Flavor physics beyond the Standard Model and the origin of the Cabibbo angle

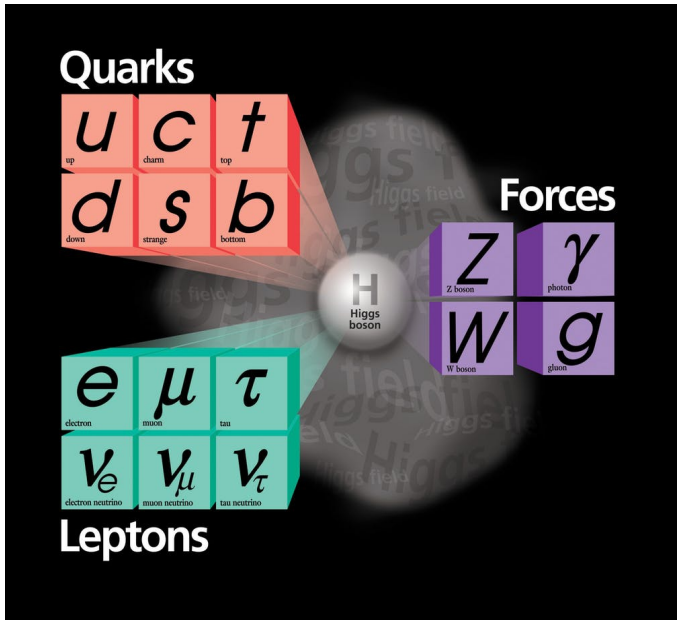
Gino Isidori
[*University of Zürich*]

- Introduction
- The two flavor puzzles
- Flavor non-universal interactions
- Future prospects
- Conclusions

University of Zurich[UZH]

European Research Council
Established by the European Commission

Introduction



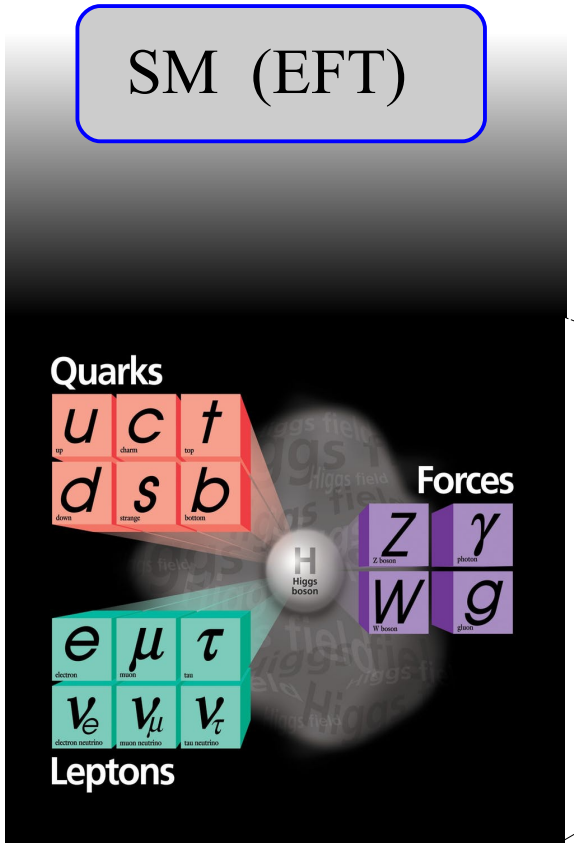
Introduction

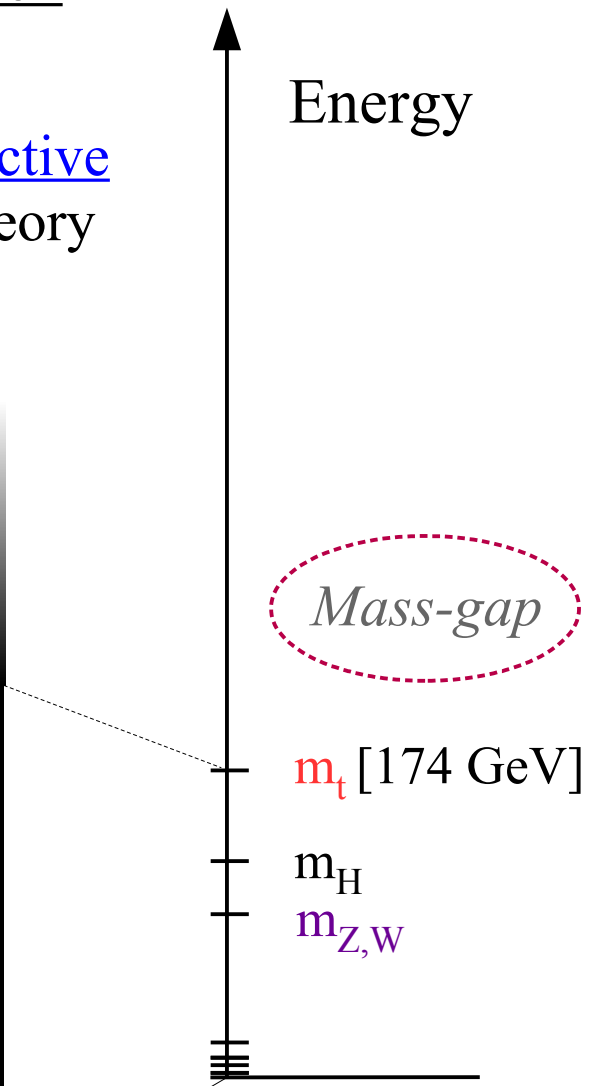
Last year we celebrated the 10th anniversary of the Higgs-boson discovery (*or the completion of the SM spectrum*).

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 the *long-range* properties of this EFT





Introduction

There are several reasons why we think the SM must be extended at high energies:

Electroweak hierarchy problem

Flavor puzzle

U(1) charges

Neutrino masses

Strong CP problem

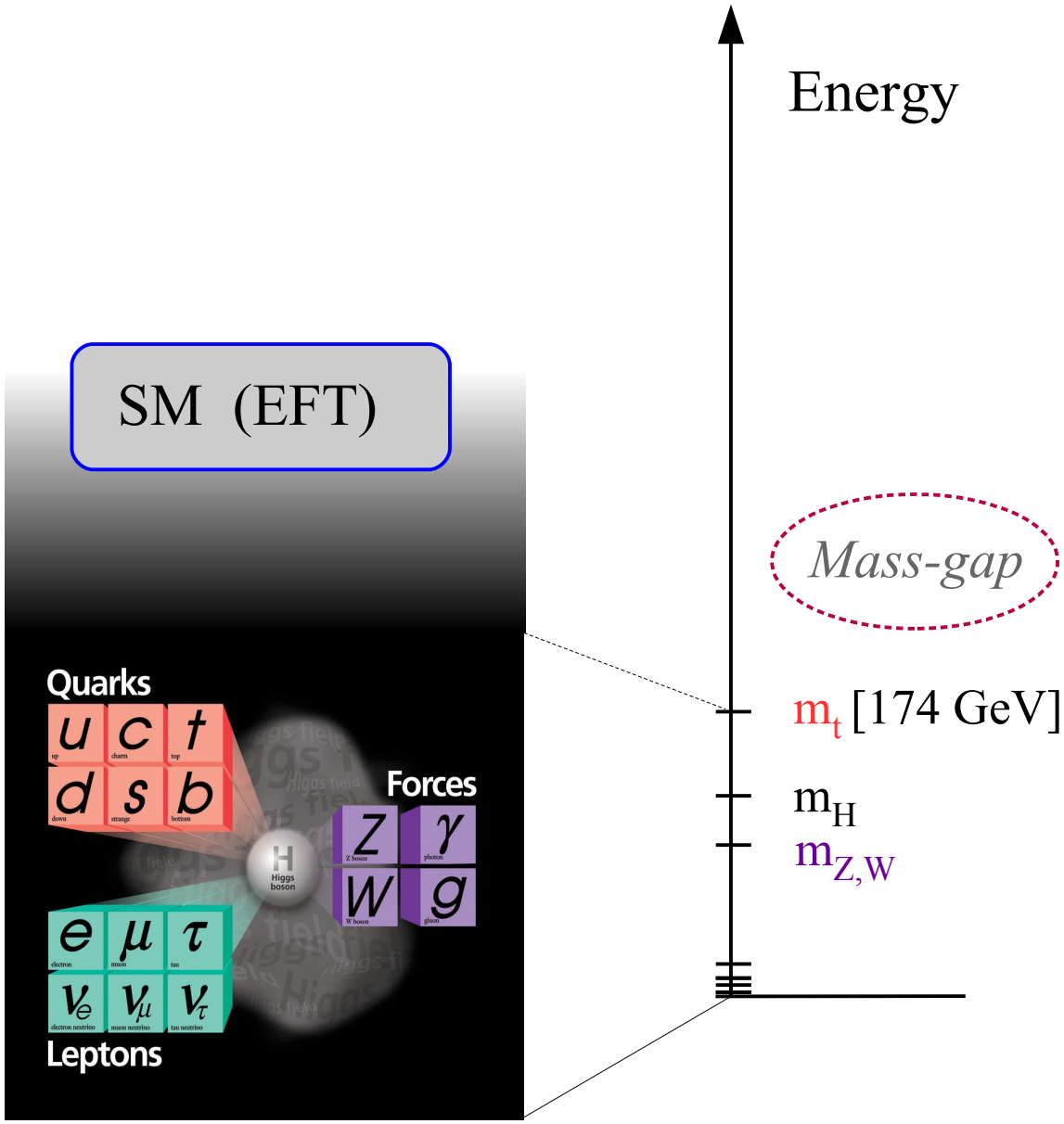
….

