Flavor non-universal interactions

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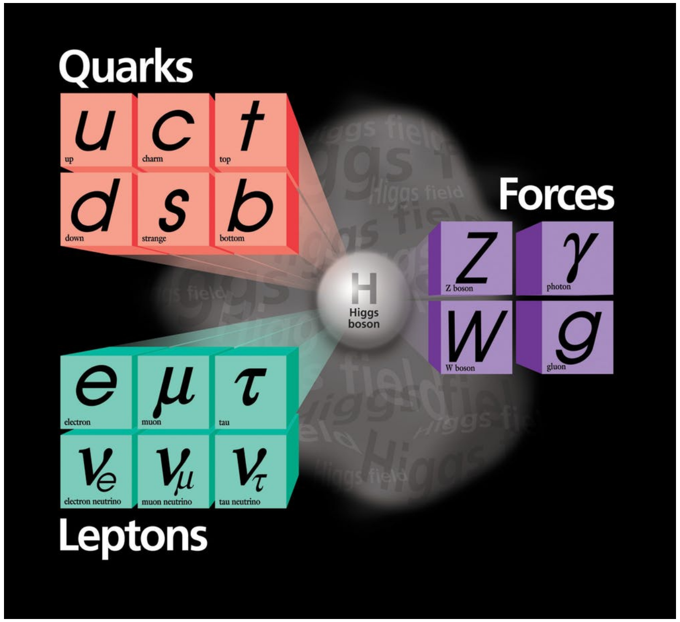
- Introduction
- The two flavor puzzles
- Flavor non-universal interactions
- Hints on non-universality in B-physics data
- Fture prospects
- Conclusions

University of Zurich UZH

European Research Council
Established by the European Commission

Introduction



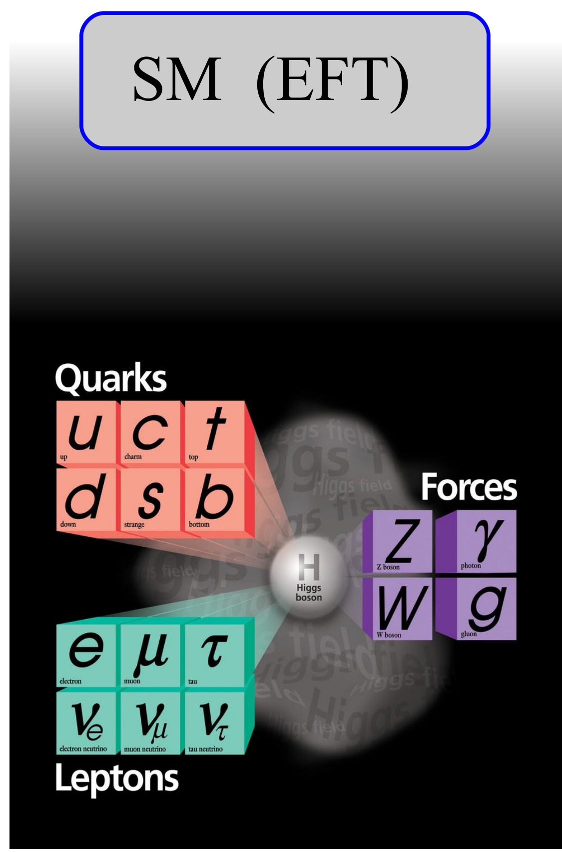
Introduction

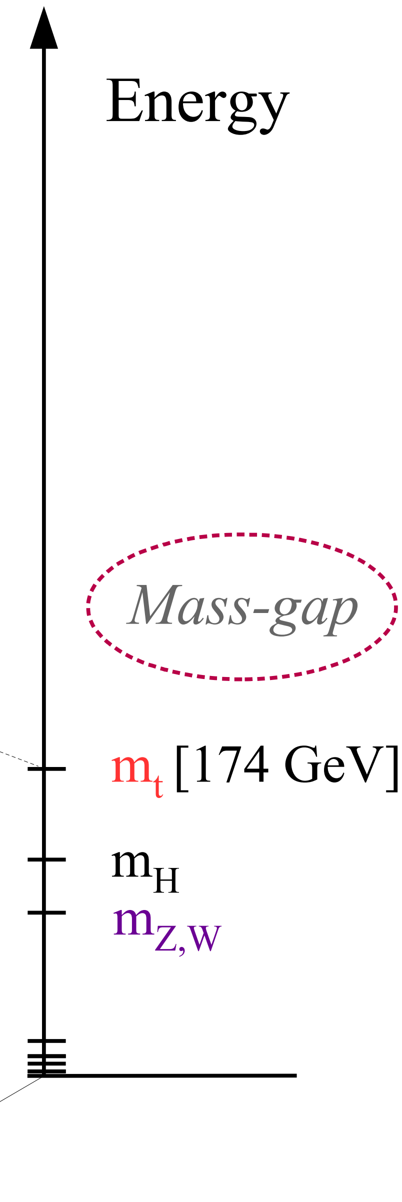
We recently celebrated the 10th anniversary of the Higgs-boson discovery (*or the completion of the SM spectrum*).

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

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

We identified only the *long-range* properties of this EFT





Introduction

Beside general QFT arguments, there are several “problems” calling for a non-trivial UV completion:

Electroweak hierarchy problem

Flavor puzzle

U(1) charges

Neutrino masses

Strong CP problem

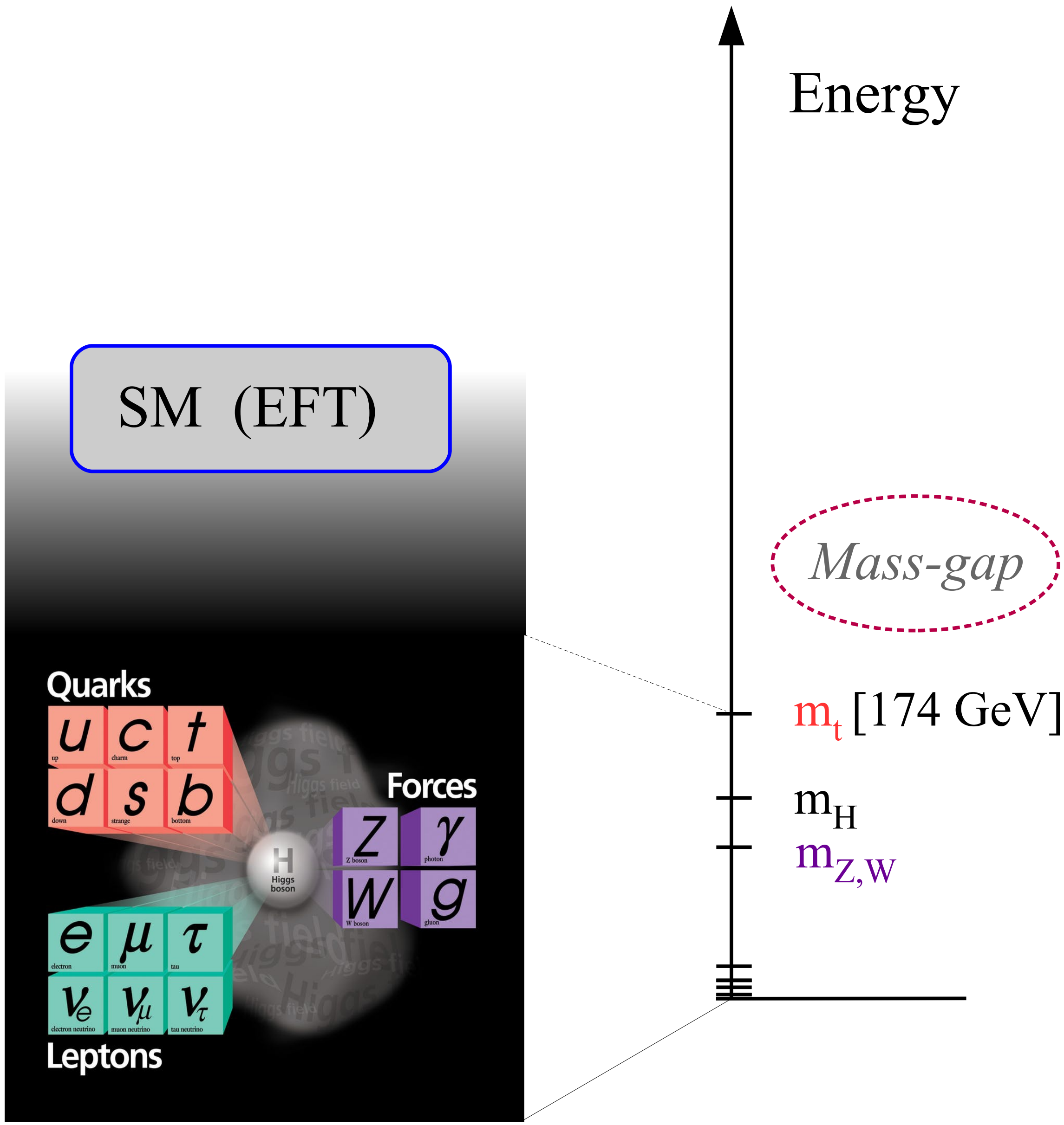
….

Dark-matter

Dark-energy

Inflation

Quantum gravity



Introduction

Beside general QFT arguments, there are several "problems" calling for a non-trivial UV completion:

Electroweak hierarchy problem

Flavor puzzle

U(1) charges

Neutrino masses

Strong CP problem

non-trivial properties of the SM Lagrangian if interpreted as EFT

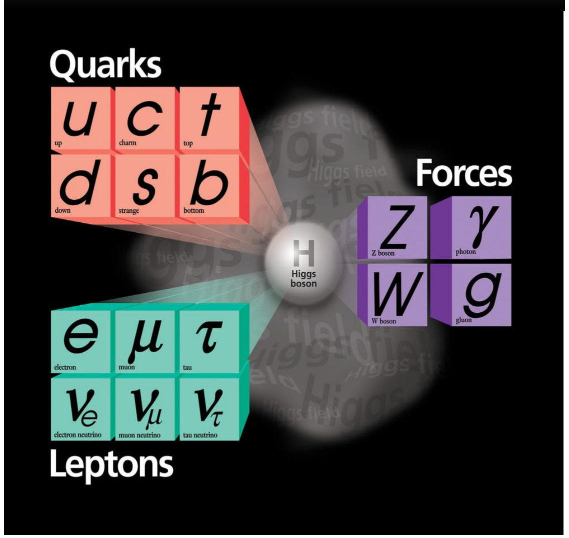
$\downarrow$

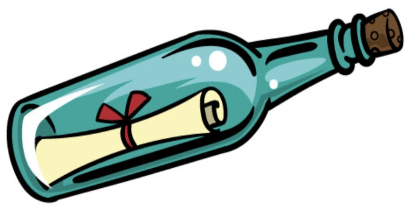
Useful hints for its UV completion

UV Theory

$\downarrow$

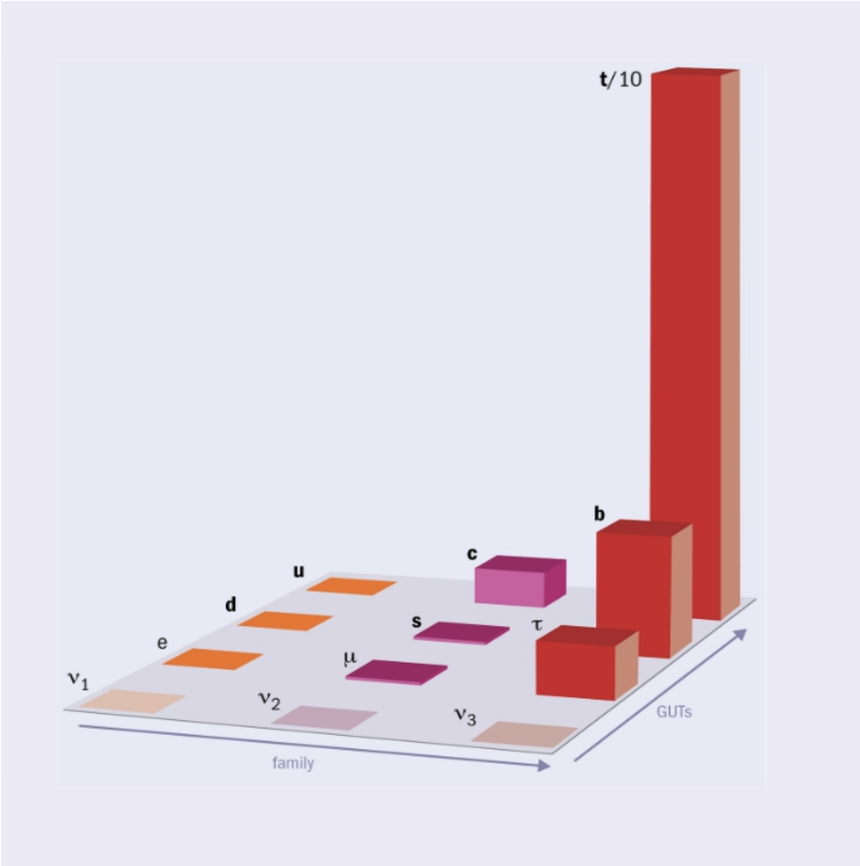
SM (EFT)





Messages from the UV we need to decode..

The two flavor puzzles



One summer I sat down and said:

"This is the summer when I'm not going to do anything but solve [the flavor] *problem."*

This was 40 years ago and I haven't solved it. No one has [...]. *That's been a frustration now for 40 years...*

[S.Weinberg, 2013]

The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental [*SM flavor puzzle*]

→ Is there a deeper explanation for this peculiar structures?

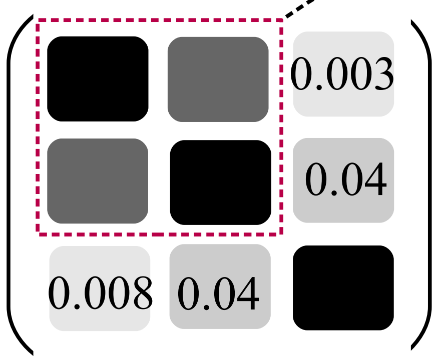
The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental:

unitarity violation of the 2×2 (light) block below 10^{-3} !

$V_{\mathrm{CKM}} \sim$

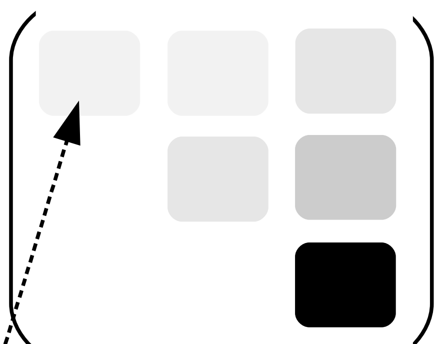


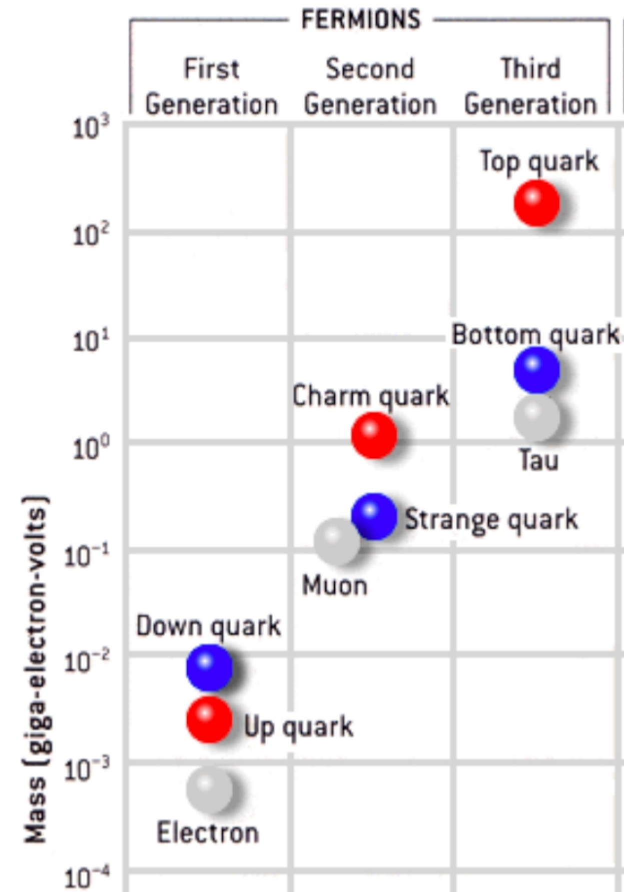
N.B.: Despite the very good knowledge we have nowadays about the CKM matrix, we are <u>not able to detect the presence of the 3rd family</u> by looking only at the 2×2 block (*as one naively would have expected...*)

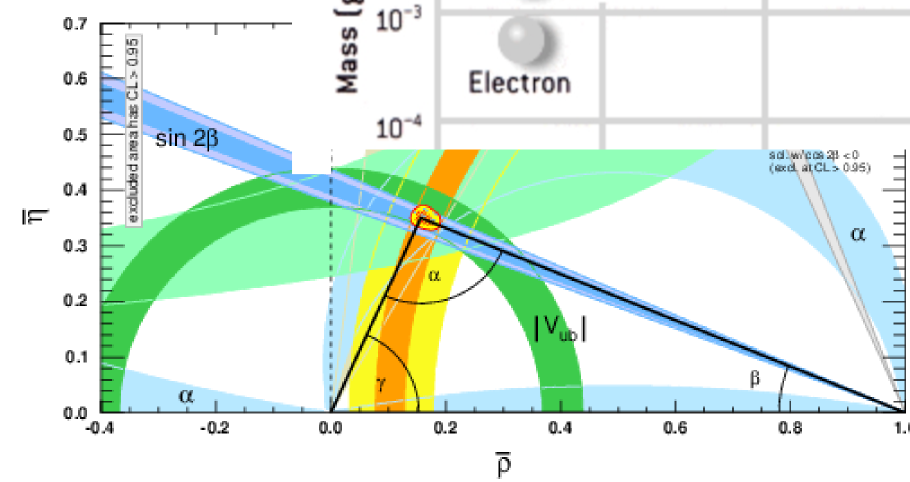
The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental:

$Y_U \sim$ 





$$y_u = \frac{\sqrt{2}\, m_u}{\langle H \rangle} \approx 10^{-5} \qquad y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle} \approx 1$$

[Y_U in the basis where Y_D is diagonal]

The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental:

$$Y_U \sim \left(\begin{array}{c|c} \overbrace{\quad < 0.01 \quad}^{U(2)_u} & 0.003 \\ & 0.04 \\ \hline & 1 \end{array}\right) \begin{array}{l} \left.\vphantom{\begin{matrix} a \\ a \end{matrix}}\right] \leftarrow U(2)_q \\ \vphantom{a} \end{array} \qquad\qquad \bar{Q}_L \, Y_U \, U_R \, H$$

What we observe in the Yukawa couplings is an approximate $U(2)^n$ symmetry acting on the light families

The two flavor puzzles

Even forgetting current anomalies, there are two (long-standing) open issues in flavor physics:

I. The observed pattern of SM Yukawa couplings does not look accidental [*SM flavor puzzle*]

→ Is there a deeper explanation for this peculiar structures?

II. If the SM is only an effective theory, valid below an ultraviolet cut-off , why we do not see any deviation from the SM predictions in the (suppressed) flavor changing processes? What constraints these observations imply on physics beyond the SM? [*NP flavor puzzle*]

→ Which is the flavor structure of physics beyond the SM?

The two flavor puzzles

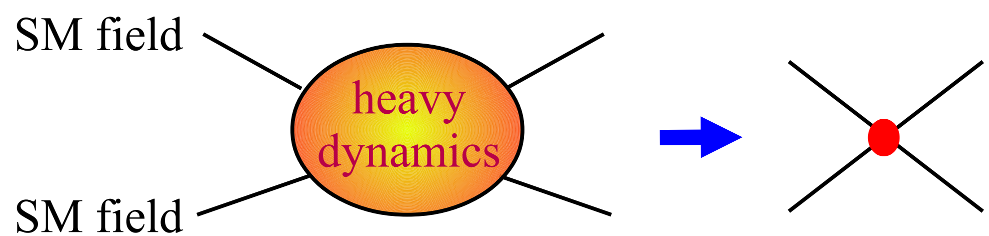
$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

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

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

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

"Remnant" of the heavy dynamics at low energies



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Large flavor symmetry

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

Flavor-degeneracy broken by the Yukawa interaction

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

"Peculiar" breaking structure

Exact & approximate (*accidental* ?) symmetries

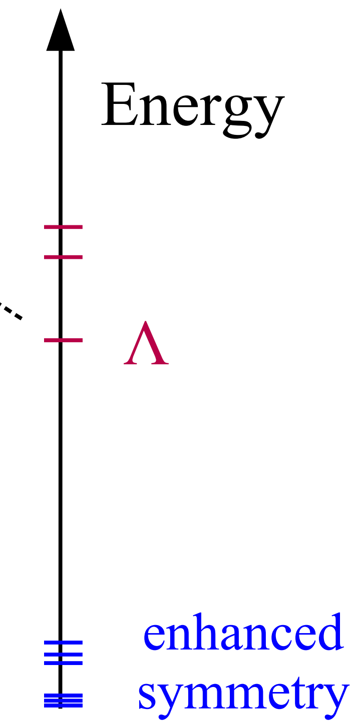
Eg:

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

▸ *Accidental symmetries in QFT* [a brief detour]

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

(long-distance interactions) (local contact interact.)



