Introduction to (quark) flavor physics

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[*University of Zürich*]

Part I

- Introduction [*the SM as an effective theory*]
- The flavor problem(s)
- Flavor symmetries [accidental *or fundamental?*]

Part II

- The LFU anomalies
- EFT considerations on the anomalies
- A possible new paradigm in flavor physics

- Conclusions

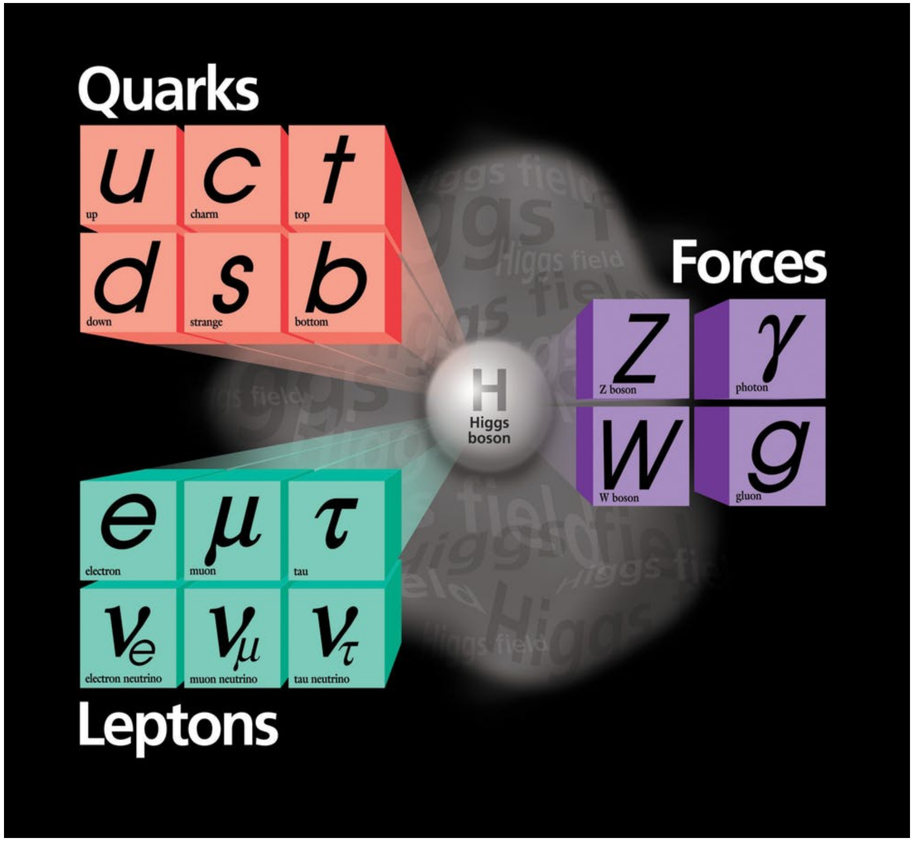
University of Zurich[UZH]

European Research Council
Established by the European Commission

Introduction

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

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



Introduction

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

⬇

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

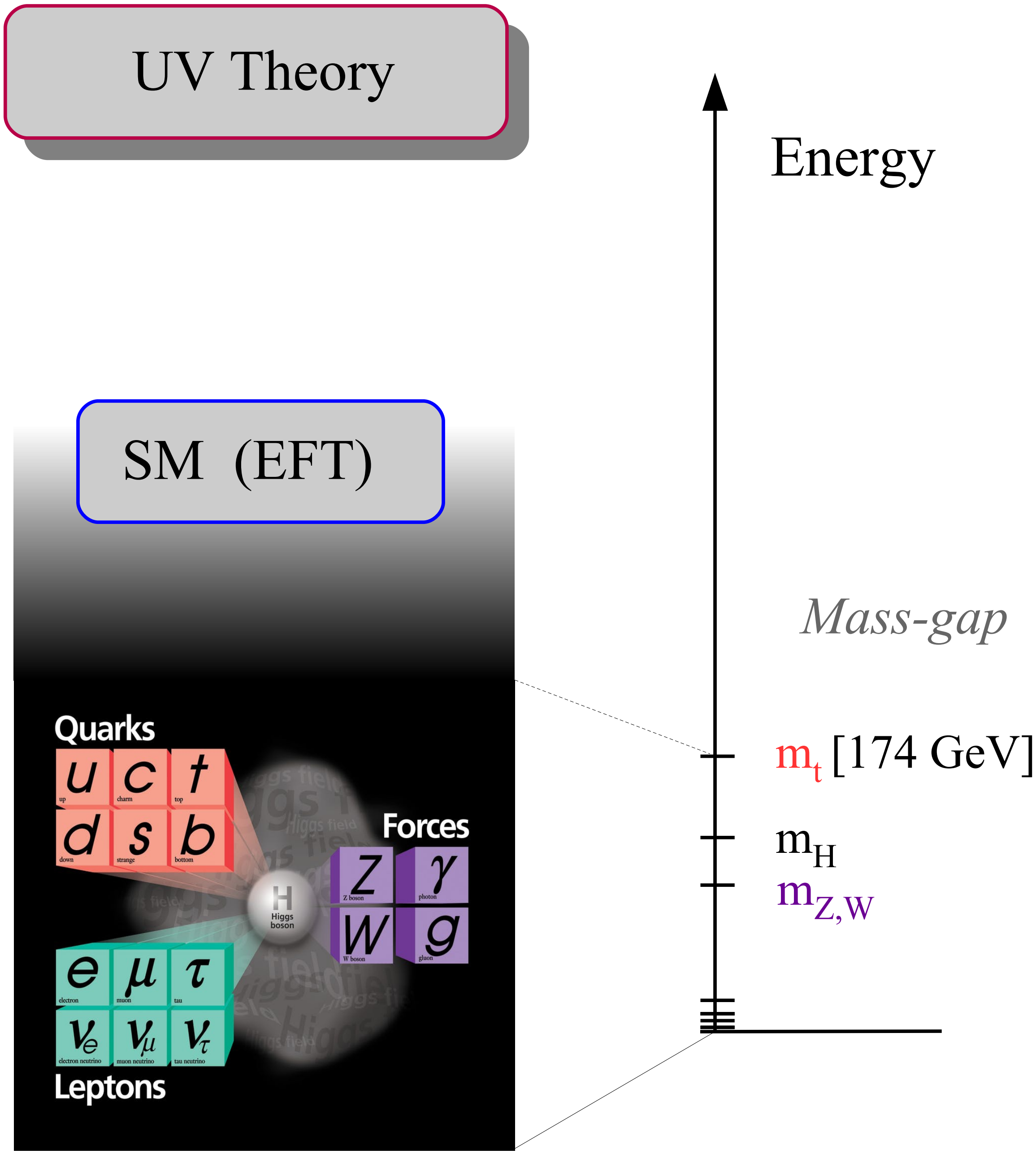
i.e. the limit (*in the range of energies and effective couplings so far probed*) of a more fundamental theory with new degrees of freedom

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

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



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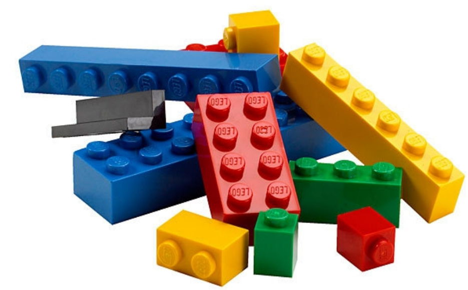
We identified the *"light"* (*"large"*) pieces of our *"construction game"* & their long-range interactions

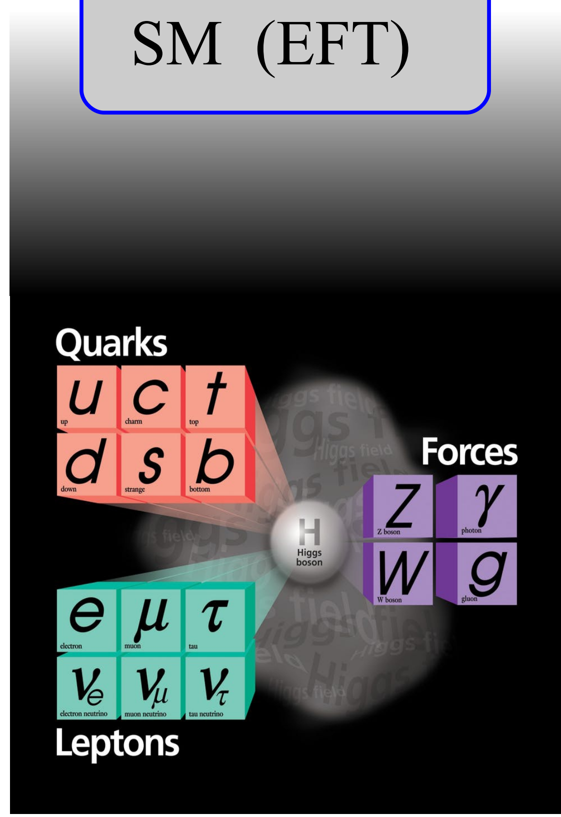
UV Theory

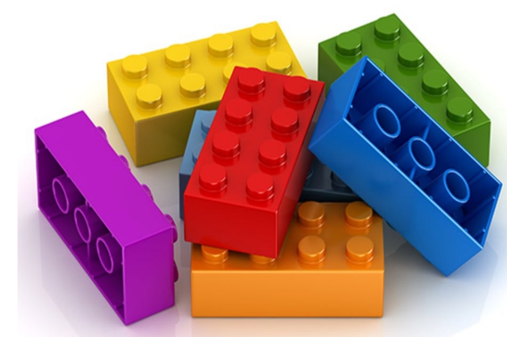
$E \sim L^{-1}$



?

SM (EFT)





Introduction

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

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...*]

UV Theory

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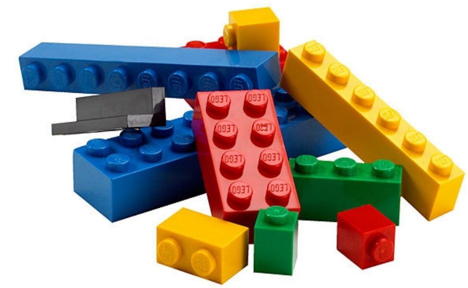

SM (EFT)

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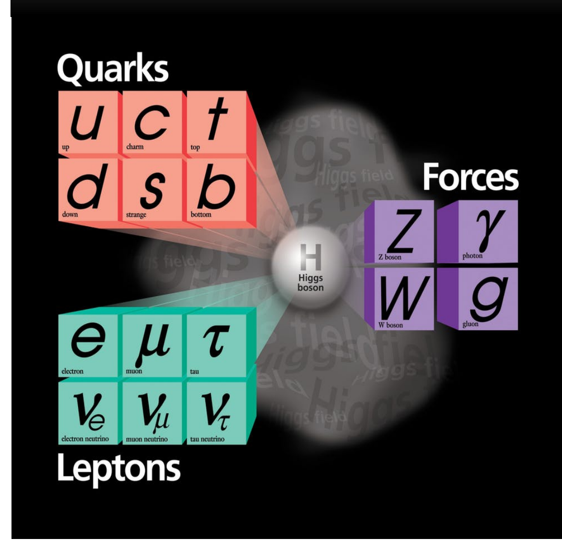
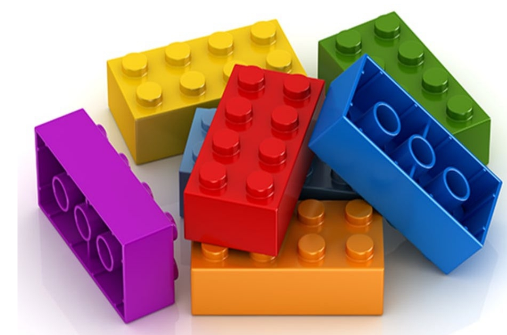




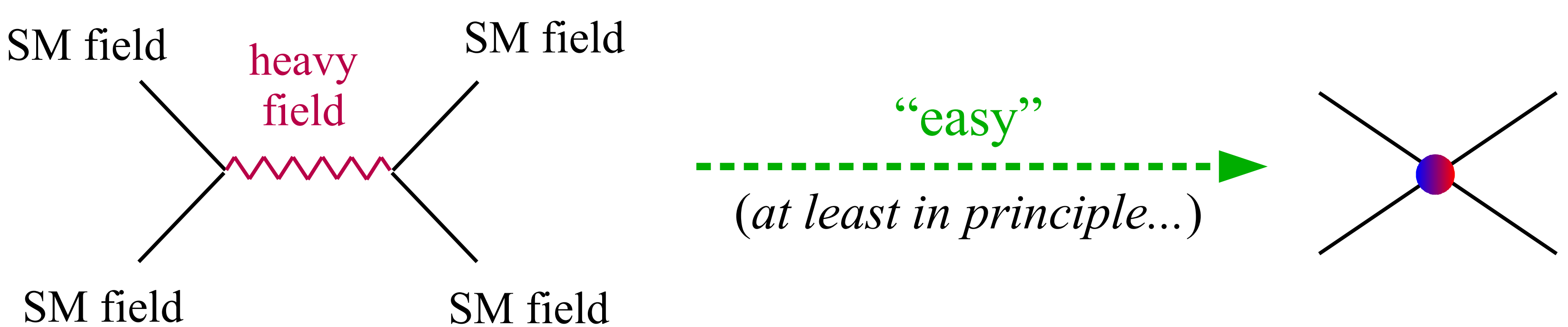
Introduction

UV Theory

low-energy "projection"

"integrate out" the heavy degrees of freedom

SM (EFT)



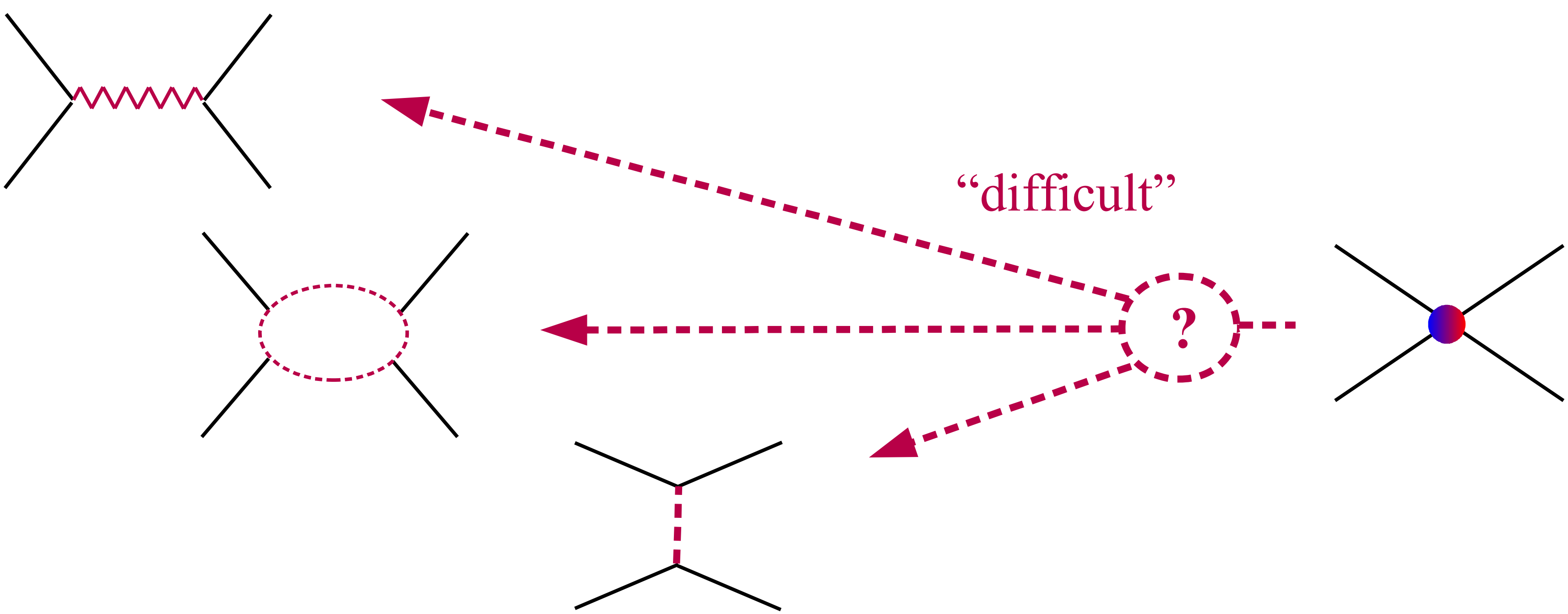
Introduction

UV Theory

low-energy “projection”

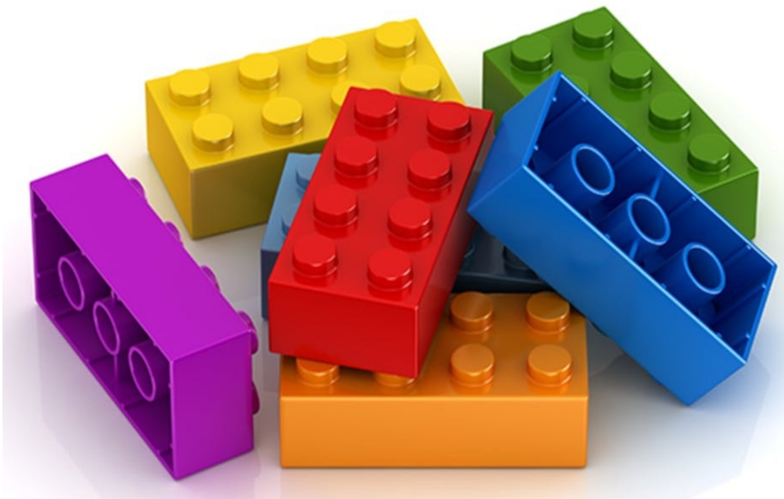
loss of information about nature & properties of the high-energy modes

SM (EFT)

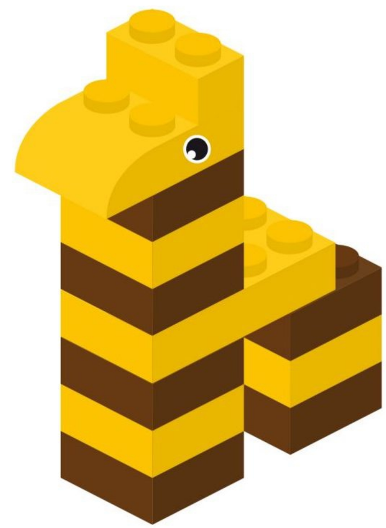


Introduction

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



$\xrightarrow{?}$



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

UV Theory

SM (EFT)

Two independent features 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

qualitative
UV imprint

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

quantitative
UV imprint

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Un-natural aspects of low-energy couplings

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

$$m_H^2\Big|_{\Lambda} + \quad \text{NP} \qquad \Delta m_H^2 \sim \Lambda^2 \quad \rightarrow \quad m_H^2\Big|_{\text{Phys}}$$

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

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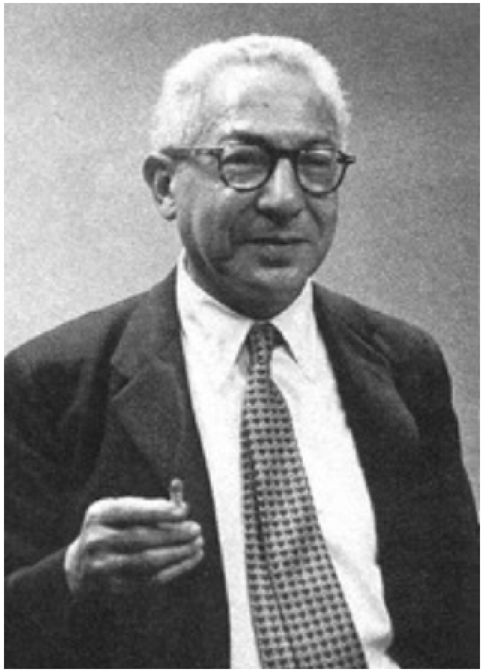
Un-natural aspects of low-energy couplings

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

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

The Flavor Problem(s)



Isidor Issac Rabi

(1898—1988)

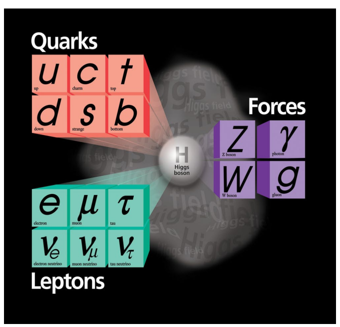
The Flavor Problem(s)

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

$\mathscr{L}_{\text{SM}}$

Operators with $d \leq 4$
with SM fields & SM symm.