Dark-matter

Dark-energy

Inflation

Quantum gravity



Introduction

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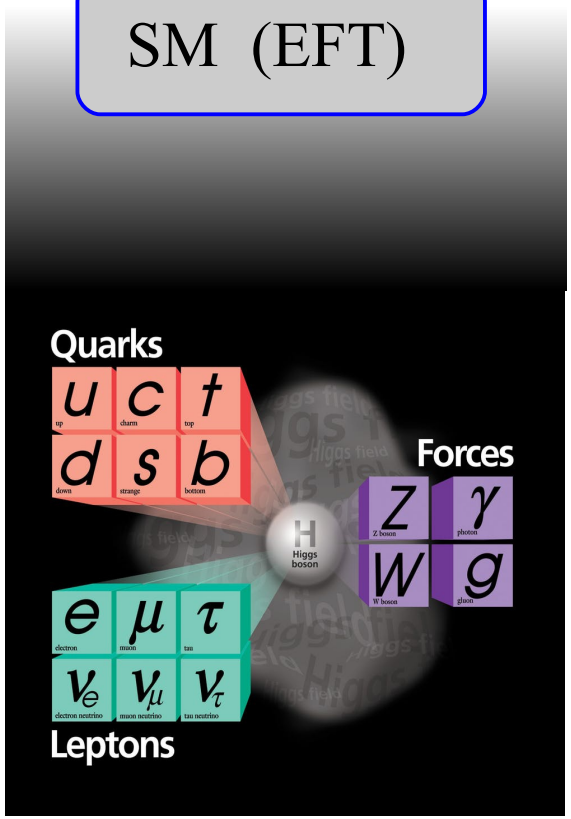
Strong CP problem

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

Useful hints for its UV completion

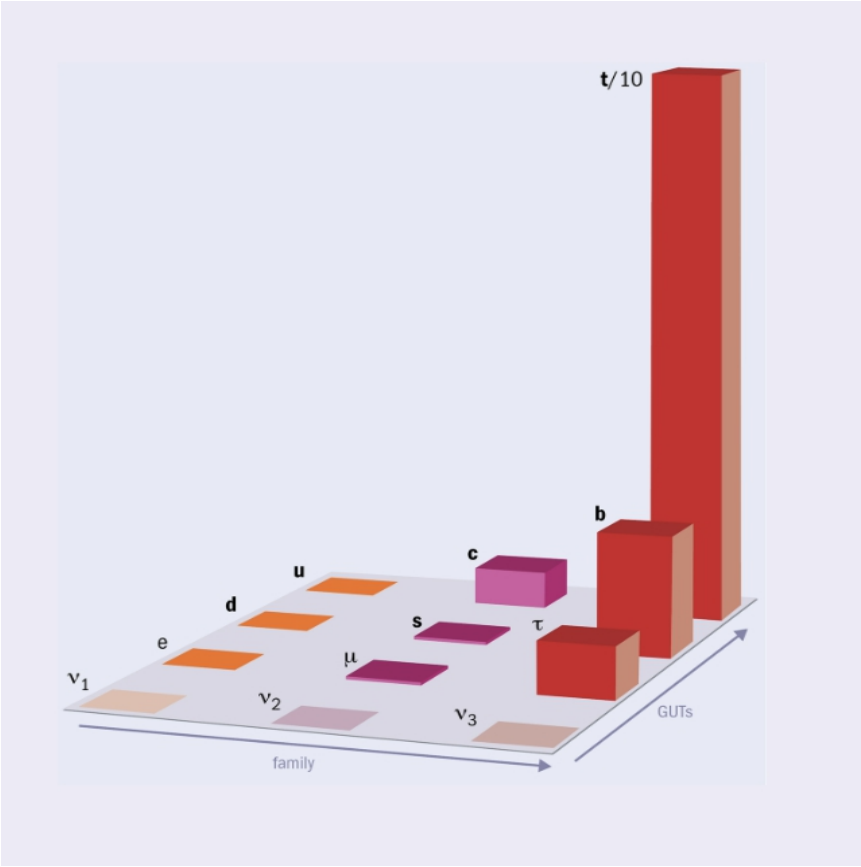
UV Theory

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

There are two (long-standing) open issues in flavor physics:

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

→ Is there a deeper explanation for this peculiar structures?

The SM flavor puzzle

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?

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

The NP flavor puzzle

The two flavor puzzles

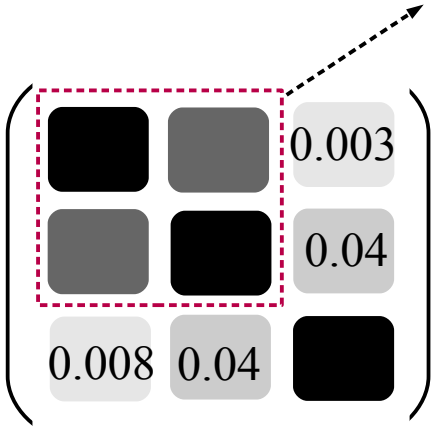
There are two (long-standing) open issues in flavor physics:

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

Eg.: (1)

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

$V_{CKM} \sim$



Despite decades of precision measurements in flavor physics, we are not able to detect the presence of the 3rd family by looking only at the 2×2 block of the quark mixing matrix (the "Cabibbo matrix")

→ talk by V. Cirigliano

The two flavor puzzles

There are two (long-standing) open issues in flavor physics:

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

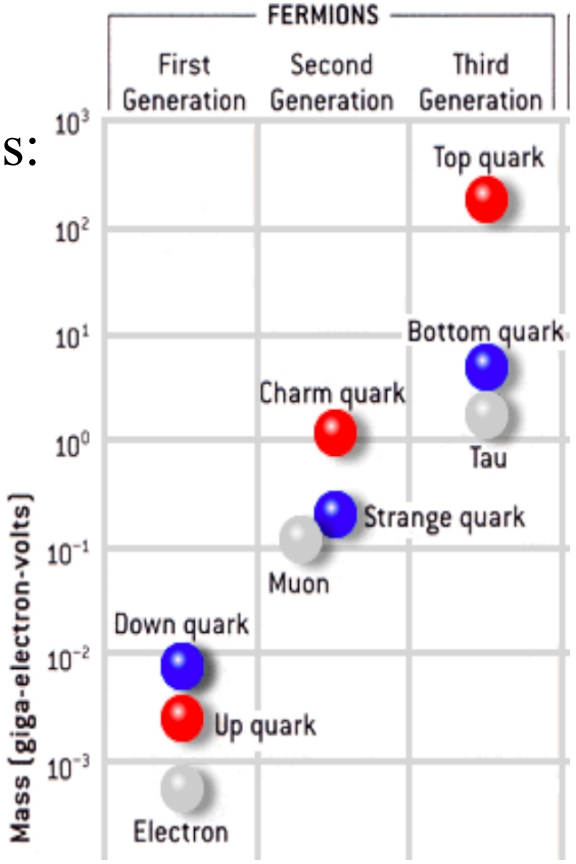
Eg.: (2)

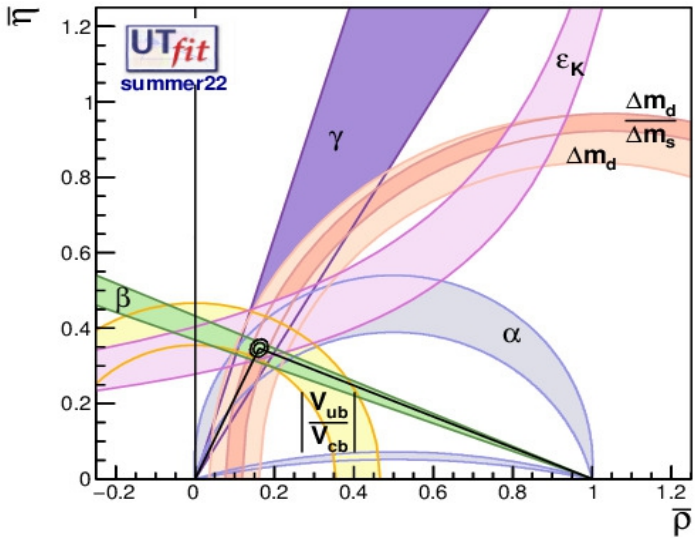
$$Y_U \sim \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \blacksquare \end{pmatrix}$$

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

$$\mathscr{L}_Y = \bar{Q}_L\, Y_U\, U_R\, H + \ldots$$

(Y_U in the basis where Y_D is diagonal)





The two flavor puzzles

There are two (long-standing) open issues in flavor physics:

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

$$Y_U \sim \begin{pmatrix} & & 0.003 \\ < 0.01 & & 0.04 \\ & & 1 \end{pmatrix}$$

$U(2)_u$ (left block) $\quad U(2)_q$ (right block)

$$\bar{Q}_L \, Y_U \, U_R \, H$$

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

The two flavor puzzles

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The two flavor puzzles

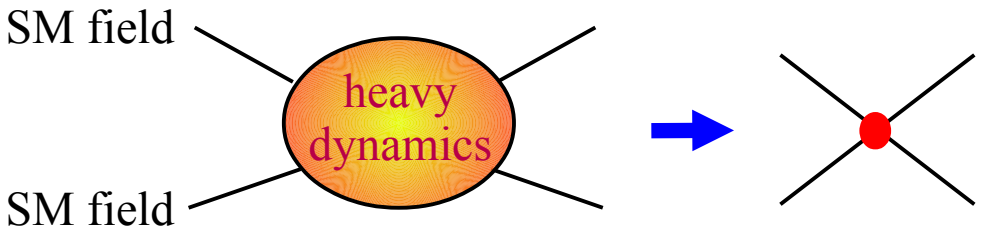
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

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

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:

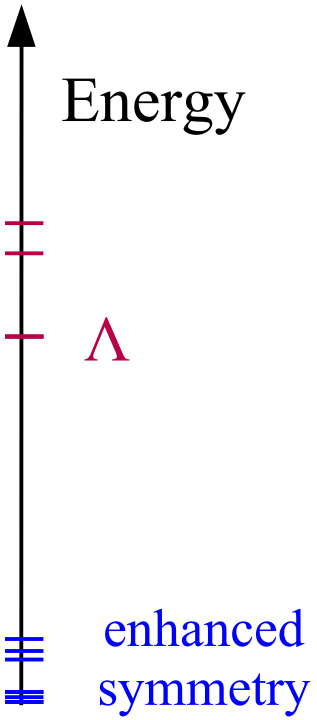
- $U(1)_{Le} \times U(1)_{L\mu} \times U(1)_{L\mu}$ = (individual) Lepton Flavor [*exact symmetry*]
- $m_u \approx m_d \approx 0 \;\rightarrow$ Isospin symmetry [*approximate symmetry*]

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*]



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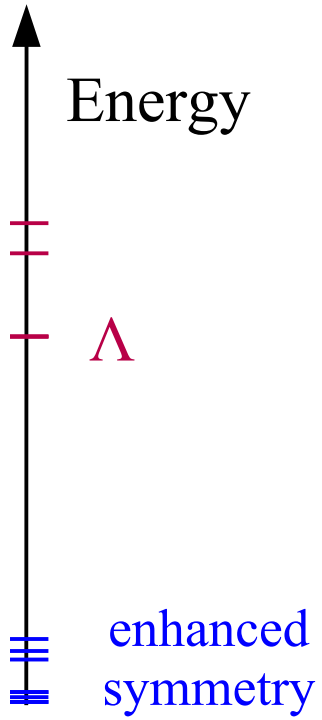

If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

Violations of accidental symmetries

Accidental symmetries in QFT [a brief detour]

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[SM-2]-EFT

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

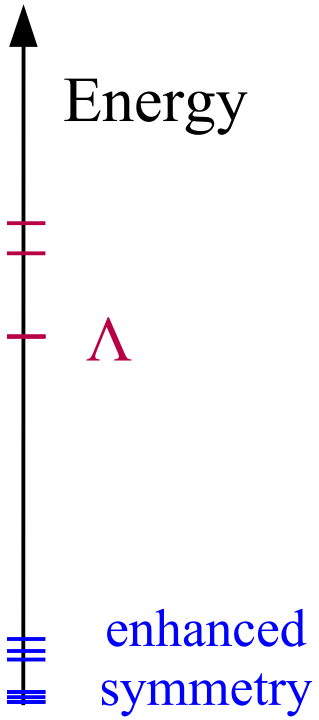
Interesting historical example:
SM with 2 generations [GIM, '70]
→ CP violation is an accidental symmetry

