B-physics anomalies and the flavor problem

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[*University of Zürich*]

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

University of Zurich UZH

European Research Council
Established by the European Commission

▶ Introduction

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

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

⬇

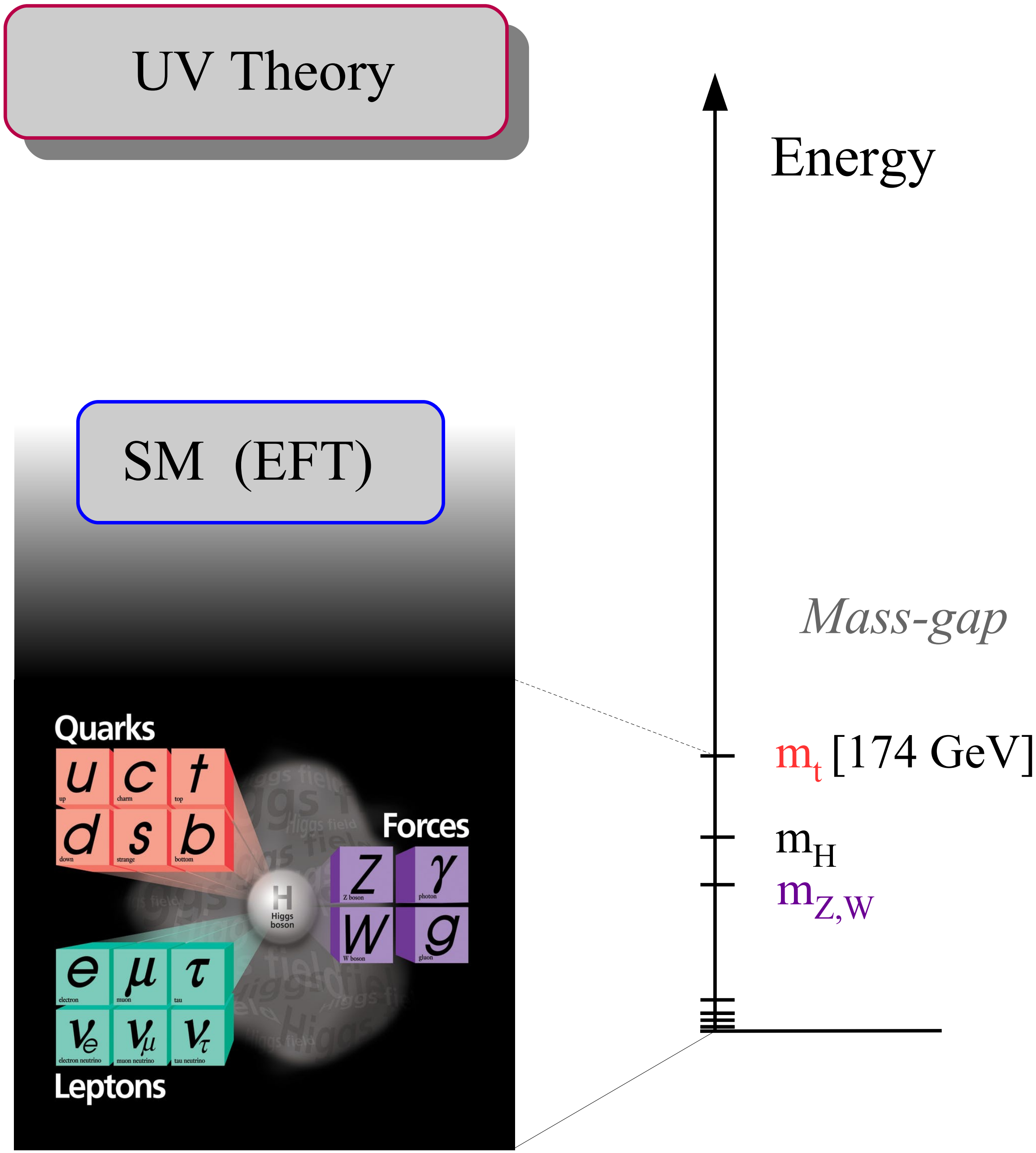
The Standard Model should be regarded as an *Effective Field Theory* (*EFT*)

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

Introduction

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

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



Introduction

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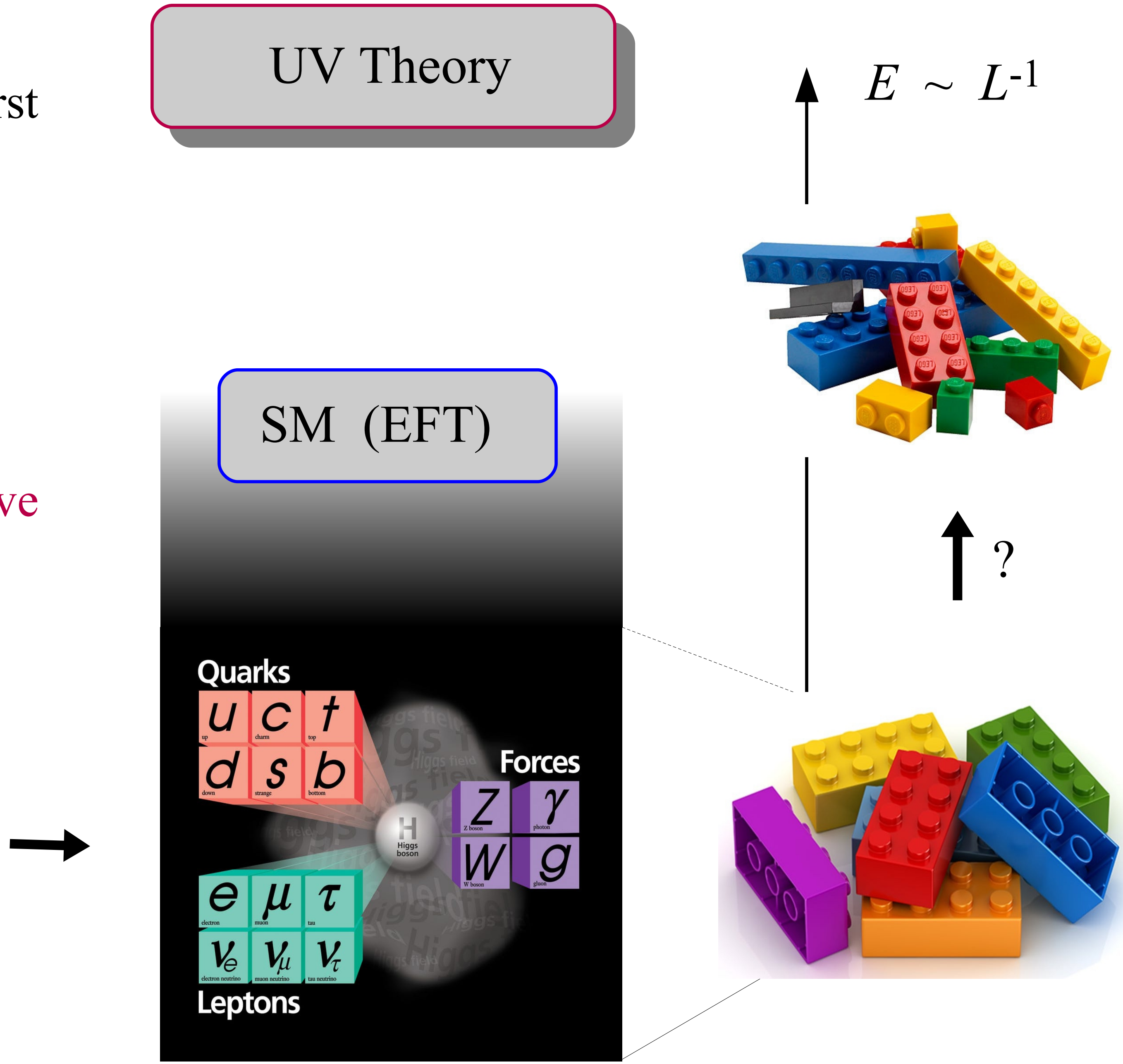
We identified the *"light"* ↔ *"large"* pieces of our *"construction game"* & their long-range interactions



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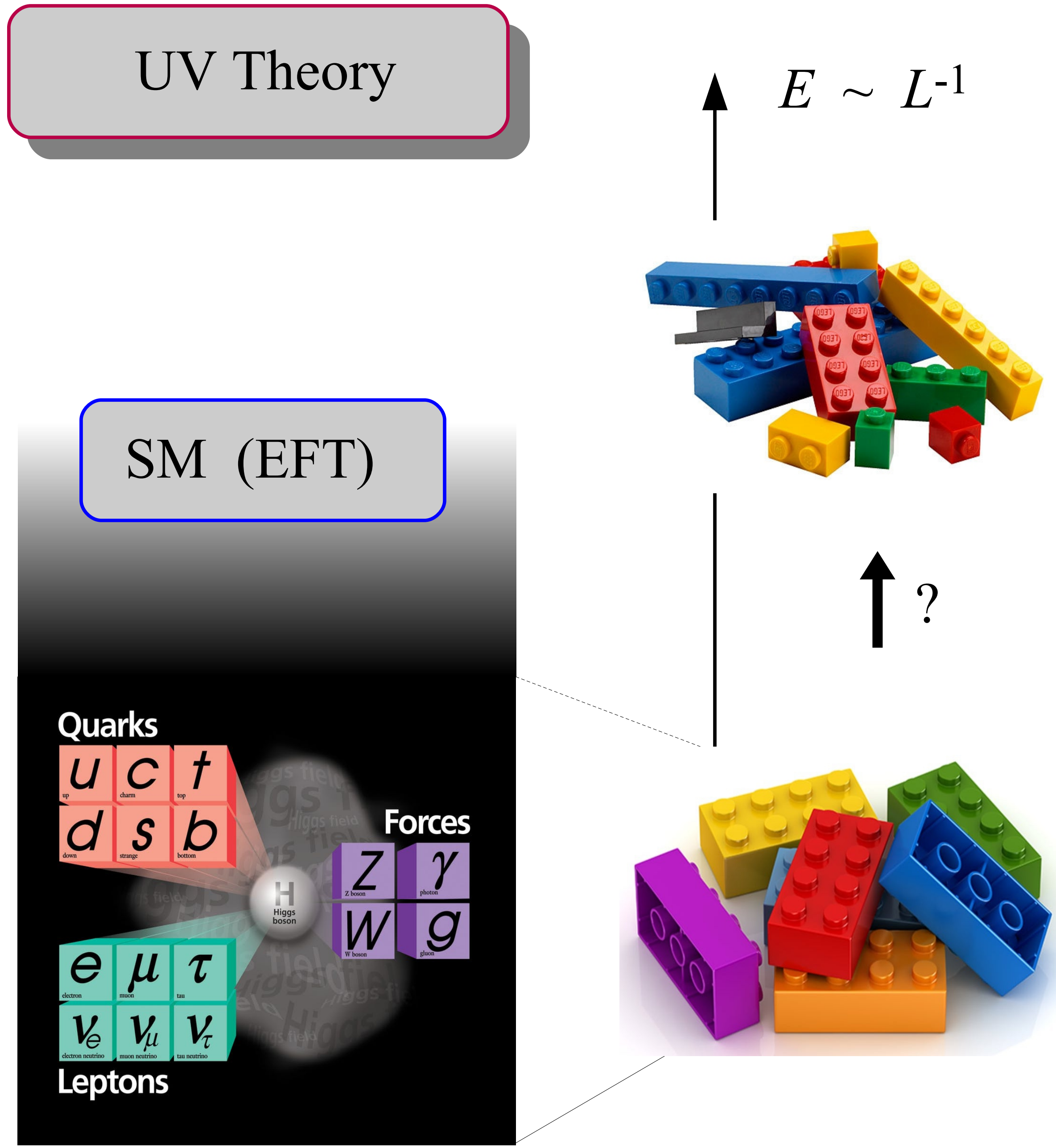
Reconstructing the UV theory from its low-energy limit is a very difficult problem with no unique solution

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



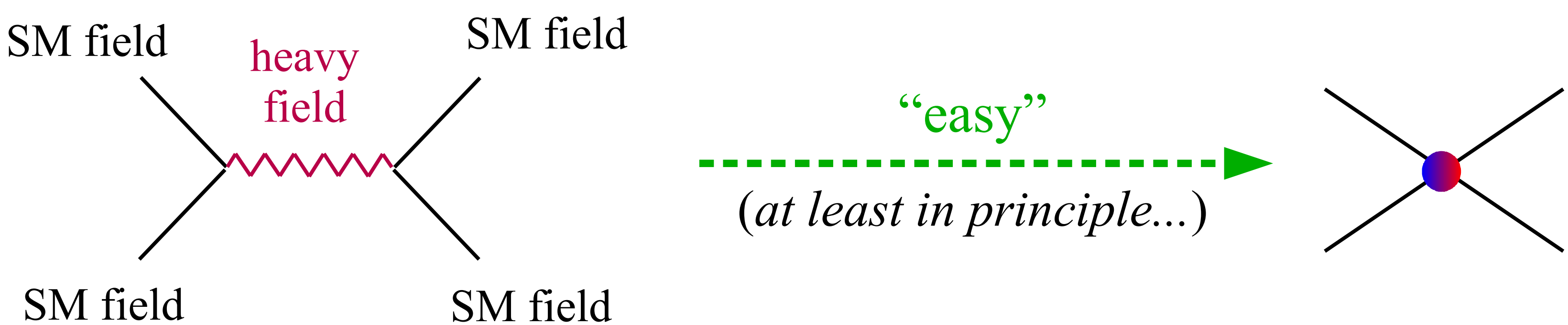
Introduction

UV Theory

low-energy "projection"

"integrate out" the heavy degrees of freedom

SM (EFT)



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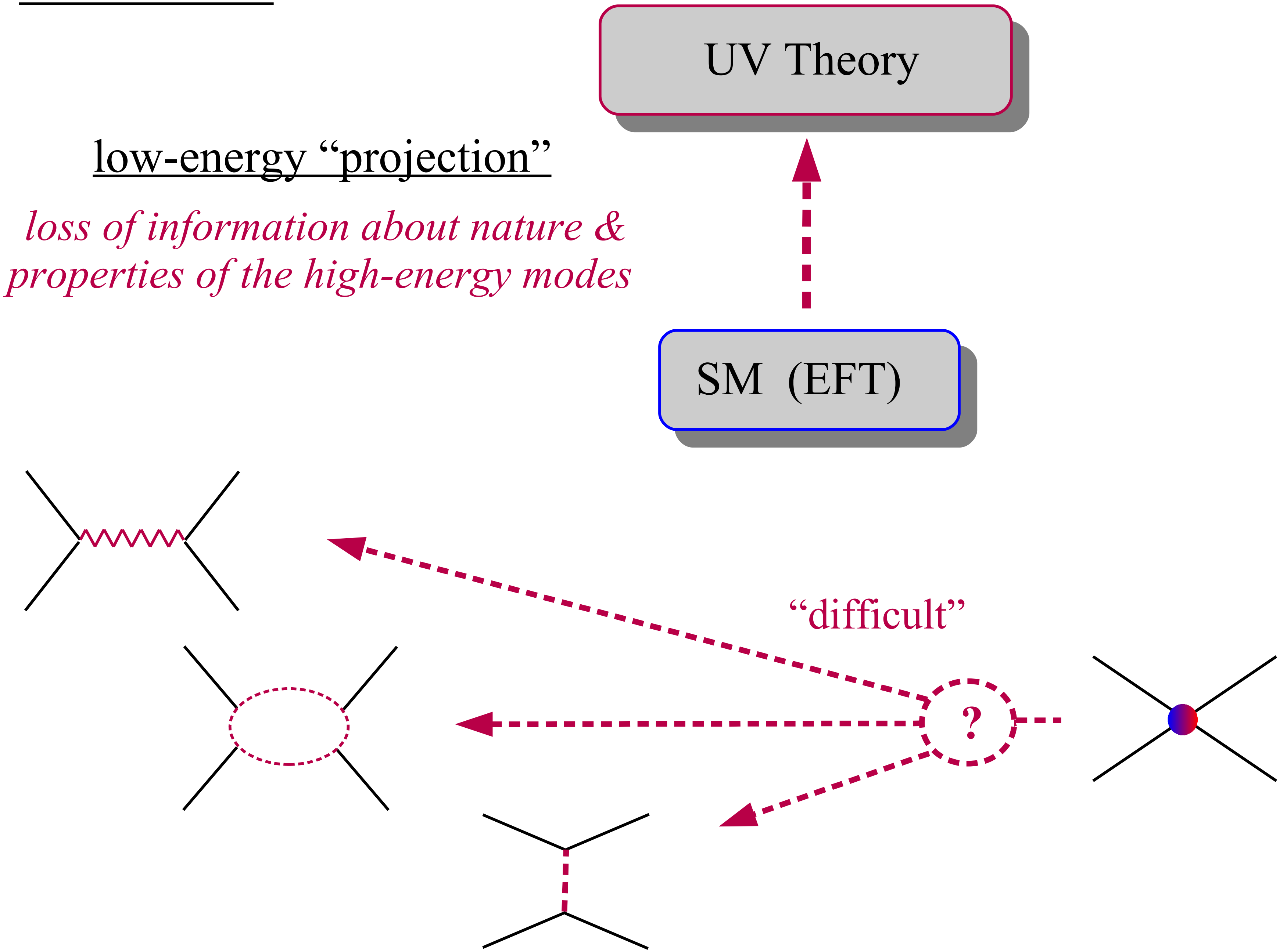
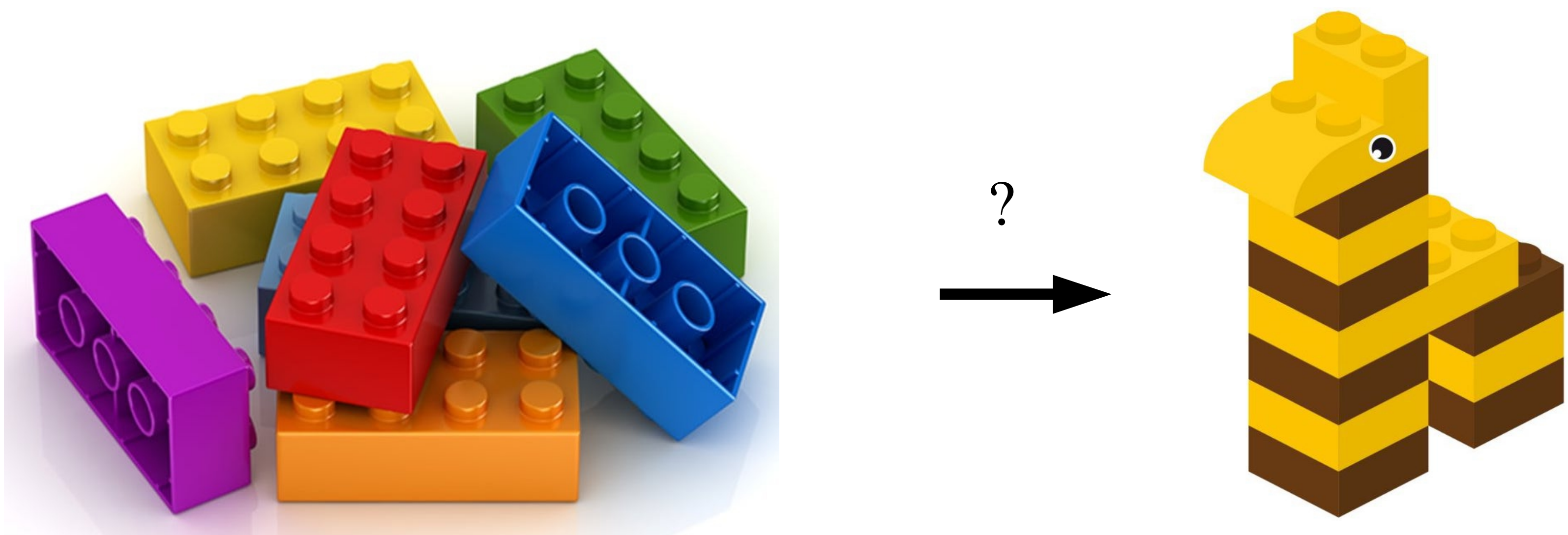