Operators with $d > 4$
with SM fields & SM symm.



Long-range forces
of the SM particles

Higgs sector
to describe
their masses

Most general description of
the heavy dynamics, as long as
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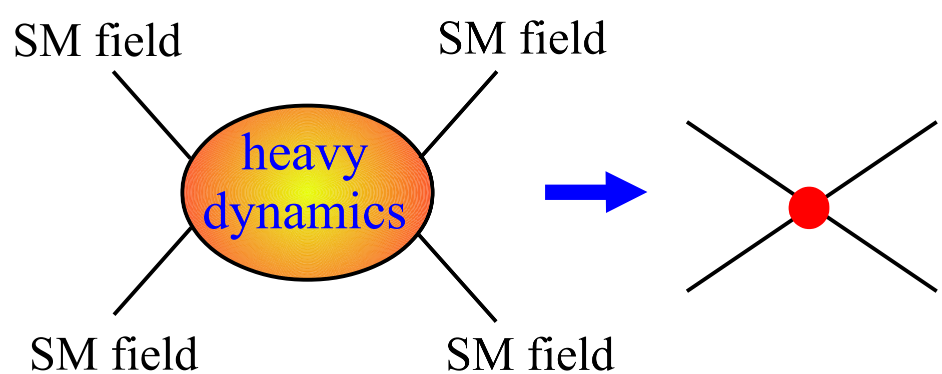

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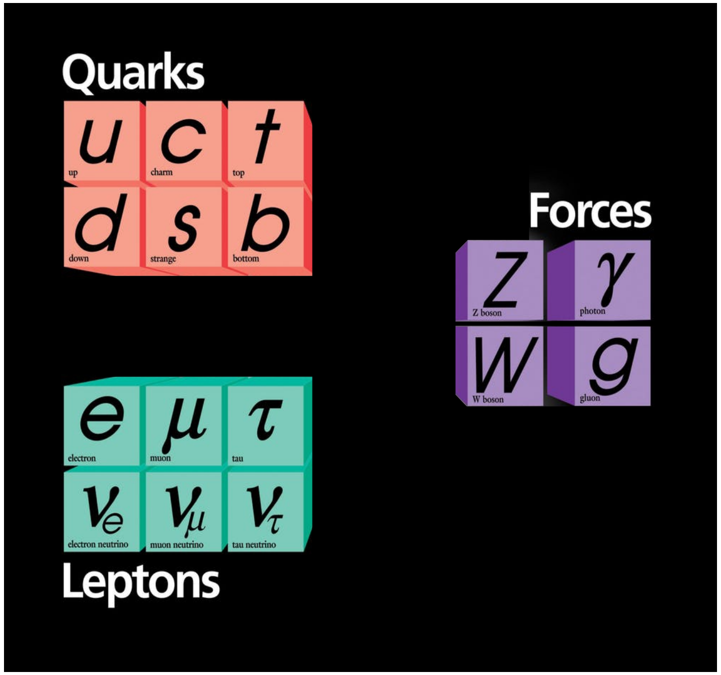
"trivial" low-energy projection

Long-range forces of the SM particles

Structure fully dictated by

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

It contains only "natural" O(1) couplings



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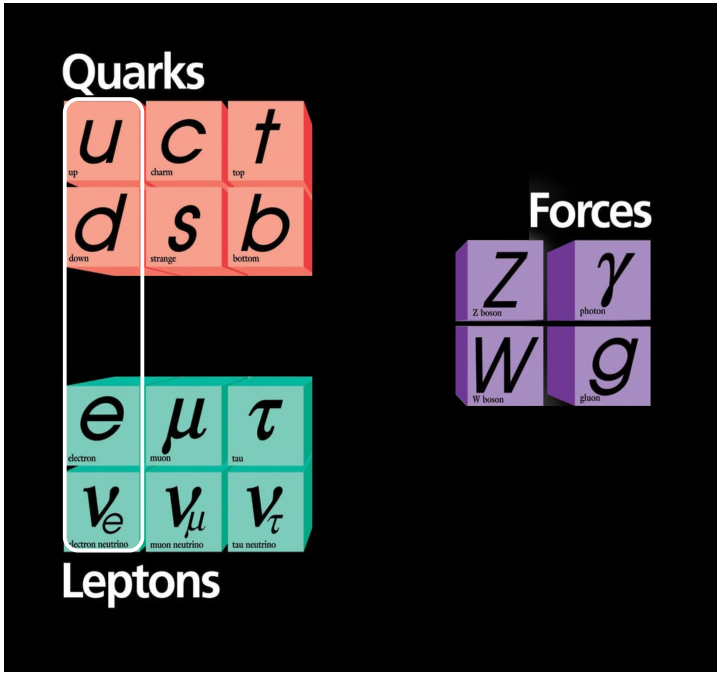
Long-range forces of the SM particles

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

$$\mathscr{L}_{\text{gauge}} = \Sigma_a -\frac{1}{4g_a^2}(F_{\mu\nu}^{a})^2 + \Sigma_\psi \Sigma_i \bar{\psi}_i i\not{D}\psi_i$$



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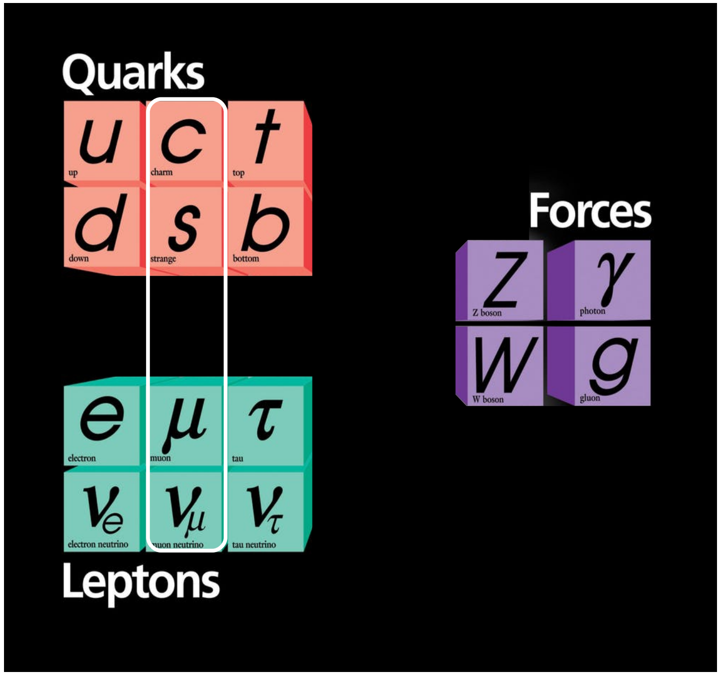

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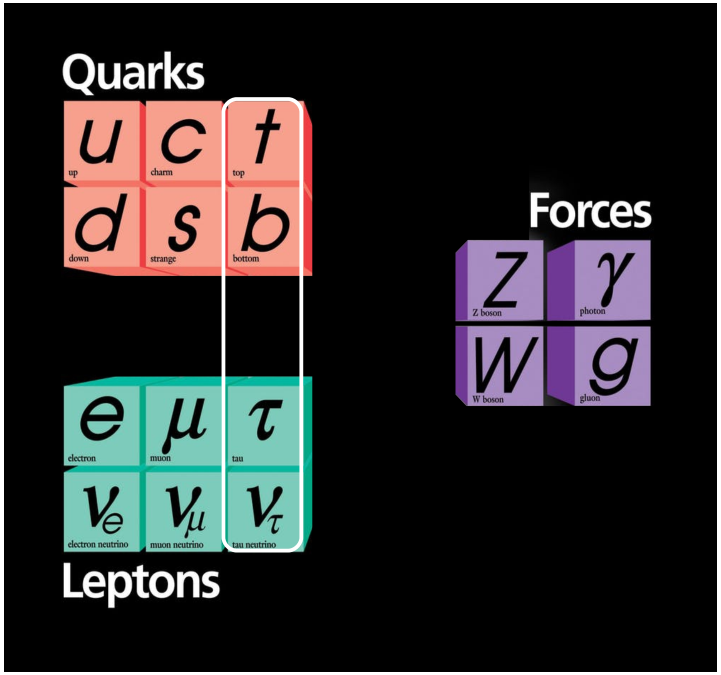

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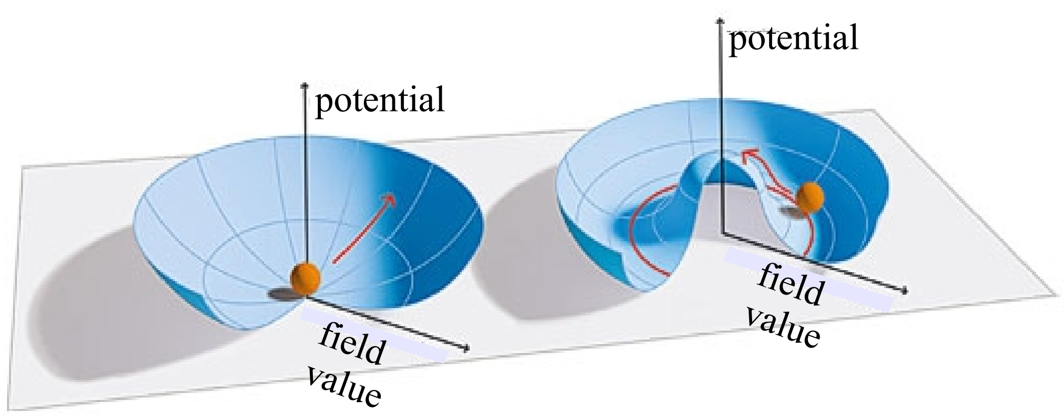
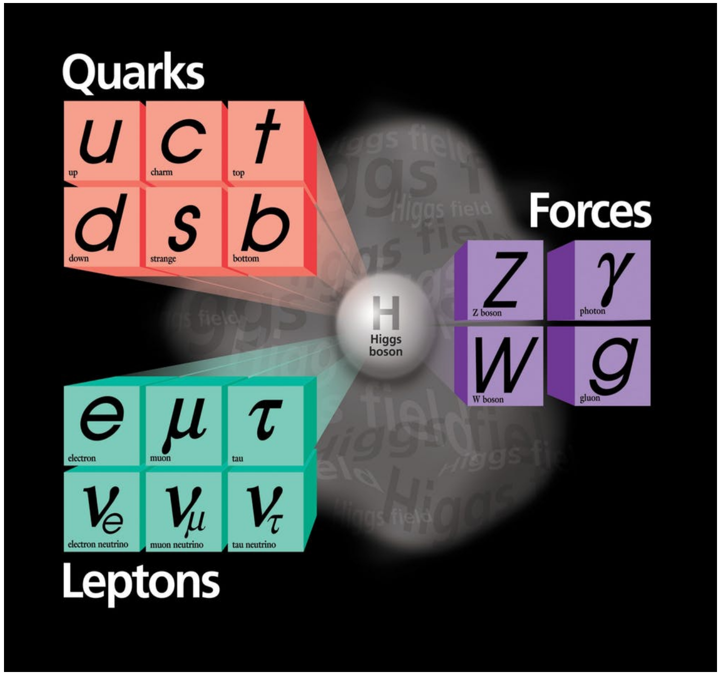
Higgs sector to describe particle masses

Within the SM part of the Lagrangian, the flavor-degeneracy is broken only by the Yukawa interaction:

$$y_{ij}\, \Psi_i \Psi_j\, H \rightarrow m_{ij}\, \Psi_i \Psi_j$$





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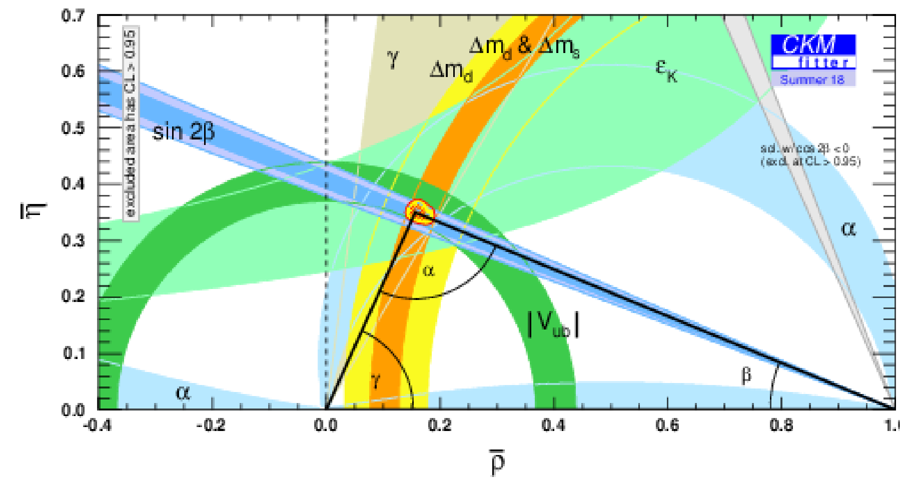

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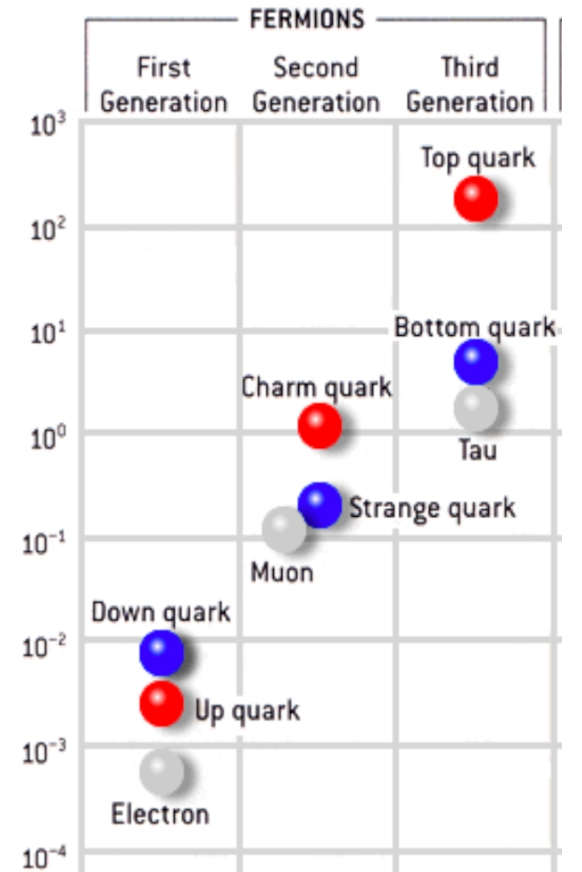
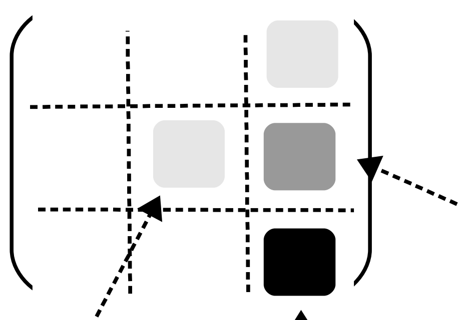


The Yukawa couplings have a peculiar hierarchical structure which does not appear to be accidental:

E.g.:

$Y_U \sim$



The SM Flavor problem

$V_{ts} \approx 0.04$

$y_c \approx 0.005$

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

The Flavor Problem(s)

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

Large flavor symmetry

Flavor-degeneracy broken by the Yukawa interaction

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

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

"Peculiar" breaking structure

Exact & approximate (*accidental* ?) symmetries

Eg:

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

The Flavor Problem(s)

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

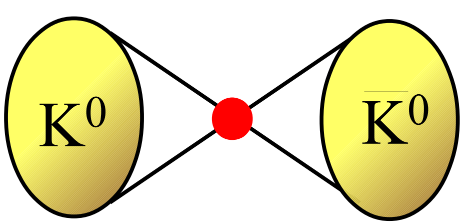
Most general description of the heavy dynamics, as long as we do not have enough energy to directly excite it

In principle, we could expect many other sources of flavor non-degeneracy from the heavy dynamics

However (beside a few *anomalies* in B-meson decays → *more later...*), we observe none