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

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

"Super-weak" interaction
[L. Wolfenstein, '64]

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



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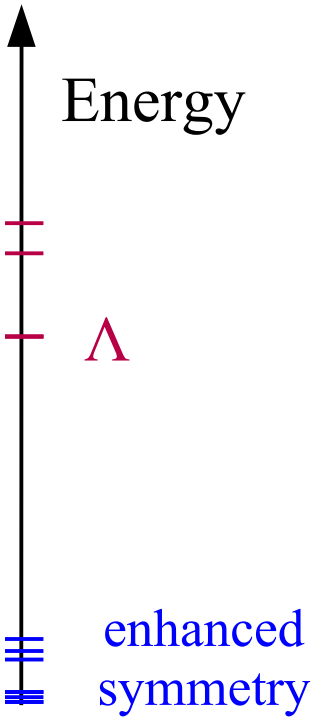

SM-3 [KM, '73]:

$$\frac{1}{\Lambda_{CP}^2} \sim \frac{(y_t^2 V_{ts} V_{td})^2}{16\pi^2 m_t^2}$$

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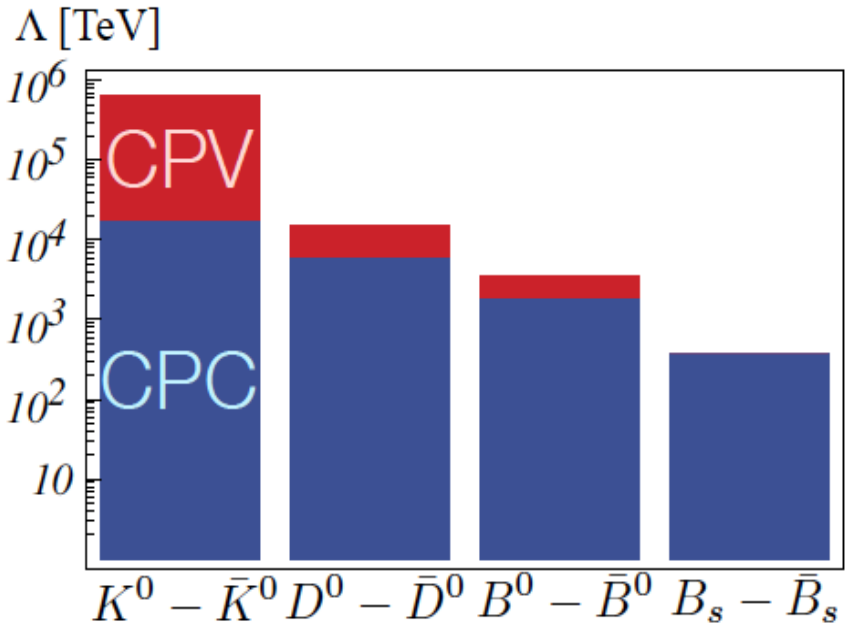
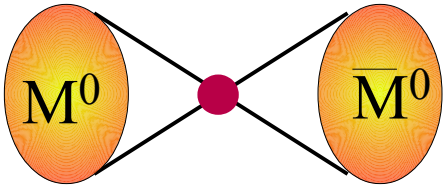
In principle, in the SM-EFT we could expect many violations of the accidental symmetries from the heavy dynamics (→ *new flavor violating effects*).
However, no clear deviations observed so far

↓

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

The NP flavor puzzle





→ talk by L. Silvestrini

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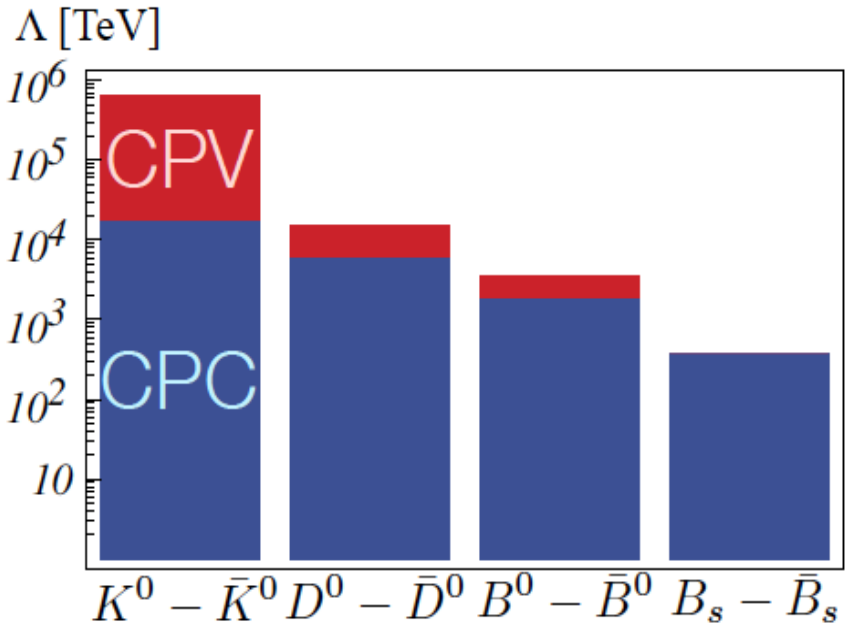
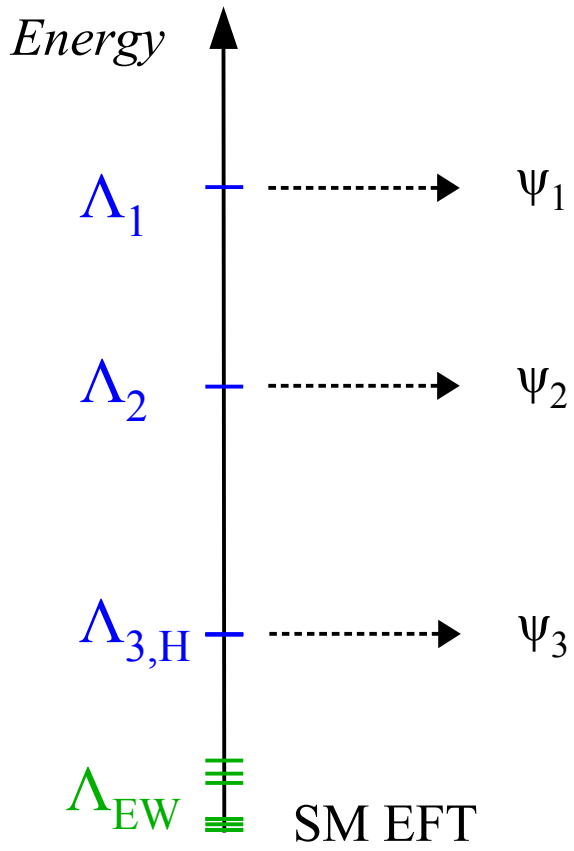


N.B. (1): These high scales can be a "mirage" [*remember CP in SM-2...*].

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

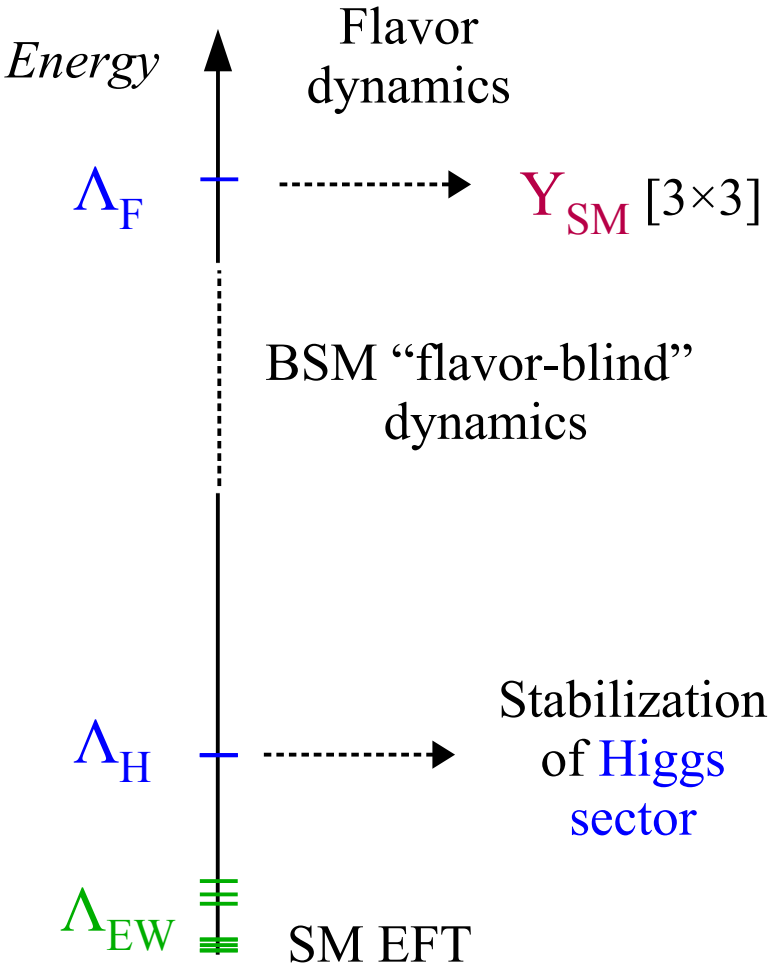
N.B. (2): $U(2)^n$ is not an accidental symmetry of the SM [→ *indication of specific UV dynamics?*]

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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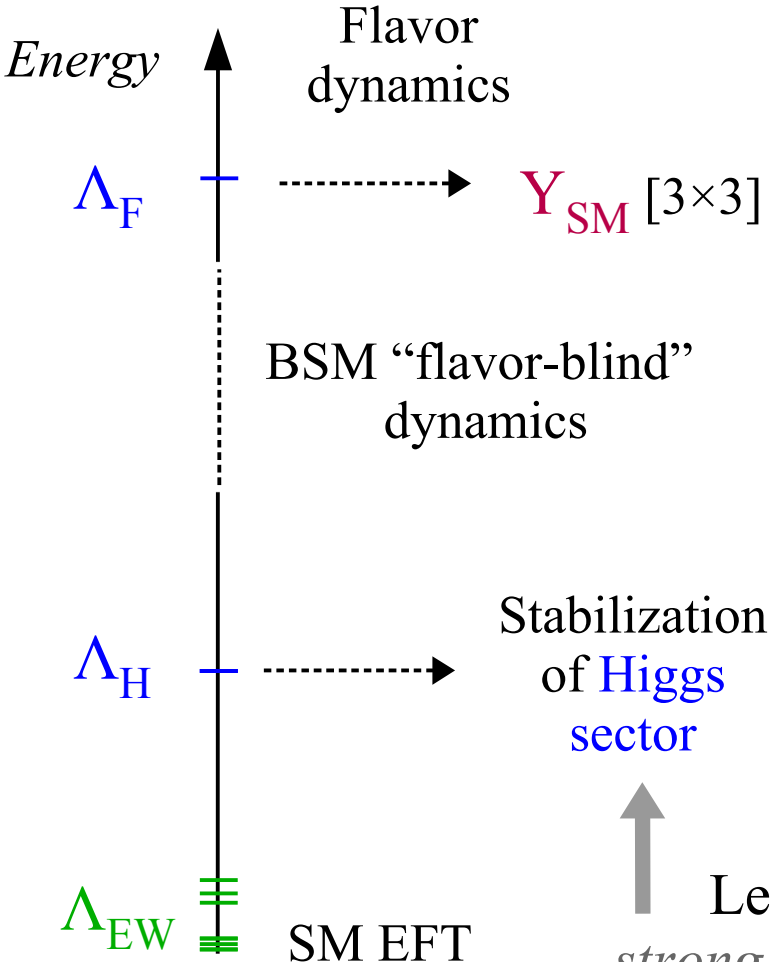