Introduction

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



Introduction

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UV Theory

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SM (EFT)

Two types of effects in QFT:

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

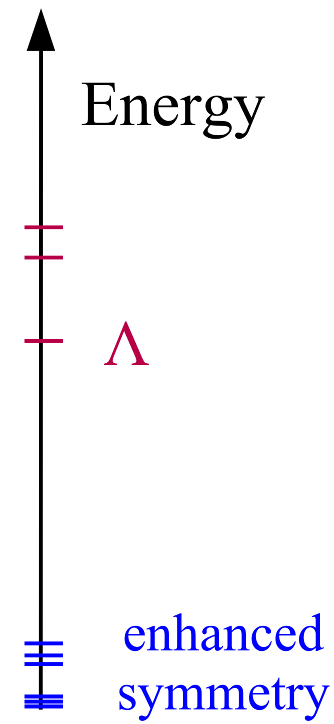
Un-natural aspects of low-energy couplings	Violations of accidental symmetries
qualitative UV imprint	*quantitative* UV imprint

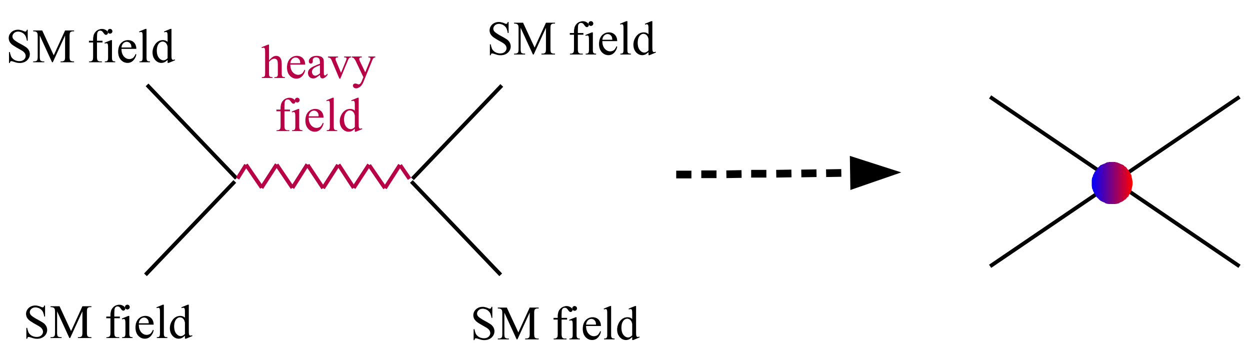
Introduction

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

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*]

Introduction

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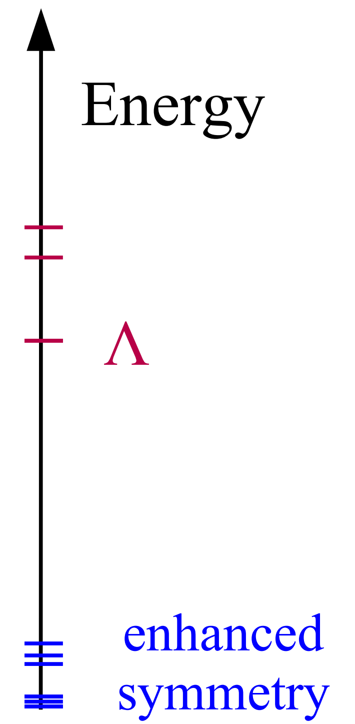
Violations of accidental symmetries



Well-known examples from the past...

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

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

Violated by: Weak interactions → $G_F \sim (250\ \text{GeV})^{-2}$

Introduction

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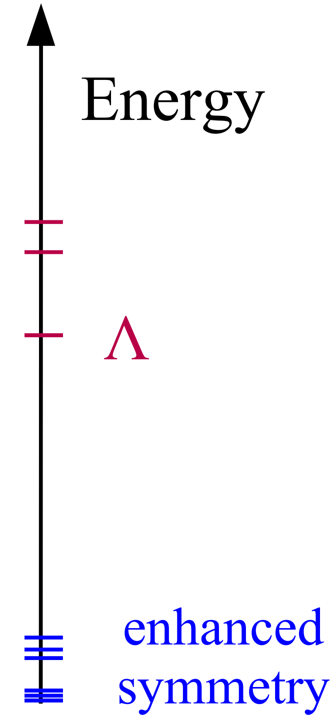

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Accidental symm.: Flavor [$U(1)^{n_f}$]
Violated by: Weak interactions $\rightarrow G_F \sim (250\ \text{GeV})^{-2}$

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

Introduction

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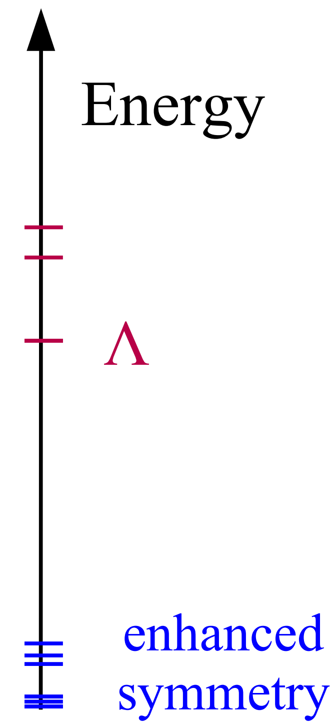
Violations of accidental symmetries



Well-known examples from the past...

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

Introduction

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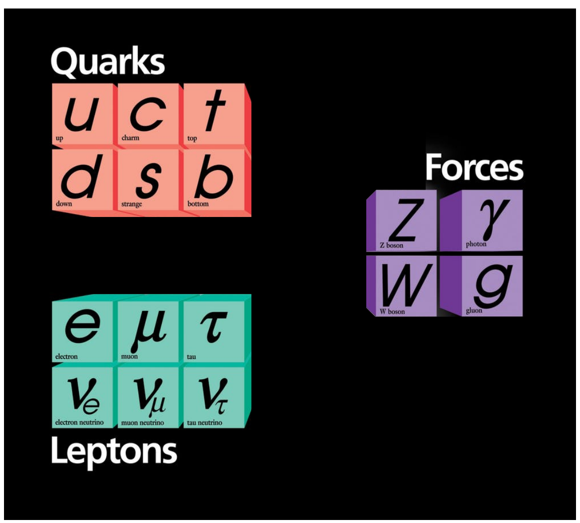
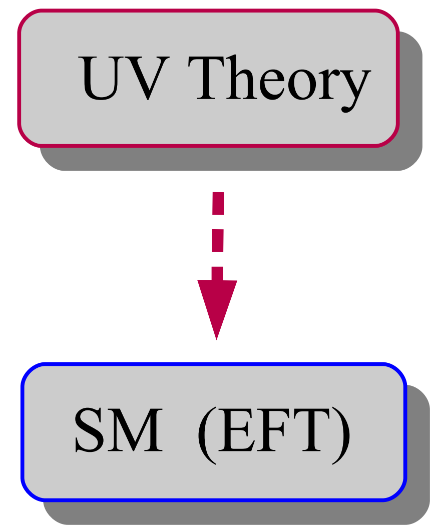
Natural
(fully dictated by gauge symmetry)

Un-natural aspects of the SM couplings





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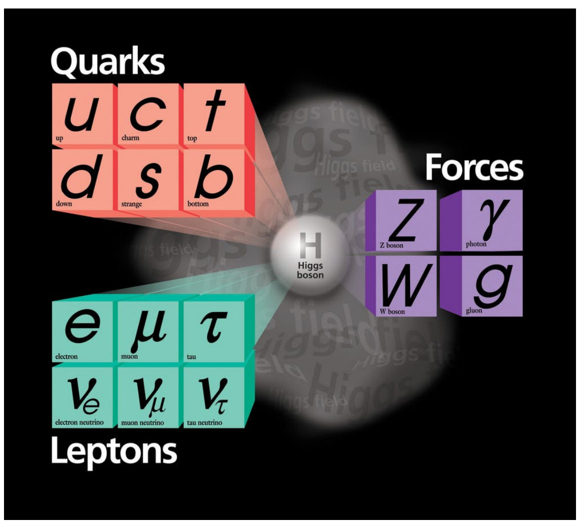
Natural
(fully dictated by gauge symmetry)

Non-trivial
UV imprints

I $m_H^2 H^2$

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

Un-natural aspects of the SM couplings



UV Theory

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SM (EFT)

Introduction

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Natural (*fully dictated by gauge symmetry*) → $\mathscr{L}_{\text{gauge}}$

$\mathscr{L}_{\text{Higgs}}$: Non-trivial UV imprints

Un-natural aspects of the SM couplings

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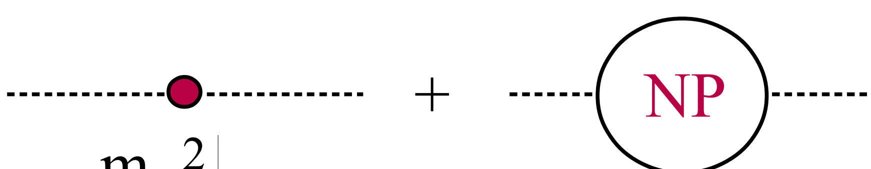
I. Electroweak hierarchy problem

Instability of the Higgs mass under quantum corrections → (*some*) New Physics (*coupled at least to* H & t) in the TeV domain



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

Introduction

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Natural (*fully dictated by gauge symmetry*)

Non-trivial UV imprints

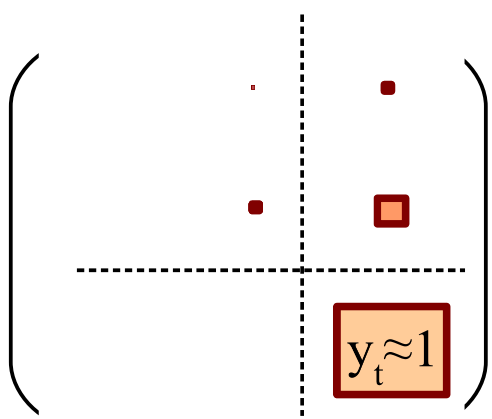
Un-natural aspects of the SM couplings

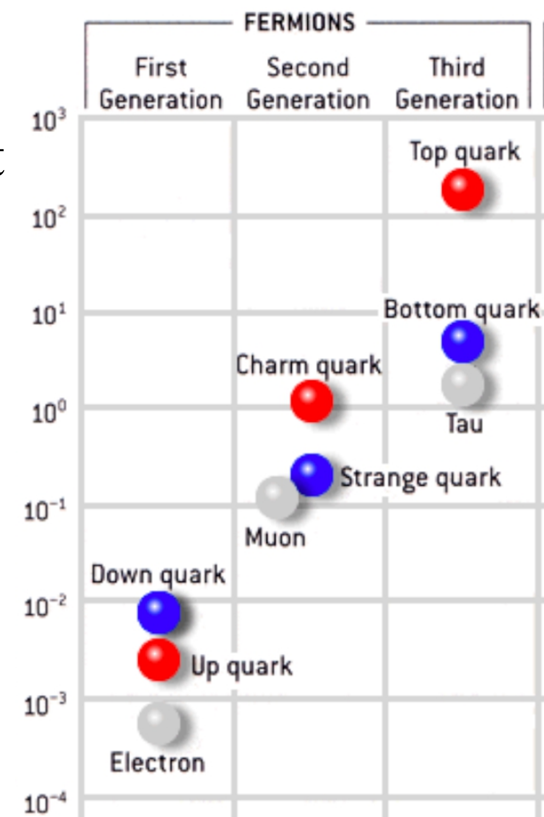
I. Electroweak hierarchy problem

II. Flavor problem

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

$Y_U \sim$





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Natural (*fully dictated by gauge symmetry*) → $\mathscr{L}_{\text{gauge}}$

Non-trivial UV imprints ($\mathscr{L}_{\text{Higgs}}$)

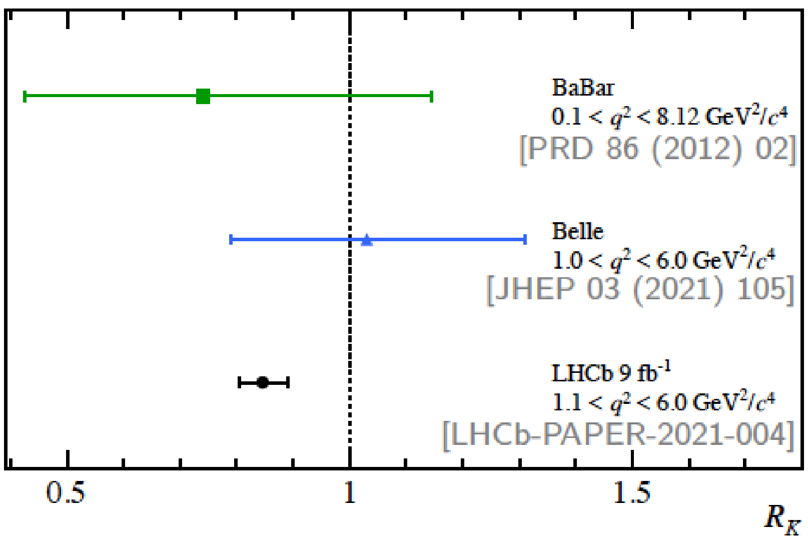
Un-natural aspects of the SM couplings

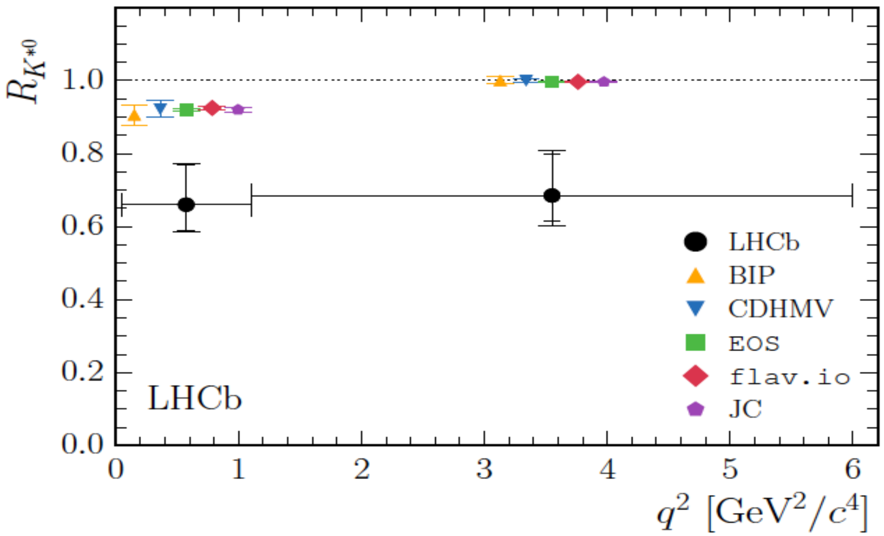
I. Electroweak hierarchy problem — *Instability of the Higgs mass under quantum corrections* → (*some*) New Physics in the TeV domain

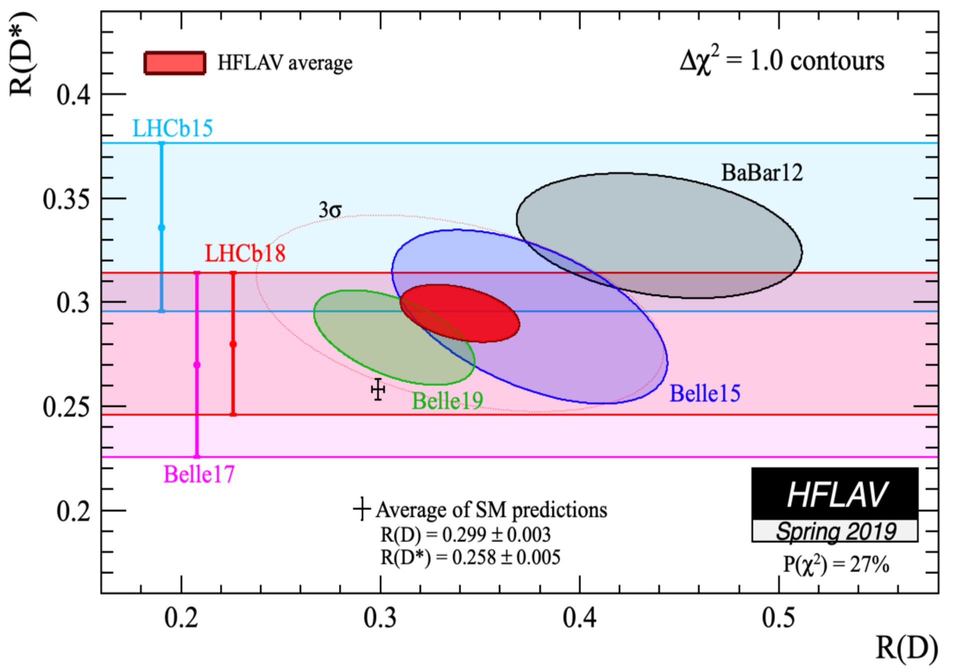
II. Flavor problem — *Un-natural hierarchies in the couplings describing fermion masses* → flavor non-universal dynamics (*at some energy scale*)

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

A closer look to the data







A closer look to the data

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

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge} + \mathscr{L}_{\rm Higgs}\Big|_{y_l = 0} \longrightarrow$$

accidental global symmetry:
3×3 (unitary) transformations of lepton fields in flavor space

A closer look to the data

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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

