Flavor physics: hints of new physics and new BSM ideas

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- Introduction
- The LFU anomalies: data and EFT
- General model-building considerations
- UV completions: 4321 & beyond
- Predictions @ low- and high-pT physics
- Conclusions

University of Zurich[UZH]

European Research Council
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Introduction

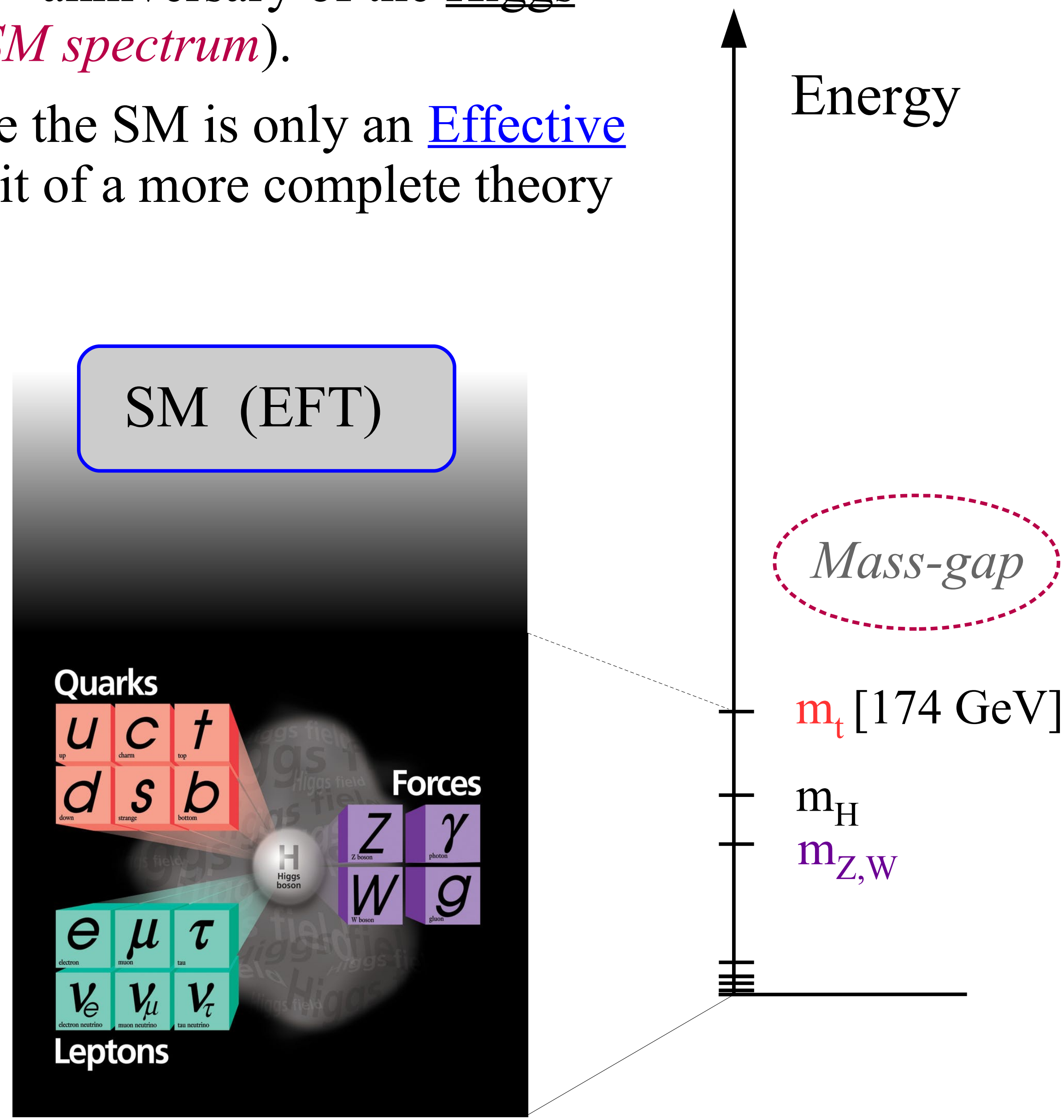
These days we are celebrating the 10th anniversary of the Higgs discovery (*or the completion of the SM spectrum*).

However, as for any QFT, we believe the SM is only an Effective Field Theory, i.e. the low energy limit of a more complete theory with more degrees of freedom

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

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

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



Introduction

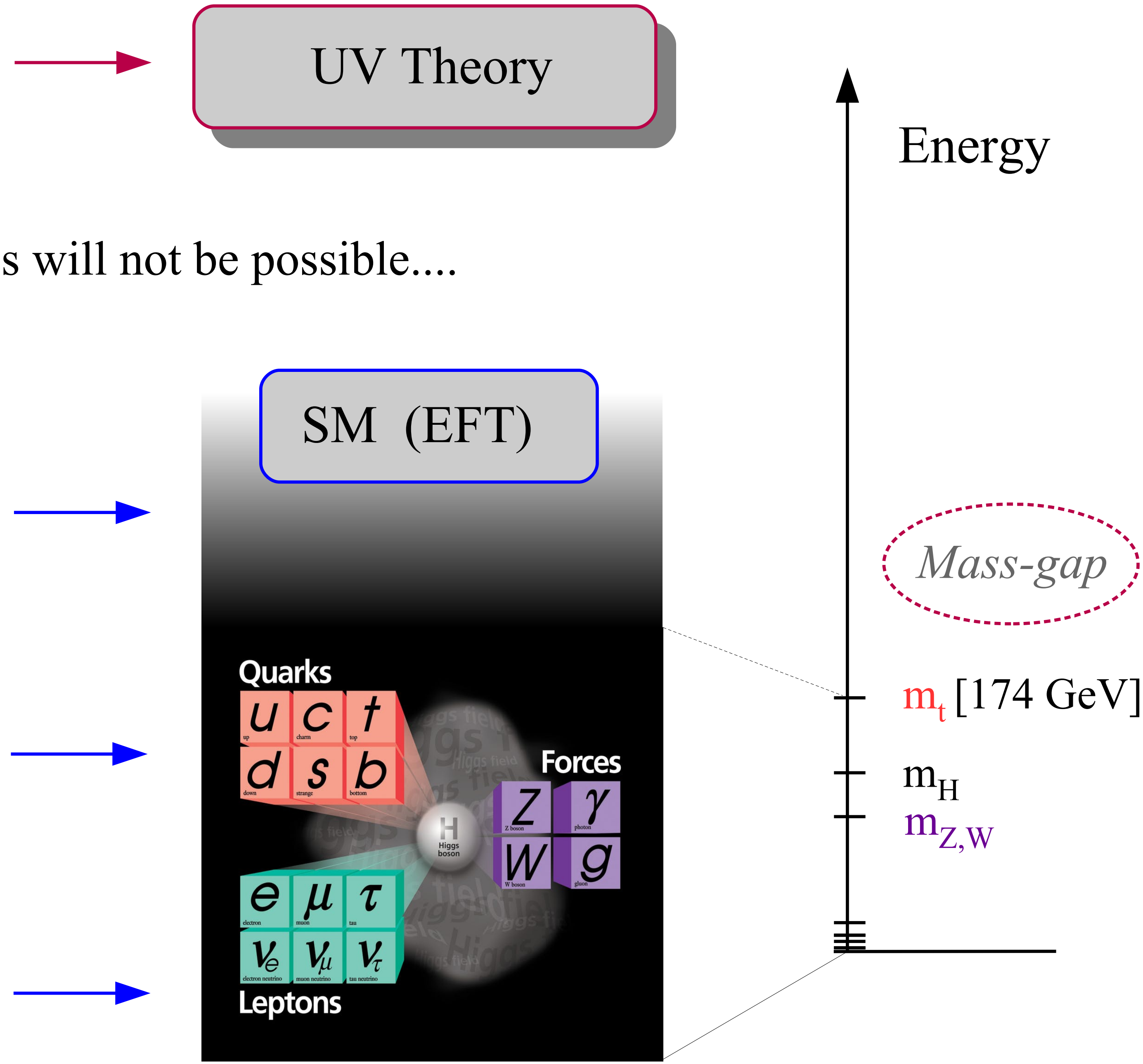
Ideally, we would like to probe the UV directly, via high-energy experiments

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:

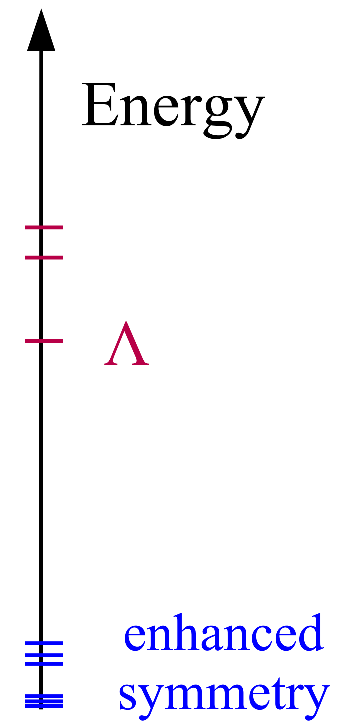
- *several tuned* (SM) *couplings*
- *several accidental* (*approximate*) *symmetries*



Introduction

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

(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*]

▶ *Introduction*

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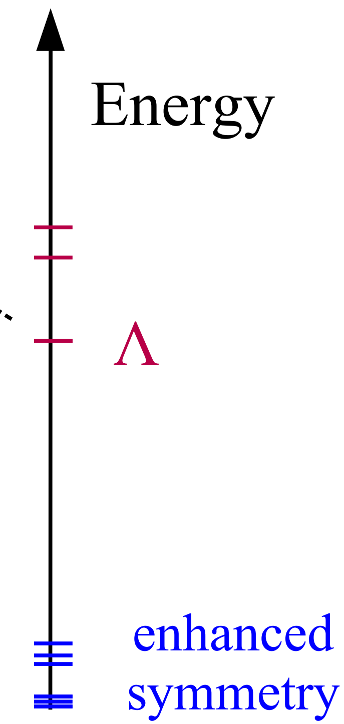


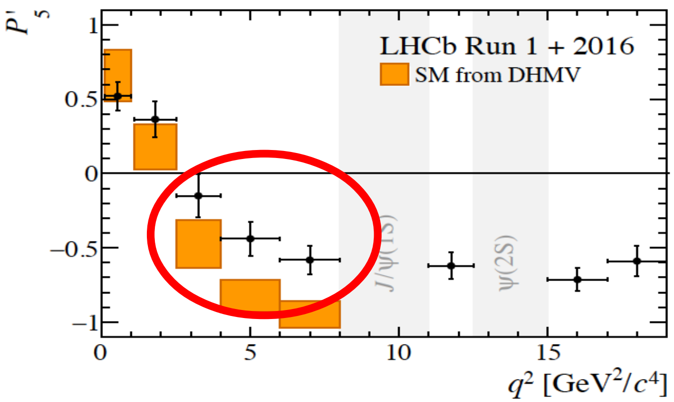
"Accidental symmetries" are symmetries which are not fundamental properties of the theory, but emerge accidentally at low energies / large distances → not enough "variables" to describe the violation of the symmetry [~ *multipole expansion*]

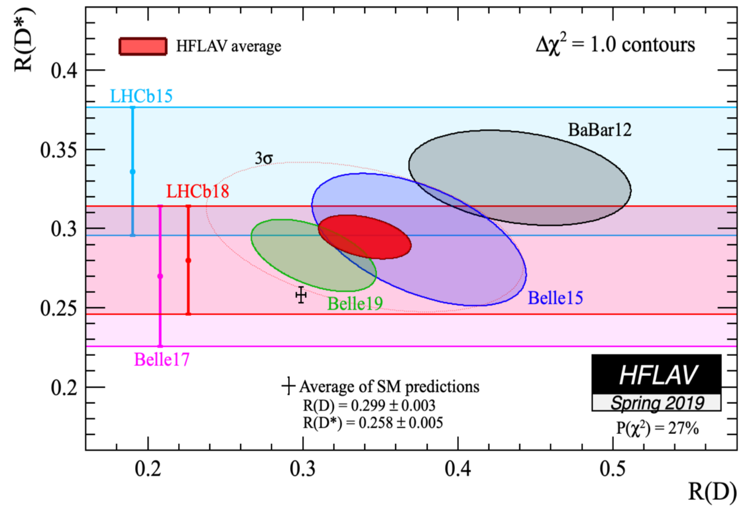
If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

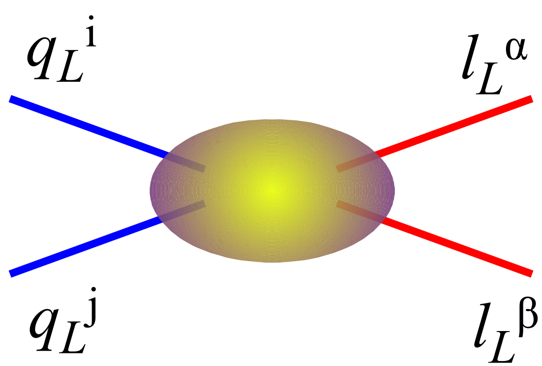
Violations of accidental symmetries

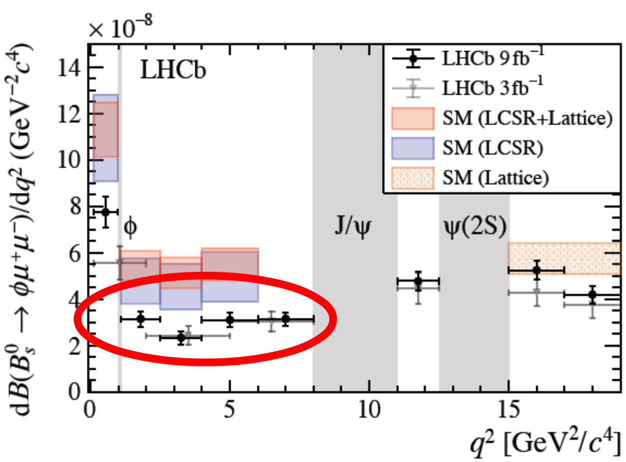
Well-known past examples... but also the hints of Lepton Flavor Universality violations recently reported in B physics belong to this category

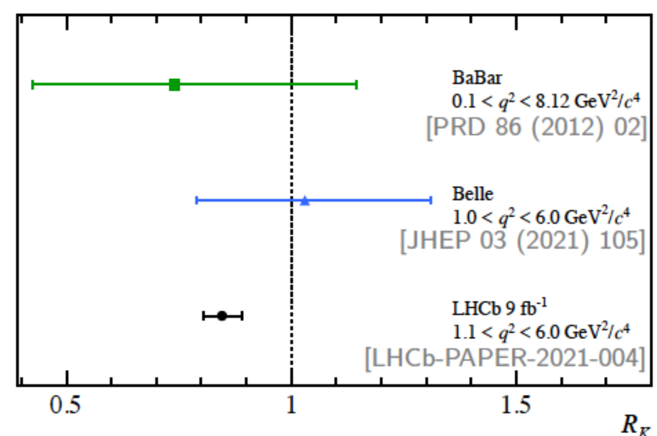
The LFU anomalies: data and EFT











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

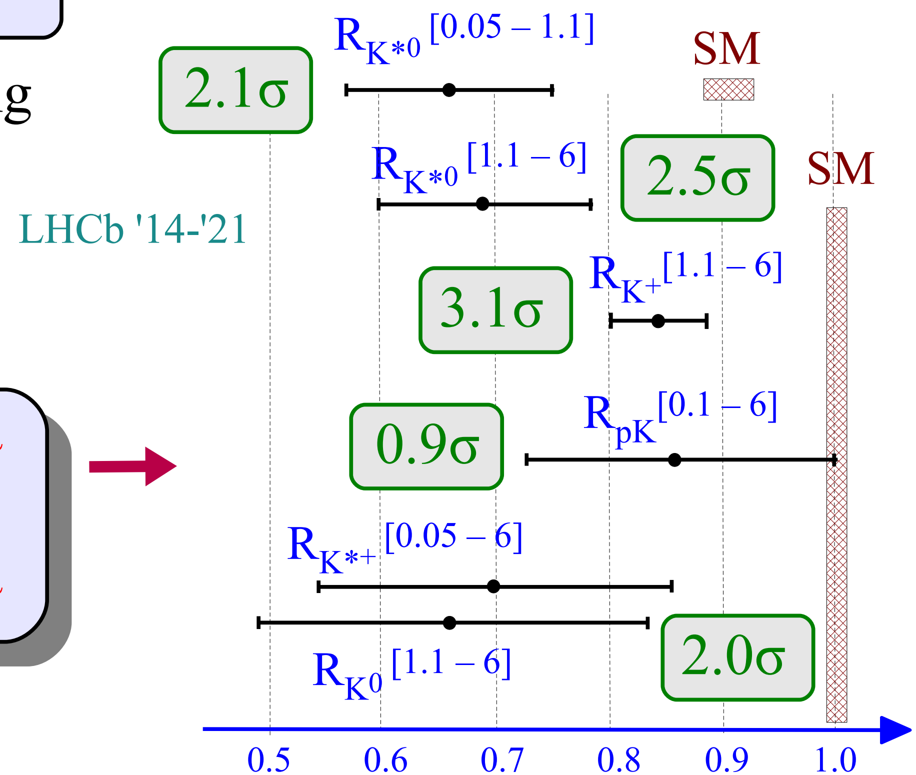
but all the lepton Yukawa couplings are small compared to SM gauge couplings, giving rise to the (*approximate*) universality of decay amplitudes which differ only by the different lepton species involved

