New theoretical aspects of flavor physics

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

University of Zurich[UZH]

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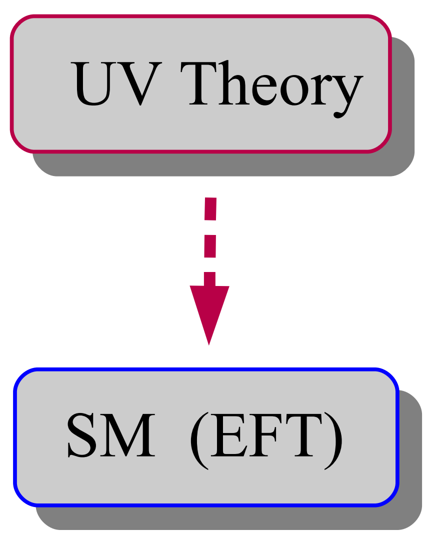
Introduction

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

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



Introduction

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

UV Theory

SM (EFT)

Two types of effects in QFT:

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

Un-natural aspects of low-energy couplings

Violations of accidental symmetries

qualitative UV imprint

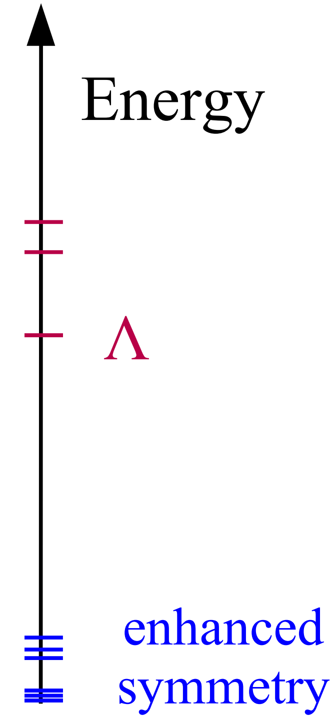
quantitative UV imprint

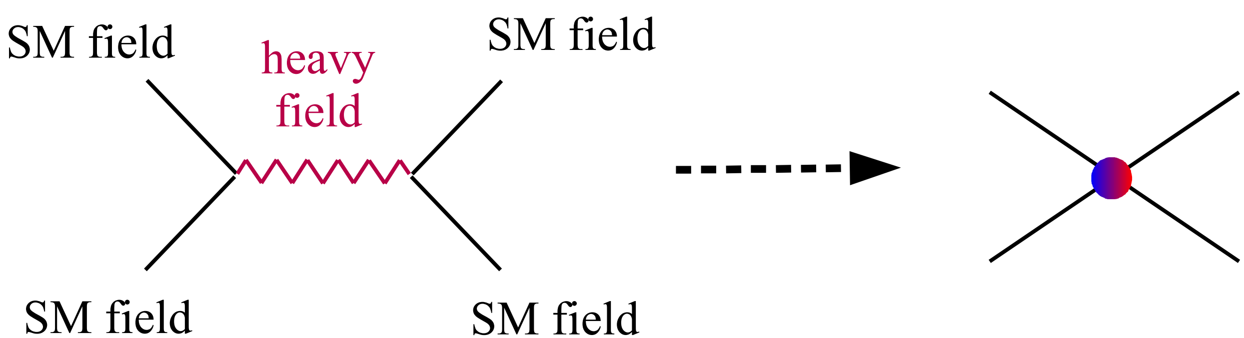
Introduction

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

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

Violations of accidental symmetries





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

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

Introduction

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Natural
(fully dictated by gauge symmetry)

Non-trivial
UV imprints

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

II $m_H^2\, H^2$

Un-natural aspects of
the SM couplings

UV Theory

SM (EFT)

Introduction

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Natural
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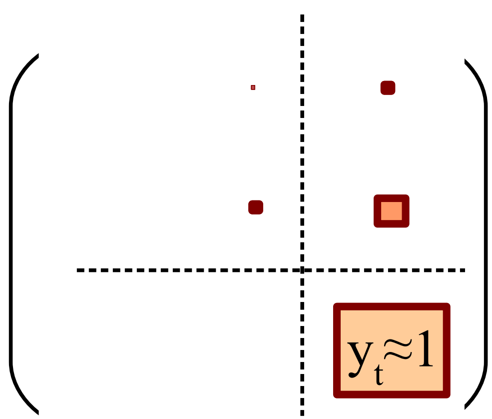
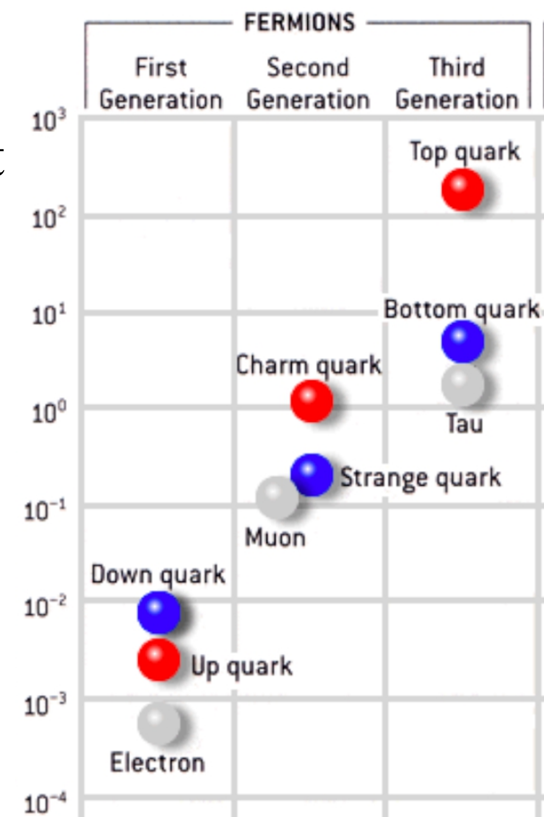
I Flavor problem

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

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

$Y_U \sim$





Introduction

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

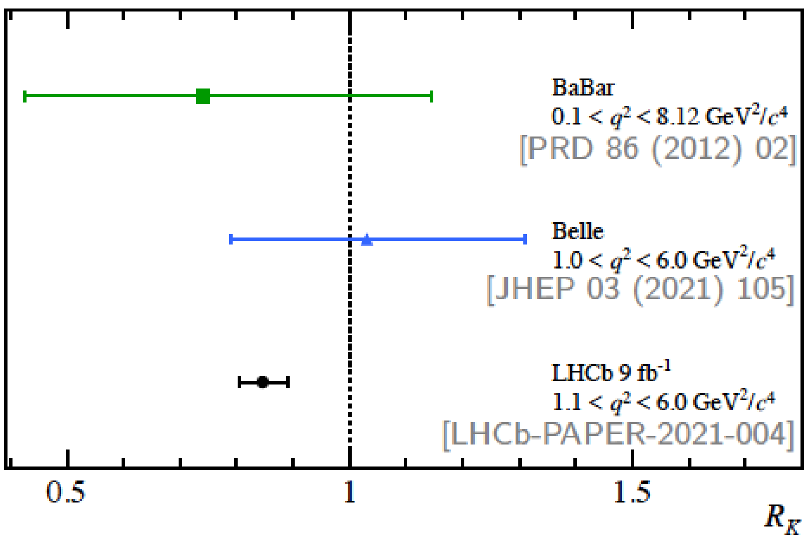
Natural
(*fully dictated by gauge symmetry*)

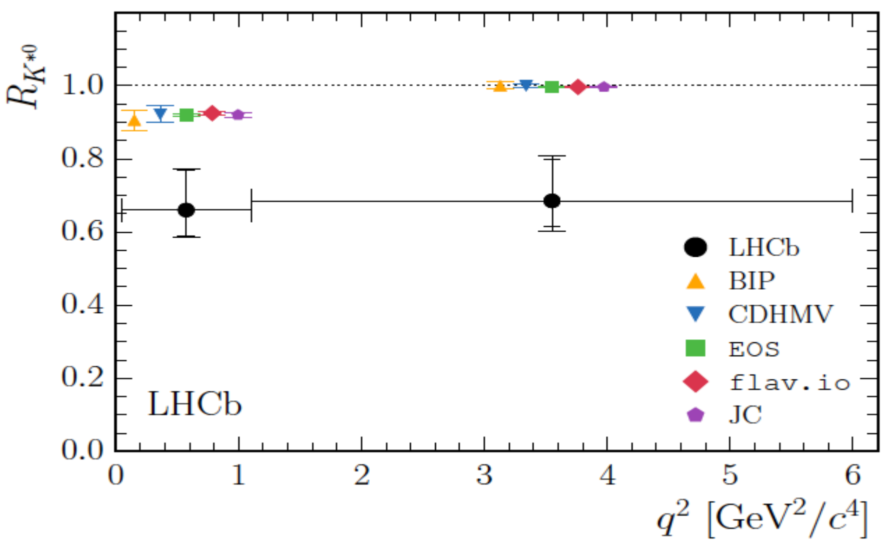
Non-trivial
UV imprints

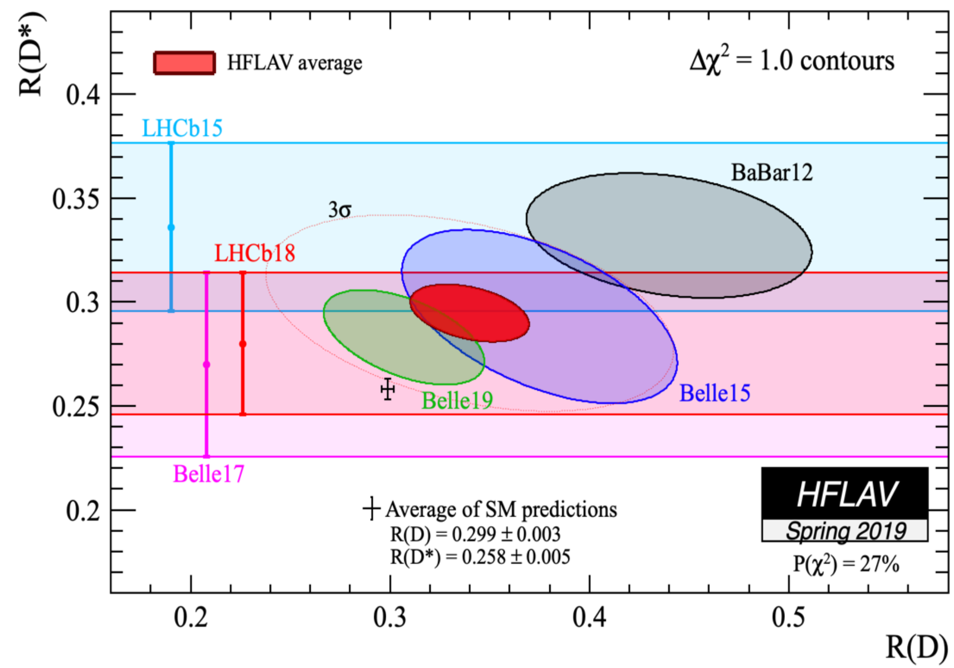
I	Flavor problem	*<u>Un-natural</u> hierarchies in the couplings describing fermion masses*	→	flavor non-universal dynamics (*at some energy scale*)
II	Electroweak hierarchy problem	*<u>Instability</u> of the Higgs mass under quantum corrections*	→	(*some*) New Physics in the TeV domain

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

The anomalies







The anomalies

Since 2013 results in semi-leptonic B decays started to exhibit tensions with the SM predictions connected to a possible violation of Lepton Flavor Universality

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

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

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

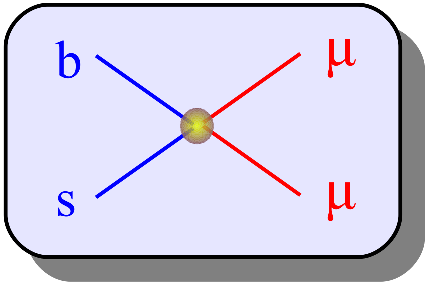
LFU is badly broken in the Yukawa sector: $y_e \sim 3\times10^{-6}$, $y_\mu \sim 3\times10^{-4}$, $y_\tau \sim 10^{-2}$

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

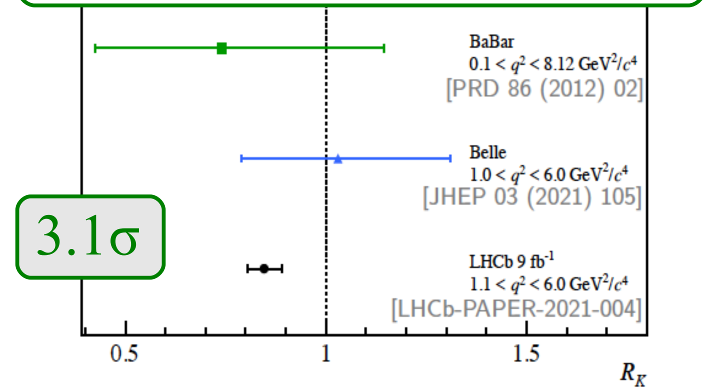
The anomalies

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

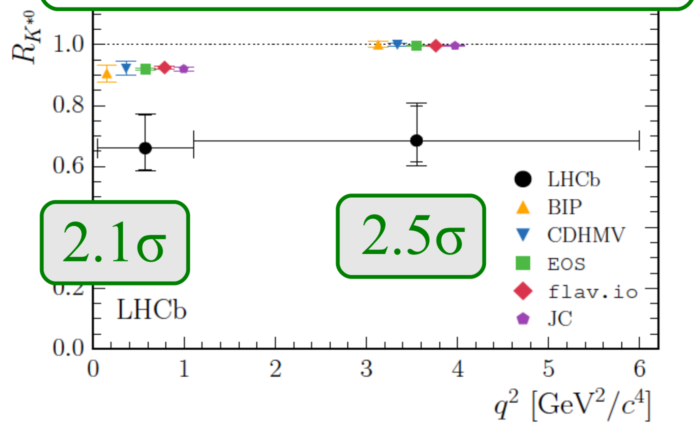
High significance: several observables pointing to the same coherent picture [3 new results in 2021]