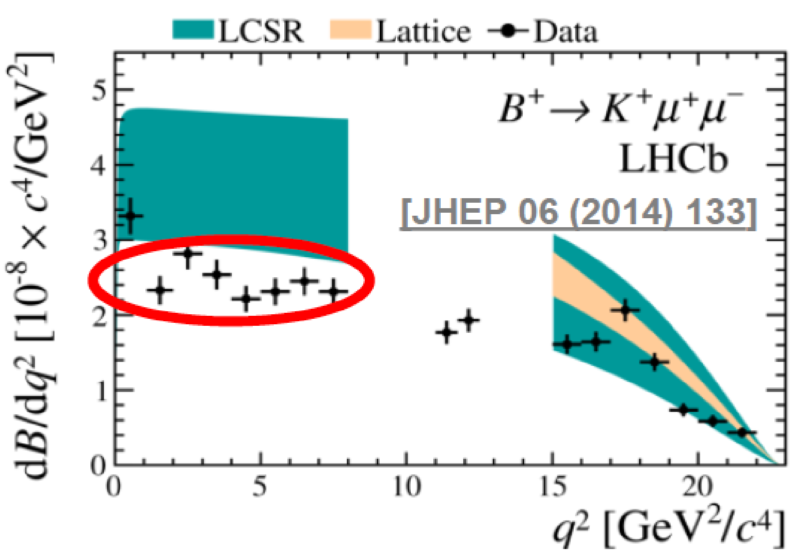
A closer look to the data

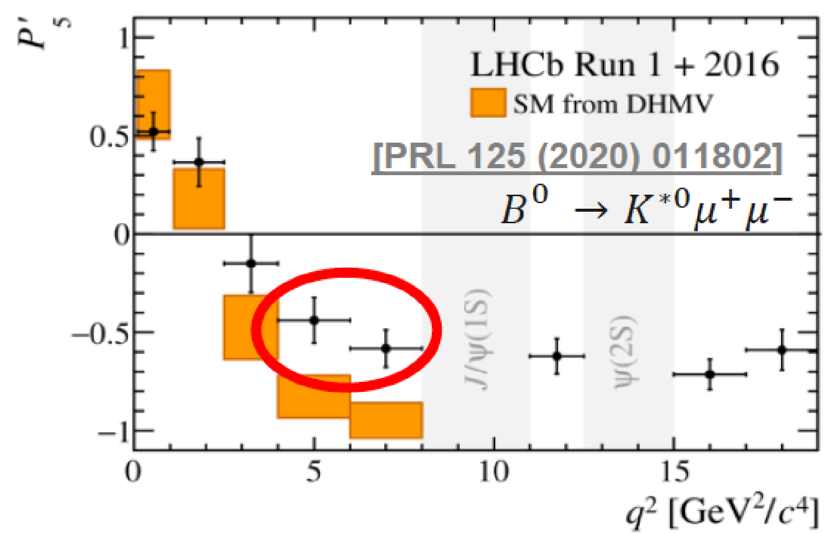
- $b \to s\, l^+ l^-$ (neutral currents)

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

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

chronological order





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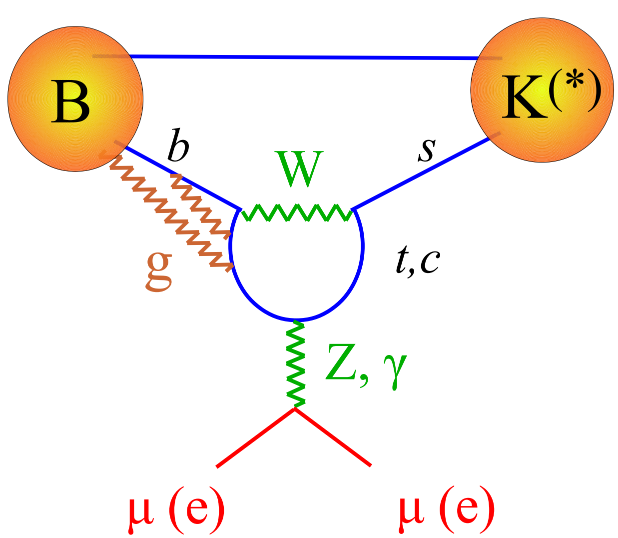
- LFU ratios (μ vs. e) in $B \rightarrow K^* \ell\ell$ & $B \rightarrow K\, \ell\ell$ — th. error <1%
- Smallness of BR($B_s \rightarrow \mu\mu$) — th. error few %



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

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

LHCb '21

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

A closer look to the data

To describe b → s*ll* decays we

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

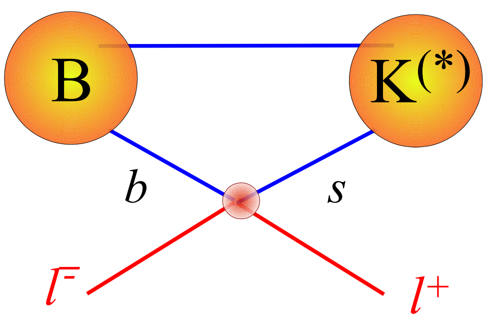
$$\mathcal{L}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \sum_i \mathcal{C}_i \mathcal{O}_i$$

FCNC operators:

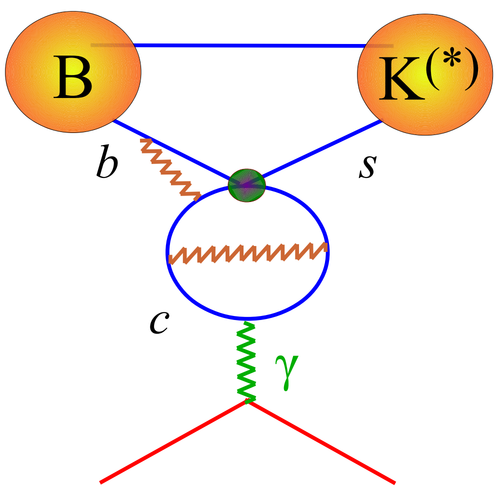
$$\mathcal{O}_{10}^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$
$$\mathcal{O}_9^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$$

Four-quark operators:

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



"easy" & "clean"



"difficult"

↓

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

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

A closer look to the data

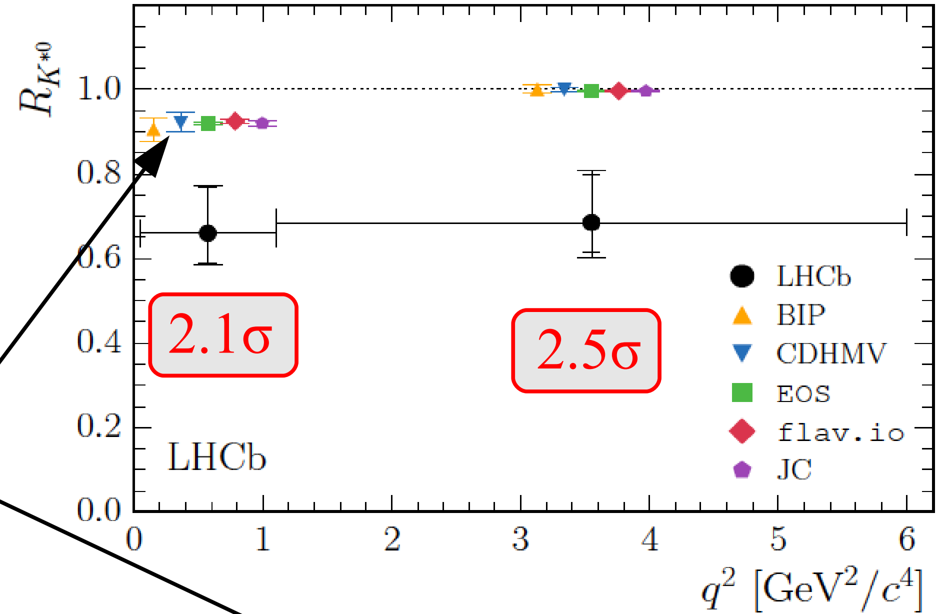
The LFU ratios:

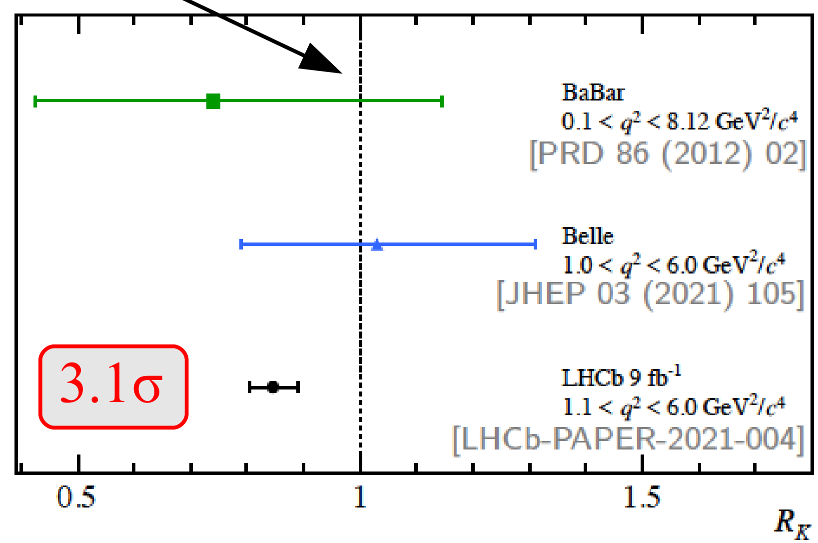
$$R_H = \frac{\int d\Gamma(B \to H\,\mu\mu)}{\int d\Gamma(B \to H\,ee)} \qquad (H = K, K^*)$$

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

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

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





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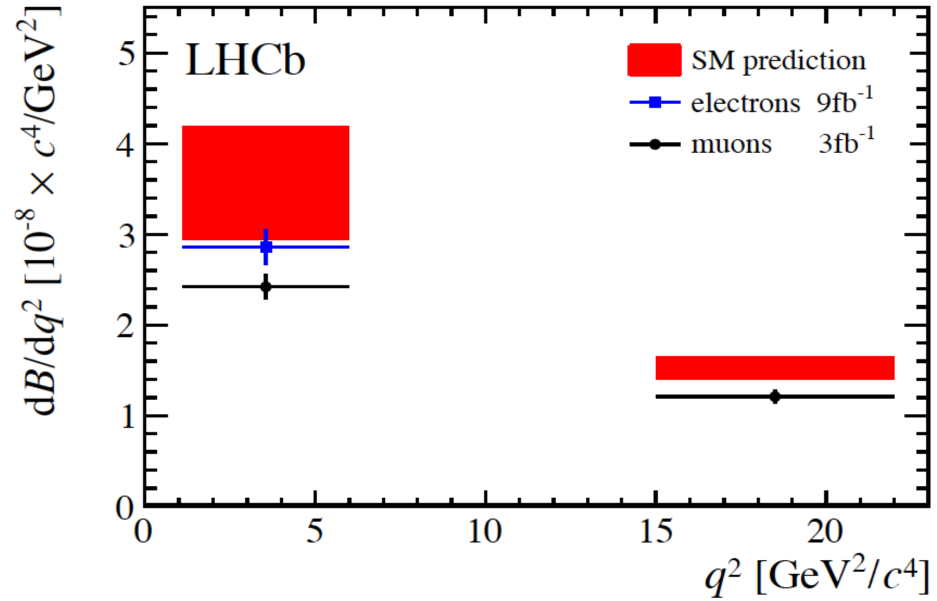
$B \to K\, ll$ LHCb '21



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

$B_s \to \mu\mu$:

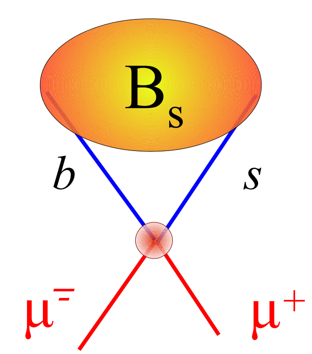
$$BR(B_s \to \mu\mu)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$

Beneke *et al.* '19

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

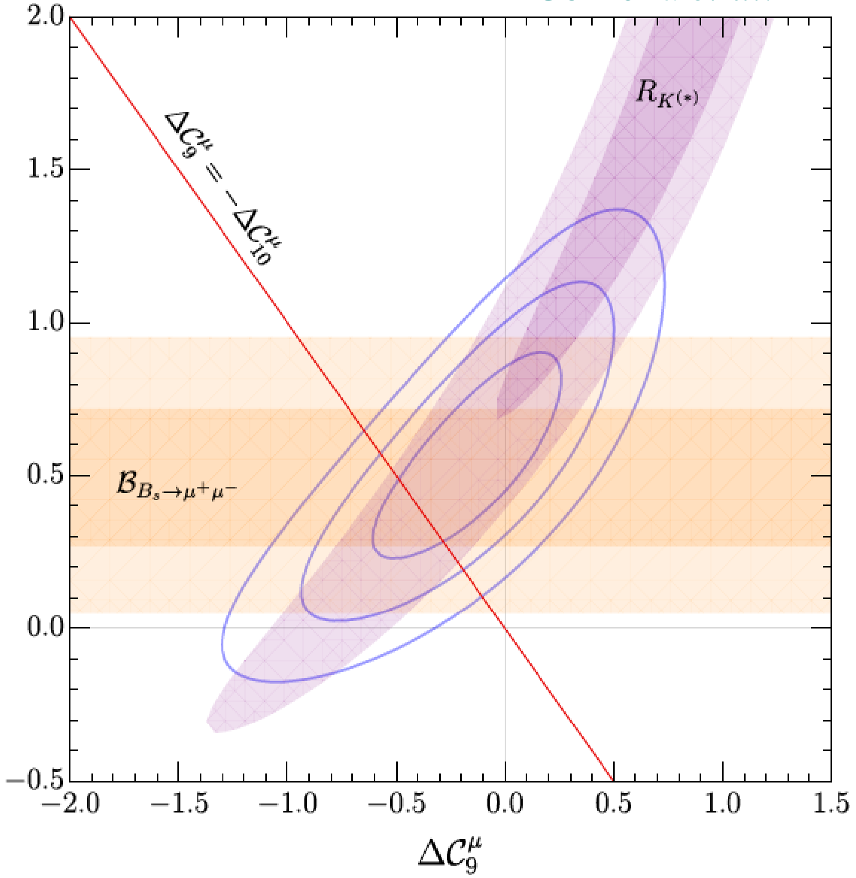
2.3σ

ATLAS+CMS+LHCb '21



A closer look to the data

Cornella *et al.* '21

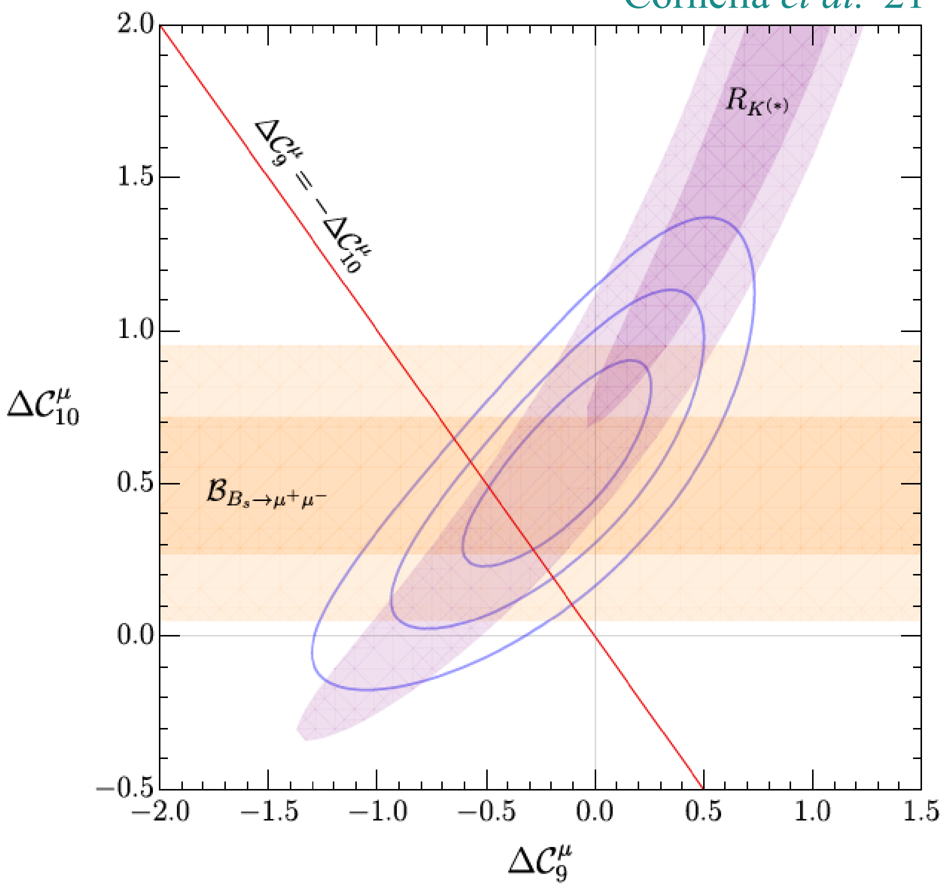


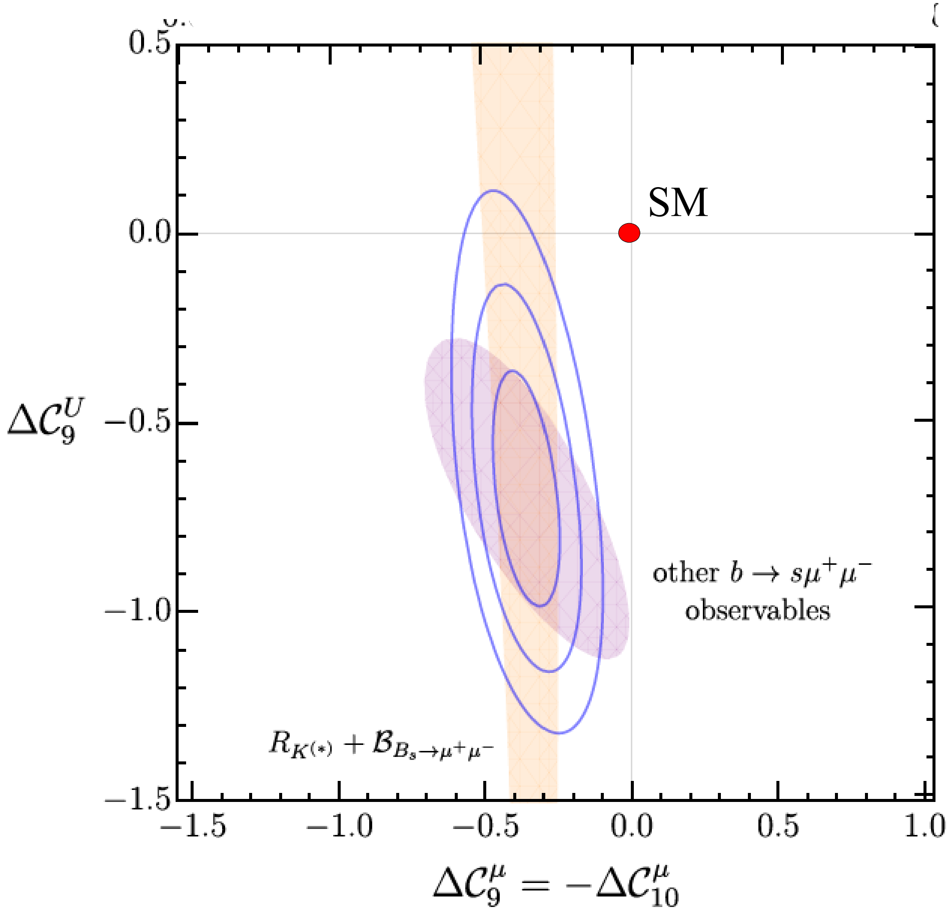
Conservative fit using "clean obs." only [$\Delta C_i^\mu = C_i^\mu - C_i^e$]:

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

A closer look to the data

Cornella *et al.* '21





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>> 5σ with current best estimate of charm contrib

