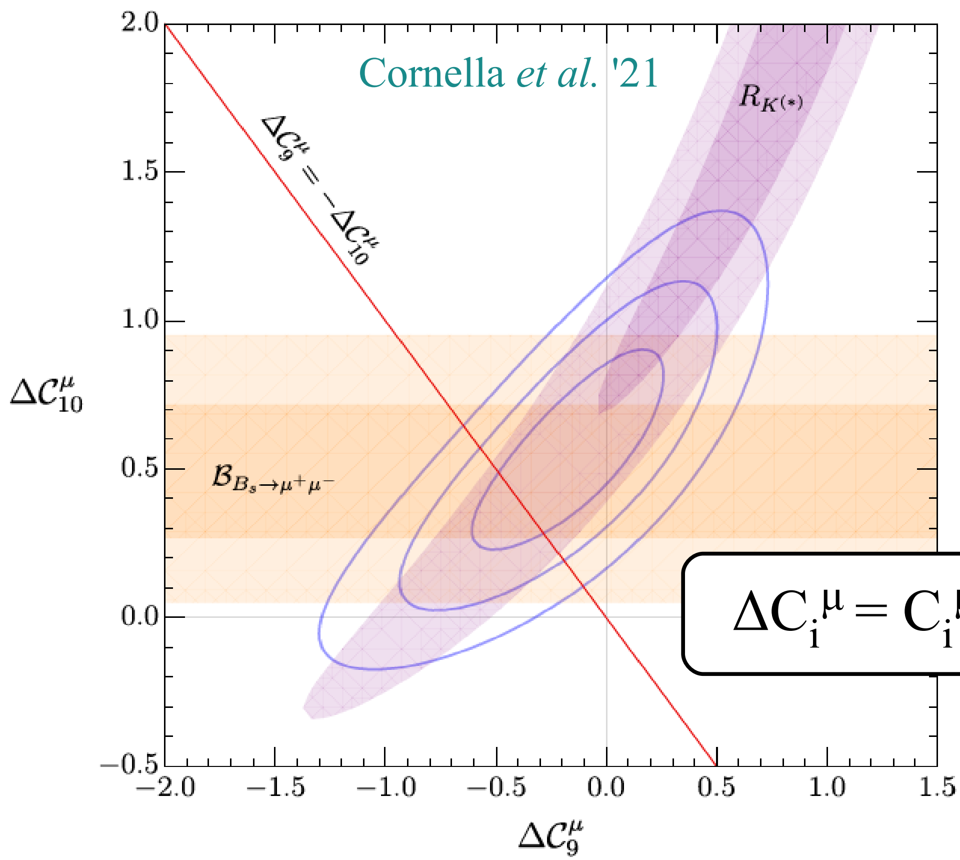


Leading short-distance effective operators:

$$\mathcal{O}_{10}^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$
$$\mathcal{O}_{9}^{\ell} = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

The LFU anomalies

- b → s l^+l^- (neutral currents): μ vs. e

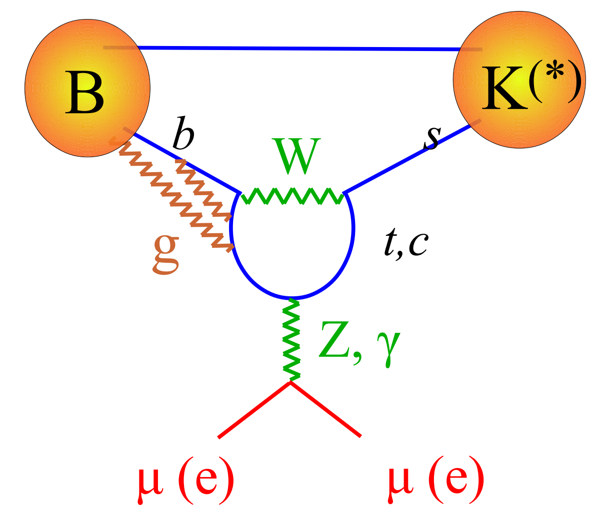


$\Delta C_i^\mu = C_i^\mu - C_i^e$

Conservative fit using "clean obs." only

$\boxed{5.0\sigma}$ significance of NP hypothesis $\Delta C_9^\mu = -\Delta C_{10}^\mu$ vs. SM

Beyond tree level in SM:



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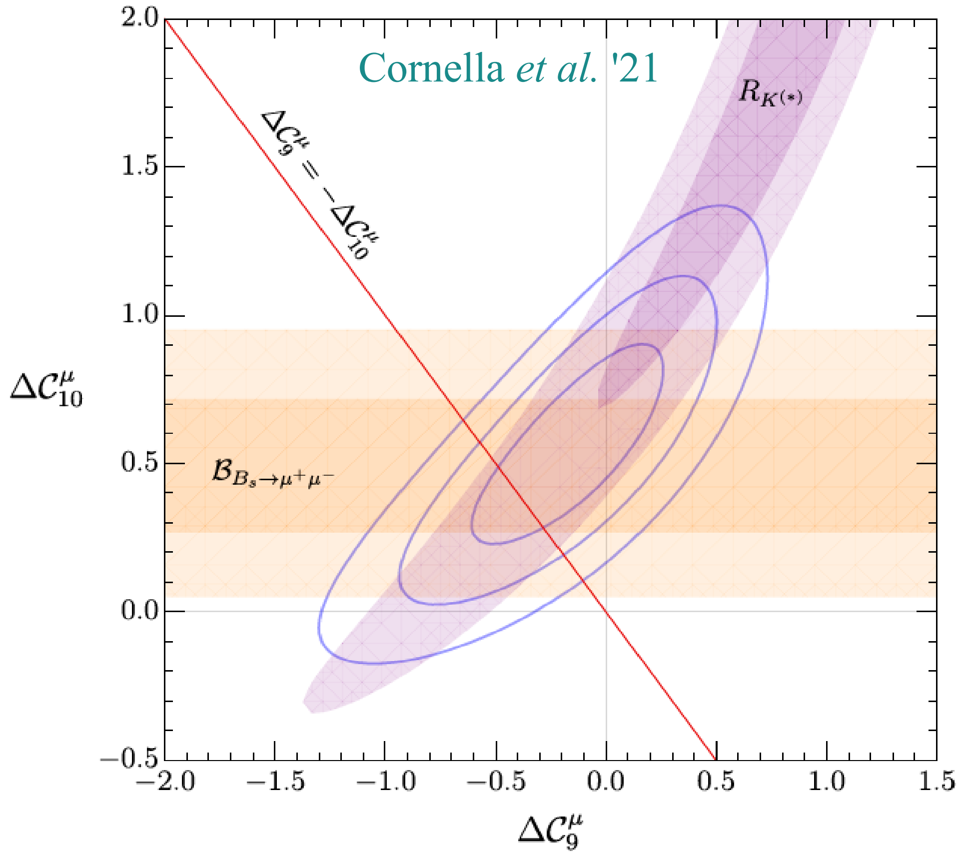
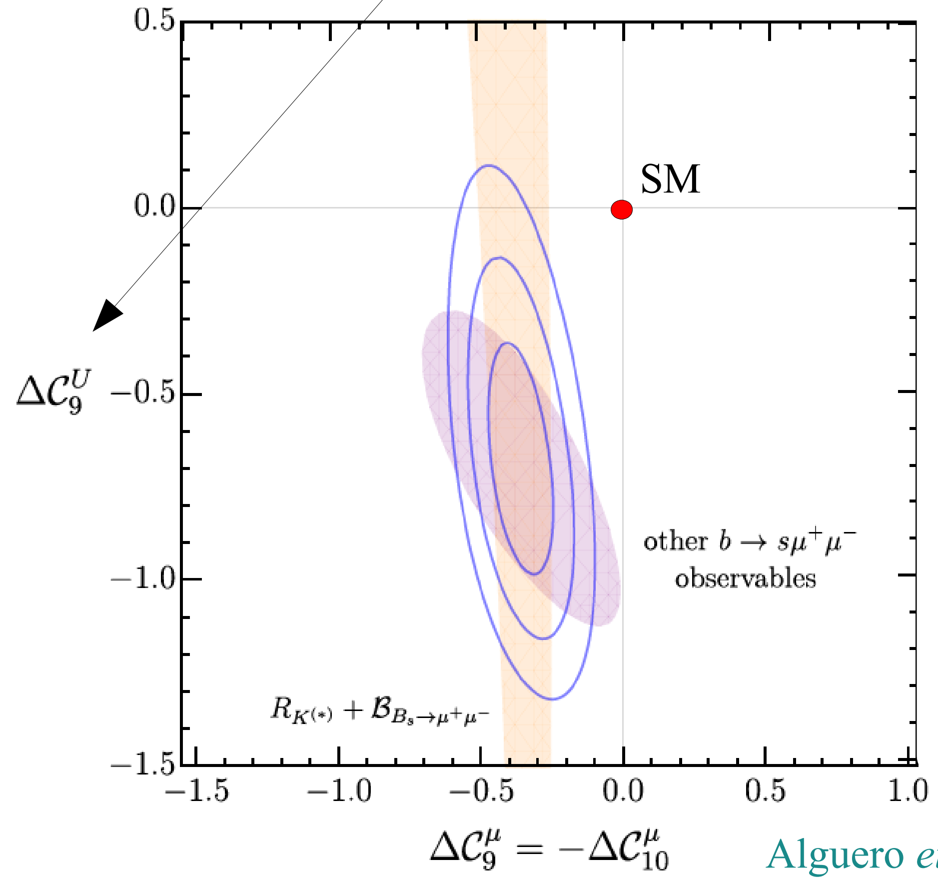
The LFU anomalies

- b → s l^+l^- (neutral currents): μ vs. e

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





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

Conservative fit using "clean obs." only

$\boxed{5.0\sigma}$ significance of NP hypothesis $\Delta C_9^\mu = -\Delta C_{10}^\mu$ vs. SM

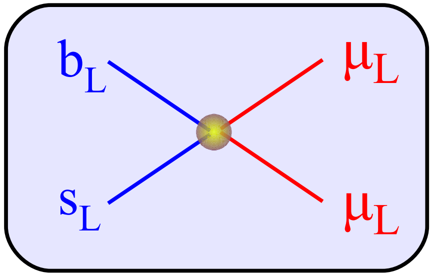
>> 5σ best estimate of charm contribution

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

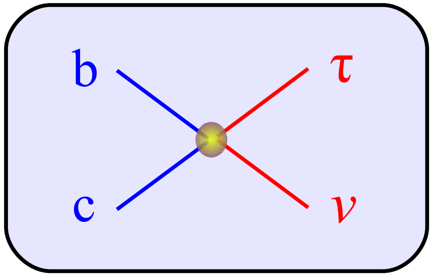
GI, Lancierini
Owen, Serra '21

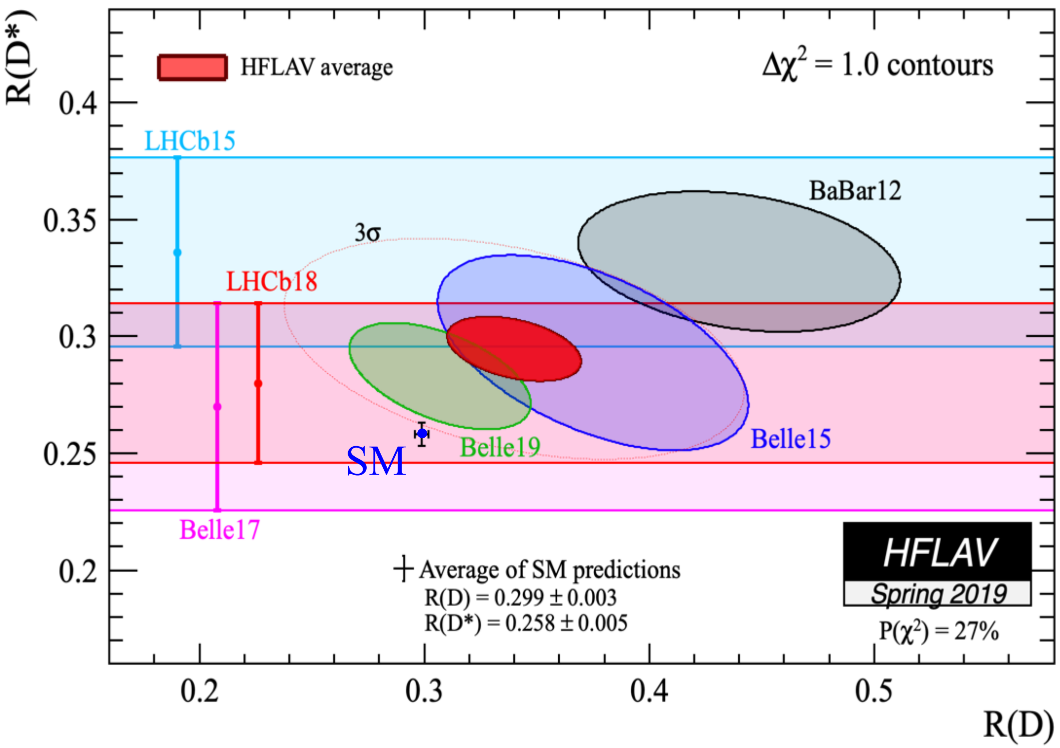
The LFU anomalies

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



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



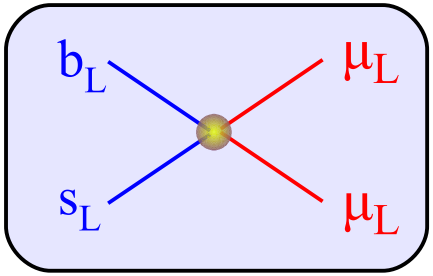


$$R(X) = \frac{\Gamma(B \to X\, \tau\nu)}{\Gamma(B \to X\, l\nu)} \quad X = D \text{ or } D^*$$

- Clean SM predictions (*uncertainties cancel in the ratios*)
- Consistent results by 3 different exp.ts: $\boxed{3.1\sigma}$ excess over SM
- Slower progress

The LFU anomalies

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



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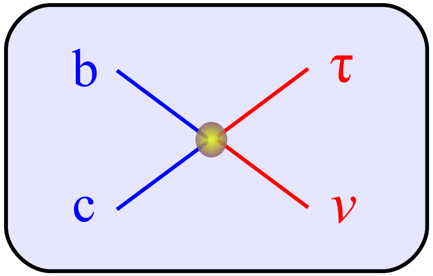

