The Flavor of New Physics

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- Introduction
- The two flavor puzzles
- Flavor non universality & flavor deconstruction
- A brief look to present data & future prospects
- Conclusions

University of Zurich[UZH]

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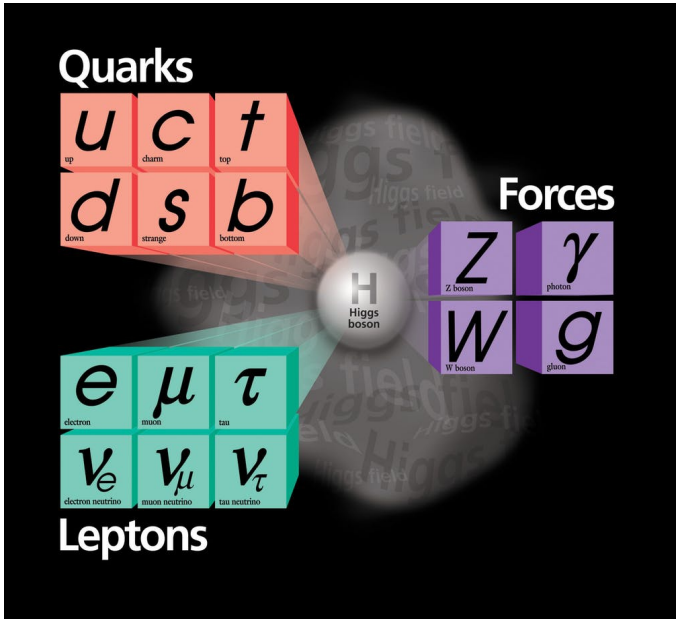
Introduction