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

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

Violations of accidental symmetries

How to explain CP violation in the SM, and the history of the KM mechanism, are a wonderful illustration of this effect

Accidental symmetries in QFT [a brief detour]

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

[SM-2]-EFT

(long-distance interactions) (local contact interact.)

Back in 1973: SM with 2 generations, as "reference model" → CP violation is an accidental symmetry [KM, '73]

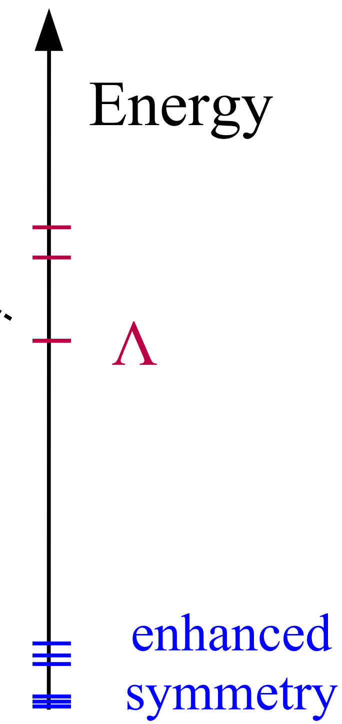
But CP violation is observed in K mixing [→ remnant of "heavy NP"]

$$\Lambda_{CP} \sim 10^4 \text{ TeV}$$

$$\frac{e^{i\delta}}{\Lambda_{CP}^2} (\bar{s}\,\Gamma\, d)^2$$

"Super-weak" interaction

[L. Wolfenstein, '64]



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[SM-2]-EFT

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Energy

Λ

enhanced symmetry

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$\Lambda_{CP} \sim 10^4$ TeV

$$\frac{e^{i\delta}}{\Lambda_{CP}^2} (\bar{s}\,\Gamma\, d)^2$$

SM-3

[KM, '73]

$$\frac{1}{\Lambda_{CP}^2} \sim \frac{(G_F\, m_t V_{ts} V_{td})^2}{4\pi^2}$$

Ellis, Gaillard, Nanopulos, '76

Key message: beware of seemingly high scales in EFT approaches: they can be a "mirage"...

The two flavor puzzles

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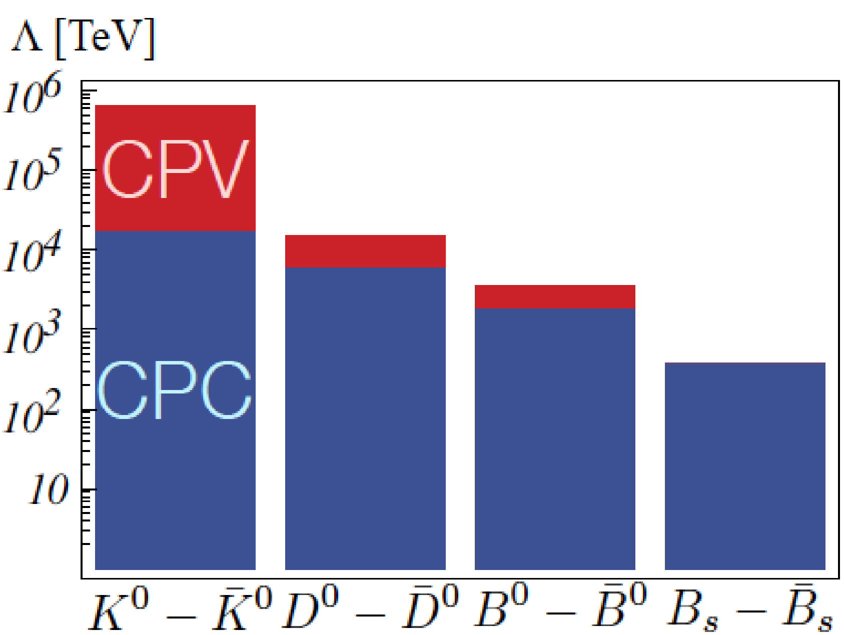
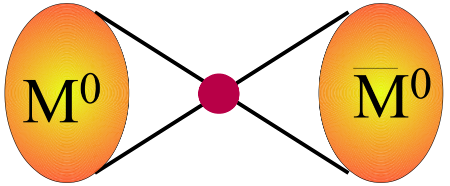
In principle, in the SM-EFT we could expect many violations of the accidental symmetries from the heavy dynamics (→ *new flavor violating effects*). However, no clear deviations observed so far

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

The NP flavor puzzle





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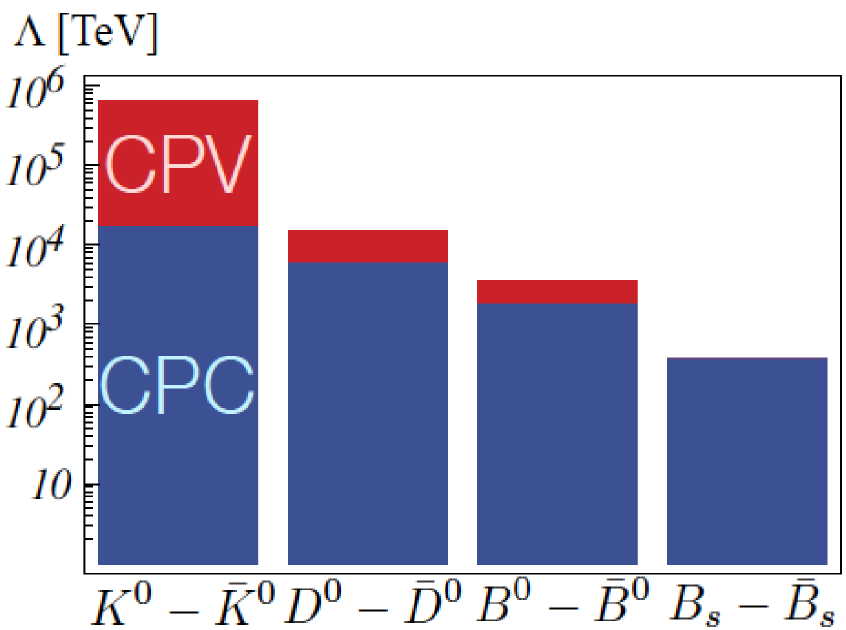


N.B. (1): These high scales can be a "mirage" [*remember CP in SM-2...*].

Only unambiguous message: no large breaking of the approximate $U(2)^n$ flavor symmetry at near-by energy scales.

N.B. (2): $U(2)^n$ is not an accidental symmetry of the SM [→ *indication of specific UV dynamics?*]

The two flavor puzzles

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

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

Yukawa couplings:
$U(3)^5 \to (\sim)\ U(2)^n$
peculiar breaking of the flavor symm.

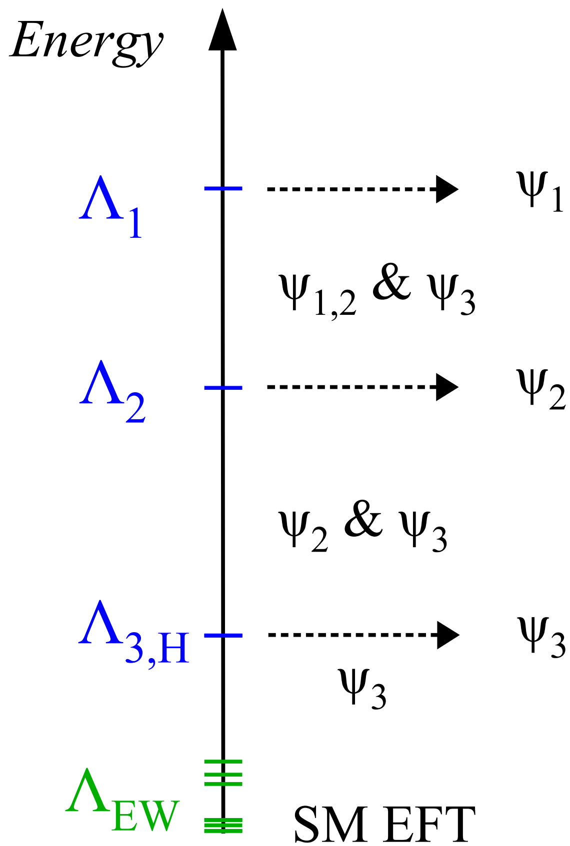
Stringent bounds on generic flavor-violating ops.
$\updownarrow$
approx. $U(2)^n$ holds also beyond the SM

The big questions in flavor physics:

- Can we find an explanation for the Yukawa hierarchies?
- Can the approximate flavor symmetries be <u>accidental symmetries?</u>
  If so, at which scale(s) are they broken?

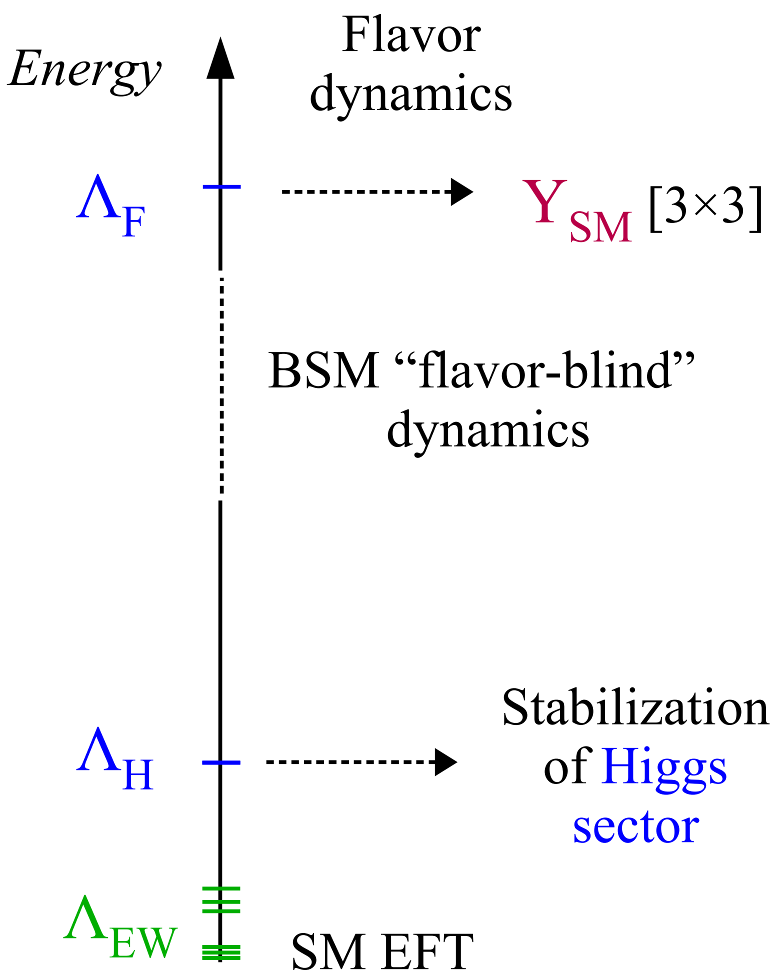
→ **Some (general) hypotheses needed to address these questions**

Flavor non-universal interactions



Flavor non-universal interactions

For a long time, the vast majority of model-building attempts to extend the SM was based on the *implicit* hypotheses of *flavor-universal* New Physics



- Concentrate on the Higgs hierarchy problem
- Postpone the flavor problem to higher scales

⬍

The "MFV paradigm"

+

"Horizontal" flavor symmetries @ high scales

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

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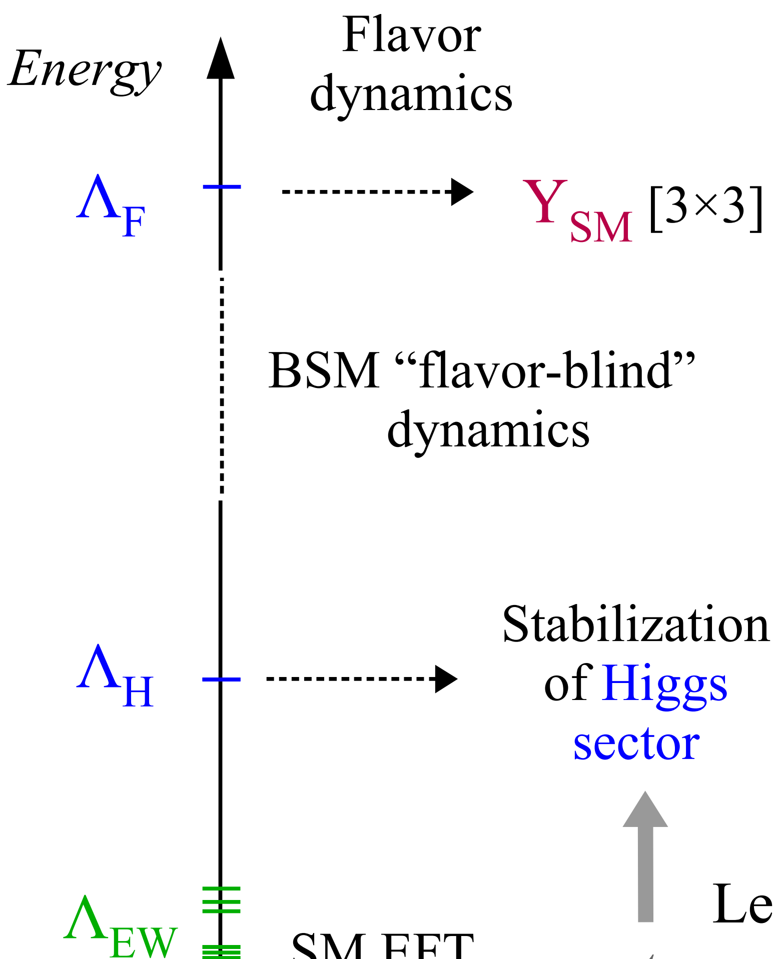

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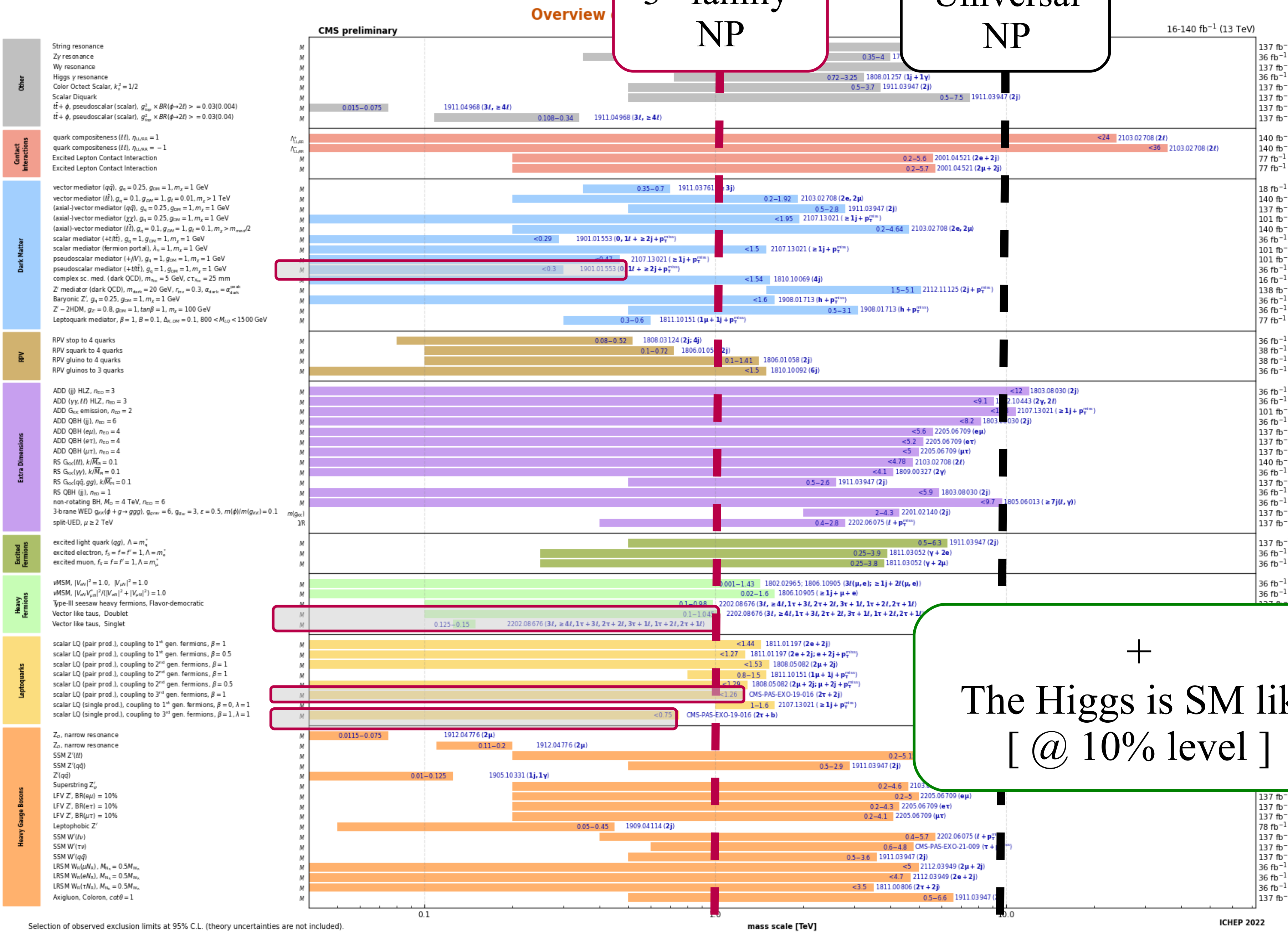
↕

The “MFV paradigm”
+
“Horizontal” flavor symmetries @ high scales

Less compelling after LHC results (run I+II):
strong bounds on NP coupled universally to all families
worsening of the Higgs hierarchy problem

Status of high-energy searches



3$^{\text{rd}}$ family NP

Universal NP

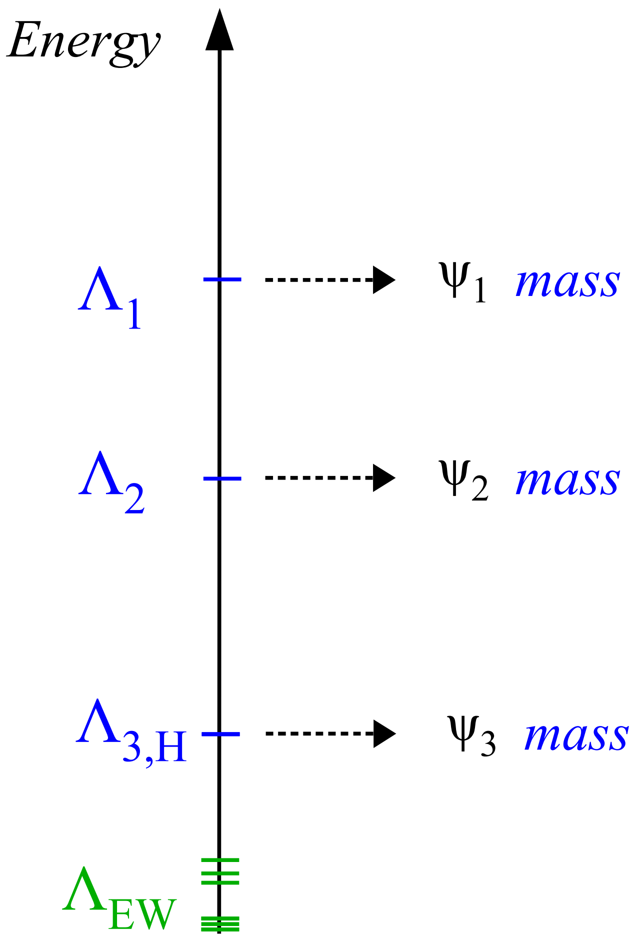
+

The Higgs is SM like [@ 10% level]

▶ *Flavor non-universal interactions*

A more efficient paradigm to address both flavor puzzles (I+II), & *possibly* the Higgs hierarchy, is a *multi-scale* UV with *flavor non-universal* interactions

Dvali & Shifman '00
Panico & Pomarol '16
⋮
Bordone *et al.* '17
Allwicher, GI, Thomsen '20
Barbieri '21
Davighi & G.I. '23



Basic idea:

- 1[st] & 2[nd] generations have small masses (+ small coupling to NP) because these are generated by new dynamics at heavier scales
- *"flavor deconstruction"* of the SM gauge symmetry → flavor hierarchies emerge as accidental symmetries

⬇

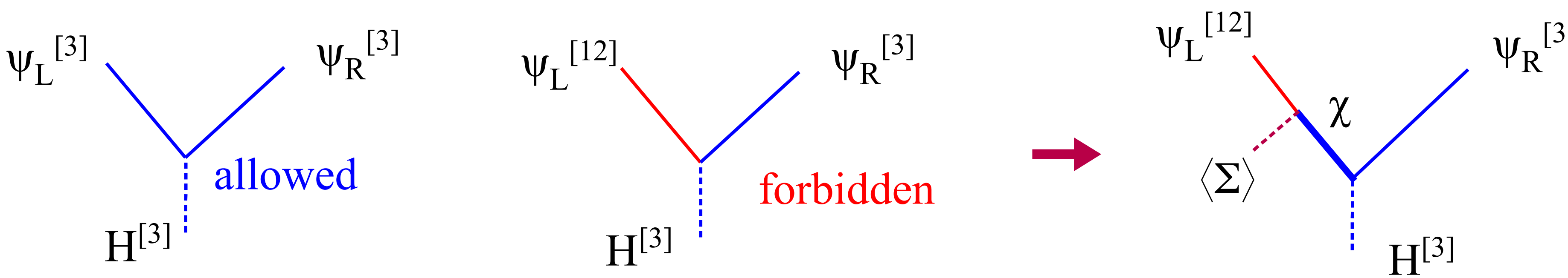
~~3 gen. = "identical copies" up to high energies~~

Flavor non-universal interactions

A more efficient paradigm to address both flavor puzzles (I+II), & *possibly* the Higgs hierarchy, is a *multi-scale* UV with *flavor non-universal* interactions

- *"flavor deconstruction"* of the SM gauge symmetries:

E.g.: $$SU(3)_c \times SU(2)_L \times U(1)_Y^{[3]} \times U(1)_Y^{[12]} \xrightarrow{\langle\Sigma\rangle} SU(3)_c \times SU(2)_L \times U(1)_Y$$



$$V_{cb} \sim \frac{\langle\Sigma\rangle}{M_\chi}$$

Flavor non-universal interactions

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- "*flavor deconstruction*" of the SM gauge symmetries:

More generally:
[@ few TeV]

$$G^{[3]} \times G^{[12]} \rightarrow G^{[\text{Univ}]}$$

Symmetry acting on 3rd gen. + Higgs

Symmetry acting on light gen.