The LFU anomalies

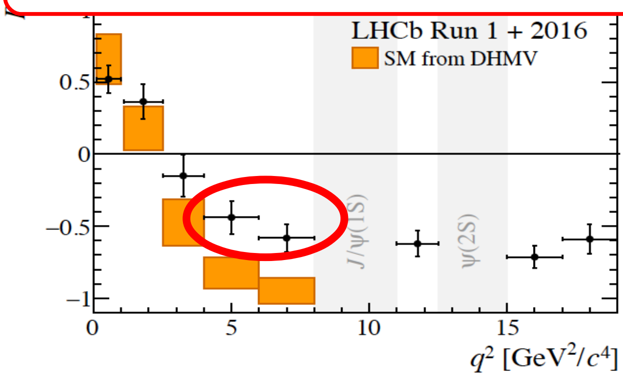
- $b \to s\, l^+ l^-$ (neutral currents): μ vs. e

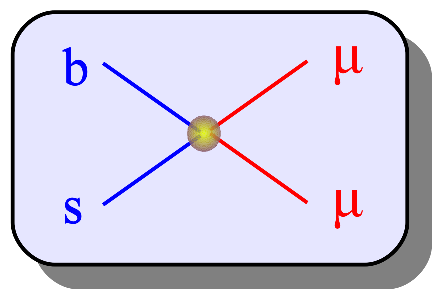
High significance: several observables pointing to the same coherent picture

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

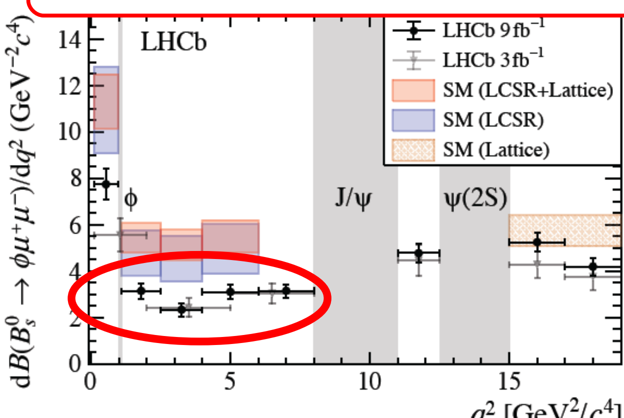


$B \to K^* \mu\mu$ angular distribution





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



$BR(B_s \to \mu\mu)$

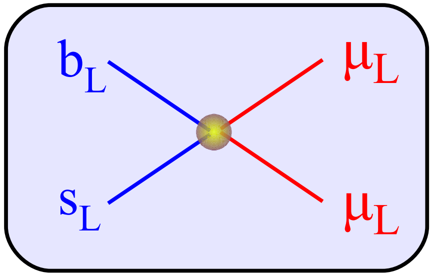
$BR_{exp} = (2.85 \pm 0.32) \times 10^{-9}$ ATLAS+CMS+LHCb '21

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

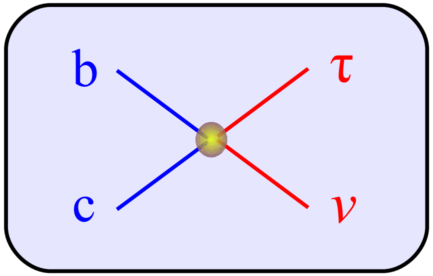
2.3σ

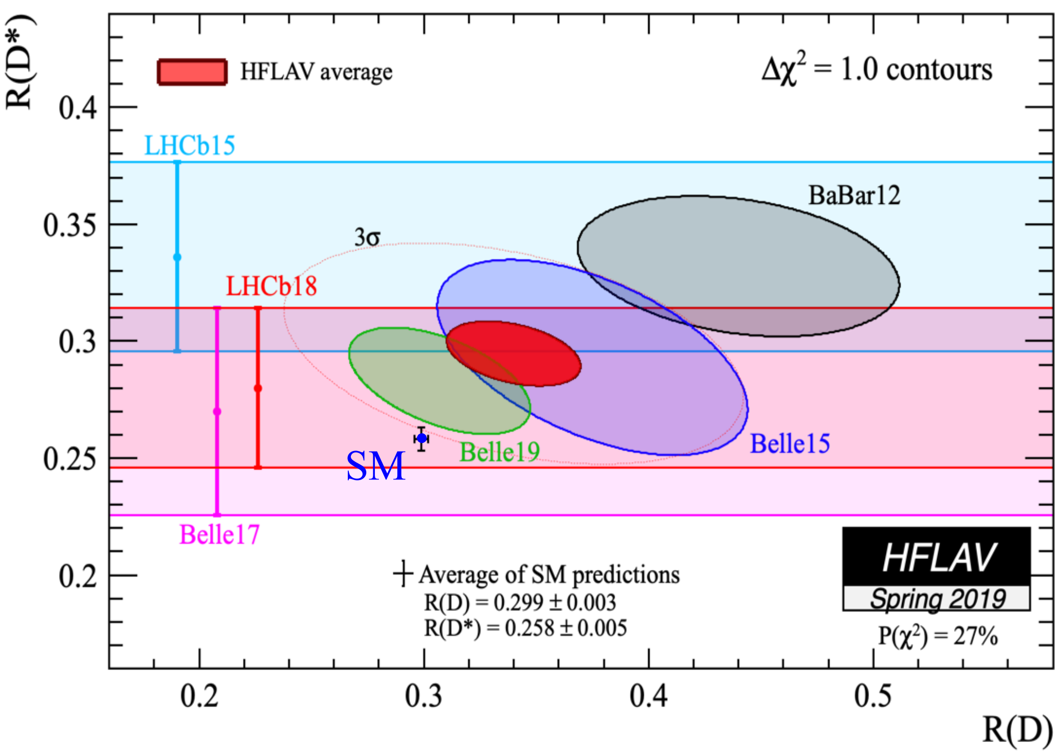
The LFU anomalies

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



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



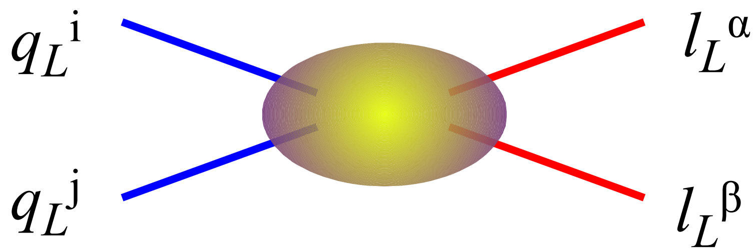


$$R(X) = \frac{\Gamma(B \to X\, \tau\nu)}{\Gamma(B \to X\, l\nu)} \quad X = D \text{ or } D^*$$

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

General 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(3rd) c(2nd) → τ(3rd) ν_τ(3rd)
- Small coupl. [*compete with SM loop-level*] in b(3rd) s(2nd) → μ(2rd) μ(2rd)

↓

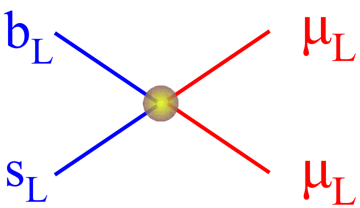
$C_{ij\alpha\beta}$ = large for 3rd generation fields + small terms for 2nd (& 1st) generations →

Link to pattern of the Yukawa couplings !

General EFT considerations

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

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



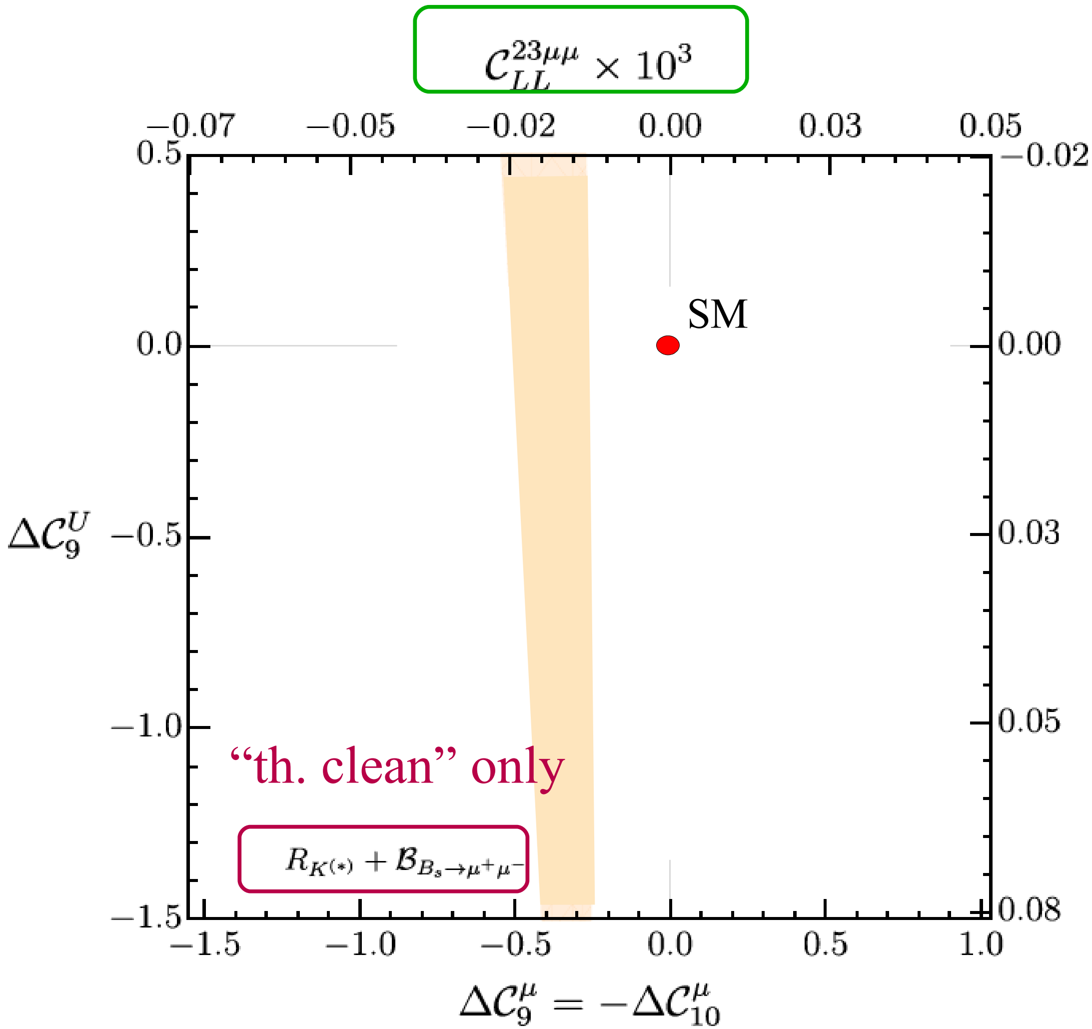
$\sim 4\times10^{-5}\ G_{Fermi}$

super-weak interaction!

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

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

"clean" effect of short-distance origin
$[\Delta C_i^\mu = C_i^\mu - C_i^e]$



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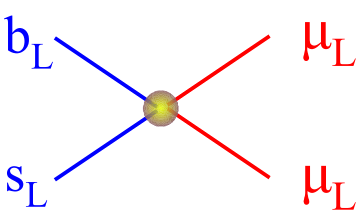
✔ $O(10^{-1})$ suppress. for each 2^{nd} gen. l_L



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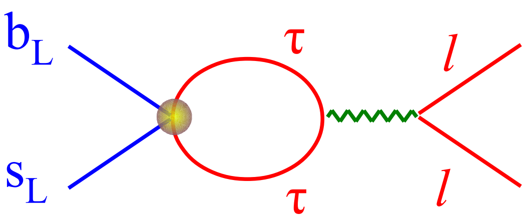
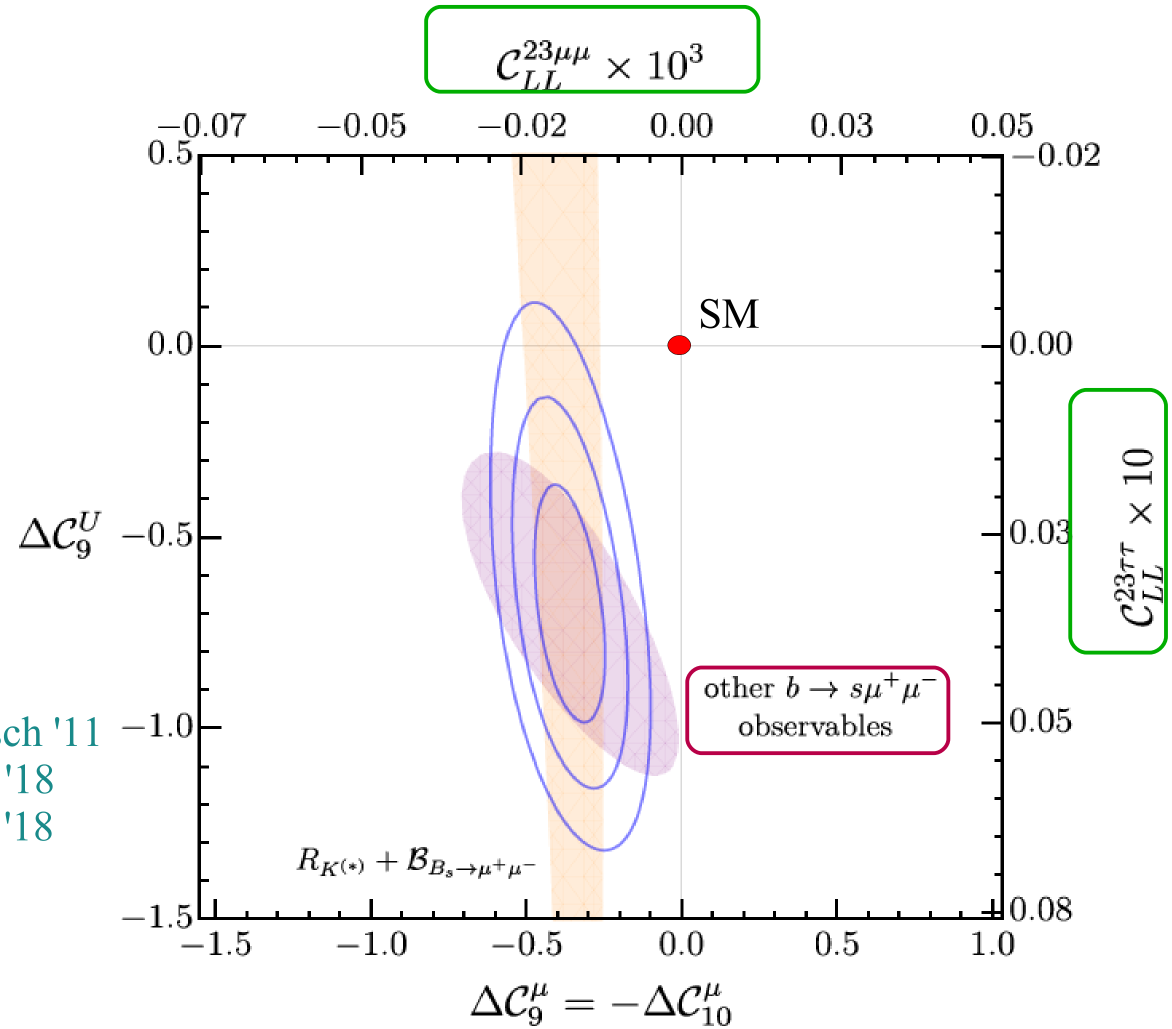
$C_{LL}^{23\mu\mu}$ ➡ $\Delta C_9^\mu = -\Delta C_{10}^\mu$



$C_{LL}^{23\tau\tau}$ ➡ ΔC_9^{Univ}

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

Same deviation in μ & e
[theoretically less clean]



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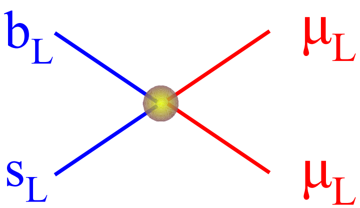
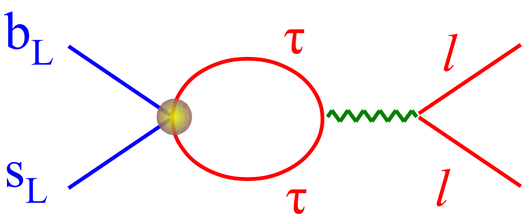


$\sim 4\times10^{-5}\ G_{\rm Fermi}$

super-weak interaction!