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⇕

The "MFV paradigm"

+

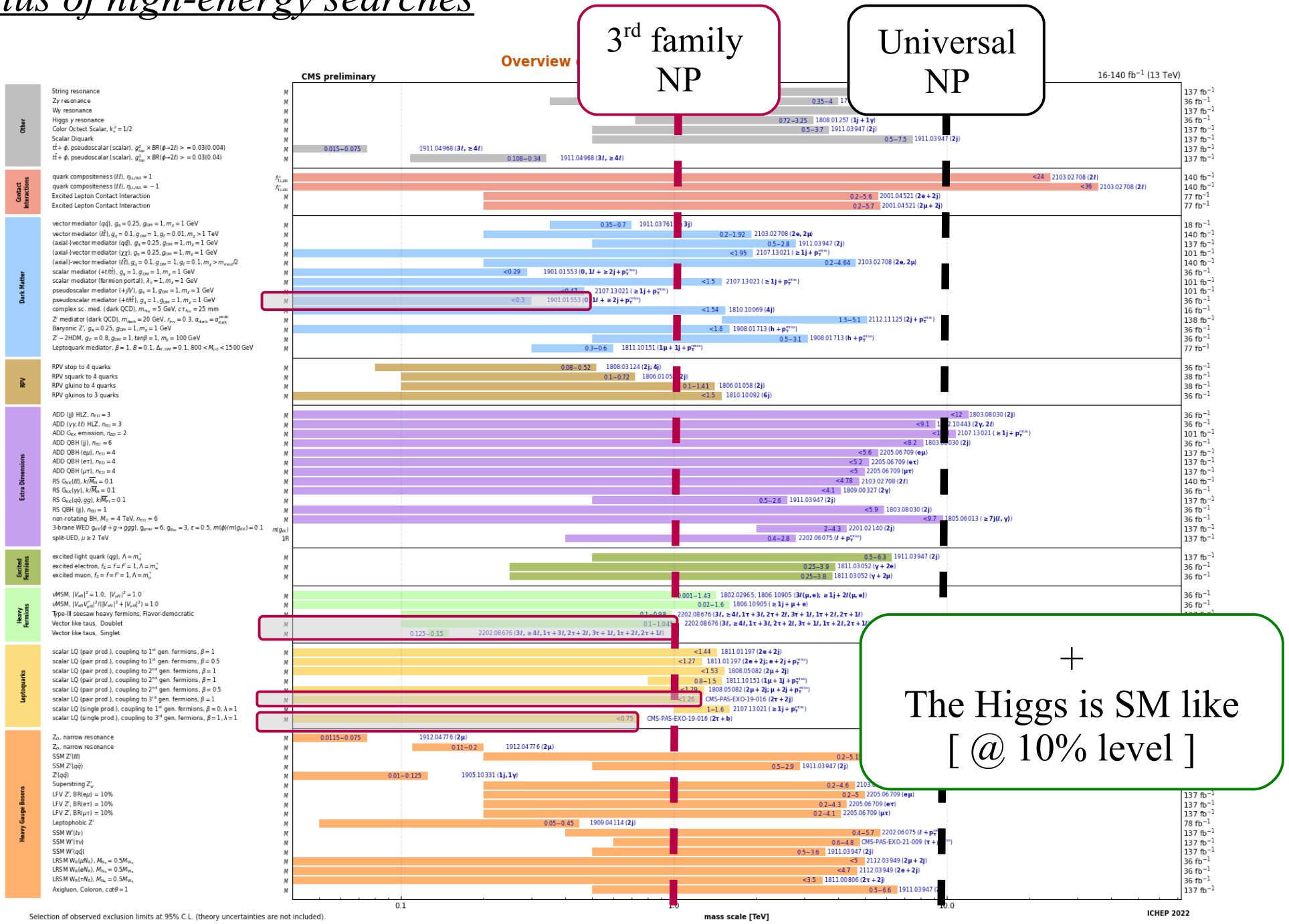
"Horizontal" flavor symmetries @ high scales

Less compelling after LHC results (run I+II):

strong bounds on NP coupled universally to all families

worsening of the Higgs hierarchy problem

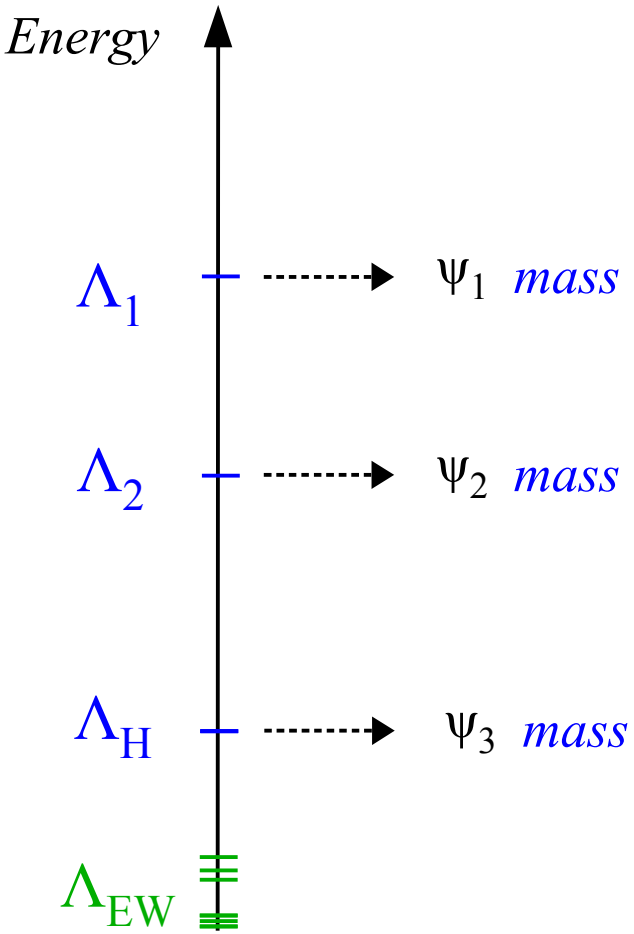
Status of high-energy searches



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:

- 1st & 2nd 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~~

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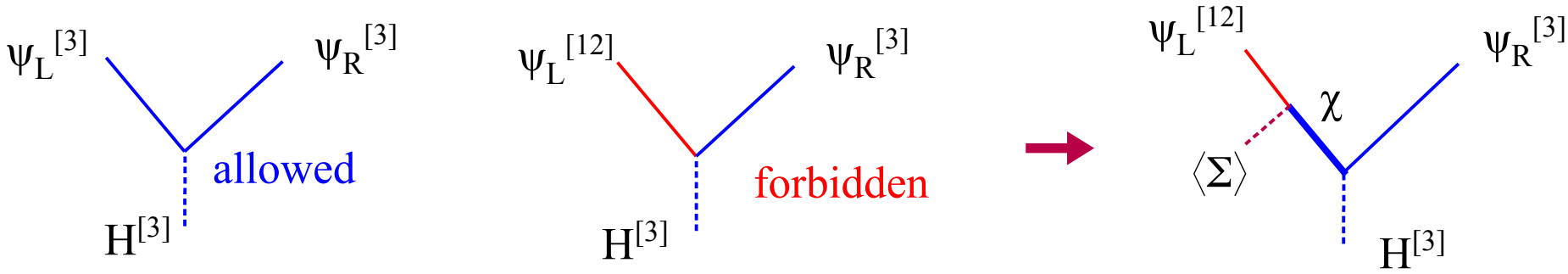
- *"flavor deconstruction"* of the SM gauge symmetries:

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



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

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

Last step of the symm. breaking chain: [@ few TeV]

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

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 $G^{[3]} \times G^{[12]} \to G^{[Univ]}$ is very general (*no tuning in the potential*) → flavor universality naturally emerges at low energies

Flavor non-universal interactions

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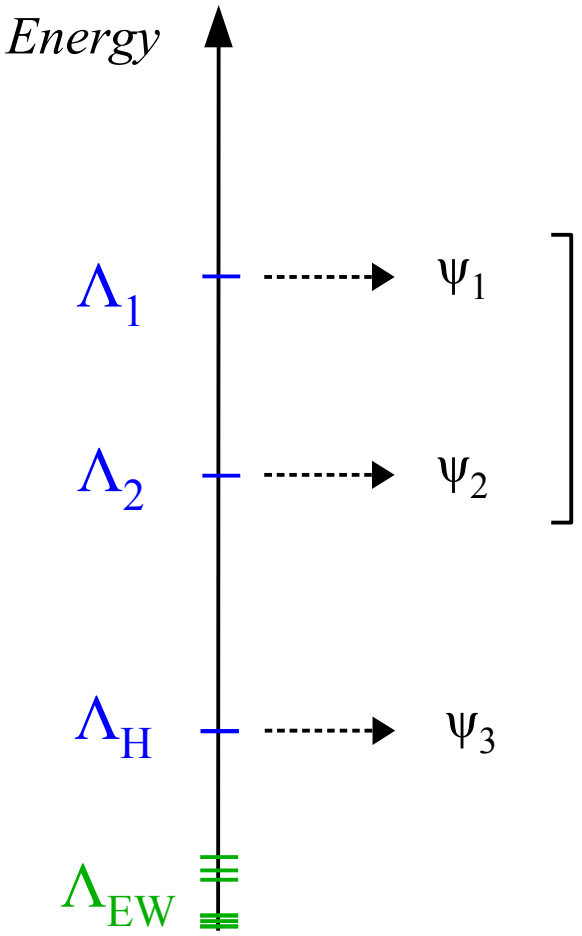
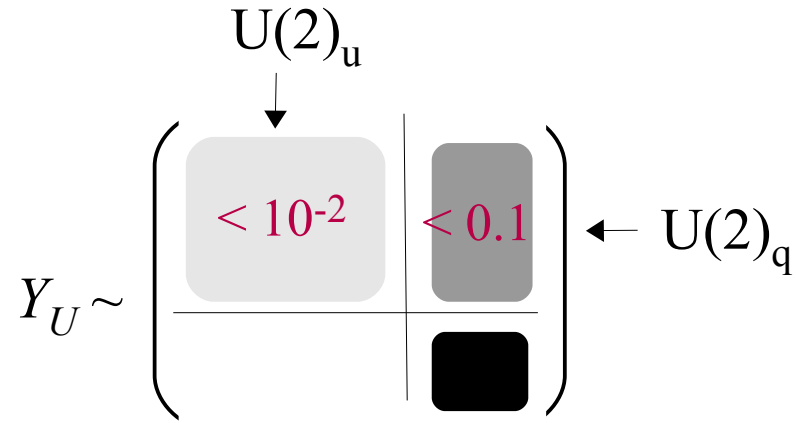