G = subset of SM gauge

- Charging the Higgs under $G_{SM}^{[3]}$ → only the Yukawa of the third generation are allowed → "solution" of the SM flavor problem
- $G_{SM}^{[12]}$ symmetry → accidental $U(2)^n$ flavor symmetry → protection of flavor-changing processes as effective as in MFV
- The symmetry-breaking pattern $G^{[3]} \times G^{[12]} \rightarrow G^{[\text{Univ}]}$ is very general (*no tuning in the potential*) → flavor universality naturally emerges at low energies

Flavor non-universal interactions

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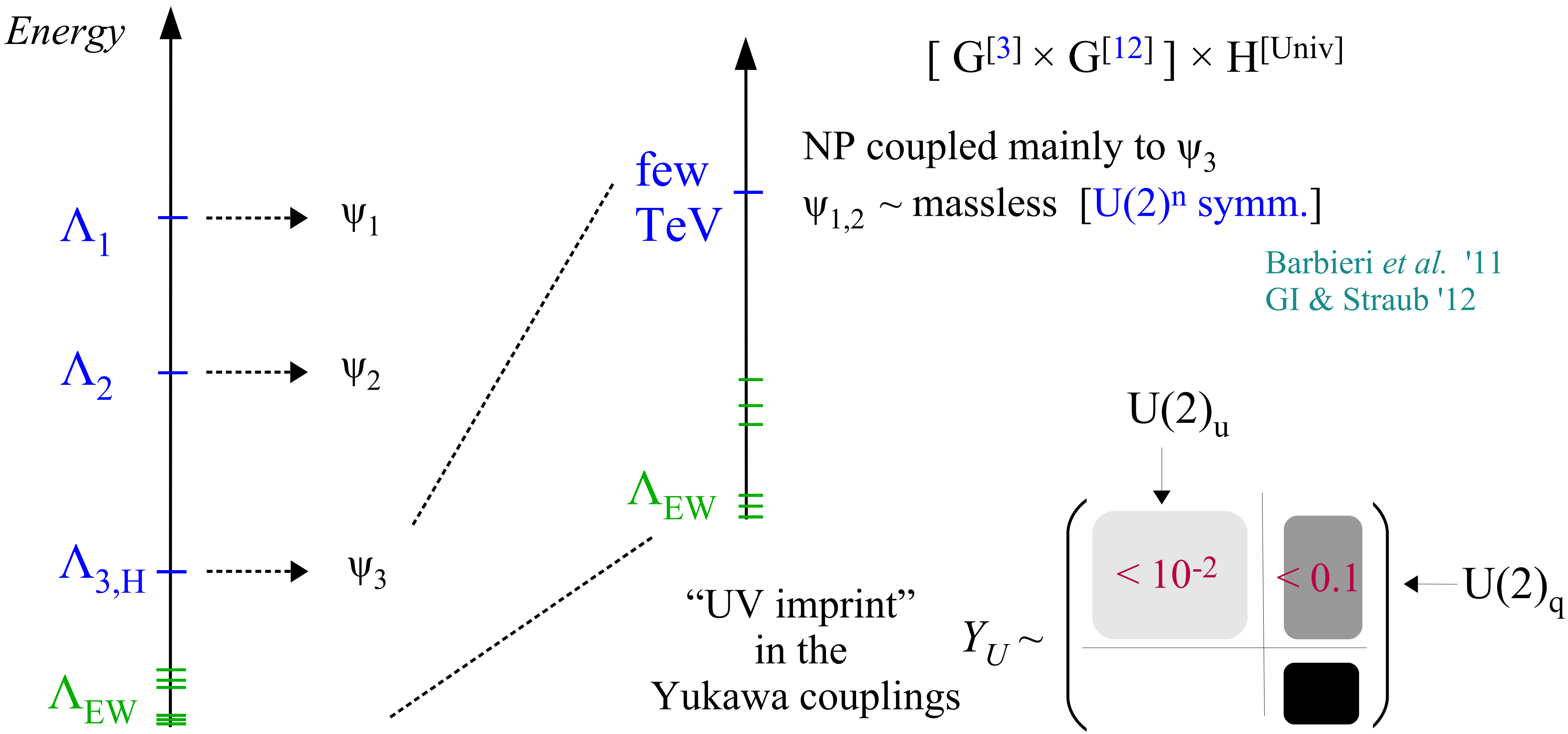
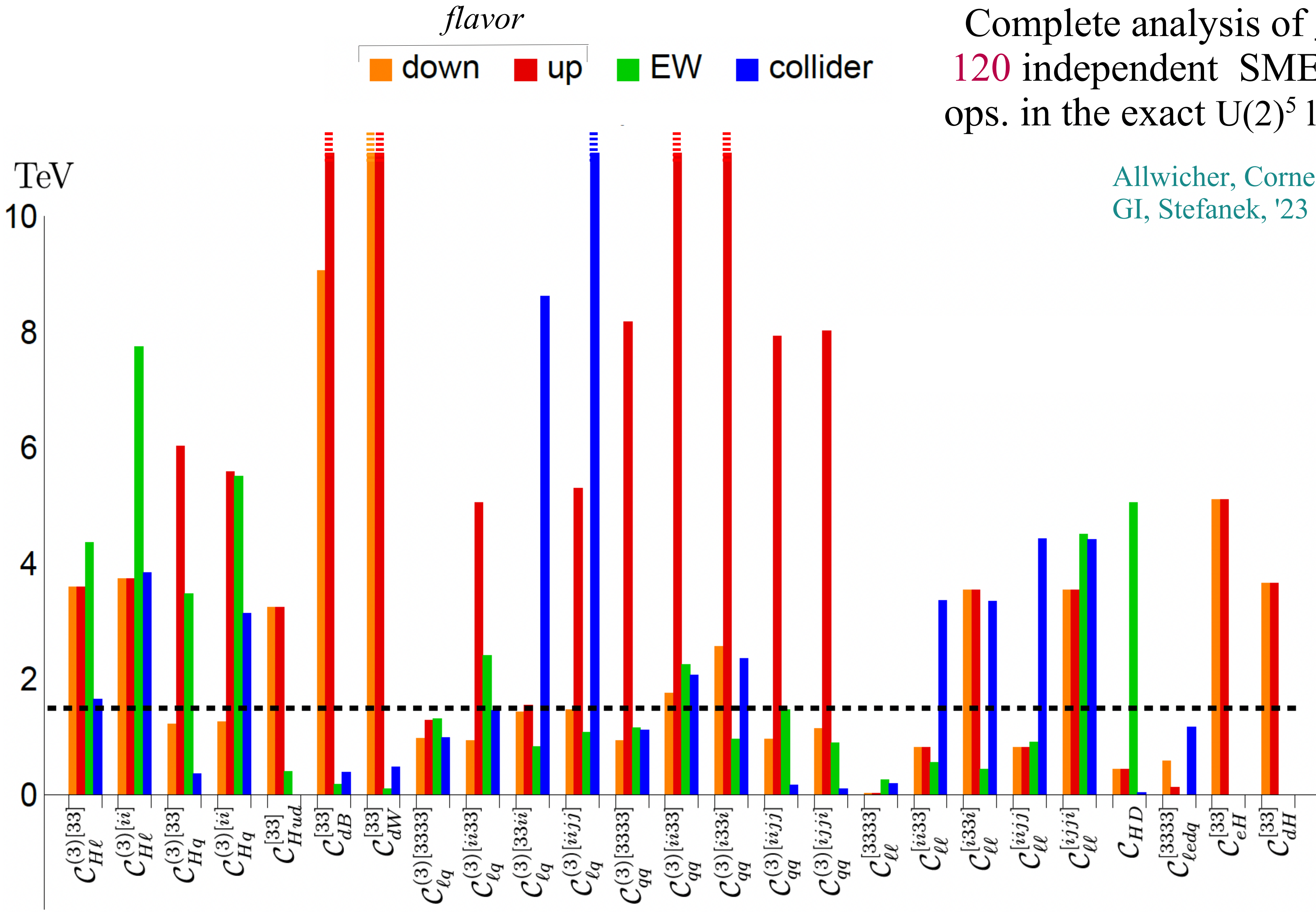


Effective organizing principle for the flavor structure of the SMEFT

▶ *SMEFT bounds in the* U(2)^5 *symmetric limit* [a brief detour]

Complete analysis of all 120 independent SMEFT ops. in the exact U(2)^5 limit

Allwicher, Cornella, GI, Stefanek, '23



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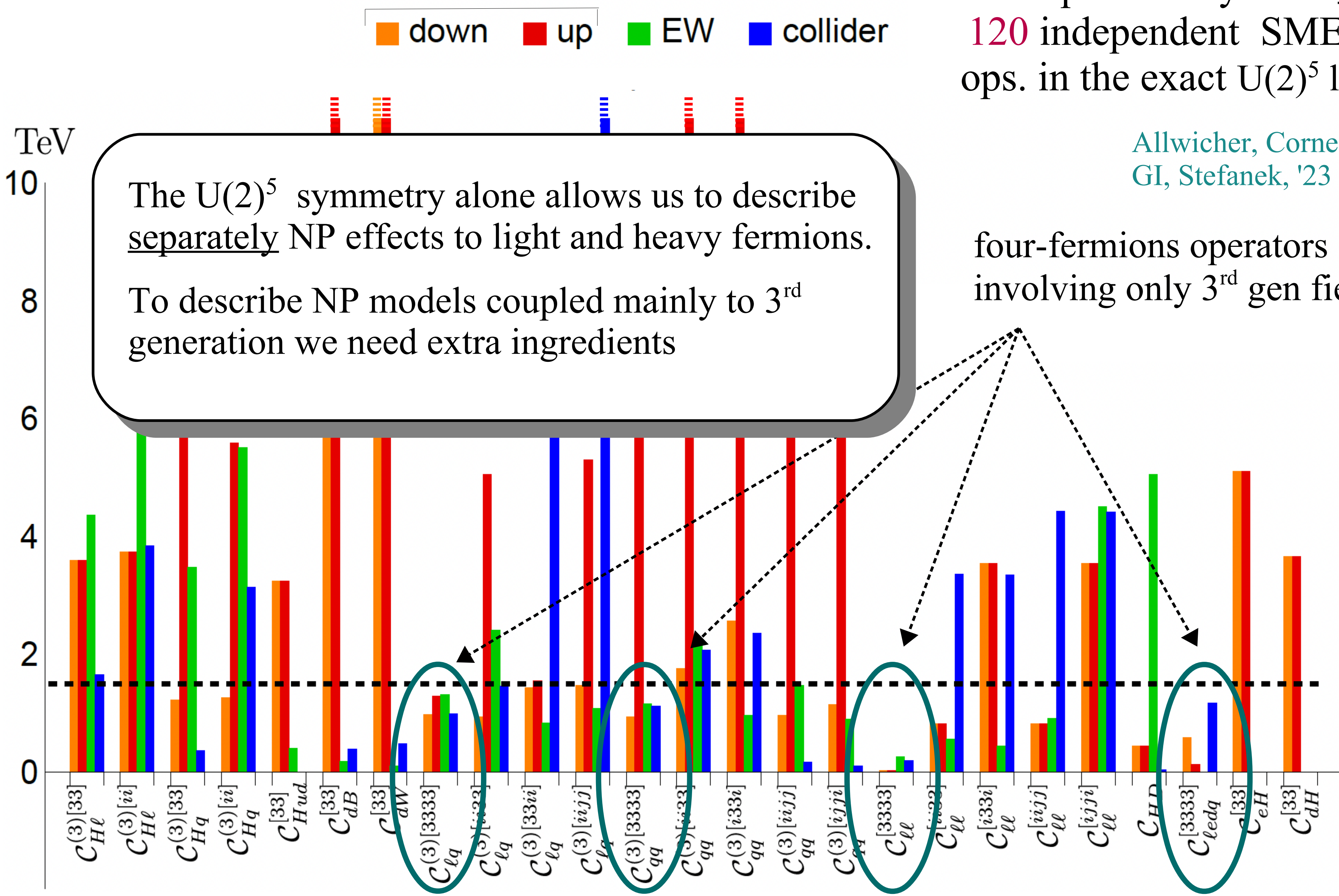

The U(2)^5 symmetry alone allows us to describe separately NP effects to light and heavy fermions.

To describe NP models coupled mainly to 3rd generation we need extra ingredients

four-fermions operators involving only 3rd gen fields

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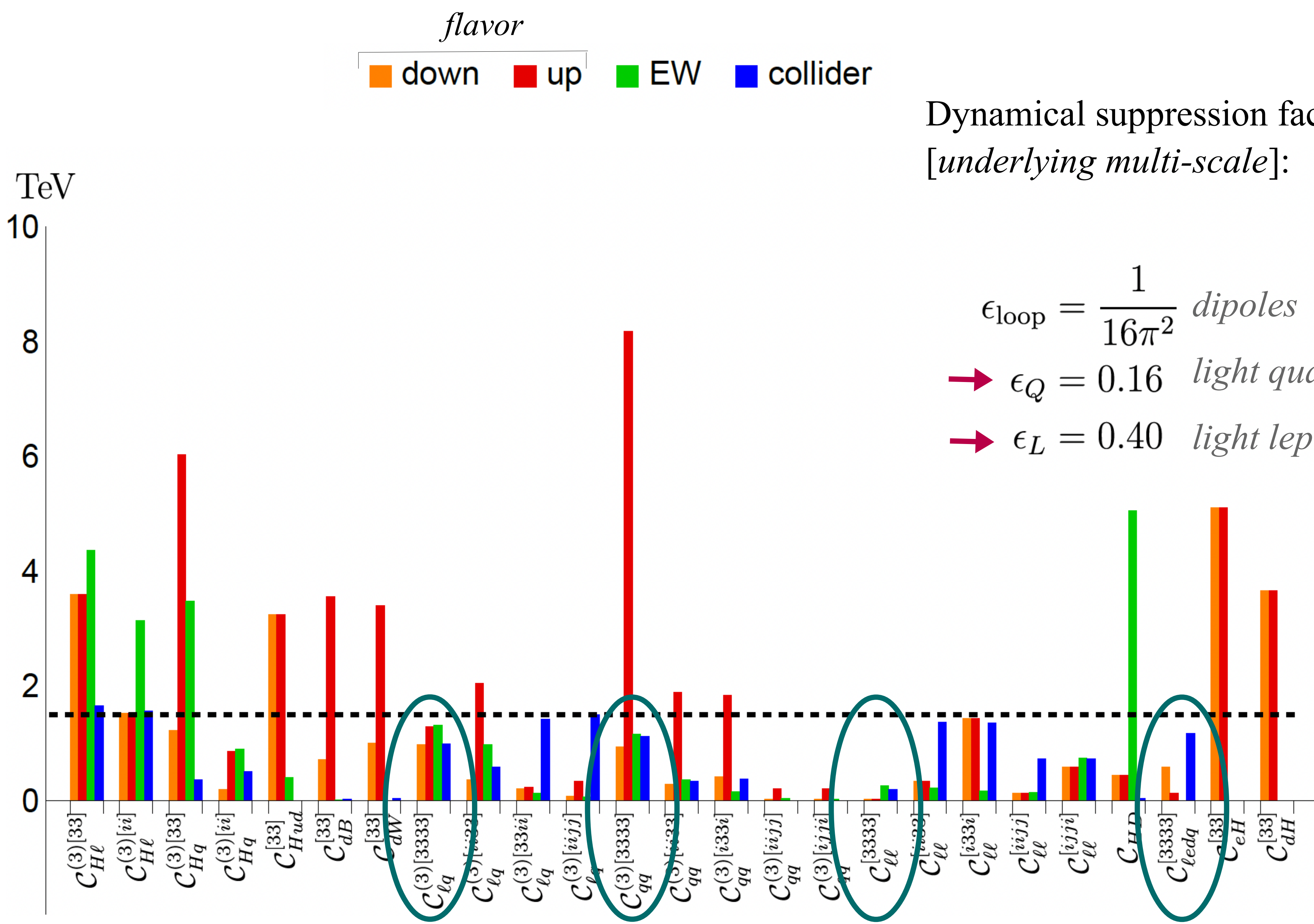


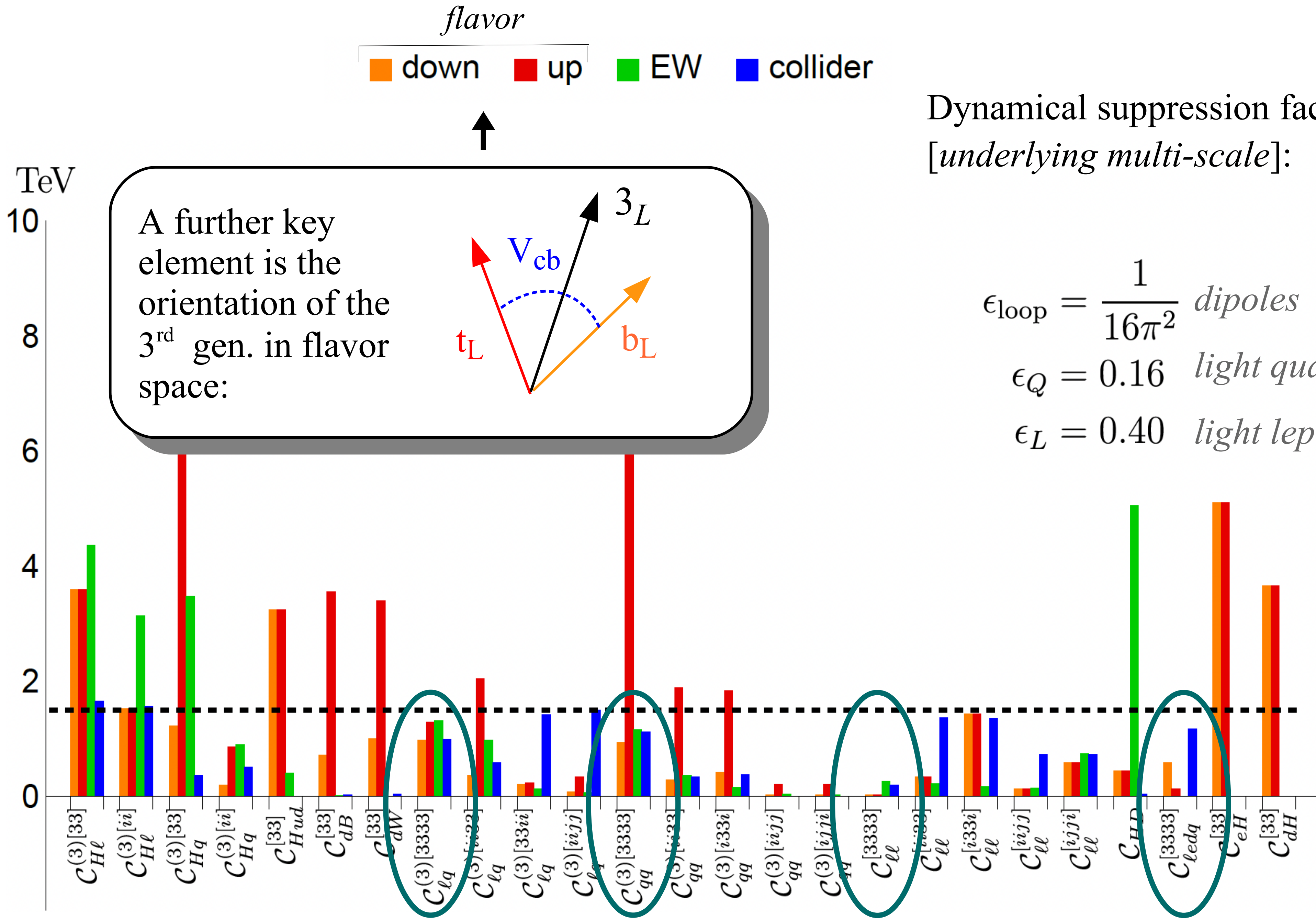
Dynamical suppression factors [*underlying multi-scale*]:

$$\epsilon_{\rm loop} = \frac{1}{16\pi^2} \quad \textit{dipoles}$$

$$\epsilon_Q = 0.16 \quad \textit{light quarks}$$

$$\epsilon_L = 0.40 \quad \textit{light leptons}$$

SMEFT bounds in the $U(2)^5$ symmetric limit [a brief detour]