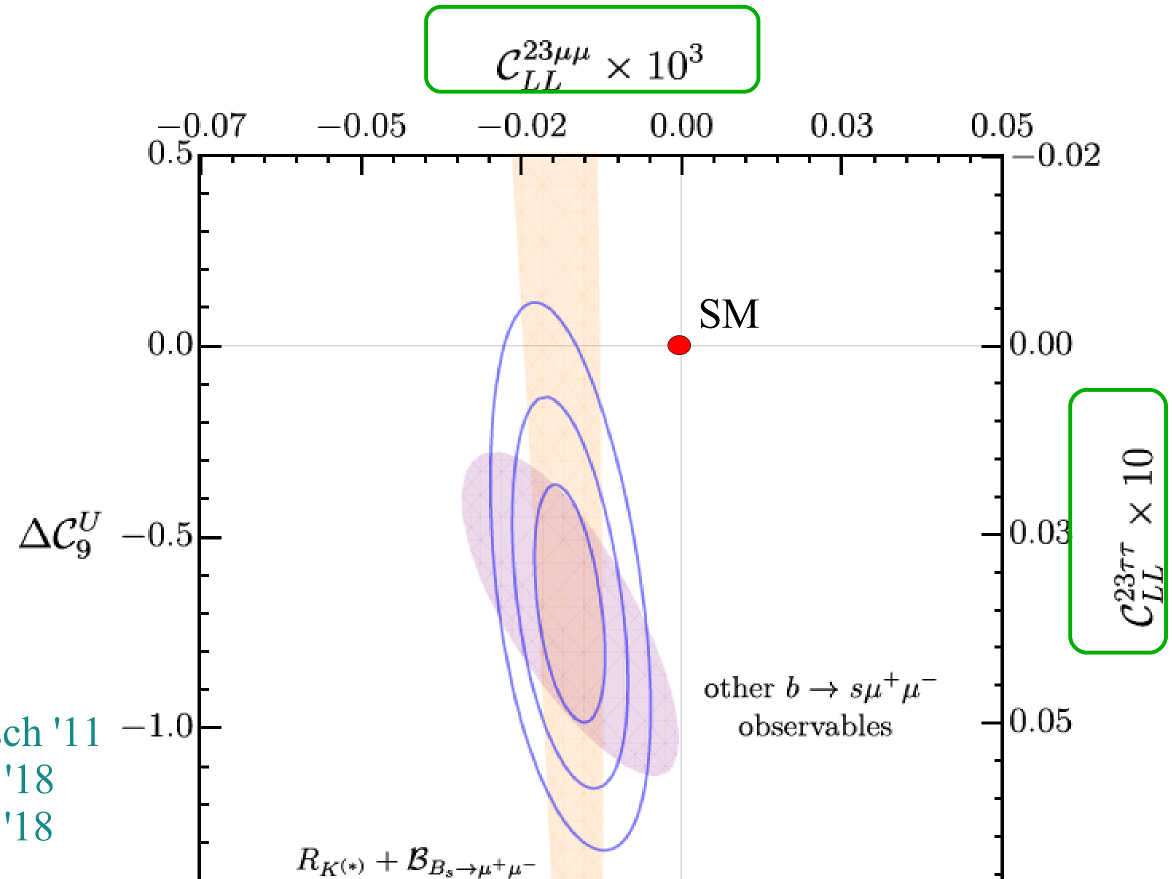
$C_{LL}^{23\mu\mu} \Rightarrow \Delta C_9^\mu = -\,\Delta C_{10}^\mu$



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

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

General 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

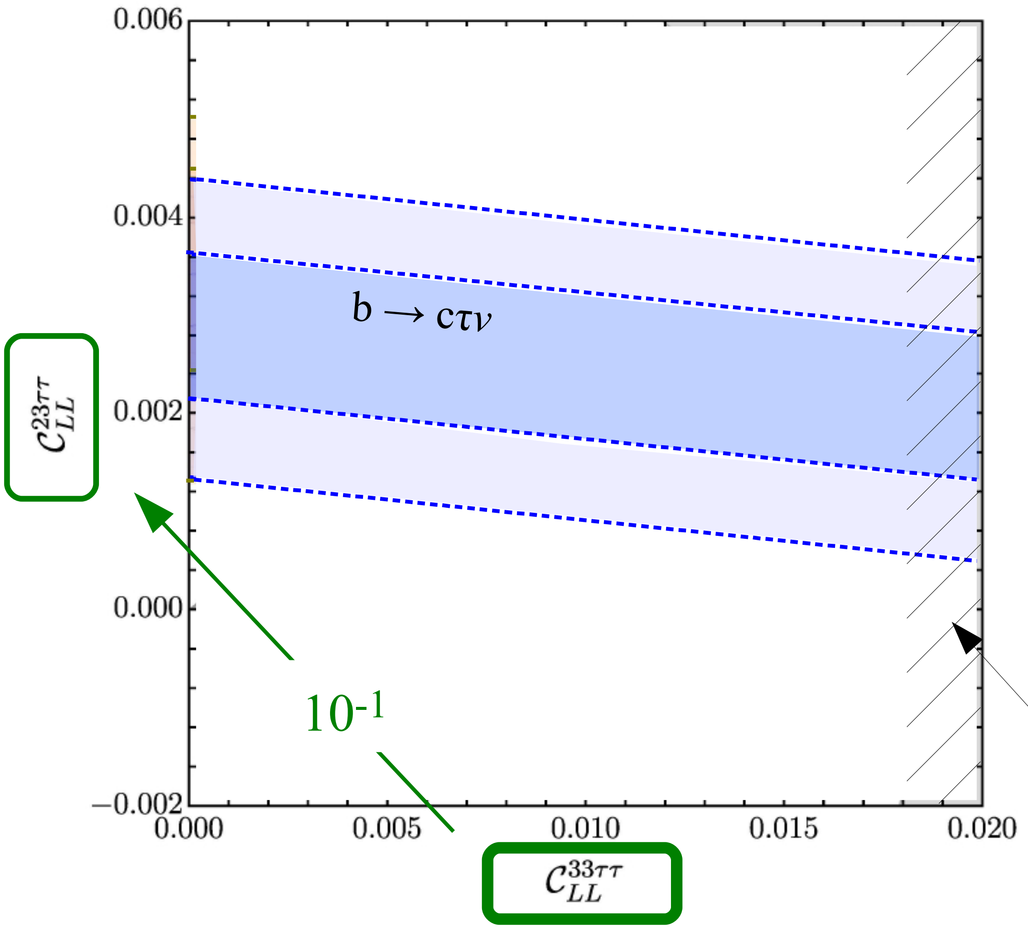
charged-currents:

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

We have chosen down-type quarks as flavor basis

↓

CKM rotation to get the charm



bounds from high-pT searches

General EFT considerations

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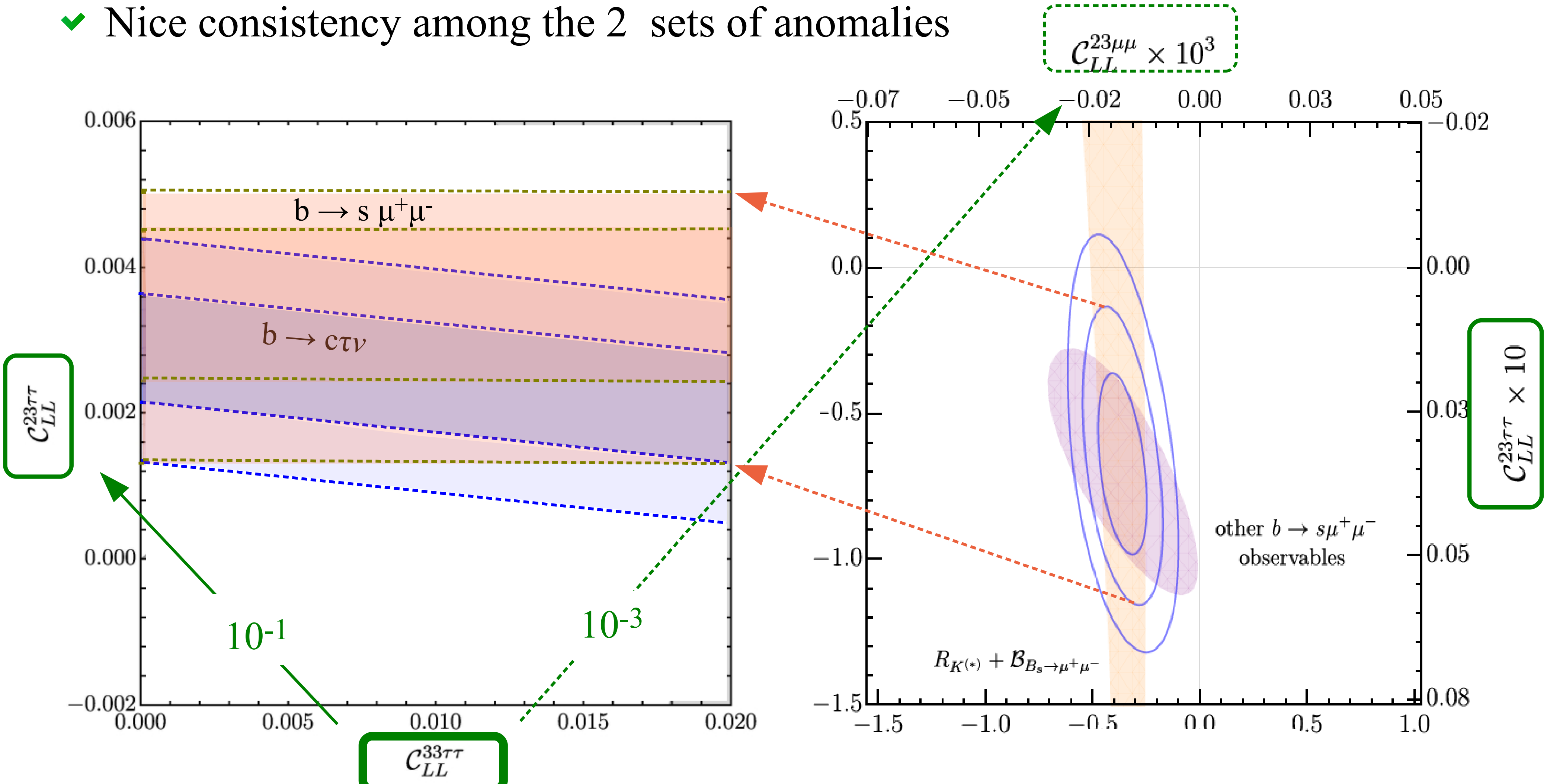
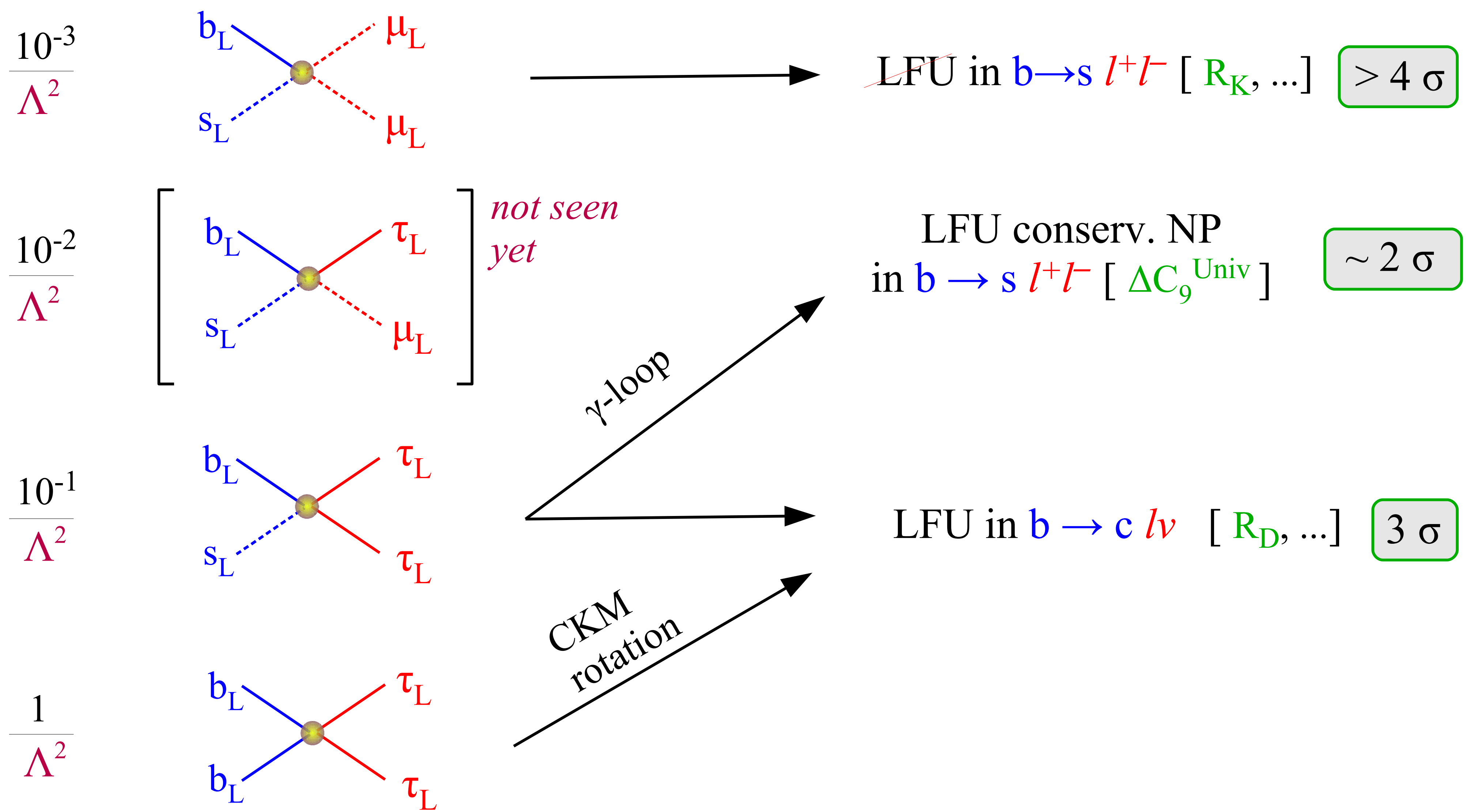
- Nice consistency among the 2 sets of anomalies



▶ *General EFT considerations*



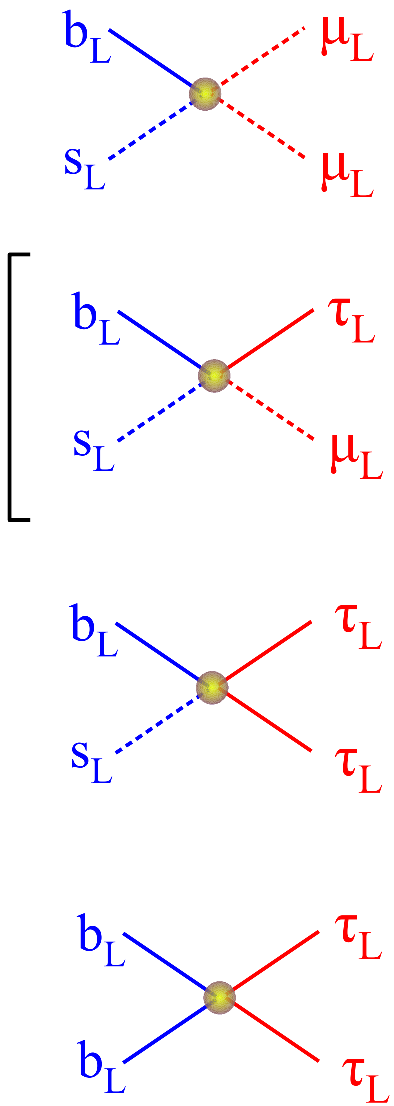
$\Lambda \approx 1.5$ TeV

▶ General EFT considerations

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

FLAVOR

$\frac{10^{-3}}{\Lambda^2}$ — $\frac{10^{-2}}{\Lambda^2}$ — $\frac{10^{-1}}{\Lambda^2}$ — $\frac{1}{\Lambda^2}$



not seen yet

LFU in $b \to s\, l^+ l^-$ [R_K, ...] $> 4\,\sigma$

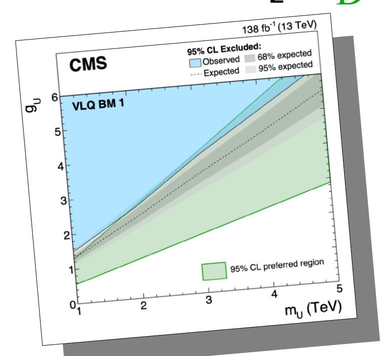
LFU conserv. NP in $b \to s\, l^+ l^-$ [$\Delta C_9^{\rm Univ}$] $\sim 2\,\sigma$