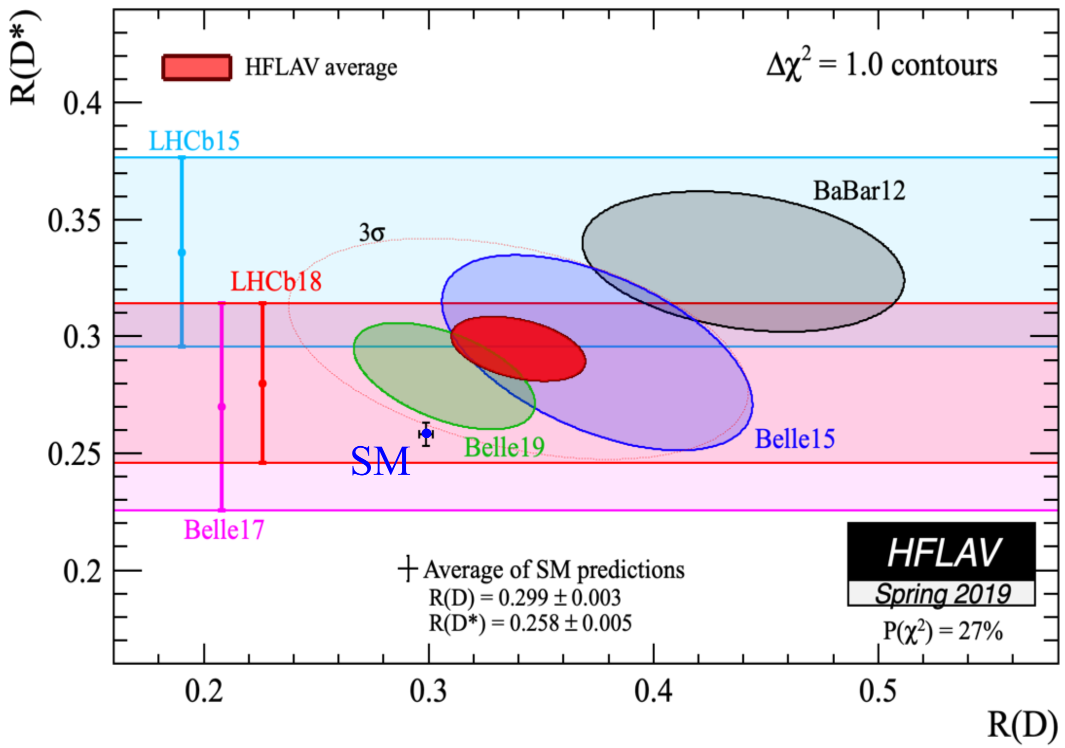

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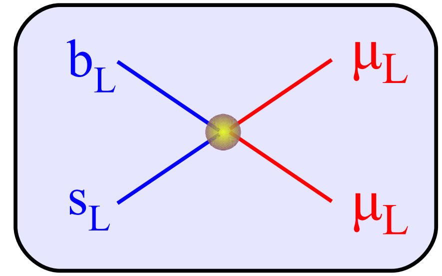
- Clean SM predictions (*uncertainties cancel in the ratios*)
- Consistent results by 3 different exp.ts: $\boxed{3.1\sigma}$ excess over SM
- Slower progress

Not general consensus...

Bordone, Jung, van Dyk '19 ~ 4σ
Martinelli, Simula, Vittorio '22 ~ 2σ

The LFU anomalies

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



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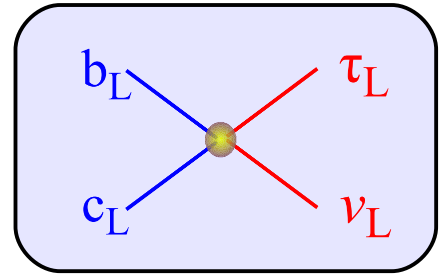

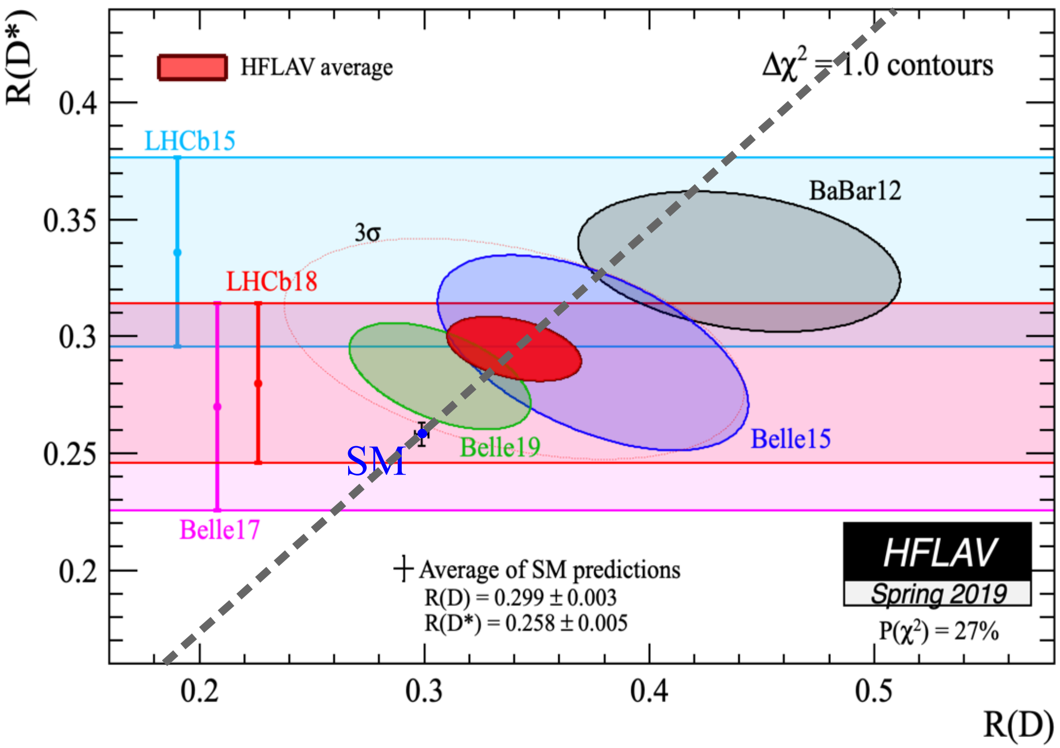

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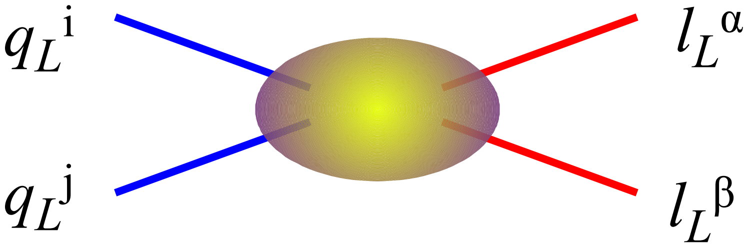
- Clean SM predictions (*uncertainties cancel in the ratios*)
- Consistent results by 3 different exp.ts: $\boxed{3.1\sigma}$ excess over SM
- Slower progress

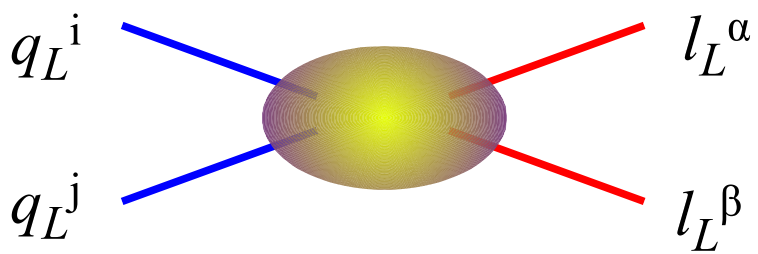
- Large NP effect competing with tree-level SM amplitude
- Left-handed NP amplitude describe well data (*but other options still possible*)

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

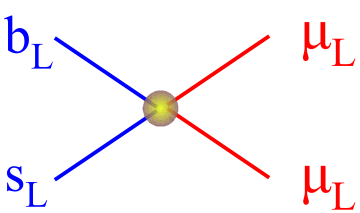
⬇

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

EFT considerations

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

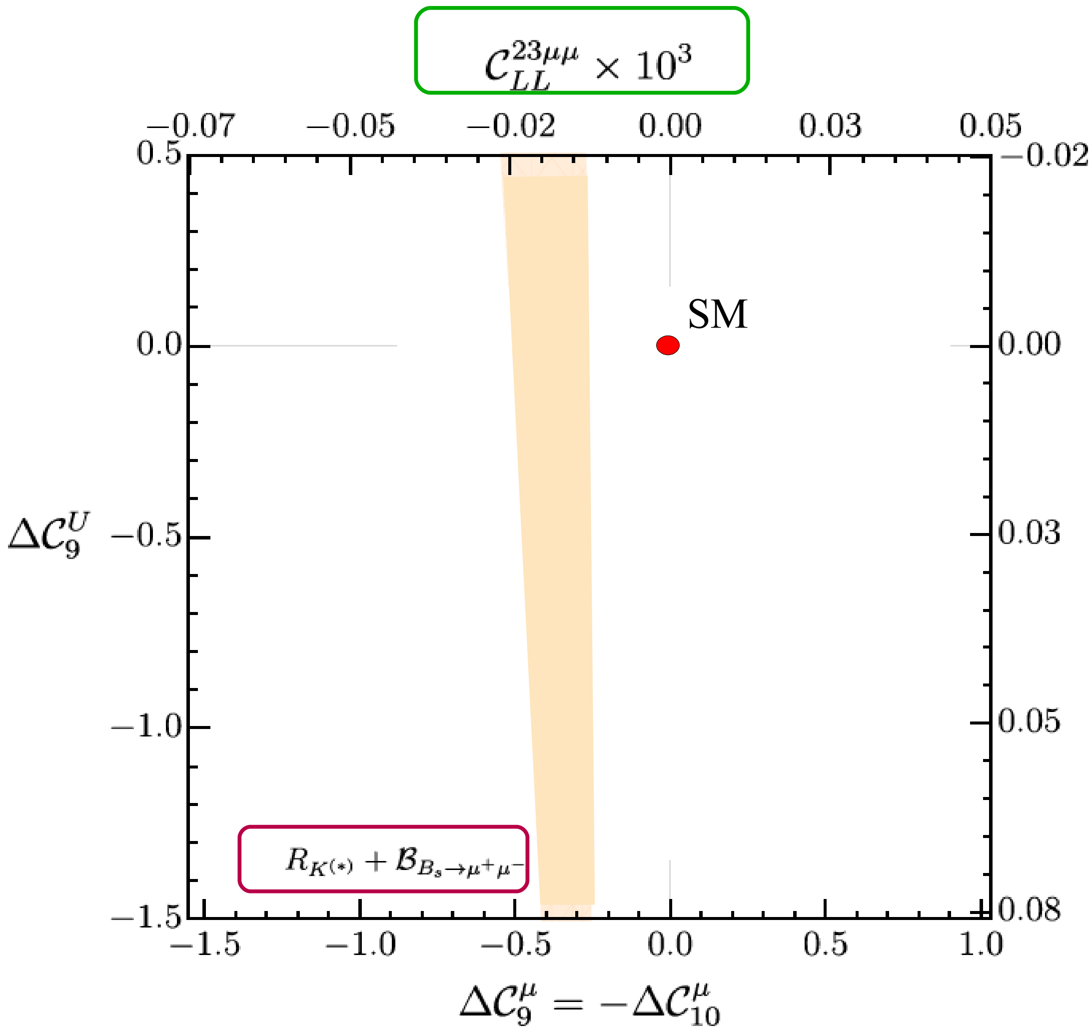
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)$$



$\sim 4\times10^{-5}\ G_{\text{Fermi}}$

super-weak interaction!

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



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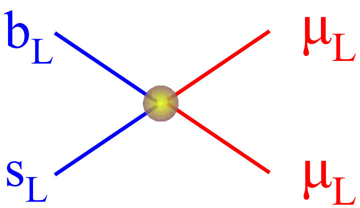
✔ $O(10^{-1})$ suppress. for each 2nd gen. l_L



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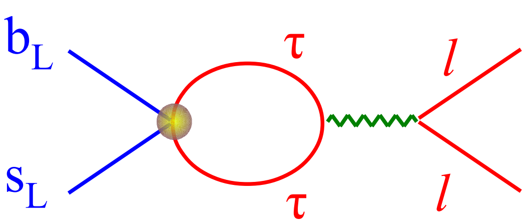
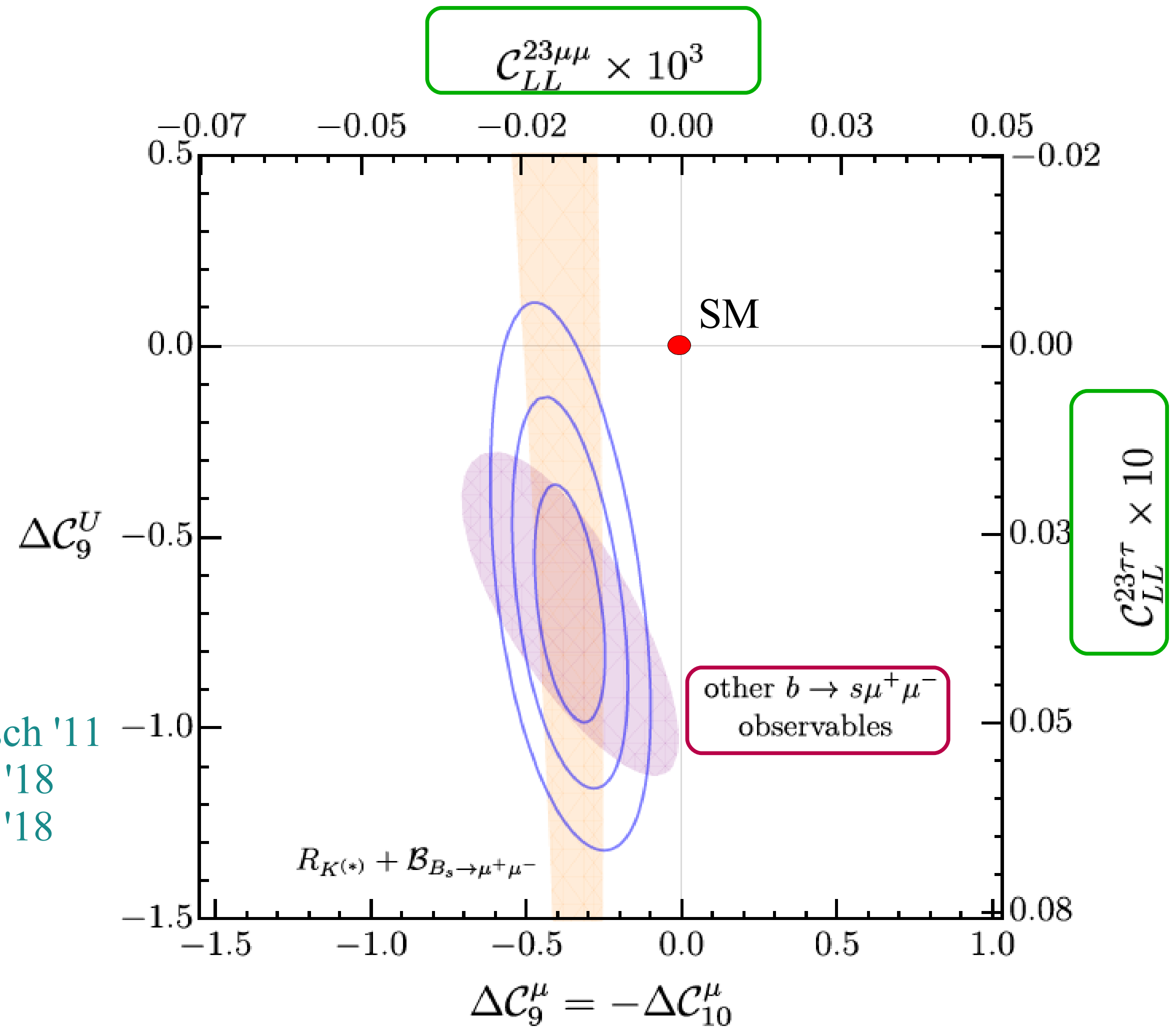