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

E.g.:



$$\frac{1}{\Lambda^2}(\bar{\psi}_i \psi_j)^2$$

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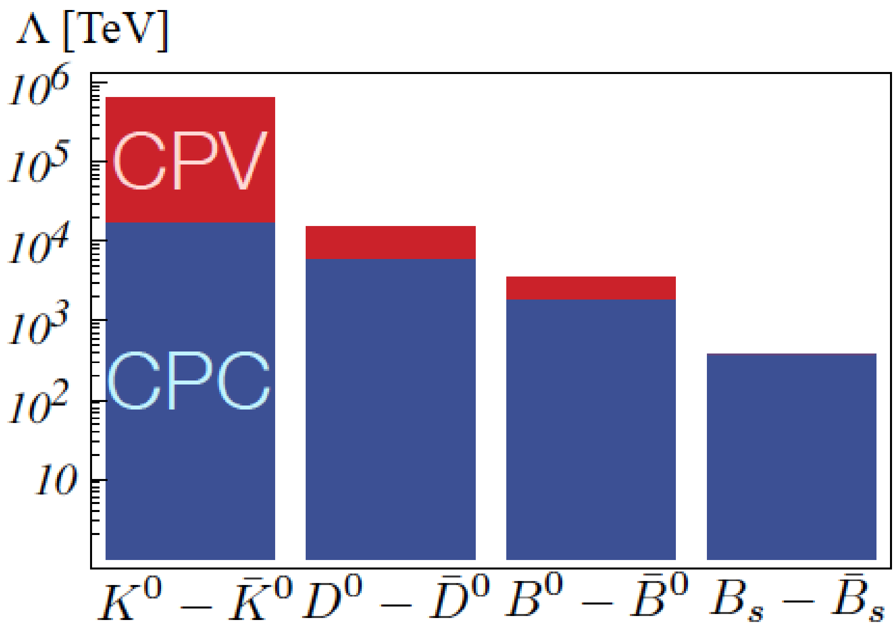
The NP Flavor problem

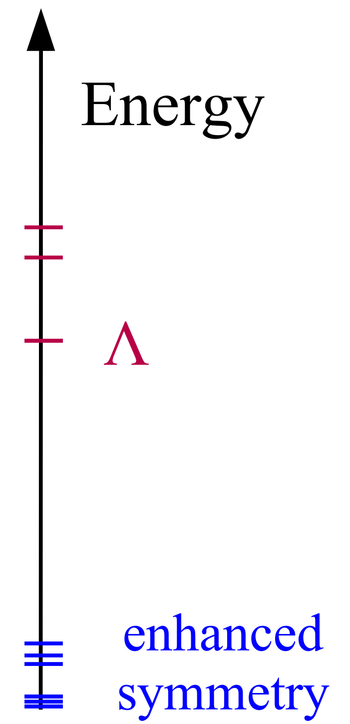


Flavor Symmetries
[*accidental or fundamental?*]

Flavor symmetries

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

We denote as "accidental symmetries" the symmetries which are not fundamental properties of the underlying theory, but emerge accidentally at low energies (*i.e. in the renormalizable part of the Lagrangian*) → not enough "variables" to describe the violation of the symmetry at large distances [~ *multipole expansion*]



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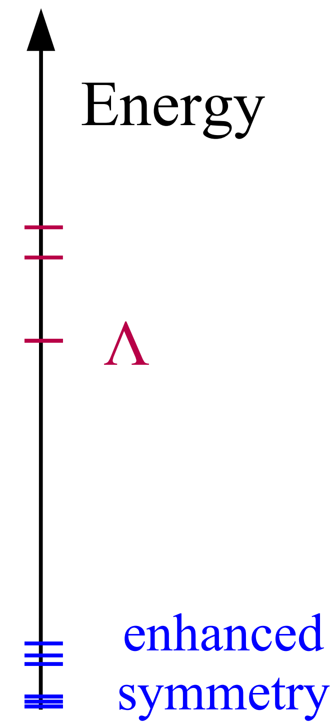

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If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

Violations of accidental symmetries

Well-known examples from the past...

Flavor symmetries

$$\mathcal{L}_{\cancel{\text{SM-EFT}}} = \mathcal{L}_{\text{gauge}} + \cancel{\mathcal{L}_{\text{Higgs}}} + \underbrace{\sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq5}}$$

[QCD+QED]-EFT

$\mathcal{L}_{mf}$

Violations of
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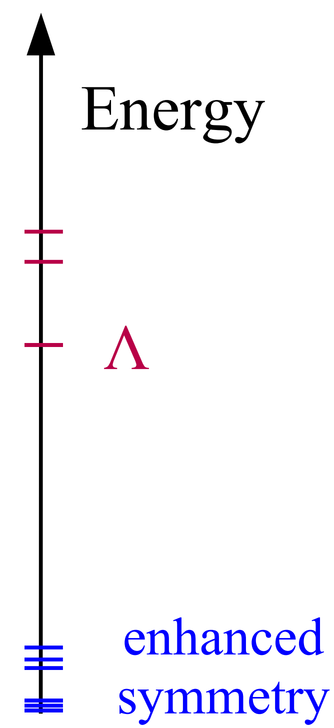


Eg: *Low-energy theory:* QED + QCD

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

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

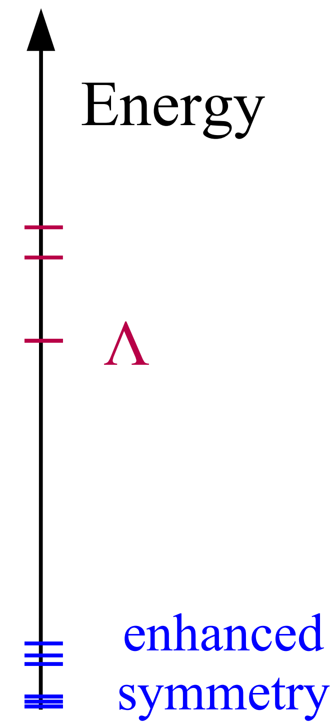
Well-known examples from the past...

▶ *Flavor symmetries*

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

[SM-2]-EFT

Violations of
accidental symmetries



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

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

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

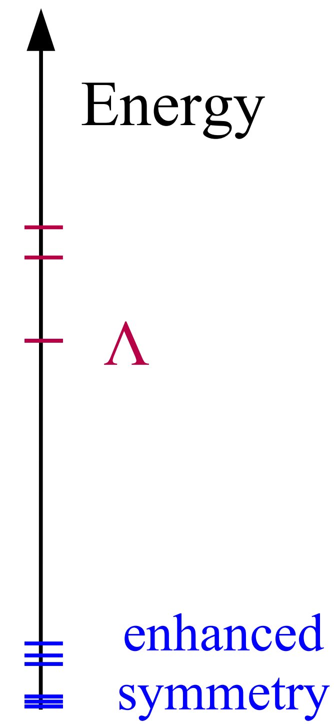
Accidental symm.: CP

Violated by: <u>"Super-weak" interaction</u> [L. Wolfenstein]:

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

Flavor symmetries

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



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

Part II

Flavor symmetries

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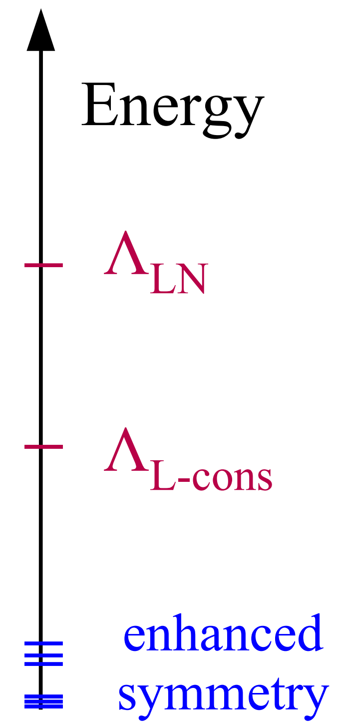

Accidental symmetries allow us to separate different sectors of the EFT $\leftrightarrow$ stable scale separation

Eg: *Total Lepton Number & neutrino masses*

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

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

N.B.: The same is true for flavor-violating terms
(*with minor technical differences related to approximate vs. exact symmetries*)

Flavor symmetries

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

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

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

Stringent bounds on generic flavor-violating ops.

The big questions in flavor physics:

- Are all the the flavor symmetries do the SM broken in the other sectors of the SM-EFT ?
- Can we make sense of the tight NP bounds from flavor-violating processes and still hope to see NP not far from the TeV scale?
- Are there sectors of the SM-EFT where we can detect new sources of flavor symmetry breaking given existing bounds?

Flavor symmetries

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Symmetry hypotheses formulated to separate the SMEFT flavor-breaking sectors:

MFV

Chivukula & Georgi, '89
D'Ambrosio *et al.* '02

- Accidental $U(3)^5$ symmetry at work up to a very high energies, not accessible in experiments (Λ_Y)
- Only breaking terms surviving at low energies are the SM Y's
- NP scale accessible in experiments is flavor blind

Lowest Λ_{NP} allowed by flavor bounds [→*Higgs hier. prob*]

Flavor symmetries

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

Symmetry hypotheses formulated to separate the SMEFT flavor-breaking sectors:

MFV

Chivukula & Georgi, '89
D'Ambrosio *et al.* '02

- Accidental $U(3)^5$ symmetry at work up to a very high energies, not accessible in experiments (Λ_Y)
- Only breaking terms surviving at low energies are the SM Y's
- NP scale accessible in experiments is flavor blind

Λ_Y

- "Inefficient" lowering of Λ_{NP} from collider bounds in the post LHC era
- No explanation of Y hierarchies

Λ_{NP} Direct-search bounds stronger for flavor-blind NP

Lowest Λ_{NP} allowed by flavor bounds [$\to$ *Higgs hier. prob*]

v

Flavor symmetries

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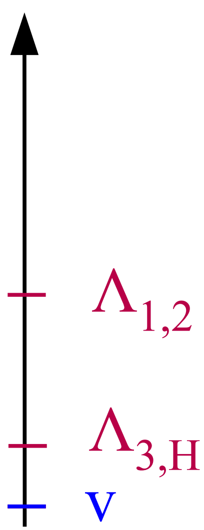
$U(2)^n$

Kagan *et al.* '09
Barbieri *et al.* '11
Blankenburg *et al.* '12

- The accidental symmetry at work in the few-TeV domain acts only on the light families

E.g.:

$$\begin{array}{cc} & U(2)_u \\ Y_U \sim & \begin{pmatrix} < 10^{-2} & < 0.1 \\ & \blacksquare \end{pmatrix} \end{array} \leftarrow U(2)_q$$



- Lowest NP scale ($\Lambda_{3,H}$) allowed by flavor & collider
[→ *potential to ameliorate the hierarchy problem*]
- Starting point approximate (flavor) symm. of $\mathscr{L}_{\text{SM}}$
[→ *potential to address the origin of Y hierarchies*]

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- The accidental symmetry at work in the few-TeV domain acts only on the light families

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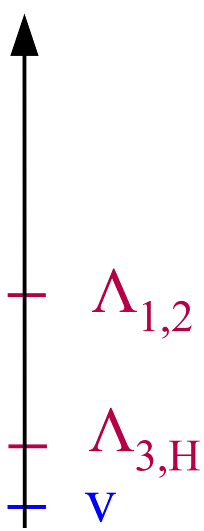
Blankenburg *et al.* '12

- Different generations structurally different
- Potentially observable effects in flavor-changing observables, despite direct searches bound

Challenge or opportunity? **Data will tell us!**



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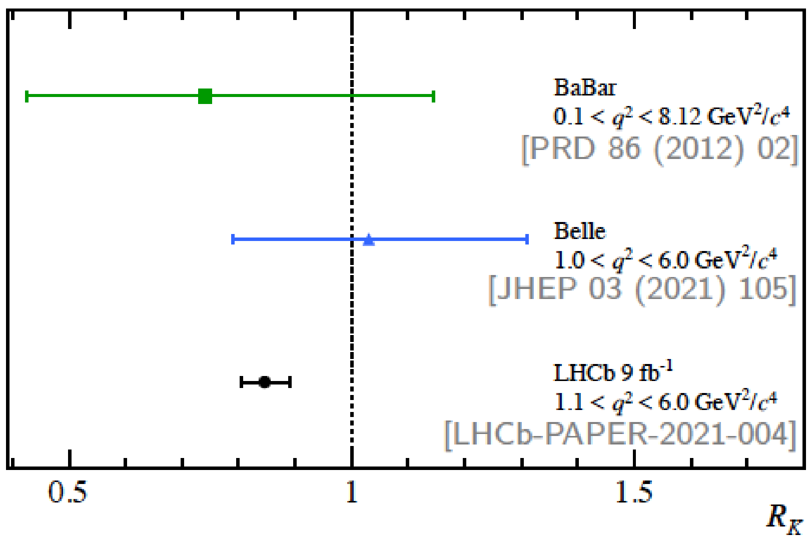
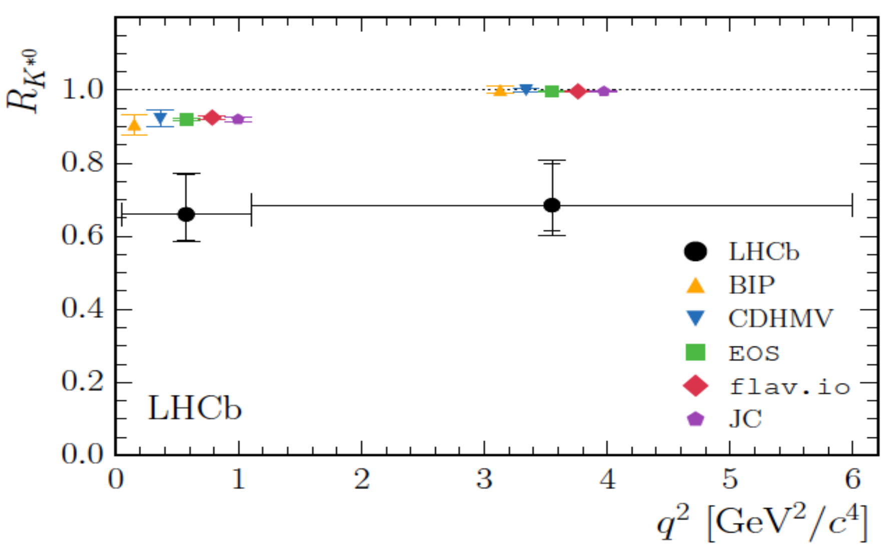
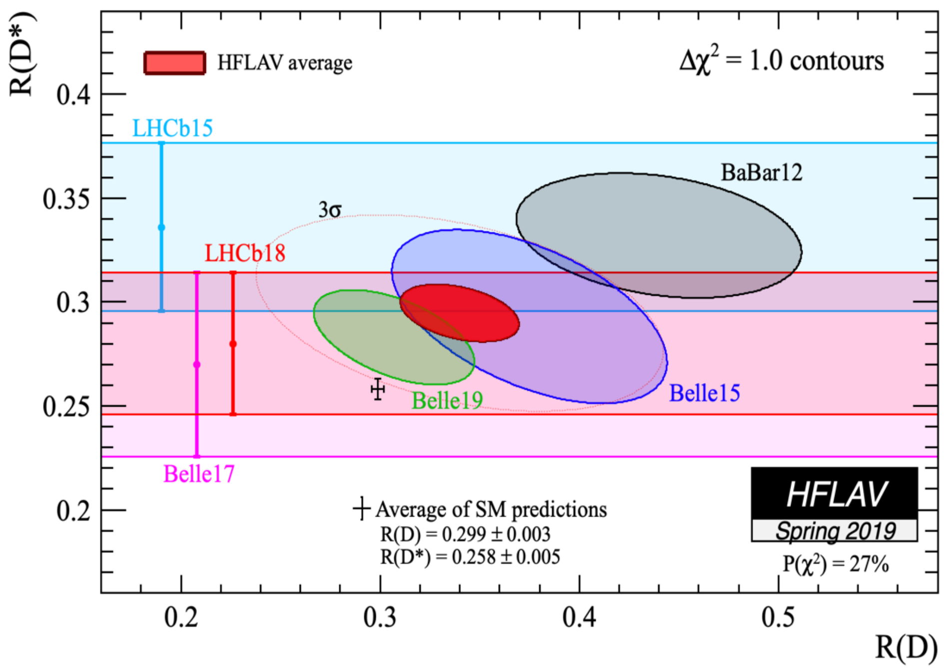
The LFU anomalies







The LFU anomalies

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

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

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

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

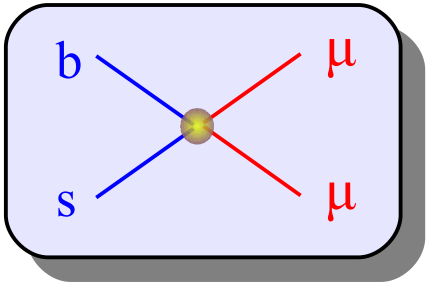
LFU is badly broken in the Yukawa sector: $y_e \sim 3\times10^{-6}$, $y_\mu \sim 3\times10^{-4}$, $y_\tau \sim 10^{-2}$

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

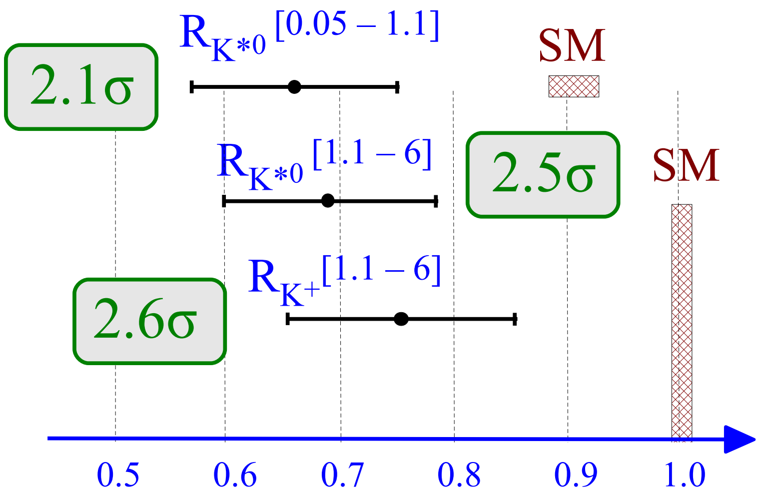
The LFU anomalies

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

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



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



LFU ratios
[LHCb – Spring 2017]

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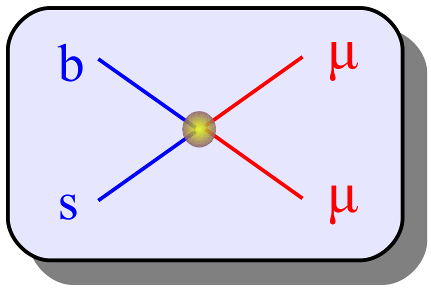