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

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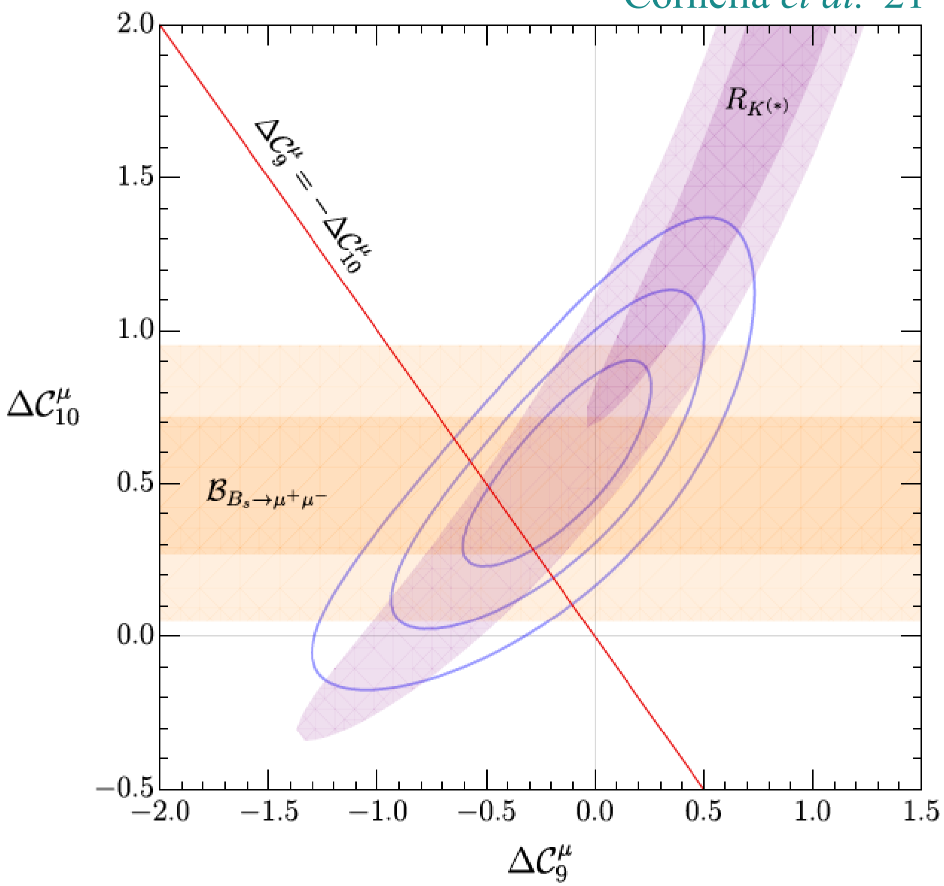

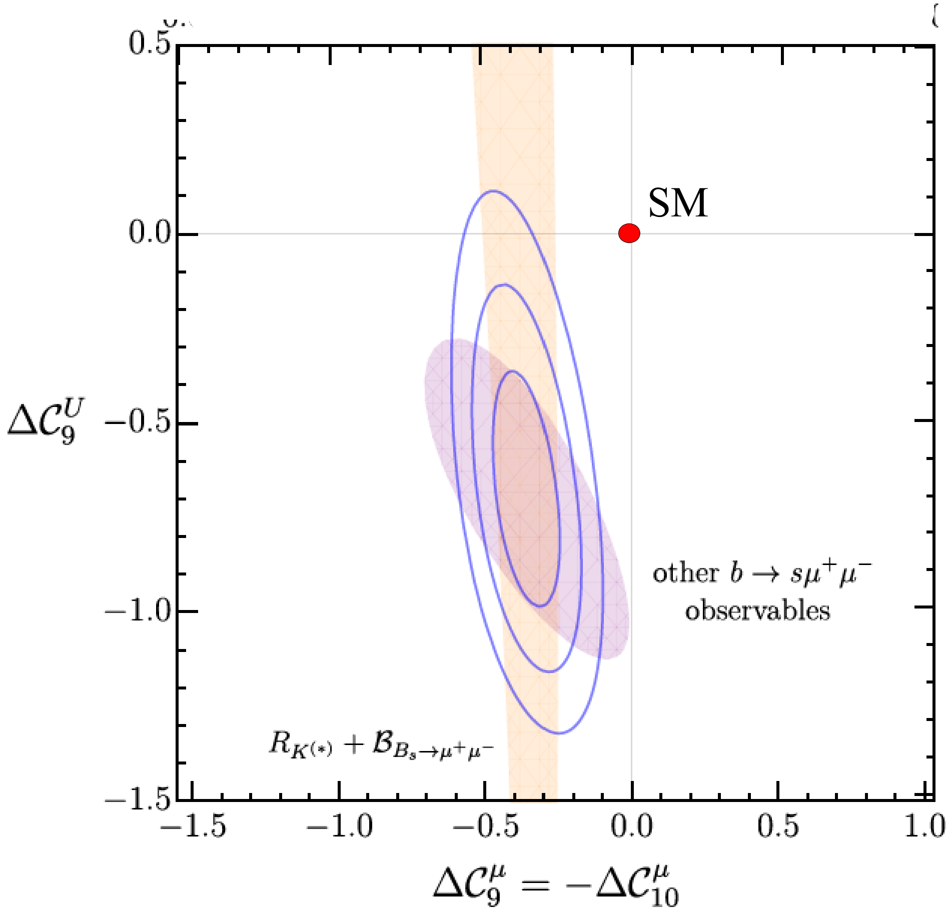

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Altmanshofer & Stangl '21

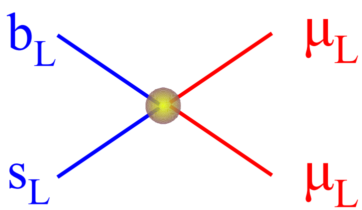
3.9σ *global significance* of NP (*very conserv. estimate*)

Lancierini, GI, Owen, Serra, '21

A closer look to the data

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

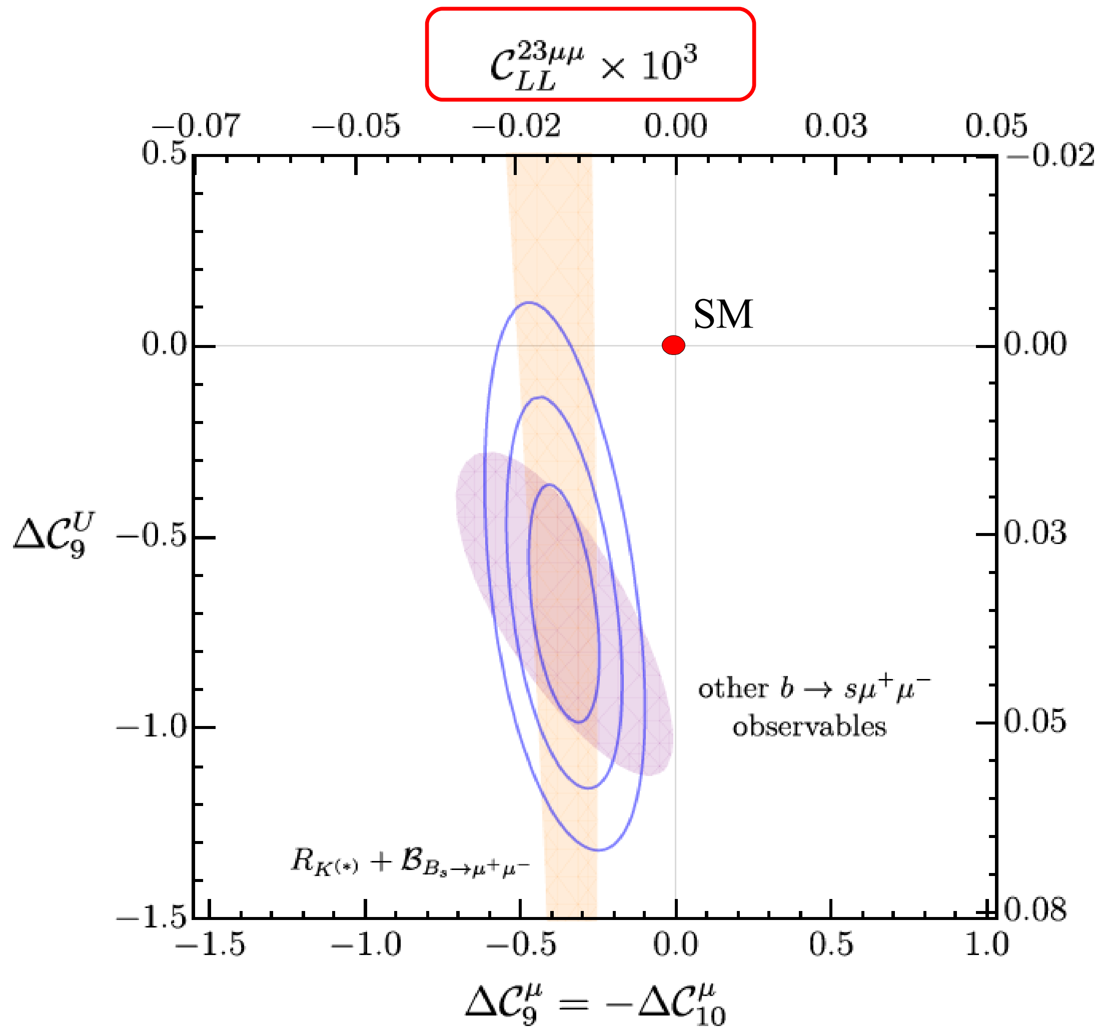
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)$$



$\sim 2\times10^{-5}\ G_{Fermi}$

super-weak interaction!

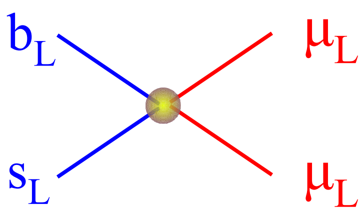
$C_{LL}^{23\mu\mu} \Rightarrow \Delta C_9^{\mu} = -\Delta C_{10}^{\mu}$



A closer look to the data

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

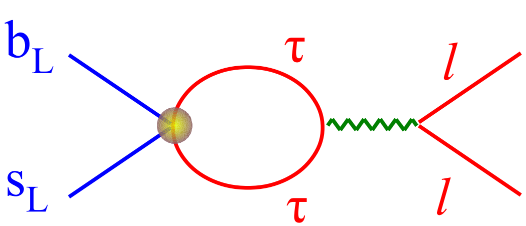
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)$$



$\sim 2\times10^{-5}\ G_{Fermi}$

super-weak interaction!

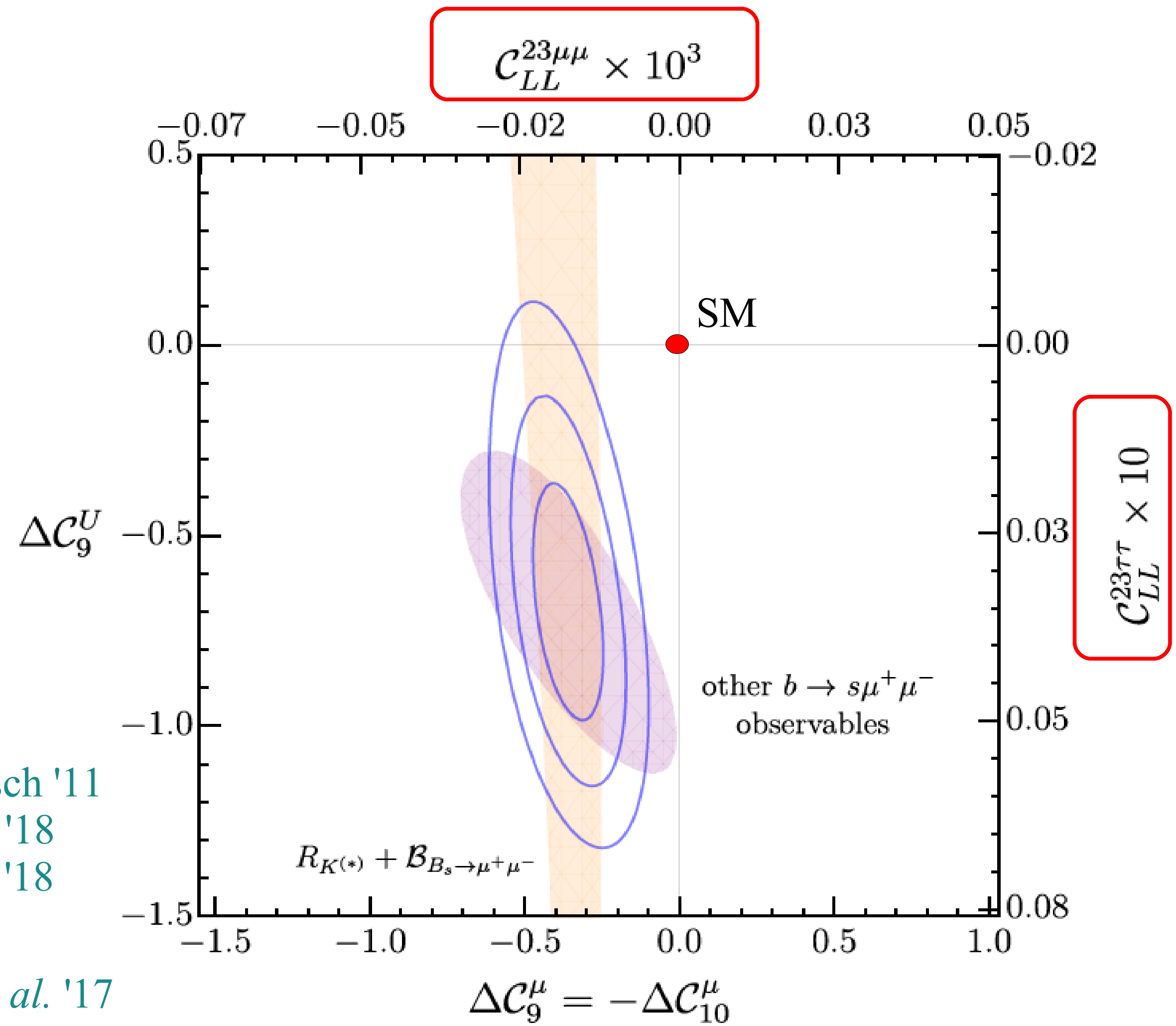
$C_{LL}^{23\mu\mu}$ ➡ $\Delta C_9^{\mu} = -\Delta C_{10}^{\mu}$



$C_{LL}^{23\tau\tau}$ ➡ ΔC_9^{Univ}

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

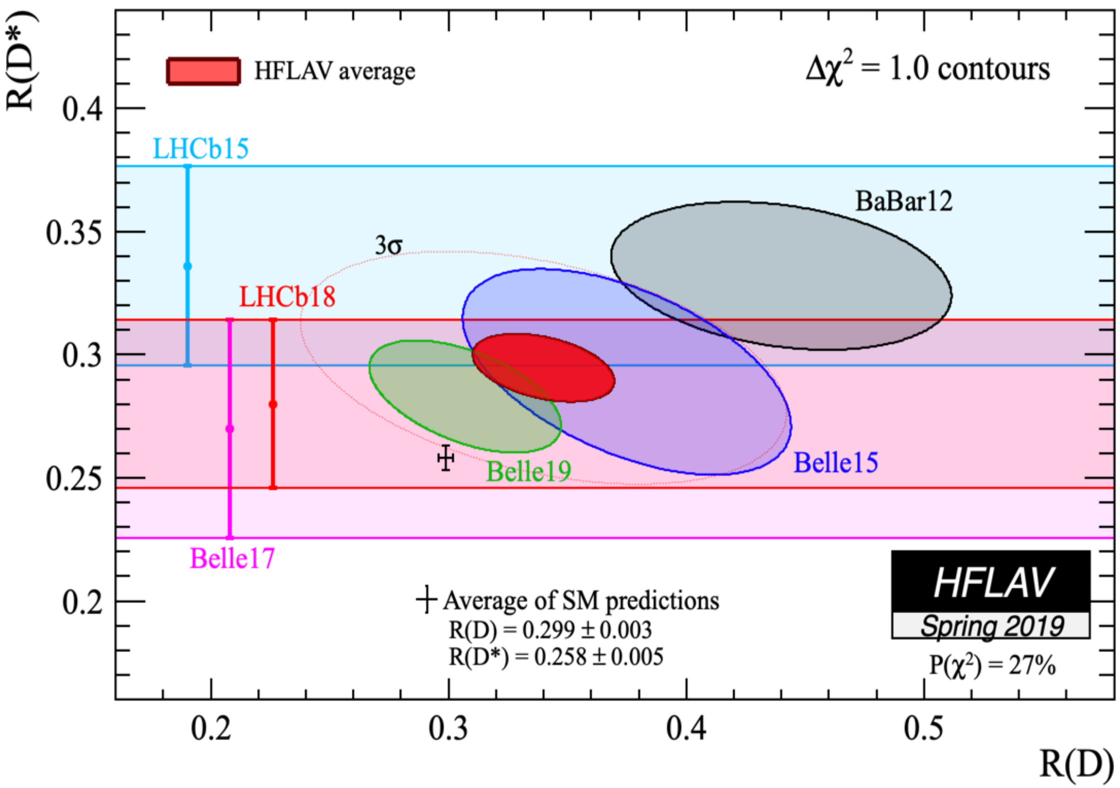
Link to CC anomaly Greljo *et al.* '17

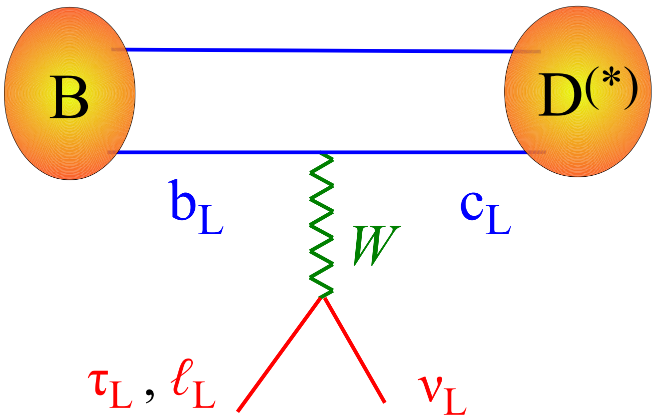


A closer look to the data

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

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



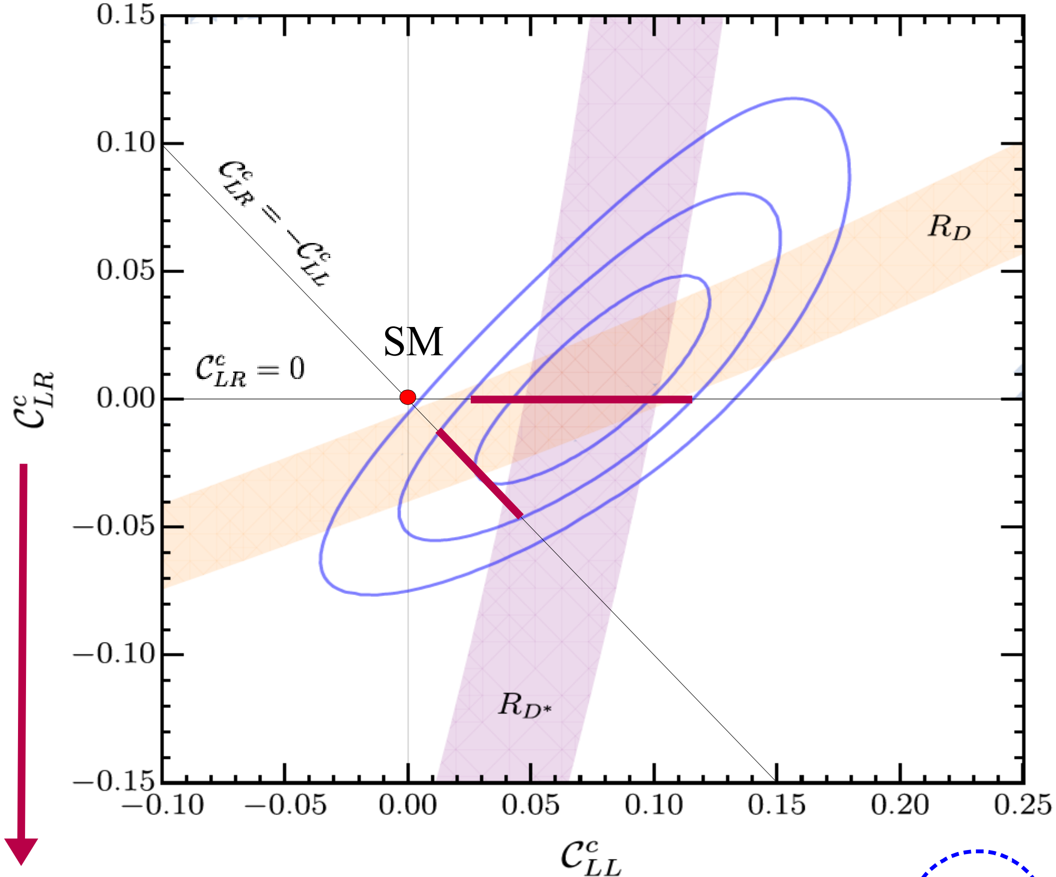


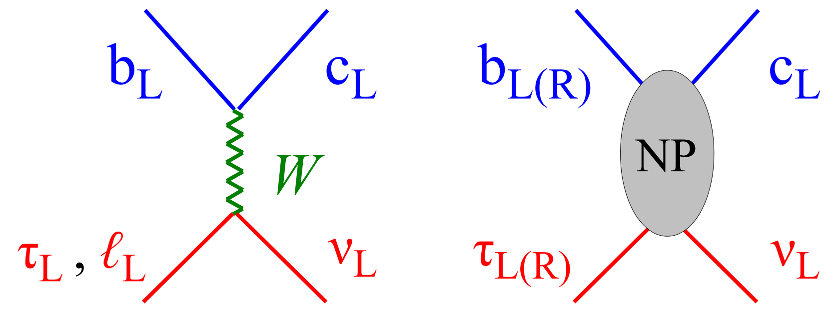
- Consistent results by three different exps. ~ 3.1σ excess over SM (*D and D* combined*)
- SM predictions quite "clean": hadronic uncertainties cancel (*to large extent*) in the ratios