$\Gamma(B^+ \to K^+ \mu\mu)(\Gamma(B^+ \to K^+ ee)$



$\Gamma(B \to K^* \mu\mu)(\Gamma(B \to K^* ee)$



The anomalies

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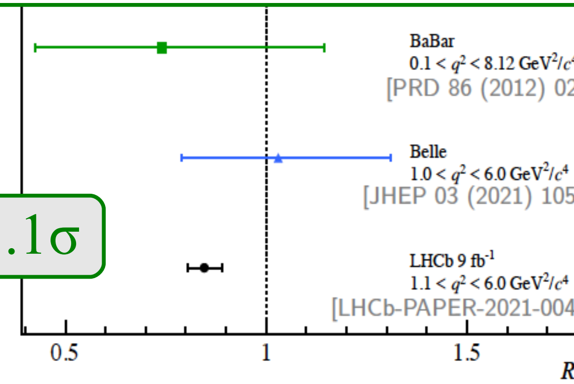
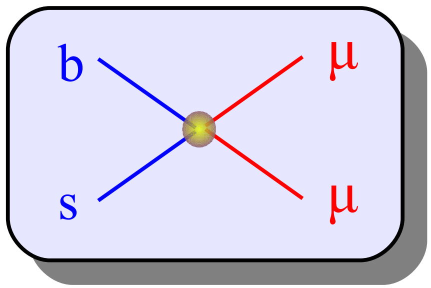
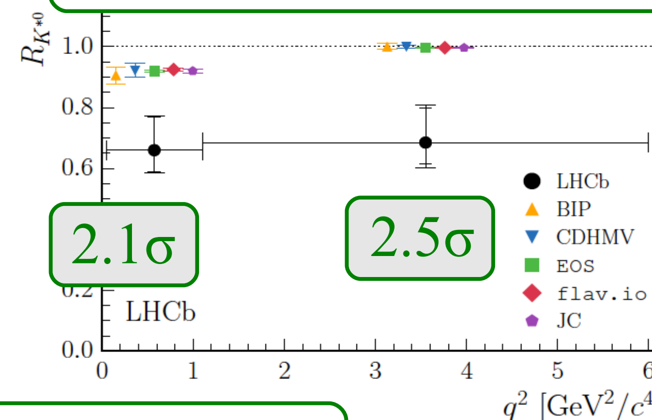
$\Gamma(B^+ \to K^+\mu\mu)/\Gamma(B^+ \to K^+ee)$



3.1σ



$\Gamma(B \to K^*\mu\mu)/\Gamma(B \to K^*ee)$



2.1σ

2.5σ

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

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

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

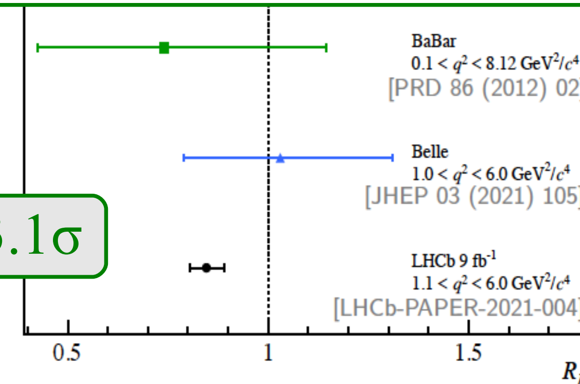
2.3σ

The anomalies

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

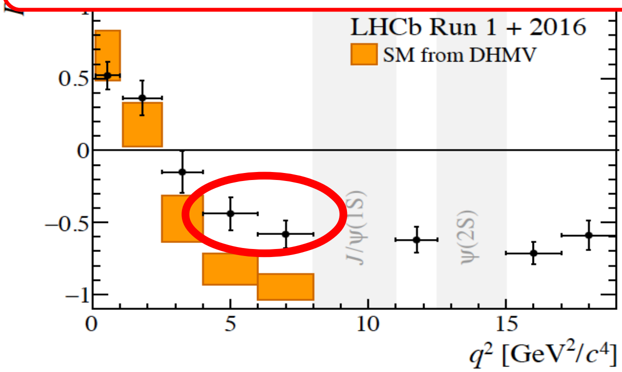
High significance: several observables pointing to the same coherent picture [3 new results in 2021]

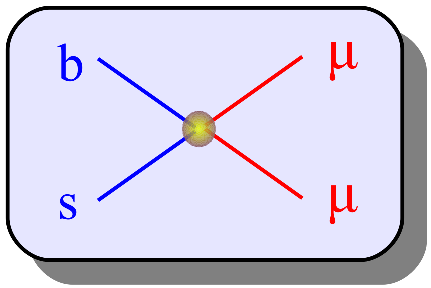
$\Gamma(B^+ \to K^+ \mu\mu) / \Gamma(B^+ \to K^+ ee)$



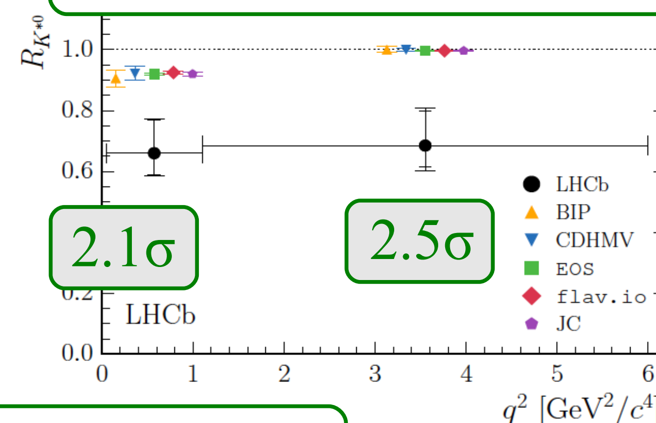
3.1σ

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



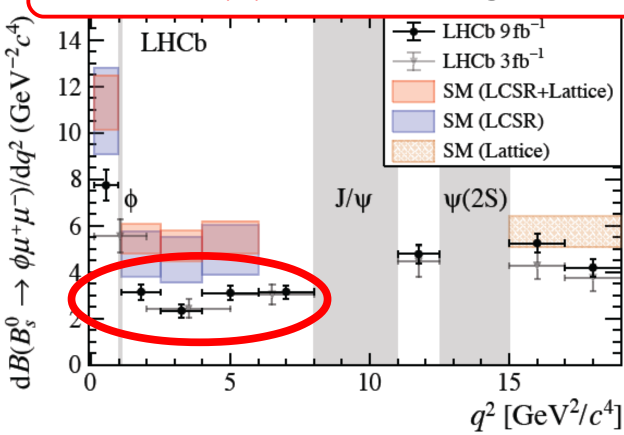


$\Gamma(B \to K^* \mu\mu) / \Gamma(B \to K^* ee)$



2.1σ 2.5σ

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



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2.3σ

The anomalies

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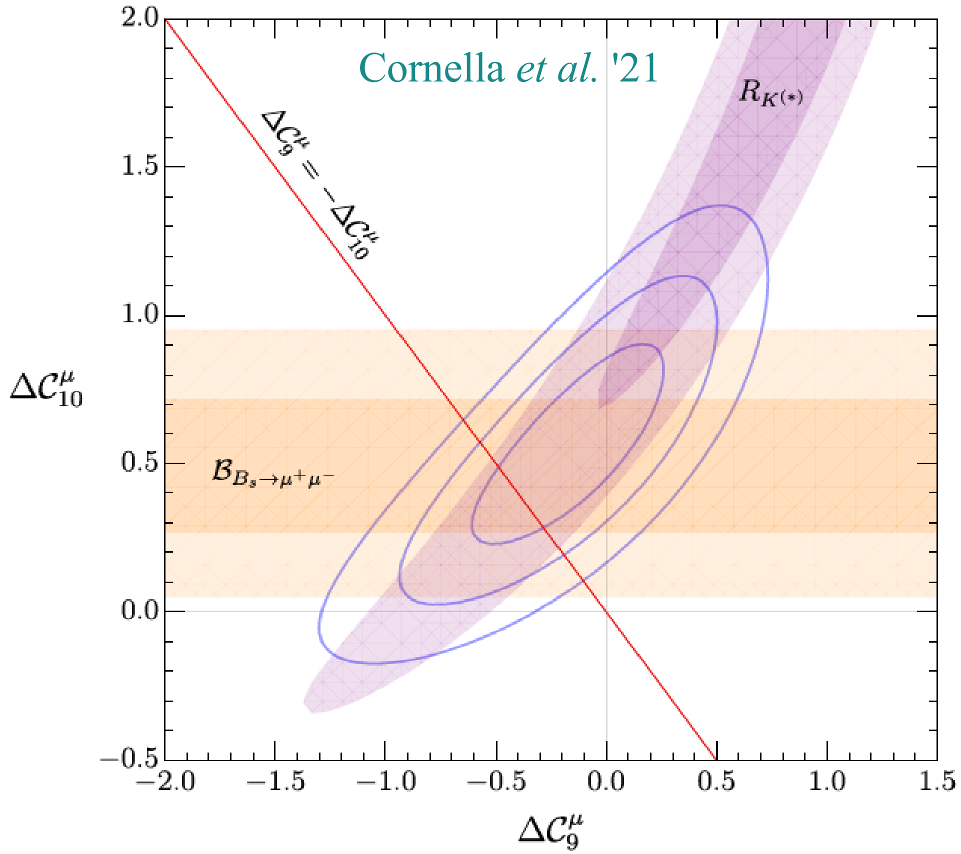
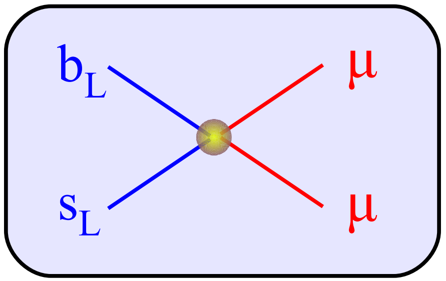


Conservative fit using "clean obs." only

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

Clean short-distance effect $[\Delta C_i^\mu = C_i^\mu - C_i^e]$:

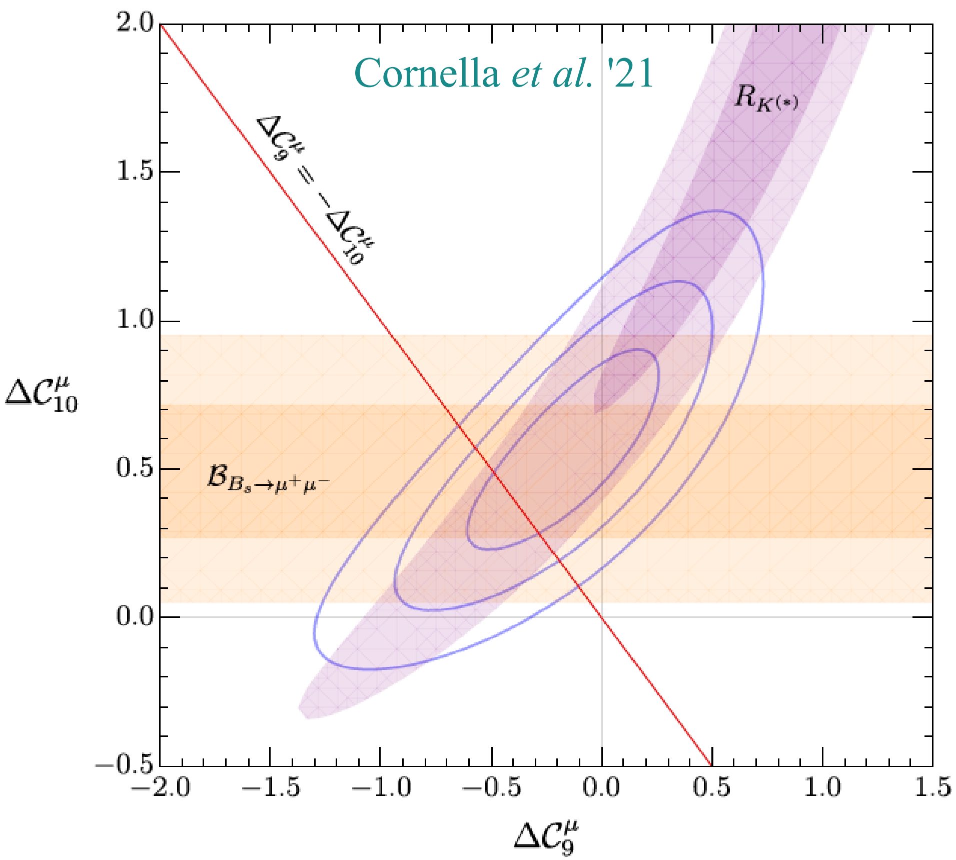
$$\mathcal{O}_{10}^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$
$$\mathcal{O}_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