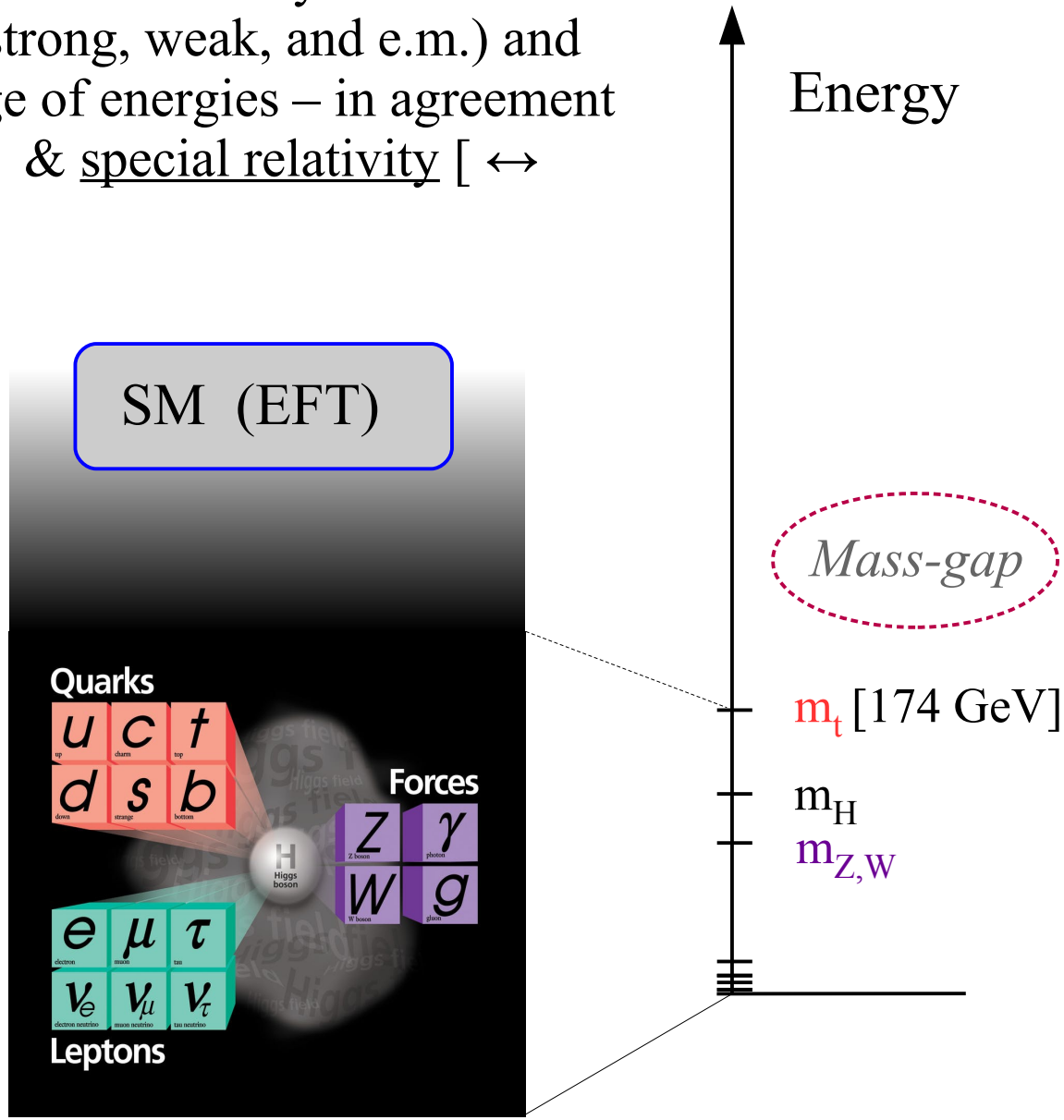
Introduction

The Standard Model (SM) is provides a remarkably successful descriptions of *fundamental forces* (strong, weak, and e.m.) and *matter constituents*, over a wide range of energies – in agreement the principles of quantum mechanics & special relativity [↔ QFT]

However, as for any QFT, it is natural to consider the SM as an Effective Field Theory, i.e. the low energy limit of a more complete theory with more degrees of freedom

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

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



Introduction

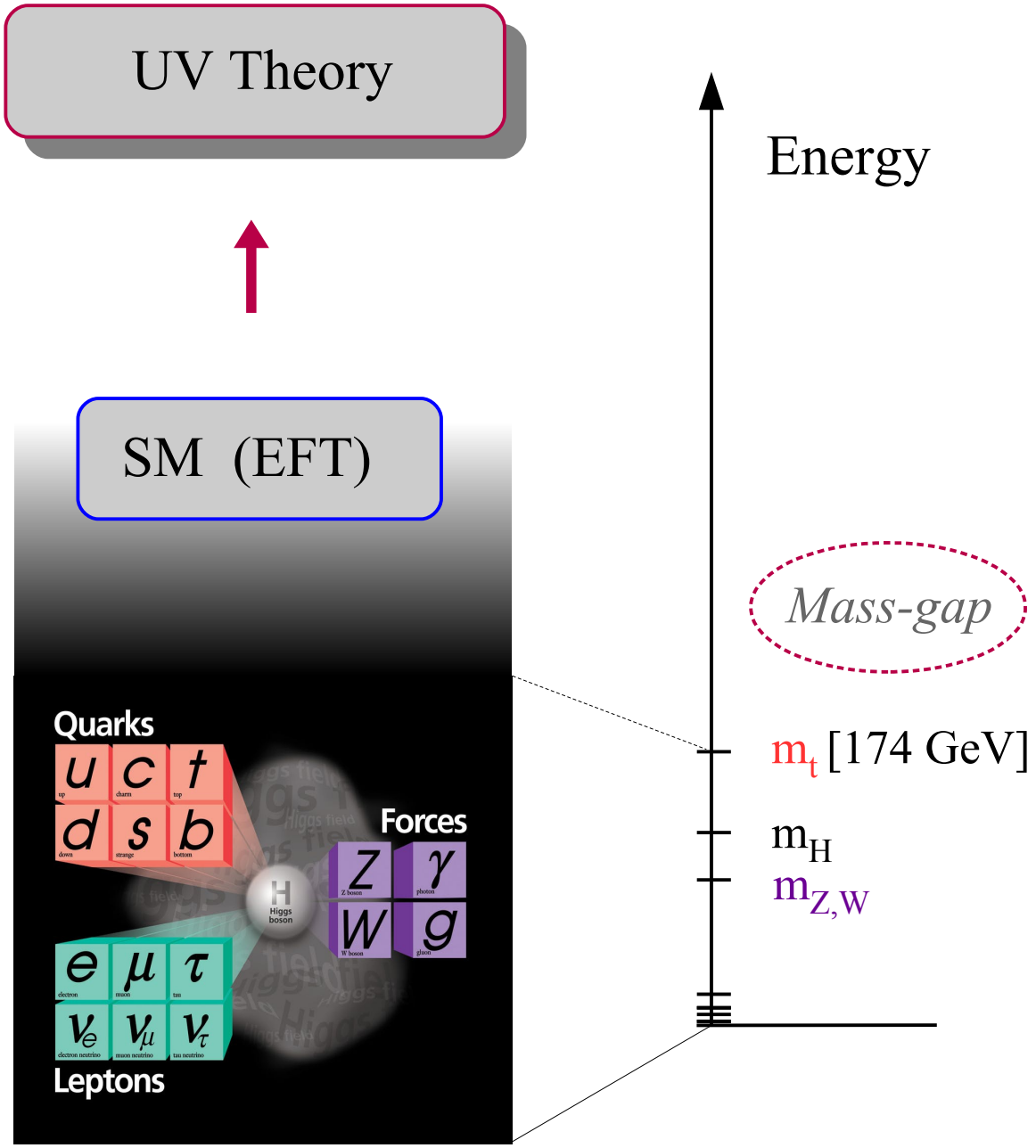
There are several reasons why we think the SM must be extended at high energies:

Electroweak hierarchy problem

Flavor puzzle
U(1) charges
Neutrino masses

Dark-matter
Dark-energy
Inflation

Quantum gravity



Introduction

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

	problem due to...	*...indicating*
Electroweak hierarchy problem	→ *Instability of the Higgs mass term*	non-trivial properties of the SM Lagrangian if interpreted as EFT
Flavor puzzle U(1) charges Neutrino masses	→ *Ad hoc tuning in the model parameters*	
Dark-matter Dark-energy Inflation	→ *Cosmological implementation of the SM*	Useful hints for its UV completion
Quantum gravity	→ *General problem of any QFT*	

Introduction

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

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Flavor puzzle

U(1) charges

Neutrino masses

Dark-matter

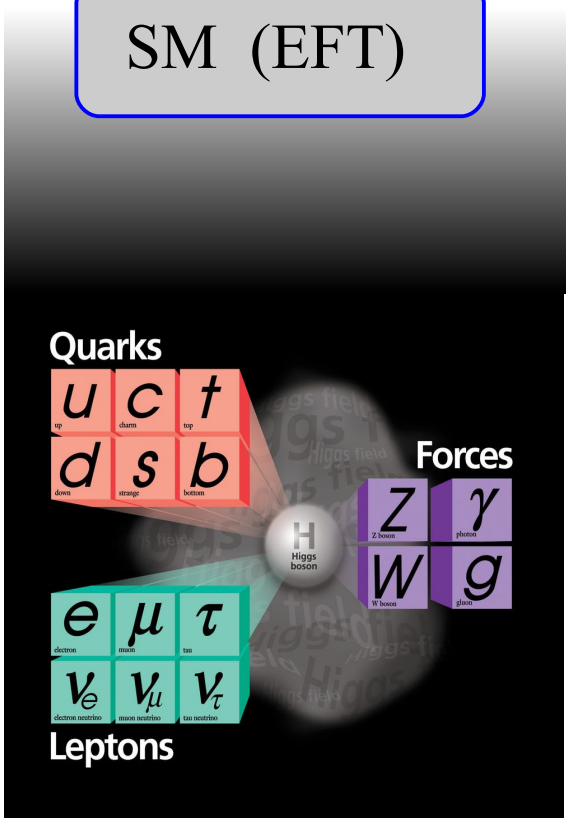
Dark-energy

Inflation

Quantum gravity

UV Theory

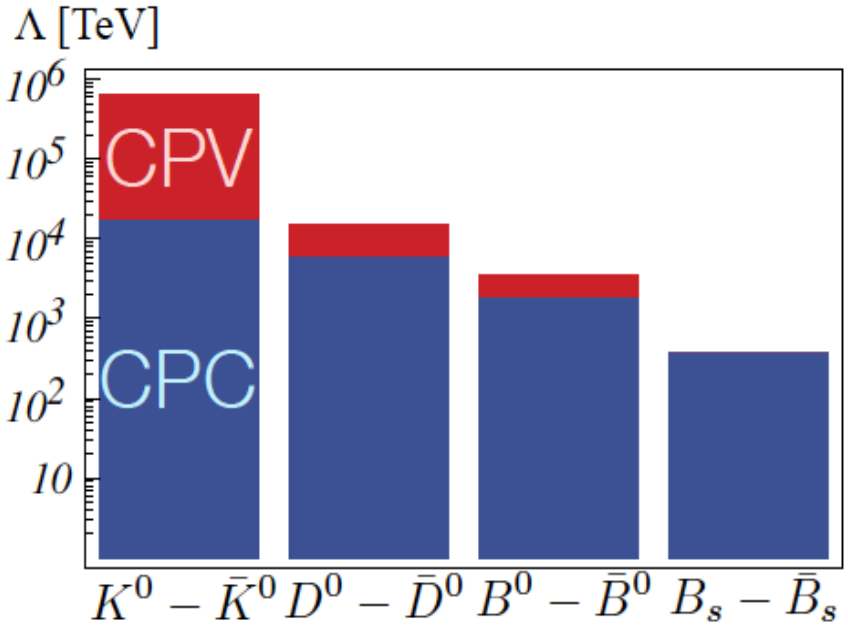
SM (EFT)



Messages from the UV we need to decode..