A closer look to the data

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

Cornella *et al.* '21





Data consistent with a universal enhancement (10-20%) of τ modes

But other options (*RH currents*) possible

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

CKM "weighted mix" as for C^c_{LL}

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

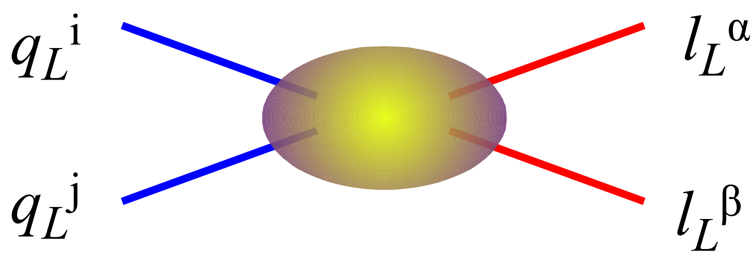
Same operator contributing to b → s *ll*

all 3rd gen. (contribute via CKM rotation)

EFT considerations

EFT considerations

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



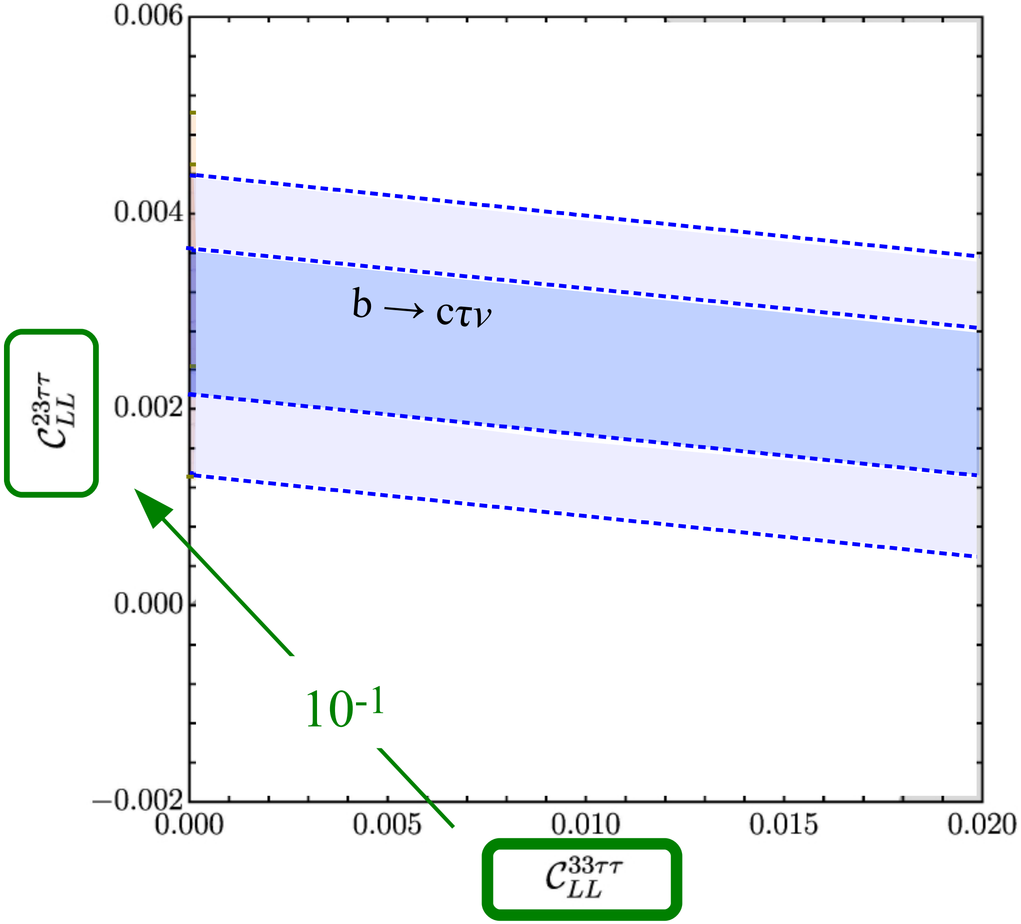
Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

- Large coupling [*competing with SM tree-level*] in $bc \to l_3 \nu_3$ [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



charged-currents only:

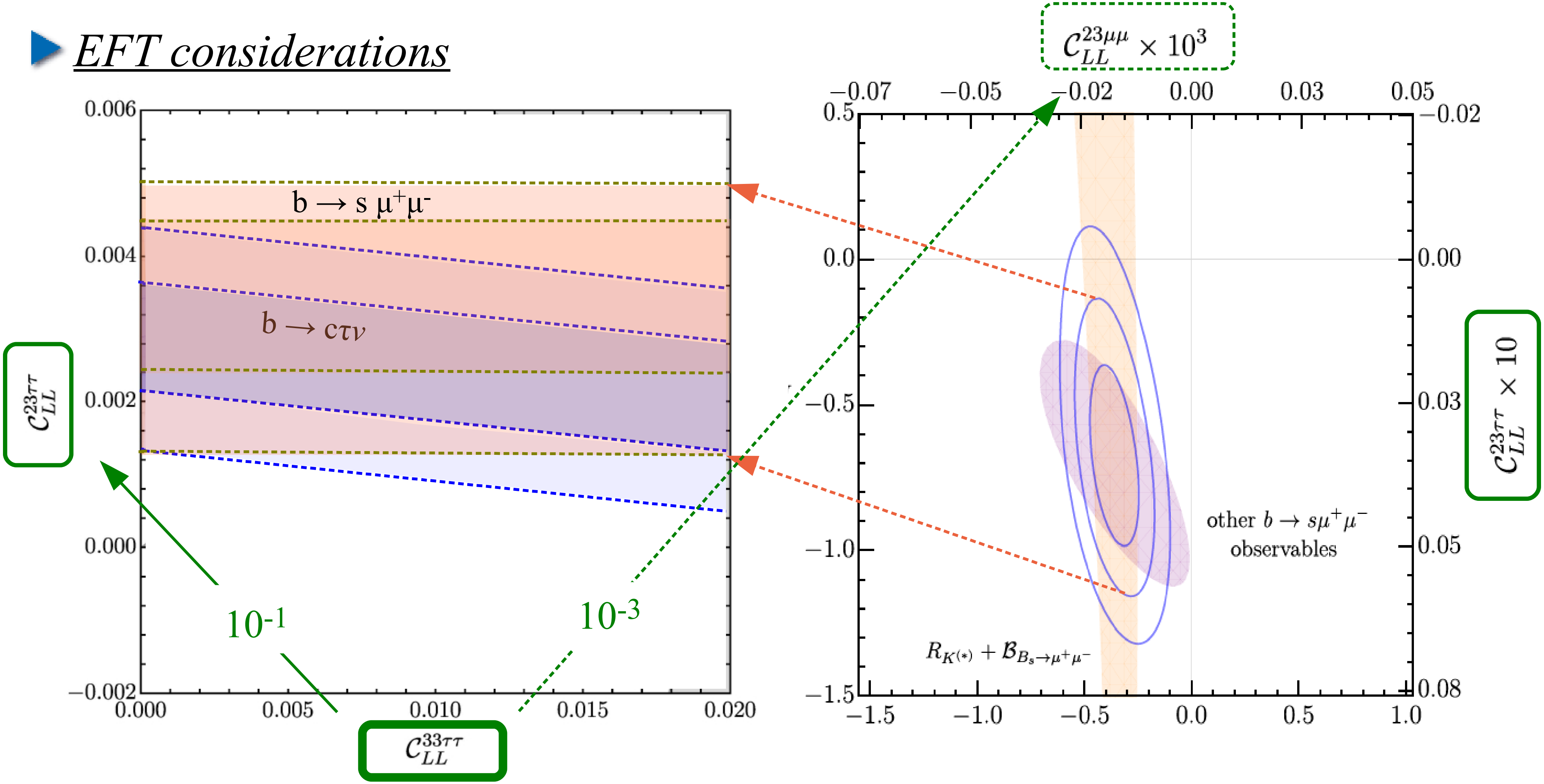
$$\frac{V_{cb}\,\mathcal{C}^{33\tau\tau}_{LL} + V_{cs}\,\mathcal{C}^{23\tau\tau}_{LL}}{V_{cb}}$$

Pattern emerging from data:

$$\mathcal{O}^{ij\alpha\beta}_{LL} = (\bar{q}^i_L \gamma_\mu \ell^\alpha_L)(\bar{\ell}^\beta_L \gamma_\mu q^j_L)$$

- ✔ $O(10^{-1})$ suppress. for each 2nd gen. q_L or l_L [*recall* $|V_{ts}| \sim 0.4\times10^{-1}$]

EFT considerations



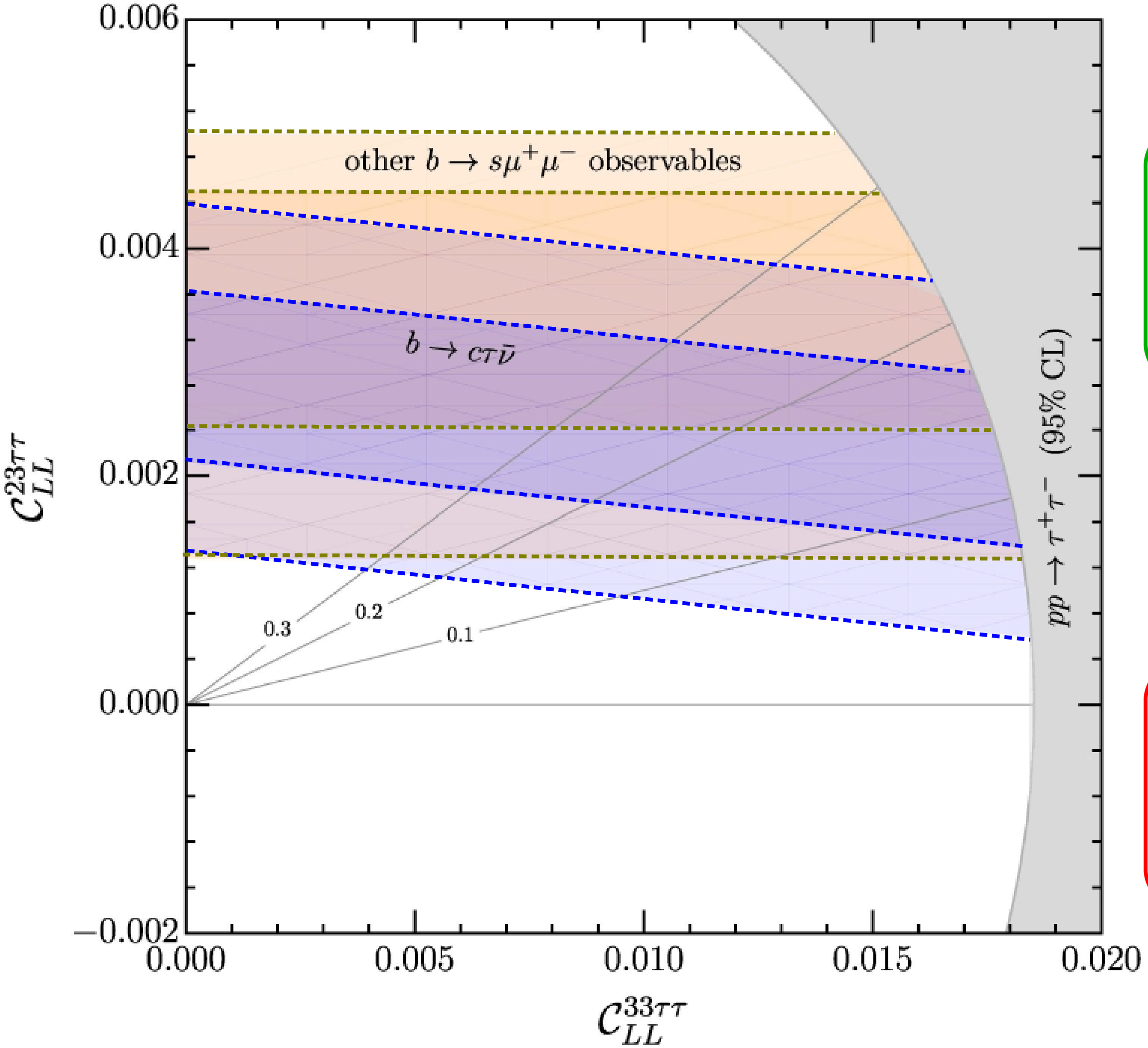
Pattern emerging from data:

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

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

▶ *EFT considerations*

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



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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)

EFT considerations

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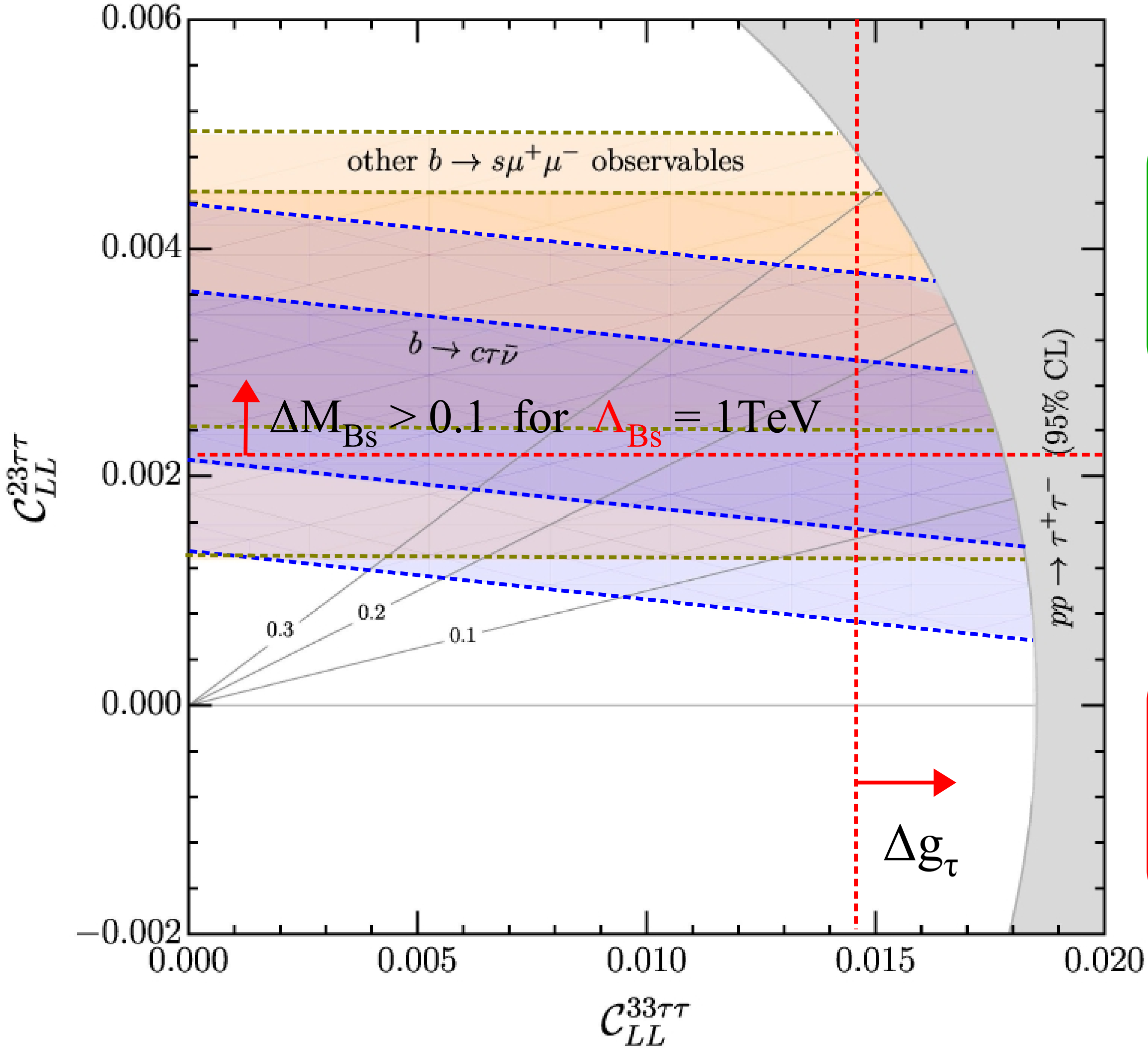

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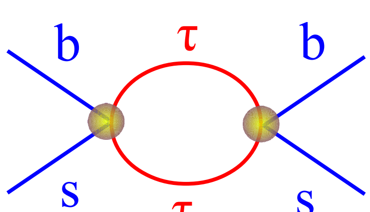
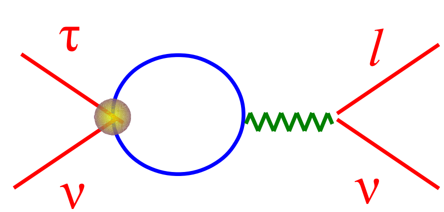