A further key element is the orientation of the 3rd gen. in flavor space:

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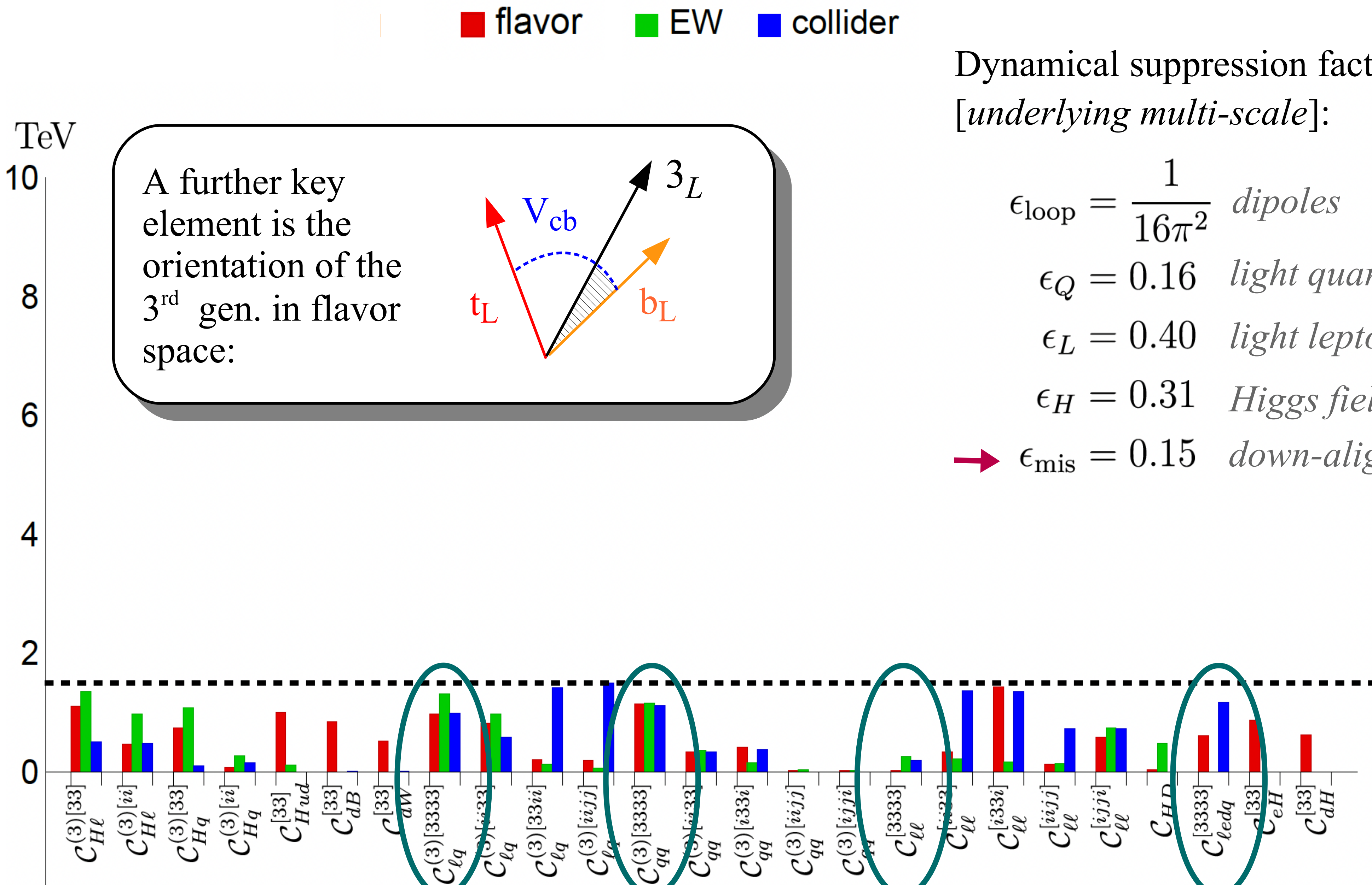

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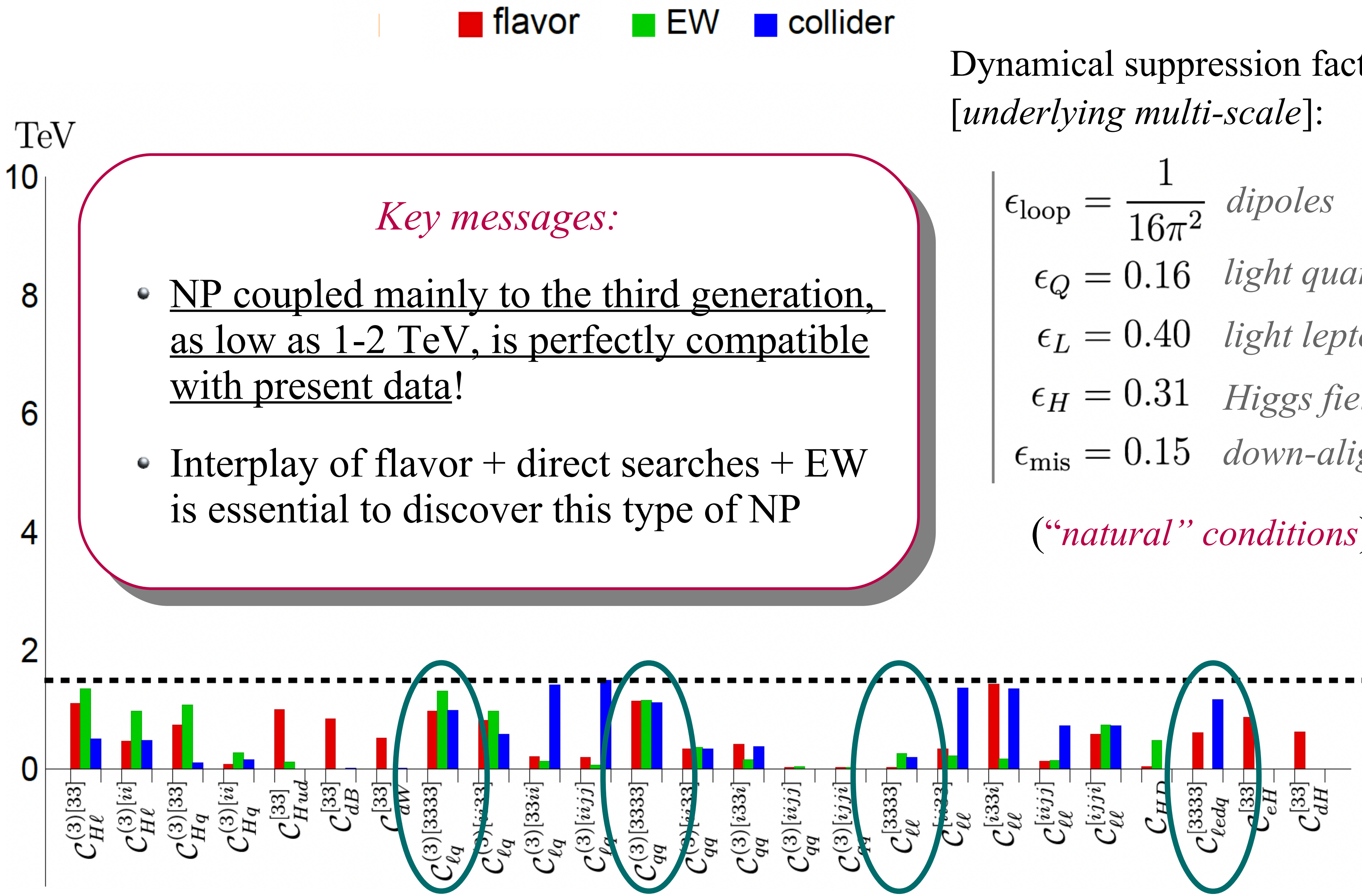
$$\epsilon_H = 0.31 \quad \textit{Higgs fields}$$

$$\epsilon_{\rm mis} = 0.15 \quad \textit{down-align.}$$

SMEFT bounds in the U(2)^5 *symmetric limit* [a brief detour]



Key messages:

- NP coupled mainly to the third generation, as low as 1-2 TeV, is perfectly compatible with present data!
- Interplay of flavor + direct searches + EW is essential to discover this type of NP

Dynamical suppression factors [*underlying multi-scale*]:

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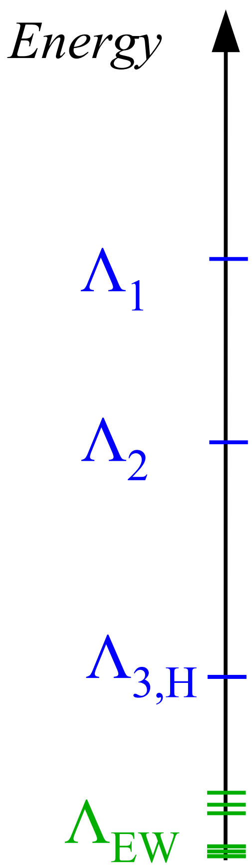
(*"natural" conditions*)

Flavor non-universal interactions

To understand which are the the most motivated options, from a dynamical point of view, we recently analysed all the extensions of the SM gauge group compatible with the following three general assumptions:

Davighi & G.I. '23



I. Obtain the $U(2)^n$ flavor symmetry as accidental symmetry of the (non- universal) gauge sector

II. Elementary Higgs up to the TeV scale → New states should preserve Higgs-mass stability

III. Explain charge-quantization → Semi-simple embedding in the UV [i.e. no U(1) groups in the UV]

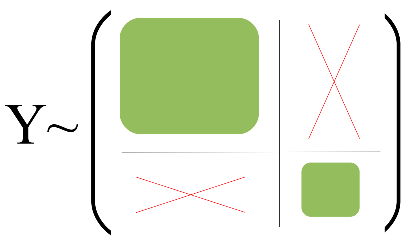
Flavor hierarchies from gauge non-universality [a brief detour]

I. $U(2)^n$ flavor symmetry as accidental symmetry of the gauge sector.

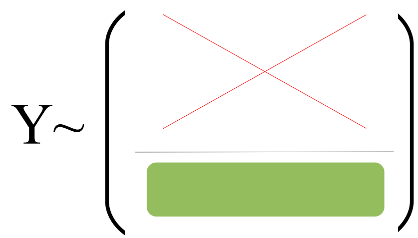
- Classify the allowed Yukawa structures under a flavor-deconstruction of three basic factors characterizing the SM fermions and the EW gauge group: $SU(2)_L \times U(1)_R \times U(1)_{B-L}$

$$\overline{\psi}_L \, Y \, \psi_R \, H$$

$U(1)_{B-L}^{[3]} \times U(1)_{B-L}^{[12]}$

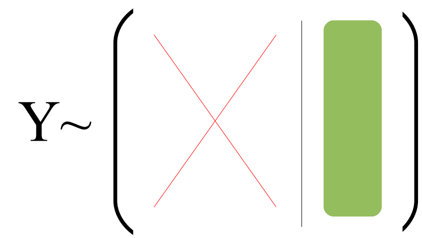


$SU(2)_L^{[3]} \times SU(2)_L^{[12]}$



H charged under $SU(2)_L^{[3]}$

$U(1)_R^{[3]} \times U(1)_R^{[12]}$



H charged under $U(1)_R^{[3]}$

- Deconstructing <u>any pair of the three</u> (or all of them) leads to the desired $U(2)^n$ flavor symmetry

Flavor hierarchies from gauge non-universality [a brief detour]

I. $U(2)^n$ flavor symmetry as accidental symmetry of the gauge sector.

- Classify the allowed Yukawa structures under a flavor-deconstruction of three basic factors characterizing the SM fermions and the EW gauge group: $SU(2)_L \times U(1)_R \times U(1)_{B-L}$

- Deconstructing any pair of the three (or all of them) leads to the desired $U(2)^n$ flavor symmetry:
  - ✓ Part of the EW group necessarily need to be deconstructed

- Minimal choice represented by SM hypercharge [$Y=T^3{}_R+(B-L)/2$]. However, $U(1)^{[3]}{}_Y \times U(1)^{[2]}{}_Y \times U(1)^{[1]}{}_Y$ has two drawbacks:
  - ✗ No immediate semi-simple embedding
  - ✗ Conflict bewteen large mixing and large hiearchies in the 1-2 sector → additional tuning is needed

Navarro & King '23
Davighi & Stefanek '23
Isidori & Barbieri '23

Flavor hierarchies from gauge non-universality [a brief detour]

II.+III. Explain charge-quantization → Semi-simple embedding in the UV

Semi-simple embeddings of the SM have been classified and there are very few possibilities, all featuring one of the possible 3 basic options:

Allanach, Gripaios, Tooby-Smith '23

- SU(4)×SU(2)×SU(2) [Pati & Salam '74]
- SU(5) [Georgi & Glashow, '74]
- SO(10) [Georgi '75, Fritzsch & Minkowski '75]

But we also require NP coupled to 3rd generation to occur at the TeV scale to preserve Higgs-mass stability

⬇

Only the Pati-Salam option surivives the strong bounds from proton stability:

$$SU(3)_c \times U(1)_{B\text{-}L} \hookrightarrow SU(4) \sim \left[\begin{array}{c|c} SU(3)_c & 0 \\ \hline 0 & 0 \end{array}\right] \left[\begin{array}{c|c} 0 & LQ \\ \hline LQ & 0 \end{array}\right] \left[\begin{array}{c|c} 1/3 & 0 \\ \hline 0 & -1 \end{array}\right]$$

▸ *Flavor hierarchies from gauge non-universality* [a brief detour]

I. + II. + III. : four basic options:

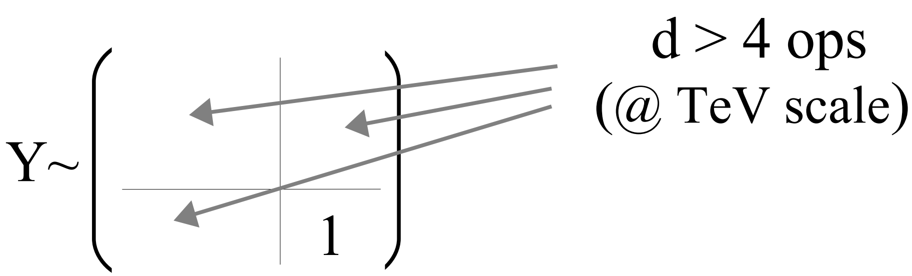
TeV-scale gauge group: $G_U \times G_3 \times H_{12}$

	G_U	G_3
1	$SU(2)_L$	$SU(4)^{[3]} \times SU(2)_R^{[3]}$
2	$SU(2)_R$	$SU(4)^{[3]} \times SU(2)_L^{[3]}$
3	$SU(4)$	$SU(2)_L^{[3]} \times SU(2)_R^{[3]}$
4	$\emptyset$	$SU(4)^{[3]} \times SU(2)_L^{[3]} \times SU(2)_R^{[3]}$

Higgs & 3rd gen. fields
charged only under these groups

Various options possible for the gauge group acting on the light families, broken at higher energies
(small inpact on δm_h given suppressed couplings to the Higgs)

Allwicher, GI, Thomsen '20
Davighi, G.I., Pesut '22
Davighi & G.I. '23



▸ *Flavor hierarchies from gauge non-universality* [a brief detour]

I. + II. + III. + general pheno bounds: two viable TeV-scale options:

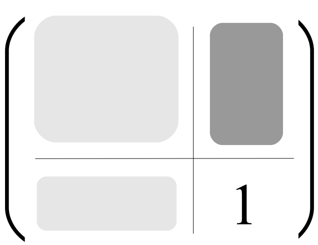
TeV-scale gauge group: $G_U \times G_3 \times H_{12}$		
	G_U	G_3
1	$SU(2)_L$	$SU(4)^{[3]} \times SU(2)_R^{[3]}$
2	~~$SU(2)_R$~~	~~$SU(4)^{[3]} \times SU(2)_L^{[3]}$~~
3	~~$SU(4)$~~	~~$SU(2)_L^{[3]} \times SU(2)_R^{[3]}$~~
4	$\emptyset$	$SU(4)^{[3]} \times SU(2)_L^{[3]} \times SU(2)_R^{[3]}$

Various options possible for the gauge group acting on the light families, broken at higher energies
(small inpact on δm_h given suppressed couplings to the Higgs)

Strongly disfavored by:

- $K_L \to \mu e$
- RH mixing

Allwicher, GI, Thomsen '20
Davighi, G.I., Pesut '22
Davighi & G.I. '23

Y~ 

General feature:

SU(4) group acting on the 3rd family, with TeV-scale breaking to avoid fine-tuning on the Higgs mass:

$$\delta m_h^2/m_h^2 < 1 \quad \to \quad \Lambda_U = M_U/g_U \lesssim 5\ \text{TeV}$$

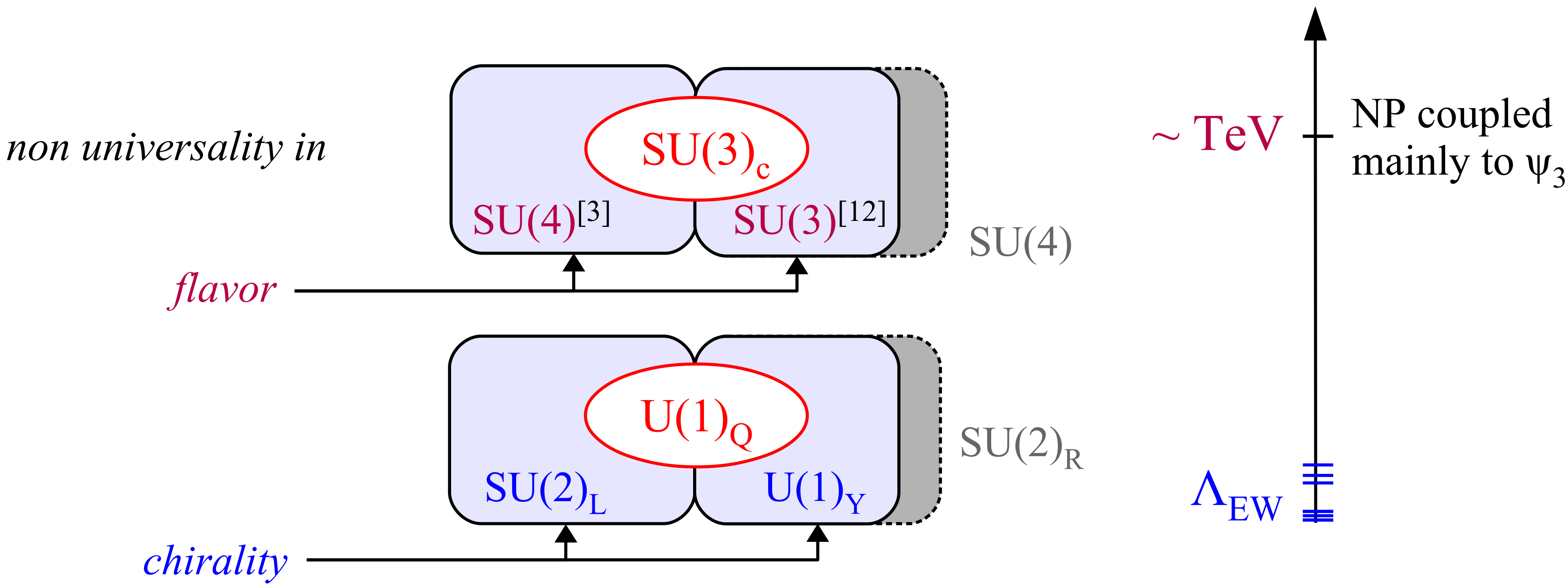
Flavor hierarchies from gauge non-universality [a brief detour]

This connects with the class of consistent TeV-scale models proposed a few years ago to address the B-physics anomalies...