- The 2×2 light block of the Yukawa coupling originates from high-scale physics [→ origin of the *Cabibbo angle*]
- No additional breaking of $U(2)^n$ is mediated at low energies

"UV imprint" in the Yukawa couplings:



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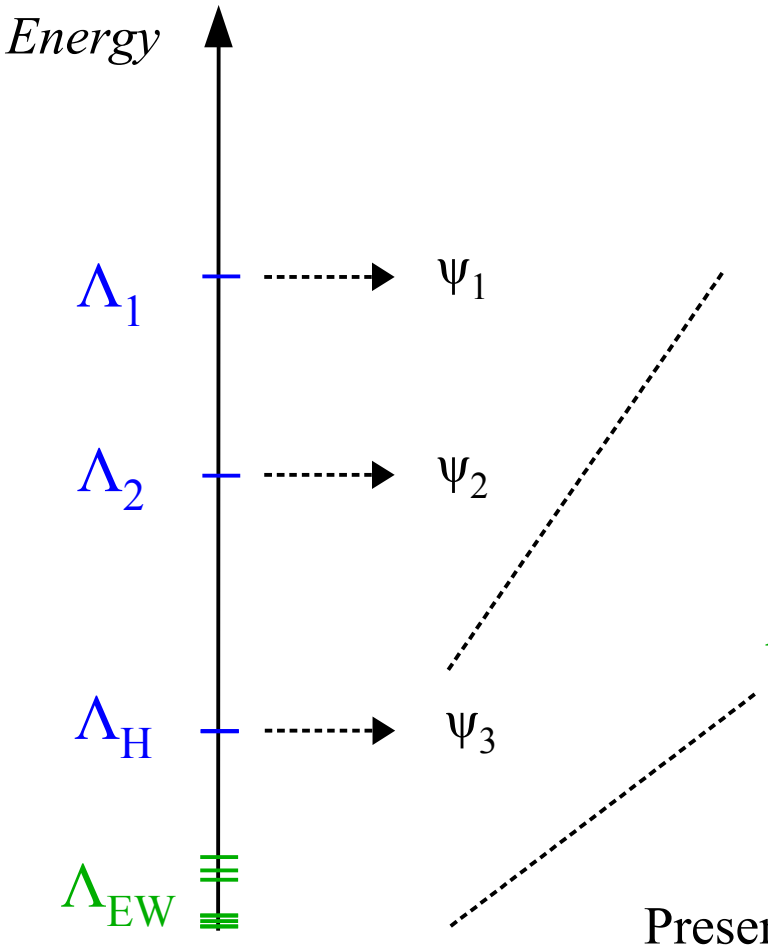
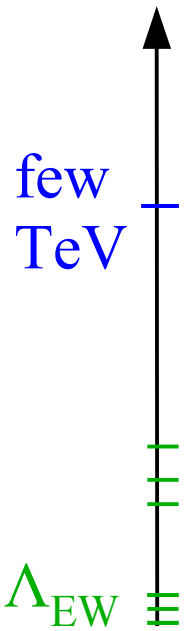




$[\, G^{[3]} \times G^{[12]} \,] \times H^{[Univ]}$

NP coupled mainly to ψ_3

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

Barbieri *et al.* '11
GI & Straub '12

Organizing principle for the SMEFT

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

Present bounds on all eff. ops. built according to this symmetry & symmetry-breaking hypotheses do not exceed ~ 1.5 TeV

Allwicher, Cornella, GI, Stefanek '23

Quark-lepton unification for the 3rd generation [a brief detour]

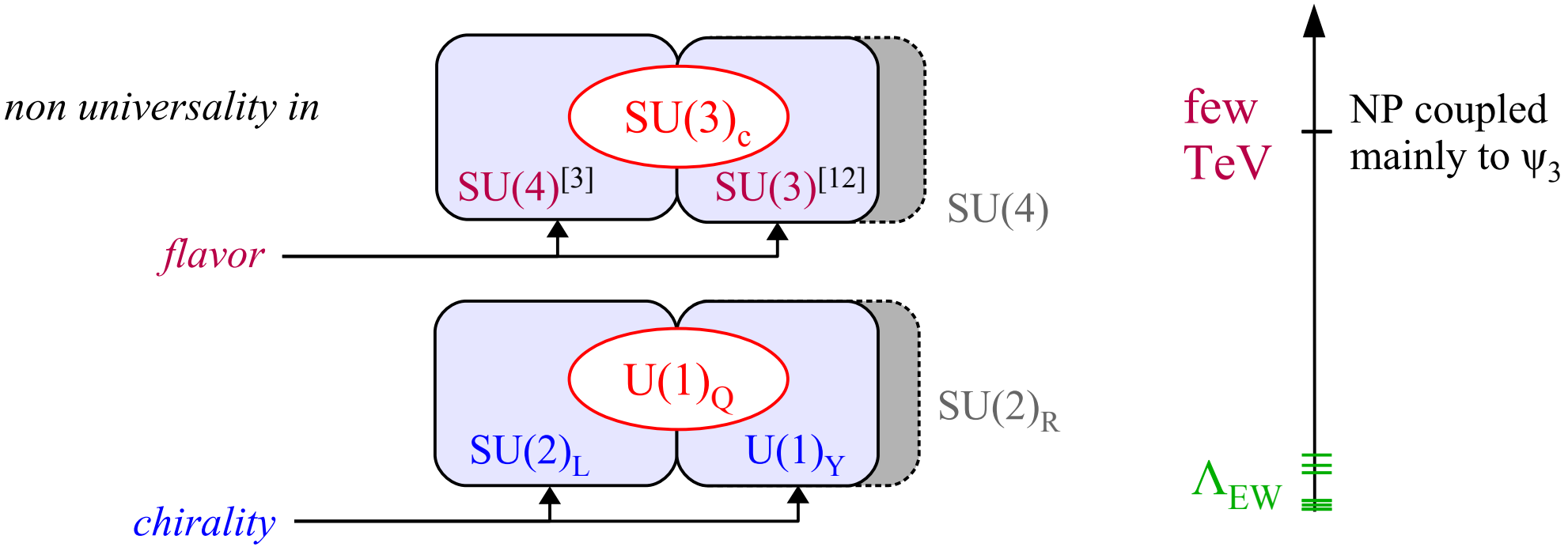
The possible options have been classified → *not many consistent choices*

A particularly interesting one is allowing quark-lepton unification a la Pati-Salam for the third-family:

$$SU(4)^{[3]} \times SU(3)^{[12]} \times G_{EW}$$

$$\downarrow$$

$$SU(3) \times SU(2)_L \times U(1)_Y$$



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↓

$SU(3) \times SU(2)_L \times U(1)_Y$

→ vector leptoquark [U_1]

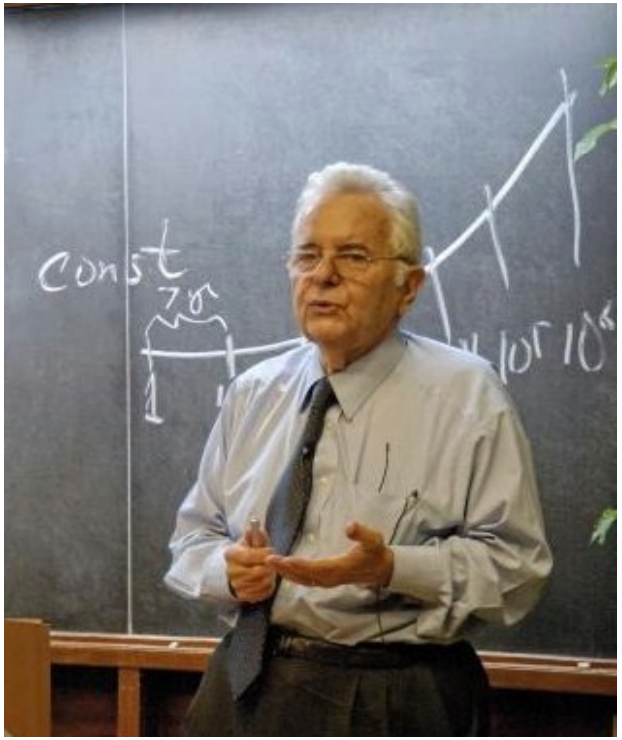
Di Luzio, Greljo, Nardecchia, '17
Bordone, Cornella, Fuentes-M, GI '17
Greljo & Stefanek, '18

- ✔ Explain charge quantization

Fermions in SU(4): $\begin{bmatrix} Q^{\alpha} \\ Q^{\beta} \\ Q^{\gamma} \\ L \end{bmatrix}$