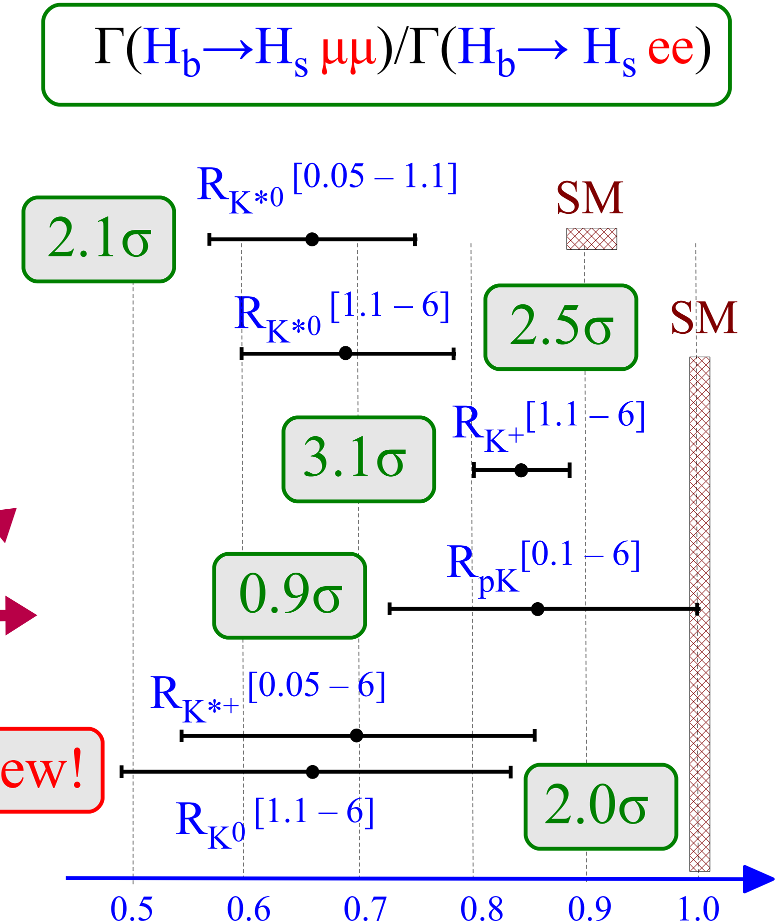

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[LHCb – Autumn 2021]

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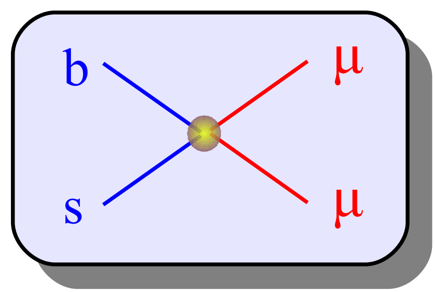

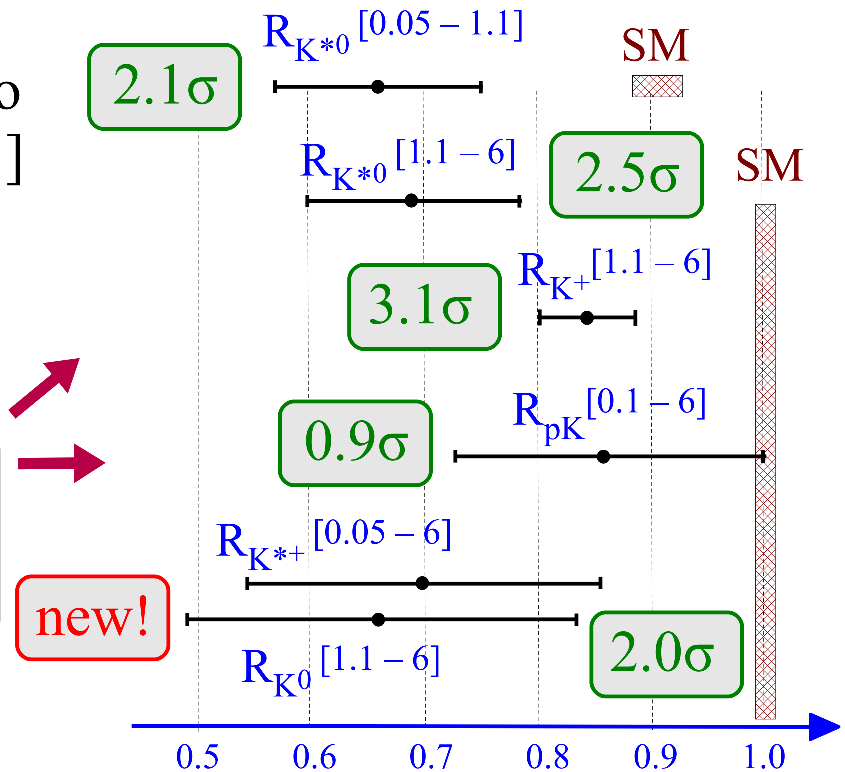

$BR(B_s \to \mu\mu)$

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

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

2.3σ

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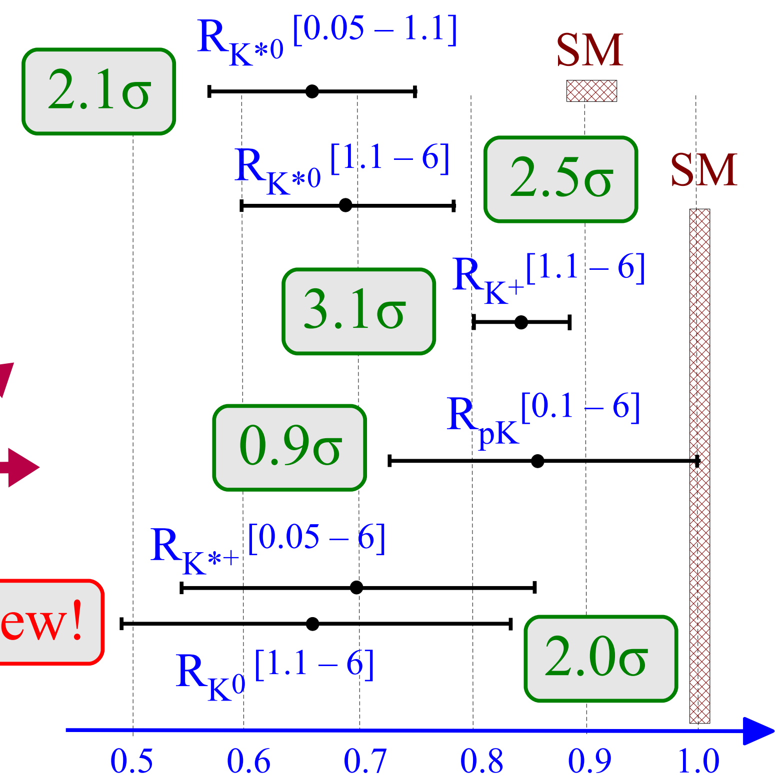
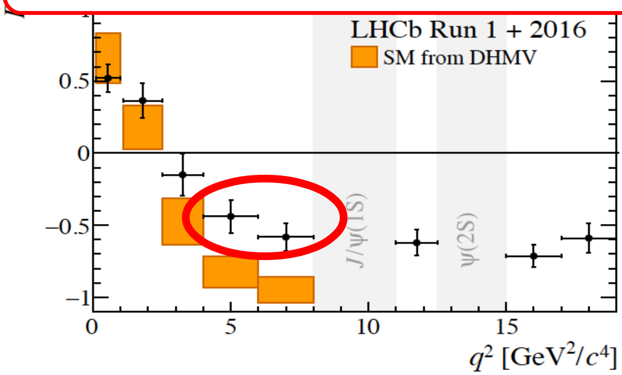
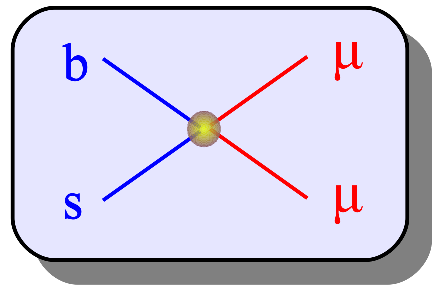
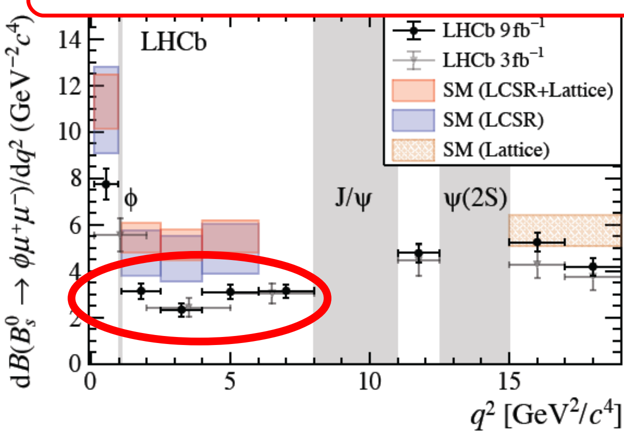


$B \to K^* \mu\mu$ angular distribution





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



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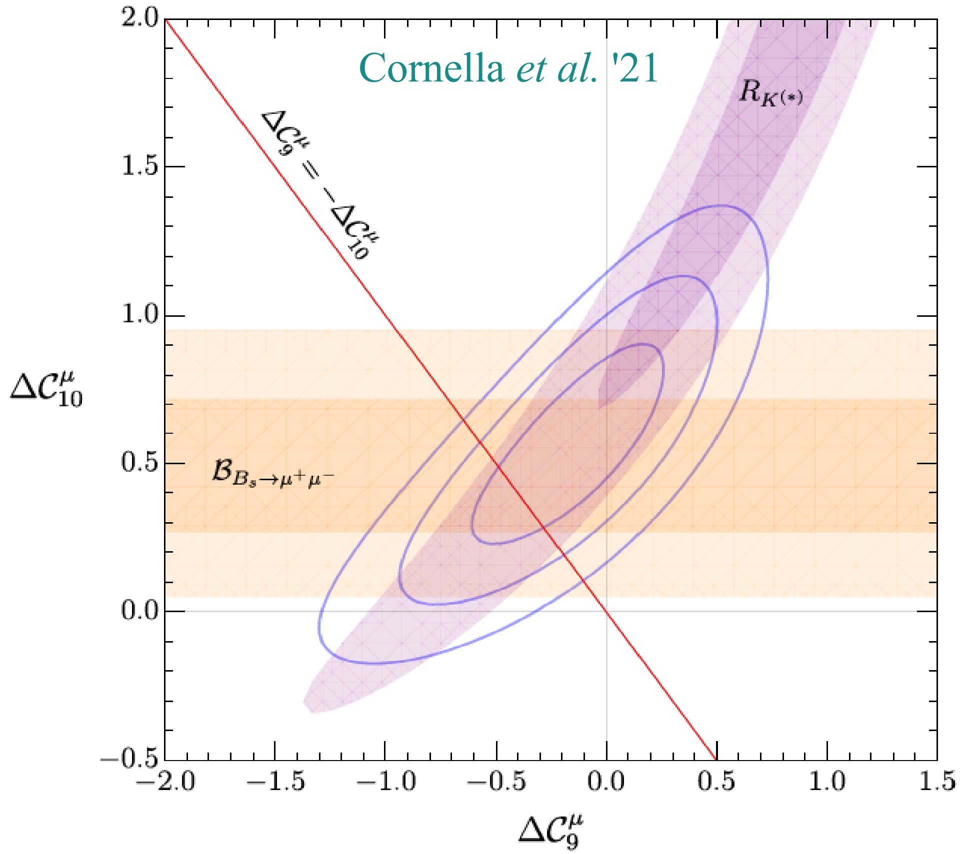
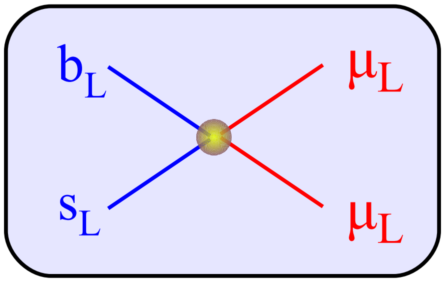


Conservative fit using "clean obs." only

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

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

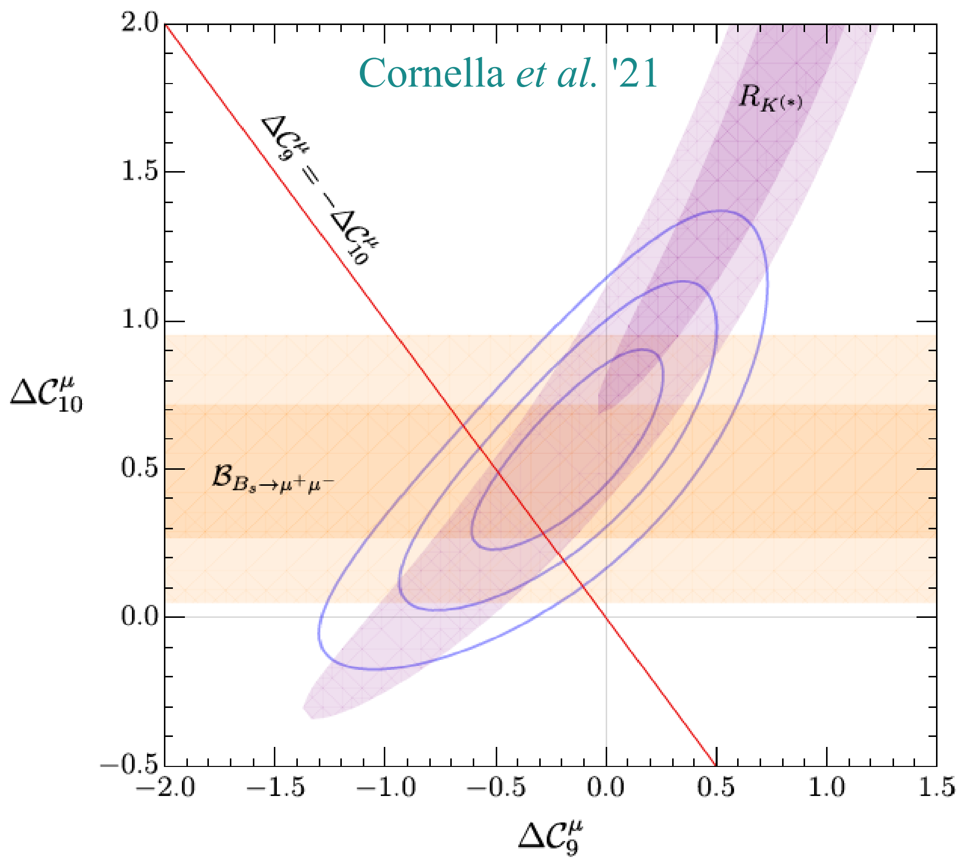
$$\mathcal{O}_{10}^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$
$$\mathcal{O}_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

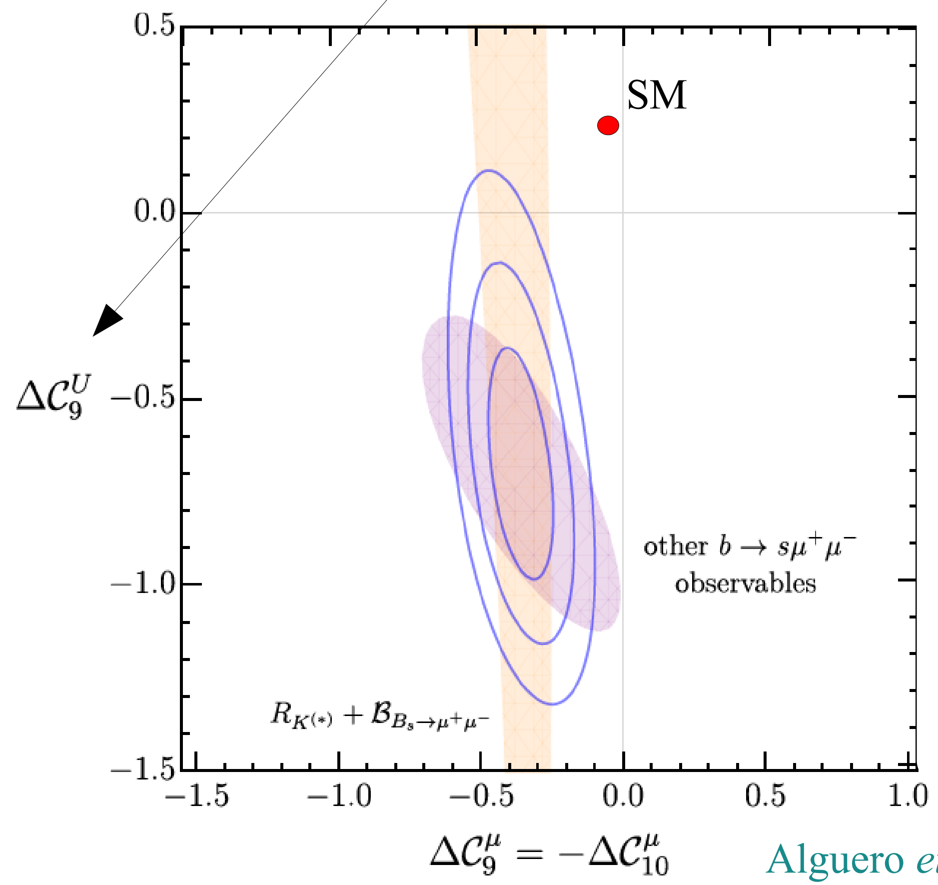


The LFU anomalies

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

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





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>> 5σ best estimate of charm contribution

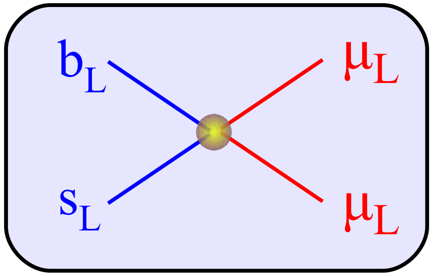
Alguero *et al.* '19
Ciuchini *et al.* '20
Li-Sheng *et al.* '21
Altmanshofer & Stangl '21

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

GI, Lancierini
Owen, Serra '21

The LFU anomalies

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



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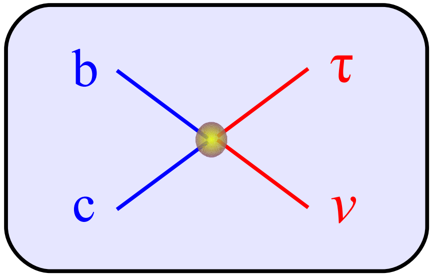