$\Delta M_{Bs} \sim (C^{23\tau\tau})^2\, \Lambda_{Bs}^{\ 2}$

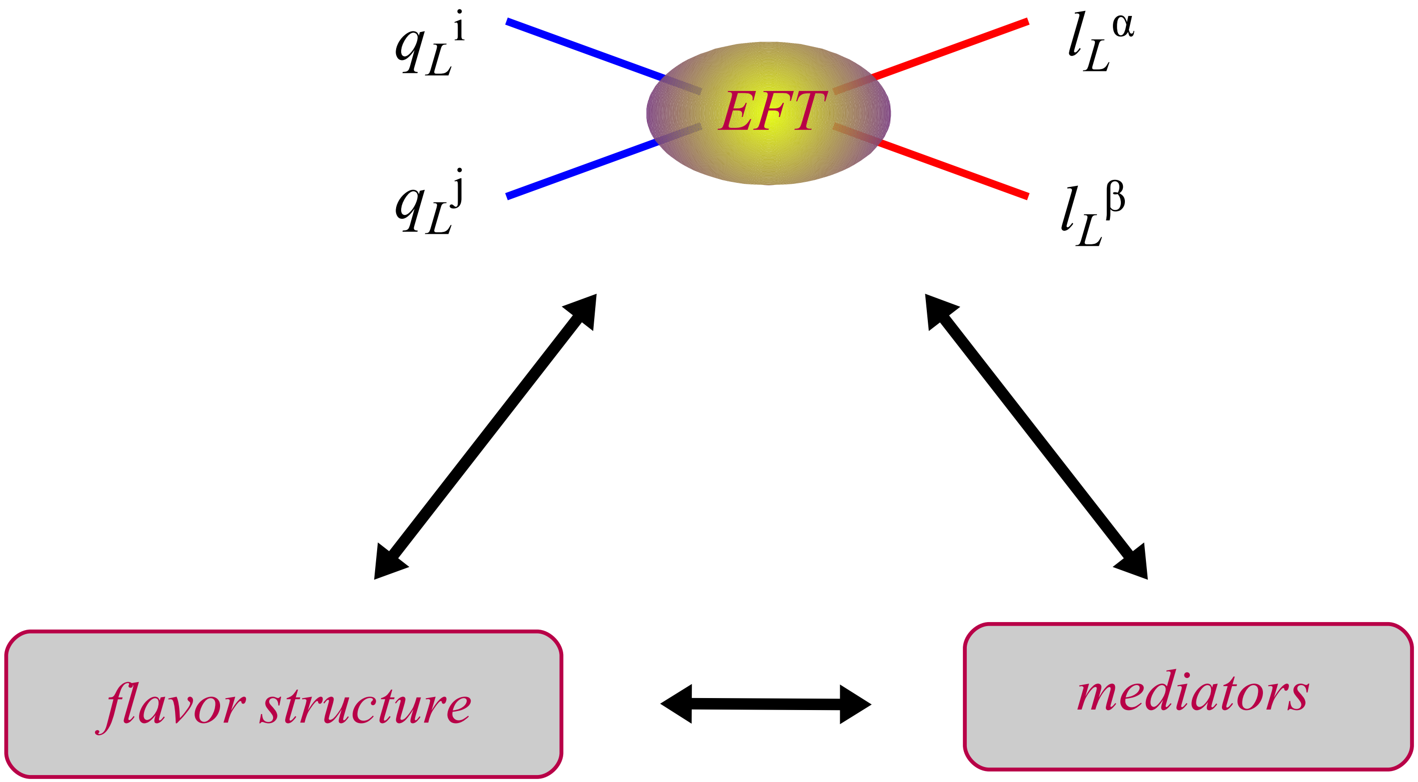


$\Delta g_\tau \sim (C^{33\tau\tau})\log(\Lambda/m_t)$

From EFT to simplified models

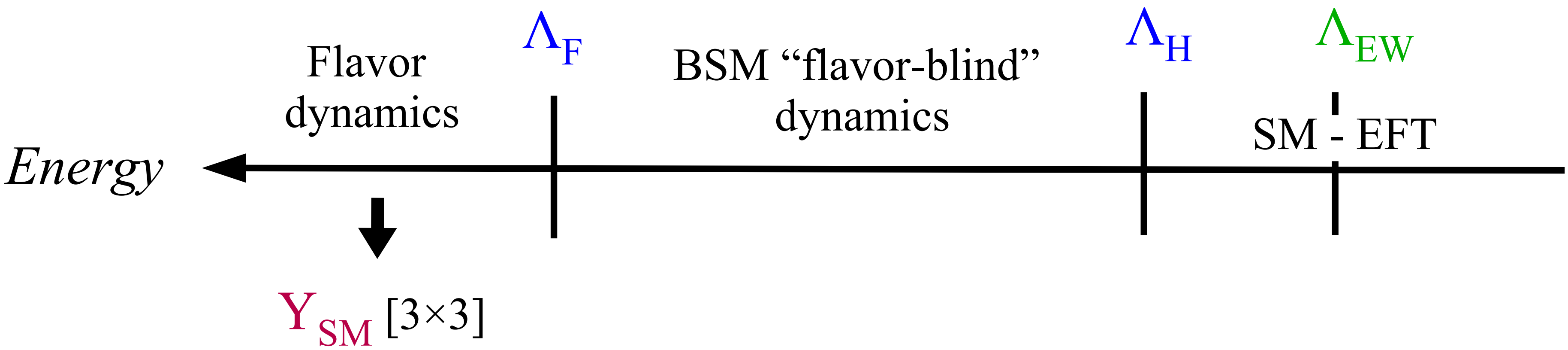
From EFT to simplified models

To move from the EFT toward more complete/ambitious models, we need to address two general aspects: the *flavor structure* of the underlying theory, and the nature of the possible *mediators*



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

The MFV paradigm:



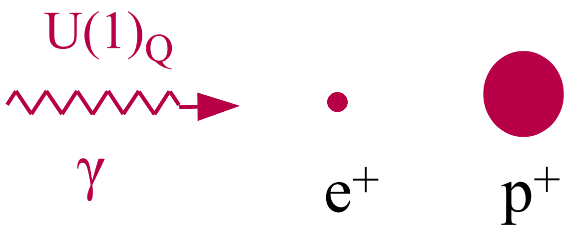
Main idea:

- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavor problem → 3 gen. = "identical copies" up to high energies

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

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

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



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

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

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

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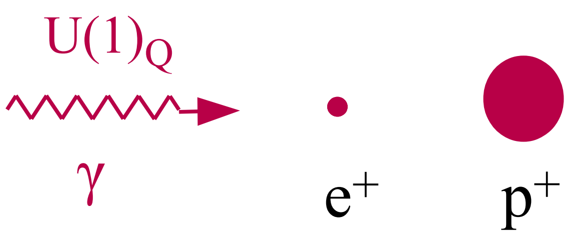
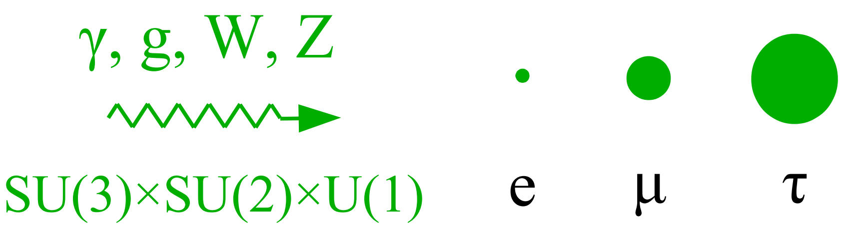


we would conclude that these two particles are "identical copies" but for their mass ...

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



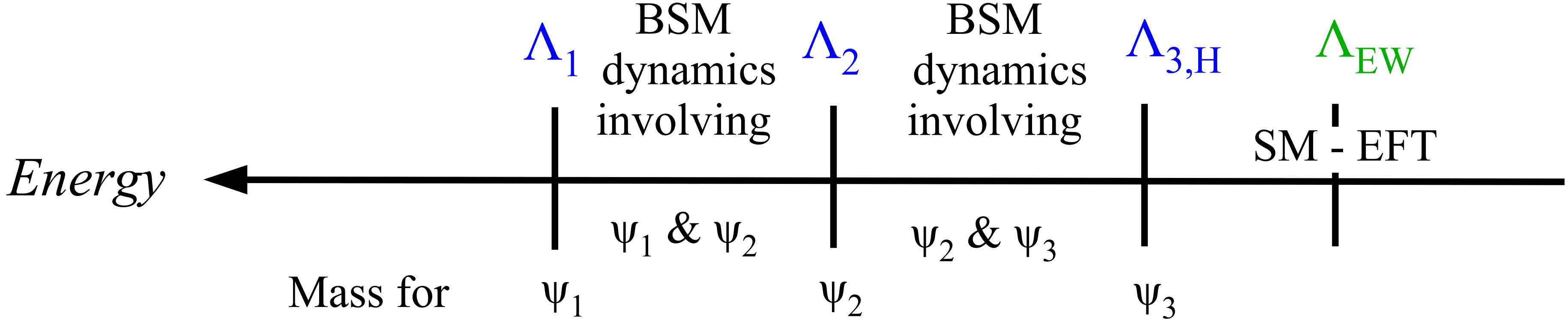
These three (families) of particles seems to be "identical copies" but for their mass ...

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

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

~~The MFV paradigm~~:

Multi-scale picture @ origin of flavor:



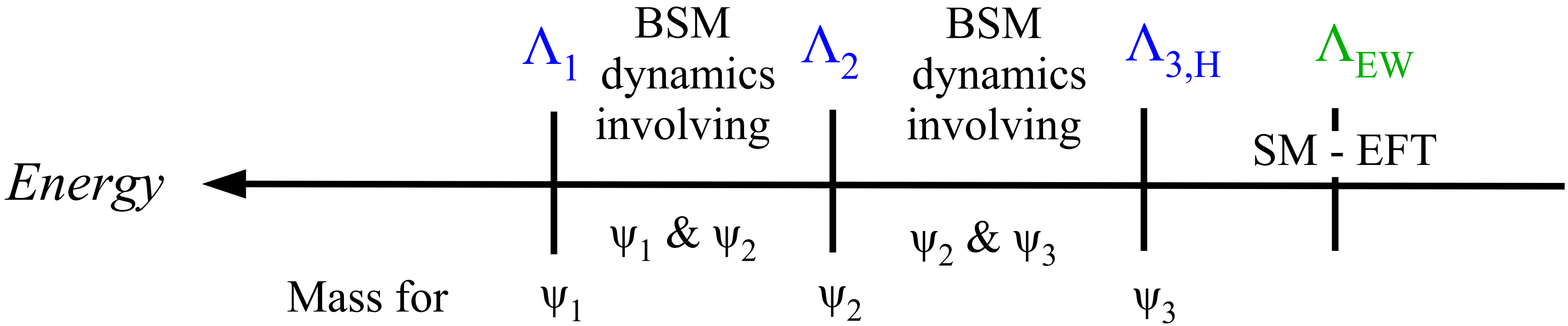
Main idea:

- 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*]

~~*The 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:

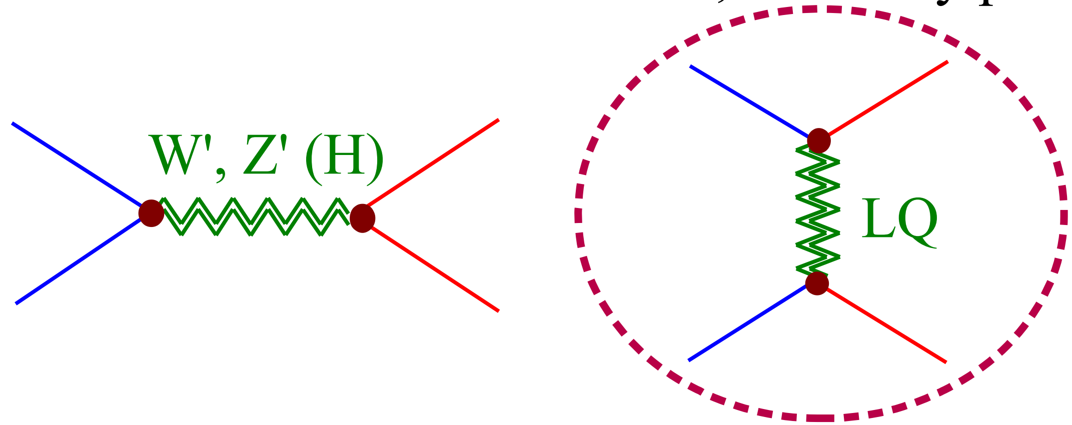
- Flavor non-universal interactions already at the TeV scale:
- 1^{st} & 2^{nd} gen. have small masses because they are coupled to NP at heavier scales

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

Non-trivial UV imprints

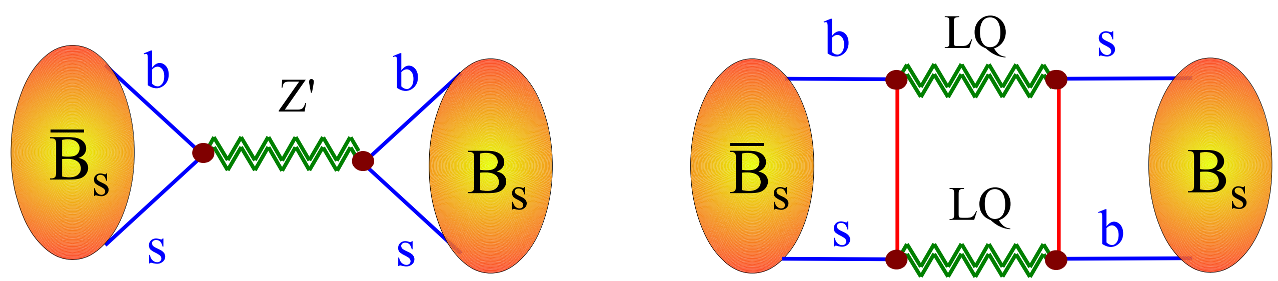
From EFT to simplified models [*the possible mediators*]

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...



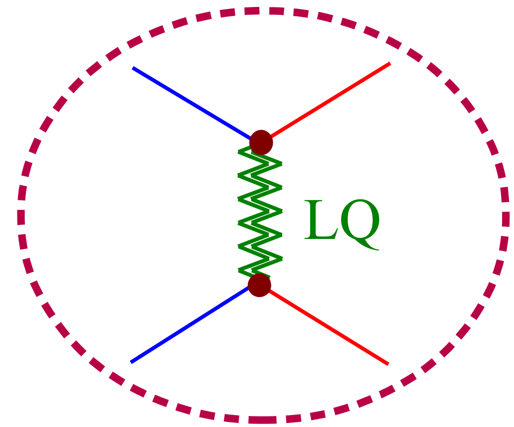
LQ (both scalar and vectors) have two general strong advantages with respect to the other mediators:

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



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

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



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

- Could mediate proton decay → not a general feature of the LQ: it depends on the model...! [*e.g. not the case in the Pati-Salam model*]
- Severe bounds from processes involving 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...*):

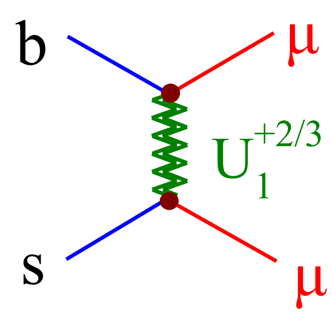
- Scalar LQ as PNG
  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
  Marzocca '18
- Scalar LQ from GUTs & R̸ SUSY
  Hiller & Schmaltz, '14; Becirevic *et al.* '16, Fajfer *et al.* '15-'17; Dorsner *et al.* '17; Crivellin *et al.* '17; Altmannshofer *et al.* '17 Trifinopoulos '18, Becirevic *et al.* '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 + ...

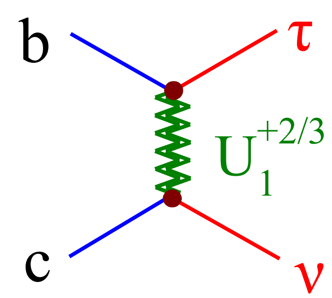
From EFT to simplified models [*the possible mediators*]

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 $3^{rd} \to 1^{st}, 2^{nd}$ gen.)

LQ of the Pati-Salam gauge group:

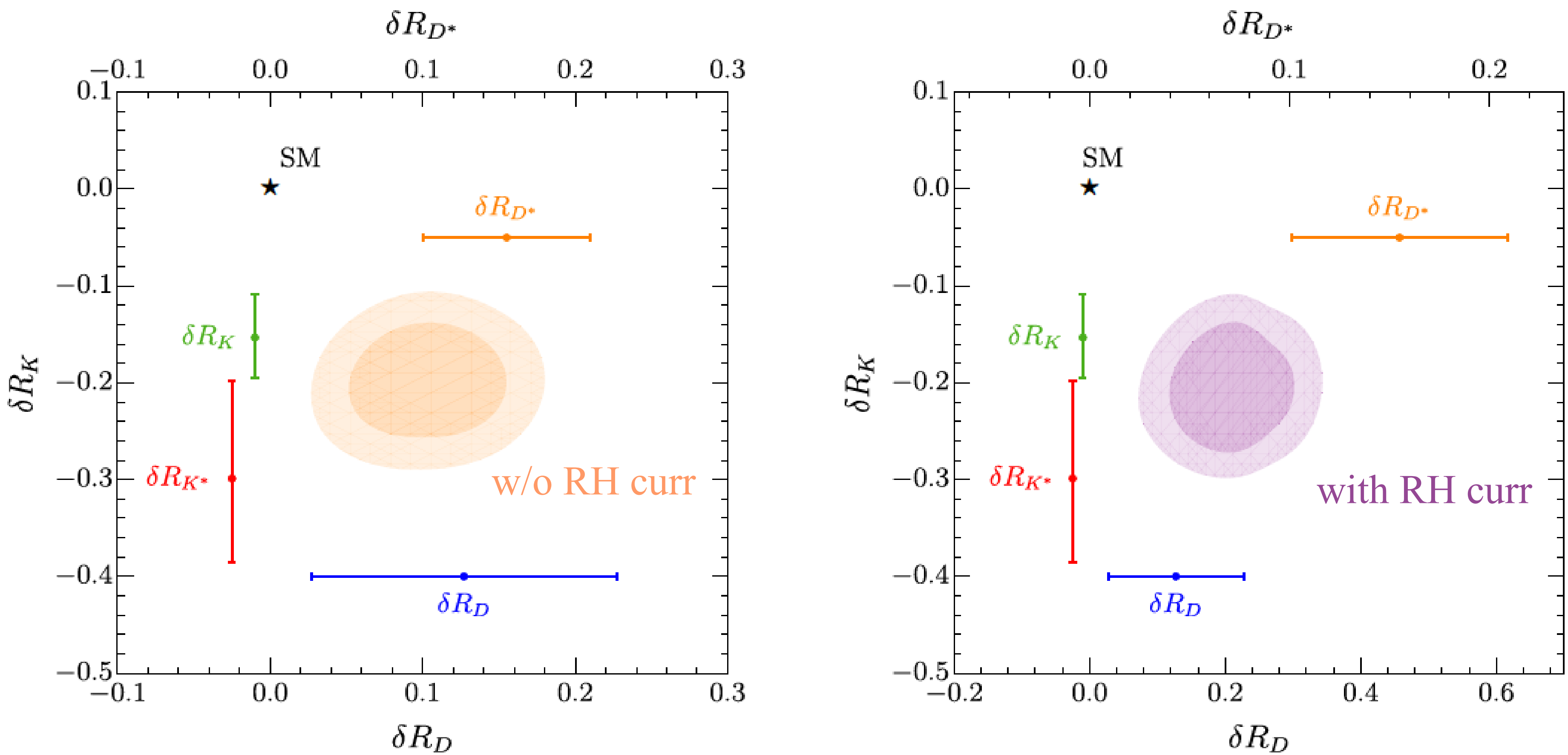
$SU(4) \times SU(2)_L \times SU(2)_R$

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:



▶ <u>*From EFT to simplified models*</u> [*the possible mediators*]

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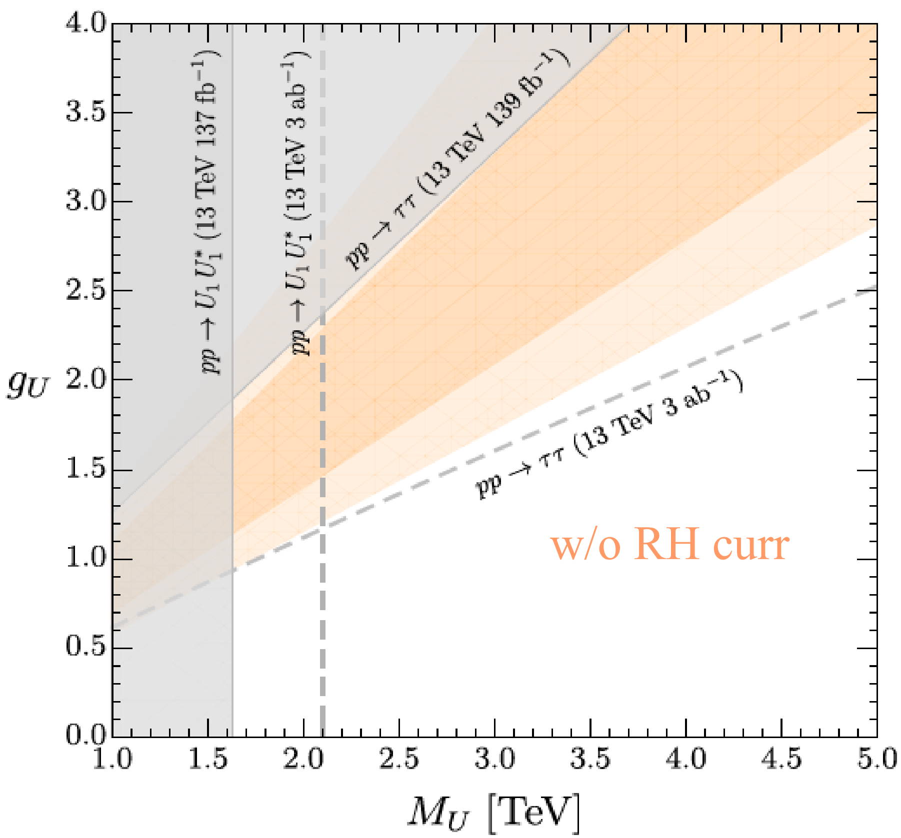
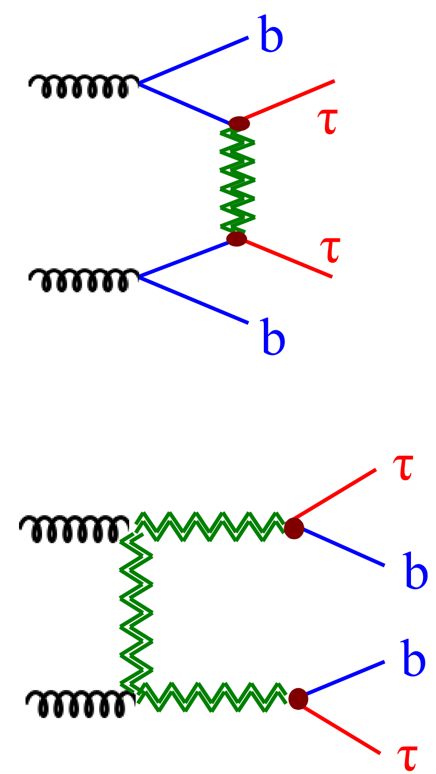
and fitting <u>all low-energy data</u> leads to an excellent description of present data which is fully <u>consistent with high-pT searches</u> [*within the reach of HL-LHC*]:





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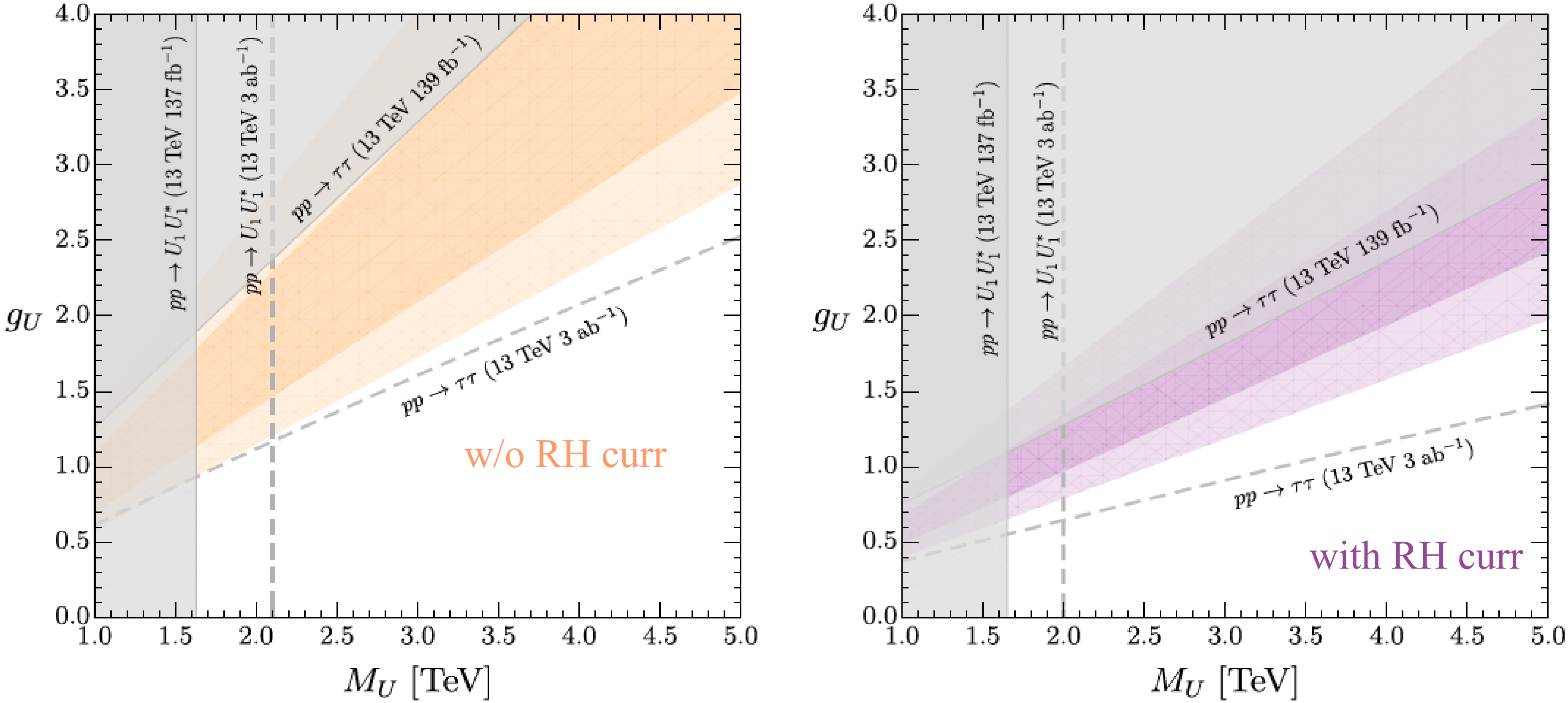
Cornella, Fuentes-Martin, Faroughi, GI, Neubert, '21



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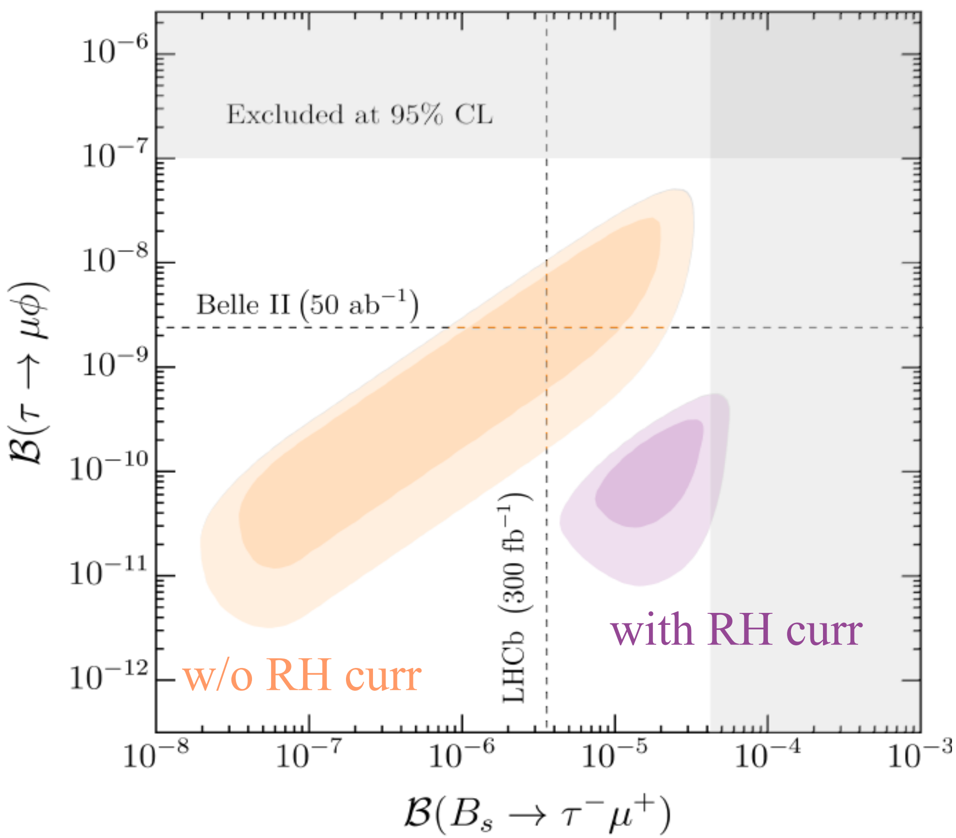
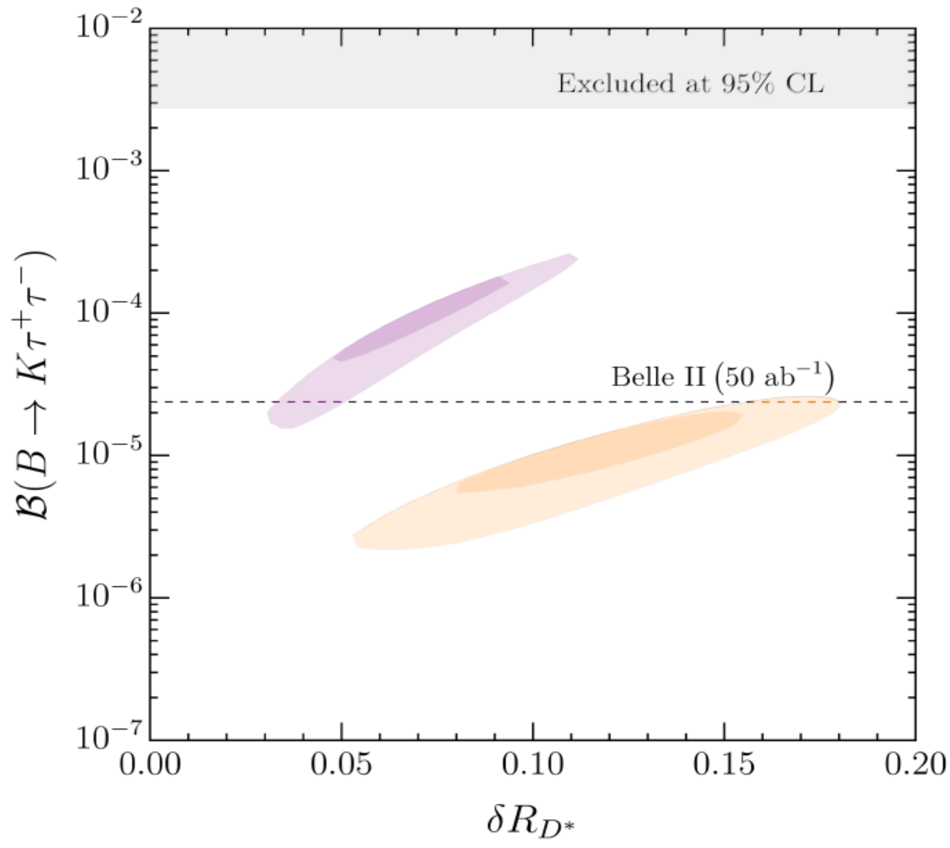
and fitting all low-energy data leads to an excellent description of present data which is fully consistent with high-pT searches, and has interesting implications for future low-energy searches:

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





Speculations on UV completions

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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):

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

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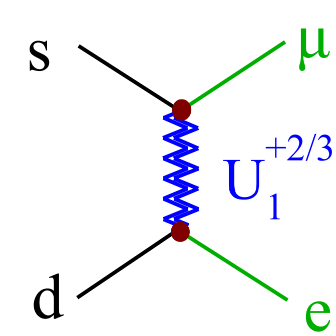
The massive LQ [U_1] arise from the breaking $SU(4) \to SU(3)_C\times U(1)_{B-L}$

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

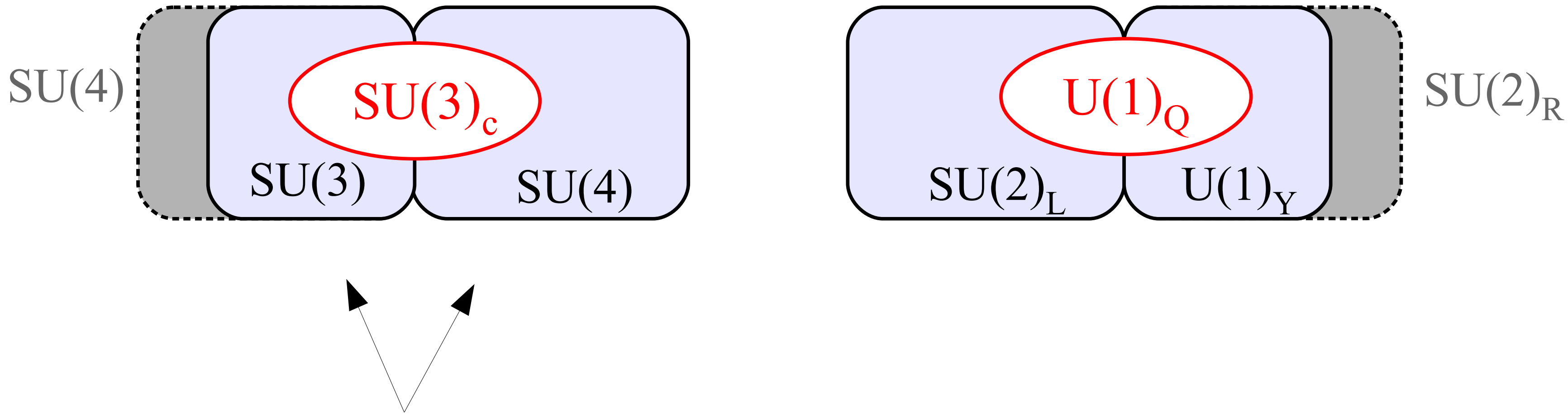


Speculations on UV completions

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

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

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



This separation is not flavor blind

Speculations on UV completions

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

- *Non-universality via mixing*

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

- *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

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

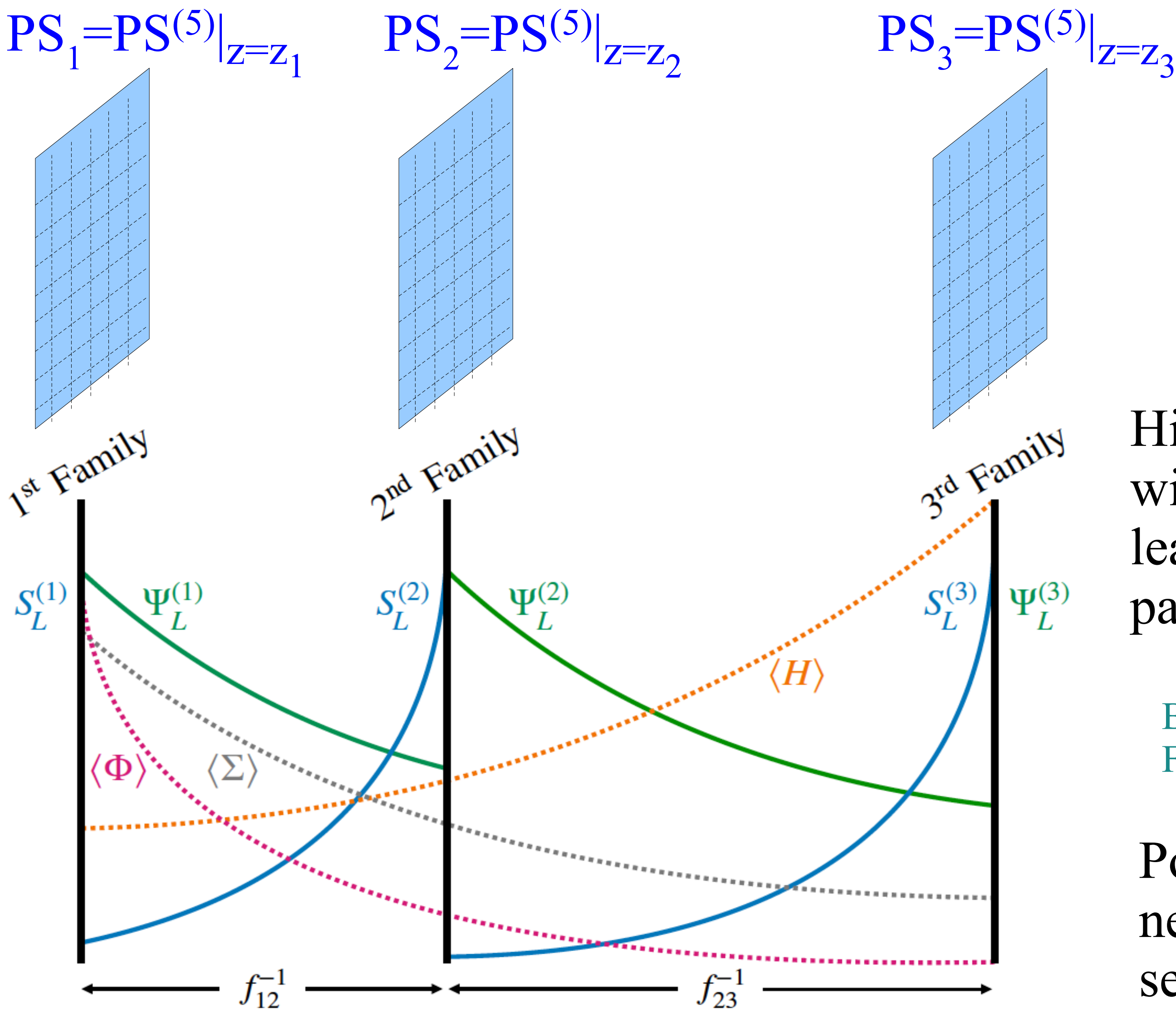
Bordone *et al.* '17

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

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

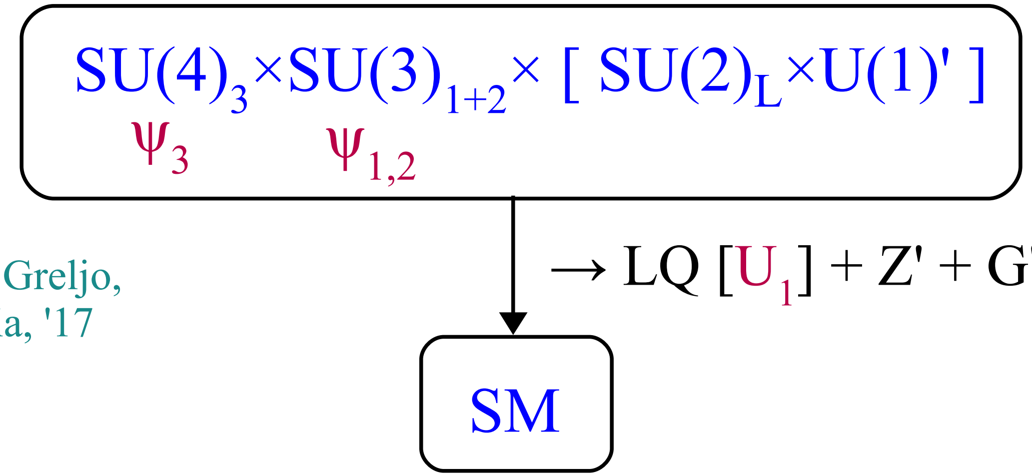
Bordone, Cornella, Fuentes-Martin, GI '17
Fuentes-Martin, GI, Pages, Stefanek '20