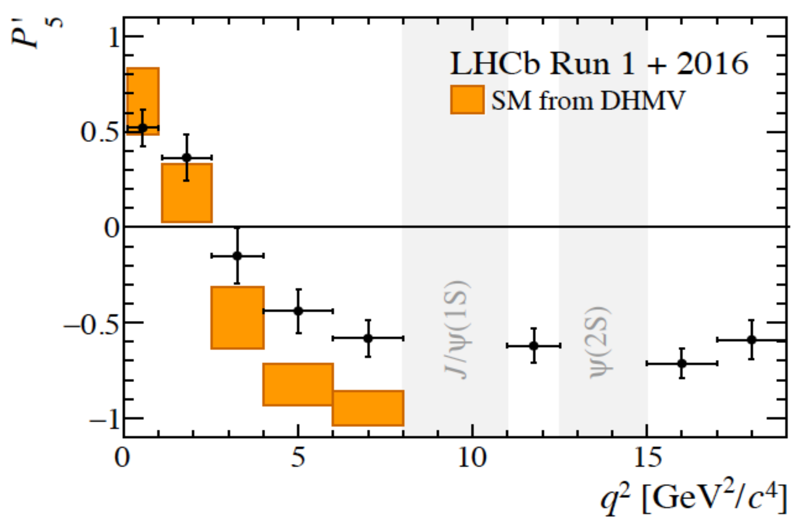
$$SU(4)^{[3]}\times SU(3)^{[12]} \times SU(2)_L \times U(1)'$$

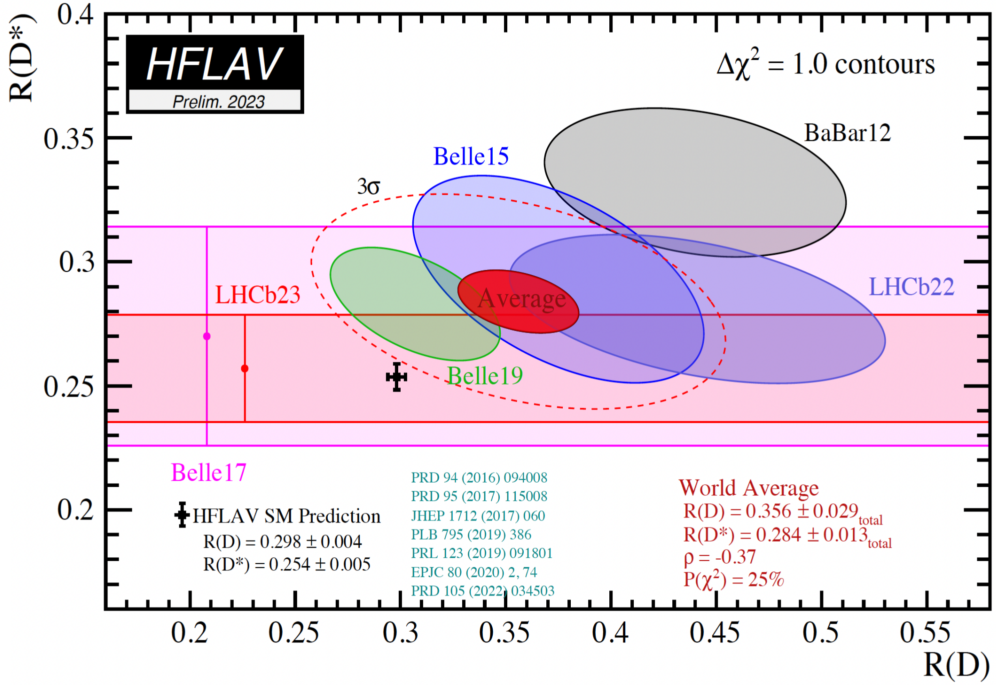
$$\downarrow \quad \rightarrow \text{LQ } [U_1] + Z' + G'$$

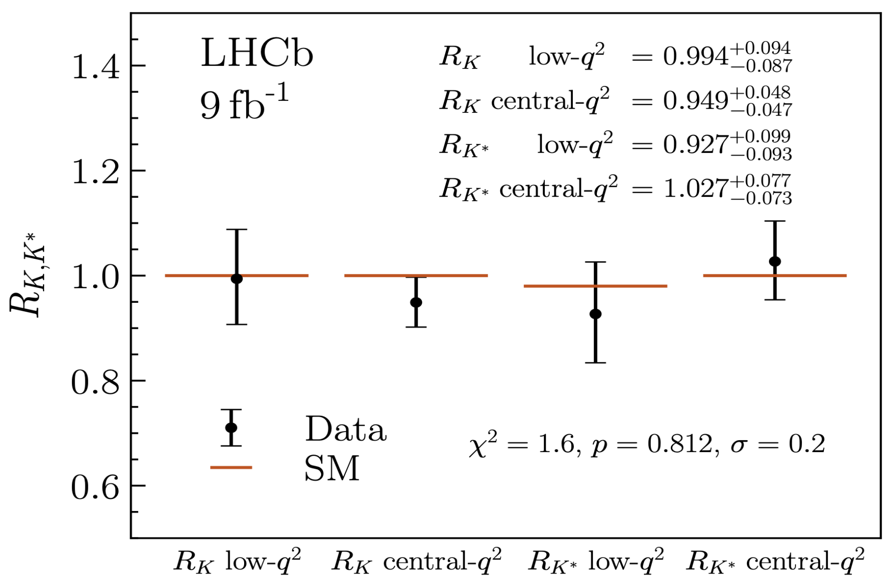
SM



Hints of non-universality in B-physics data







Hints of non-universality in B-physics data

Since 2013, experimental data in various semi-leptonic B decays started to exhibit tensions with the SM predictions. Several channels are involved, but they are all related to the following two classes of partonic transitions:

$b \to c\, l\nu$ (*Charged Currents*) $b \to s\, l^+ l^-$ (*Neutral Currents*)

Most of the anomalies are connected to a possible breaking of Lepton Flavor Universality = accidental symmetry of the SM Lagrangian in the limit where we neglect the lepton Yukawa couplings

Even if the significance went down recently (*not completely...*), worth to discuss as example of consistent TeV-scale (new) physics that could be revealed by precision flavor experiments

Hints of non-universality in B-physics data

Since 2013, experimental data in various semi-leptonic B decays started to exhibit tensions with the SM predictions. Several channels are involved, but they are all related to the following two classes of partonic transitions:

$b \to c\, l\nu$ (*Charged Currents*) $b \to s\, l^+l^-$ (*Neutral Currents*)

The "anomalies" can be grouped into 3 categories:

I. ~~LFU~~ anomaly in CC [τ vs. (μ, e)] — $b \to c\, l\nu$

II. ΔC_9 (*lepton-universal*) anomaly in NC modes

III. ~~LFU~~ anomaly in NC [μ vs. e] & BR($B_s \to \mu\mu$)

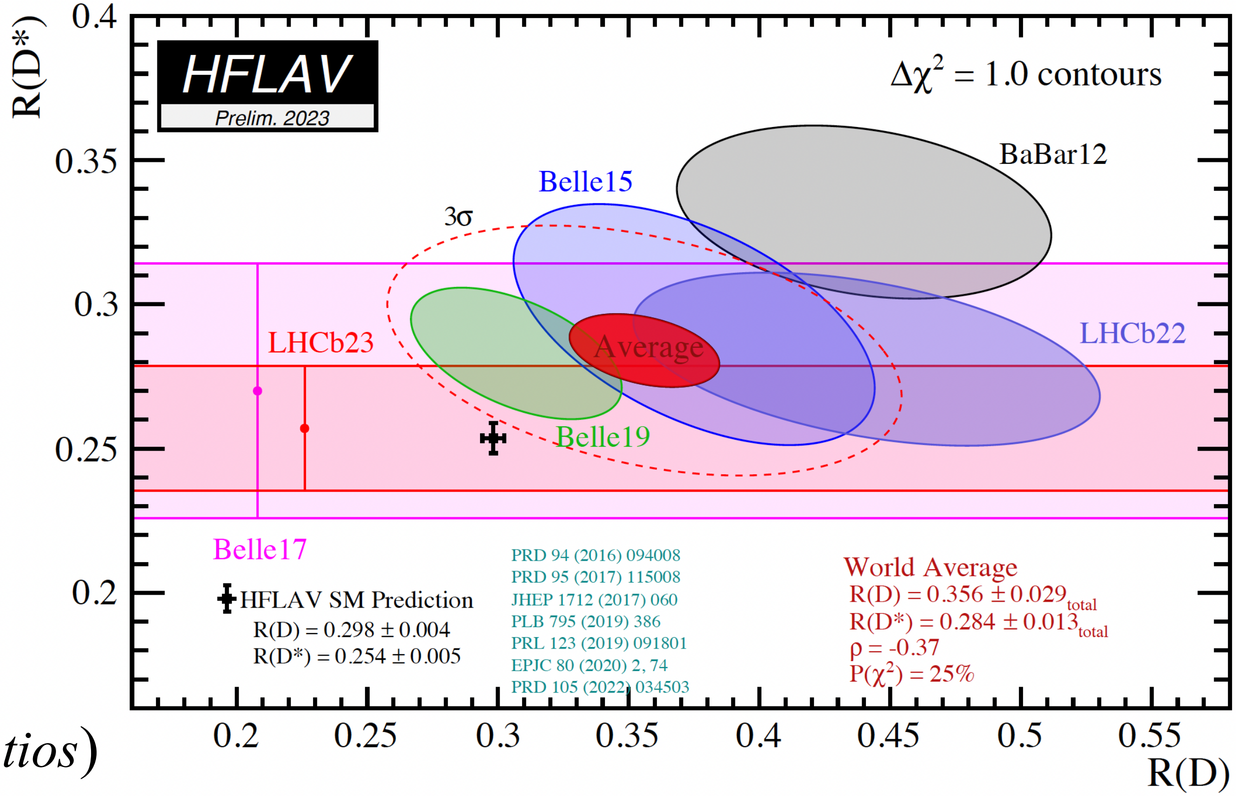
II. and III. — $b \to s\, l^+l^-$

Hints of non-universality in B-physics data

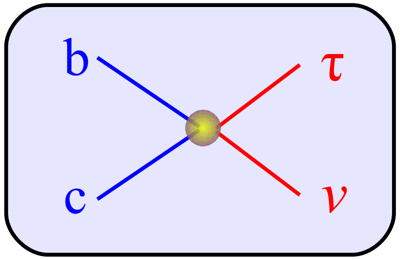
I. ~~LFU~~ anomaly in CC
[τ vs. (μ, e)]

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

X = D or D*



- Clean SM predictions (*uncertainties cancel in the ratios*)
- 3.0σ excess over SM
- Compete with SM @ tree-level → *low scale of NP*



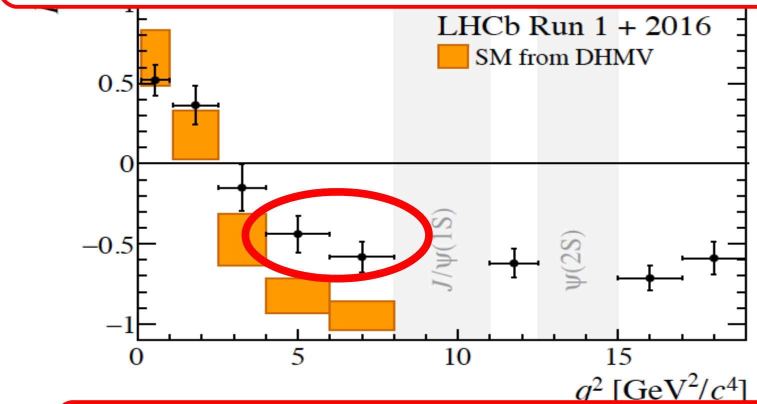
▶ *Hints of non-universality in B-physics data*

II. ΔC_9 (*lepton-universal*) anomaly in NC modes

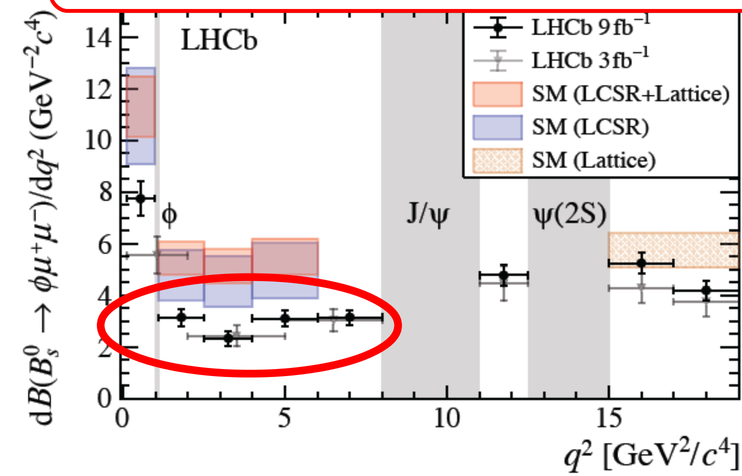
$$\mathcal{O}_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

- Possible contamination from SM long-distance (*charming penguins*)
- All attempts to compute the effect agree on ~ 3σ deviation from SM
- Compete with SM @ loop-level

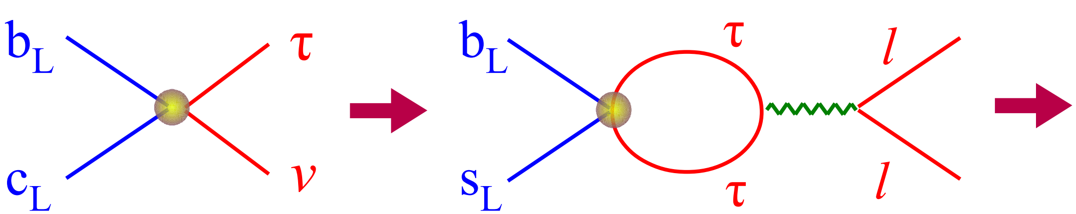
$B \to K^* \mu\mu$ angular distribution



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



Possible explanation connected to CC (hence 3rd family LFU violation):



$\Delta C_9^{\rm Univ}$

N.B.: correct sign & size !

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

Hints of non-universality in B-physics data

II. ΔC_9 (*lepton-universal*) anomaly in NC modes

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

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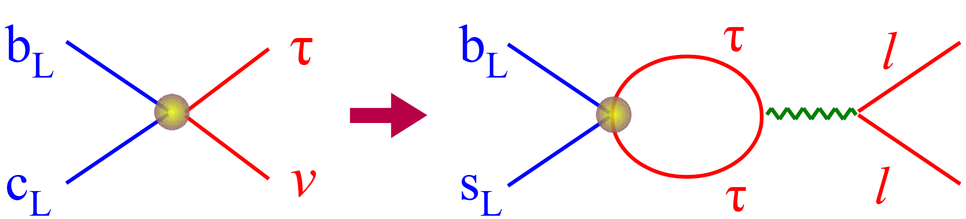
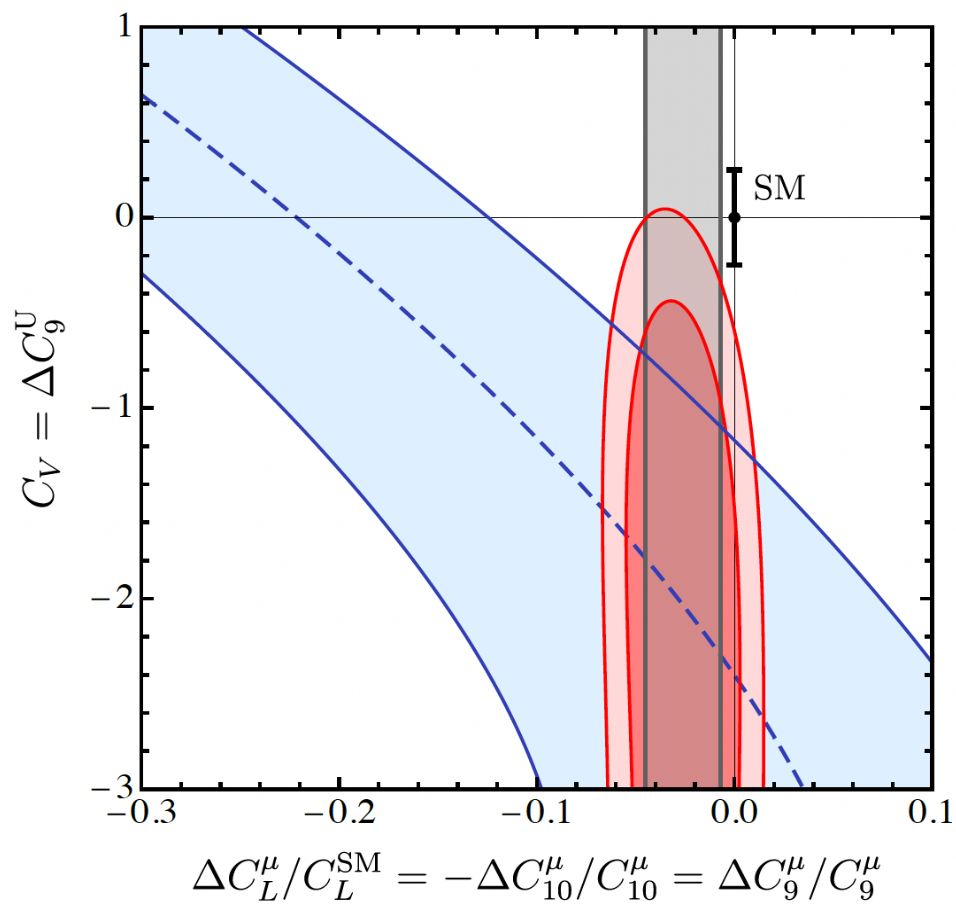