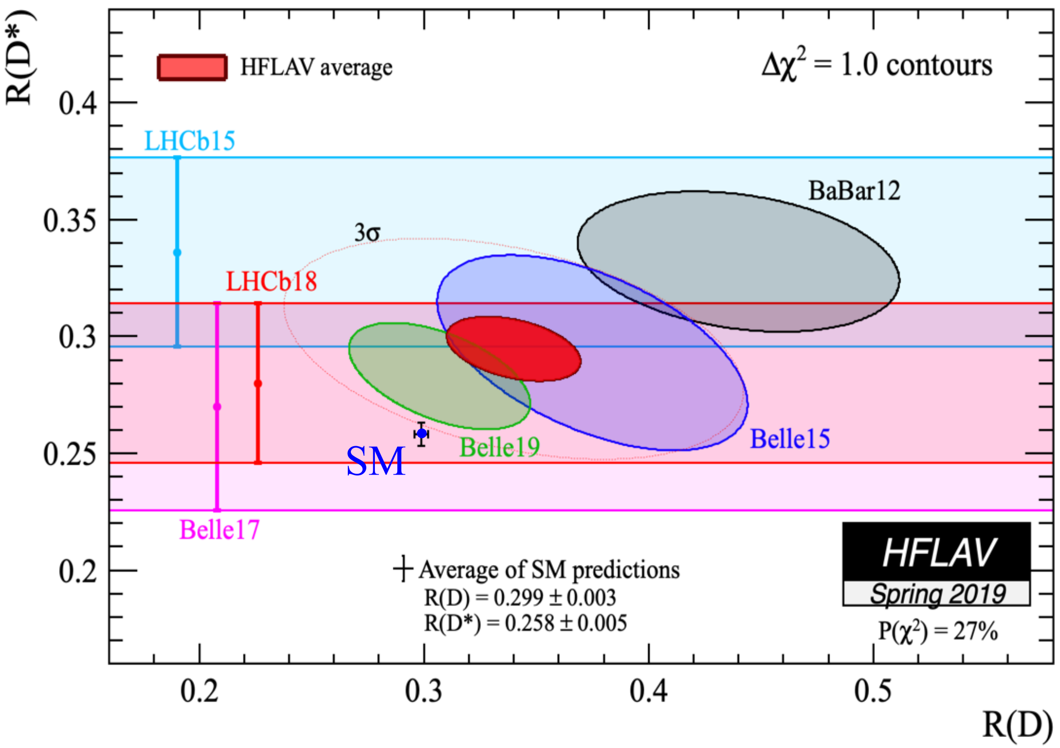

$$R(X) = \frac{\Gamma(B \rightarrow X\, \tau\nu)}{\Gamma(B \rightarrow X\, l\nu)} \qquad X = D \text{ or } D^*$$

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

The LFU anomalies

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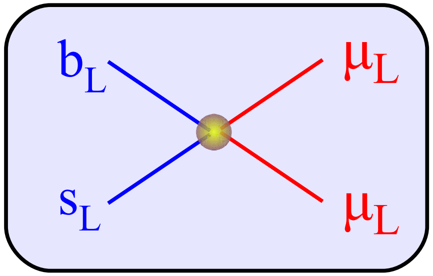

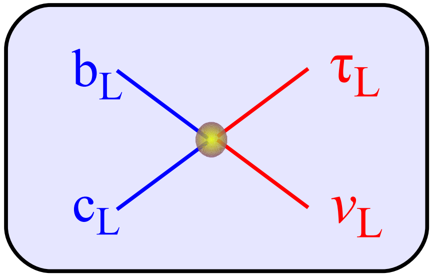

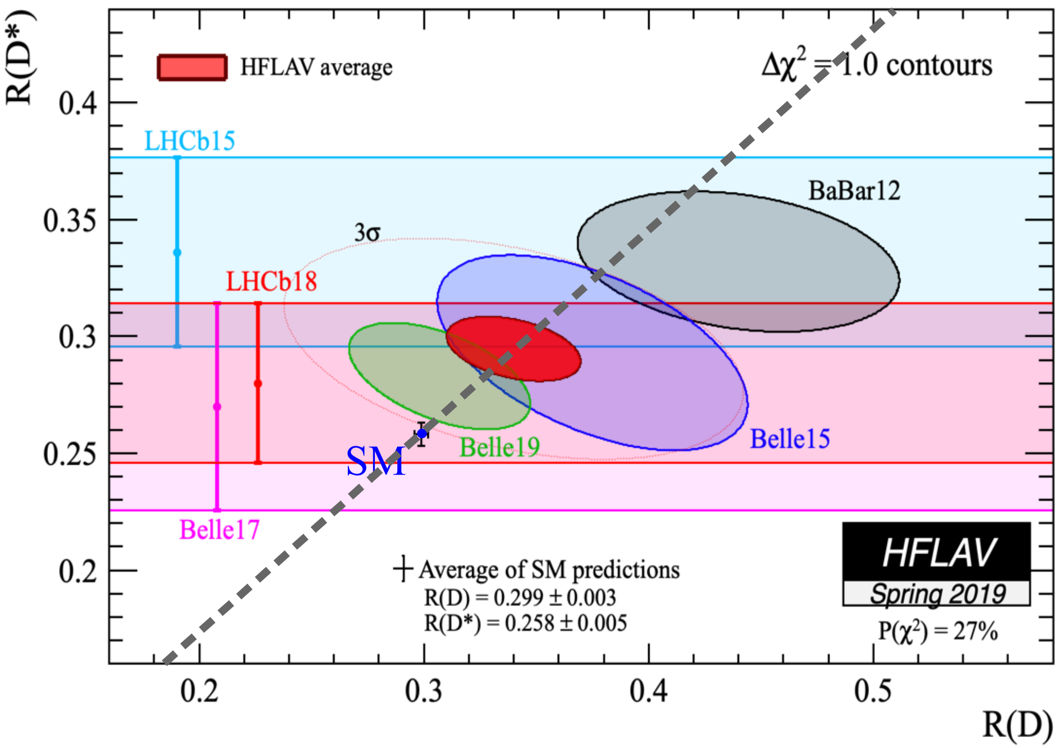

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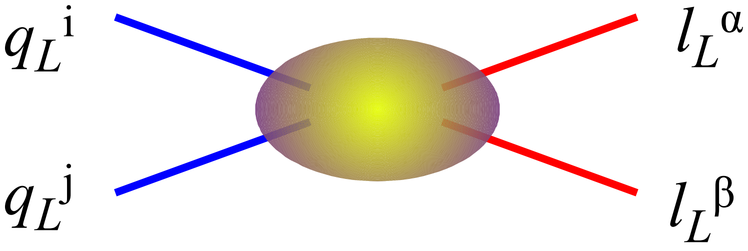
- Slower progress

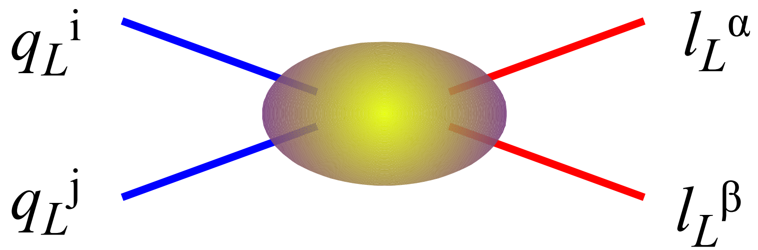
- Large NP effect competing with tree-level SM amplitude
- Left-handed NP amplitude describe well data (*but other options still possible*)

EFT considerations on the LFU anomalies



EFT considerations

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



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

- Large 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*}, ...]

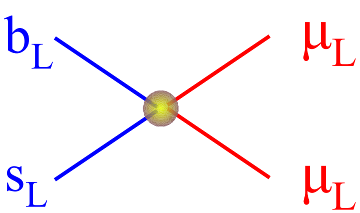
↓

$C_{ij\alpha\beta}$ = 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

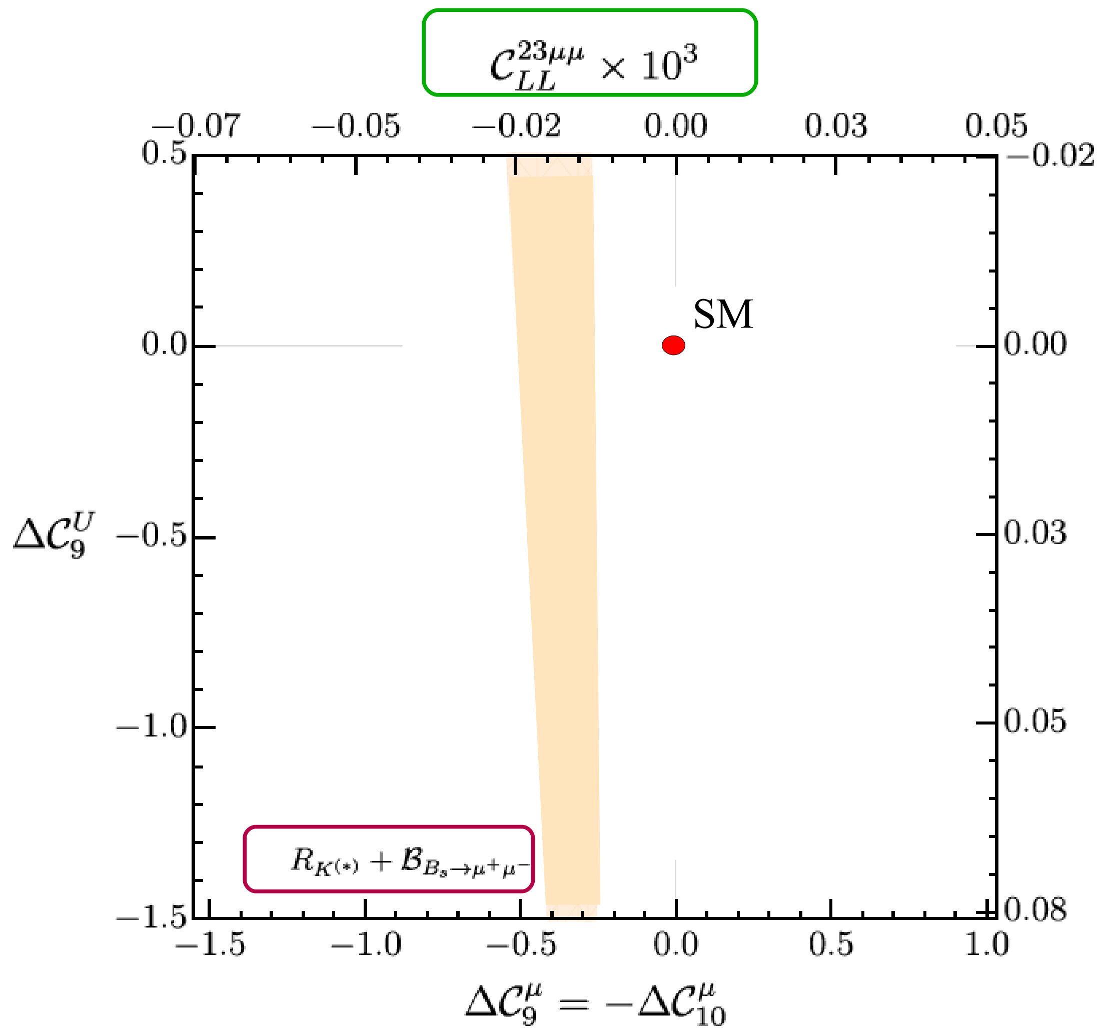
$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma_\mu q_L^j)$$



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

super-weak interaction!

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



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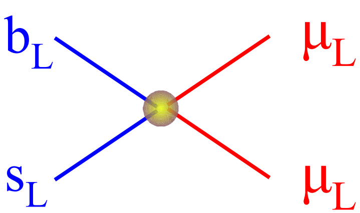
✓ O(10^{-1}) suppress. for each $2^{\rm nd}$ gen. l_L



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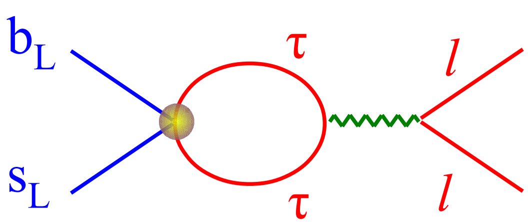
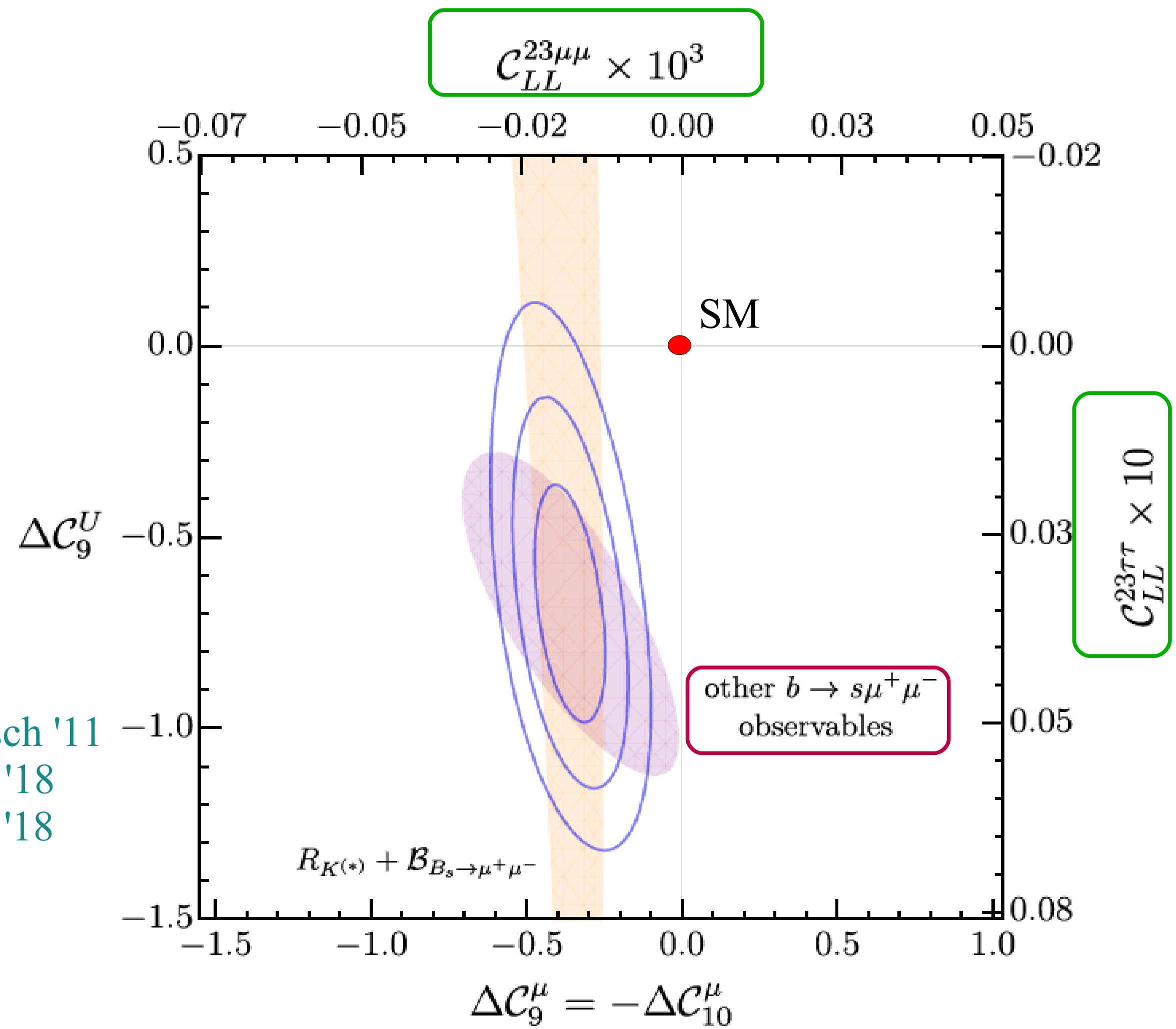


$C_{LL}^{23\tau\tau} \Rightarrow \Delta C_9^{\rm Univ}$

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



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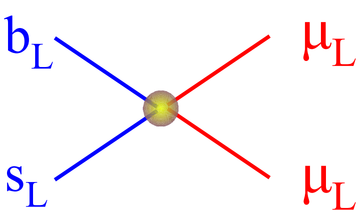

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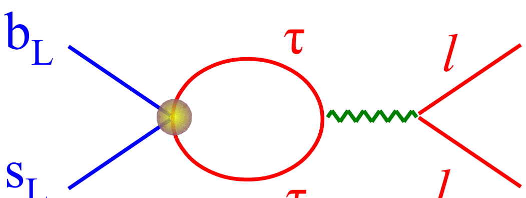

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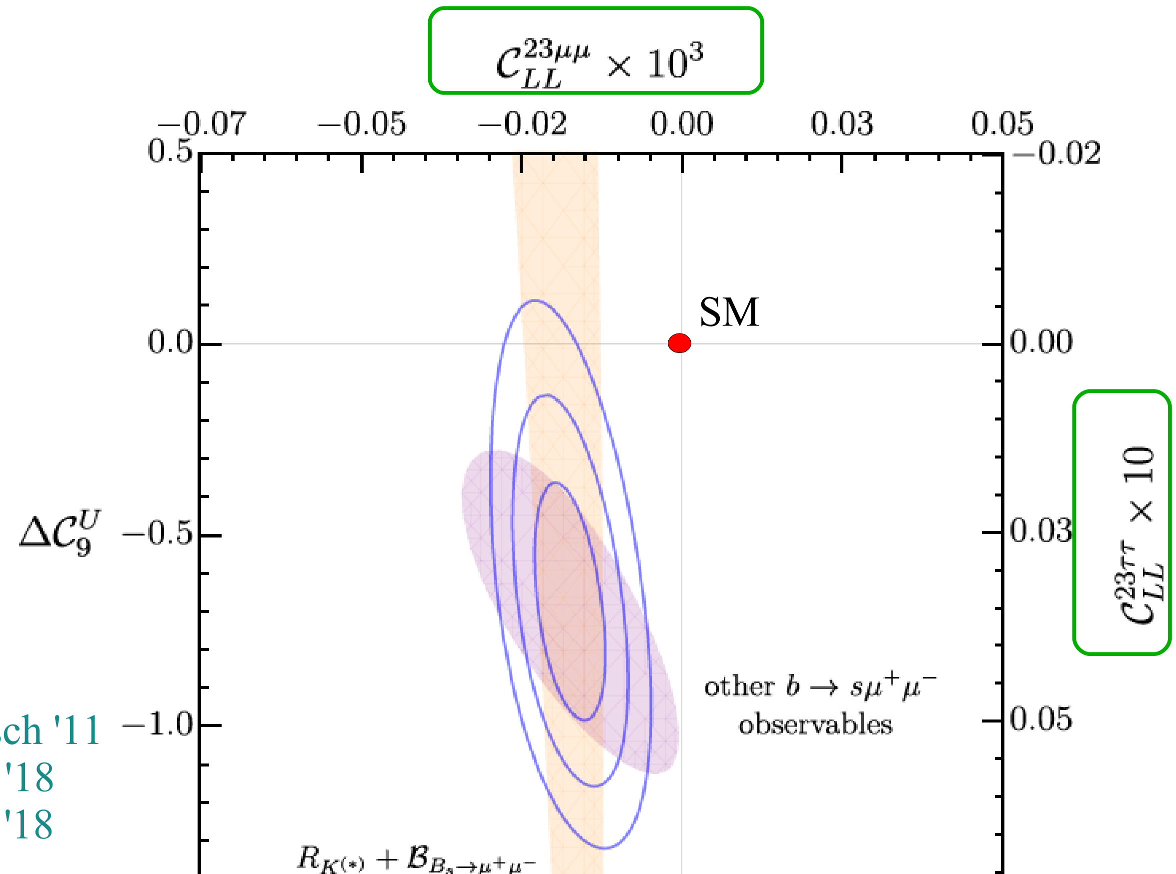
Link to CC anomaly