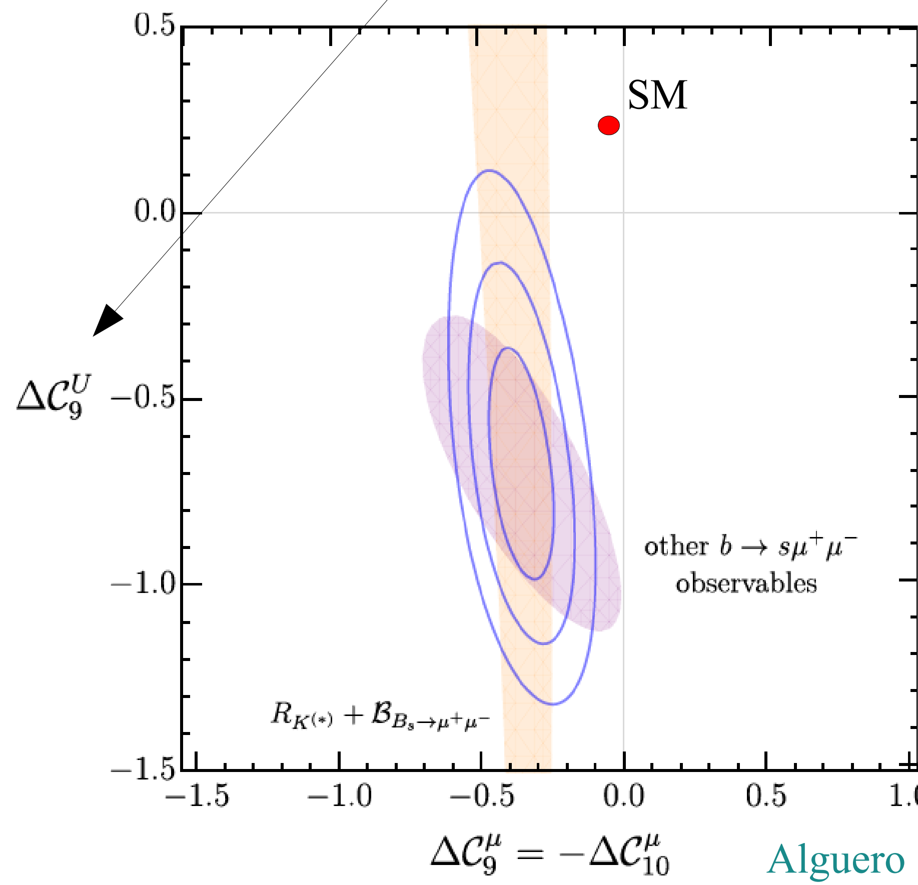


The anomalies

- 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

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

>> 5σ best estimate of charm contribution

4σ *global significance* of NP (*very conserv. estimate*) Lancierini *et al.* '21

The anomalies

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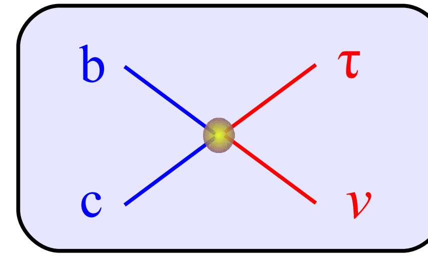
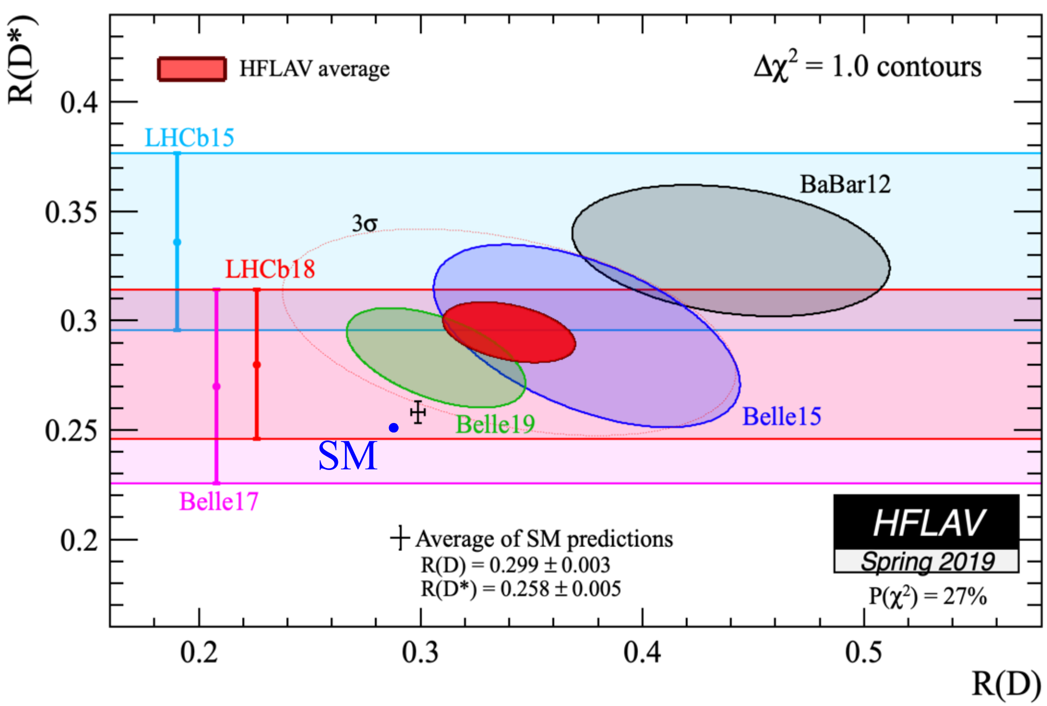


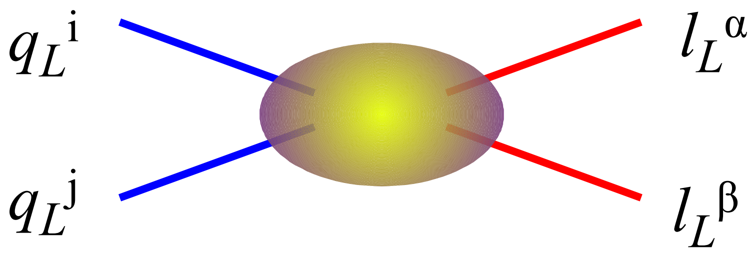


$$R(X) = \frac{\Gamma(B \to X\, \tau\nu)}{\Gamma(B \to X\, l\nu)}$$

X = D or D*

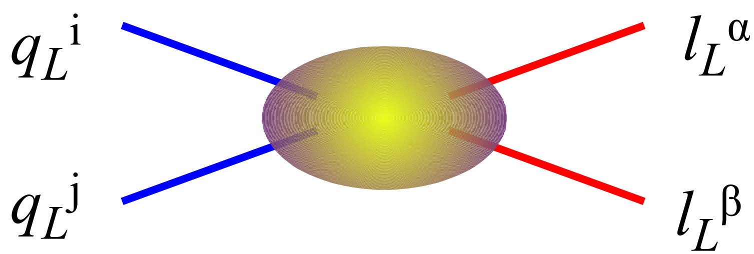
- Clean SM predictions (*uncertainties cancel in the ratios*)
- Smaller significance and slower progress
- Consistent results by 3 different exp. → 3.1σ excess over SM

EFT considerations



EFT considerations

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- We definitely need non-vanishing left-handed current-current operators although other contributions are also possible



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

- Large coupling [*competing with SM tree-level*] in $bc \to l_3\,\nu_3$ [R_D, R_{D*}]
- Small coupling [*competing with SM loop-level*] in $bs \to l_2\ l_2$ [R_K, R_{K*}, ...]

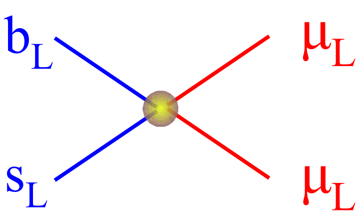
↓

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

EFT considerations

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

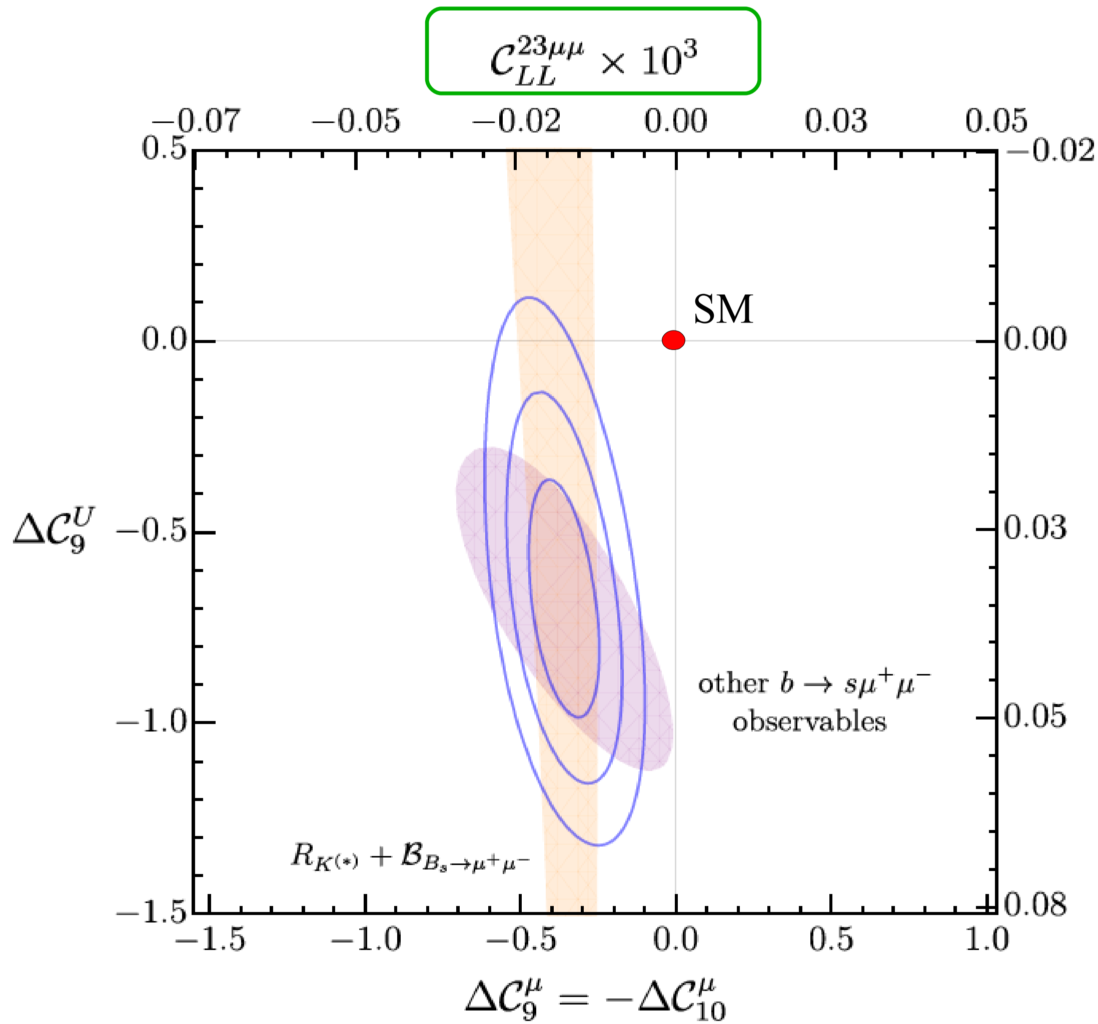
$$\boxed{\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)}$$



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

super-weak interaction!

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



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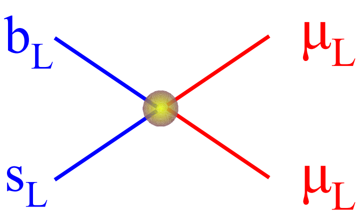
✓ O(10^{-1}) suppress. for each 2nd gen. l_L



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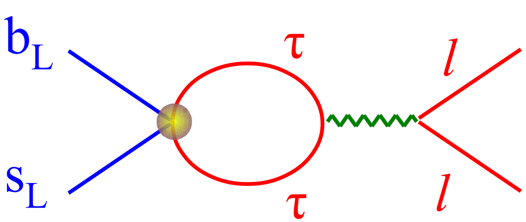
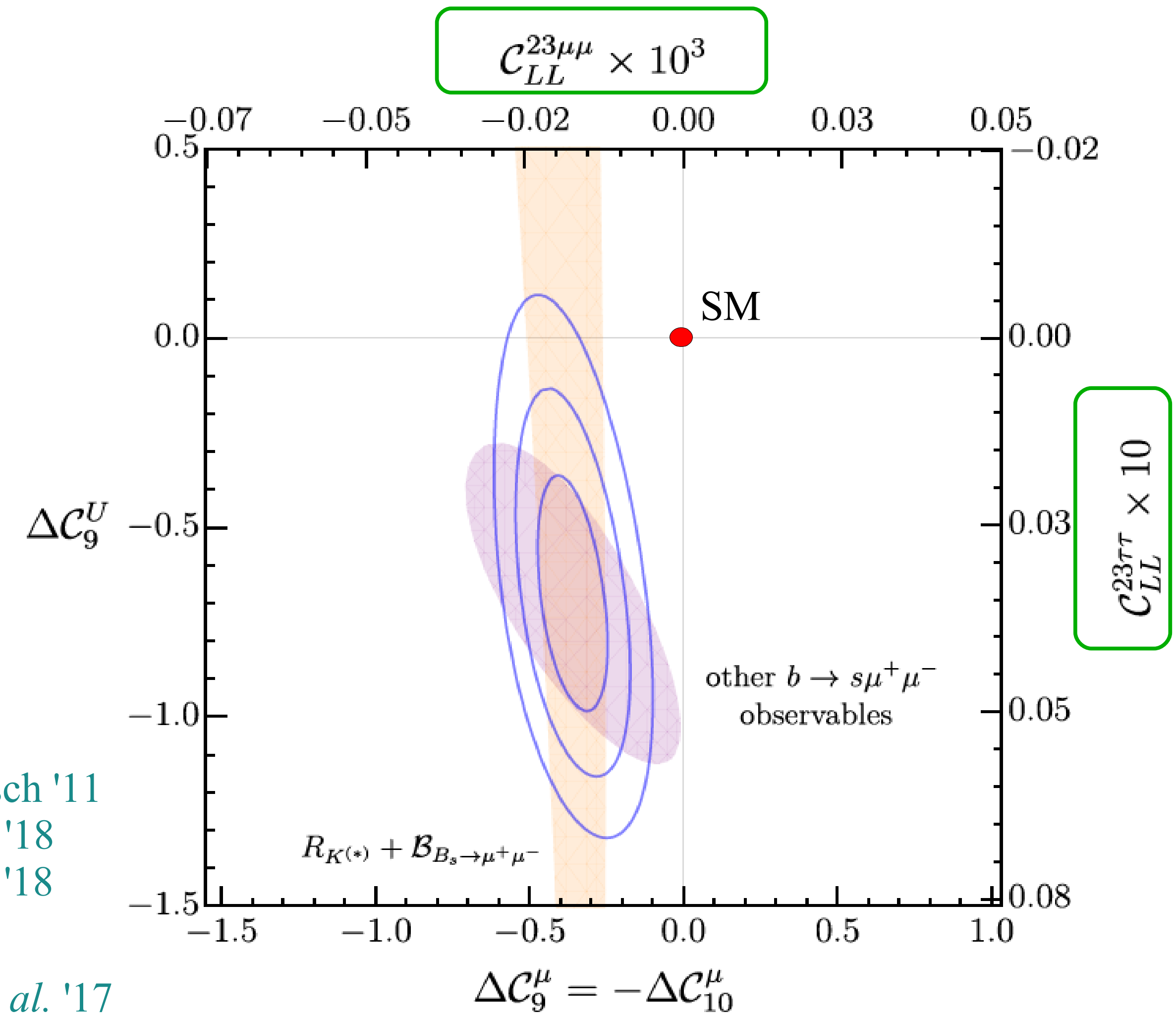