2σ consistent indication from $b \to s\, l^+ l^-$ (*semi-inlcusive*) at high q^2

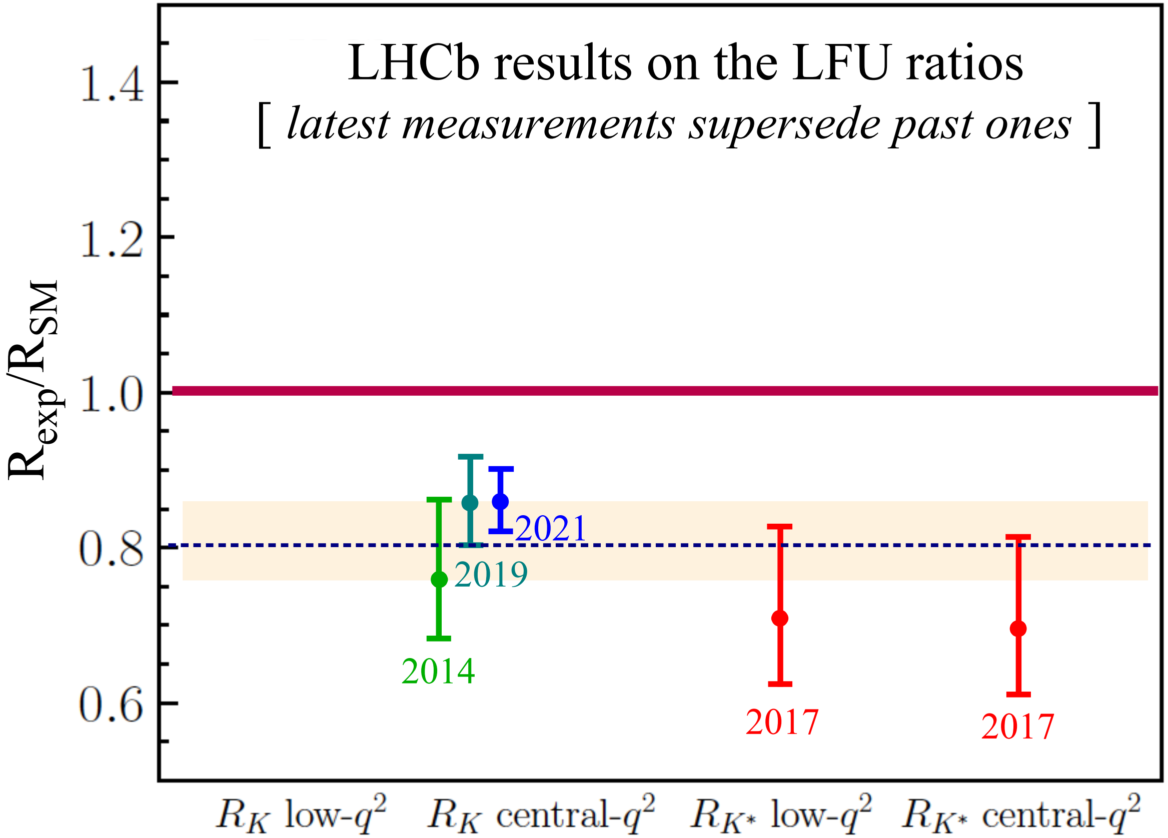
GI, Poloski, Tinari '23



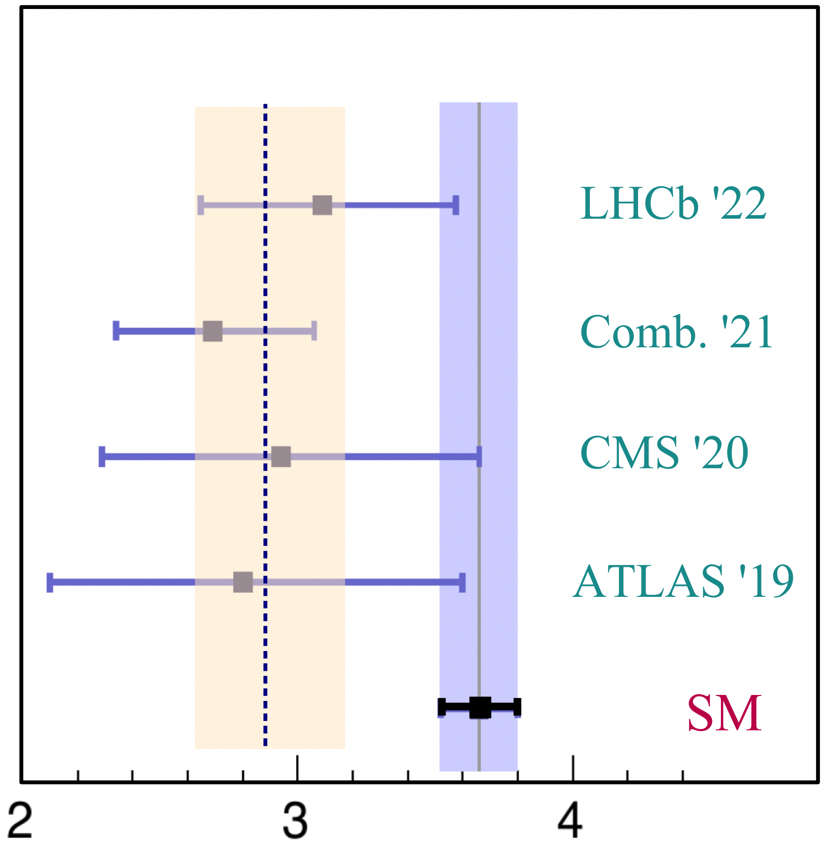
Hints of non-universality in B-physics data

III. ~~LFU~~ anomaly in NC [μ vs. e] & BR($B_s \to \mu\mu$)

- Clean SM predictions
  (*LFU ratios + no long-distance in* $B_s \to \mu\mu$)
- Highest significance till summer 2022



$10^9 \times B(B_s \to \mu\mu)$

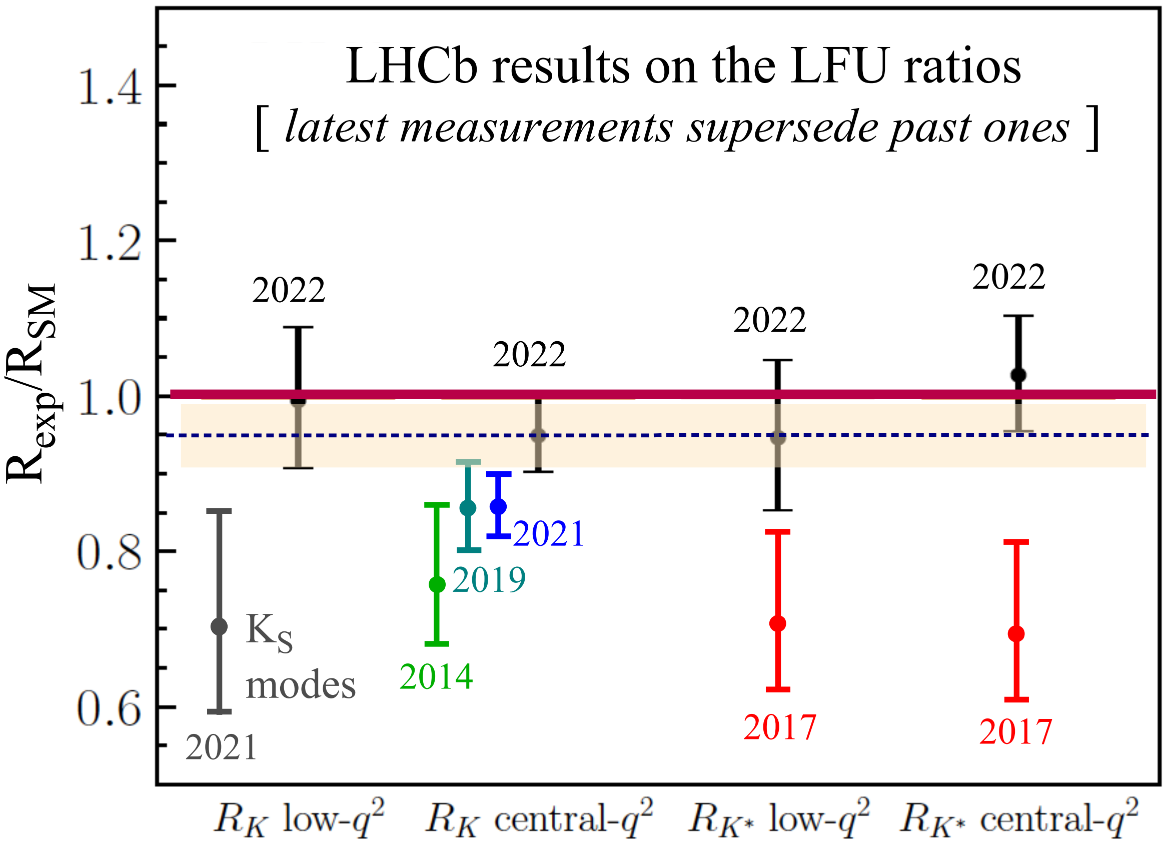


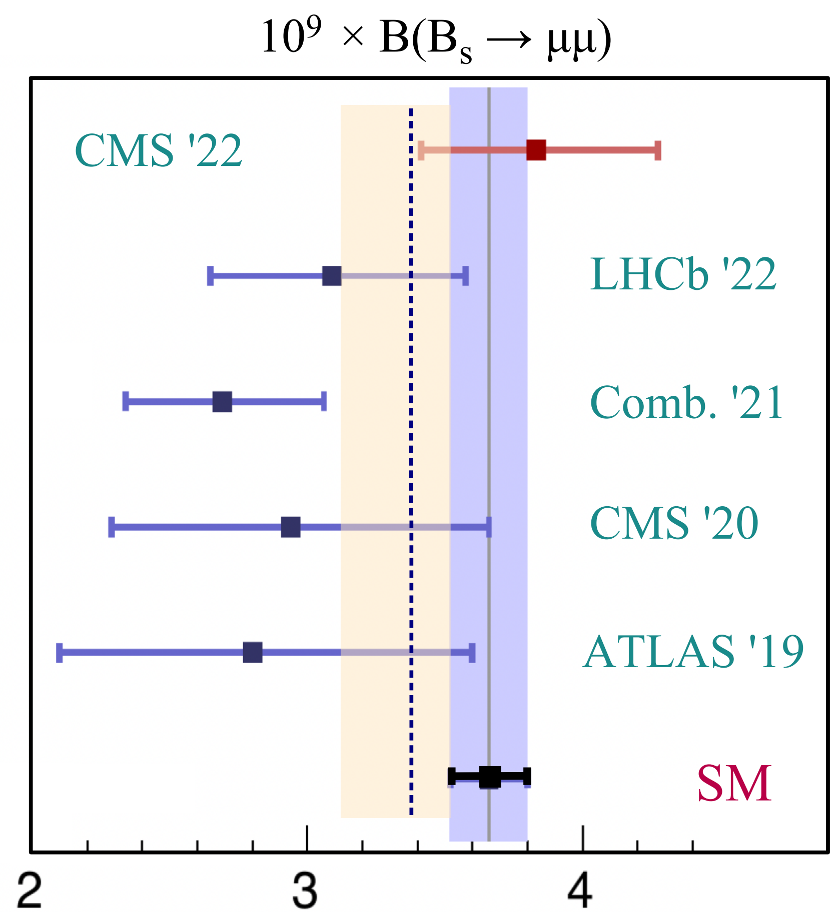
Hints of non-universality in B-physics data

III. ~~LFU~~ anomaly in NC & BR($B_s \to \mu\mu$)

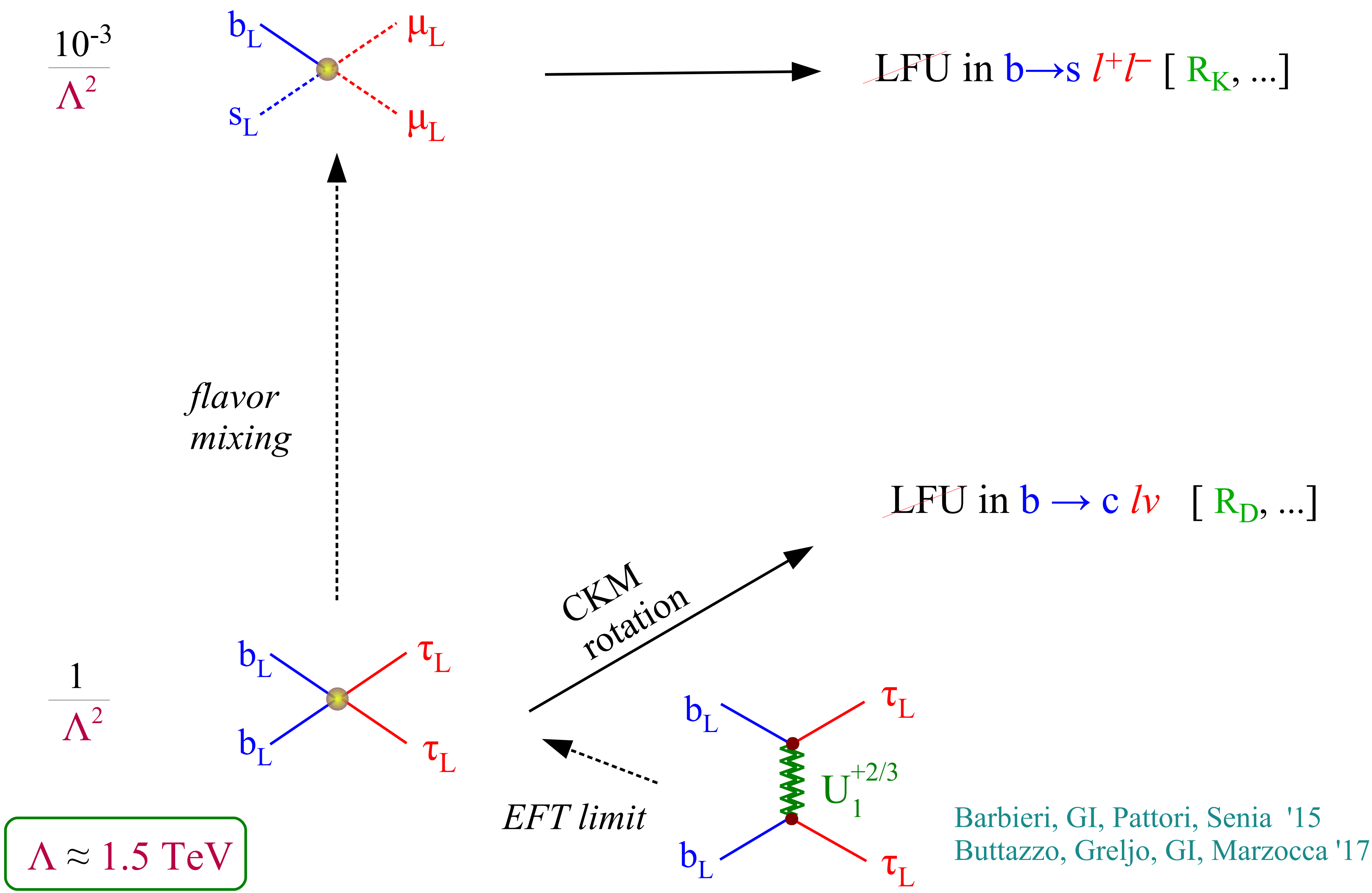
- Clean SM predictions
  (*LFU ratios + no long-distance in* $B_s \to \mu\mu$)
- ~~Highest significance till summer 2022~~

N.B.: *While the overall loss of NP significance is high, the implications for multi-scale flavor models are modest*

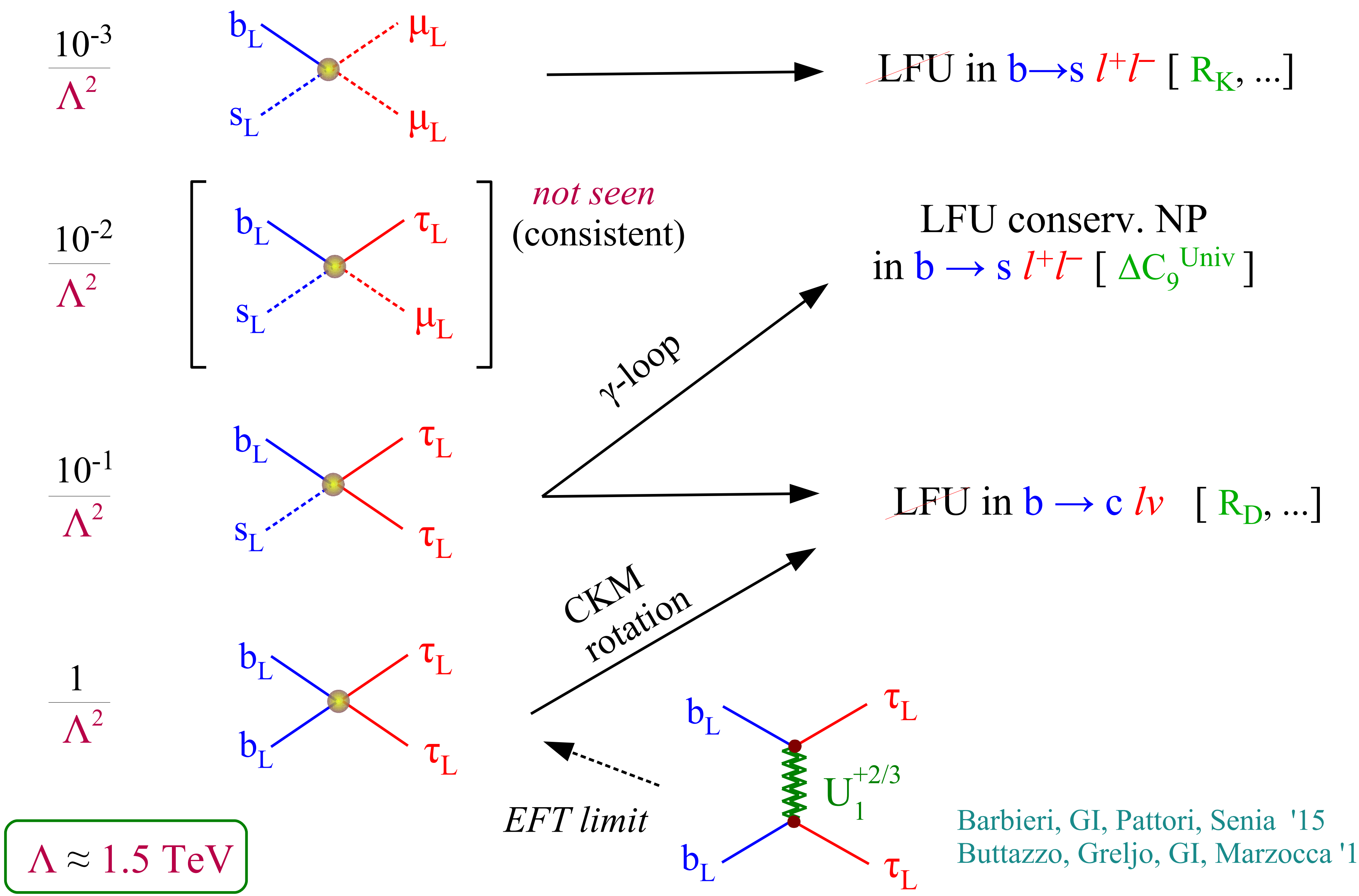




Hints of non-universality in B-physics data

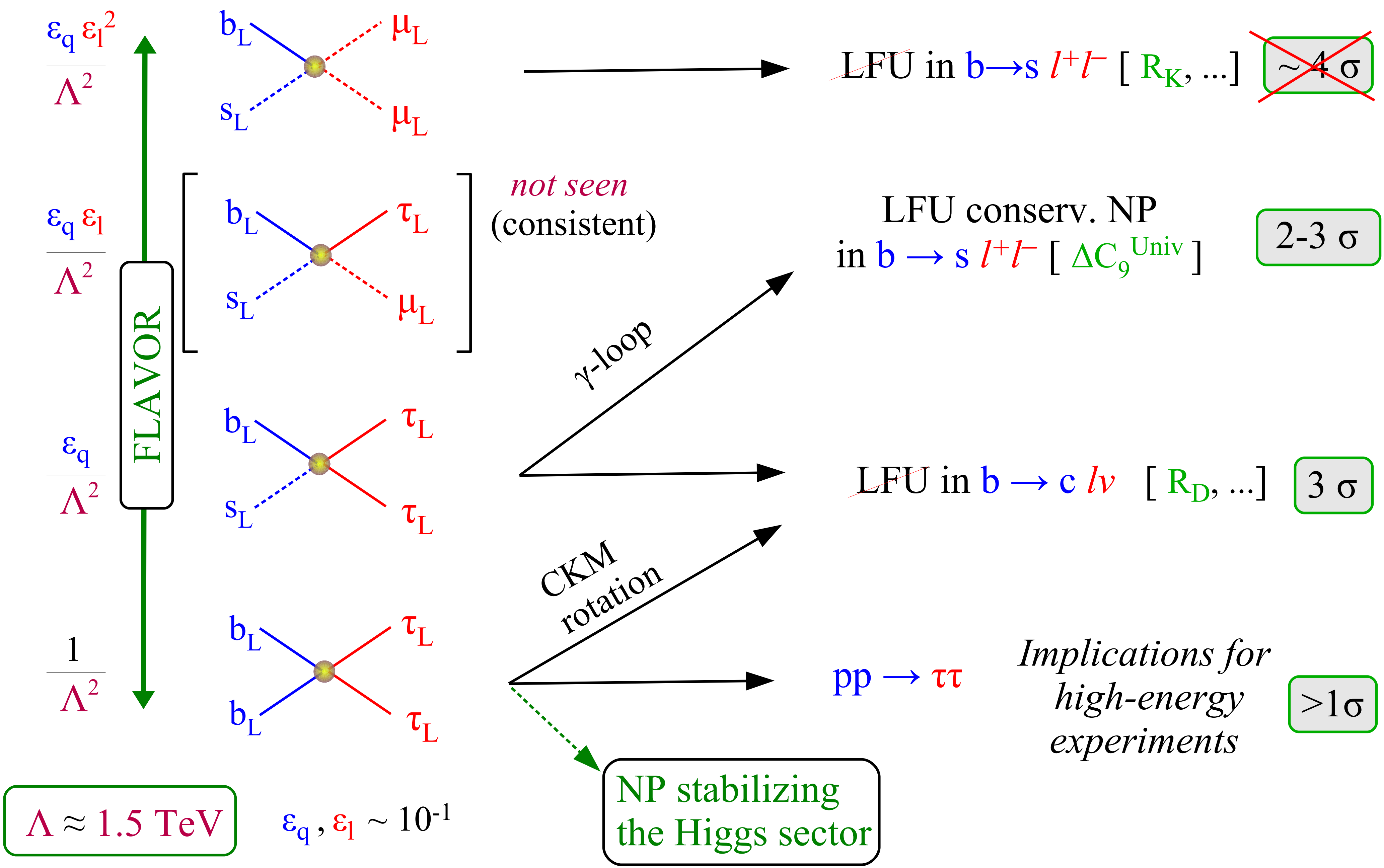


Hints of non-universality in B-physics data



Barbieri, GI, Pattori, Senia '15
Buttazzo, Greljo, GI, Marzocca '17

Hints of non-universality in B-physics data

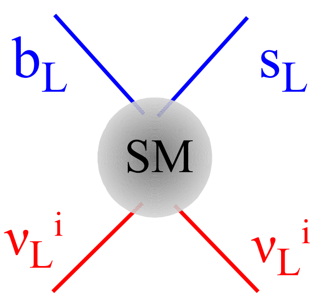


Future prospects

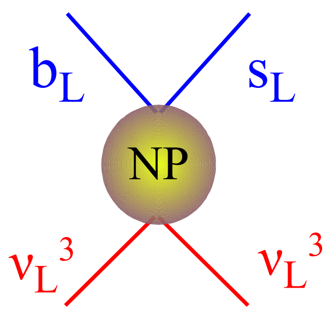
Future prospects

The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements (*with different degree of model-dependence*)

E.g.: I) Deviations from SM in $b \to s\nu\nu$ rates [3rd gen. ν in the final state]



identical for all neutrino species

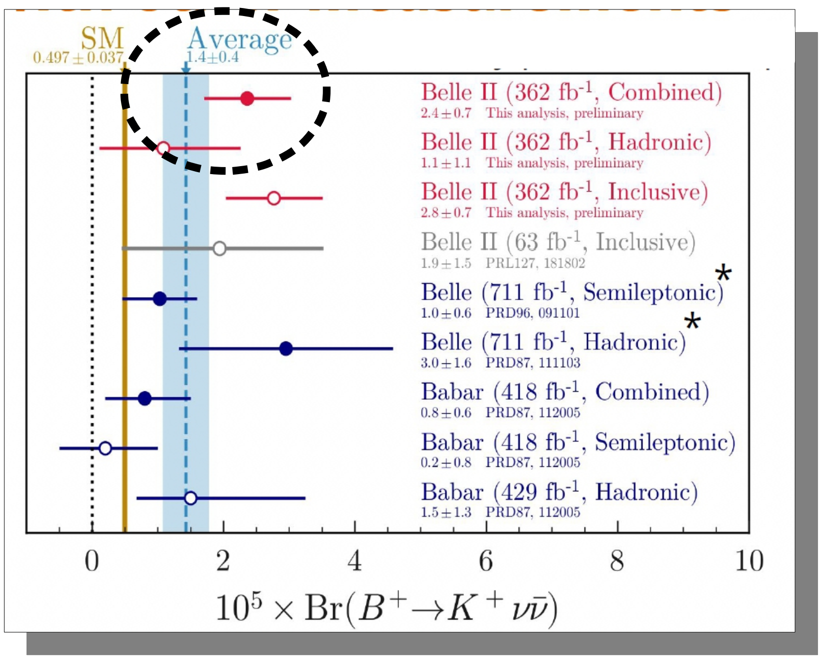


relevant only for 3rd gen. neutrinos

Unambiguos prediction of 30-50% enhancement of $B(B \to K\nu\nu)$ in the model with vector LQ, given data on R(D).