γ-loop

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

CKM rotation

$pp \to \tau\tau$



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

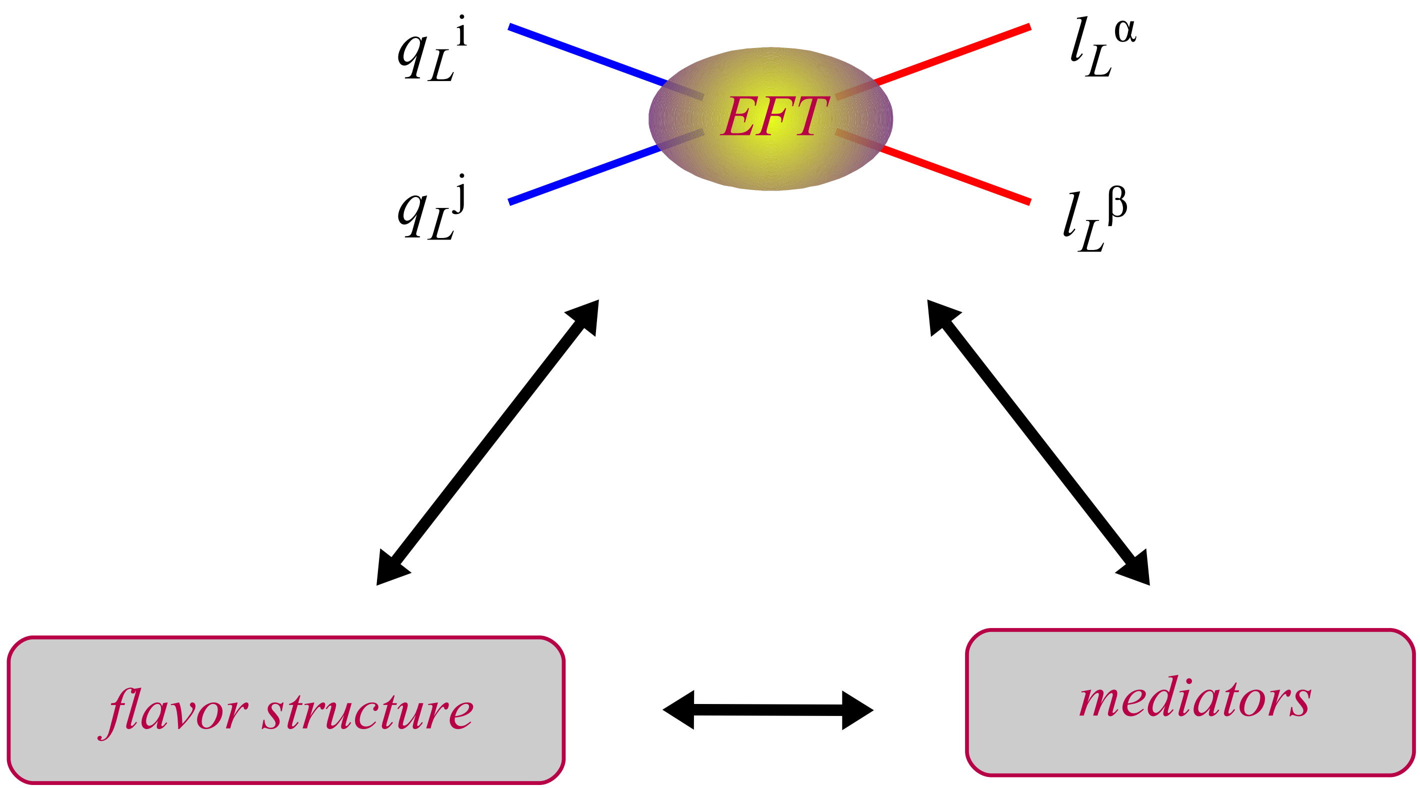
NP stabilizing the Higgs sector

$\Lambda \approx 1.5$ TeV

General model-building considerations

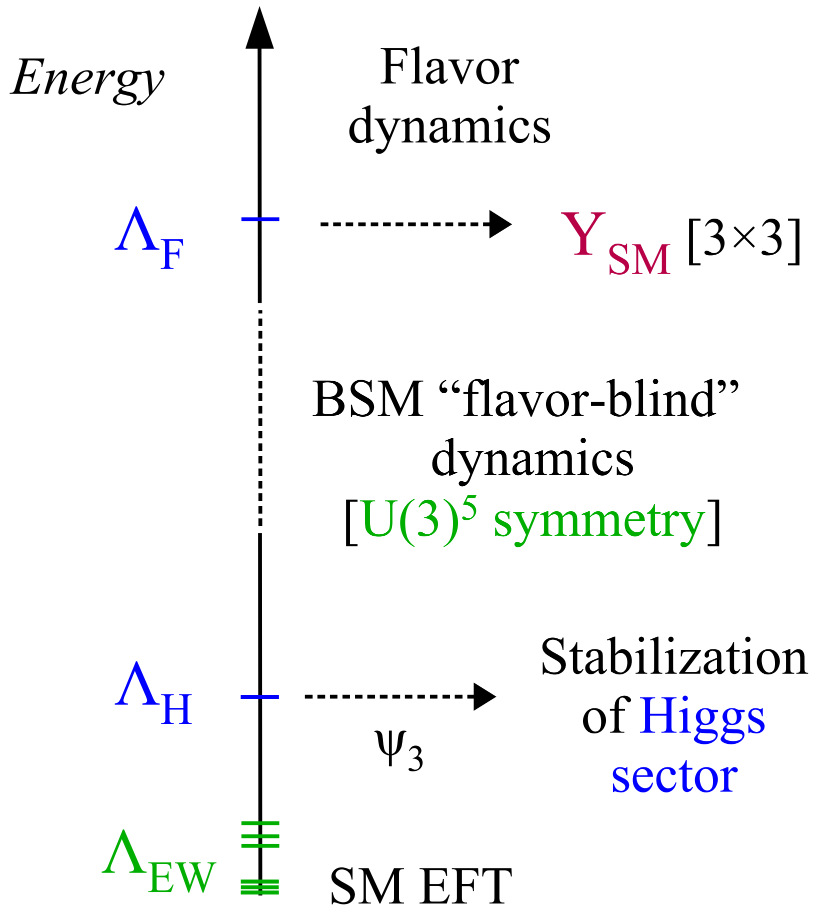
General odel-building considerations

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*



▶ General odel-building considerations

The old (Minimal Flavor Violation) paradigm:



Main idea:

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

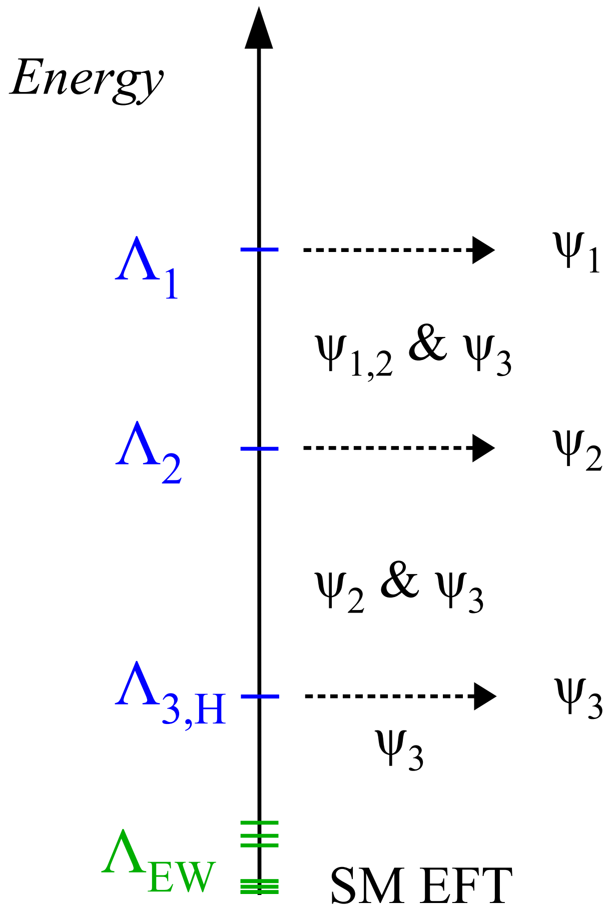
⬇

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

▶ General odel-building considerations

~~*The old (MFV) 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:

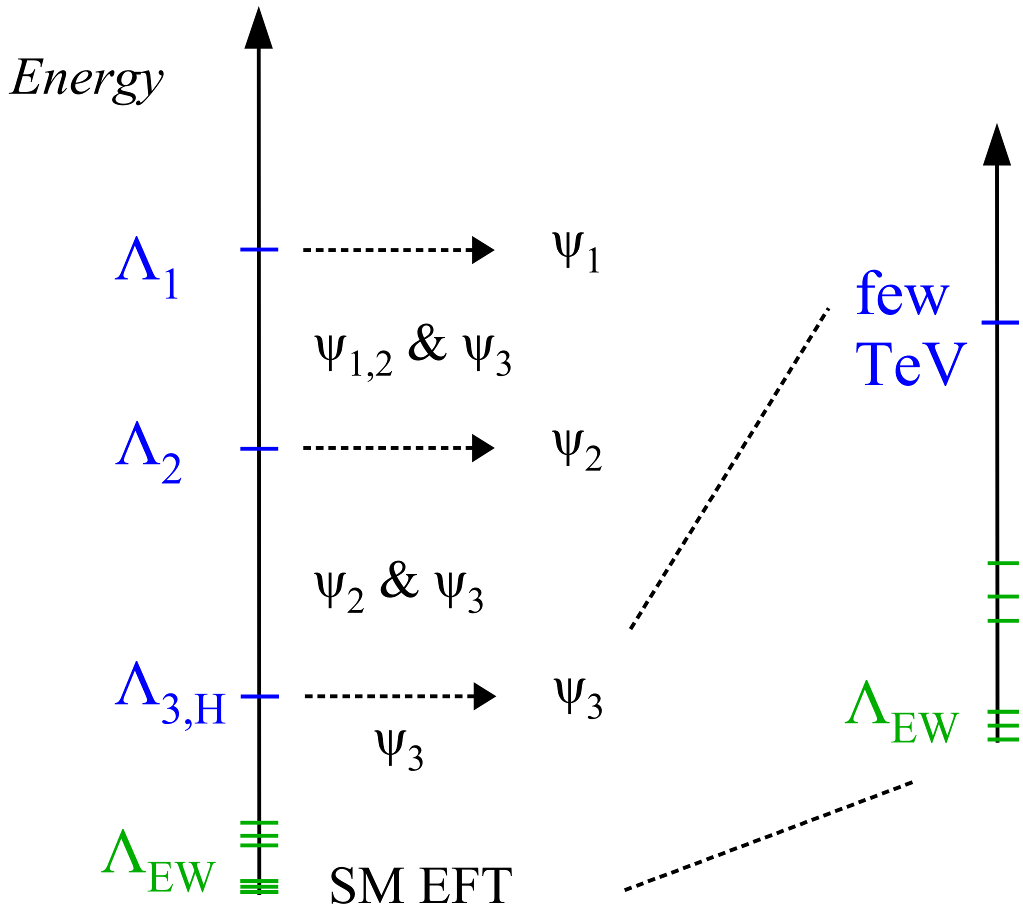
- Flavor non-universal interactions already at the TeV scale:
- 1st & 2nd gen. have small masses because they are coupled to NP at heavier scales

⬇

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

General odel-building considerations

~~*The old (MFV) paradigm*~~ *Multi-scale picture @ origin of flavor:*

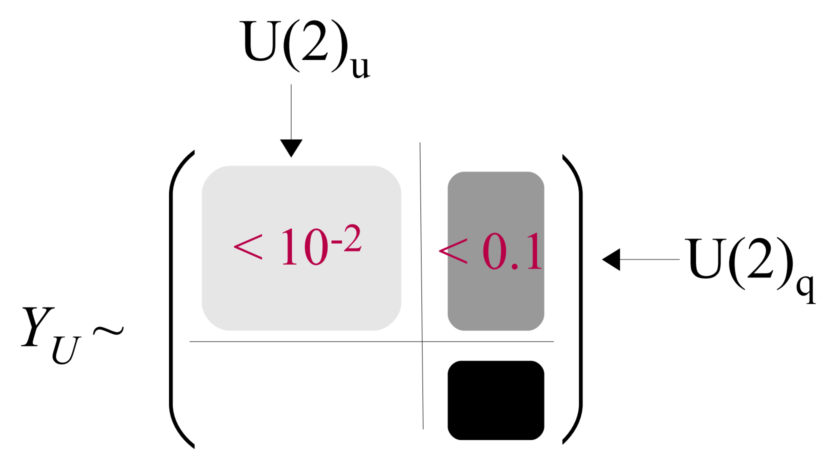


NP coupled mainly to ψ_3

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

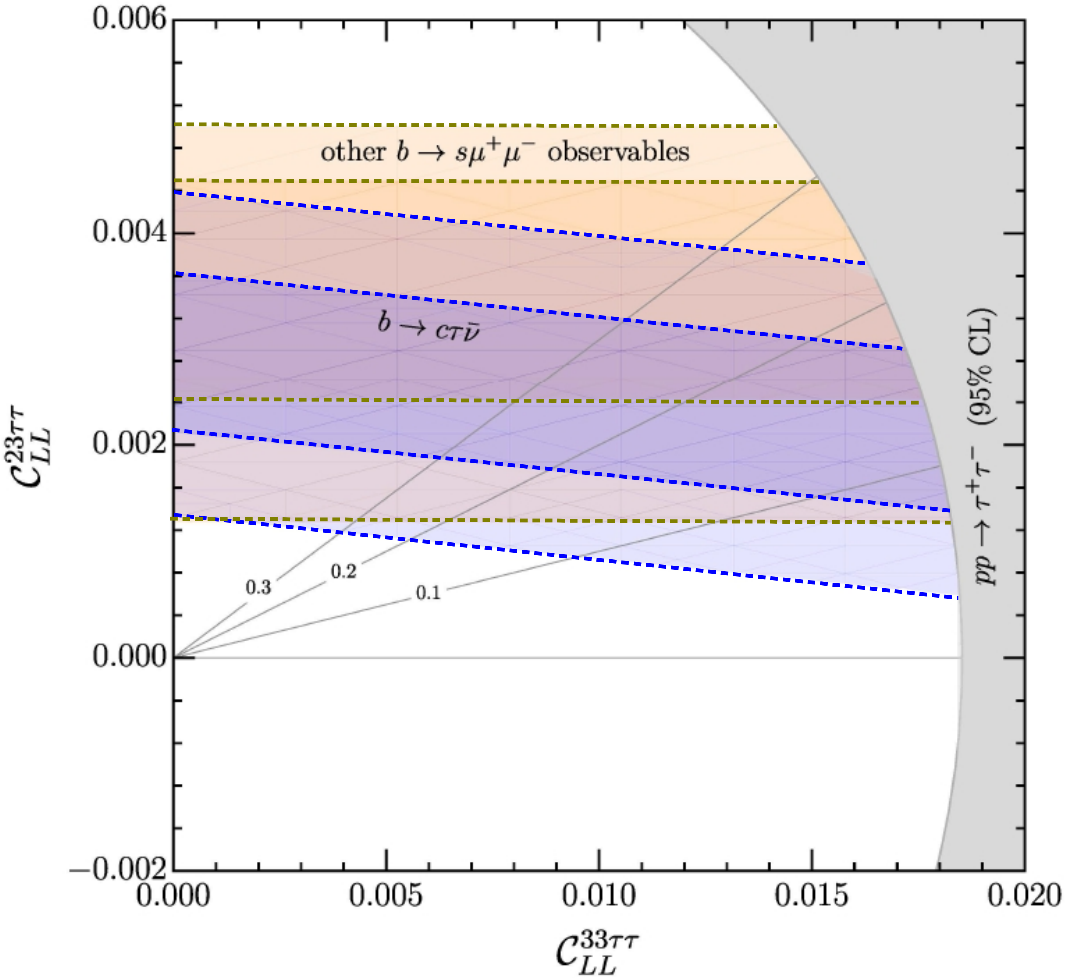
Barbieri *et al.* '11

"UV imprint" in the Yukawa couplings:



General odel-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...