$C_{LL}^{23\tau\tau} \Rightarrow \Delta C_9^{\text{Univ}}$

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

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



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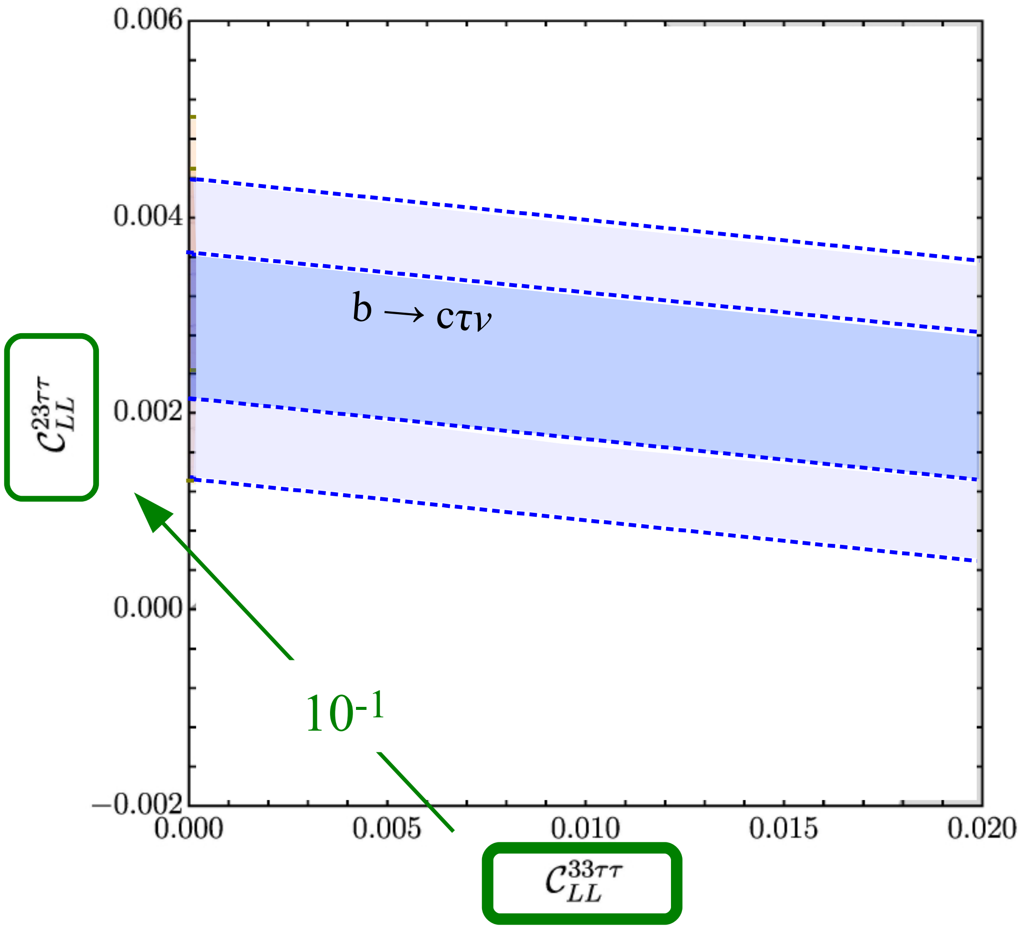


charged-currents:

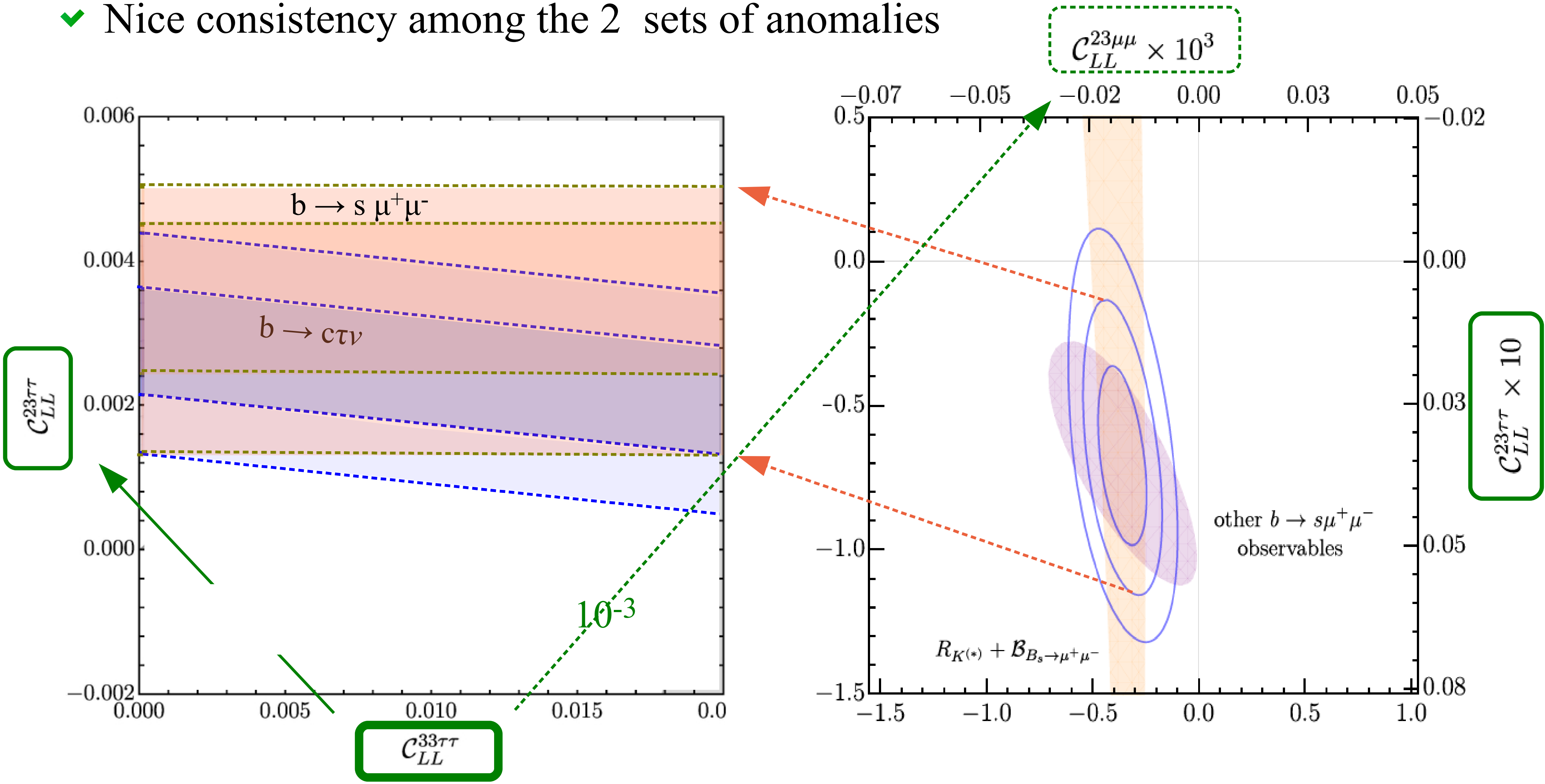
$$\frac{V_{cb}\,\mathcal{C}_{LL}^{33\tau\tau} + V_{cs}\,\mathcal{C}_{LL}^{23\tau\tau}}{V_{cb}}$$

EFT considerations

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

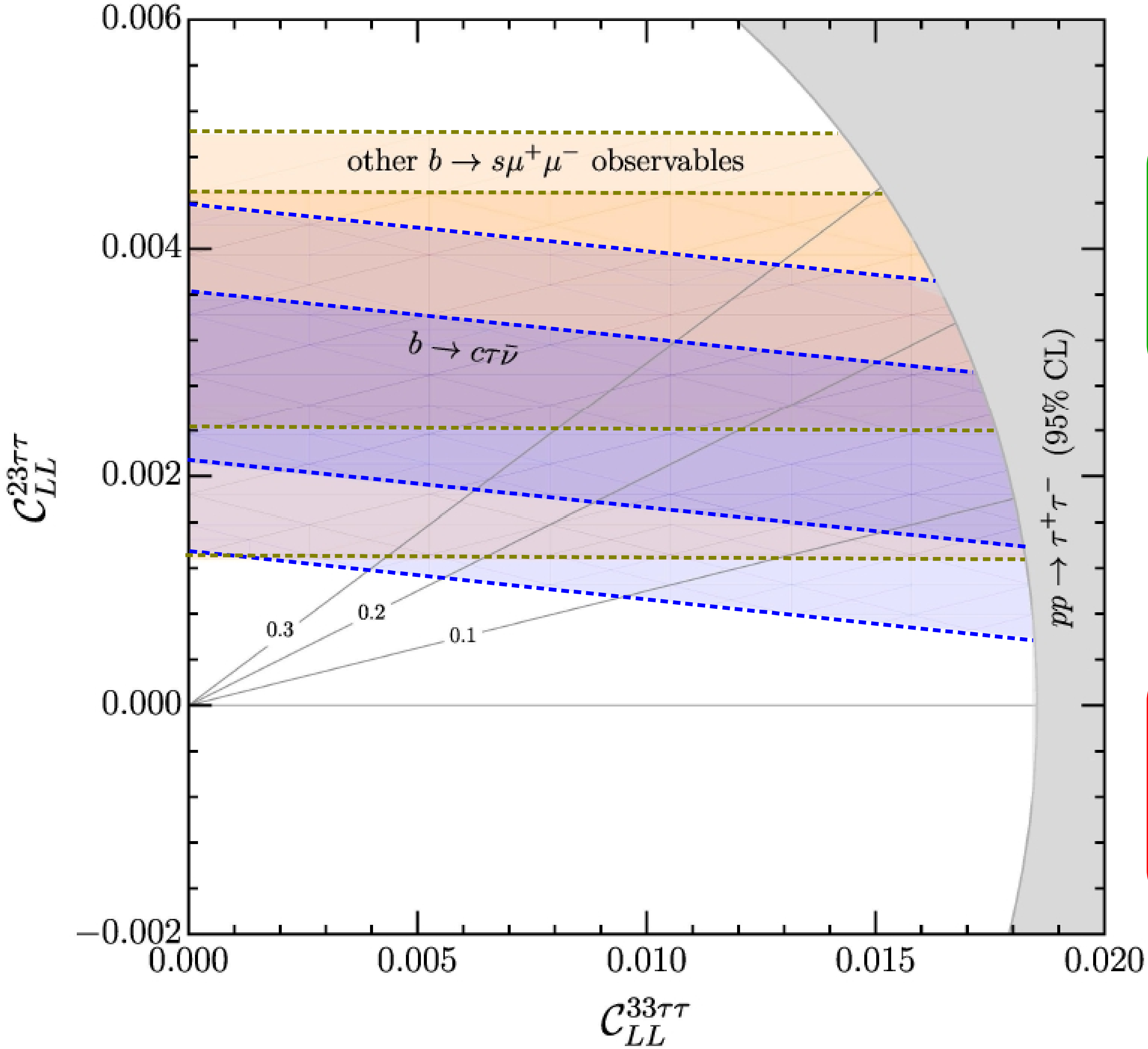
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)$$

- O(10^{-1}) suppress. for each 2^{nd} gen. q_L or l_L [*recall* $|V_{ts}| \sim 0.4\times10^{-1}$]
- Nice consistency among the 2 sets of anomalies



EFT considerations

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



Pattern emerging from data:

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

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

- ✖ Four-quarks (ΔF=2)
- ✖ Four-leptons (τ→μνν)
- ✖ Semi-leptonic $O^{(1\text{-}3)}$ (b→sνν)