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

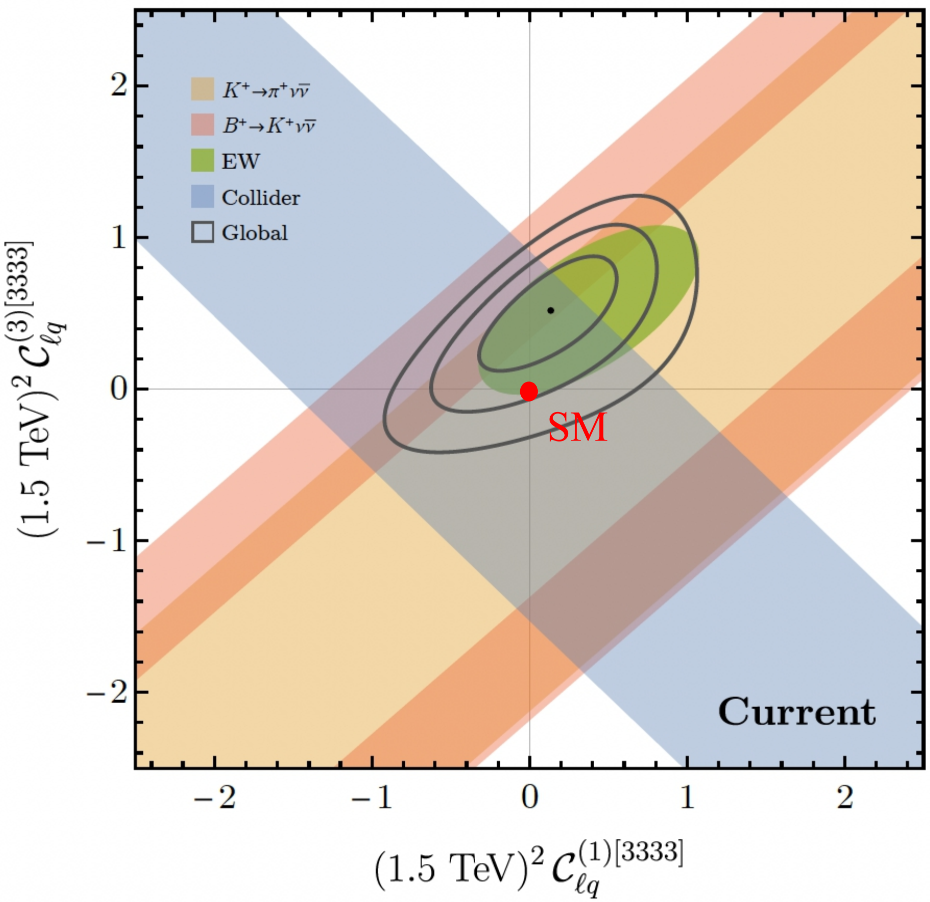
Belle-II @ EPS '23

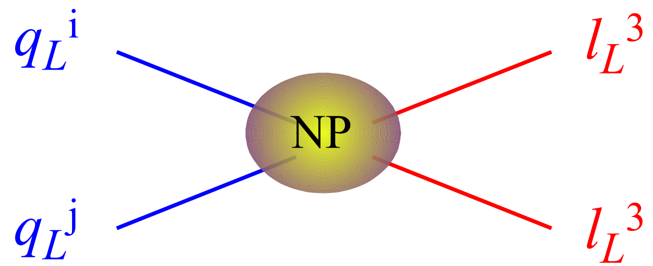


Future prospects

The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements (*with different degree of model-dependence*)

E.g.: II) Deviations from SM in $b \to s\nu\nu$ rates... and $s \to d\nu\nu$ rates

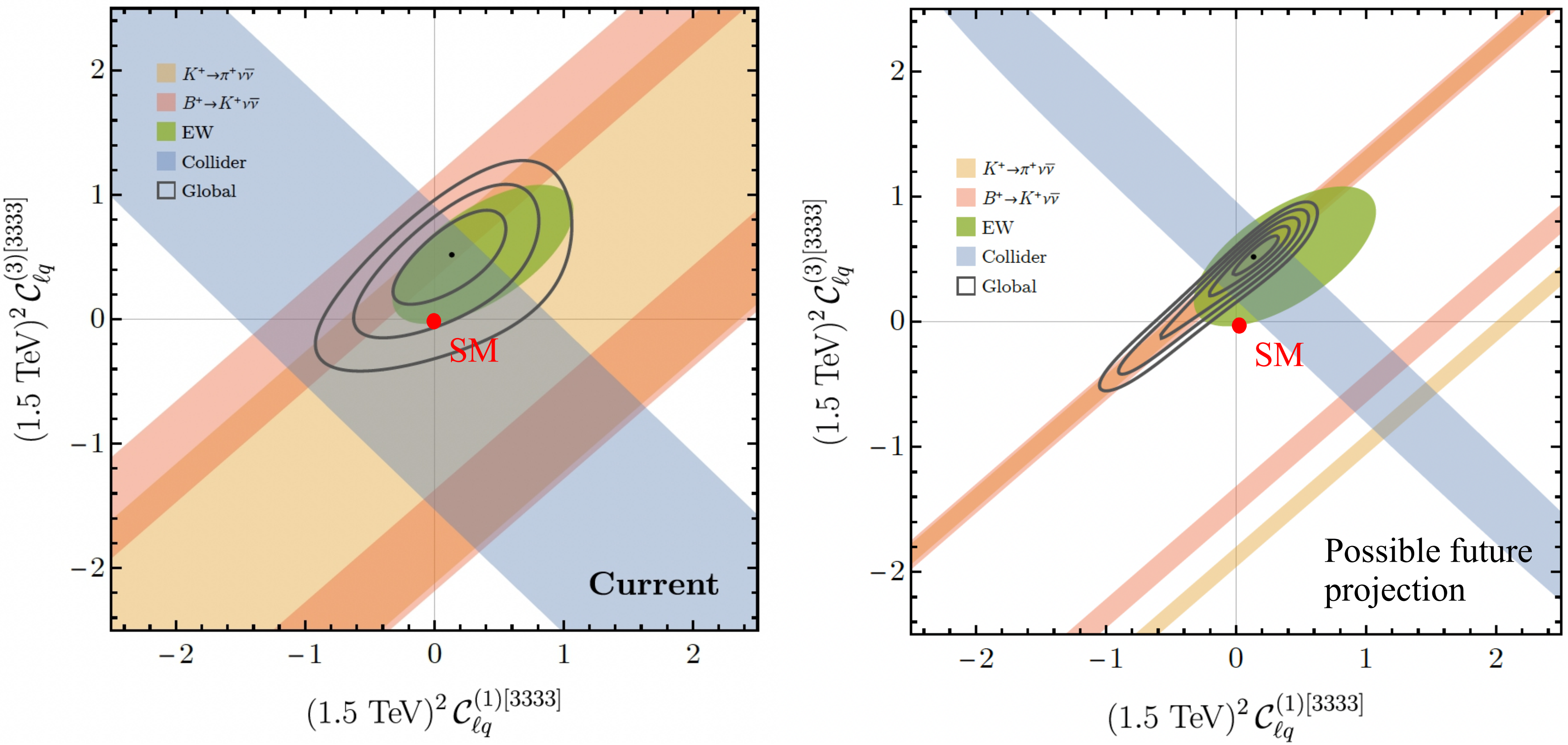




Future prospects

The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements (*with different degree of model-dependence*)

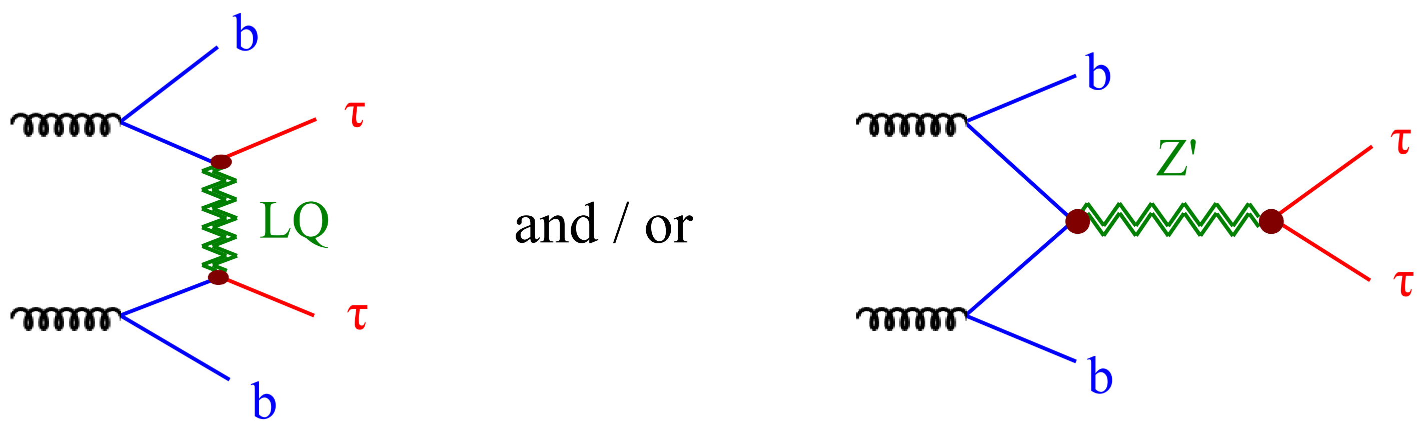
E.g.: II) Deviations from SM in b→sνν rates... and s→dνν rates



Future prospects

The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements & collider observables

E.g.: III) $pp \to \tau\bar{\tau}$ (+ b-jets)

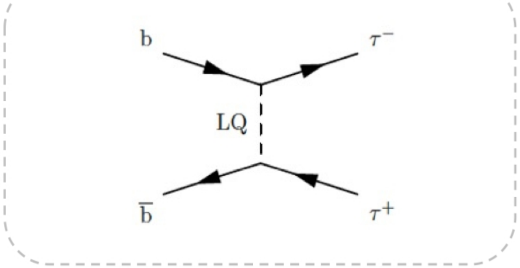


Future prospects

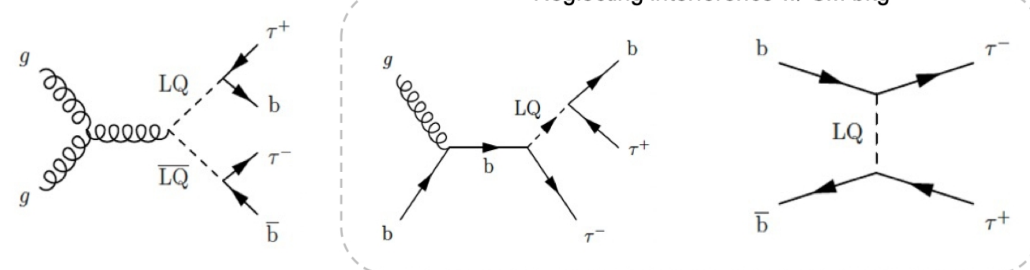
Aurelio Juste [*Moriond EW* '23]

LQ-b-τ: Comparison of recent results

Including interference w/ SM bkg

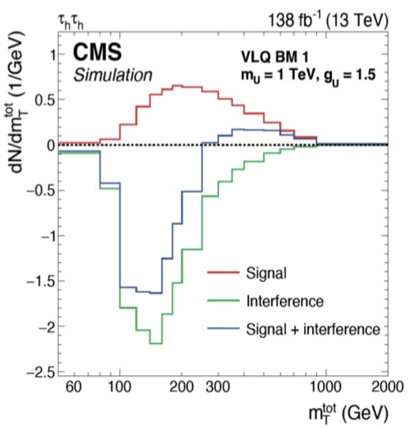


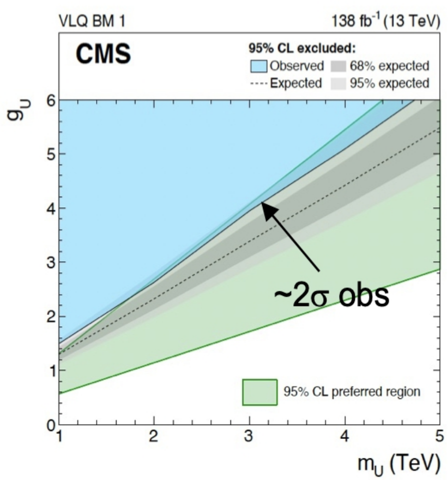
Neglecting interference w/ SM bkg



Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

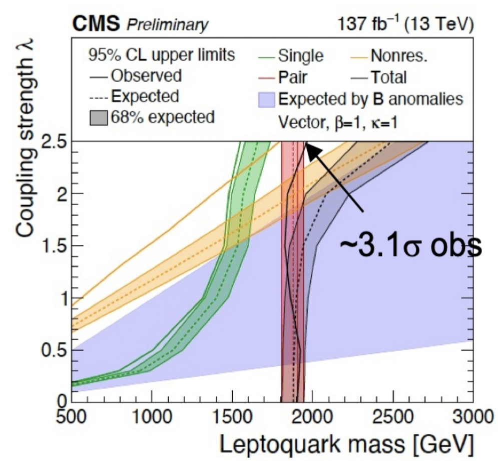
CMS-HIG-21-001



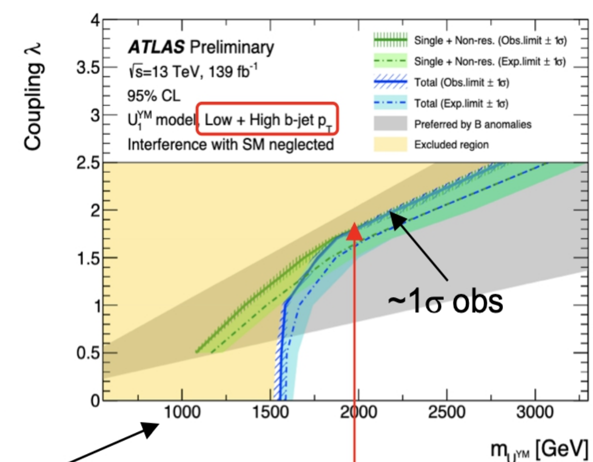


Shown at Moriond EW 2022

CMS-PAS-EXO-19-016



EXOT-2022-39

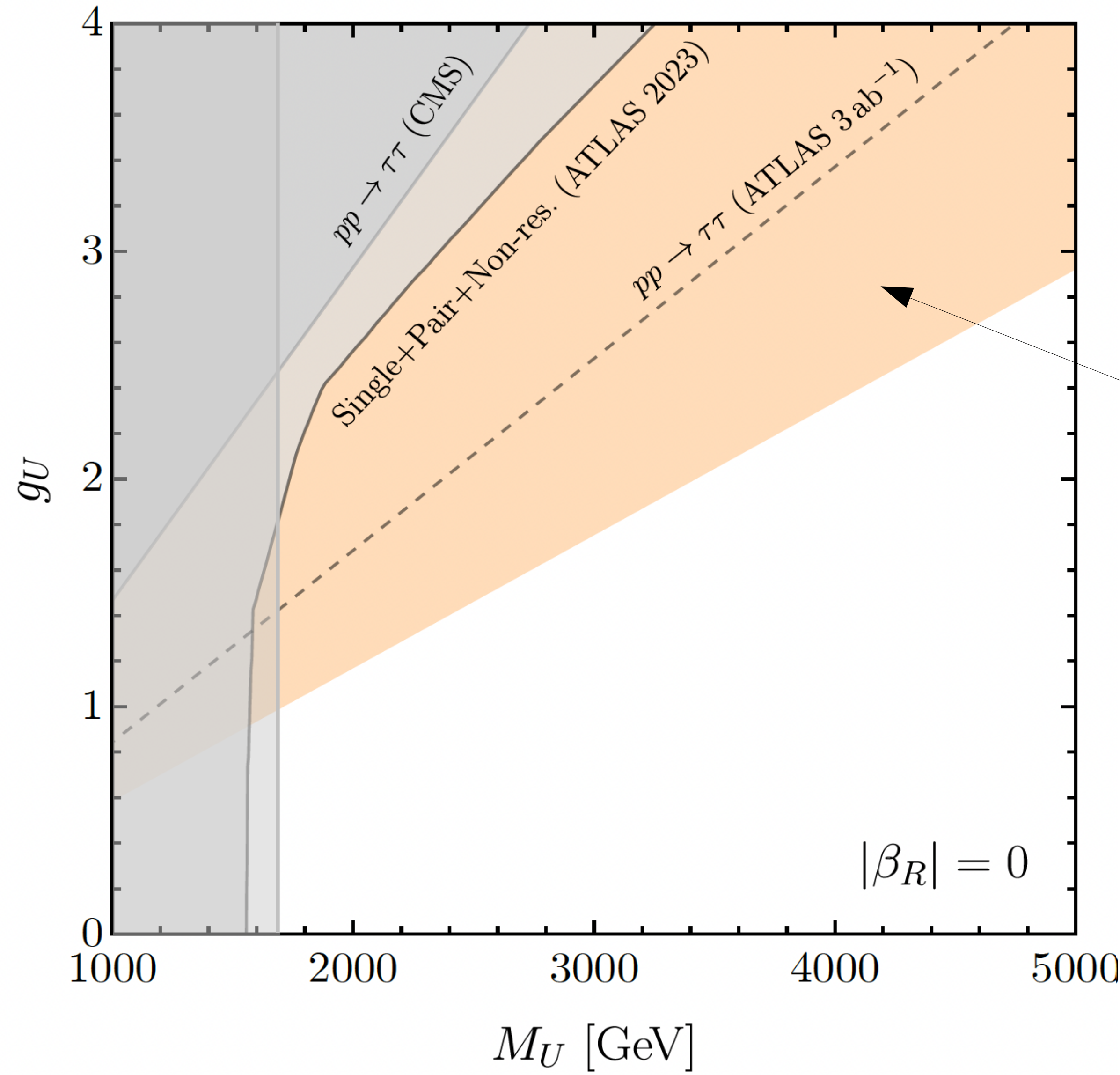


Large improvement in sensitivity when adding low b-jet p_T category

Excludes CMS' excess

Need to clarify interference issue for future interpretations

Future prospects



Updated preferred region by b → c low-energy data

Aebischer *et al.* '22

Relevant NLO QCD corrections

Haisch, Schnell, Schulte '22

Conclusions

- Flavor physics represents one the most intriguing aspects of the SM and, at the same time, a great opportunity to investigate the nature of physics beyond the SM.