- ✔ Might explain some existing tensions in B-physics data

Future prospects



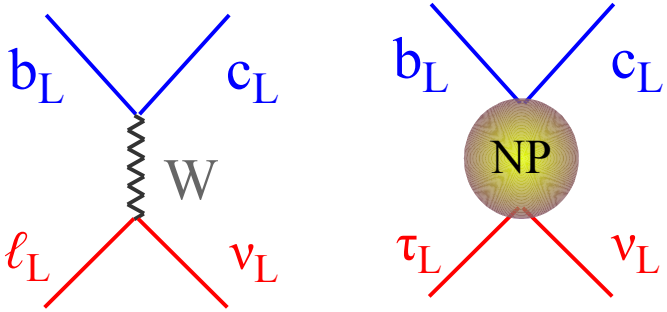
Future prospects

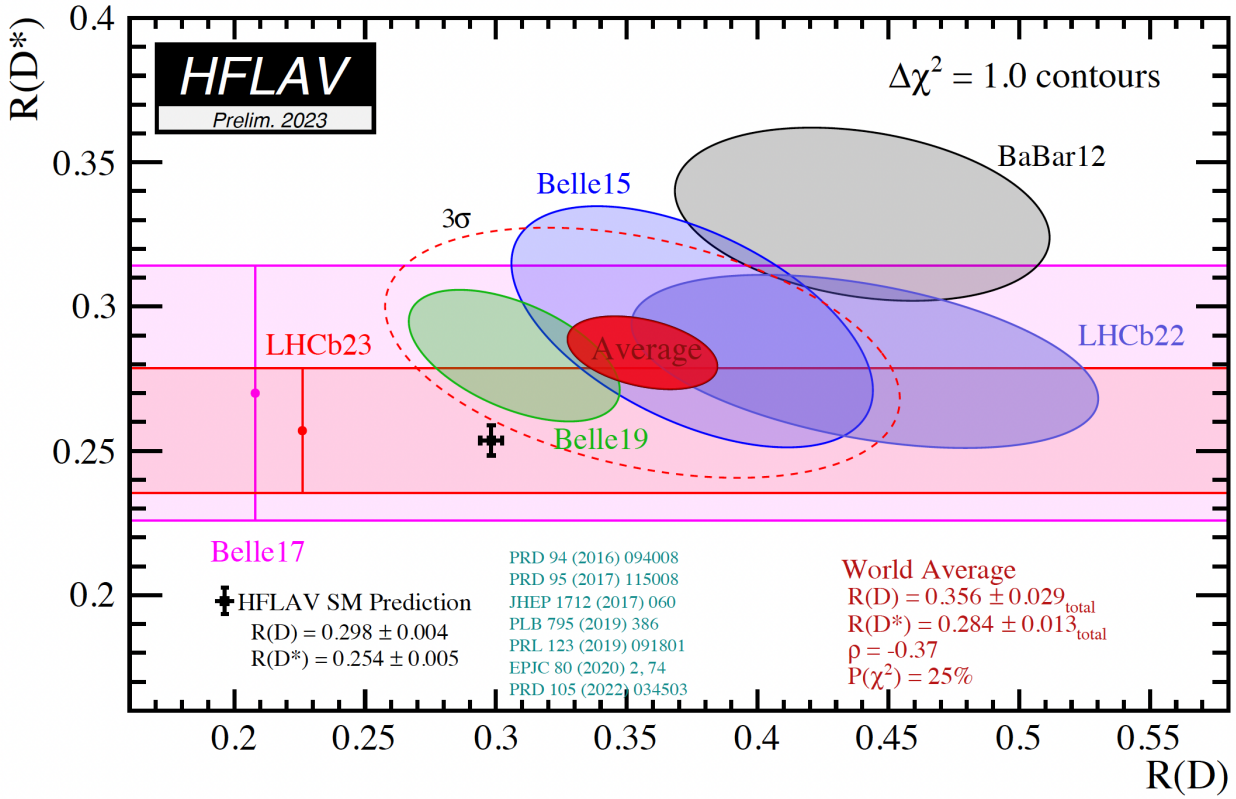
The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements (*with different degree of model-dependence*)

E.g.: I) Lepton universality violations in $b \to c\tau\nu$ decays

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

X = D or D*

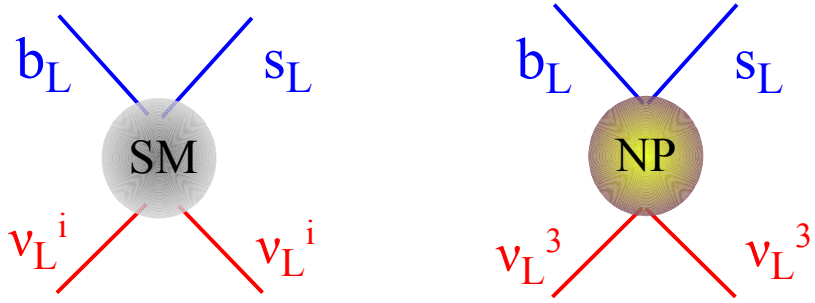




Future prospects

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*)

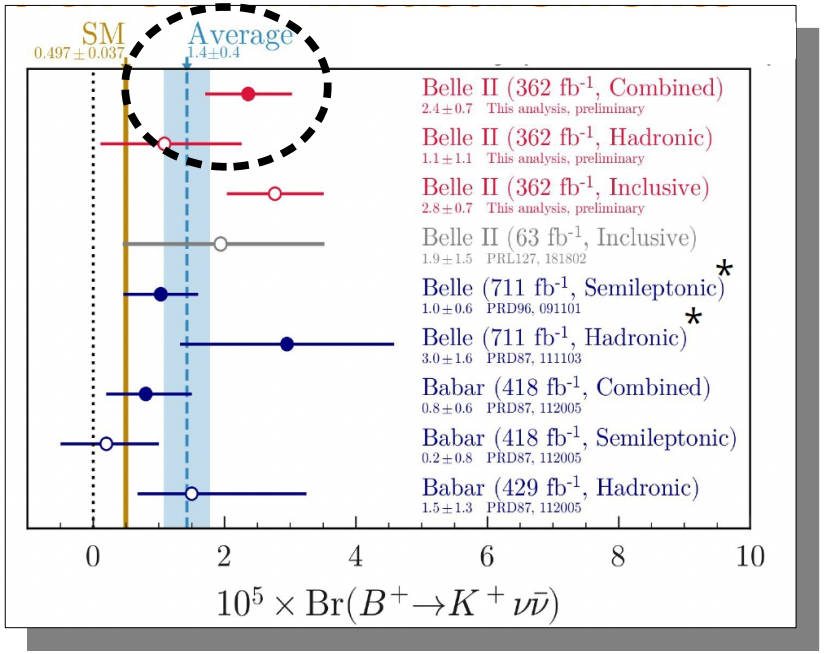
E.g.: II) Deviations from SM in $b\to s\nu\nu$ rates [3rd gen. ν in the final state]



identical for all neutrino species

relevant only for 3rd gen. neutrinos

Belle-II @ EPS '23



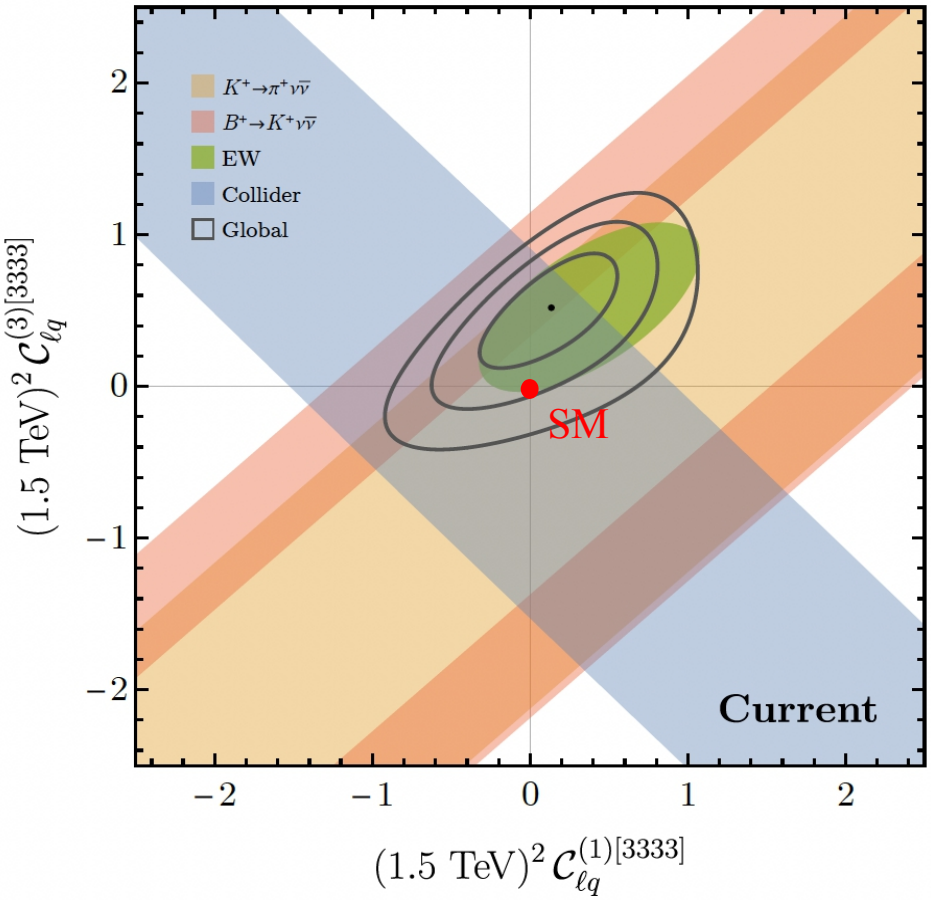
Unambiguos prediction of 30-50% enhancement of $B(B\to K\nu\nu)$ in the model with vector LQ, given data on R(D).

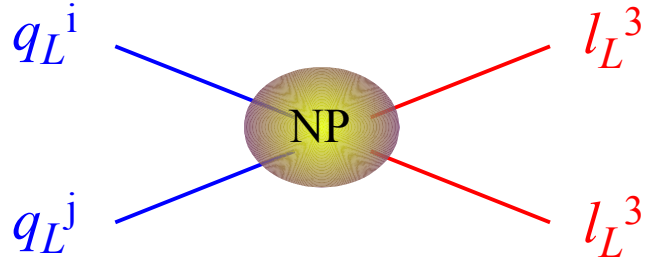
Fuentes-Martin, GI, Konig, Selimovic, '20