$C_{LL}^{23\tau\tau} \Rightarrow \Delta C_9^{\mathrm{Univ}}$

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



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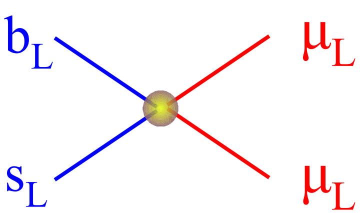

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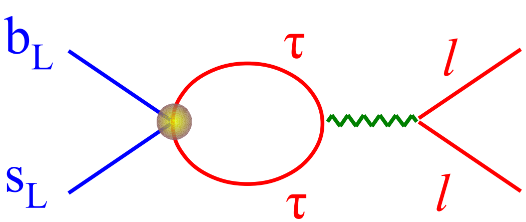
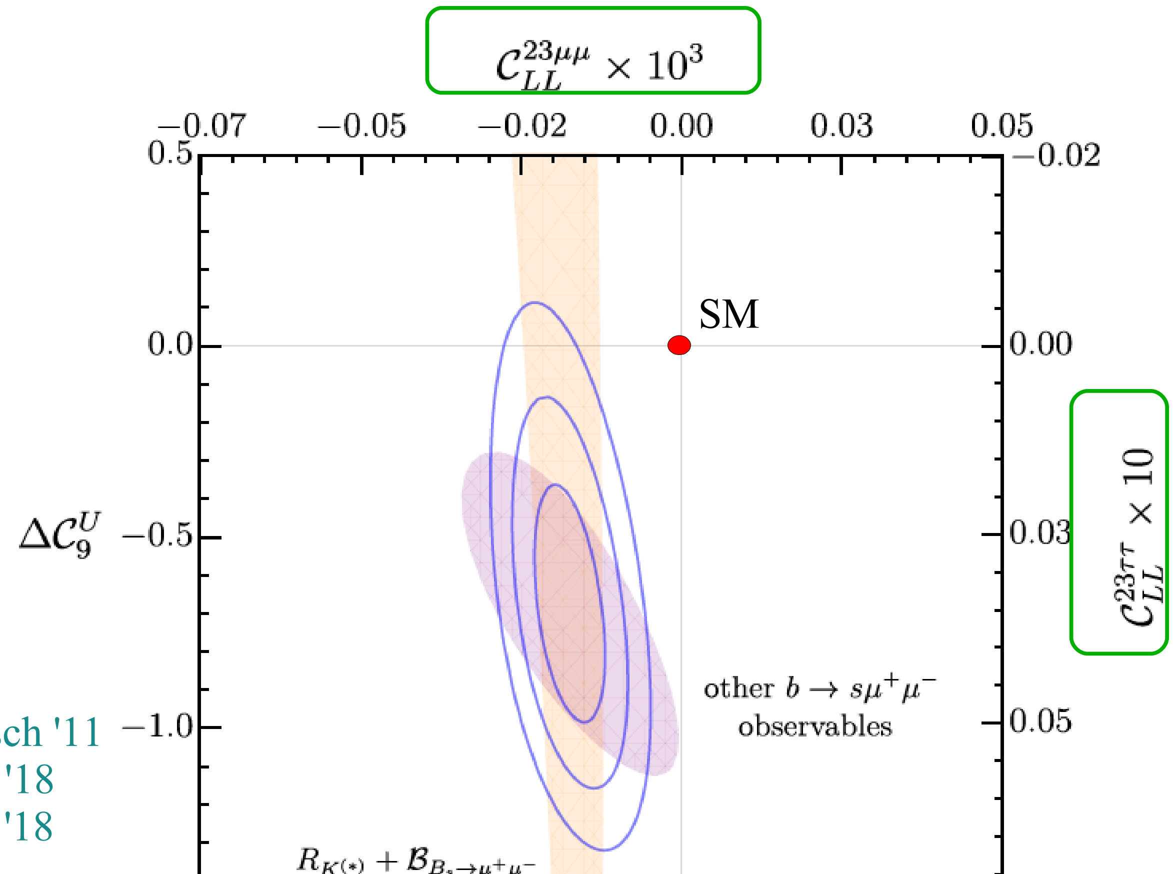


$C_{LL}^{23\tau\tau} \Rightarrow \Delta C_9^{Univ}$

Link to CC anomaly

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



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

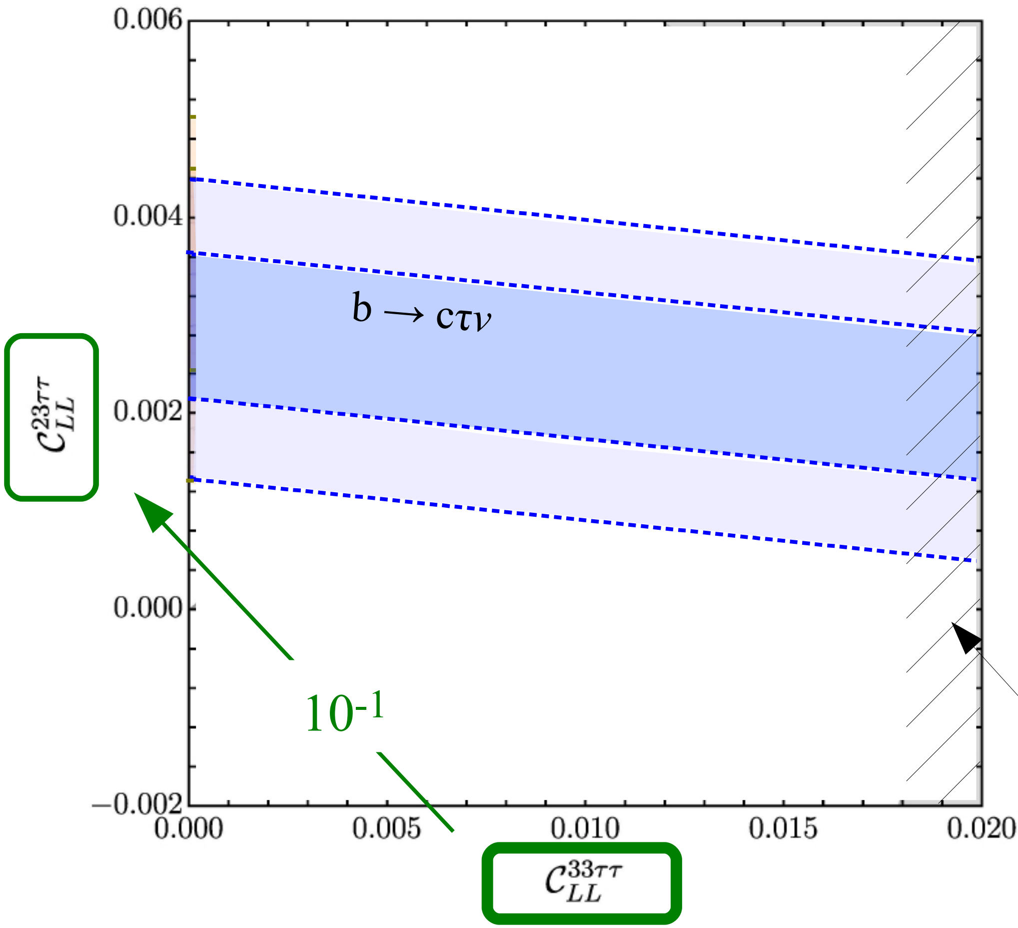
Data point to (short-distance) NP effects in operators of the type

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

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

charged-currents:

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



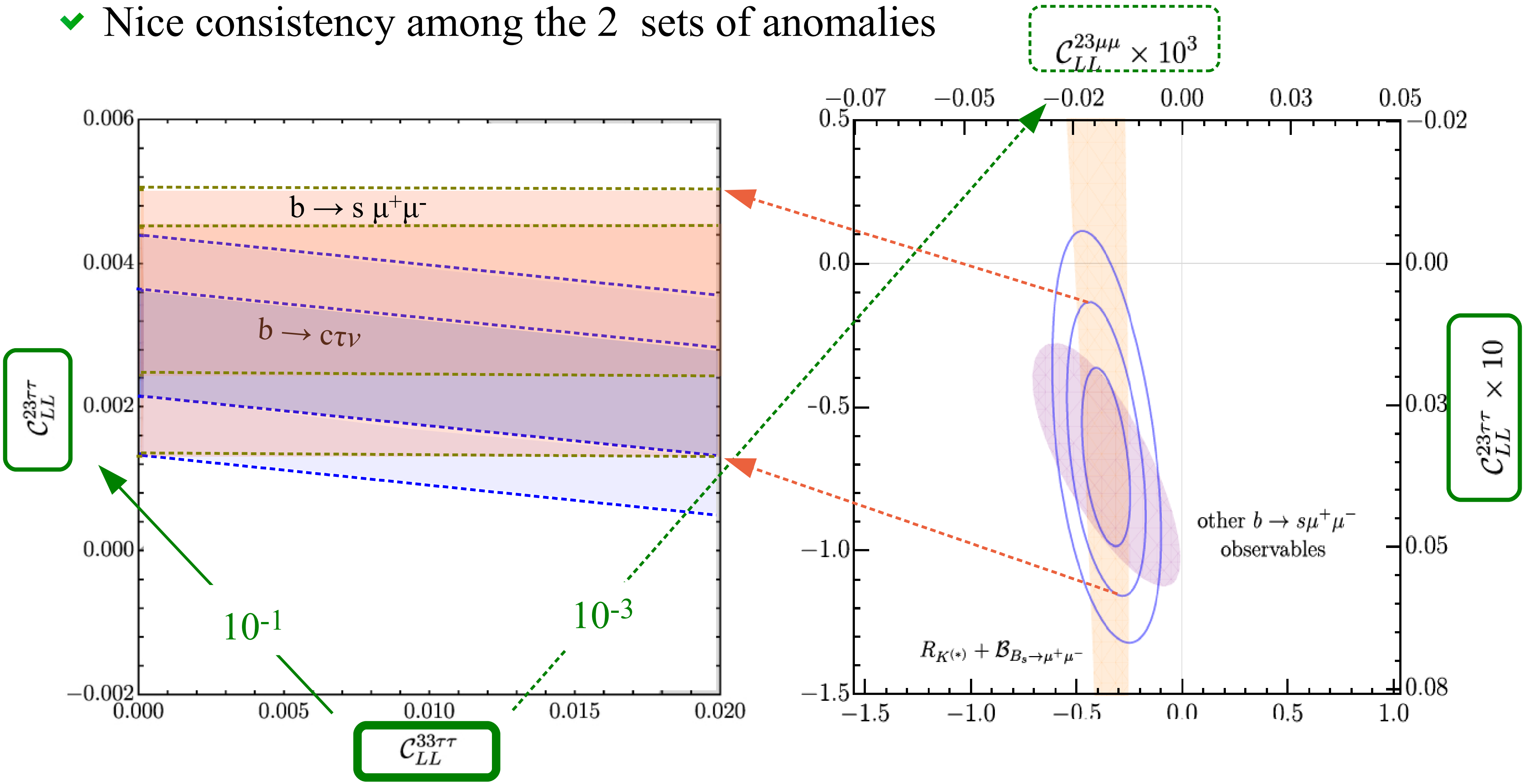
bounds from high-pT searches

EFT considerations

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

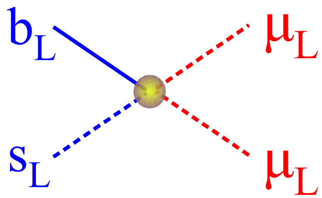
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)$$

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



EFT considerations

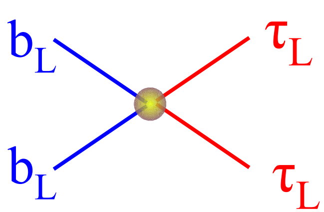
$\frac{10^{-3}}{\Lambda^2}$



~~LF~~U in $b \to s\, l^+ l^-$ [R_K, ...] $\boxed{5\,\sigma}$

"*natural*" flavor connection

$\frac{1}{\Lambda^2}$

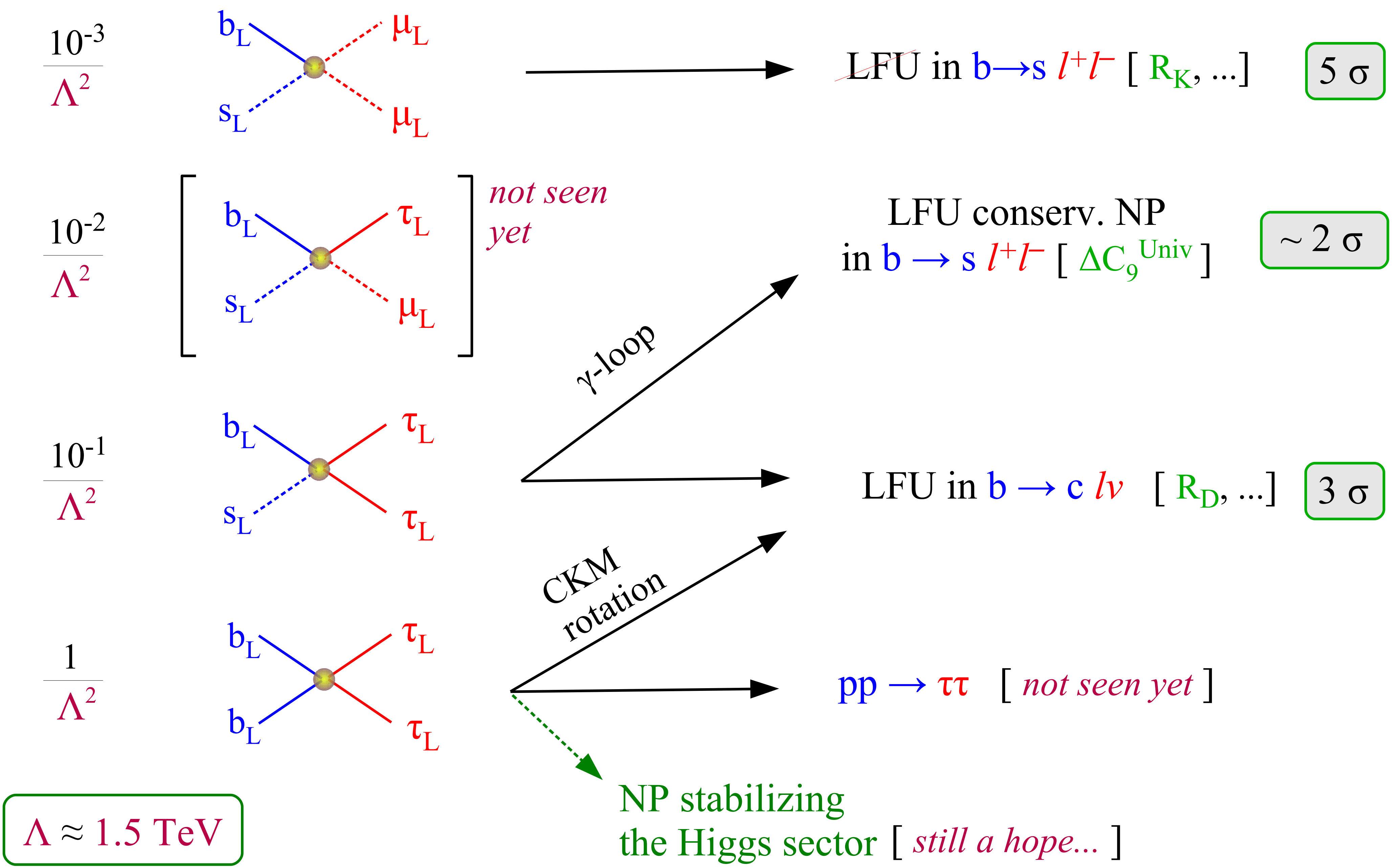


CKM rotation

LFU in $b \to c\, l\nu$ [R_D, ...]