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 $O^{(1\text{-}3)}$ ($b\to s\nu\nu$)

⬇

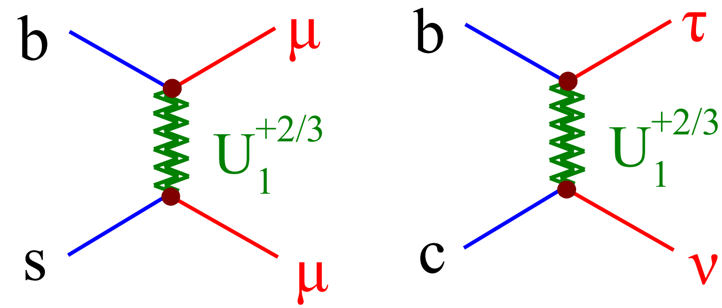
Leptoquarks

General odel-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]



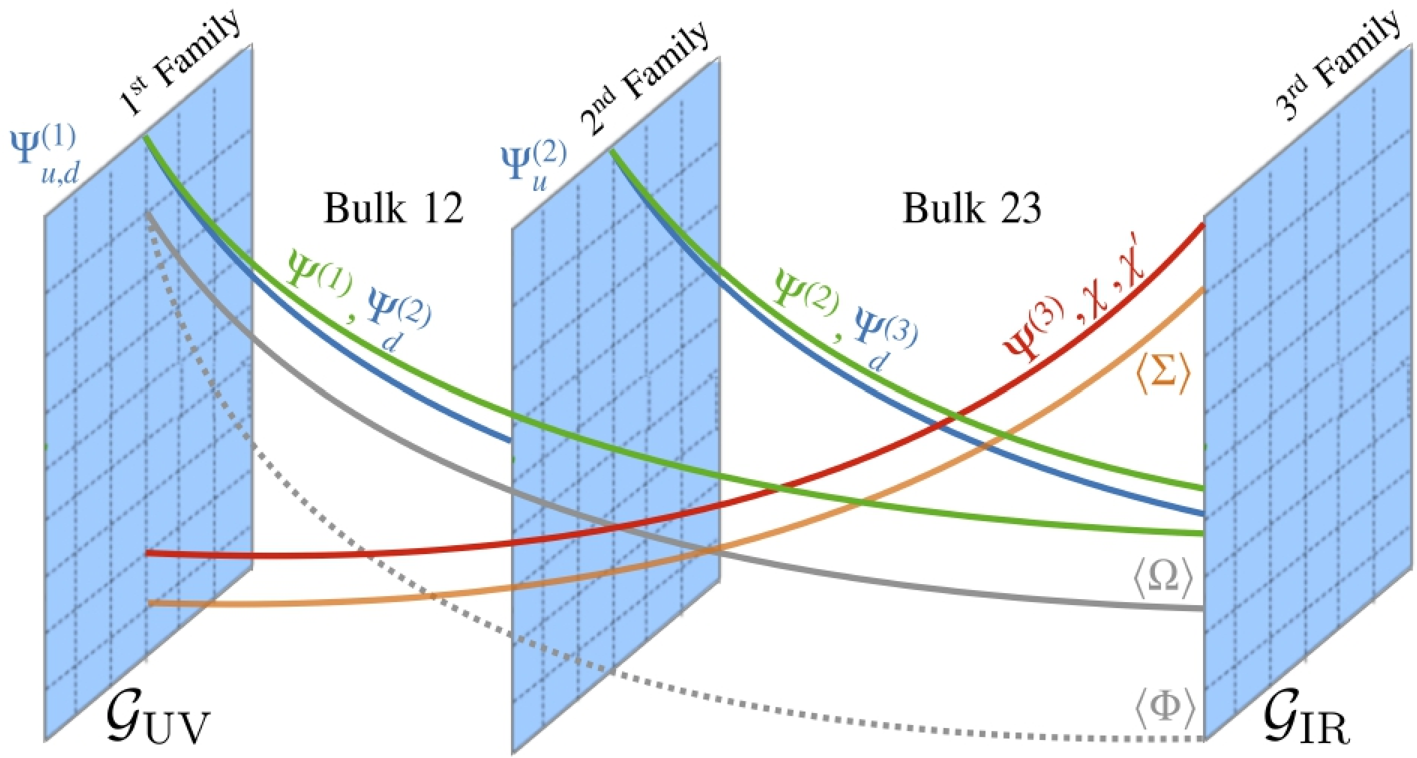
Barbieri, GI, Pattori, Senia '15

- mediator: U_1
- flavor structure: $U(2)^n$
- UV completion: SU(4) [→ quark-lepton unification]

We identifid this path back in 2015, as a motivated simplfied model...

...after 7 years, this is one of the very few options still in place for combined explanations & we understand much better its possible UV completion

UV completions: 4321 & beyond



UV completions: 4321 & beyond

First observation: the Pati & Salam group, proposed in the 70's to unify quarks & leptons predicts the 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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Pati-Salam group: $SU(4)\times SU(2)_L\times SU(2)_R$

Fermions in SU(4):

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

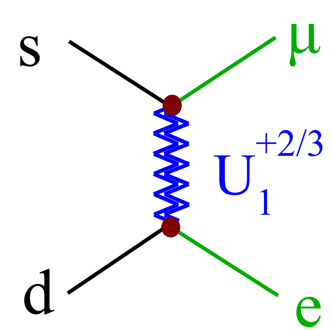
Main Pati-Salam idea:
Lepton number as "the 4th color"

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

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

Attempts to solve this problem simply adding extra fermions or scalars

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



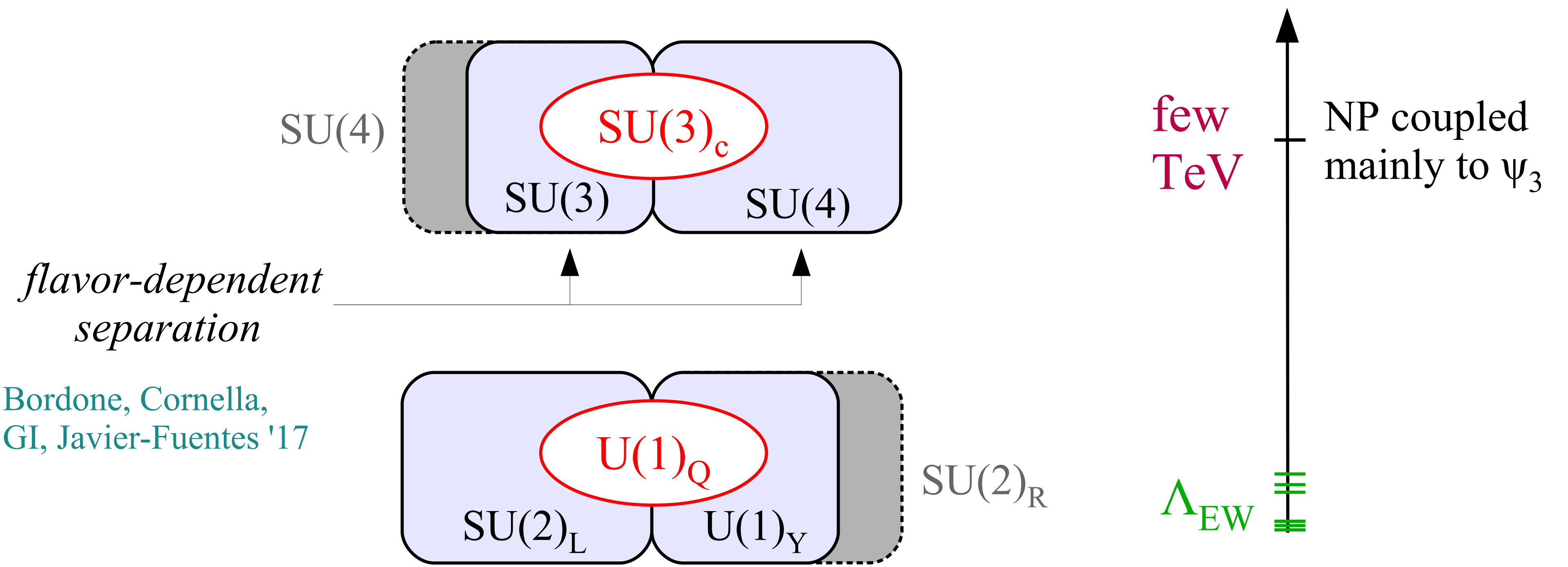
UV completions: 4321 & beyond

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

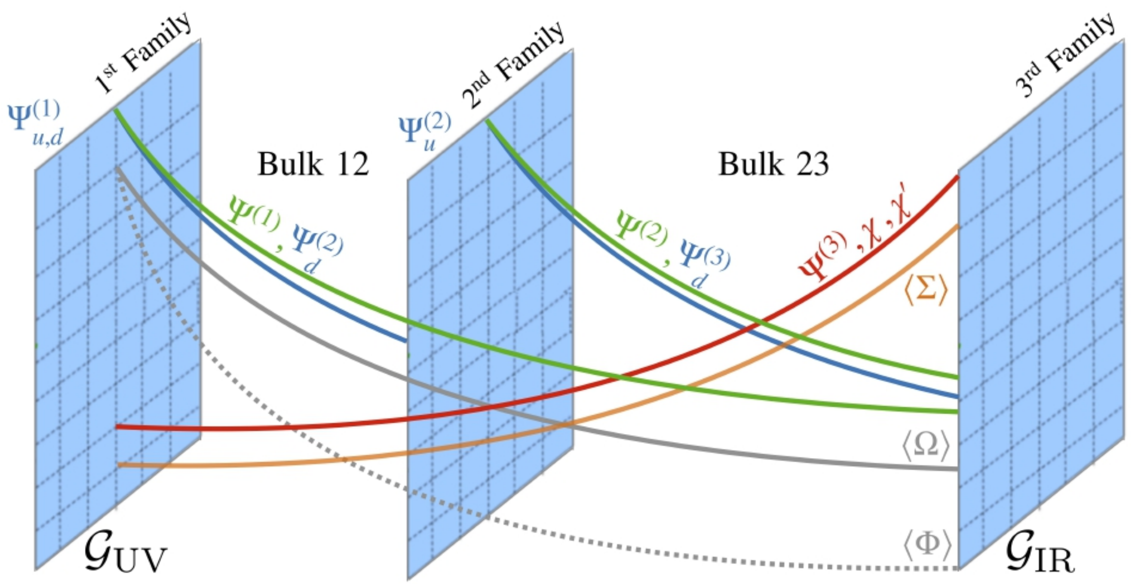
Di Luzio, Greljo, Nardecchia, '17



Bordone, Cornella, GI, Javier-Fuentes '17

▶ UV completions: 4321 & beyond

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

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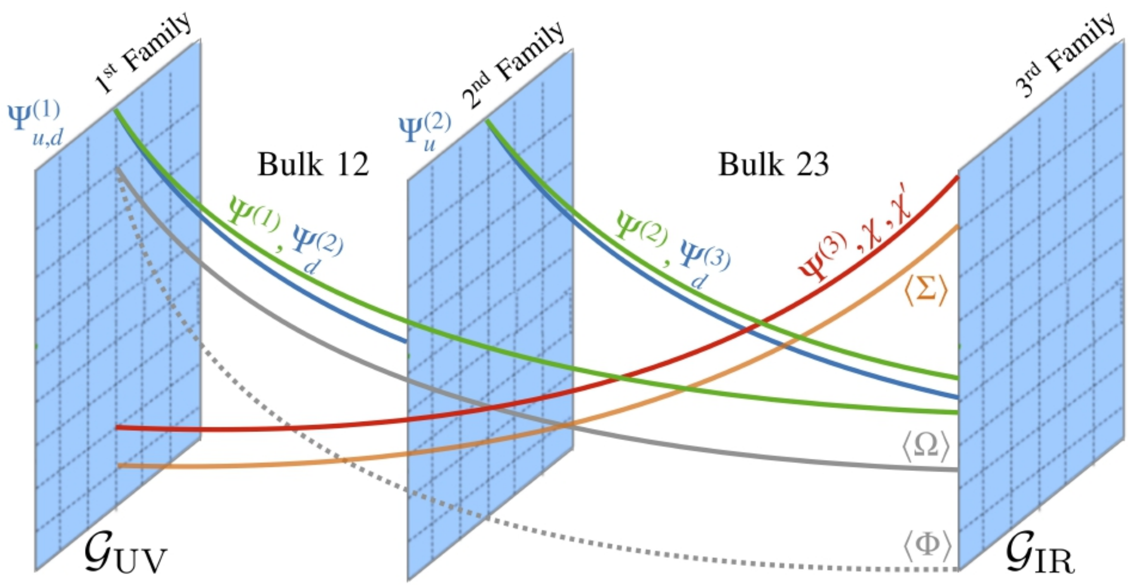

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Dvali & Shifman, '00

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Bordone, Cornella, GI, Javier-Fuentes '17

- Anarchic neutrino masses via inverse see-saw mechanism — Fuentes-Martin, GI, Pages, Stefanek '22

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

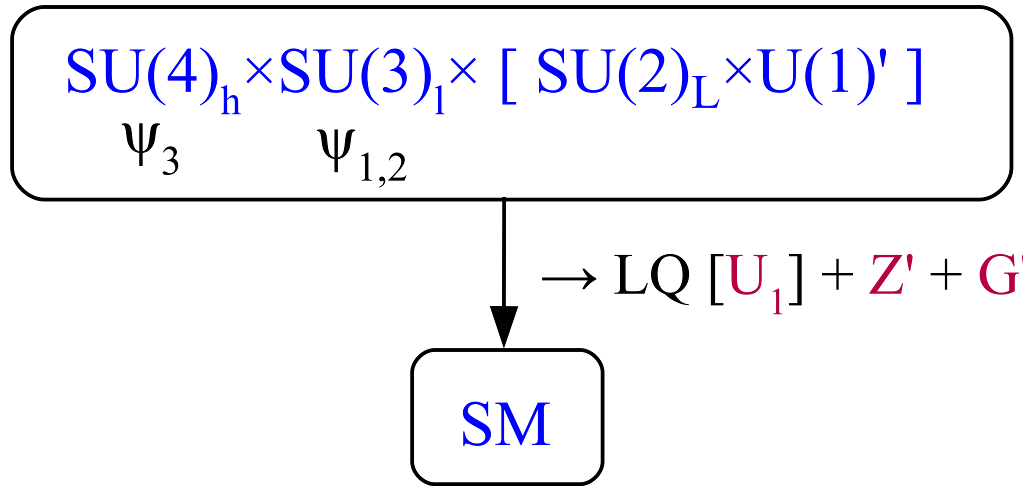
→ Light Higgs as pseudo Goldstone

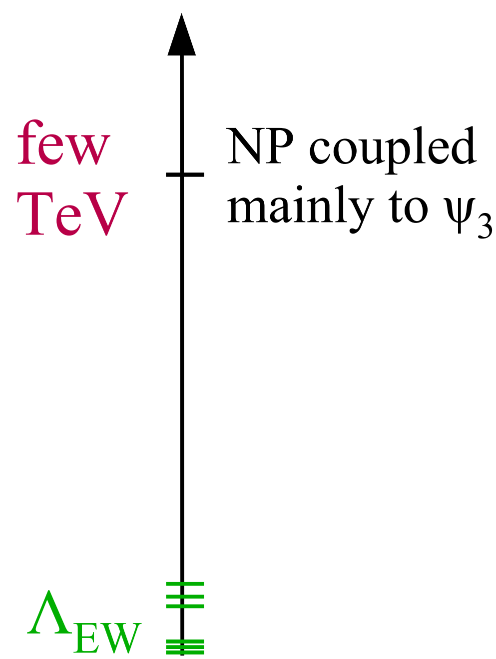
Fuentes-Martin, Stangl '20
Fuentes-Martin, GI, Lizana, Selimovic, Stefanek '22

Agashe, Contino, Pomarol '05

UV completions: 4321 & beyond

Even in ambitious UV completions, collider and low-energy pheno are controlled by the 4321 gauge group that rules TeV-scale dynamics
→ new heavy mediators [G' & Z']





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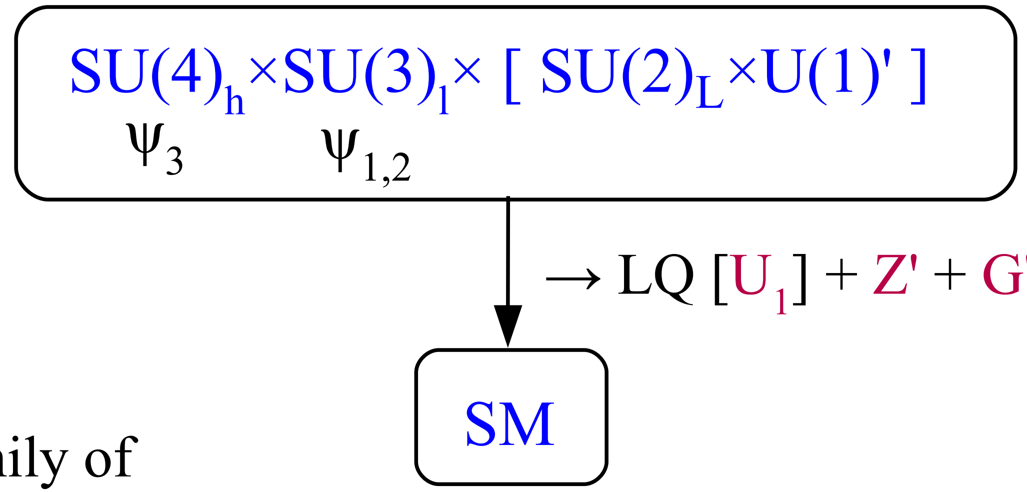
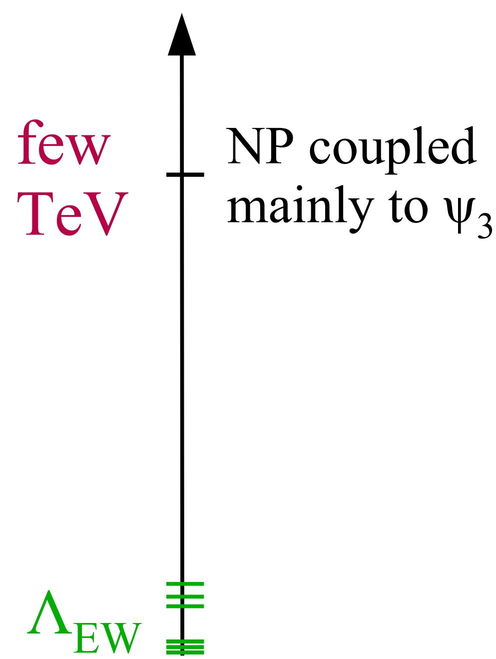