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

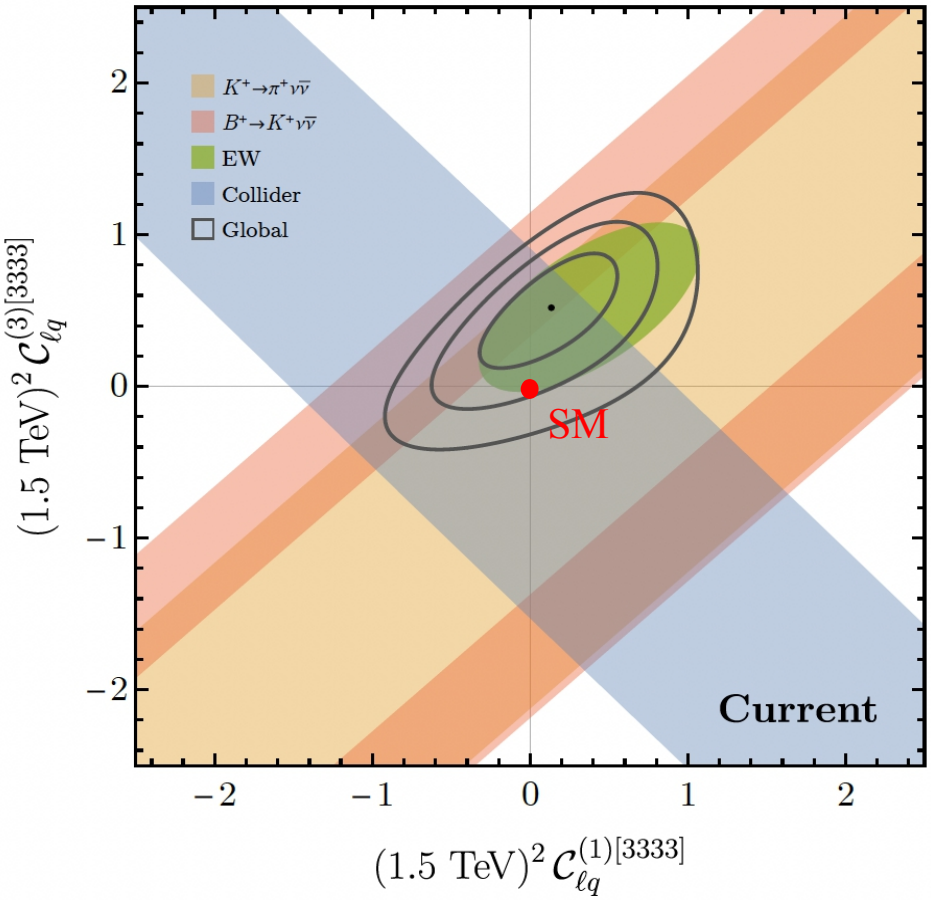


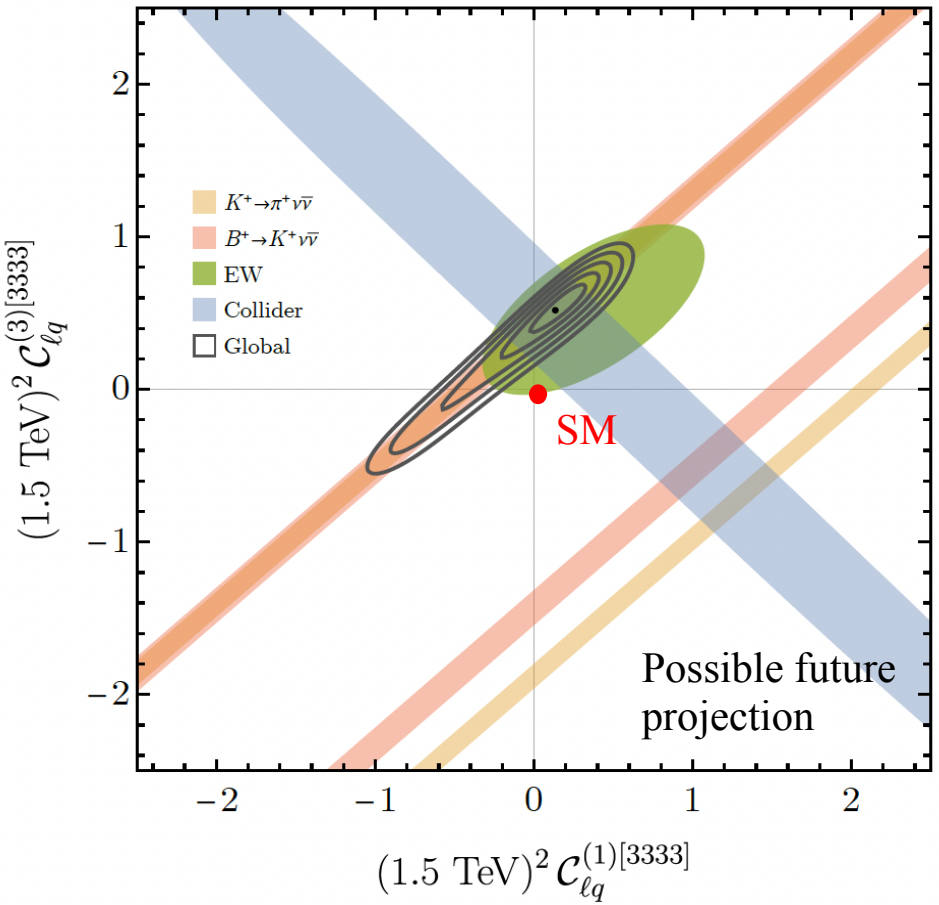


Future prospects

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 (*with different degree of model-dependence*)

E.g.: II) Deviations from SM in b→svv rates... and s→dvv rates

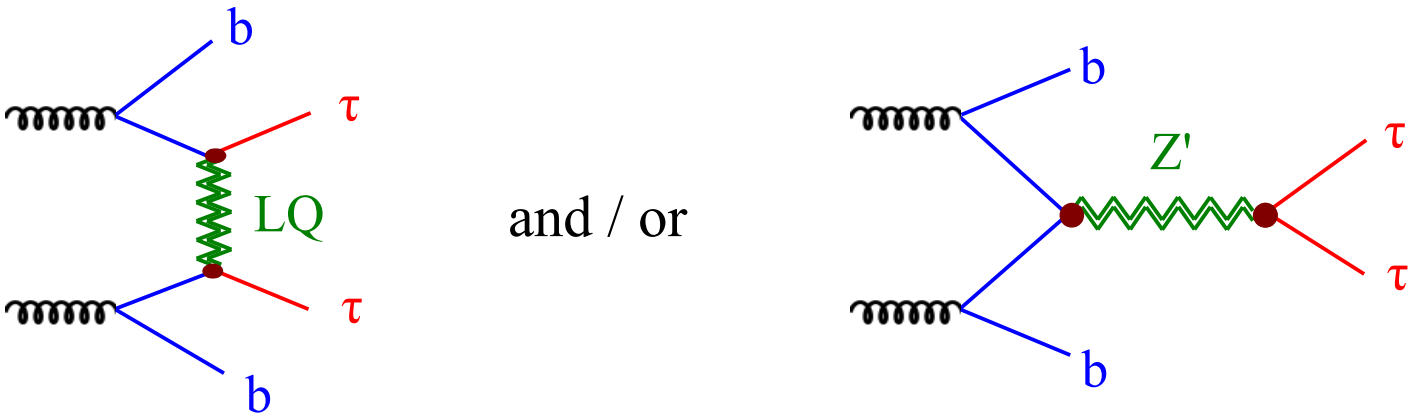




Future prospects

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)

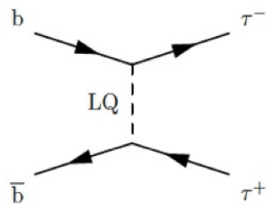


Future prospects

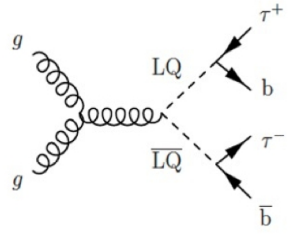
Aurelio Juste [*Moriond EW* '23]

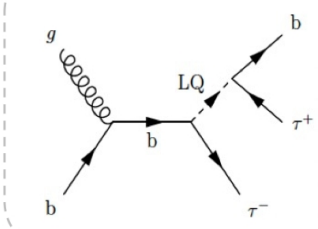
LQ-b-τ: Comparison of recent results

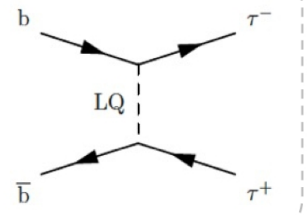
Including interference w/ SM bkg



Neglecting interference w/ SM bkg

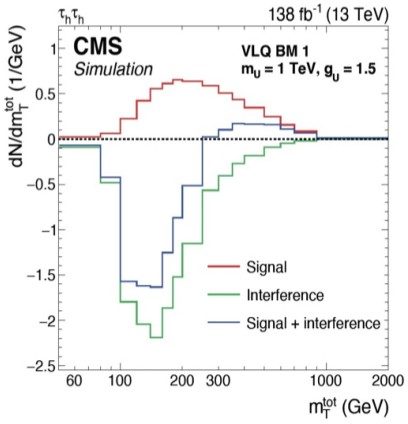


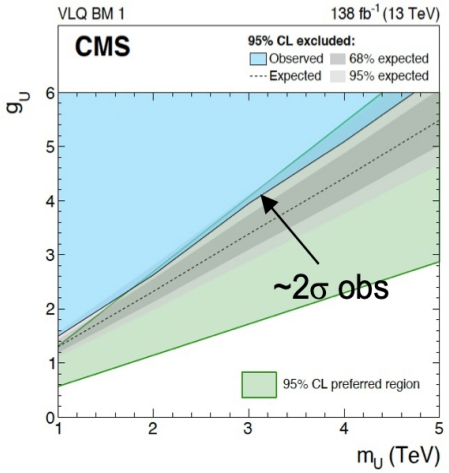




Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

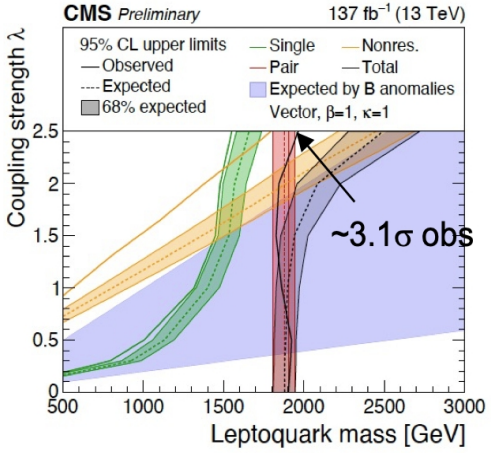
[CMS-HIG-21-001]



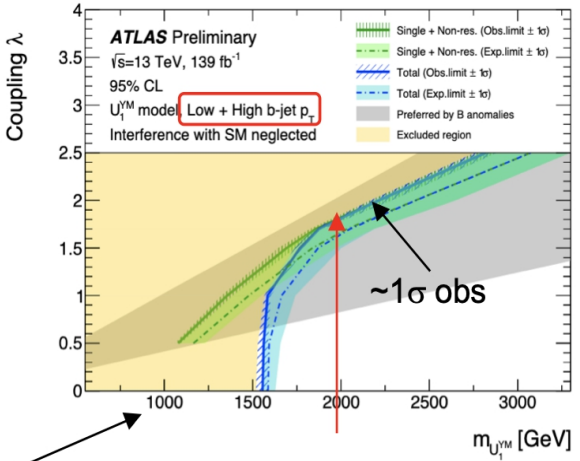


Shown at Moriond EW 2022

[CMS-PAS-EXO-19-016]



[EXOT-2022-39]



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

Need to clarify interference issue for future interpretations

Conclusions

- Sixty years after Cabibbo laid down the cornerstone of Flavor Physics, this field continue to be extremely lively and fascinating:
  Flavor Physics still hides interesting puzzles and might be the key to understand the nature of physics beyond the Standard Model

- *We are far from having archived a simple explanation about the origin of the Cabibbo angle*... but new interesting ideas have been proposed. Among them, the hypothesis of "flavor deconstruction" of the SM gauge symmetries – with TeV scale new dynamics coupled mainly to the third generation – is particularly appealing.