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

EFT considerations



▶ EFT considerations

An exciting "narrow path" connecting old problems and recent anomalies

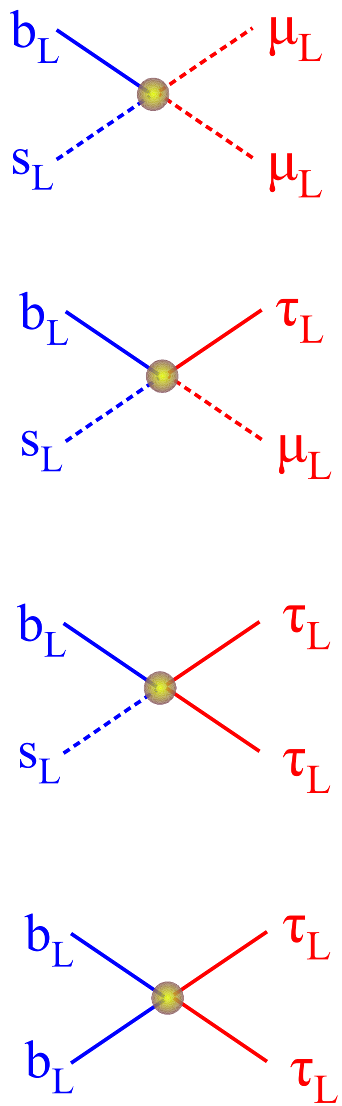
$\frac{10^{-3}}{\Lambda^2}$

$\frac{10^{-2}}{\Lambda^2}$

FLAVOR

$\frac{10^{-1}}{\Lambda^2}$

$\frac{1}{\Lambda^2}$



not seen yet

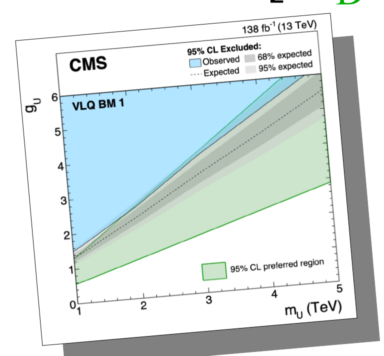
→ ~~LFU~~ in $b \to s\, l^+ l^-$ [R_K, ...] — 5 σ

γ-loop → LFU conserv. NP in $b \to s\, l^+ l^-$ [$\Delta C_9^{\mathrm{Univ}}$] — ~ 2 σ

→ LFU in $b \to c\, l\nu$ [R_D, ...] — 3 σ

CKM rotation

→ $pp \to \tau\tau$ — ~ 1 σ



$\Lambda \approx 1.5$ TeV

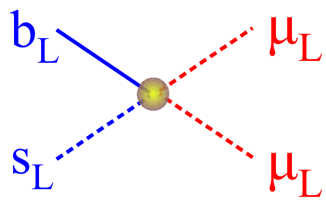
NP stabilizing the Higgs sector

Higgs = pNGB of the new dynamics (↔ LQ mass)

EFT considerations

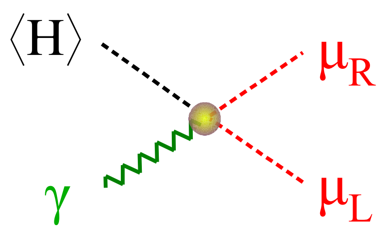
A possible alternative story...

$|V_{ts}| \dfrac{1}{\Lambda^2}$



$\longrightarrow$ ~~LFU~~ in $b \to s\, l^+ l^-$ [R_K, ...] $\boxed{5\ \sigma}$

$\dfrac{e}{16\pi^2} \dfrac{1}{\Lambda^2}$



$\longrightarrow$ $\Delta a_\mu = (a_\mu^{exp} - a_\mu^{SM})$ $\boxed{\sim 4\ \sigma}$

(*more controversial...*)

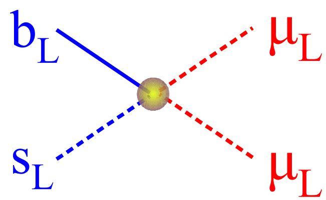
Ignoring the (*less convincing*) *CC anomaly other paths are certainly possible...*

$\boxed{\Lambda \approx 10\ \text{TeV}}$

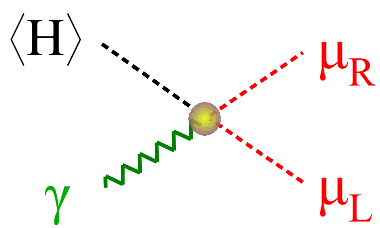
EFT considerations

A possible alternative story...

$|V_{ts}| \dfrac{1}{\Lambda^2}$



$\dfrac{e}{16\pi^2} \dfrac{1}{\Lambda^2}$

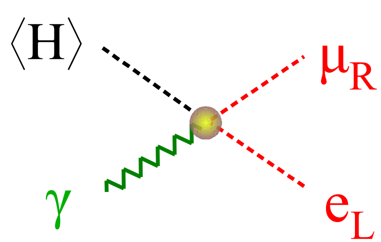


Possible unified description by means of a new interaction with special role for muons (and maybe tau's)

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

However...

$\dfrac{e}{16\pi^2} \dfrac{\Theta_{\mu e}}{\Lambda^2}$



$|\Theta_{\mu e}| < 2\times 10^{-5}$

Tight constraint involving several ops → Exact flavor symm. @ work the lepton sector → *different behavior of quarks & leptons*

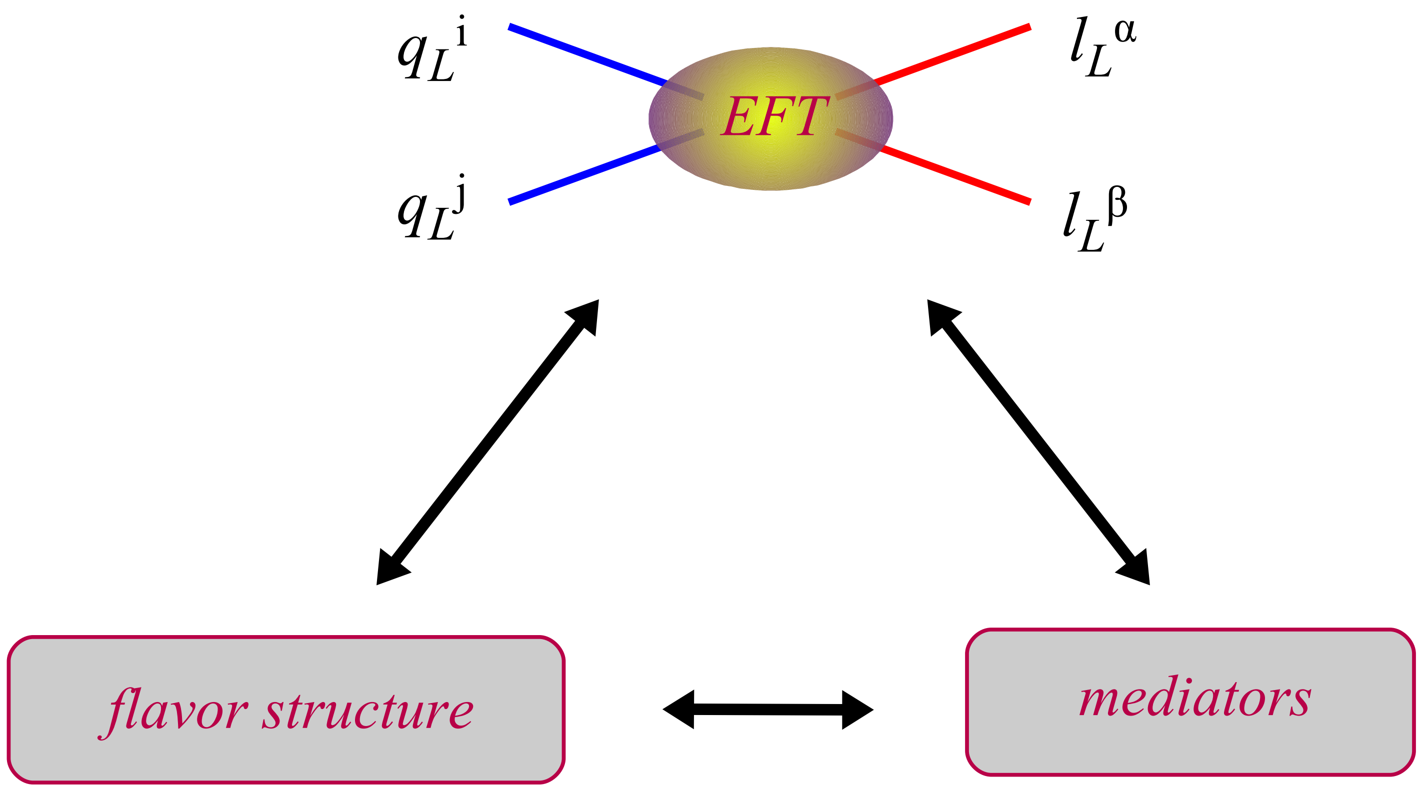
GI, Pages, Wilsch '21

$\Lambda \approx 10$ TeV

Model-building considerations

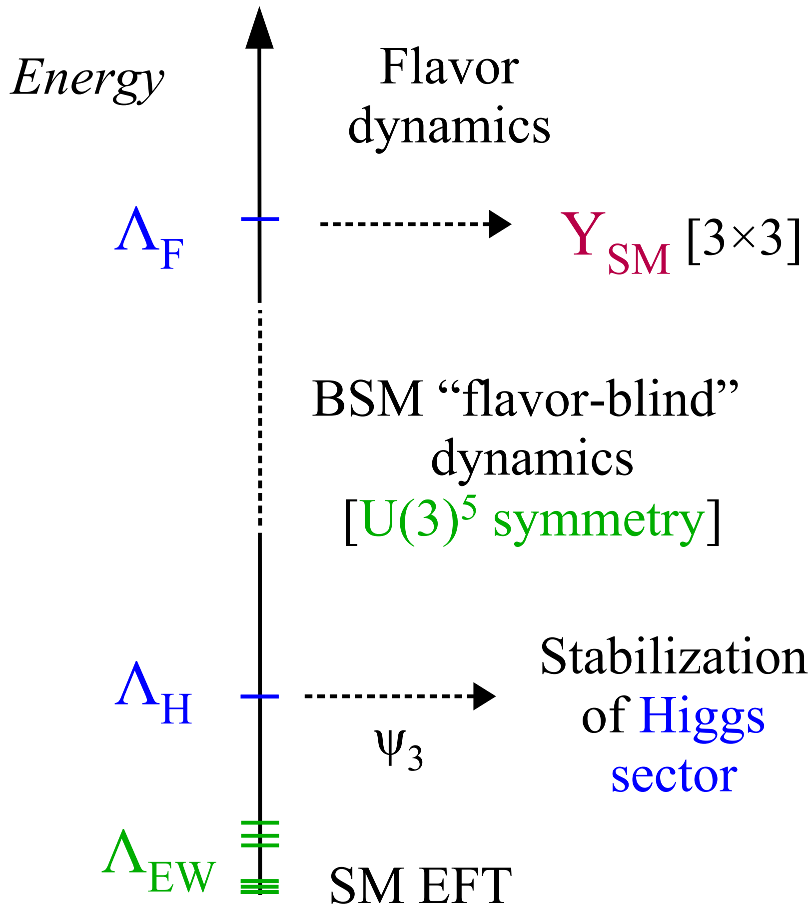
Model-building considerations

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 (Minimal Flavor Violation) paradigm:



Main idea:

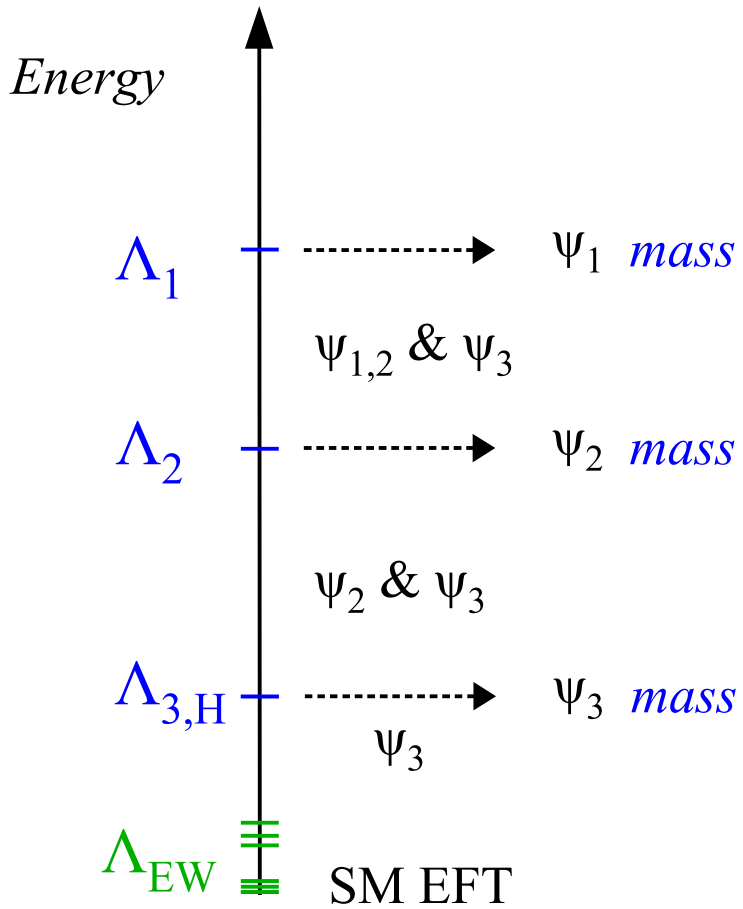
- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavor problem

⬇

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

Model-building considerations

~~The old (MFV) paradigm~~



Multi-scale picture @ origin of flavor:

Bordone *et al.* '17
Allwicher, GI, Thomsen '20
Barbieri '21

Panico & Pomarol '16
⋮
Dvali & Shifman '00

Main idea:

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

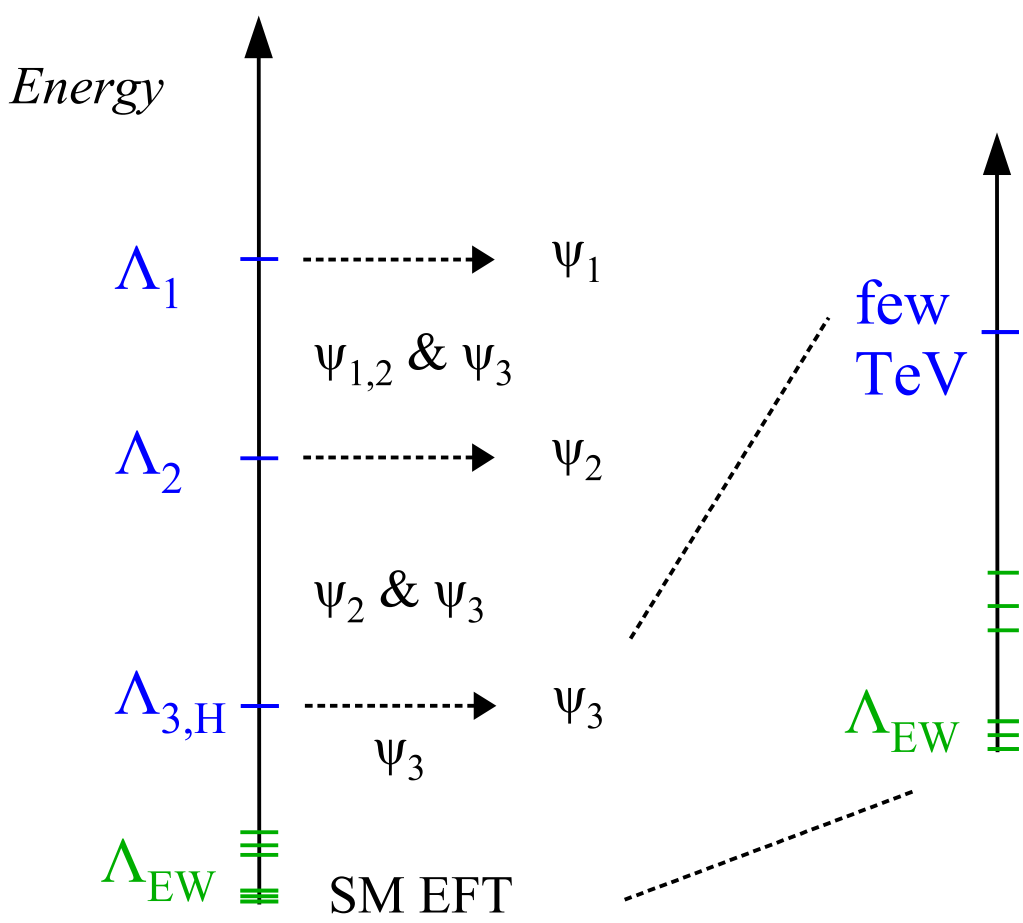
↓

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

Model-building considerations

~~The old (MFV) paradigm~~

Multi-scale picture @ origin of flavor:

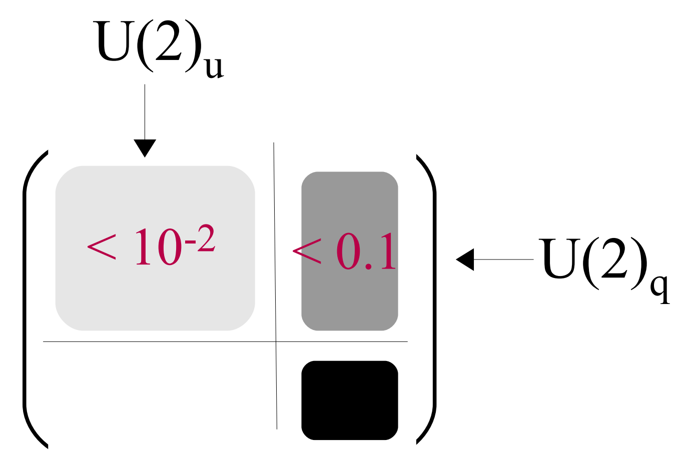


NP coupled mainly to ψ_3

$\psi_{1,2}$ ~ massless [$U(2)^n$ symm.]

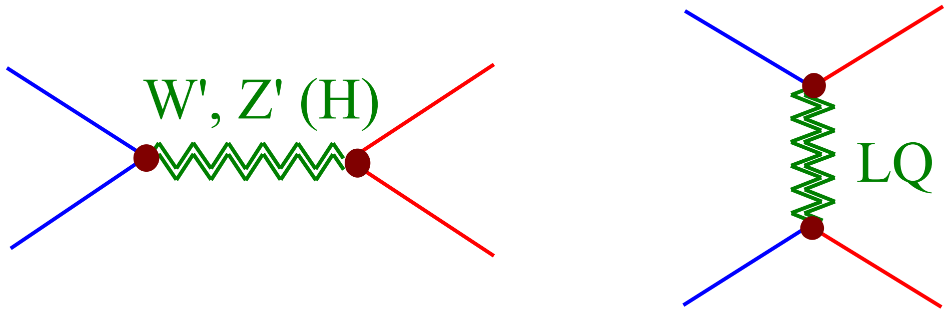
Barbieri *et al.* '11

"UV imprint" in the Yukawa couplings: $Y_U \sim$



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...



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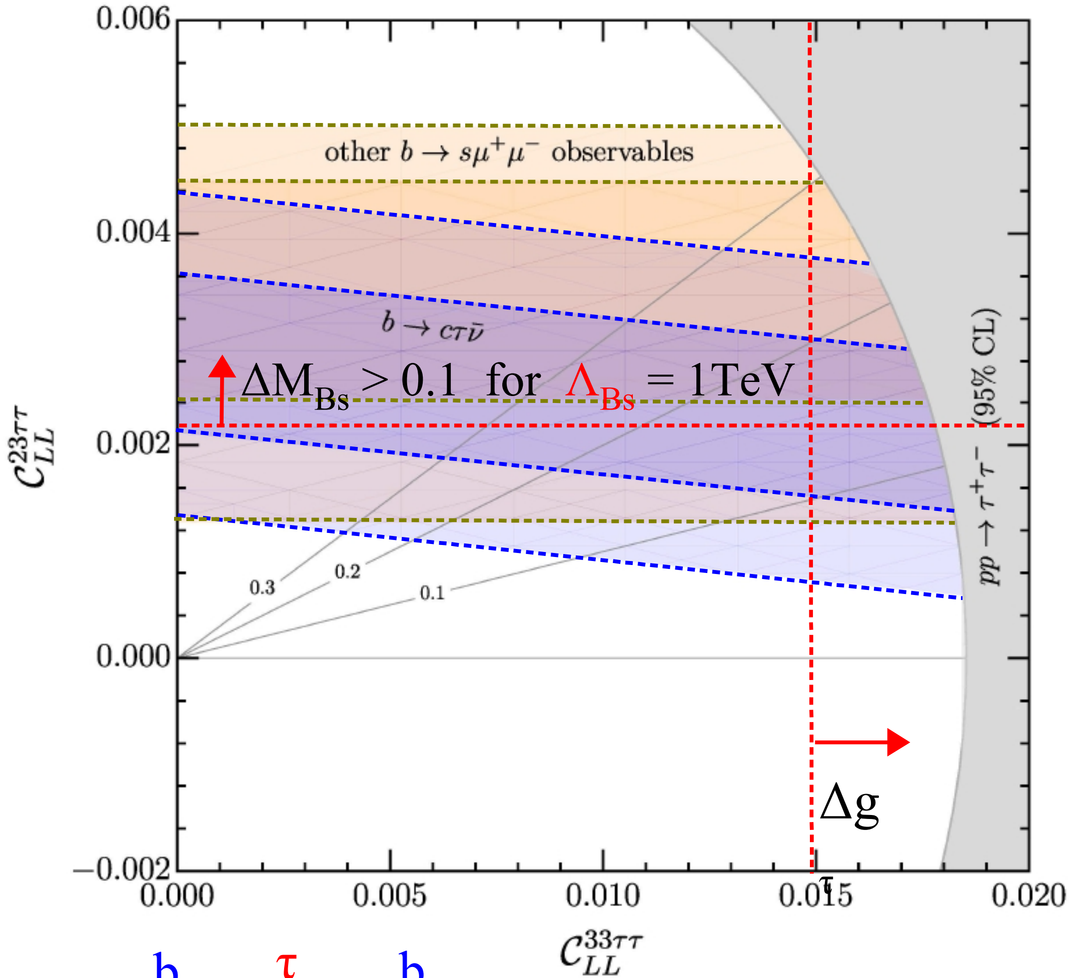
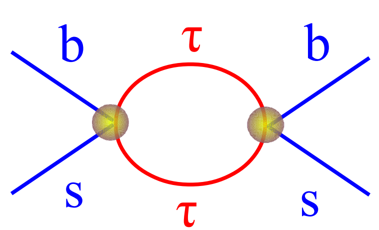


Pattern emerging from data:

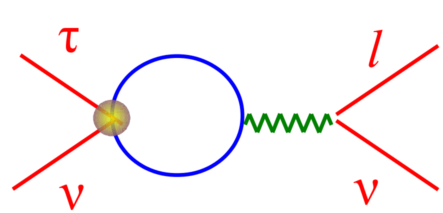
- ✔ O(10^{-1}) for each 2nd gen. q_L or l_L
- ✔ Nice consistency among the two sets of anomalies

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

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



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



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

Model-building considerations

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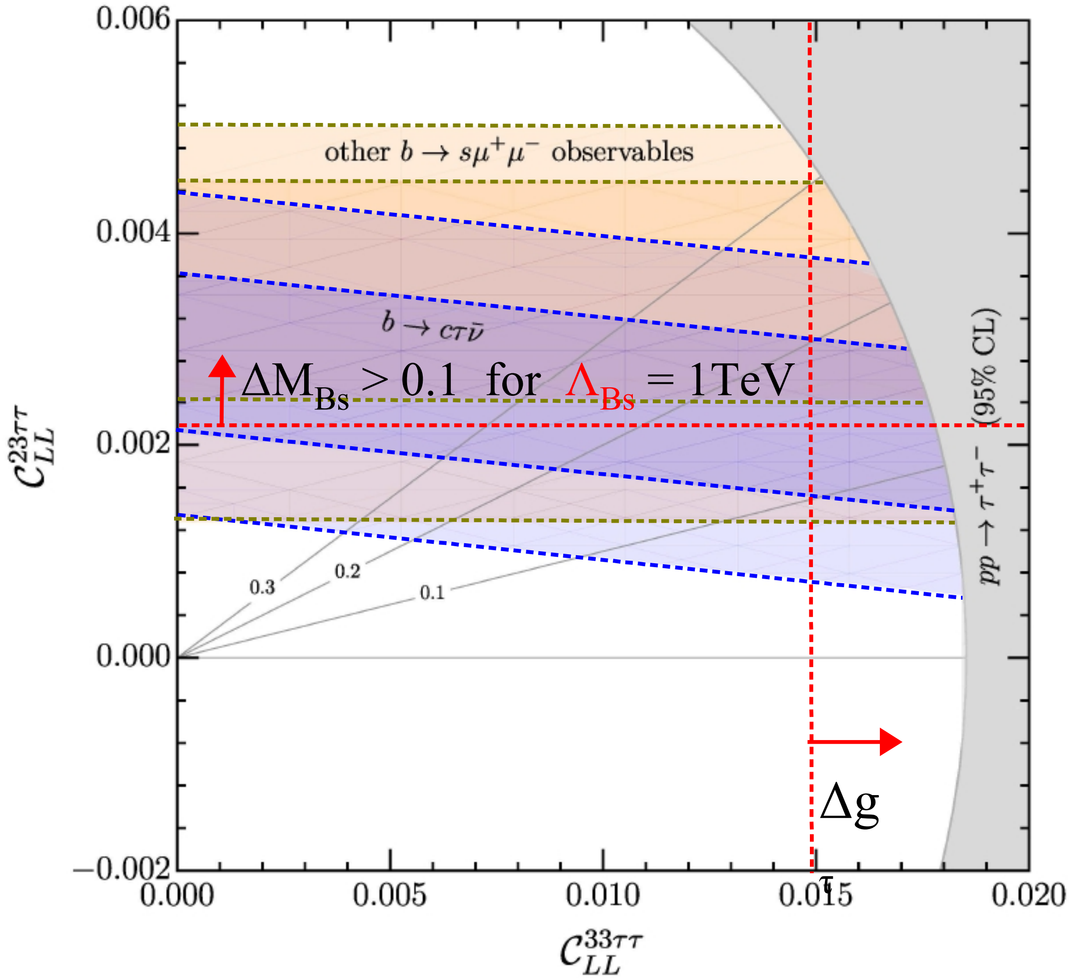

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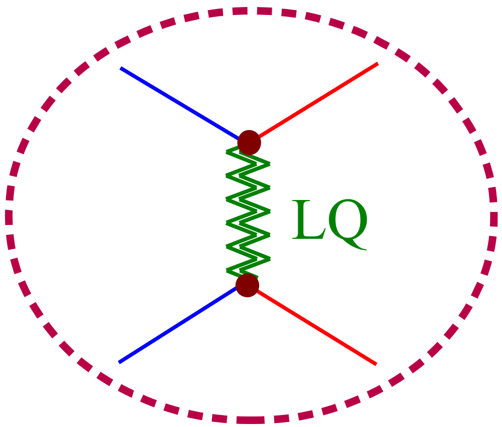
⬇

Leptoquarks

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 & $\not{R}$ SUSY
  Hiller & Schmaltz, '14; Becirevic *et al.* '16, Fajfer *et al*. '15-'17; Dorsner *et al.* '17; Crivellin *et al.* '17; Altmannshofer *et al.* '17 Trifinopoulos '18, Becirevic *et al.* '18 + ...

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

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

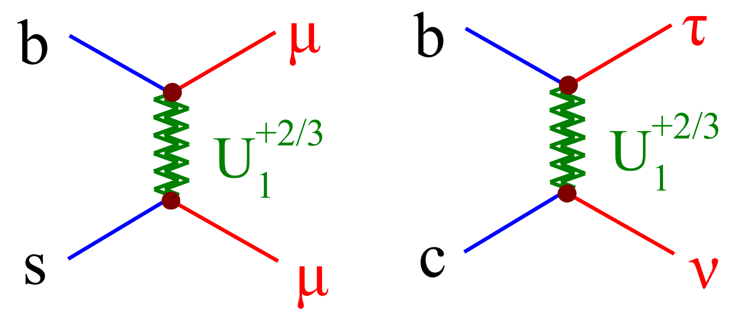
- LQ as Kaluza-Klein excit.
  Megias, Quiros, Salas '17
  Megias, Panico, Pujolas, Quiros '17
  Blanke, Crivellin, '18 + ...

Model-building considerations

Which LQ explains which anomaly?