A key role is played by at least one family of
→ vector-like fermions (= fermions with both chiralities having same gauge quantum numbers) that mix with mainly with the 3rd gen. of (SM-like) chiral fermions

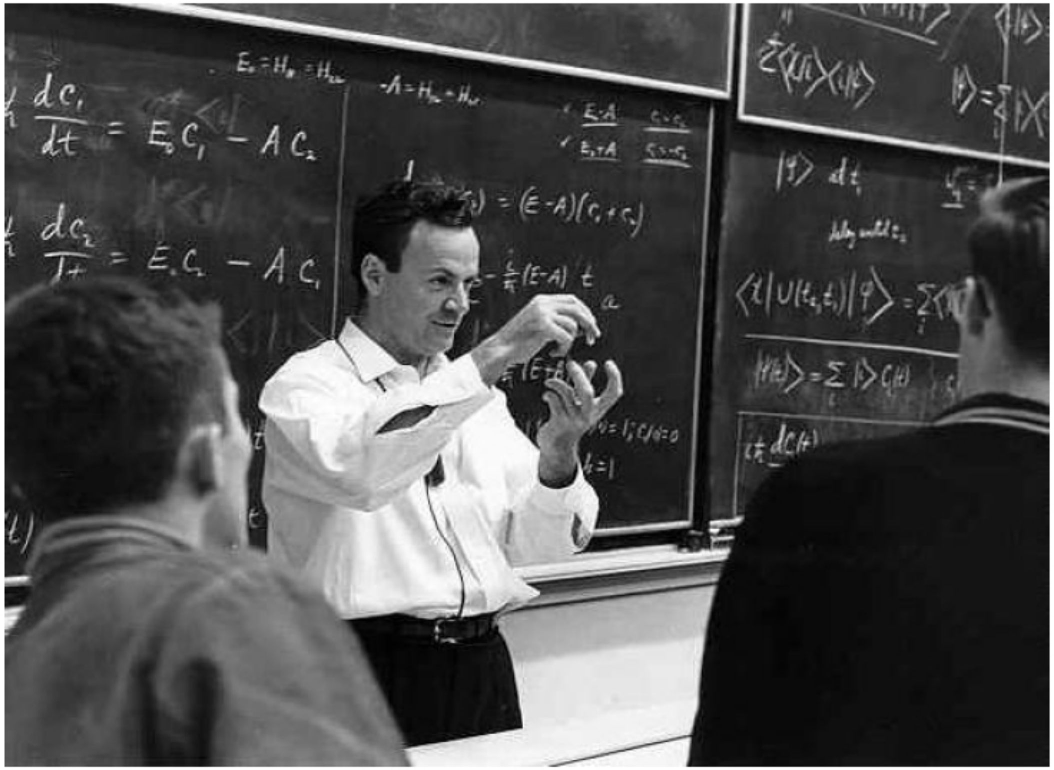
→ talk by J. Lizana

⬇

- Positive features the EFT reproduced
- Calculability of $\Delta F=2$ processes
- Precise (non-trivial) predictions for high-energy physics



Predictions @ low- & high-energies



"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

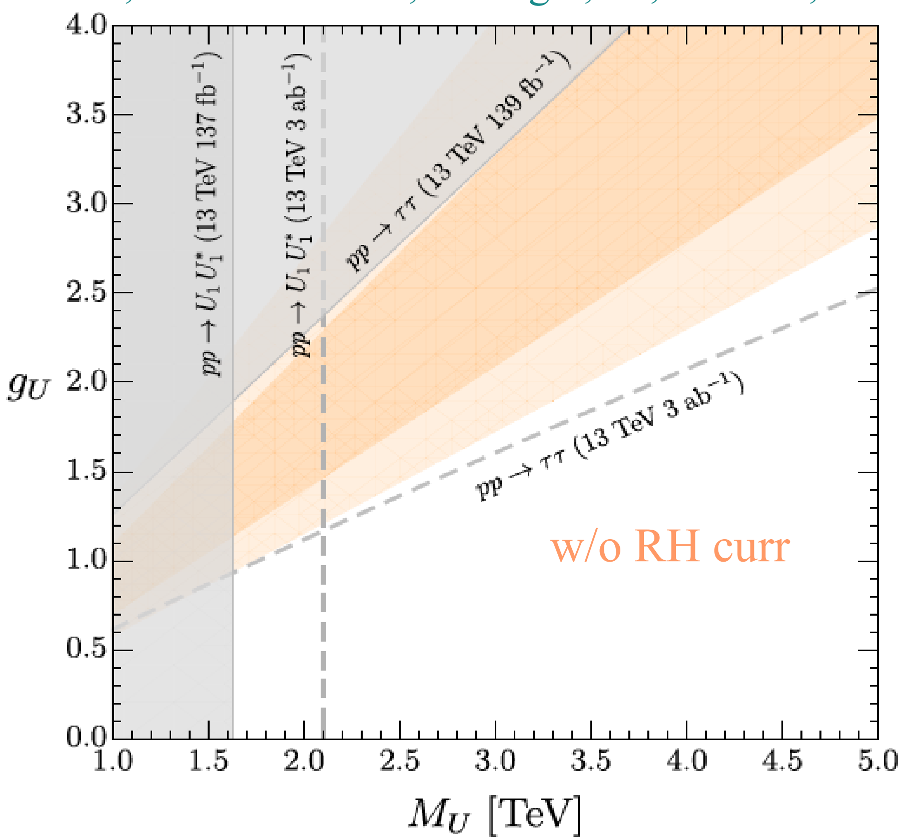
Predictions @ low- & high energies

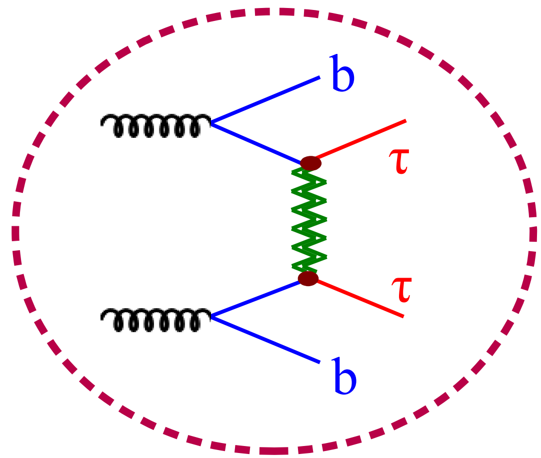
I General predcitons of U_1 exchange @ high-energies

[Very general, directly connected to the EFT analysis]

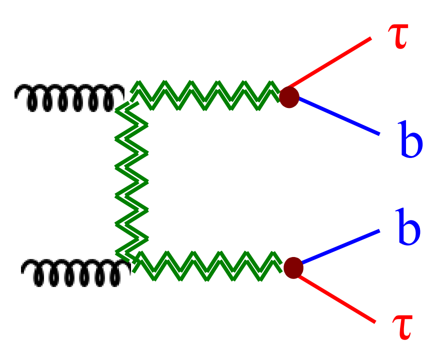
pp → ττ

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





Faroughi, Greljo, Kamenik '16



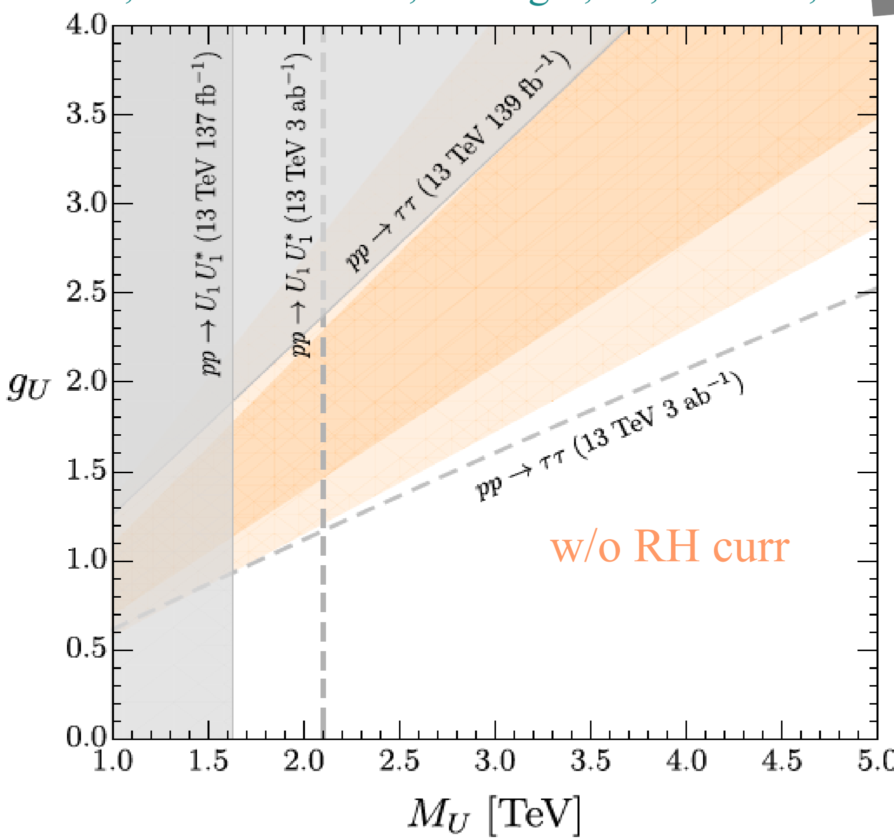
▶ Predictions @ low- & high energies

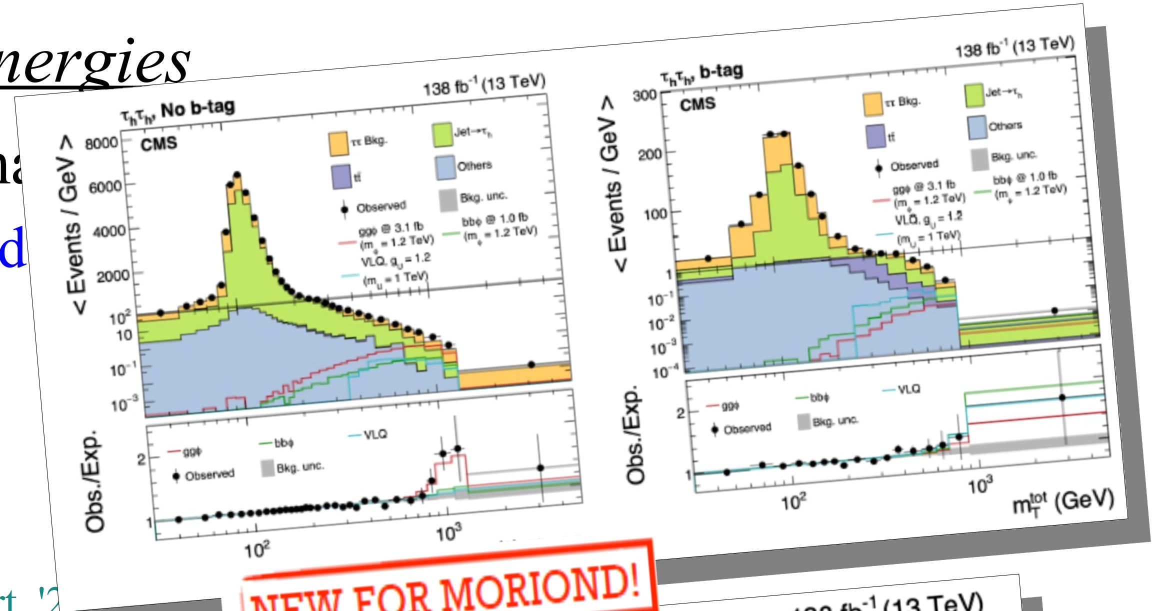
I General predcitons of U_1 excha

[Very general, directly connected

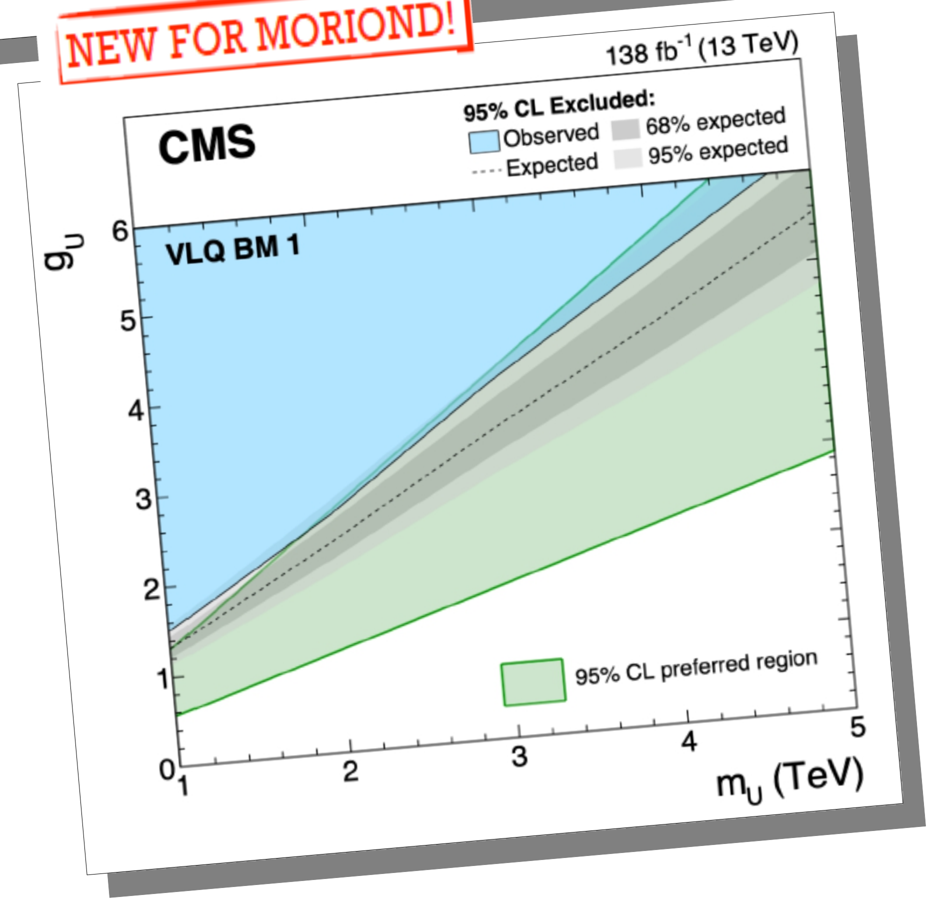
pp → ττ

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





NEW FOR MORIOND!