- The idea of a *multi-scale construction at the origin of the flavor hierarchies* has several appealing aspects. Key observation: non-universal gauge interactions at the TeV scale, involving mainly the 3rd family, offer a new way to look at the EW hierarchy problem (and the absence of direct signals of NP so far).

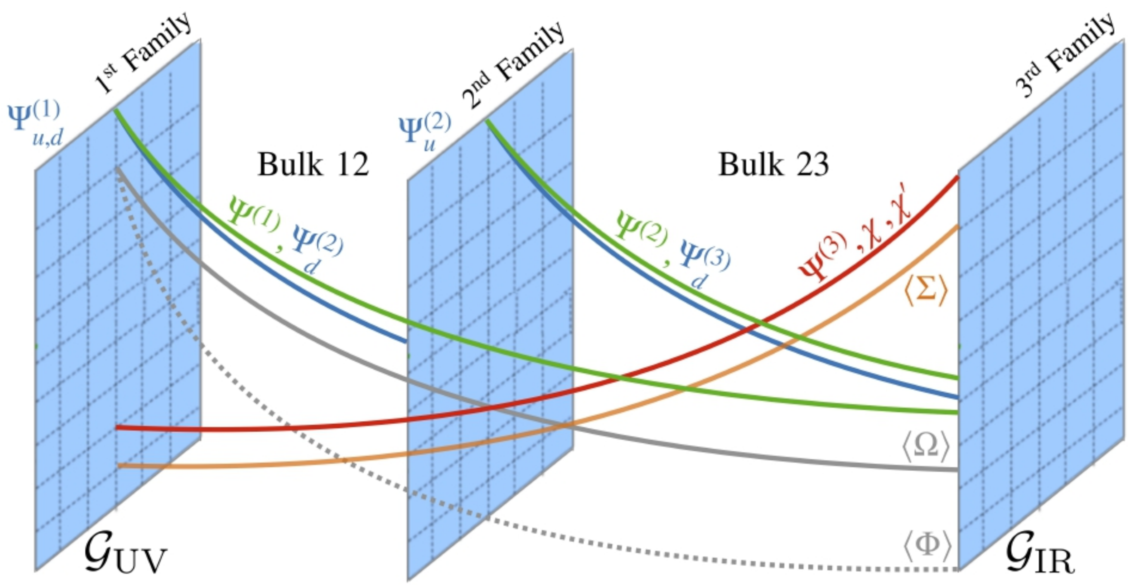
- The model-building efforts along this direction, initially triggered by the B anomalies, are still very motivated and mildly affected by the recent change in low-energy data.

- If these ideas corrects, new non-standard effects should emerge soon both at low and at high energies ($\rightarrow$ very interesting opportunities for run-3...).


Backup

Leptoquarks & 4321: UV completions

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



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

Dvali & Shifman, '00

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

Bordone, Cornella, GI, Javier-Fuentes '17

- Anarchic neutrino masses via inverse see-saw mechanism Fuentes-Martin, GI, Pages, Stefanek '22
- "Holographic" Higgs from appropriate choice of bulk/brane gauge symm.
  [$G_{\text{bulk-23}} = SU(4)_3 \times SU(3)_{1,2} \times U(1) \times SO(5)$ $G_{IR} = SU(3)_c \times U(1)_{B\text{-}L} \times SO(4)$]

→ Light Higgs as pseudo Goldstone

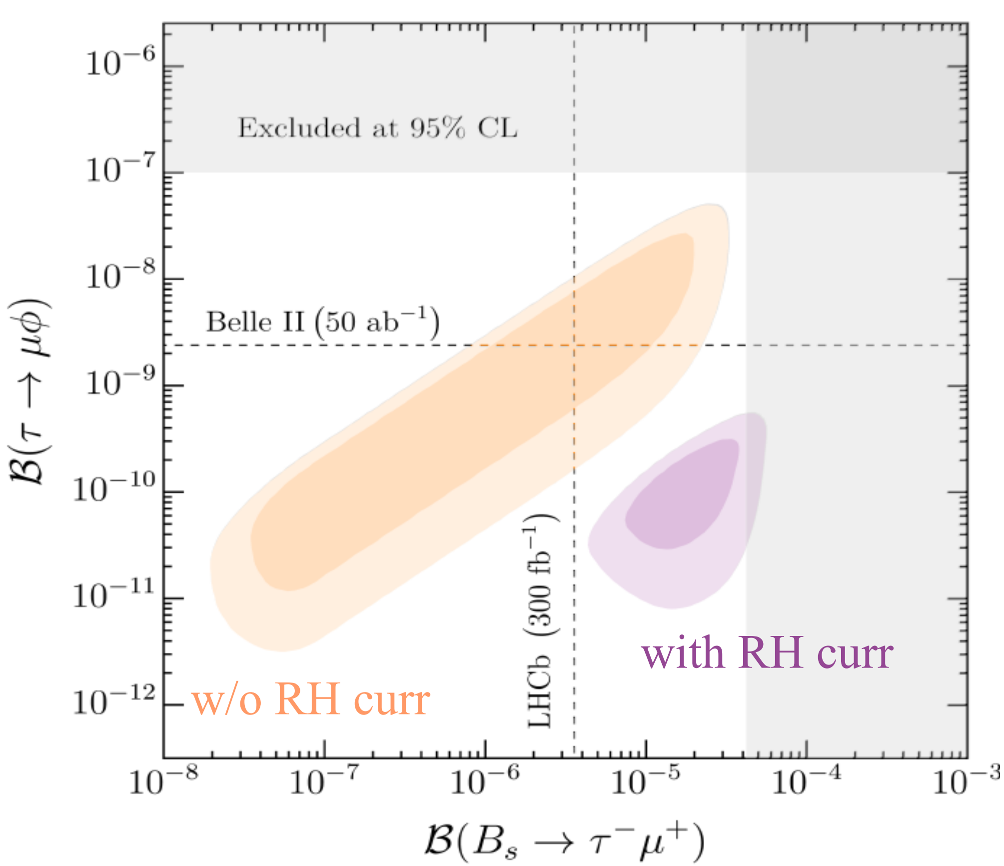
Fuentes-Martin, Stangl '20
Fuentes-Martin, GI, Lizana, Selimovic, Stefanek '22

Agashe, Contino, Pomarol '05

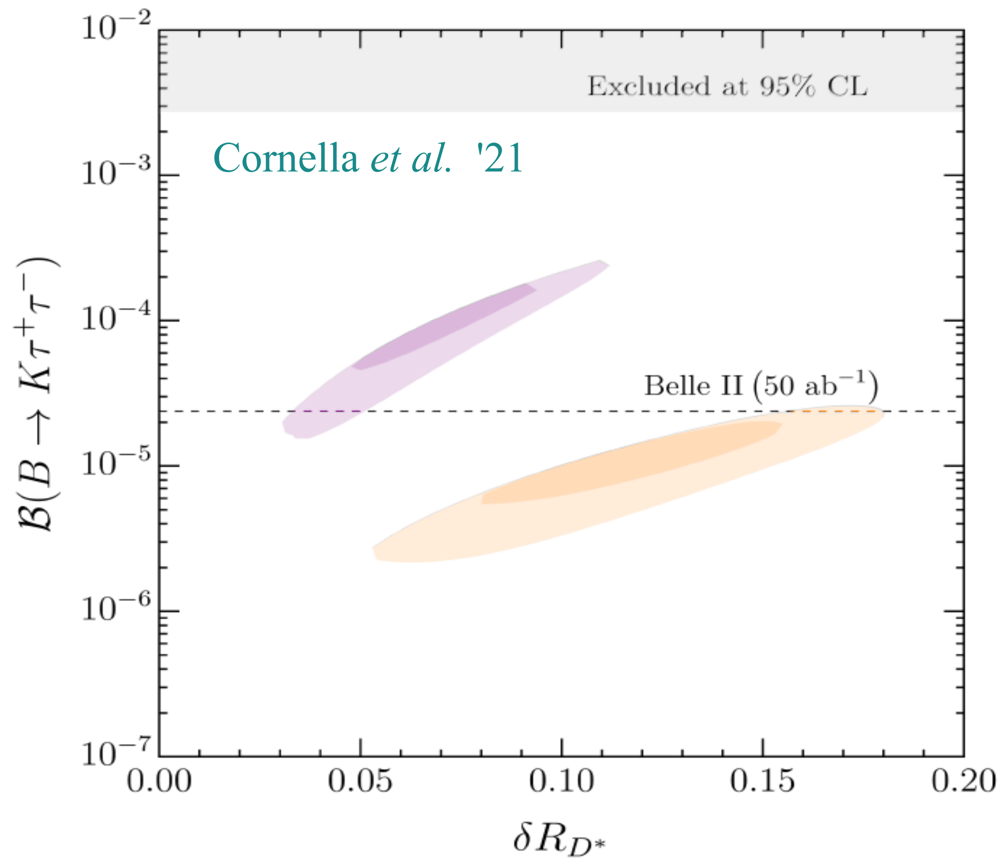
Leptoquarks & 4321: implications

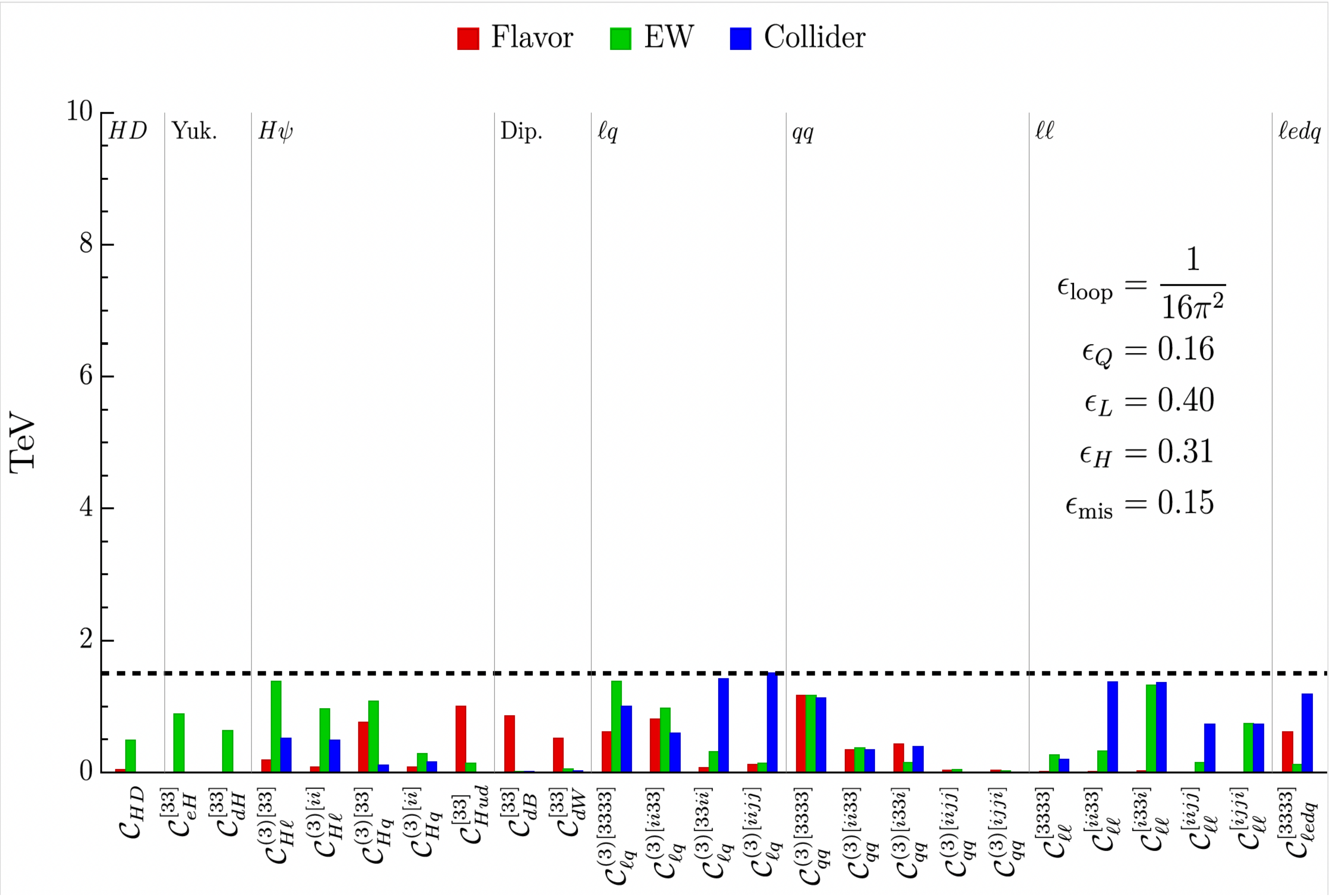
→ Rare decays of b and τ

τ → μ LFV
(in B and tau decays)

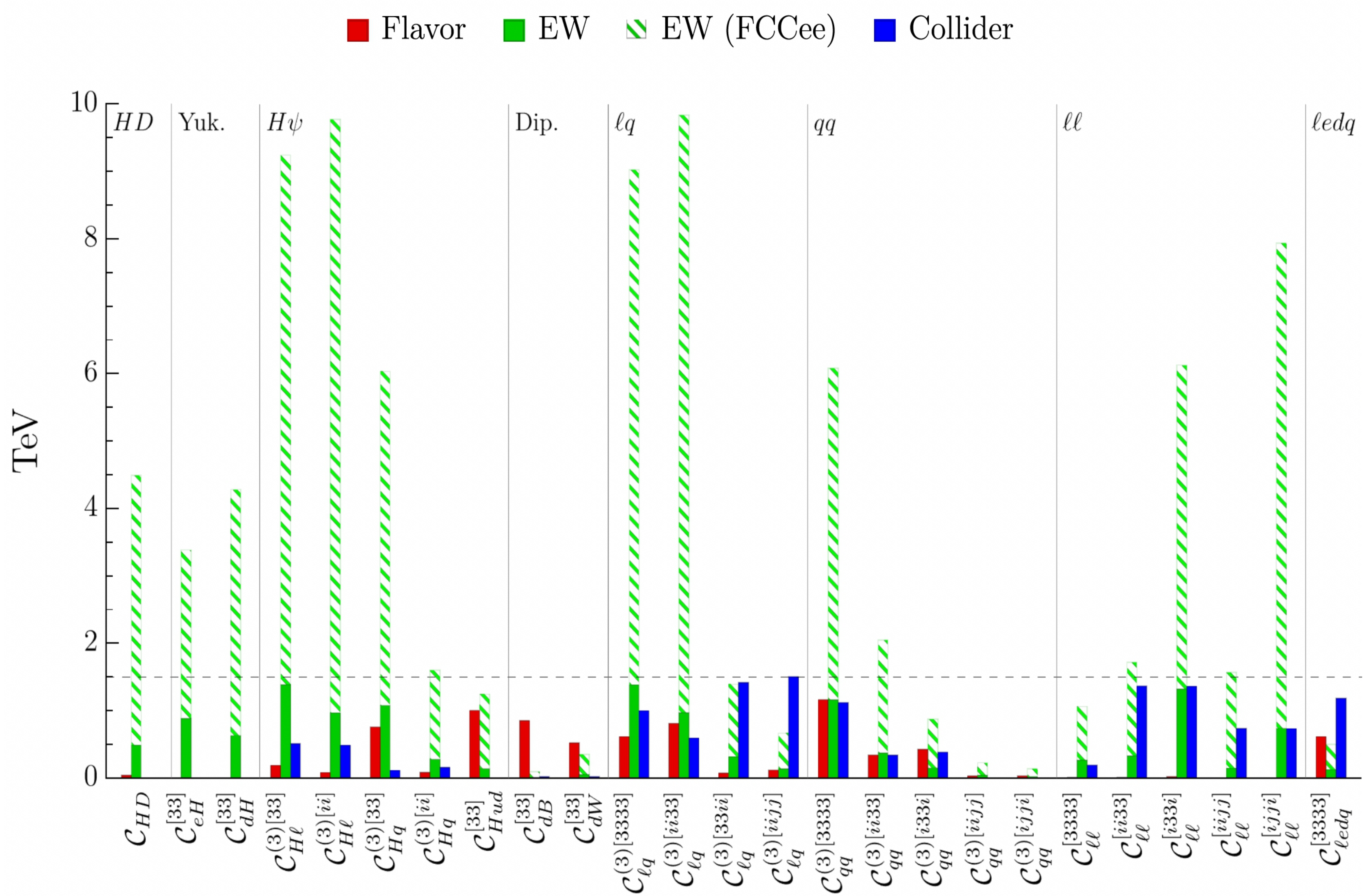


largely enhanced b→sττ rates
(in all channles)





Flavor
EW
Collider
TeV
HD
Yuk.
$H\psi$
Dip.
ℓq
qq
$\ell\ell$
ℓedq
$\epsilon_{\rm loop} = \frac{1}{16\pi^2}$
$\epsilon_Q = 0.16$
$\epsilon_L = 0.40$
$\epsilon_H = 0.31$
$\epsilon_{\rm mis} = 0.15$
$\mathcal{C}_{HD}$
$\mathcal{C}_{eH}^{[33]}$
$\mathcal{C}_{dH}^{[33]}$
$\mathcal{C}_{H\ell}^{(3)[33]}$
$\mathcal{C}_{H\ell}^{(3)[ii]}$
$\mathcal{C}_{Hq}^{(3)[33]}$
$\mathcal{C}_{Hq}^{(3)[ii]}$
$\mathcal{C}_{Hud}^{[33]}$
$\mathcal{C}_{dB}^{[33]}$
$\mathcal{C}_{dW}^{[33]}$
$\mathcal{C}_{\ell q}^{(3)[3333]}$
$\mathcal{C}_{\ell q}^{(3)[ii33]}$
$\mathcal{C}_{\ell q}^{(3)[33ii]}$
$\mathcal{C}_{\ell q}^{(3)[iijj]}$
$\mathcal{C}_{qq}^{(3)[3333]}$
$\mathcal{C}_{qq}^{(3)[ii33]}$
$\mathcal{C}_{qq}^{(3)[i33i]}$
$\mathcal{C}_{qq}^{(3)[iijj]}$
$\mathcal{C}_{qq}^{(3)[ijji]}$
$\mathcal{C}_{\ell\ell}^{[3333]}$
$\mathcal{C}_{\ell\ell}^{[ii33]}$
$\mathcal{C}_{\ell\ell}^{[i33i]}$
$\mathcal{C}_{\ell\ell}^{[iijj]}$
$\mathcal{C}_{\ell\ell}^{[ijji]}$
$\mathcal{C}_{\ell edq}^{[3333]}$


Flavor
EW
EW (FCCee)
Collider
TeV
0
2
4
6
8
10
HD
Yuk.
$H\psi$
Dip.
ℓq
qq
$\ell\ell$
ℓedq
$\mathcal{C}_{HD}$
$\mathcal{C}_{eH}^{[33]}$
$\mathcal{C}_{dH}^{[33]}$
$\mathcal{C}_{H\ell}^{(3)[33]}$
$\mathcal{C}_{H\ell}^{(3)[ii]}$
$\mathcal{C}_{Hq}^{(3)[33]}$
$\mathcal{C}_{Hq}^{(3)[ii]}$
$\mathcal{C}_{Hud}^{[33]}$
$\mathcal{C}_{dB}^{[33]}$
$\mathcal{C}_{dW}^{[33]}$
$\mathcal{C}_{\ell q}^{(3)[3333]}$
$\mathcal{C}_{\ell q}^{(3)[ii33]}$
$\mathcal{C}_{\ell q}^{(3)[33ii]}$
$\mathcal{C}_{\ell q}^{(3)[iijj]}$
$\mathcal{C}_{qq}^{(3)[3333]}$
$\mathcal{C}_{qq}^{(3)[ii33]}$
$\mathcal{C}_{qq}^{(3)[i33i]}$
$\mathcal{C}_{qq}^{(3)[iijj]}$
$\mathcal{C}_{qq}^{(3)[ijji]}$
$\mathcal{C}_{\ell\ell}^{[3333]}$
$\mathcal{C}_{\ell\ell}^{[ii33]}$
$\mathcal{C}_{\ell\ell}^{[i33i]}$
$\mathcal{C}_{\ell\ell}^{[iijj]}$
$\mathcal{C}_{\ell\ell}^{[ijji]}$
$\mathcal{C}_{\ell edq}^{[3333]}$