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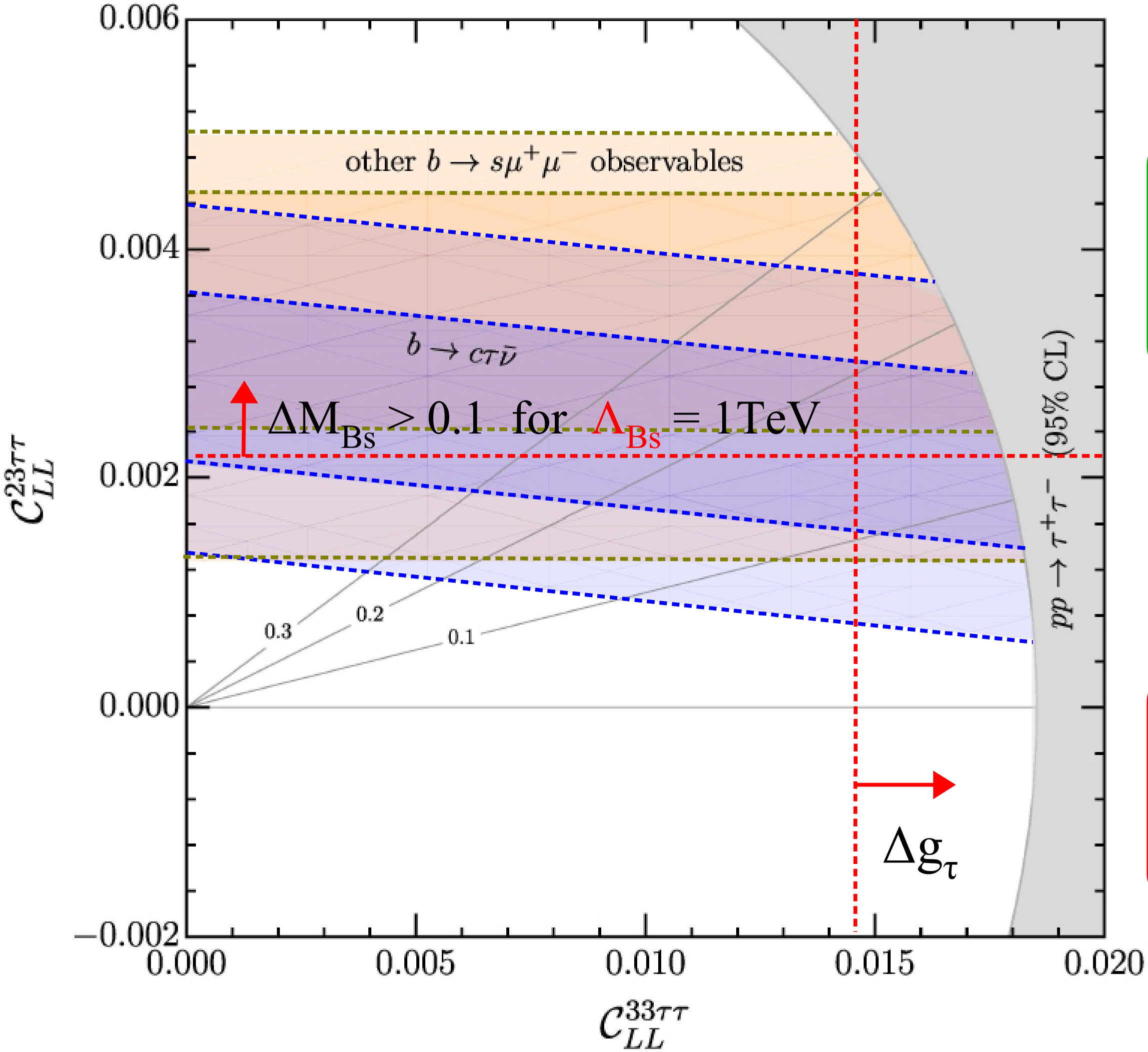

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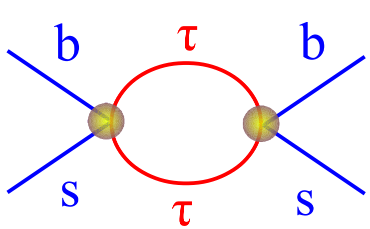
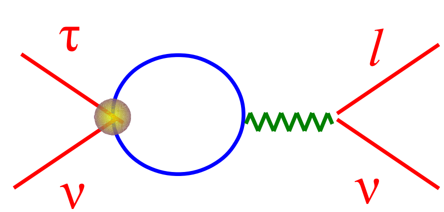
What we do <u>not</u> see (*seem to call for an additional ~ loop suppression*):

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

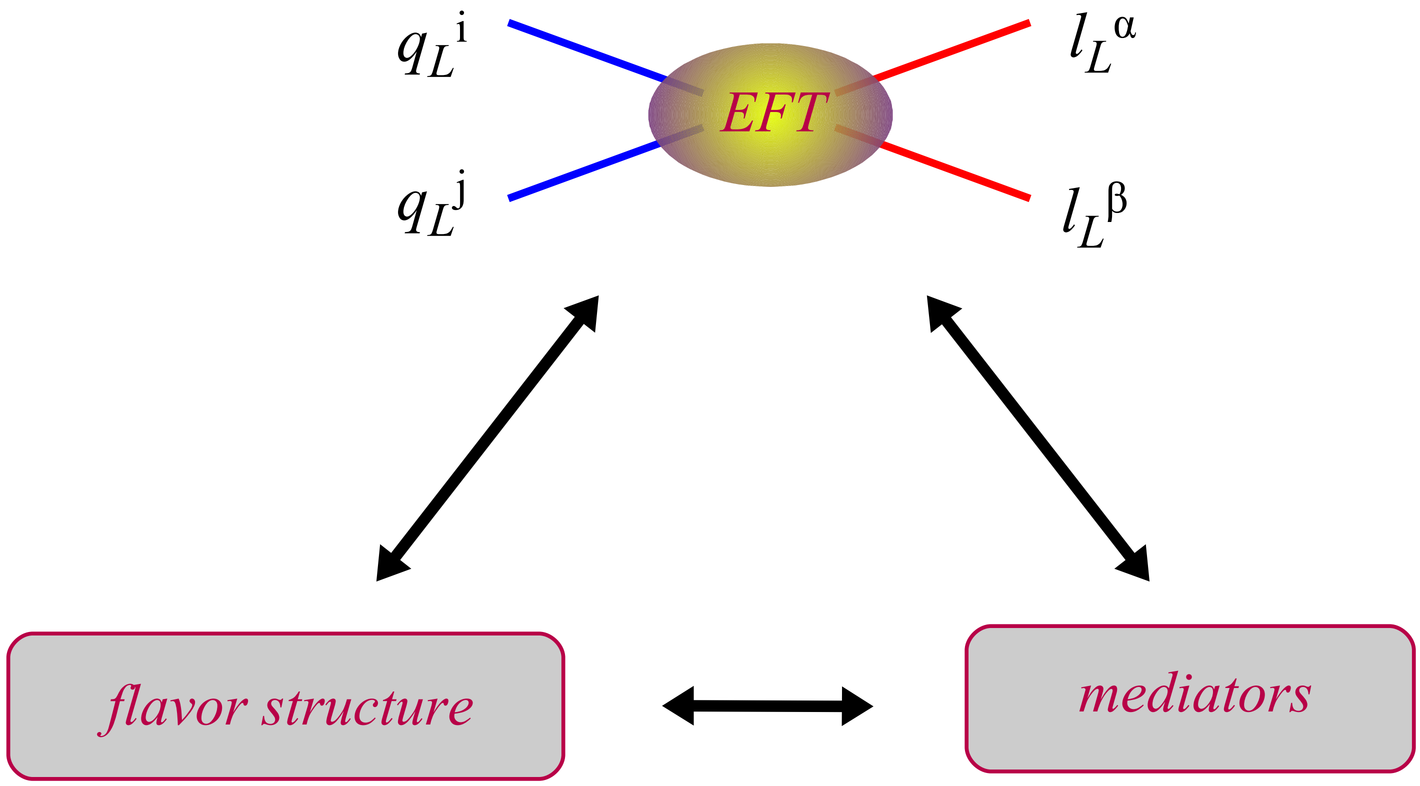


$\Delta M_{B_s} \sim (C^{23\tau\tau})^2\, \Lambda_{B_s}{}^2$



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

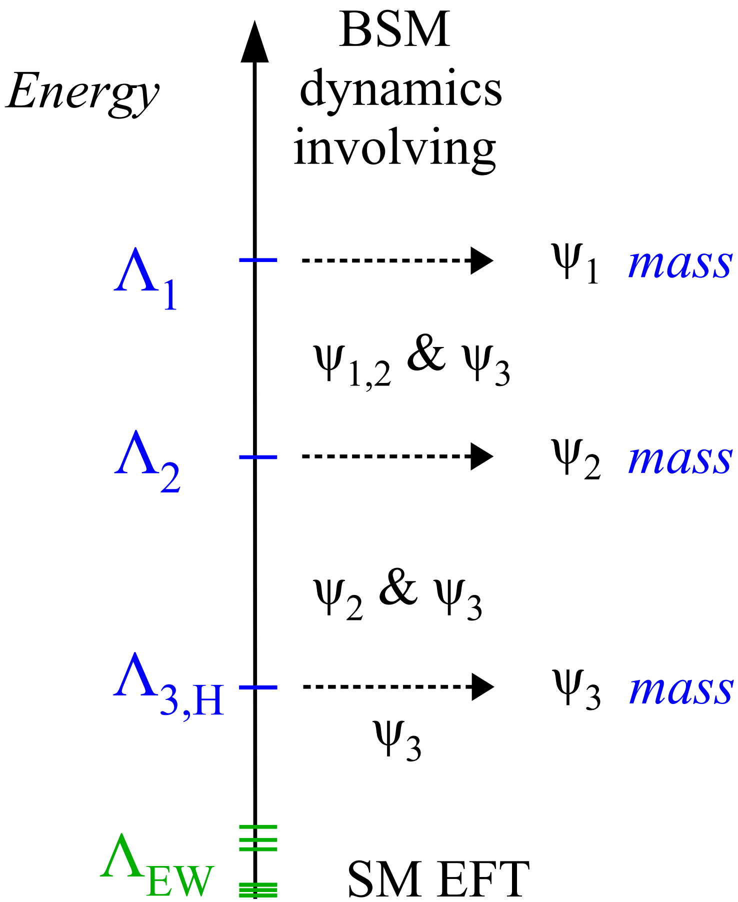
From EFT to simplified models



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

Multi-scale picture @ origin of flavor:

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



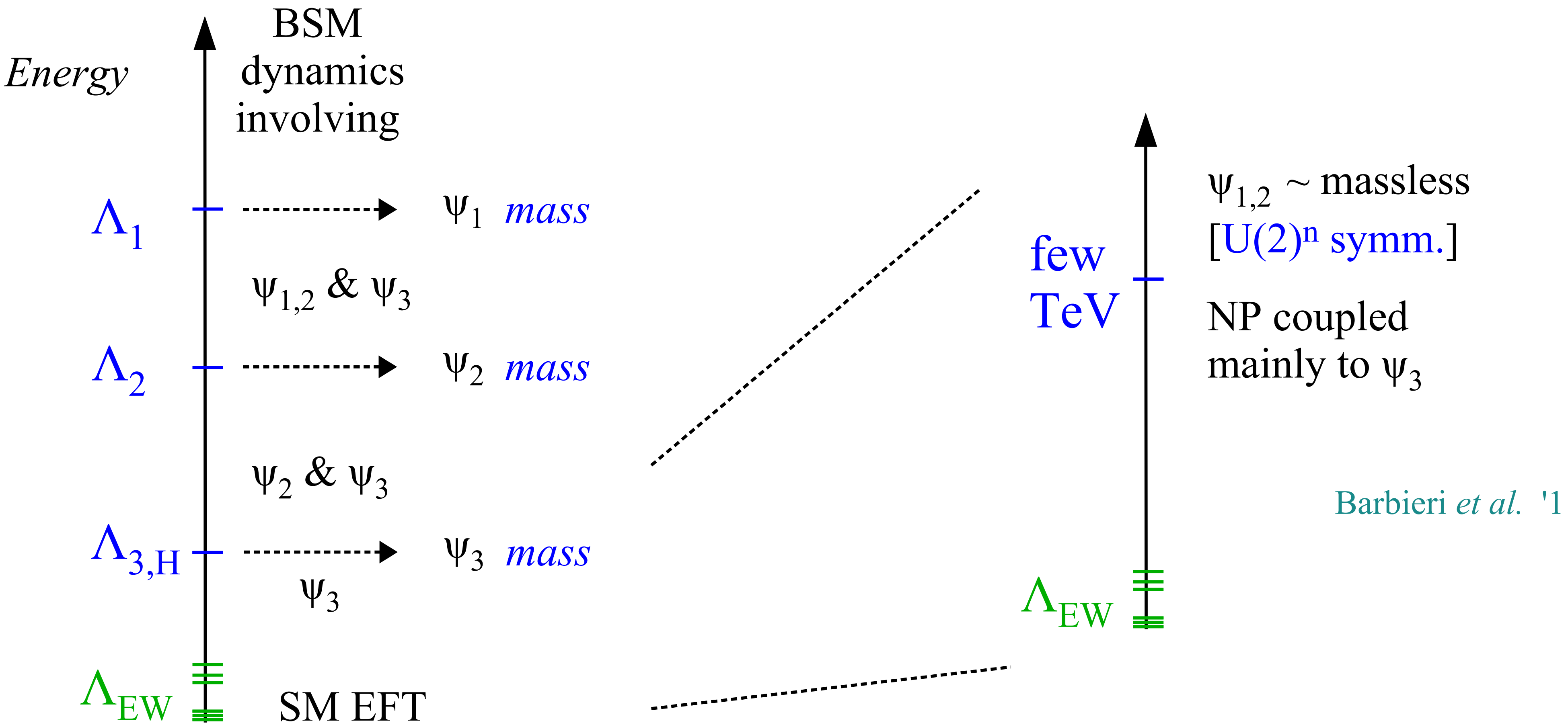
Main idea:

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

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

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

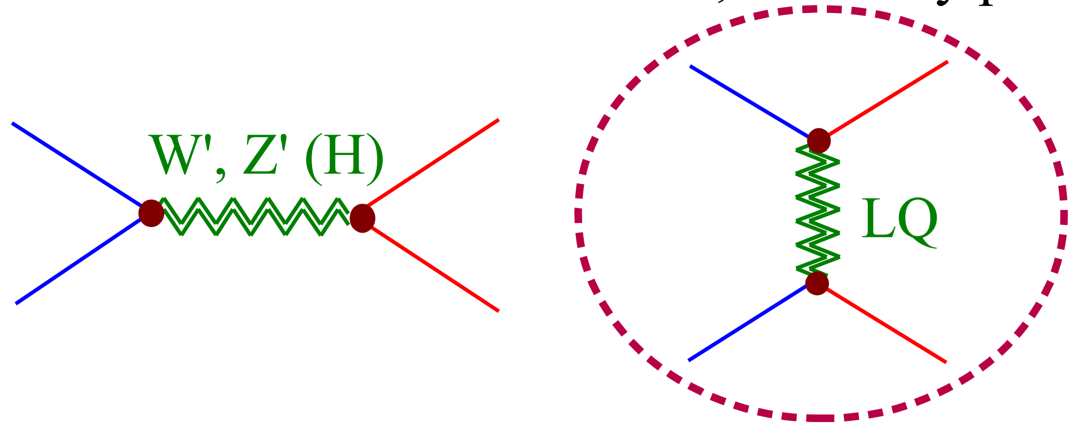
Multi-scale picture @ origin of flavor:



$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \underbrace{\mathscr{L}_{\text{Higgs}} + \mathscr{L}_{Y} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}}_{\text{Non-trivial UV imprints}}$$

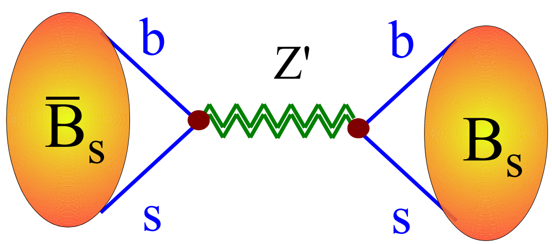
From EFT to simplified models [*the possible mediators*]

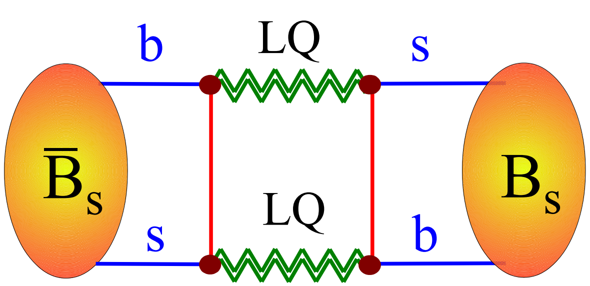
Which mediators can generate the effective operators required for by the EFT fit?
If we restrict the attention to tree-level mediators, not many possibilities...



LQ (both scalar and vectors) have two general strong advantages with respect to the other mediators:

I. $\Delta F=2$ & $\tau \to l\nu\nu$





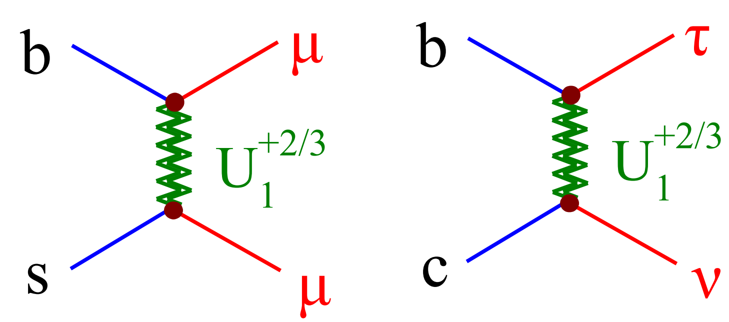
II. Direct searches: 3rd gen. LQ are also in better shape as far as direct searches are concerned (*contrary to Z'...*).

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

Which LQ explains which anomaly?

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

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

LQ of the Pati-Salam gauge group:

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

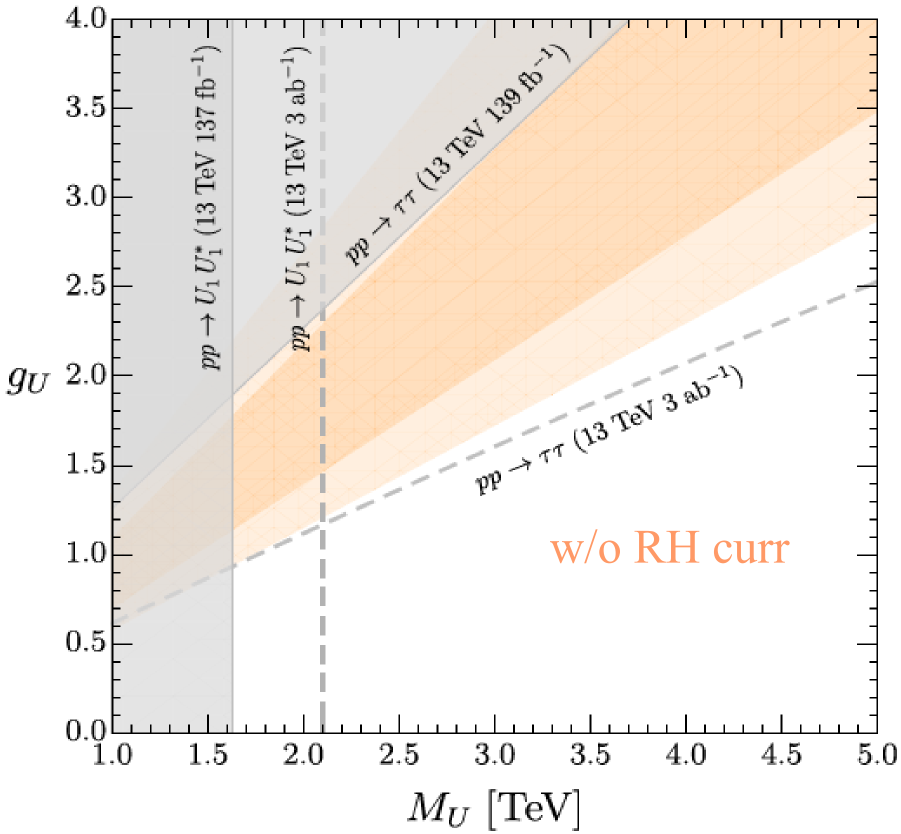
▶ From EFT to simplified models [the possible mediators]

Considering the U_1 only

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

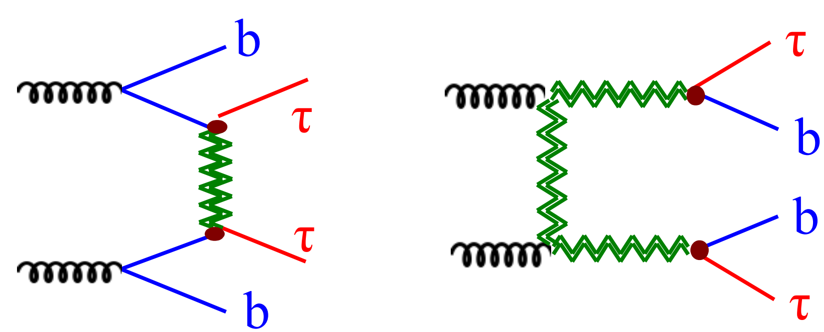
and fitting all low-energy data leads to an excellent description of present data which is fully consistent with high-pT searches [*within the reach of HL-LHC*]...

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

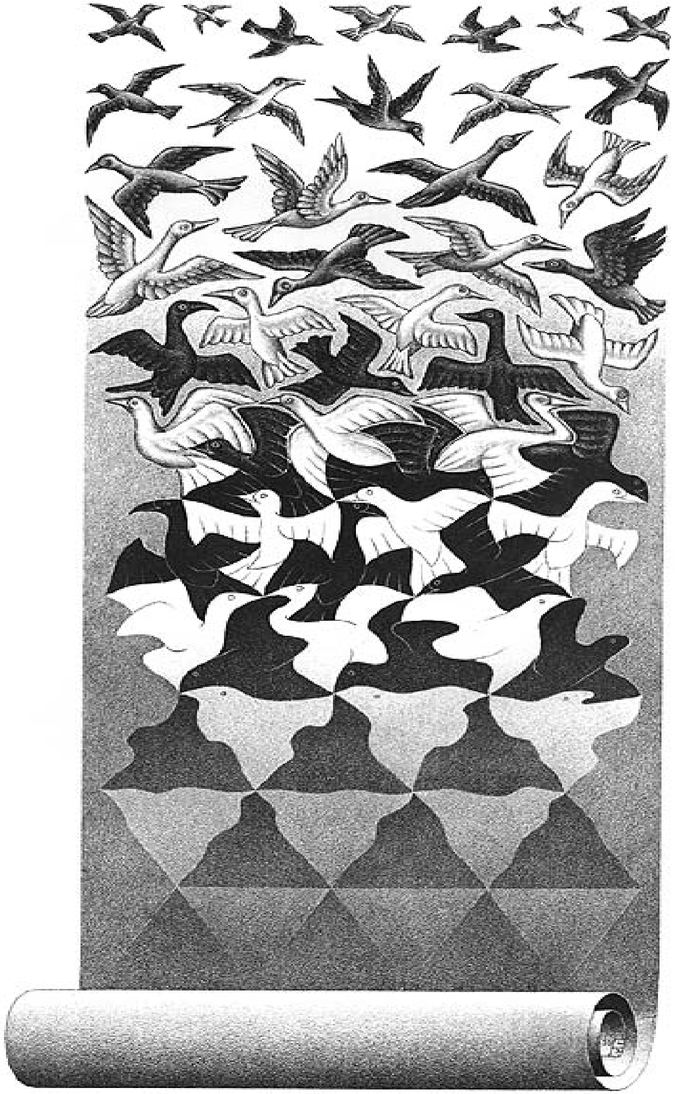


… plus interesting implications for future low-energy searches [*LFV in τ and B decays, B→ Kττ, …*]

→ More in the talk by C. Cornella



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:

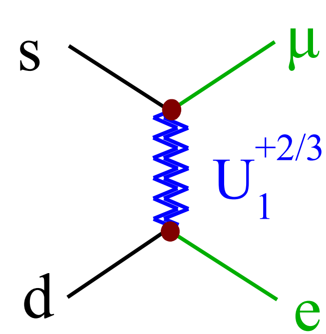
Pati-Salam group: $SU(4)\times SU(2)_L\times SU(2)_R$

Fermions in SU(4): $\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix}$ $\begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$

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

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

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 $K_L \rightarrow \mu e$]



Attempts to solve this problem simply adding extra fermions or scalars

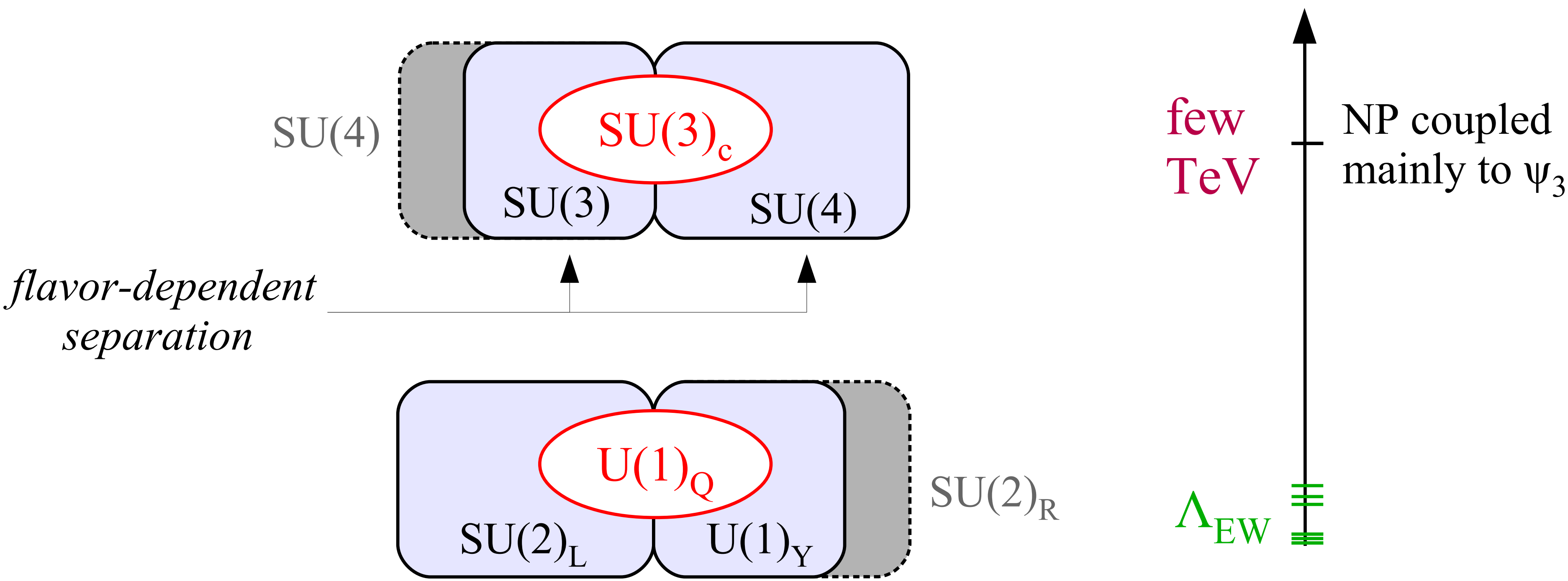
Calibbi, Crivellin, Li, '17;
Fornal, Gadam, Grinstein, '18
Heeck, Teresi, '18