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



Size (and need) of $C^{23\tau\tau}$ pre-dicted from CC before this effect was observed in NC

Greljo *et al.* '17

EFT considerations

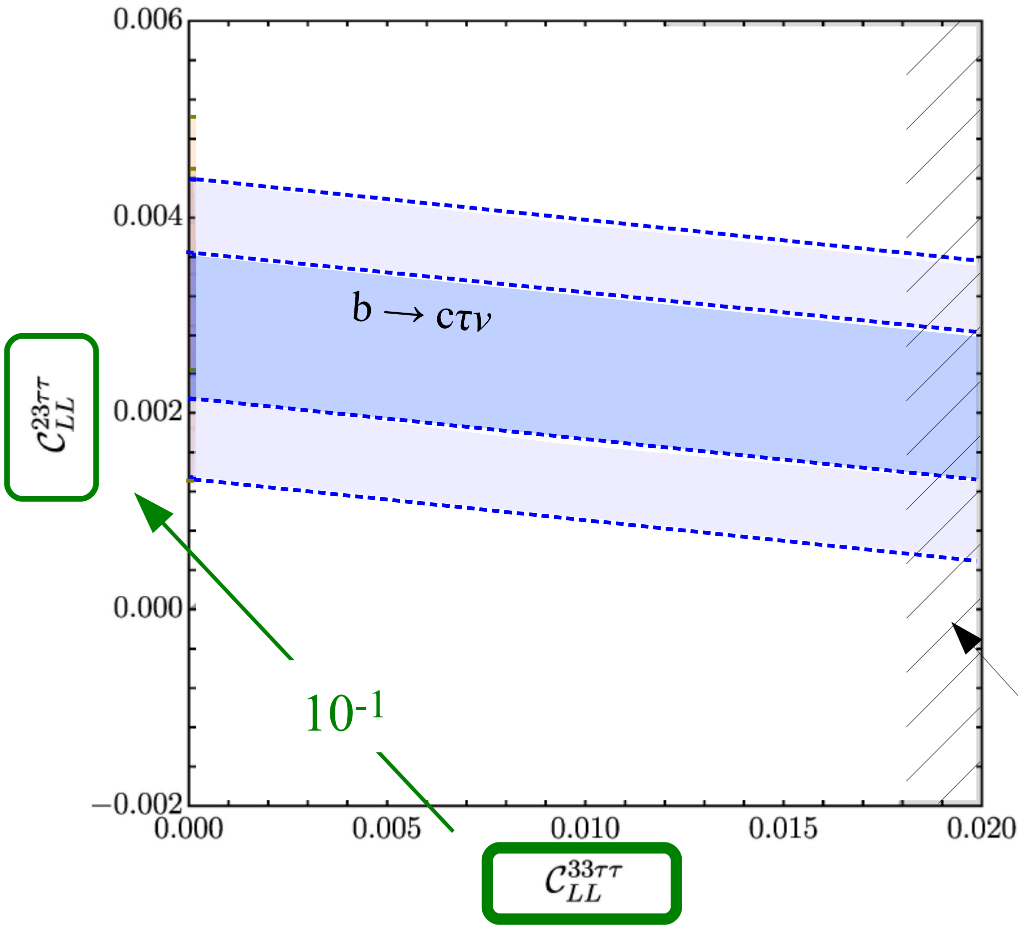
Data point to (short-distance) NP effects in operators of the type

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

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

charged-currents:

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



bounds from high-pT searches

EFT considerations

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

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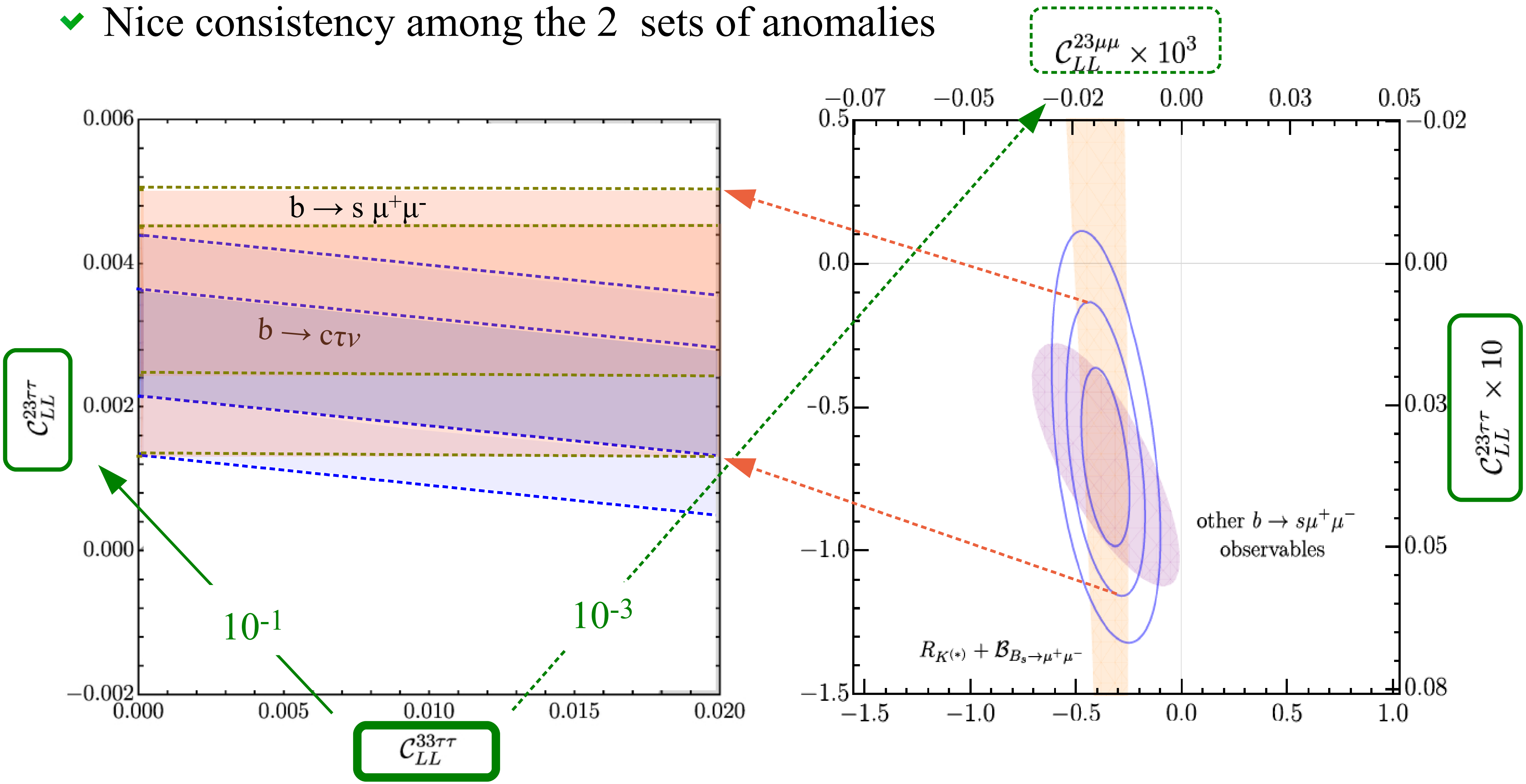
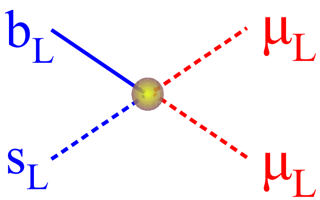
- O(10^{-1}) suppress. for each 2nd gen. q_L or l_L
- Nice consistency among the 2 sets of anomalies



EFT considerations

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



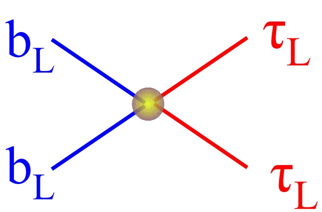
~~LF~~U in $b \to s\, l^+ l^-$ [R_K, ...] $\boxed{5\ \sigma}$

"natural" connection

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

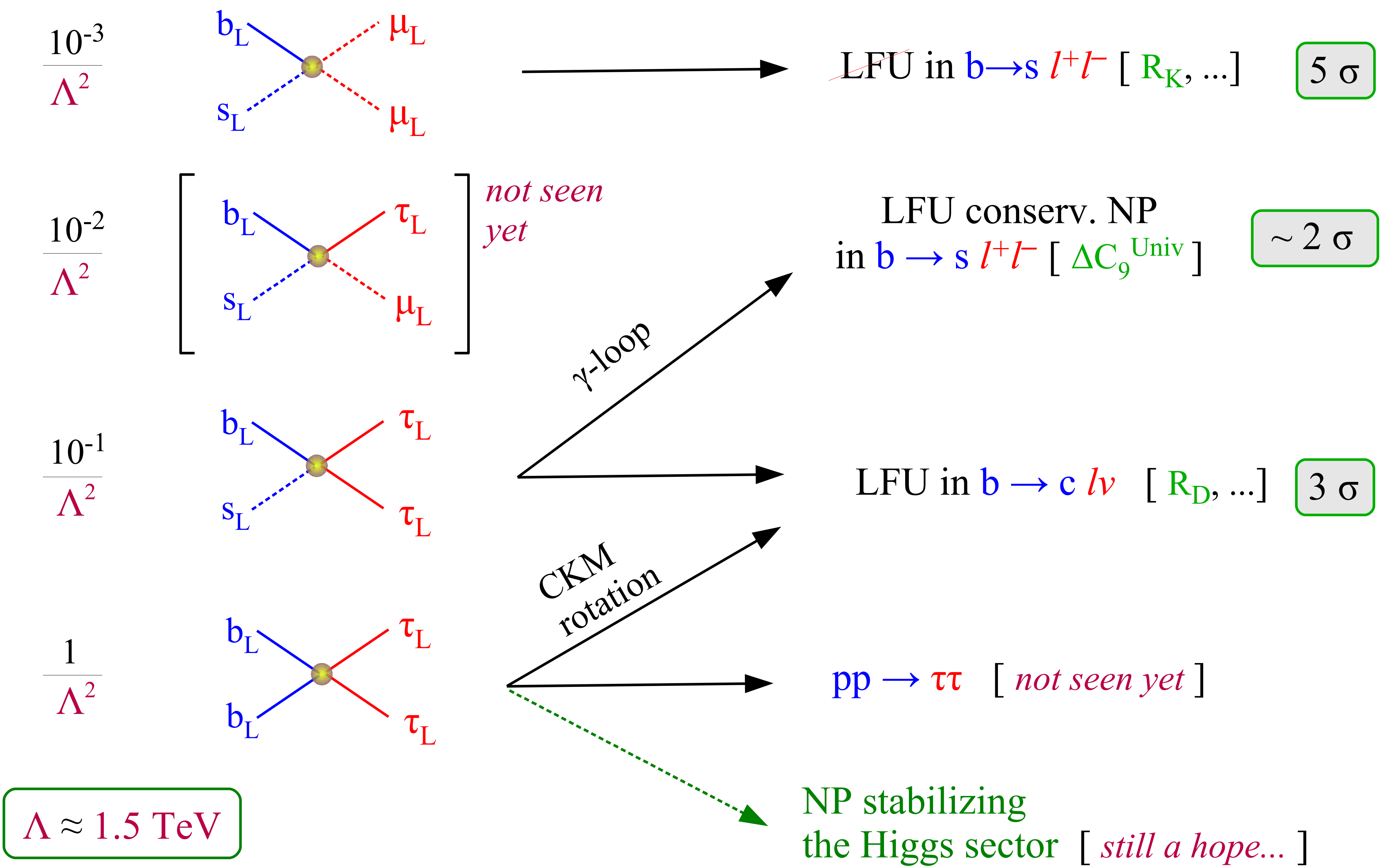
CKM rotation

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



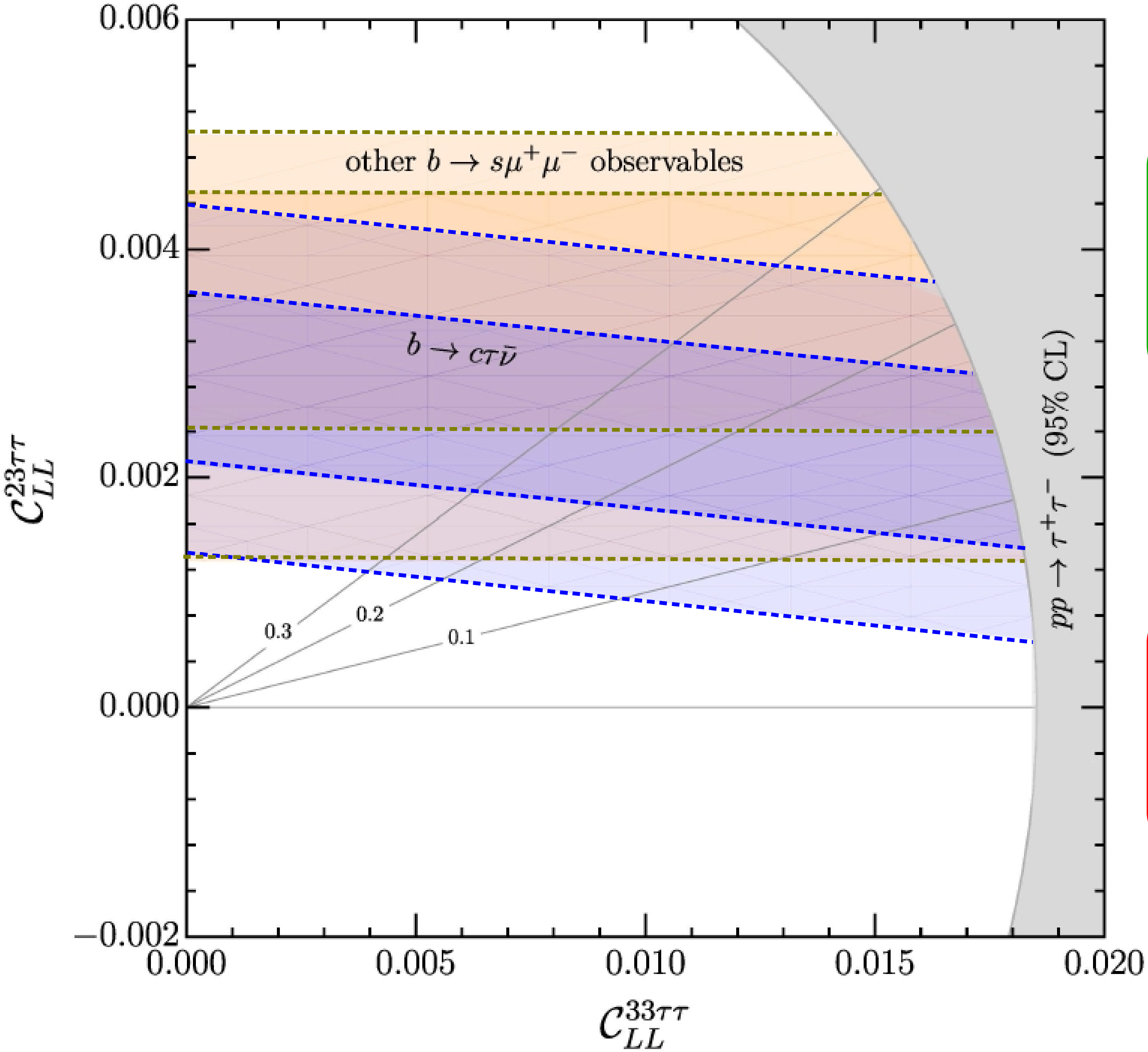
$\boxed{\Lambda \approx 1.5\ \text{TeV}}$

EFT considerations



EFT considerations

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



Pattern emerging from data:

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

What we do <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)

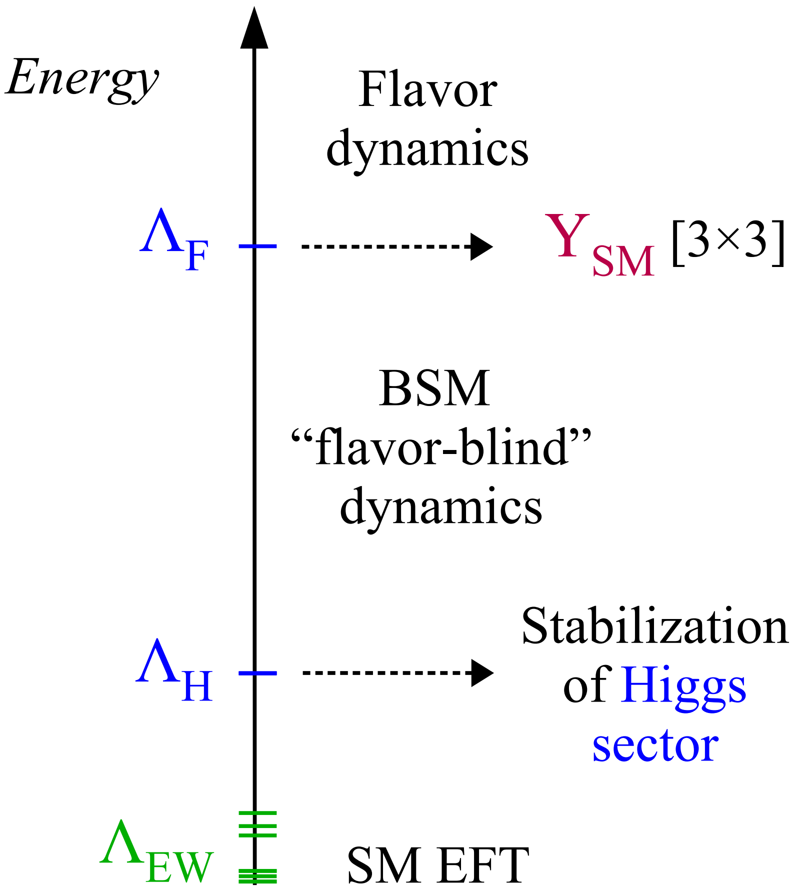
↓

Leptoquarks
as tree-level mediators
of the LFU anomalies

A possible new paradigm in flavor physics

A new paradigm in flavor physics

The old (MFV) paradigm:



Main idea:

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

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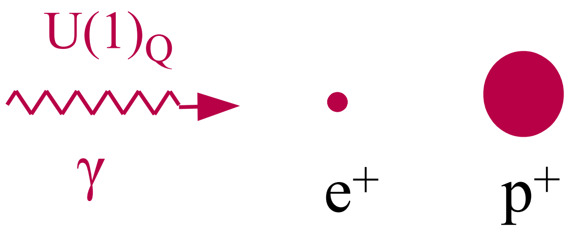
3 gen. = "identical copies" up to high energies

A new paradigm in flavor physics

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 ...