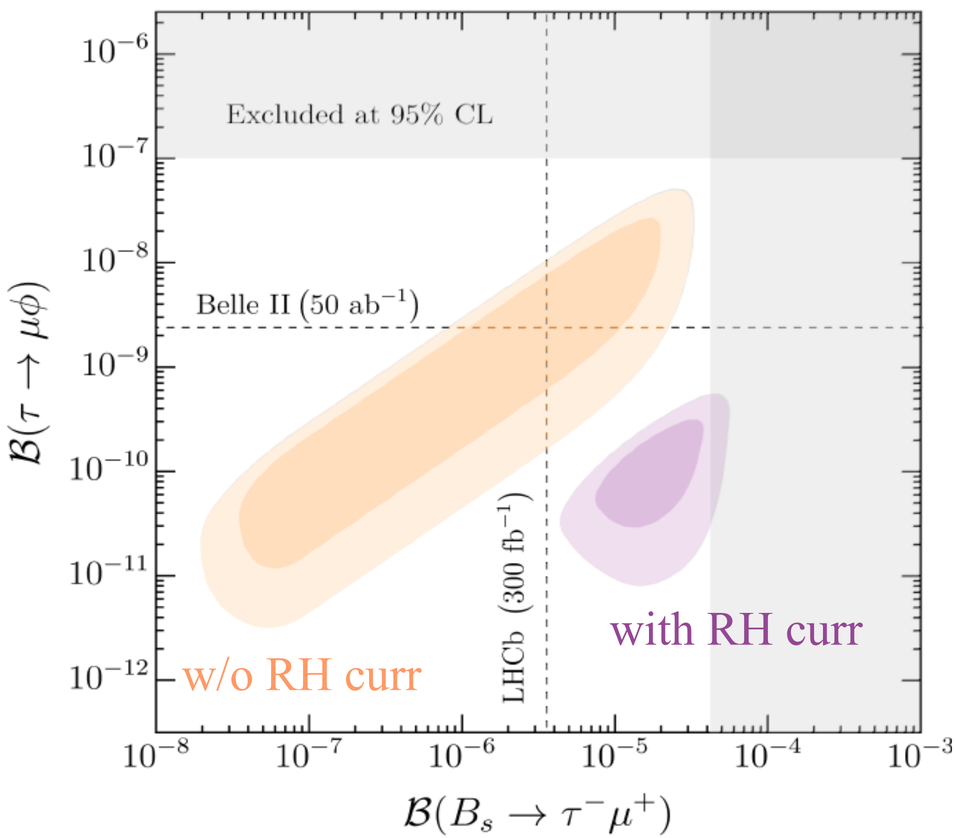


▶ Predictions @ low- & high energies

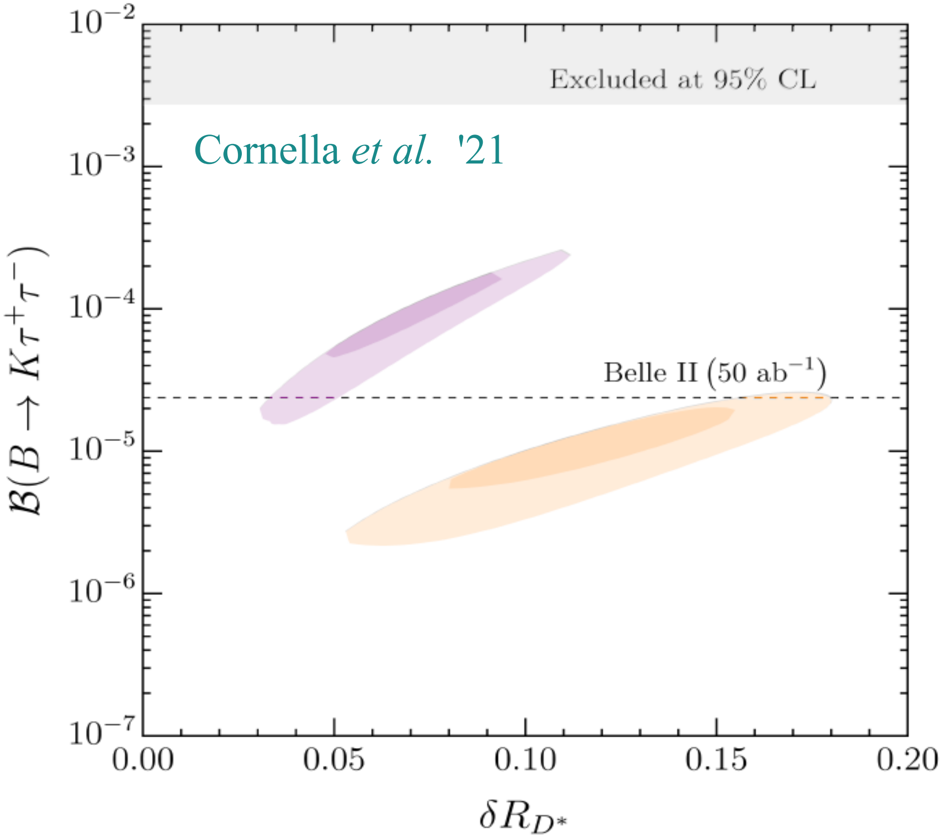
II General predcitons of U_1 exchange @ low-energies

[UV insensitive observables, closely connected to the EFT analysis]

$\tau \to \mu$ LFV
(in B and tau decays)



largely enhanced $b \to s\tau\tau$ rates
(in all channles)



Predictions @ low- & high energies

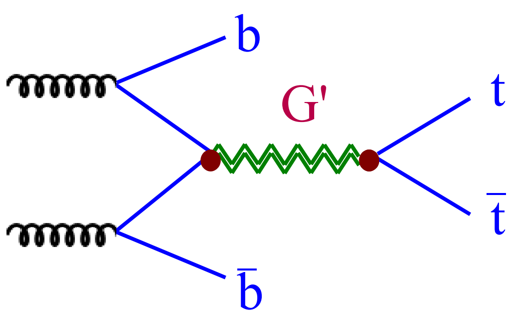
III General predcitons of 4321 models @ high-energies

[More model dependent, not directly connected to the EFT analysis]

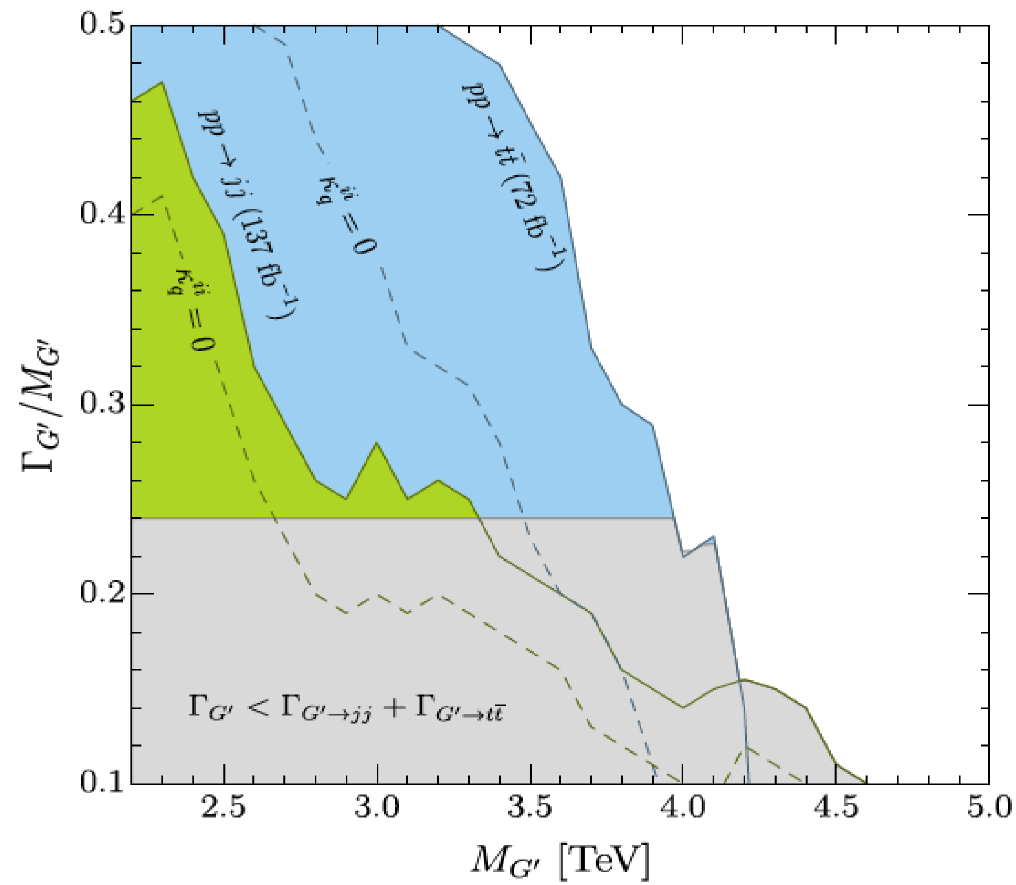
$SU(4)_h \times SU(3)_l \times [\, SU(2)_L \times U(1)' \,]$ → SM

→ $U_1 + Z' + G'$

New striking collider signature:
G' (“*coloron*”) = heavy color octet, coupled mainly to 3[rd] generation quarks



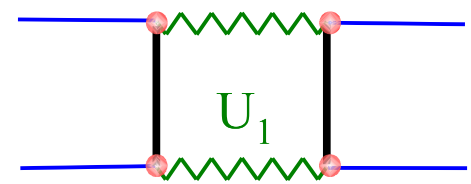
→ strongest constraint on the scale of the model from pp → $t\,\bar{t}$



▶ *Predictions @ low- & high energies*

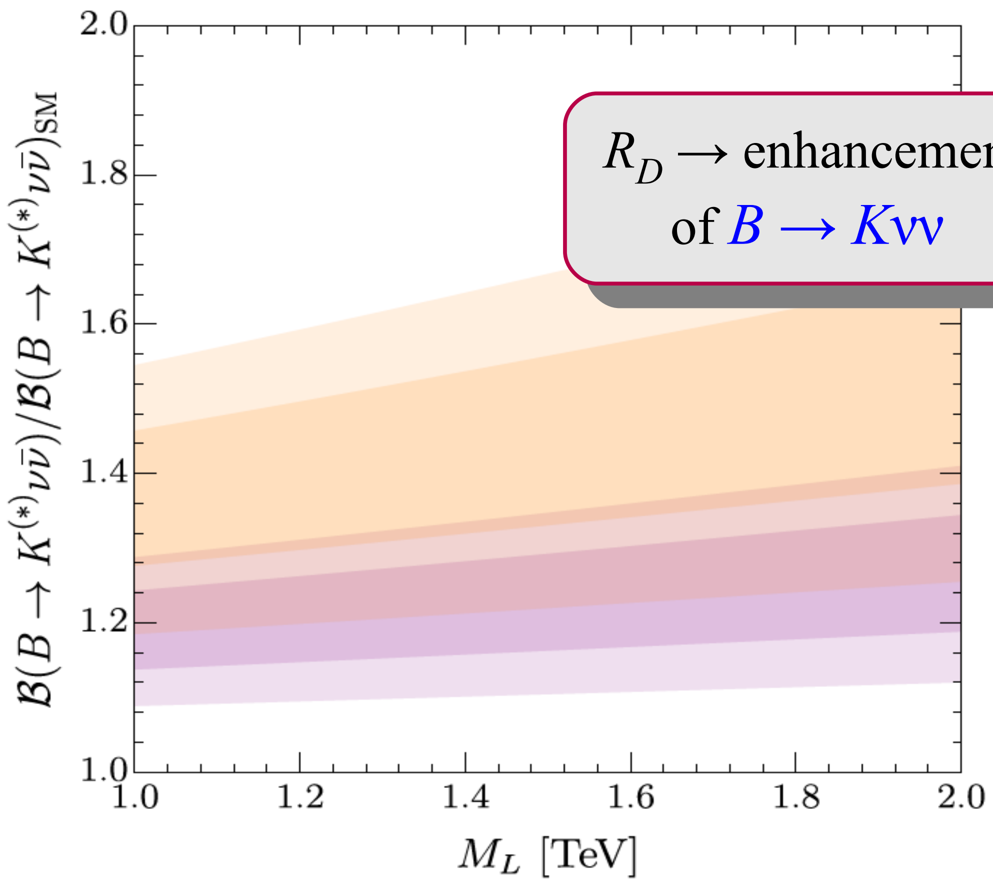
IV Specific predcitons of 4321 @ low-energies

[UV sensitive low-energy observables]

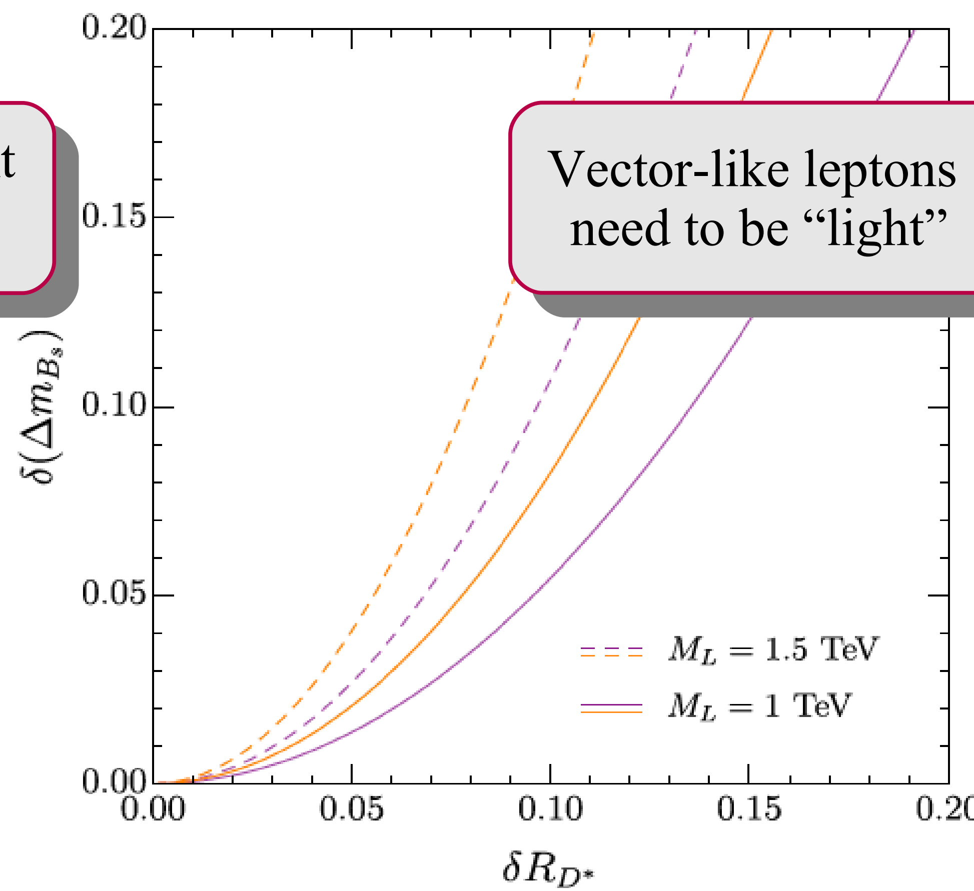


A) $B \to K\nu\nu$

B) B_s mixing [ΔF=2]



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

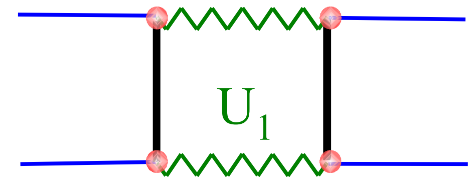


Vector-like leptons need to be "light"

Fuentes-Martin, GI, Konig, Selimovic, '20
Cornella *et al.* '21

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

Predictions @ low- & high energies



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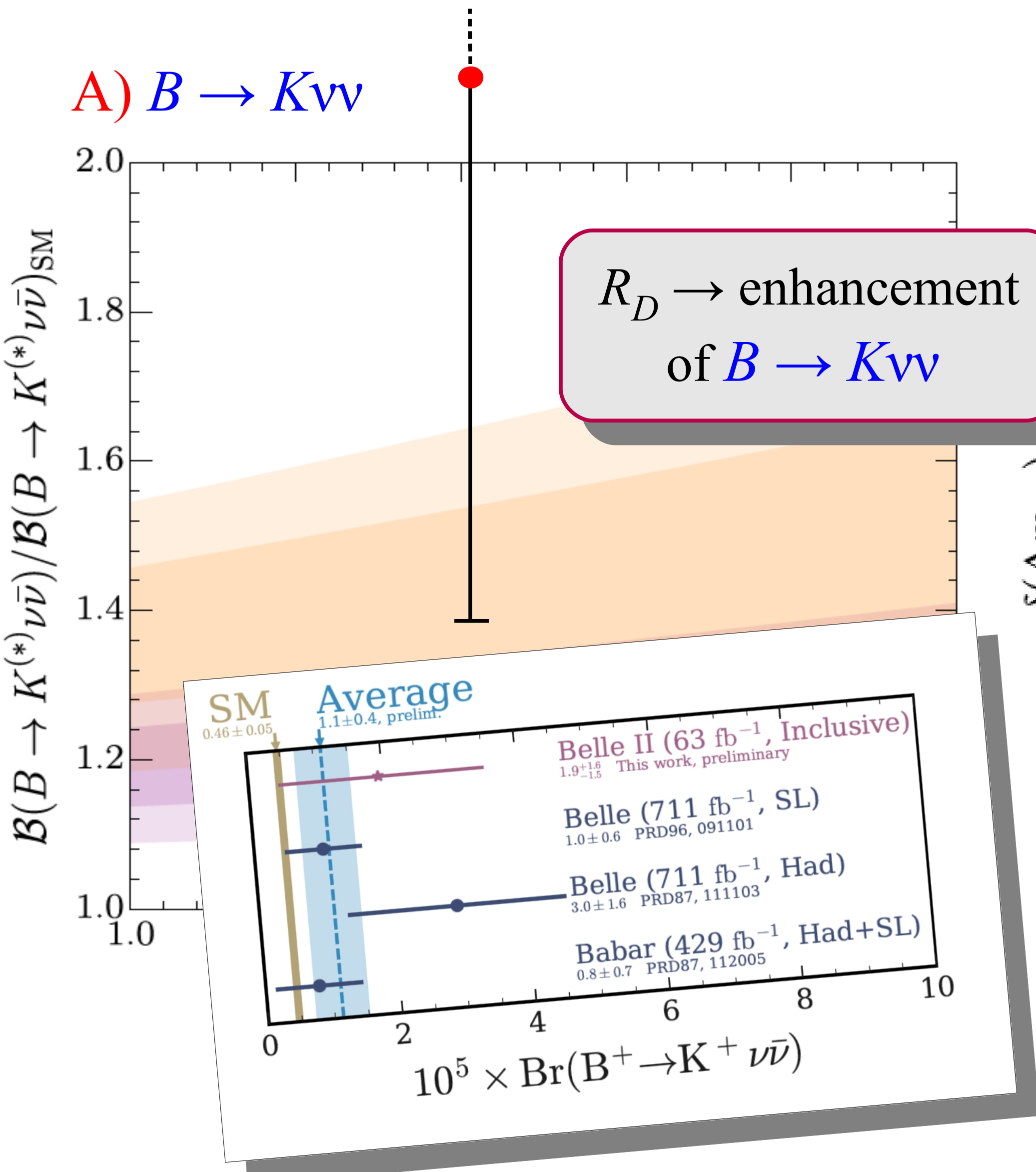