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

Angelescu, Becirevic, DAF, Sumensari [1808.08179]



Barbieri, GI, Pattori, Senia '15

- mediator: U_1
- flavor structure: $U(2)^n$
- UV completion: SU(4)

LQ of the Pati-Salam gauge group:

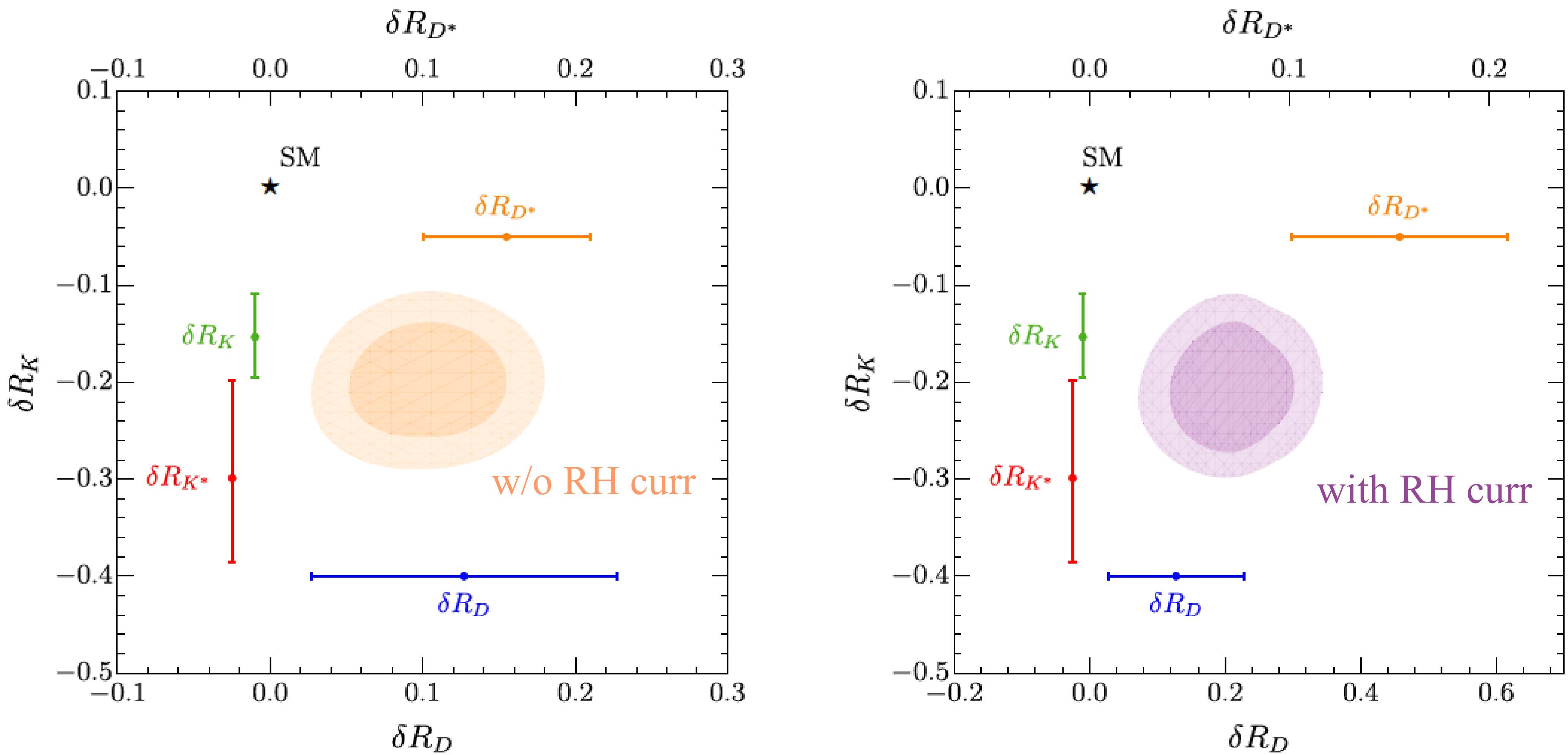
$\boxed{SU(4)} \times SU(2)_L \times SU(2)_R$

Model-building considerations

Considering the U_1 only

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

→ excellent description of all available low-energy data [*beyond tree-level...*] :



▶ Model-building considerations

Considering the U_1 only

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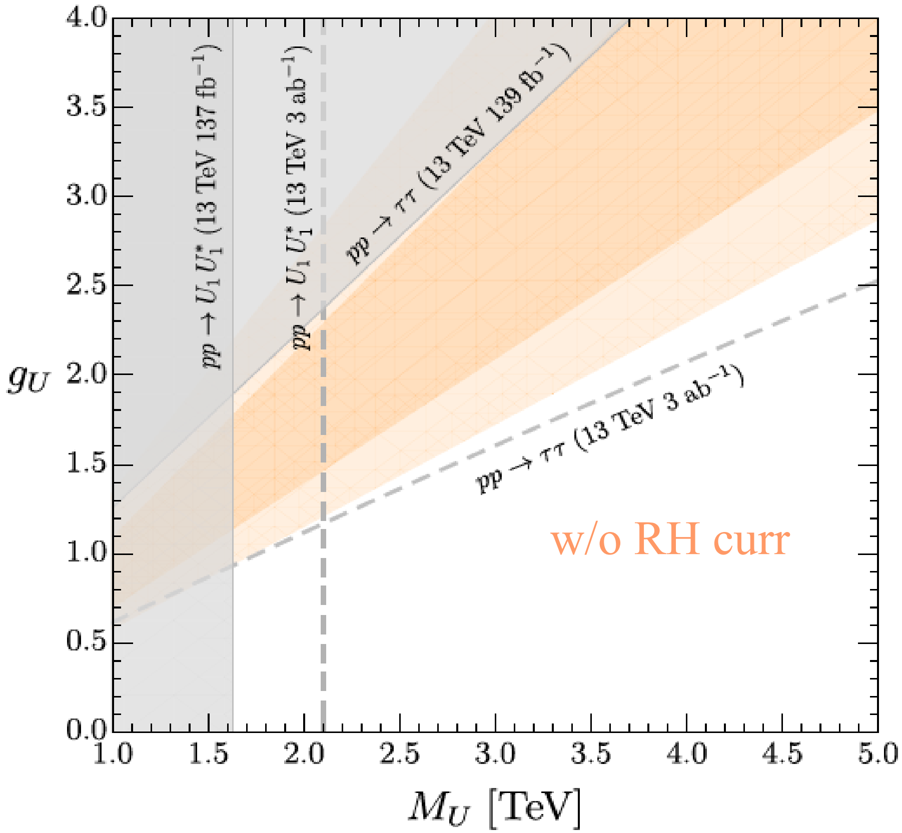
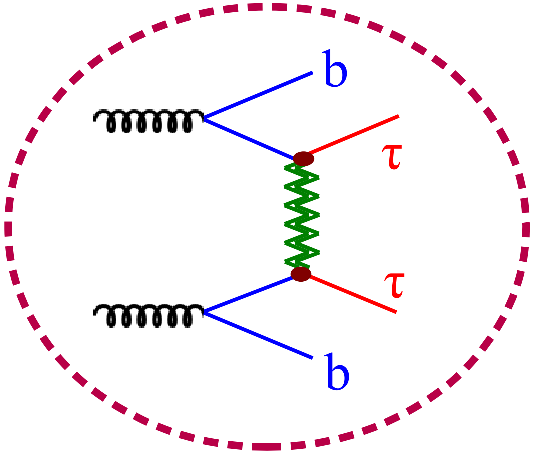
→ excellent description of all available low-energy data

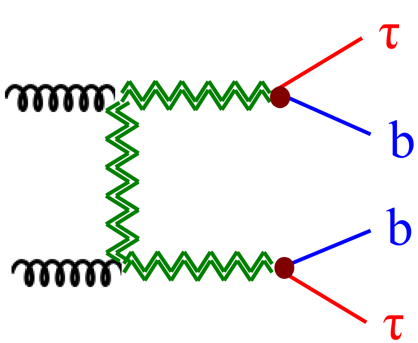
→ consistent with present high-energy data → *signals within the reach of HL-LHC*:

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





Faroughi, Greljo, Kamenik '16



▶ Model-building considerations

Considering the U_1 only

$\mathscr{L} \supset$ ...

→ excellent description of all availab...
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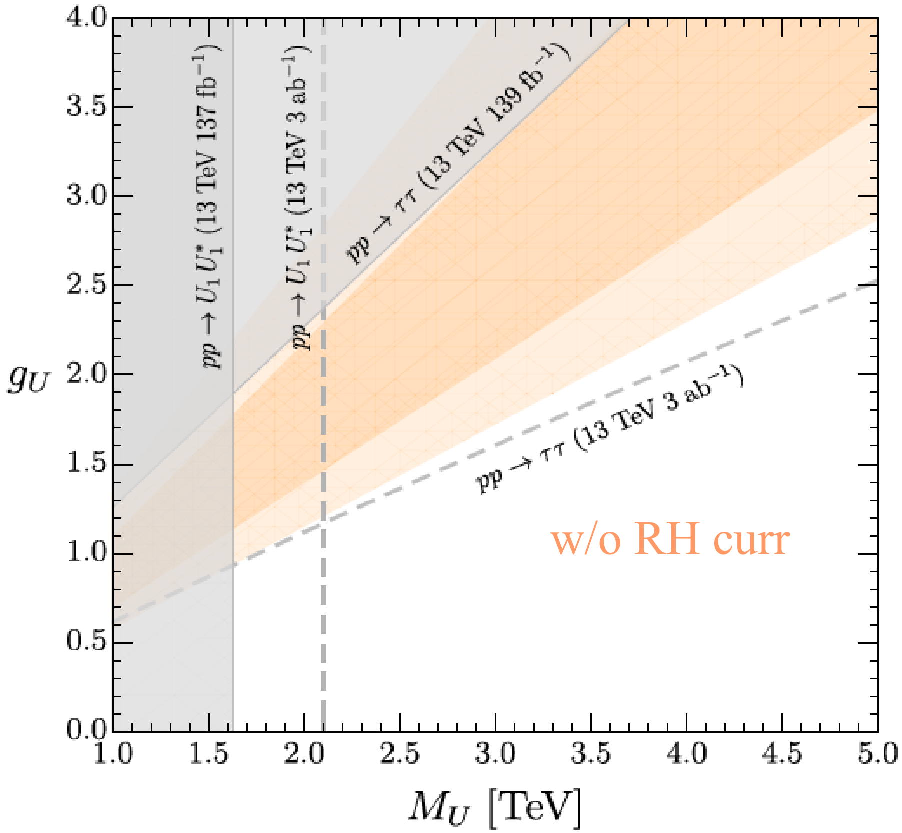
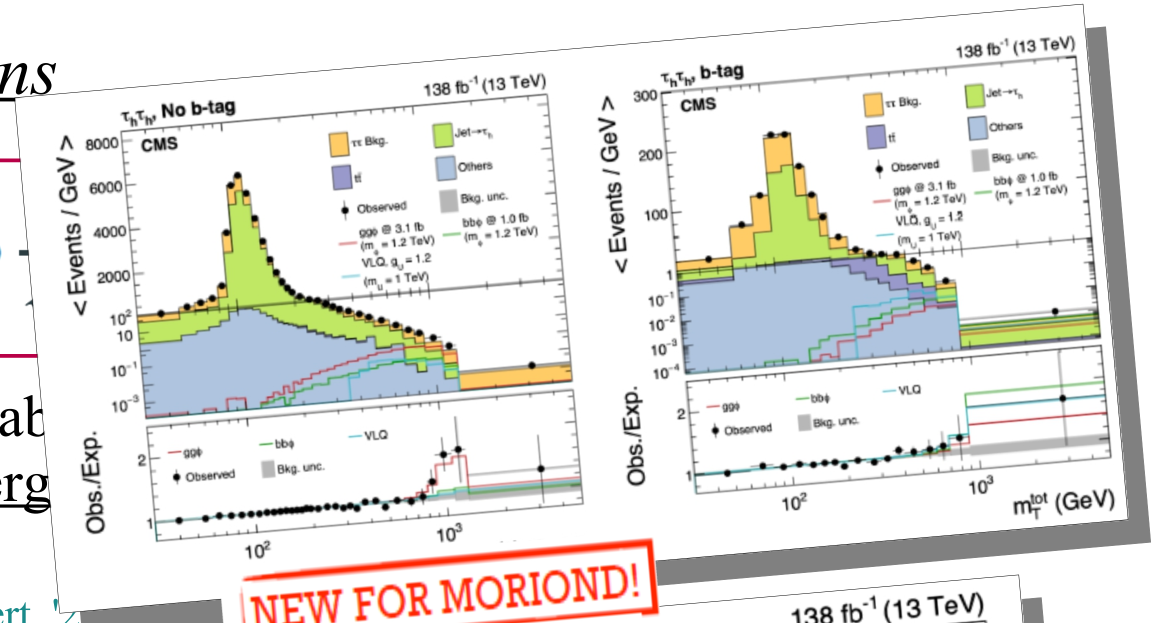
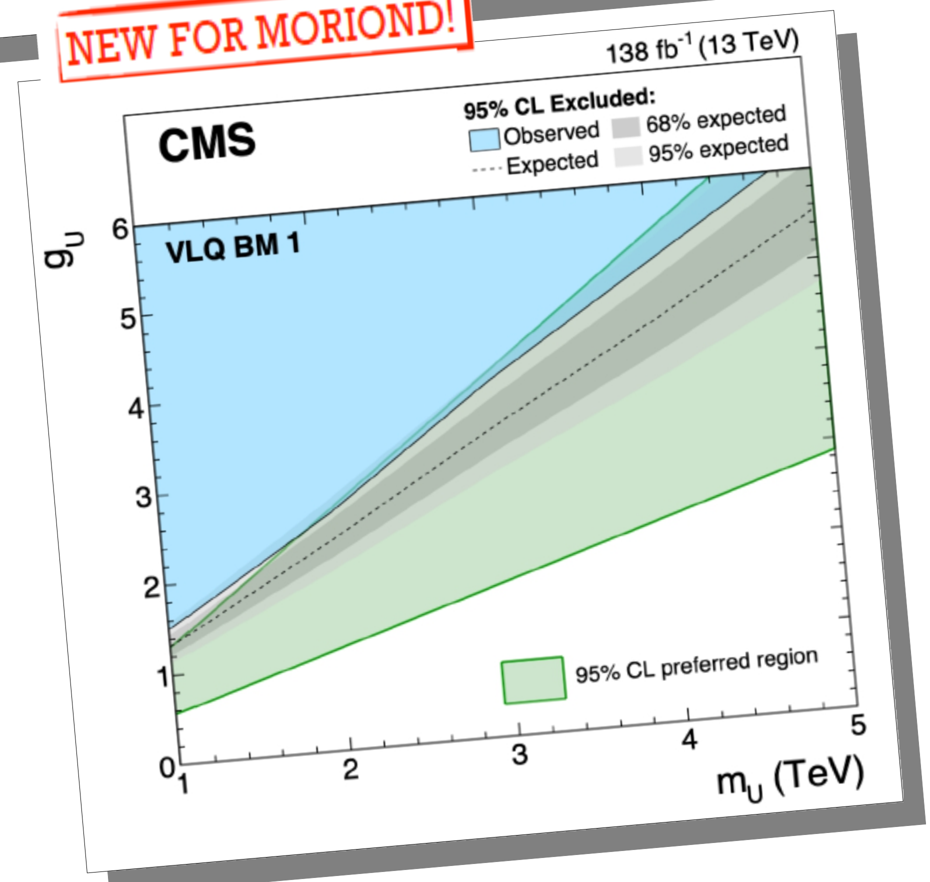
Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '2...





NEW FOR MORIOND!