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

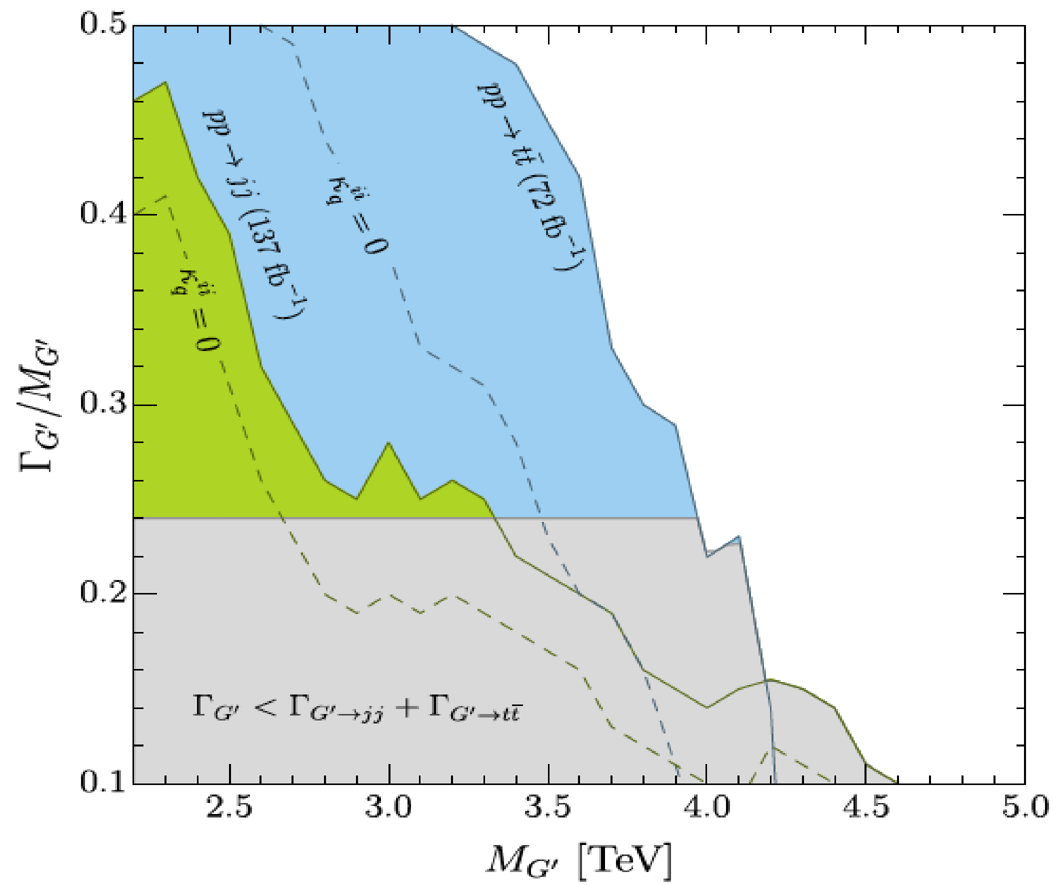
Di Luzio, Greljo, Nardecchia, '17



Despite the apparent complexity, the construction is highly constrained

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

} *consistent with present data !*

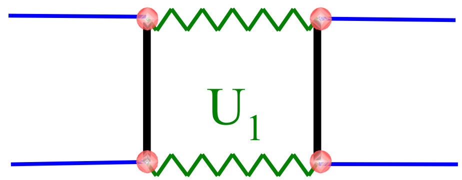


New striking collider signature:
G' ("*coloron*" = *heavy color octet*)

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

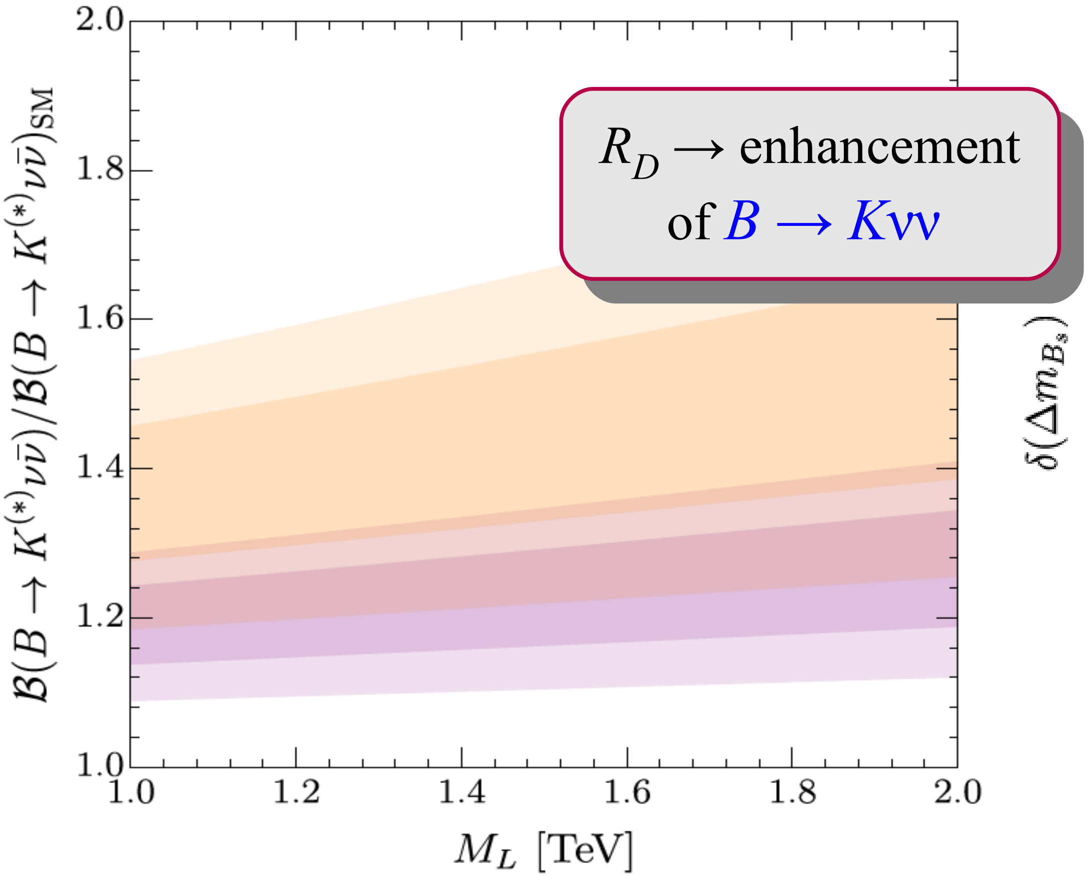
Speculations on UV completions

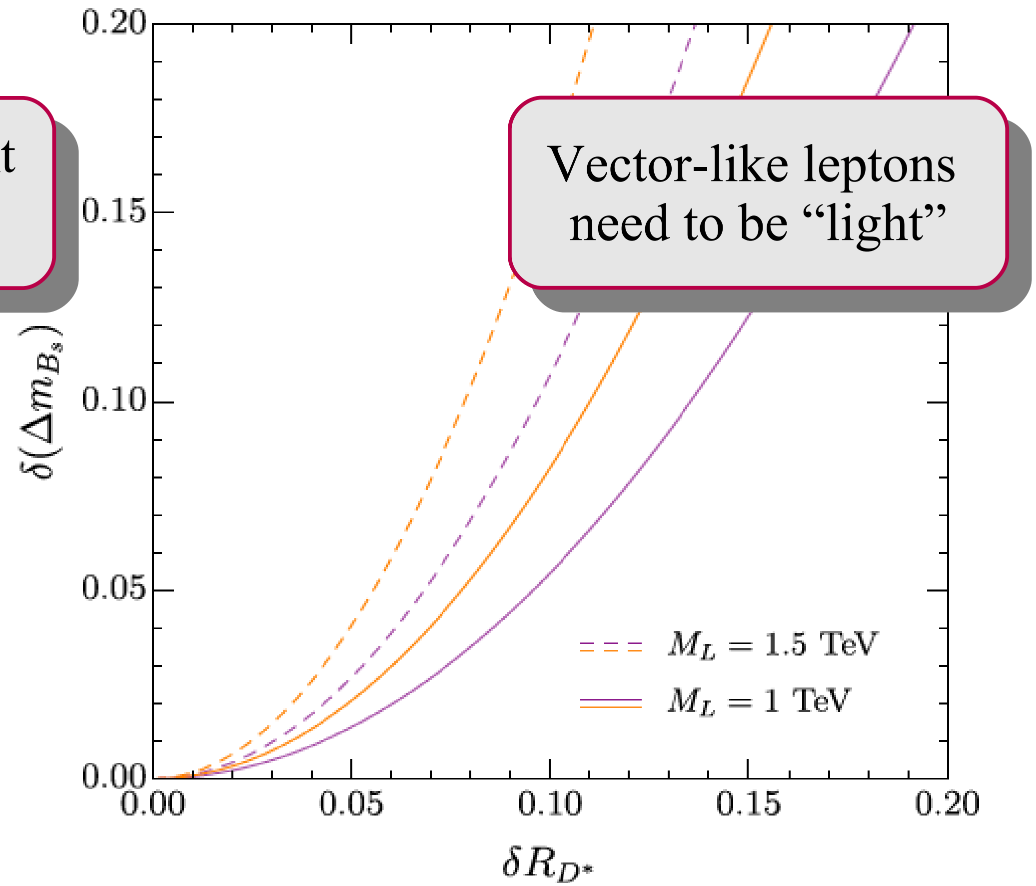
UV-sensitive observables in 4321 models



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

B) B_s mixing [ΔF=2]





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

Conclusions

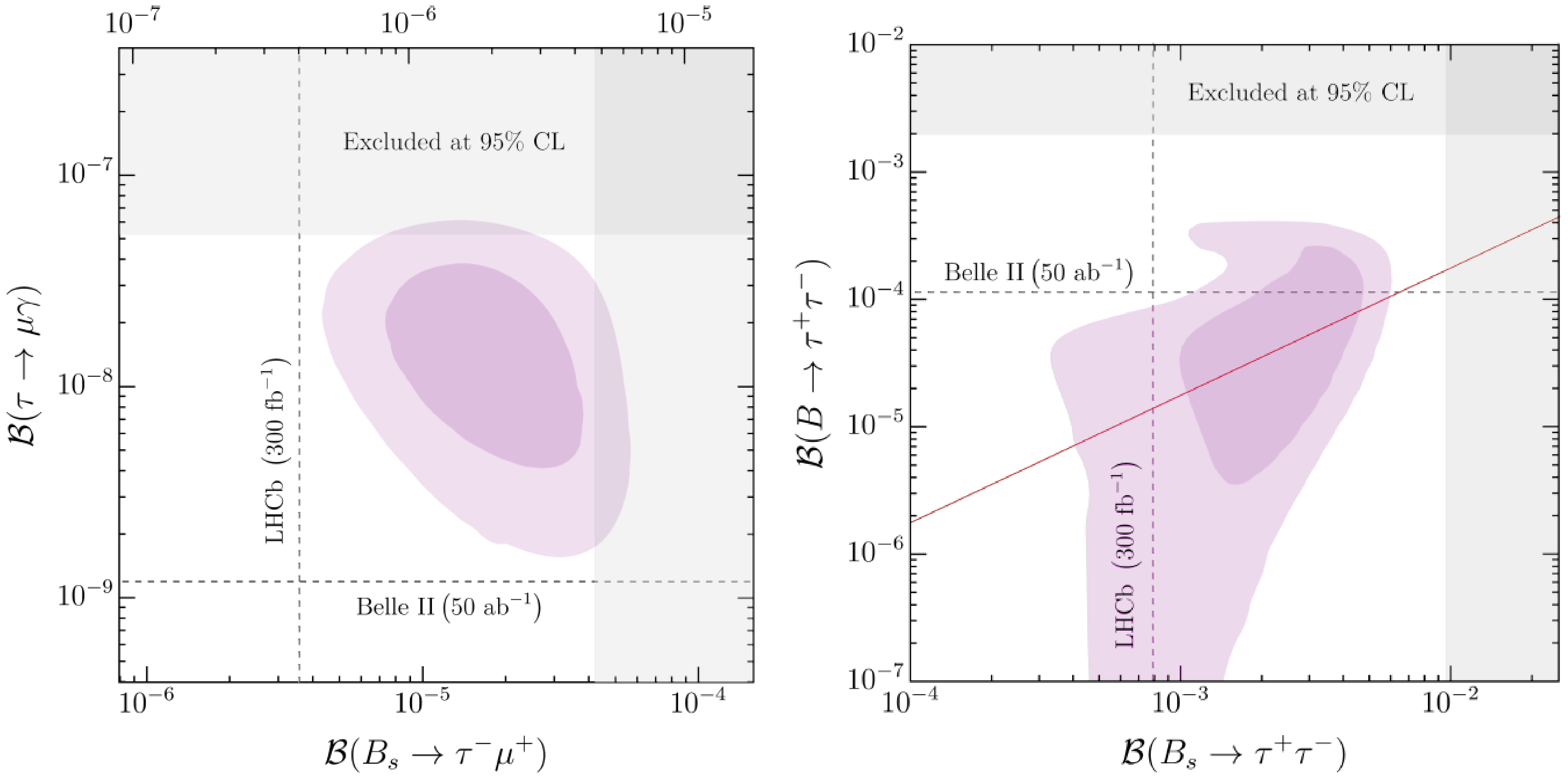
- The statistical significance of the LFU anomalies is growing: in the $b \to s\ell\ell$ system the chance this is a pure statistical fluctuation is marginal...
- If combined, the two sets of anomalies point to non-trivial flavor dynamics around the TeV scale, involving mainly the 3rd family → connection 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)

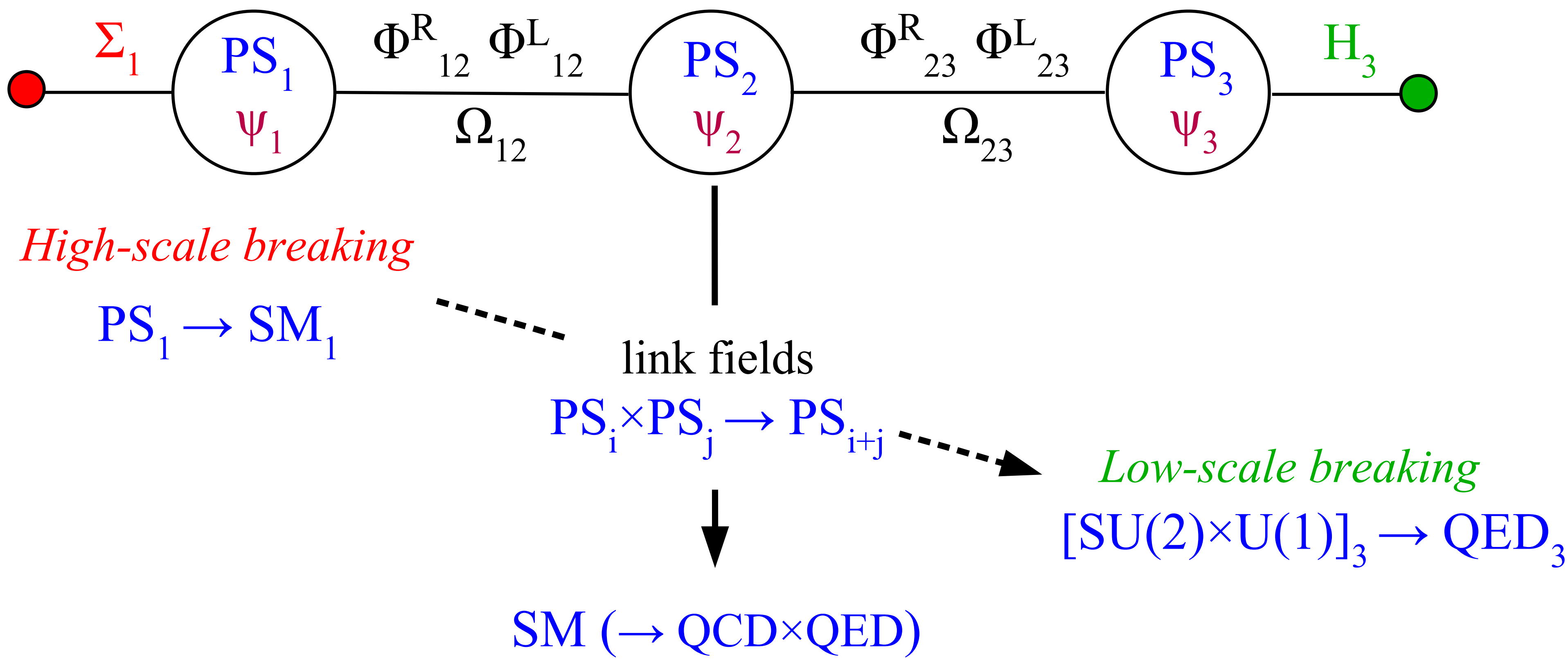

Backup

Other low-energy observables



Speculations on UV completions

The PS^3 set-up: Bordone, Cornella, Fuentes-Martin, GI, '17



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

Speculations on UV completions