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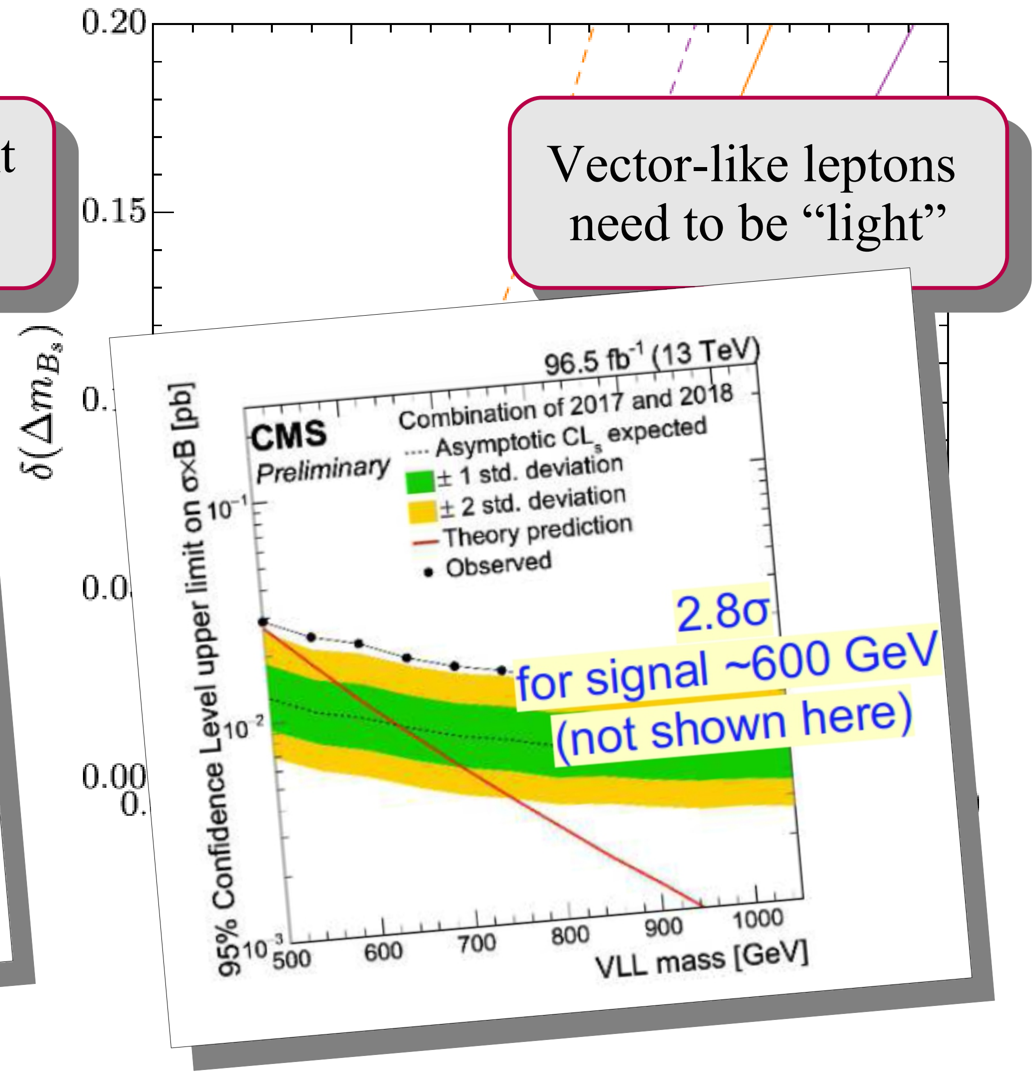


Vector-like leptons need to be "light"

Conclusions

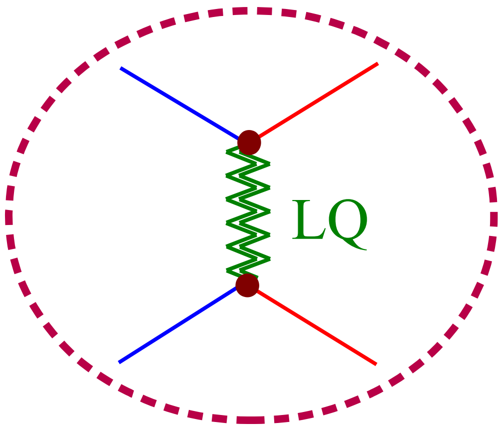
- The nice *picture* that emerged in 2015 of connecting the two sets of anomalies with the origin of the SM flavor hierarchies, and quark-lepton unification is still valid, and has become possibly more appealing...

- A new (theoretical) ingreideint that emerged in the last few years is the possibilty of connecting this picture also to a solution of the EW hierarchy problem: non-trivial flavor dynamics around the TeV scale, involving mainly the 3rd family + 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


Backup

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
  + ...

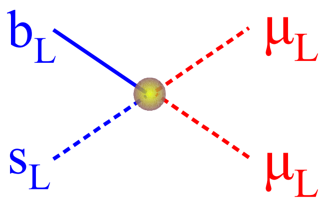
- Vector LQ as techni-fermion resonances
  Barbieri *et al*. '15; Buttazzo *et al*. '16,
  Barbieri, Murphy, Senia, '17 + ...

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

EFT considerations

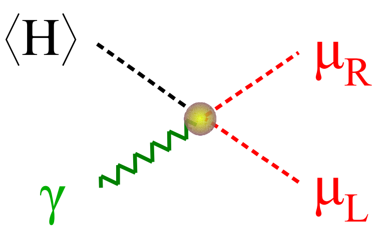
A possible alternative story...

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



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

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



→ $\Delta a_\mu = (a_\mu^{exp} - a_\mu^{SM})$ ~ 4 σ

(*more controversial...*)

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

$\Lambda \approx 10$ TeV

▸ EFT considerations

A possible alternative story...

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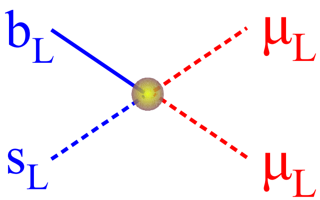

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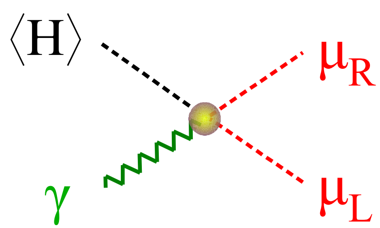
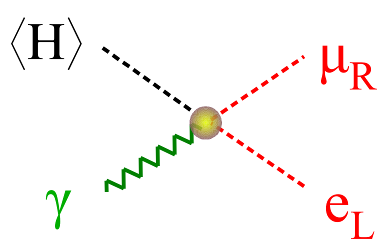


Possible unified description by means of a new interaction with special role for muons (and maybe tau's)

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

However...

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



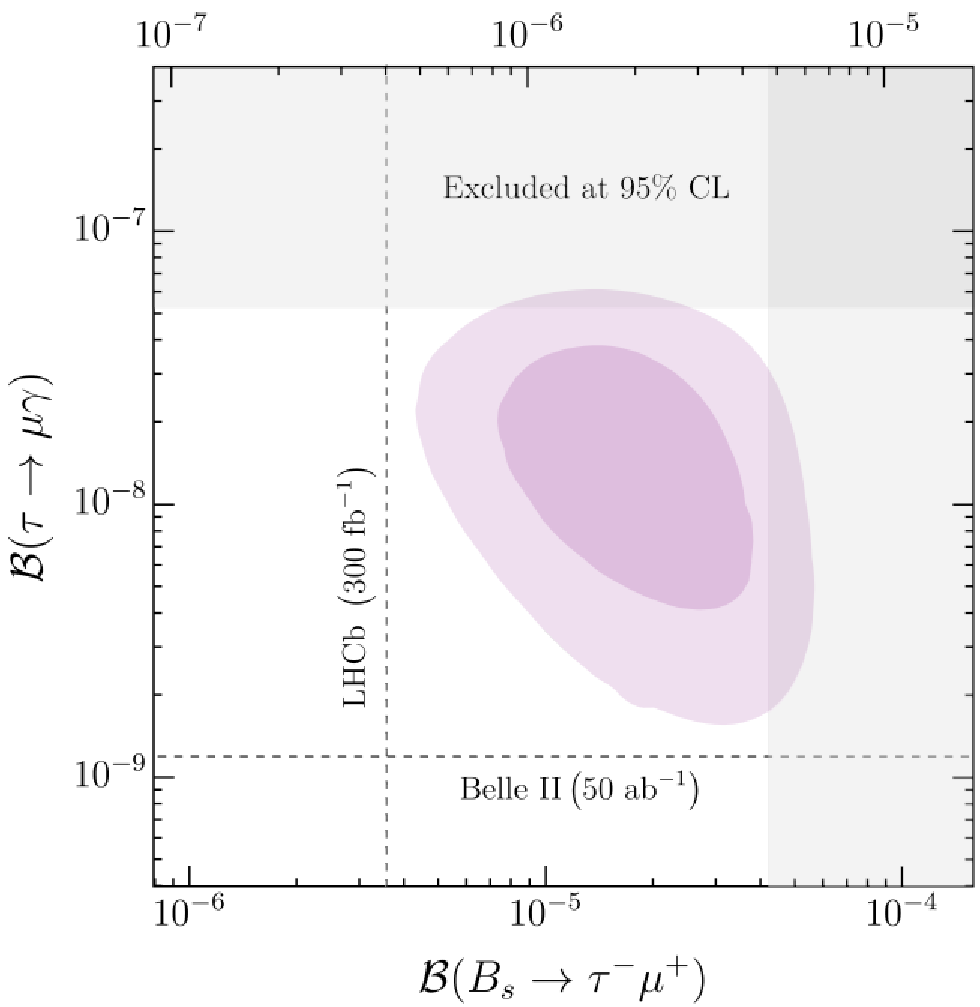
$|\Theta_{\mu e}| < 2\times10^{-5}$

$\Lambda \approx 10$ TeV

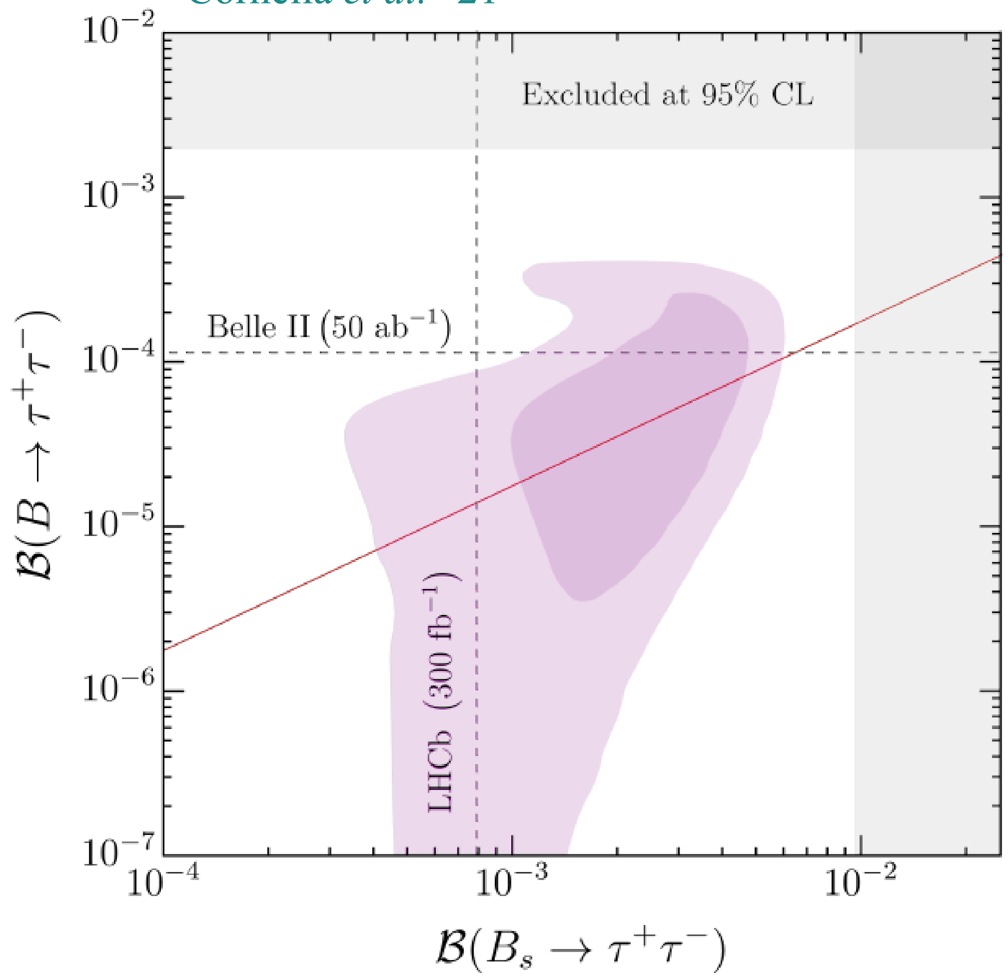
Tight constraint involving several ops → Exact flavor symm. @ work the lepton sector → *different behavior of quarks & leptons*

GI, Pages, Wilsch '21

Other low-energy observables

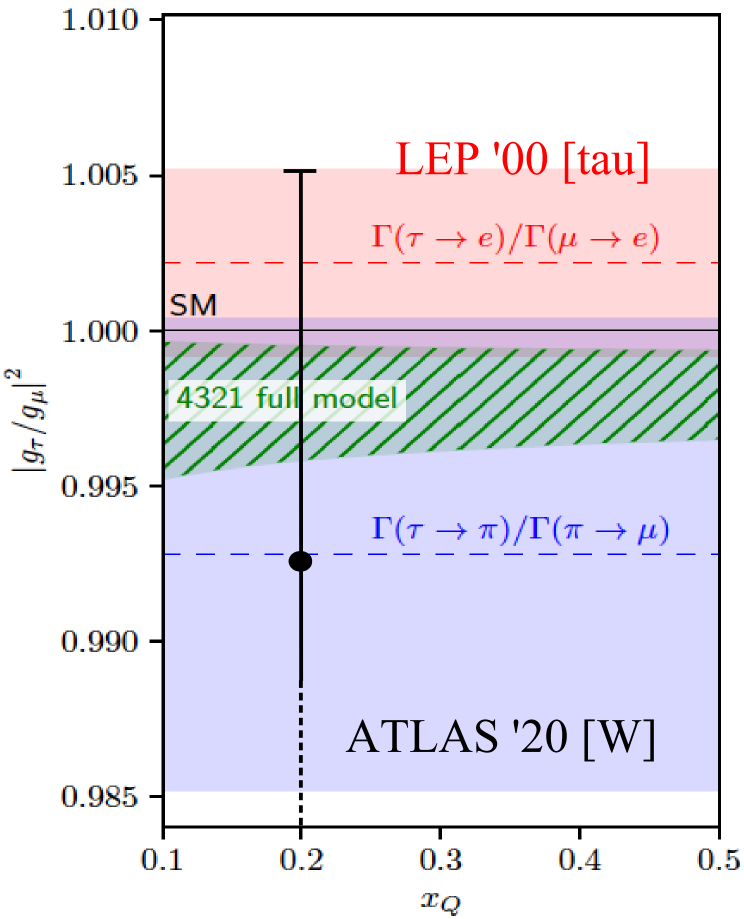


Cornella *et al.* '21



Other low-energy observables

Tests of universality in tau decays:



Allwicher, GI, Selimovic, '21

U_1 LQ