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



Speculations on UV completions

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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.*

UV completions

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

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

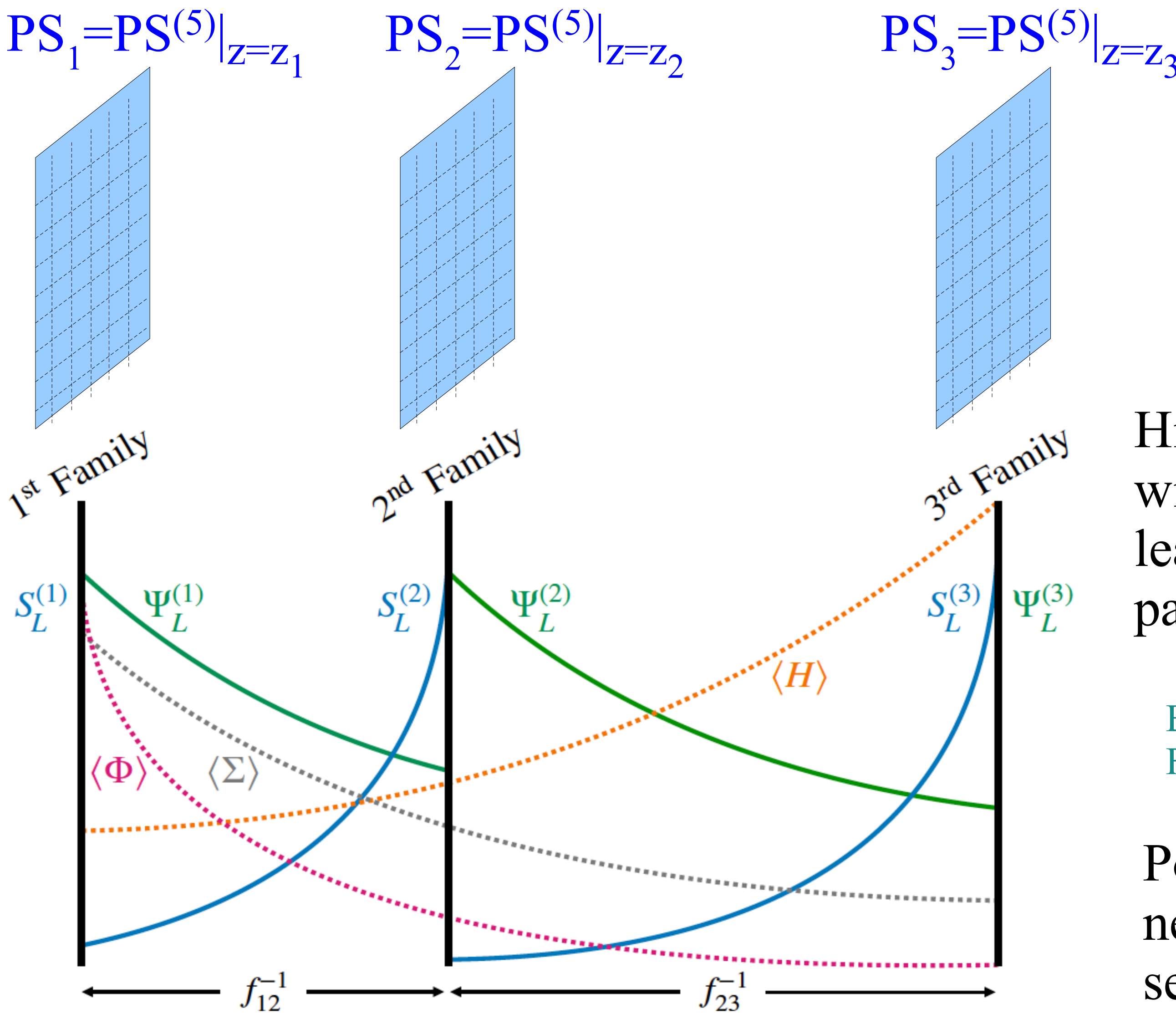
$SU(4)_h \times SU(4)_l \times G_{EW} \times G_{HC}$
Fuentes-Martin & Stangl '20

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

$[\,PS\,]_{\text{warped-5d, 3-branes}}$
Fuentes-Martin *et al.* '20 + *work in prog.*

Speculations on UV completions

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



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

Dvali & Shifman, '00

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

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

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

Speculations on UV completions

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

Di Luzio, Greljo, Nardecchia, '17

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

ψ_3 $\psi_{1,2}$

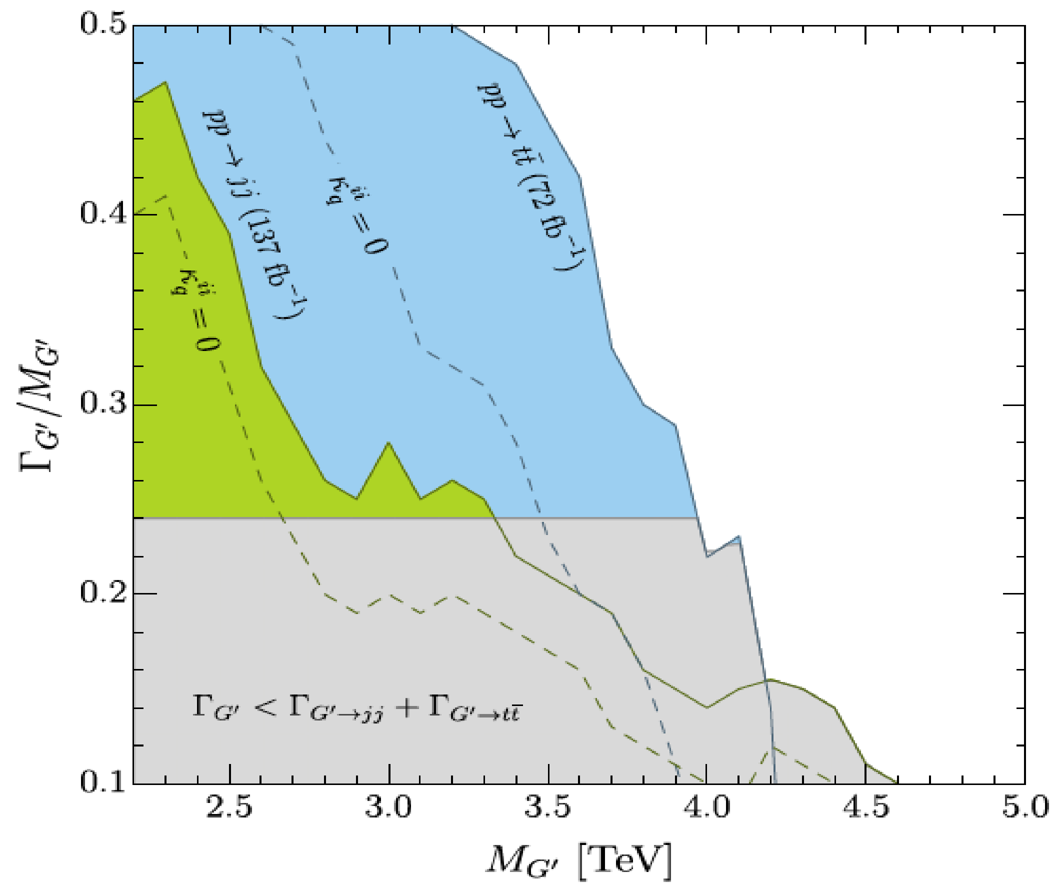
$\rightarrow$ LQ [U_1] + Z' + G'

SM

Despite the apparent complexity, the construction is highly constrained

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

consistent with present data !



New striking collider signature:
G' ("*coloron*" = *heavy color octet*)

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

Conclusions

- The statistical significance of the LFU anomalies is growing: in the $b \to s\ell\ell$ system the chance this is a pure statistical fluctuation is marginal...
- <u>If combined,</u> 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]
- <u>No contradiction</u> with existing low- & high-energy data, <u>but new non-standard effects should emerge soon</u> in both these areas

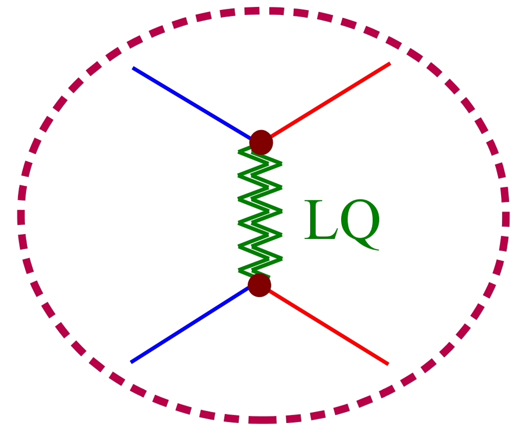
⬇

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


Backup

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

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



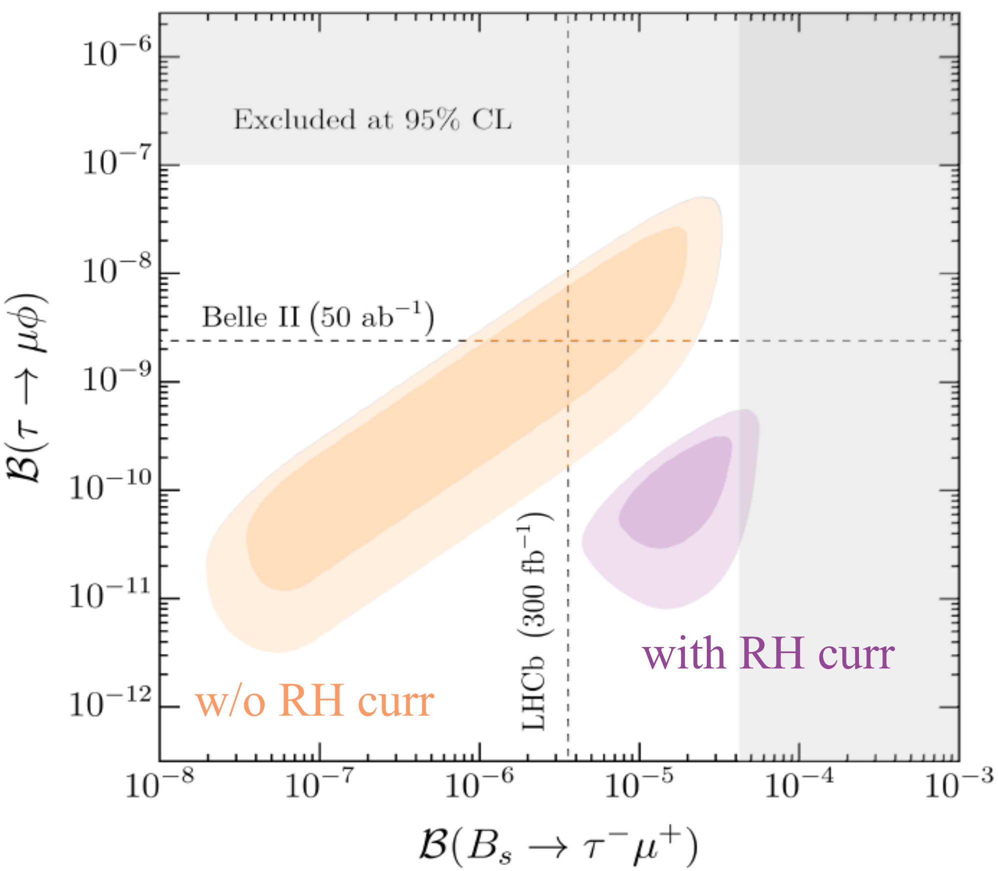
- Could mediate proton decay → not a general feature of the LQ: it depends on the model...! [*e.g. not the case in the Pati-Salam model*]
- Severe bounds from processes involving μ & e (such as $K_L \to \mu e$) → avoided with non-trivial flavor structure [*e.g. non-univ. interactions*]

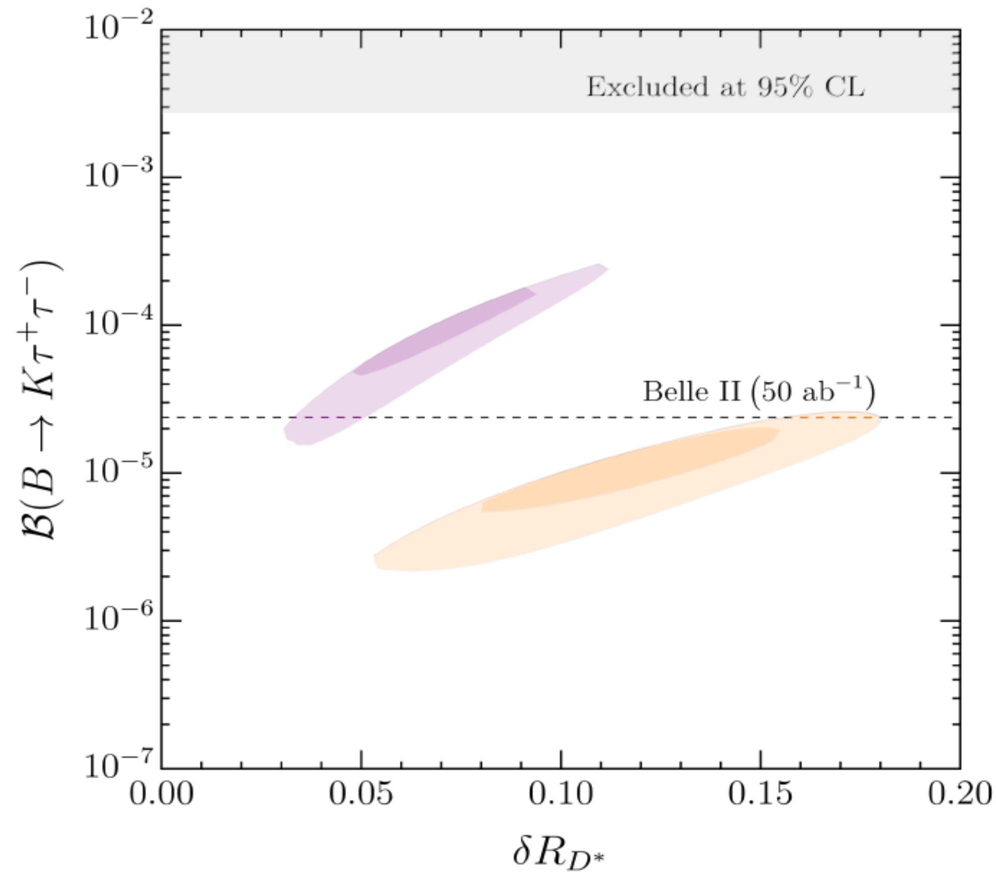
On the other hand, they are a "natural" feature in many SM extensions → "Renaissance" of LQ models (*to explain the anomalies, but not only...*):

- 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 + ...