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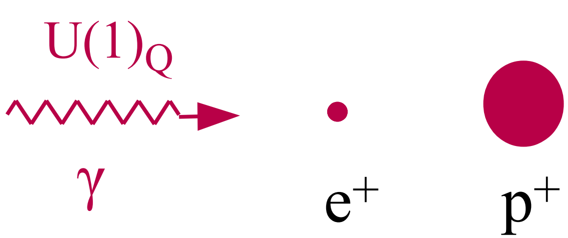
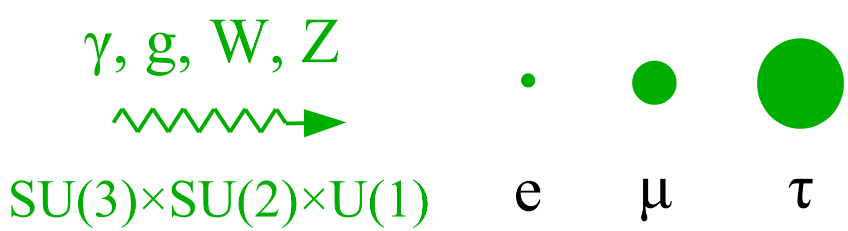


we would conclude that these two particles are "identical copies" but for their mass ...

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

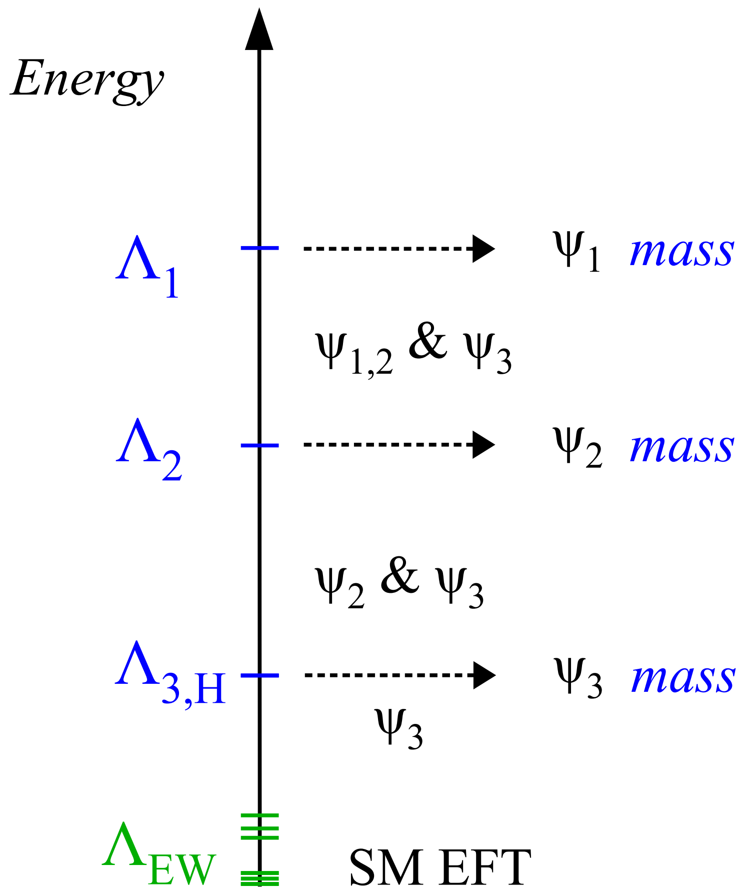


These three (families) of particles seems to be "identical copies" but for their mass ...

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

A new paradigm in flavor physics

~~*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:
- 1st & 2nd gen. have small masses because they are coupled to NP at heavier scales

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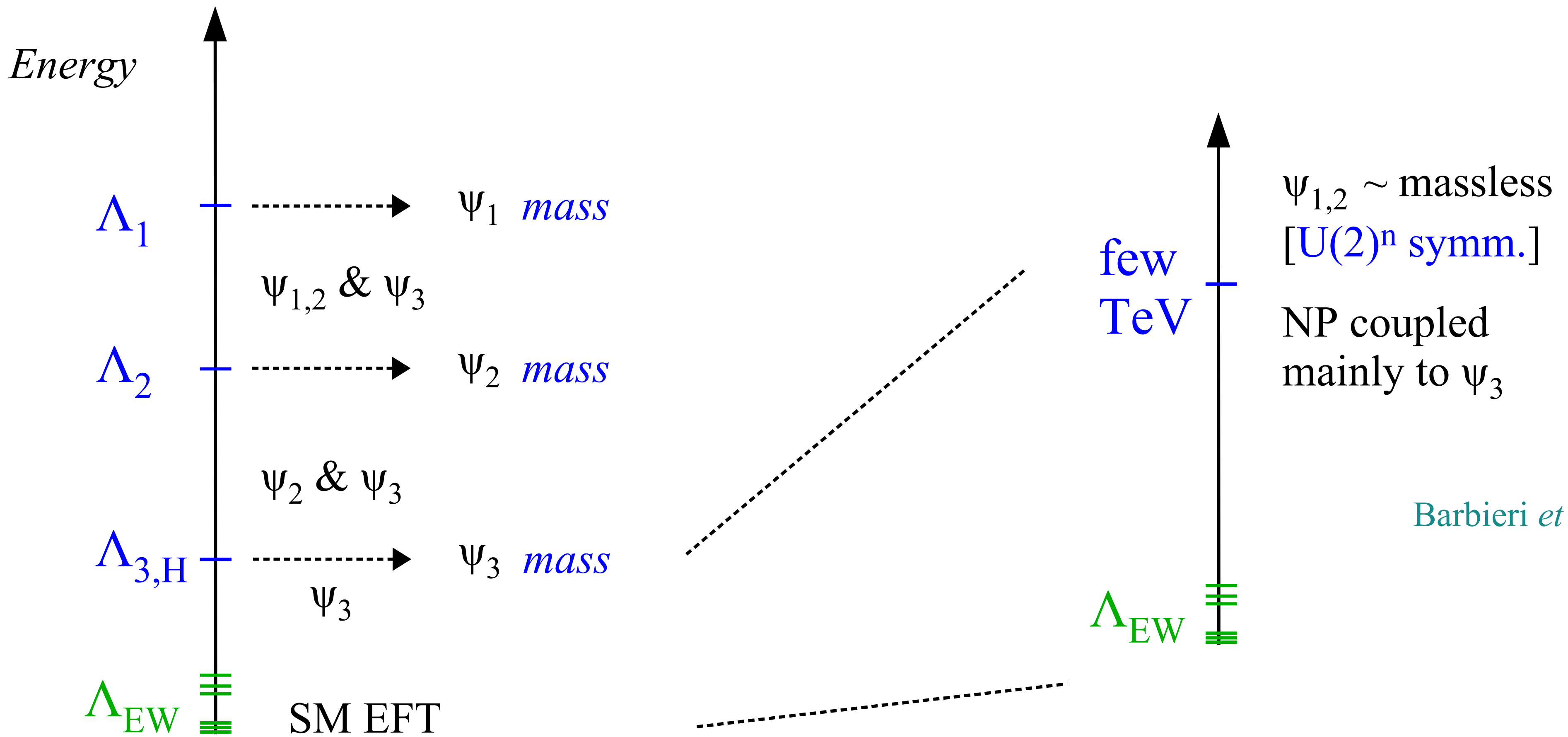
~~3 gen. = "identical copies" up to high energies~~

A new paradigm in flavor physics

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



Barbieri *et al.* '11

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

A new paradigm in flavor physics

IF the multi-scale picture is correct.... we should expect to see several other BSM effects in low-energy observables (independently *of the specific natures of the mediators*)

⬇

- Exciting (and vast) program for Belle-II, complementary to the one of LHCb and other facilities.
- This program is essential to characterize the NP sector.

A new paradigm in flavor physics

If the multi-scale picture is correct, we should expect to see several other BSM effects in low-energy observables.

E.g.: correlations among down-type FCNCs [*using the results of* U(2)-*based EFT*]:

	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$
$b \to s$	R_K, R_{K^*} *present anomalies*	$B \to K^{(*)}\,\tau\tau$ ⋮	$B \to K^{(*)}\,\nu\nu$ ⋮
$b \to d$	$B_d \to \mu\mu$ $B \to \pi\,\mu\mu$ $B_s \to K^{(*)}\,\mu\mu$ ⋮	$B \to \pi\,\tau\tau$ ⋮	$B \to \pi\,\nu\nu$ ⋮
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi\,\nu\nu$

A new paradigm in flavor physics

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	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$
$b \to s$	R_K, R_{K^*} O(20%) R_D	$B \to K^{(*)}\,\tau\tau$ $\to$ 100×SM	$B \to K^{(*)}\,\nu\nu$ O(1)
$b \to d$ R_K	$B_d \to \mu\mu$ $B \to \pi\,\mu\mu$ $B_s \to K^{(*)}\,\mu\mu$ O(20%) [R_K=R_π]	$B \to \pi\,\tau\tau$ $\to$ 100×SM	$B \to \pi\,\nu\nu$ O(1)
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi\,\nu\nu$ O(1)

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$b \to d$	$B_d \to \mu\mu$ $B \to \pi\, \mu\mu$ $B_s \to K^{(*)}\, \mu\mu$ O(20%) [$R_K = R_\pi$]	$B \to \pi\, \tau\tau$ $\to$ 100×SM	$B \to \pi\, \nu\nu$ O(1)	$B \to \pi\, \tau\mu$ $\to \sim 10^{-7}$	$B \to \pi\, \mu e$???
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi\, \nu\nu$ O(1)	*NA*	$K \to \mu e$???

A new paradigm in flavor physics

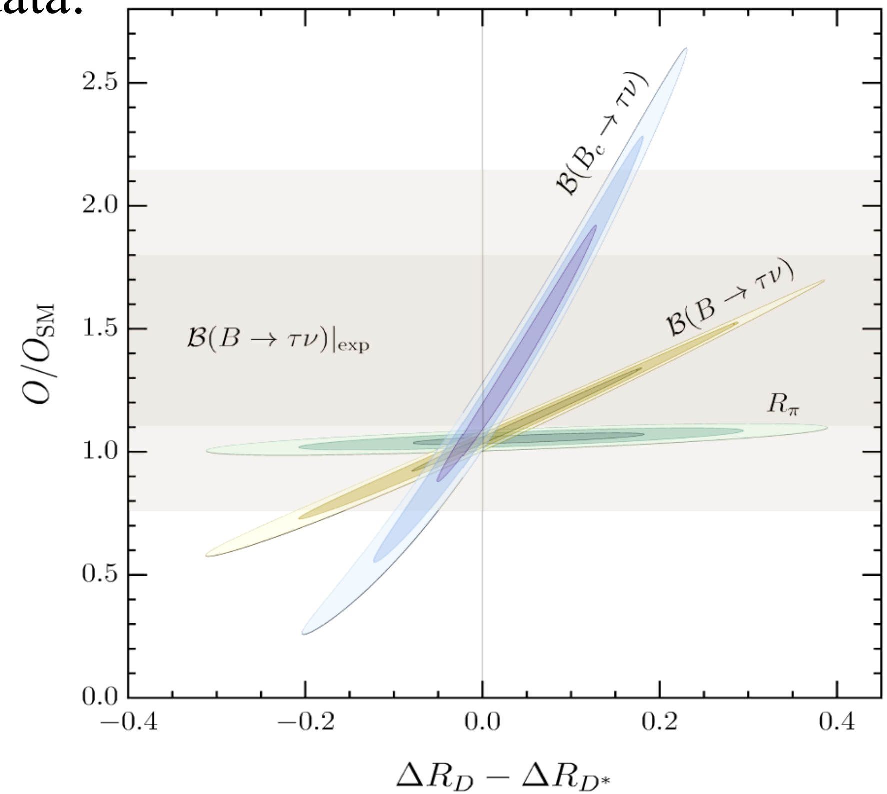
E.g. (II): charged-current observebles

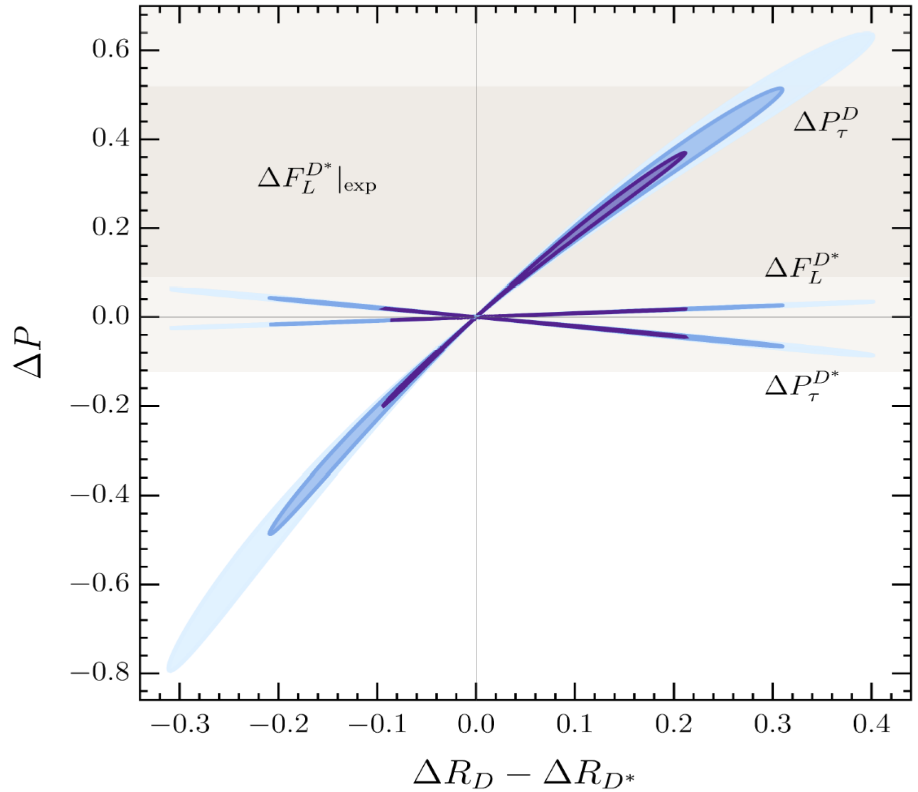
Minimal setup:

- LH nature of NP → universality of all $R^{\tau/\mu}(b\to c)$ ratios [$R_D = R_{D*} = \ldots$]
- U(2) symmetry → $R^{\tau/\mu}(b\to c)$=$R^{\tau/\mu}(b\to u)$ universality [$R_D = R_\pi = \ldots$]

To be tested with data:

Fuentes-Martin, GI, Pages, Yamamoto, '19



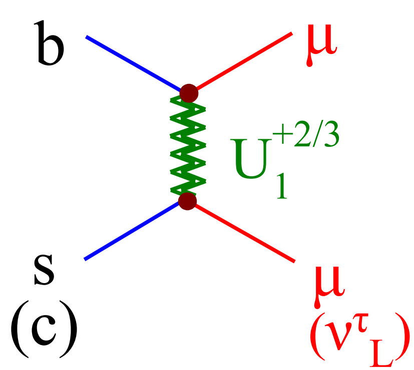


A new paradigm in flavor physics

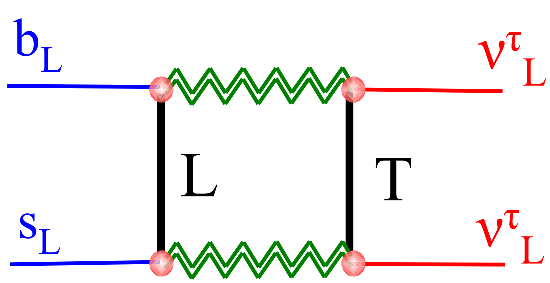
E.g. (III): loop-induced FCNCs

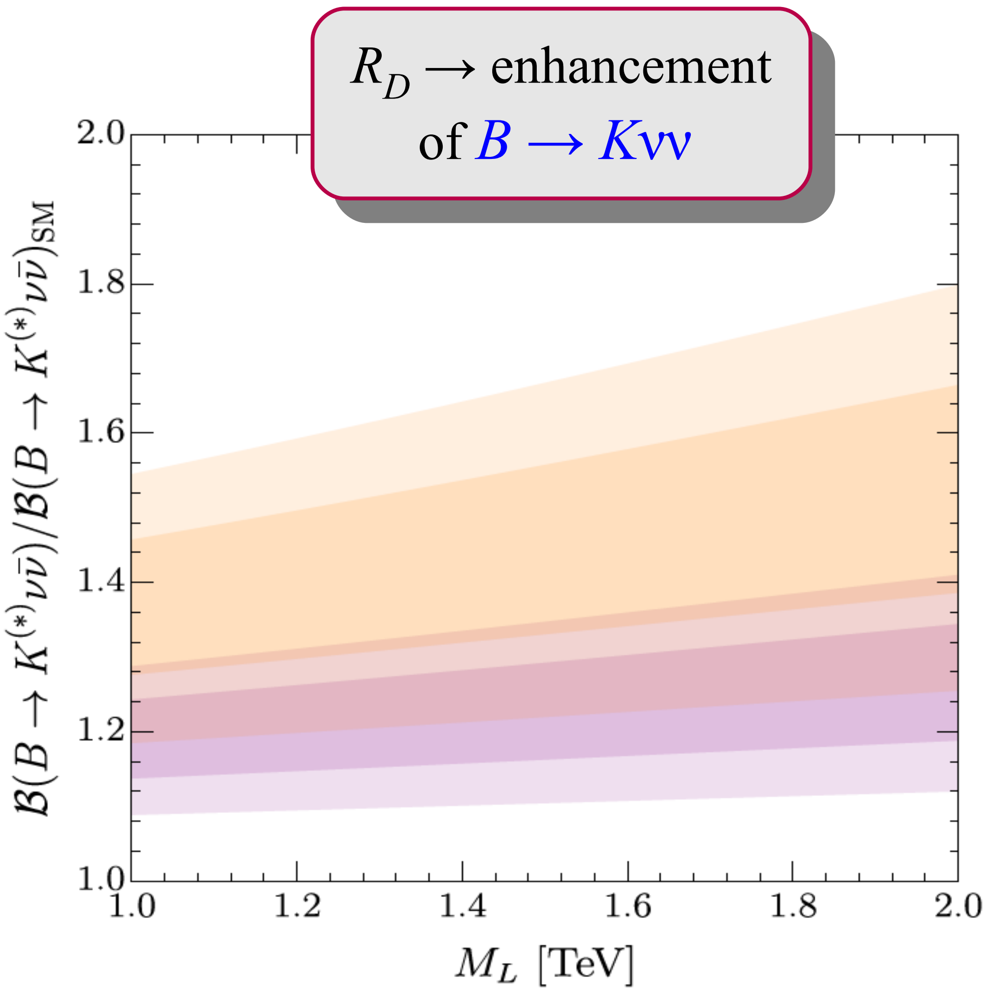
$B \to K^{(*)} \nu\nu$

No tree-level contribution from the "most succesfull" mediator



But one-loop indiced amplitude:





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

Conclusions

- Flavor is an essential ingredient to understand the structure of physics beyond the SM. This statement, which we deduce already by the SM Yukawa structure, is reinforced by the recent anomalies
- The statistical significance of the LFU anomalies is growing: in the $b \to s\ell\ell$ 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

⬇

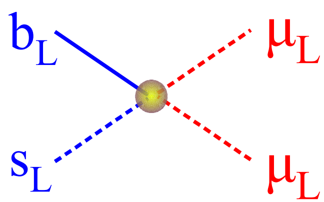
Very interesting (near-by!) future...
(both on the exp., the pheno,
and the model-building point of view)


Backup

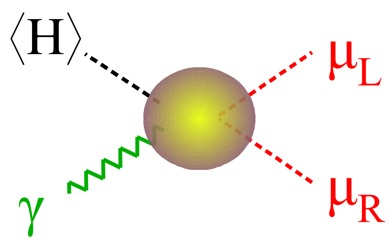
EFT considerations

The situation might be different if the charged-current anomalies will go away [→ *key role of Belle-II in clarifying this...*]

A possible alternative “story”:



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



→ Δa_μ^{NP} $\boxed{\sim 4\ \sigma}$

(*more controversial...*)

Possible unified description by means of a new interaction with <u>special role for muons</u> (and maybe tau's) → Z' is back !

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

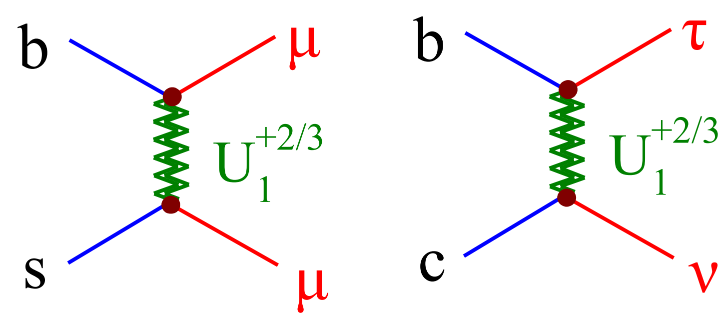
Greljo, Stangl, Thomsen '21
Baum *et al.* '21
Davighi, '21
Altmannshofer *et al.* '21
\+ *many others…*

From EFT to simplified models

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]



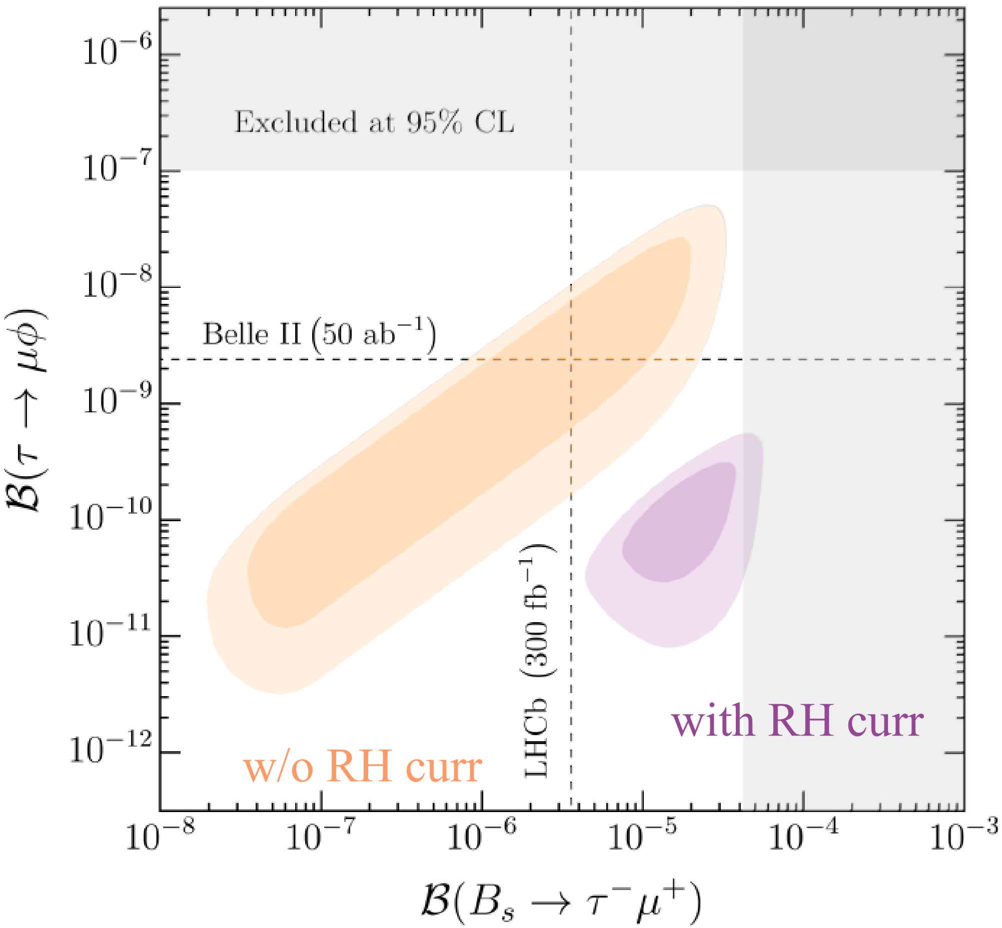
Barbieri, GI, Pattori, Senia '15

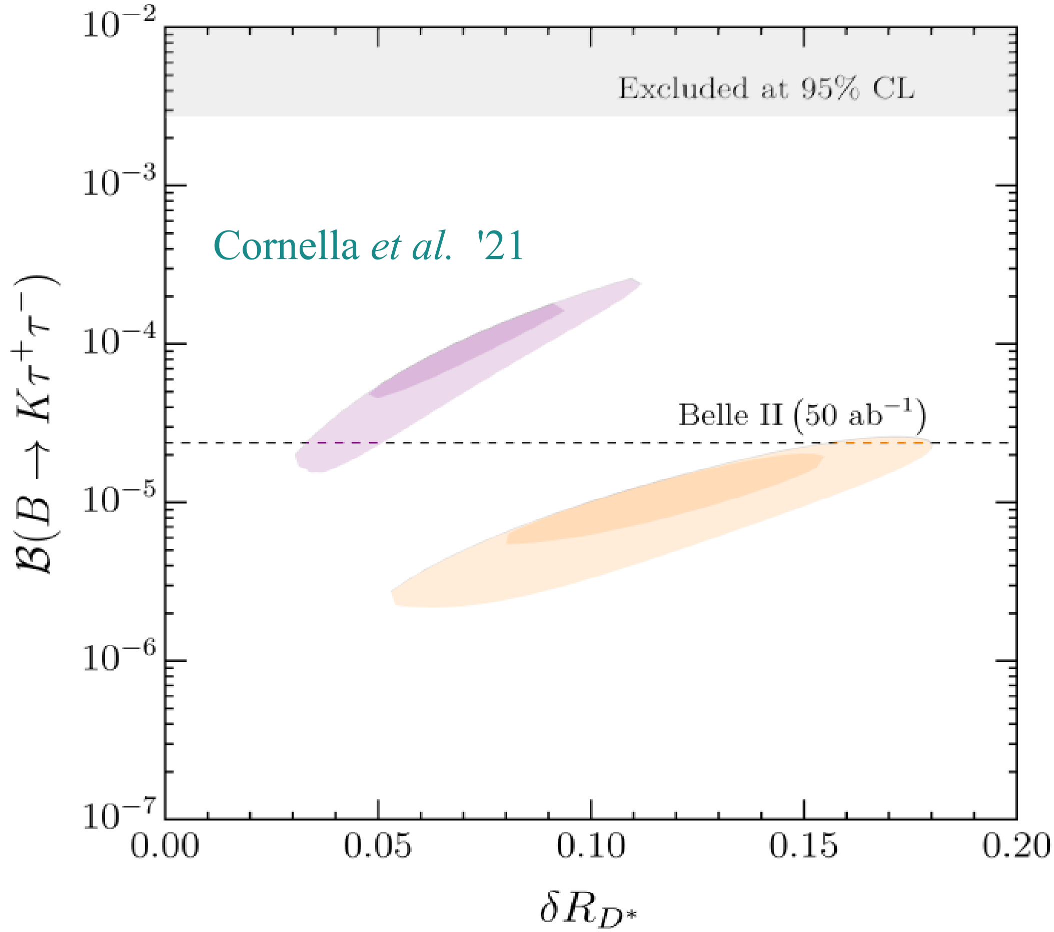
- mediator: U_1
- flavor structure: $U(2)^n$

LQ of the Pati-Salam gauge group:

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

▶ Other low-energy observables





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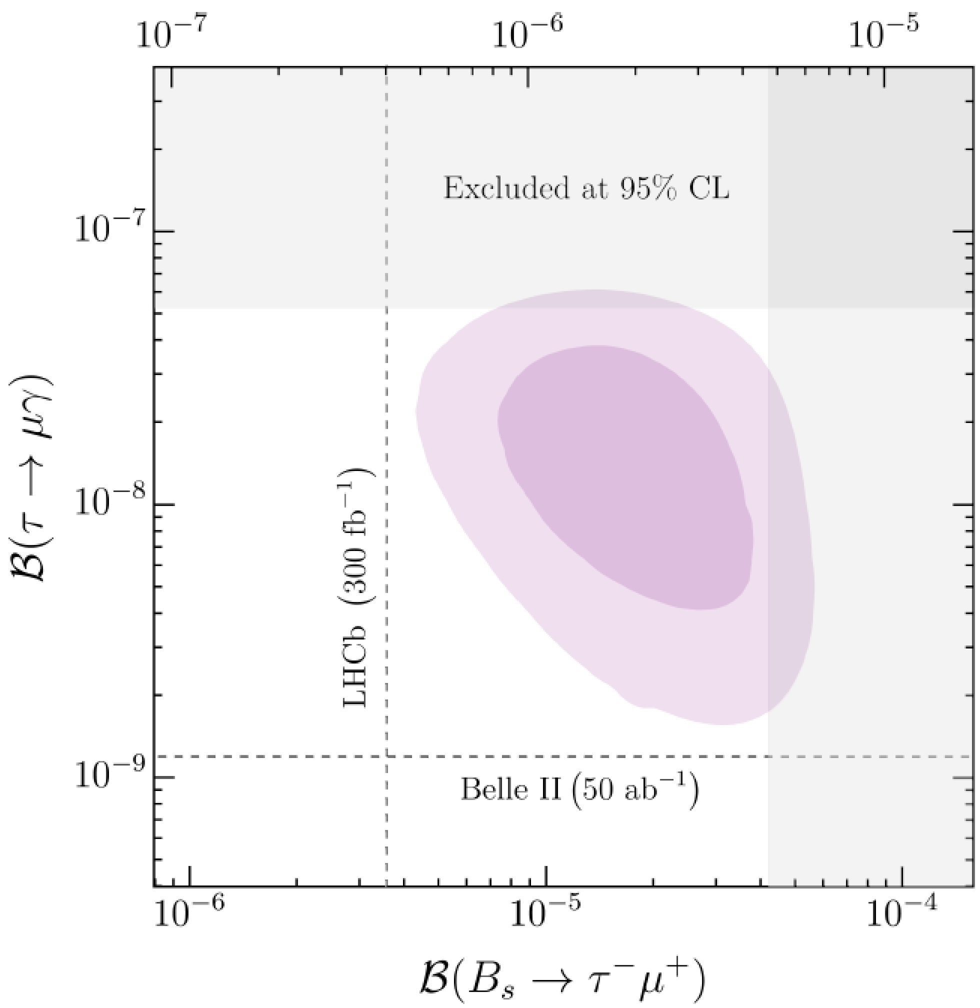
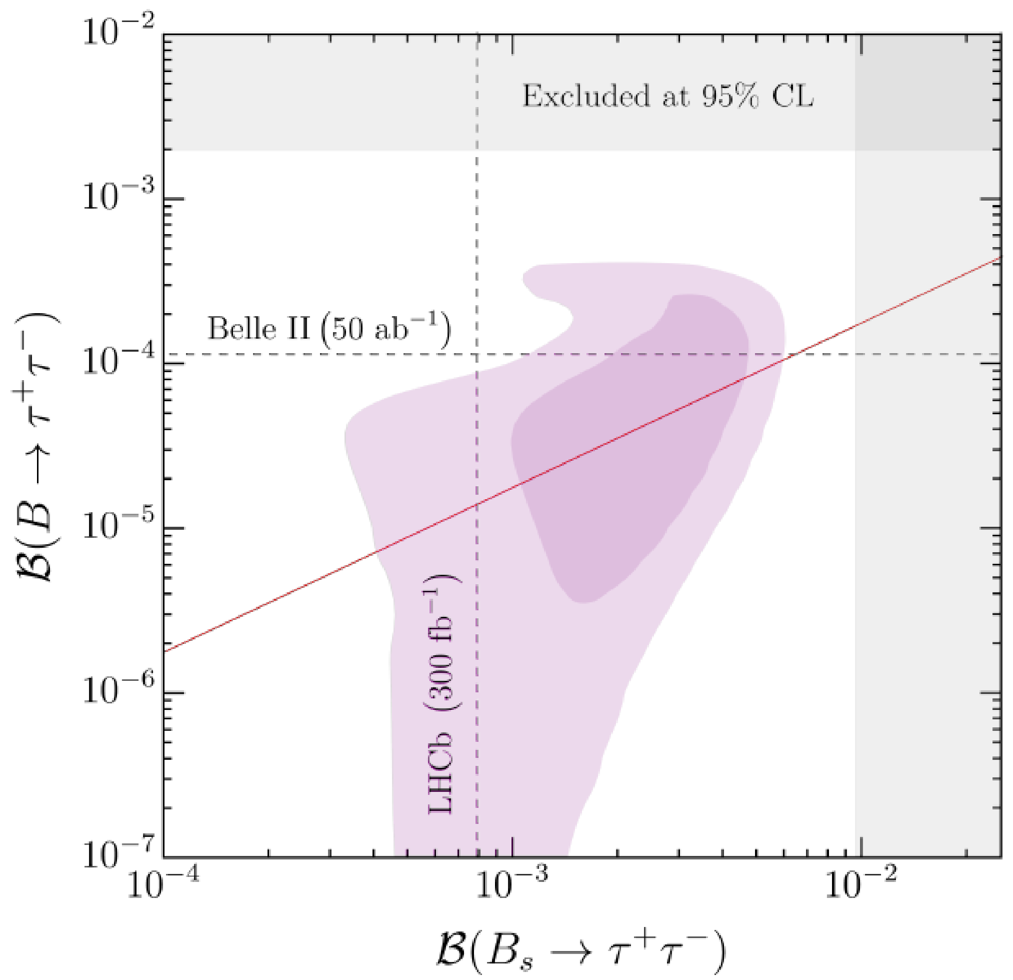
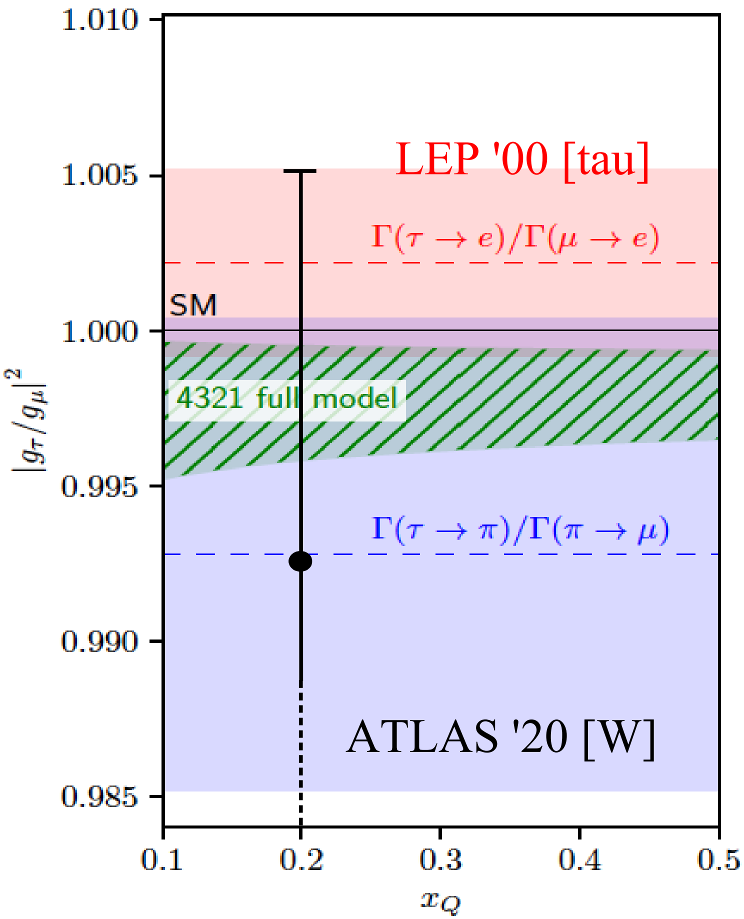




Other low-energy observables

Tests of universality in tau decays:



Allwicher, GI, Selimovic, '21

U_1 LQ