- Beside it's theoretical appeal, this is an hypothesis that we can test in the near future with the the planned experimental program in flavor physics (*I'm sure Nicola would have liked it...*)


Backup

Minimal flavor deconstruction

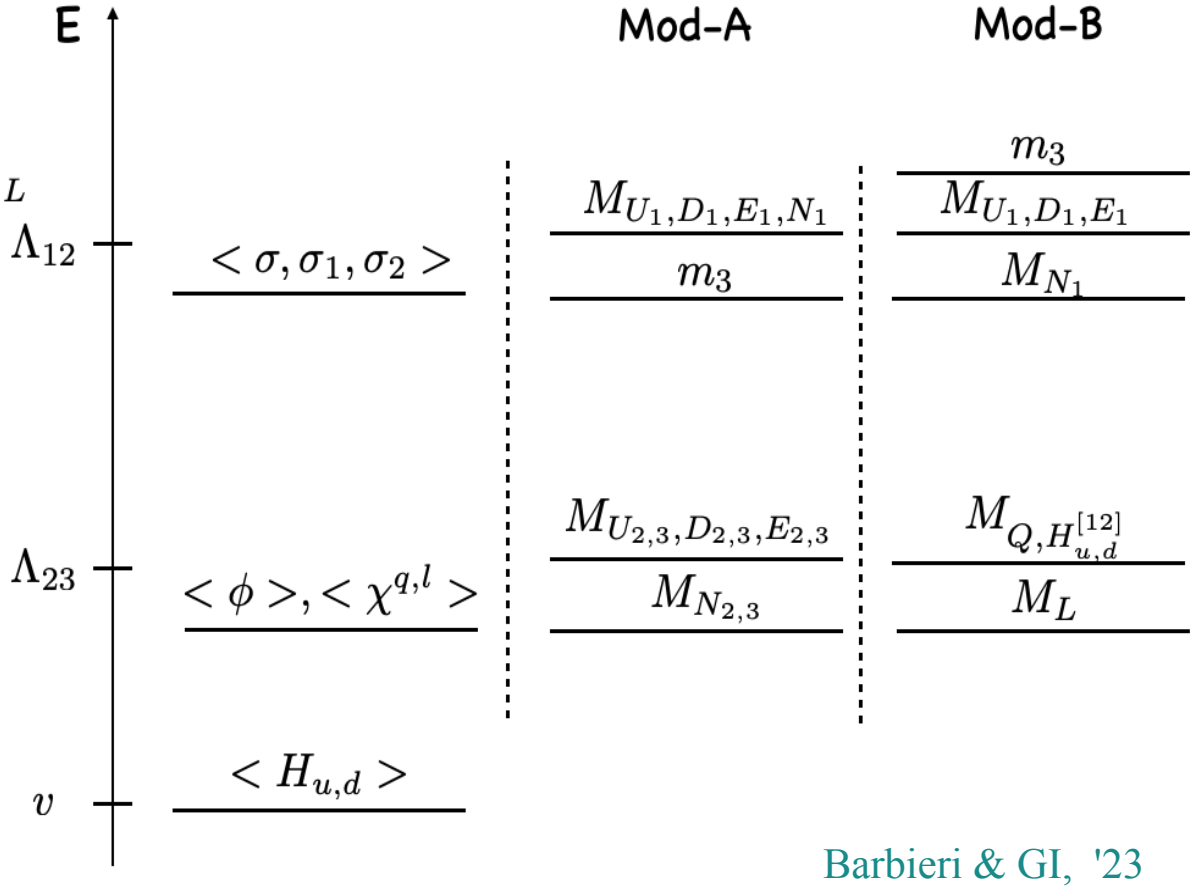
$$U(1)_Y^{[3]} \times U(1)_{T_{3R}}^{[12]} \times U(1)_{B-L}^{[2]} \times U(1)_{B-L}^{[1]}$$

$$\downarrow$$

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

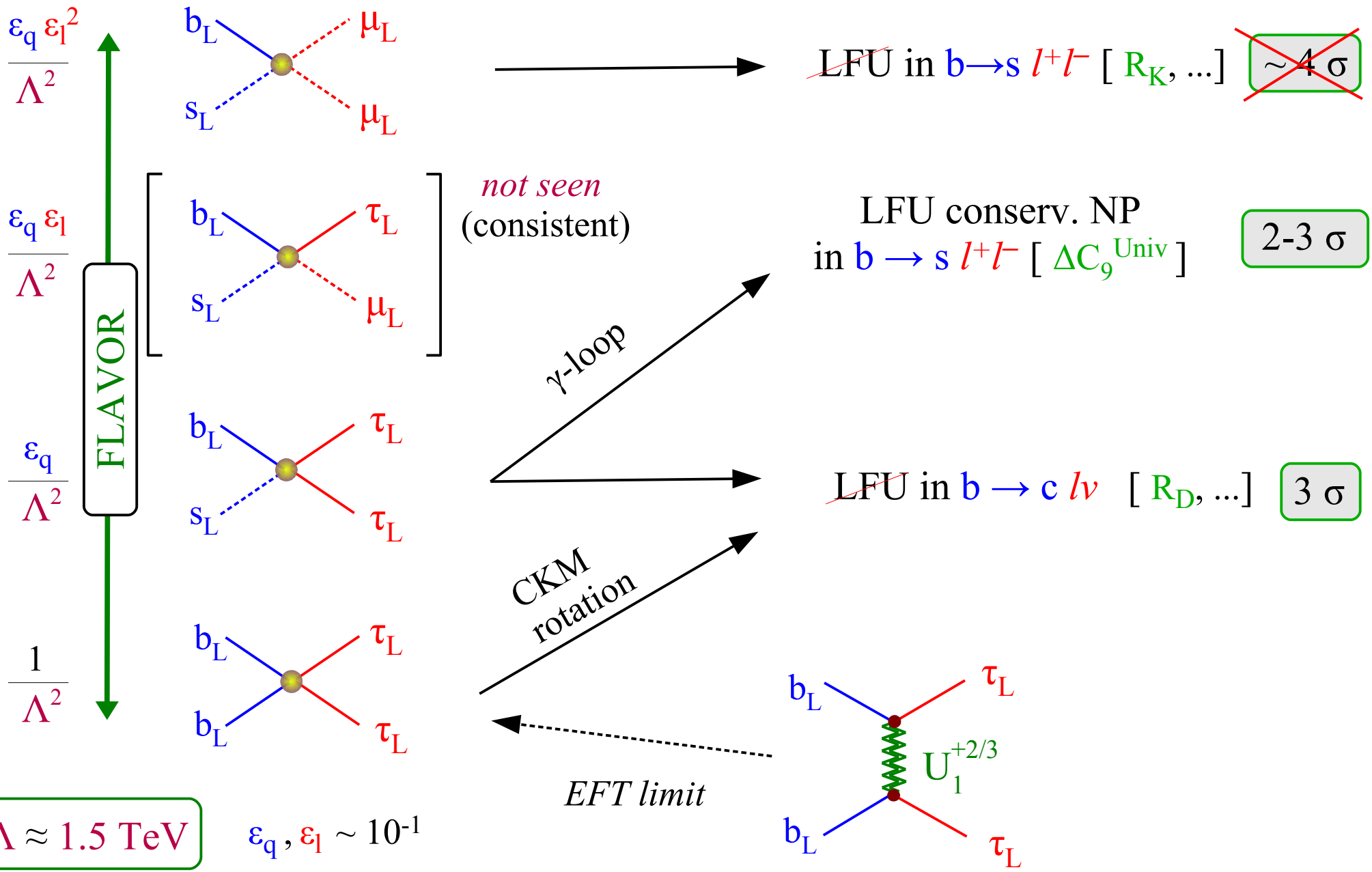
$$\downarrow$$

$$U(1)_Y$$

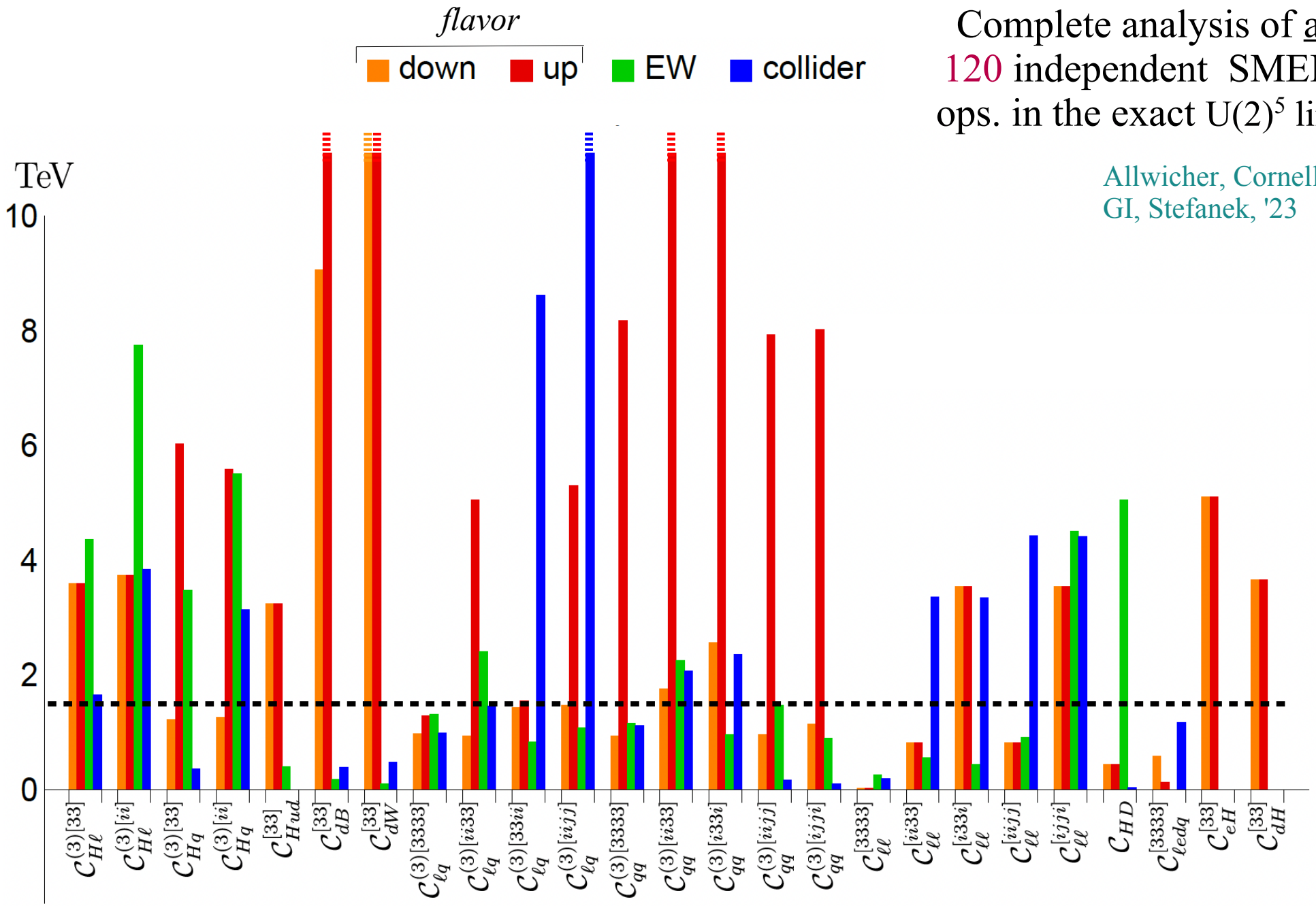


Barbieri & GI, '23

More about B-physics anomalies



SMEFT bounds in the U(2)^5 symmetric limit



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

Allwicher, Cornella, GI, Stefanek, '23

SMEFT bounds in the $U(2)^5$ symmetric limit