Other low-energy observables

UV-insensitive observables (EFT predictions):

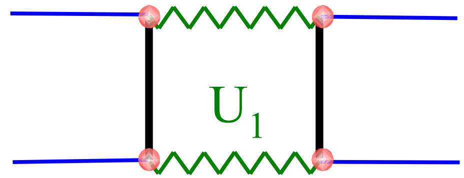




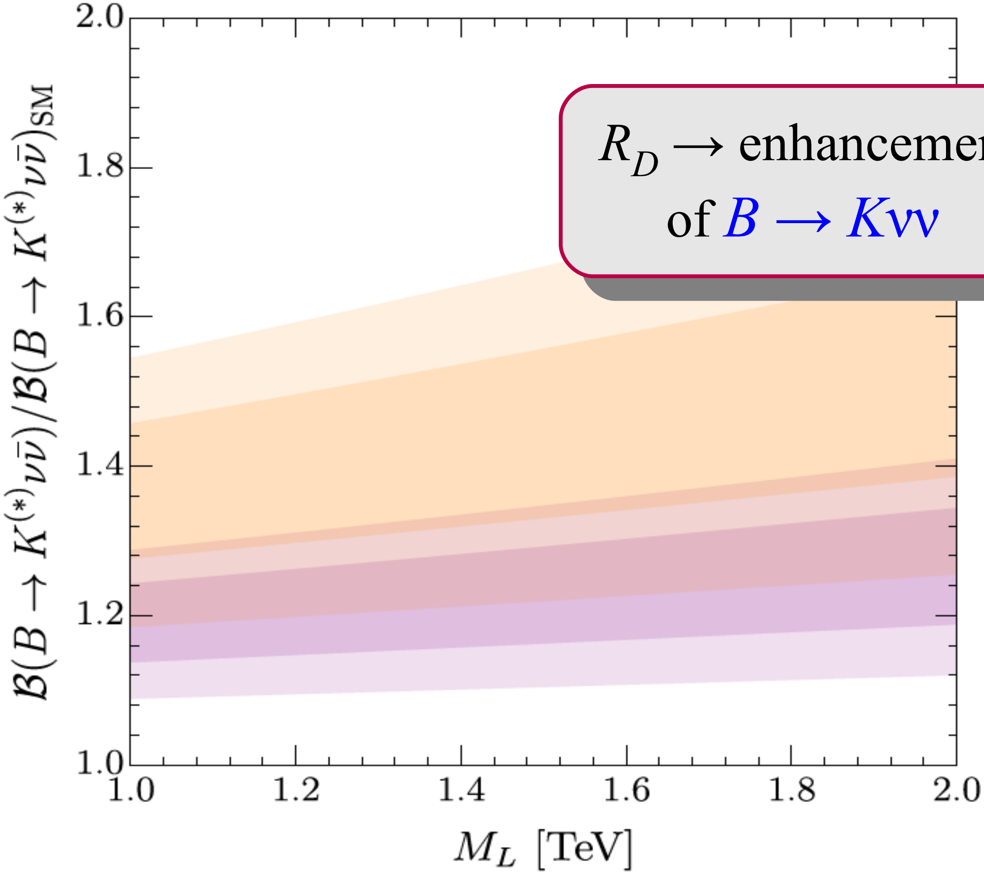
Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21

Other low-energy observables

UV-sensitive observables:

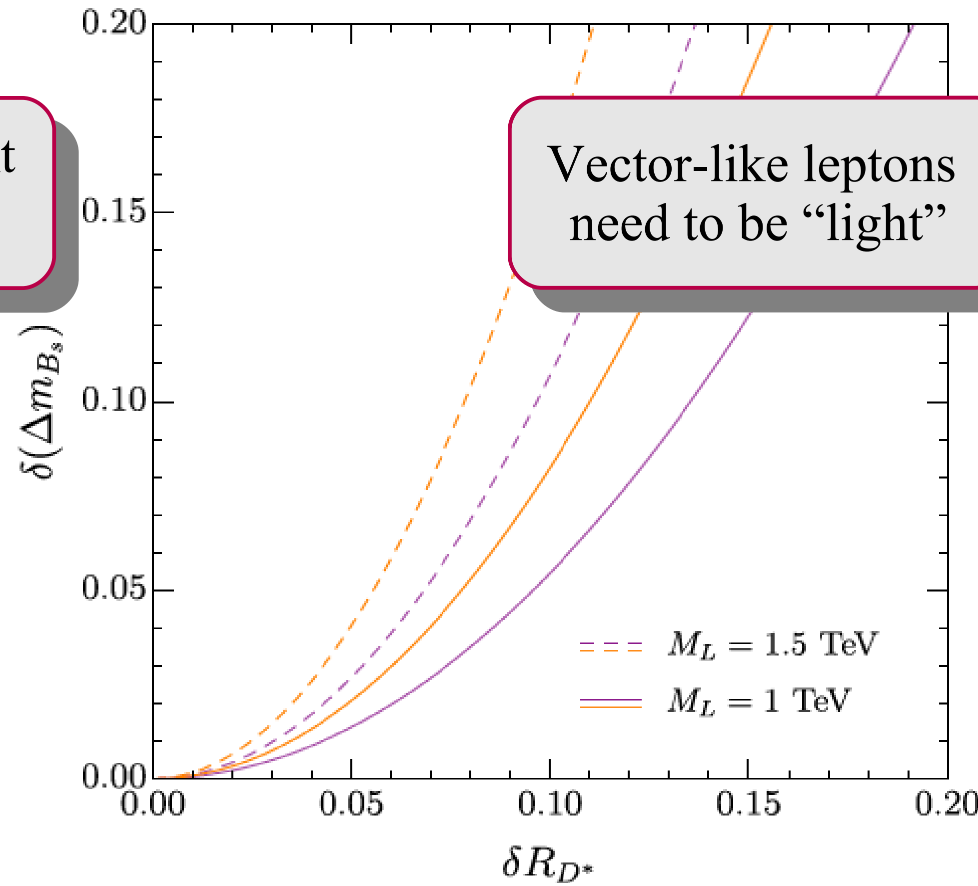


A) $B \to K\nu\nu$



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

B) B_s mixing [ΔF=2]

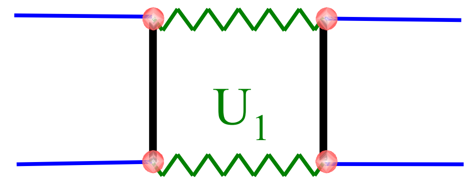


Vector-like leptons need to be "light"

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

Other low-energy observables

UV-sensitive observables:



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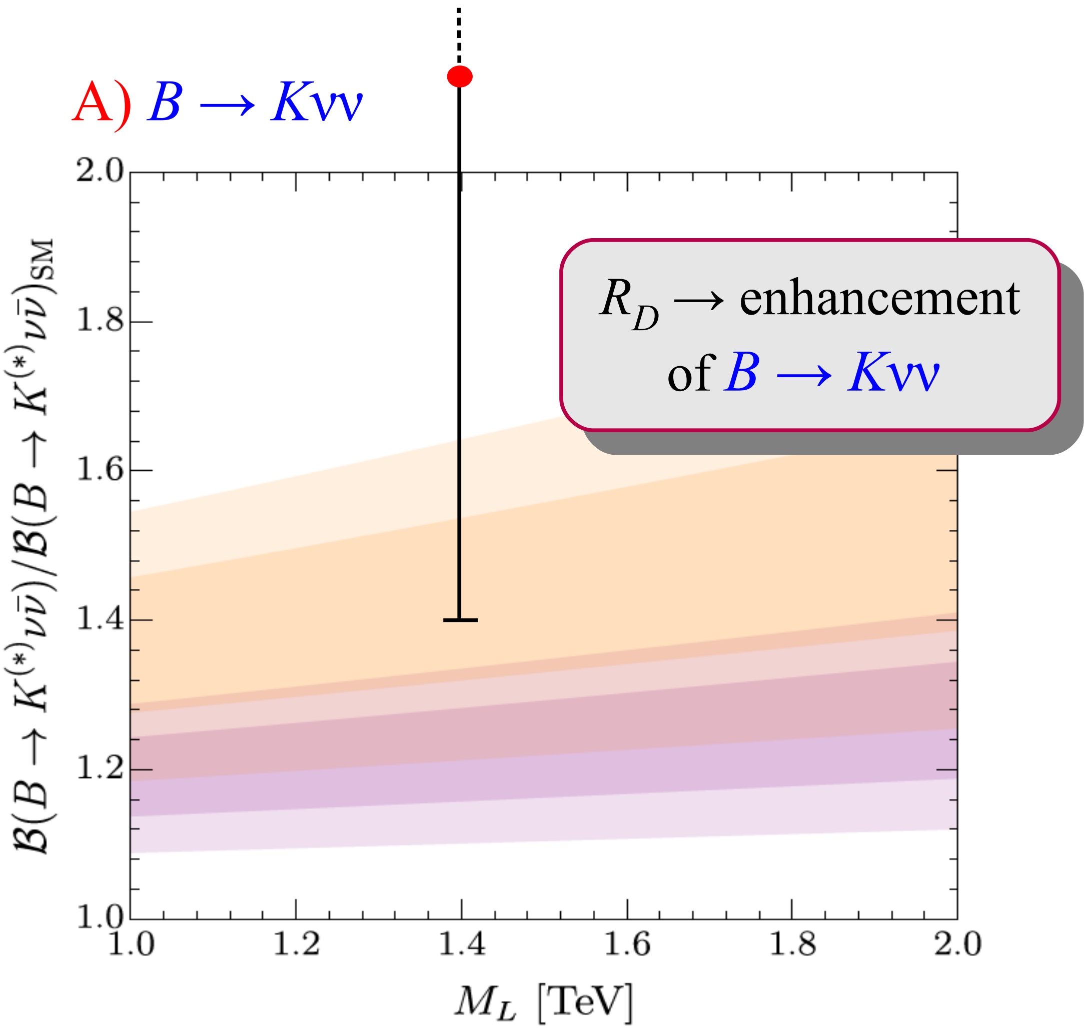

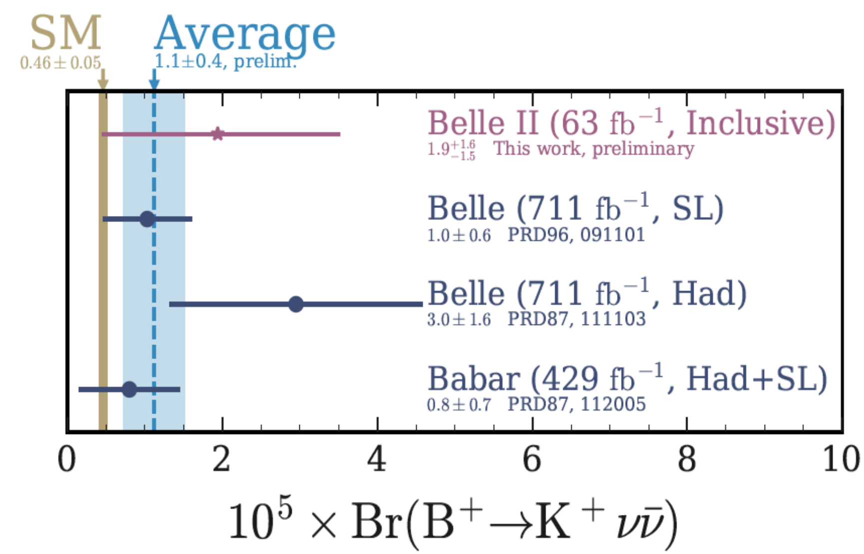

Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21
Fuentes-Martin, GI, Konig, Selimovic, '20