Model-building considerations

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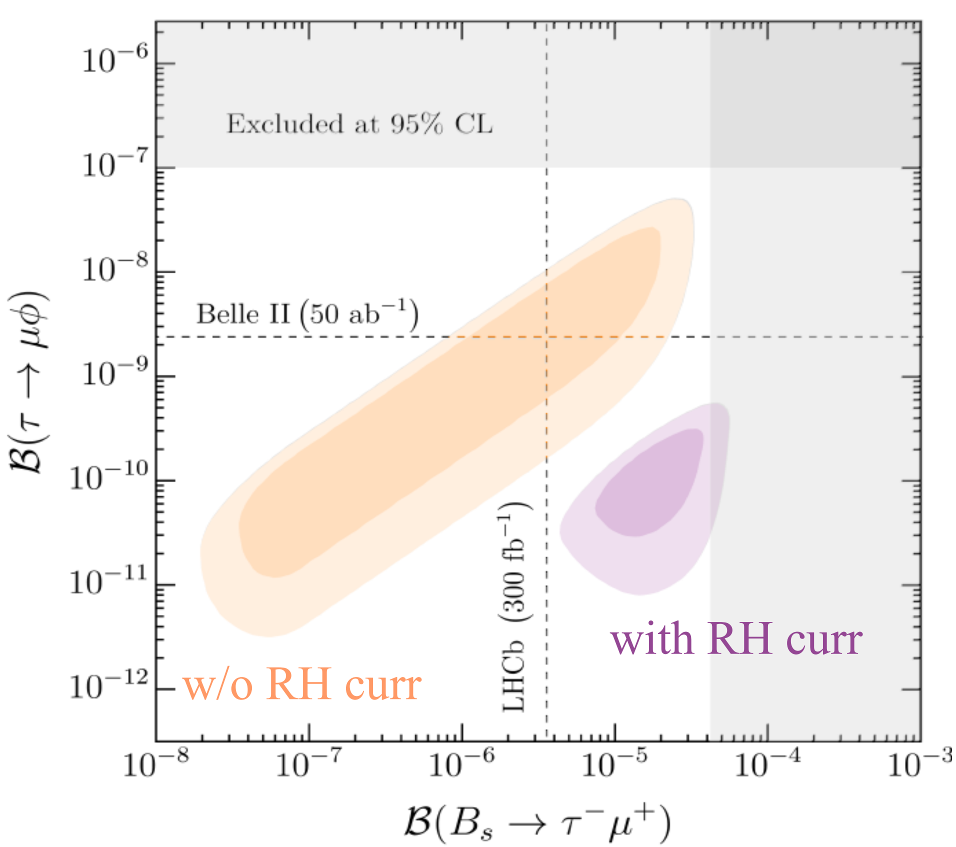
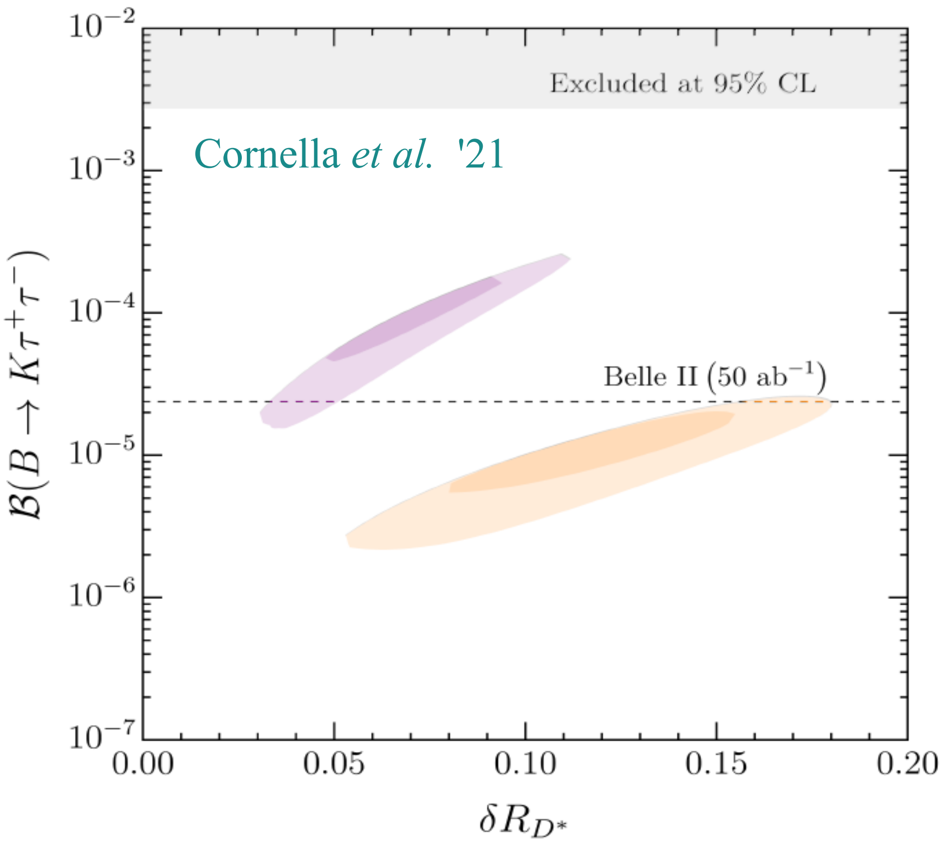
→ excellent description of all available low-energy data
→ consistent with present high-energy data → *signals within the reach of HL-LHC*
→ *interesting implications also for future low-energy searches:*





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

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

Fermions in SU(4):

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

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

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

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

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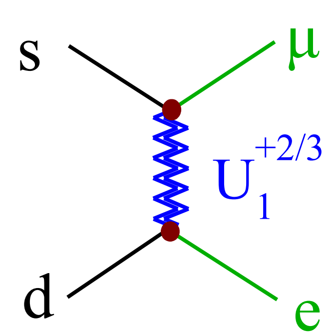
The problem of the "original PS model" are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \to \mu e$]

Attempts to solve this problem simply adding extra fermions or scalars

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



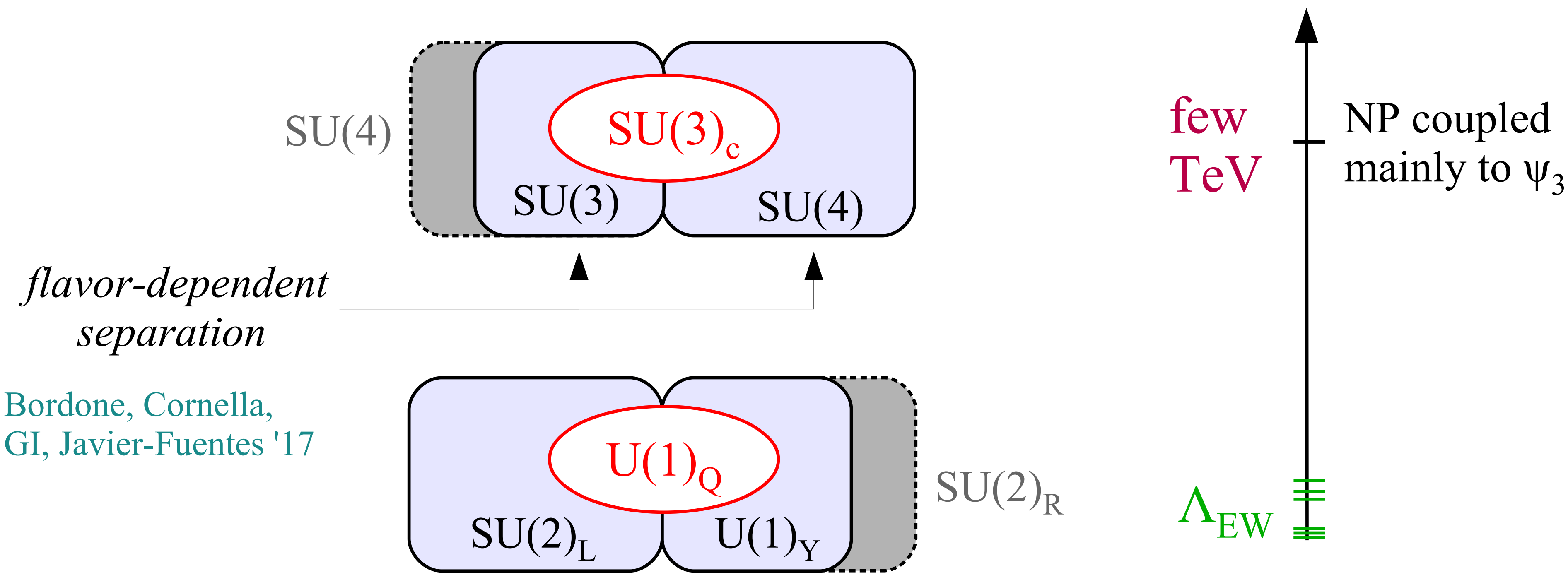
Speculations on UV completions

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

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

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

Di Luzio, Greljo, Nardecchia, '17



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- *flavor universality*

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- *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

UV completions

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

Fuentes-Martin & Stangl '20

$SU(4)\times SU(3)\times G_{EW}$

Di Luzio, Greljo, Nardecchia, '17

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

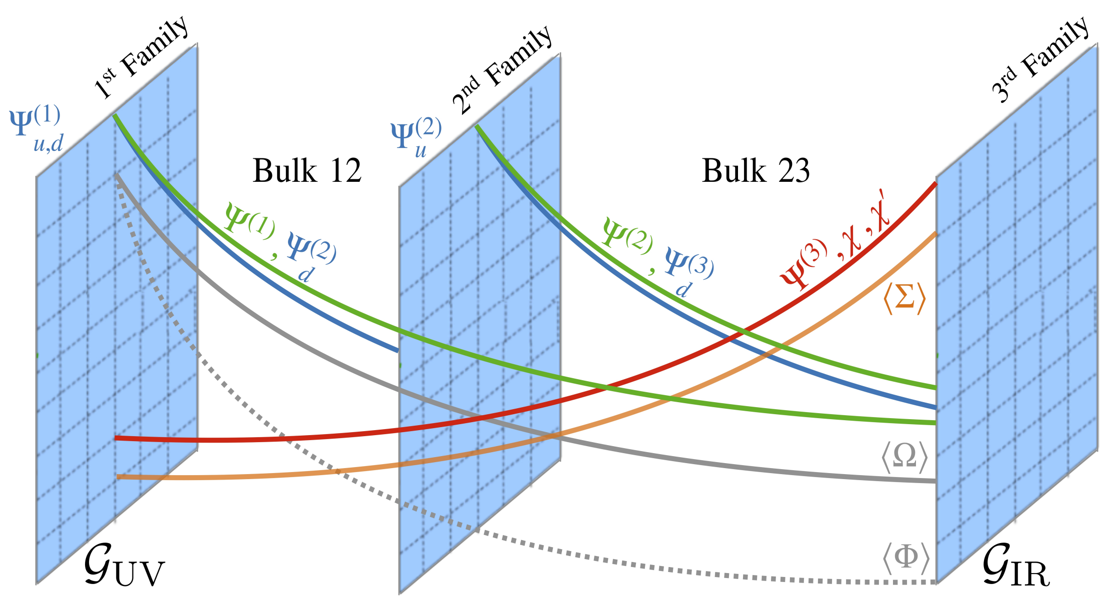
Bordone, Cornella, GI, Fuentes-Martin '17

$[\, SU(4)_h\times SU(4)_l \,]_{\text{warped-5D, 3-branes}}$

Fuentes-Martin, GI, Lizana, Selimovic, Stefanek '22

Speculations on UV completions

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



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

Dvali & Shifman, '00

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

Bordone, Cornella, GI, Javier-Fuentes '17

- Anarchic neutrino masses via inverse see-saw mechanism

Fuentes-Martin, GI, Pages, Stefanek '22

- "Holographic" (pNGB) Higgs from appropriate choice of bulk/brane gauge symm.
[$G_{\text{bulk-23}} = SU(4)_3 \times SU(3)_{1,2} \times U(1) \times SO(5)$ $\quad G_{IR} = SU(3)_c \times U(1)_{B-L} \times SO(4)$]

Fuentes-Martin, Stangl '20
Fuentes-Martin, GI, Lizana, Selimovic, Stefanek '22

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

$SU(4)_3 \times SU(3)_{1+2} \times [\, SU(2)_L \times U(1)' \,]$

ψ_3 $\psi_{1,2}$

Di Luzio, Greljo, Nardecchia, '17

$\rightarrow$ LQ $[U_1]$ + Z' + G'

SM

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'^i_L	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
u'^i_R	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
d'^i_R	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
ℓ'^i_L	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
e'^i_R	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
ψ'_L	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
ψ'_u	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$1/2$
ψ'_d	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
χ^i_L	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
χ^i_R	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
H_1	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
H_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
Ω_1	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
Ω_3	$\bar{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
Ω_{15}	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$	0

- 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*

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

$SU(4)_3 \times SU(3)_{1+2} \times [\, SU(2)_L \times U(1)' \,]$

ψ_3 $\psi_{1,2}$

Di Luzio, Greljo, Nardecchia, '17

$\to$ LQ [U_1] + Z' + G'

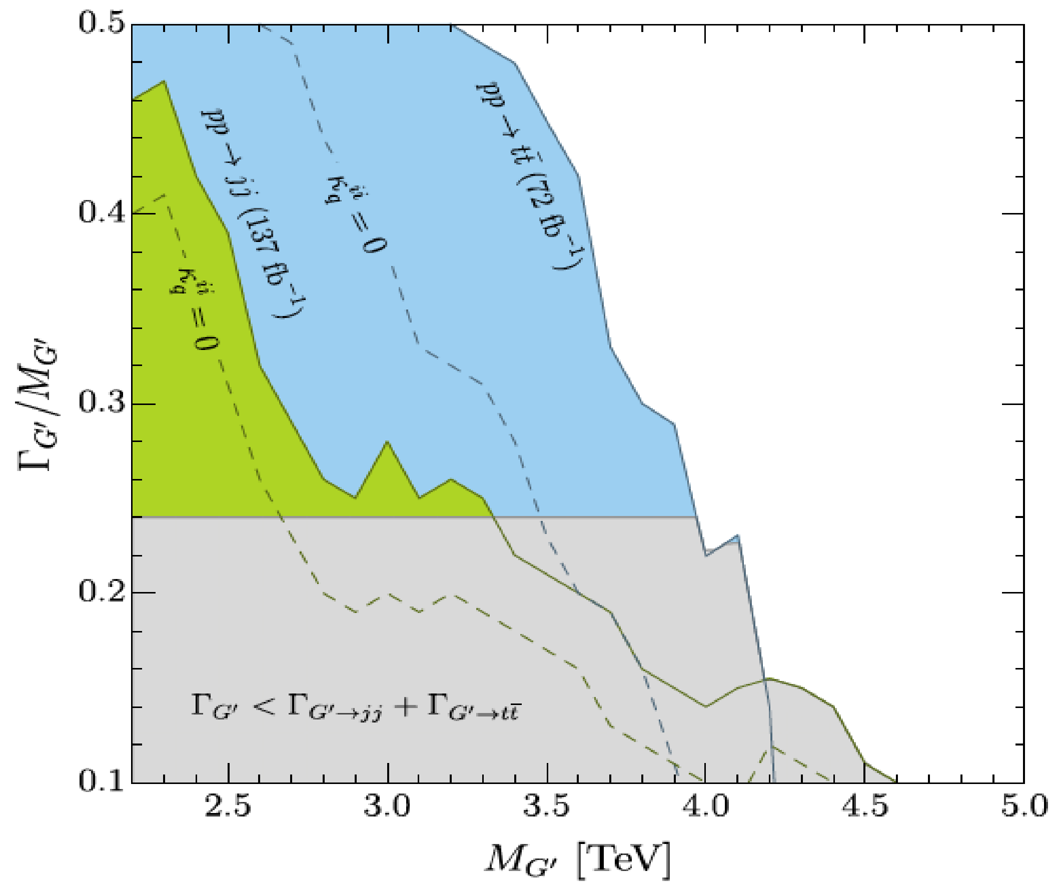
SM

Despite the apparent complexity, the construction is highly constrained

New striking collider signature:

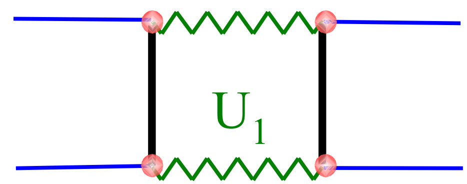
G' ("*coloron*") = heavy color octet, coupled mainly to 3rd generation quarks

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



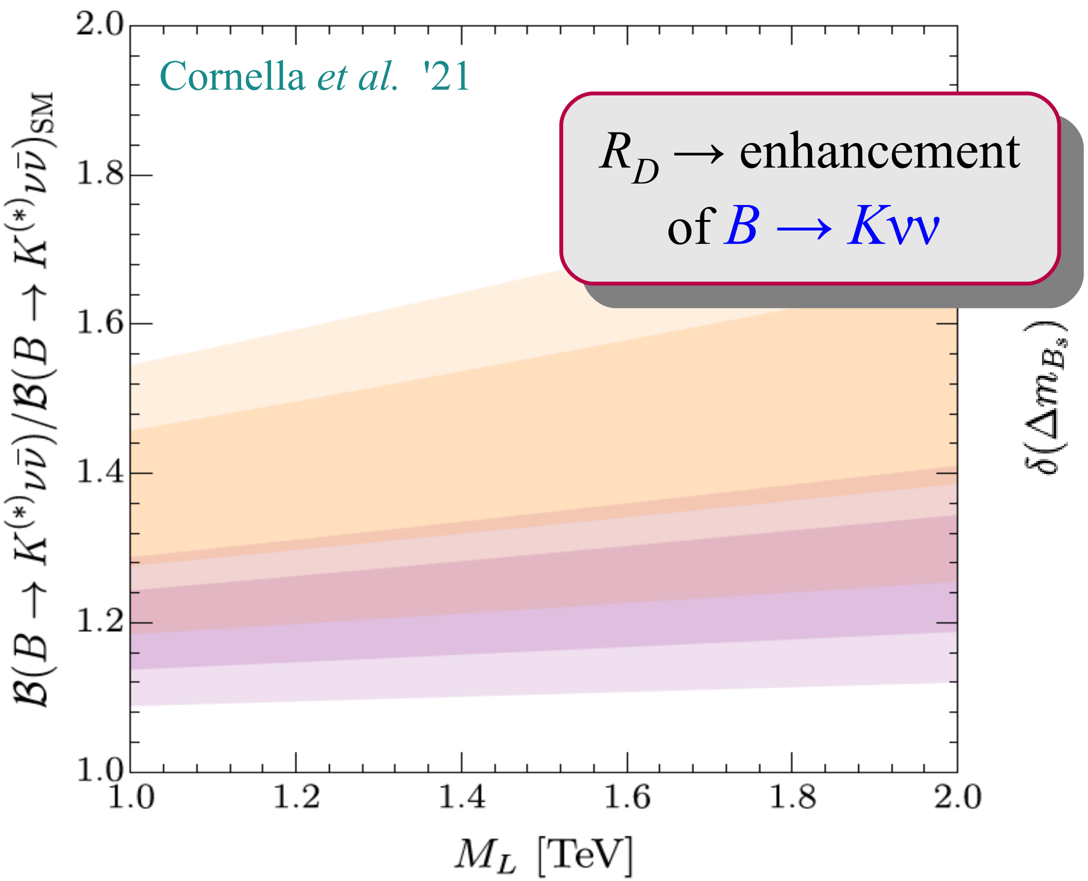
Speculations on UV completions

UV-sensitive observables in 4321 models

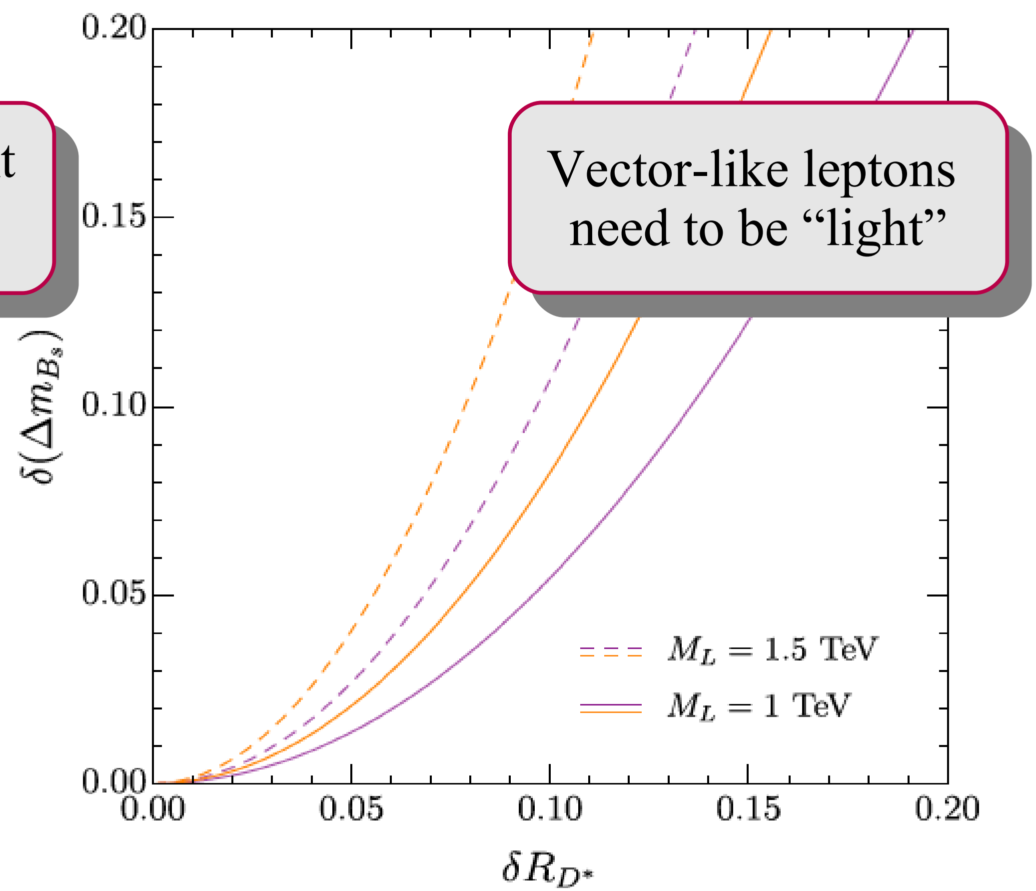


A) $B \to K\nu\nu$

B) B_s mixing [ΔF=2]



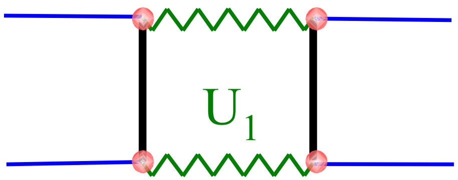
Fuentes-Martin, GI, Konig, Selimovic, '20



Di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner '18

Speculations on UV completions

UV-sensitive observables in 4321 models



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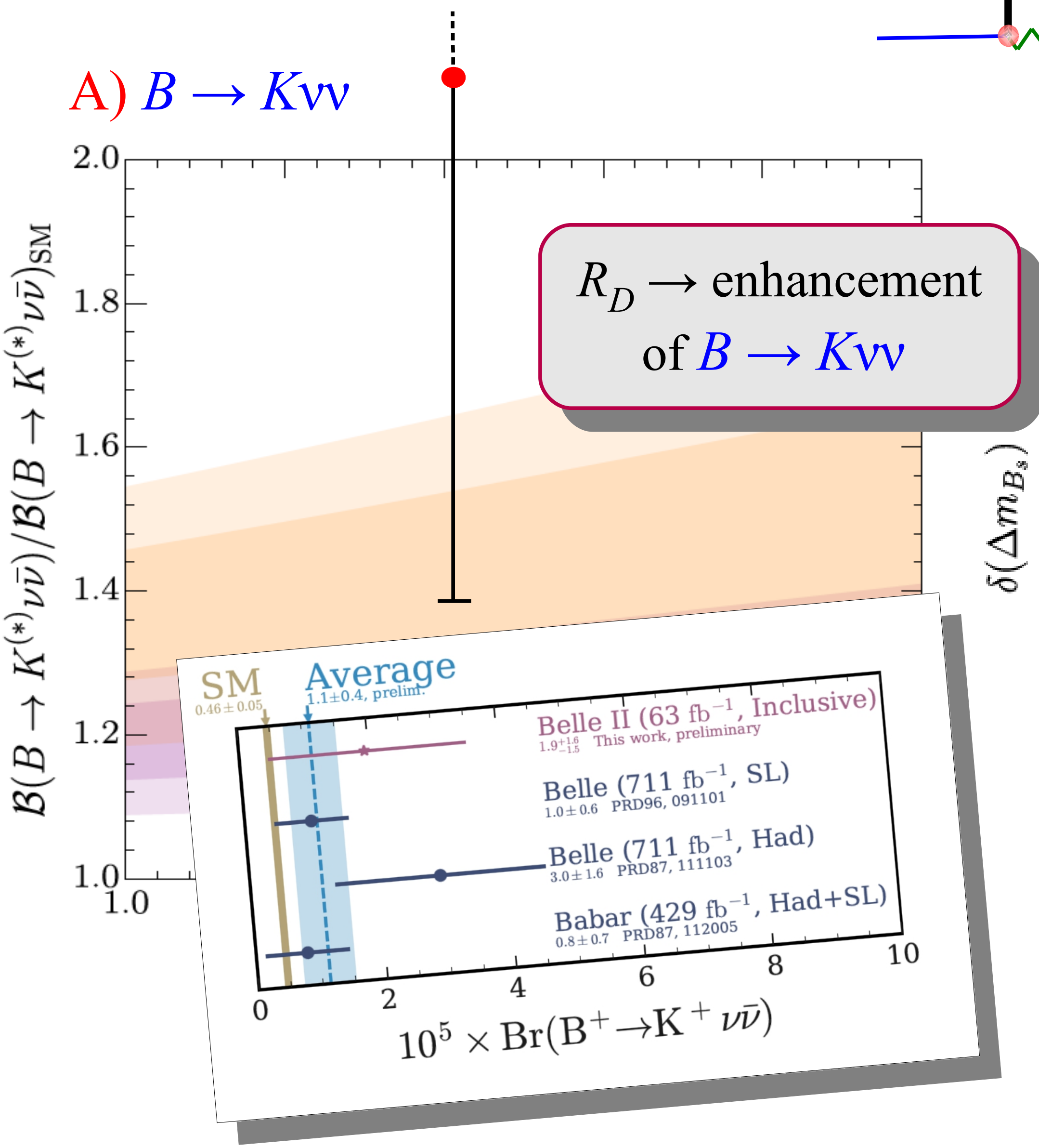

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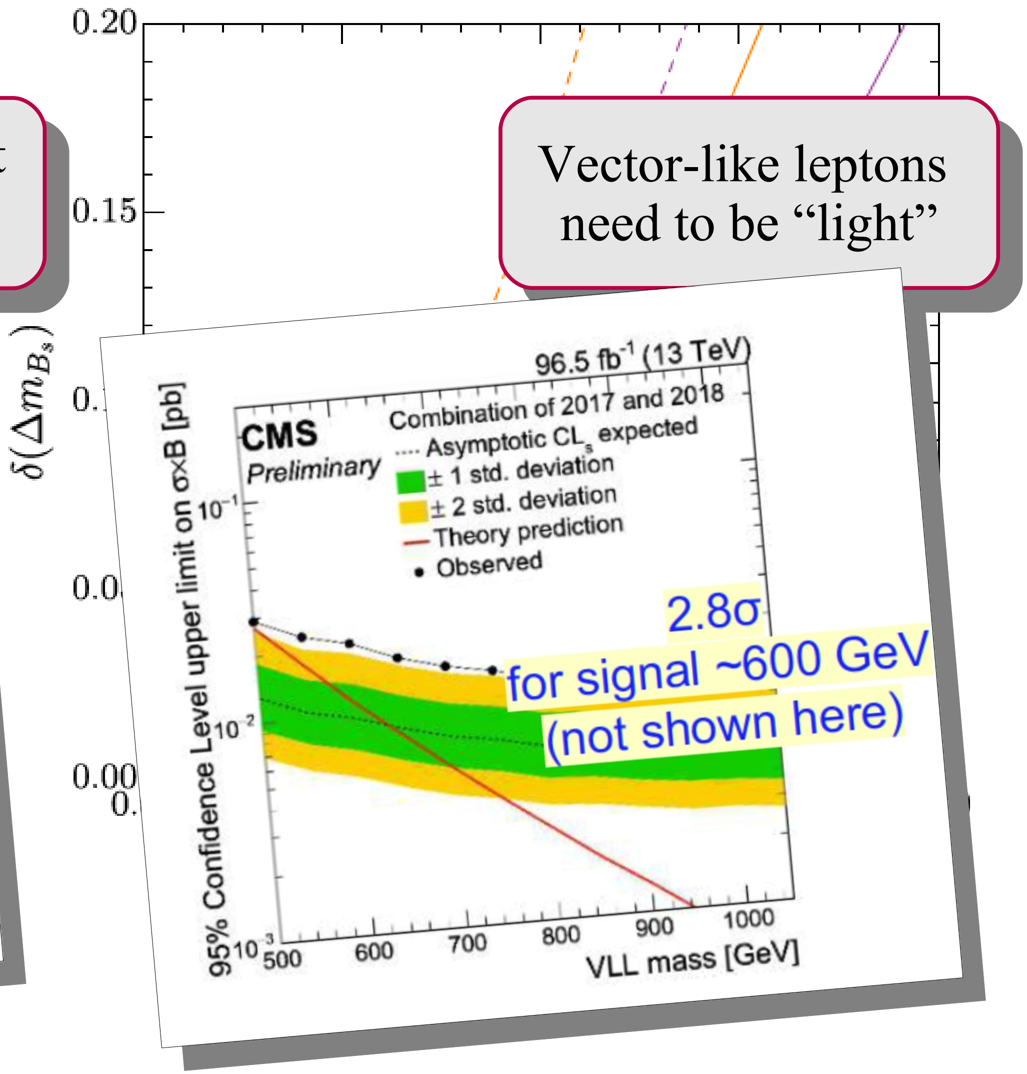

Conclusions

- 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 in B physics

- The statistical significance of the LFU anomalies is growing: in the $b\to s\ell\ell$ system, the chance this is a pure statistical fluctuation is marginal.

- If combined, the two sets of anomalies point to non-trivial flavor dynamics around the TeV scale, involving mainly the 3rd family → connection to the origin of flavor [multi-scale picture at the origin of flavor hierarchies]

- No contradiction with existing low- & high-energy data, but new non-standard effects should emerge soon in both these areas

⬇

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