The two flavor puzzles

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



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

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

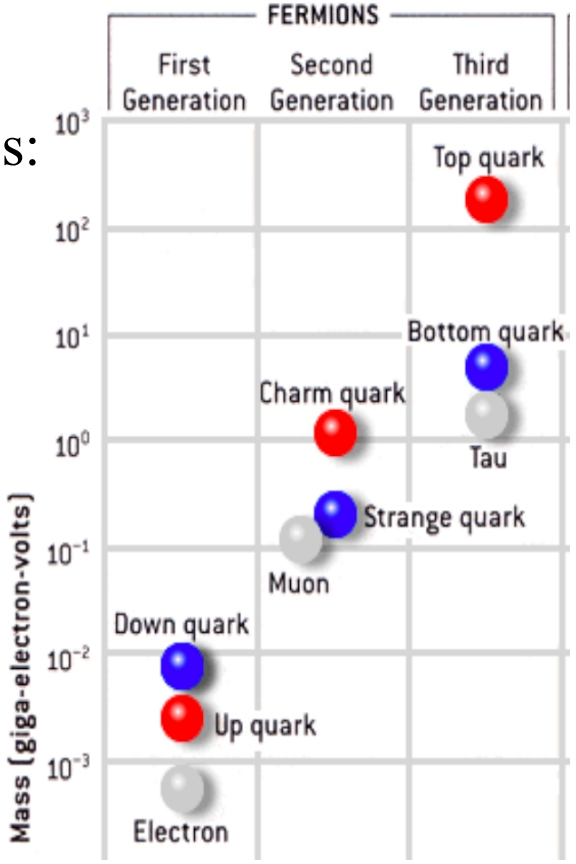
Eg.: (2)

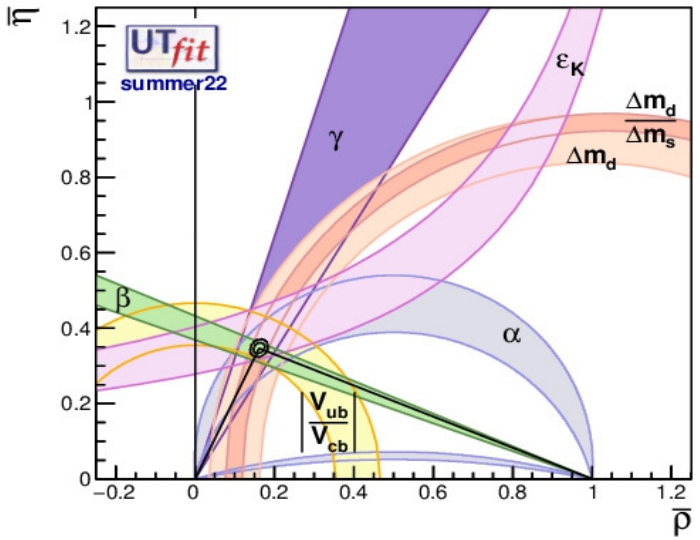
$$Y_U \sim \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \blacksquare \end{pmatrix}$$

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

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

(Y_U in the basis where Y_D is diagonal)





The two flavor puzzles

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

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

$U(2)_u$ (top) and $U(2)_q$ (right)

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

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 NP flavor puzzle

- *A brief look to the SM as an effective theory:*

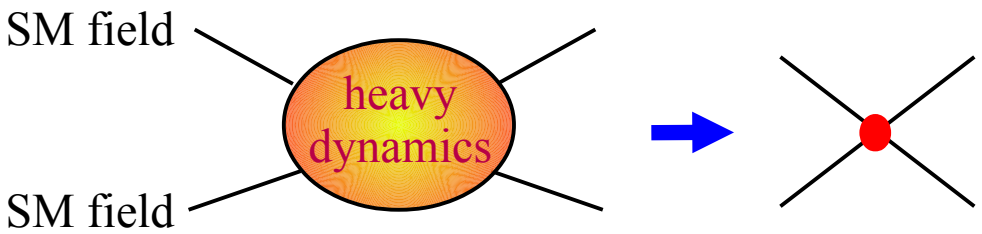
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

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*]

The two flavor puzzles

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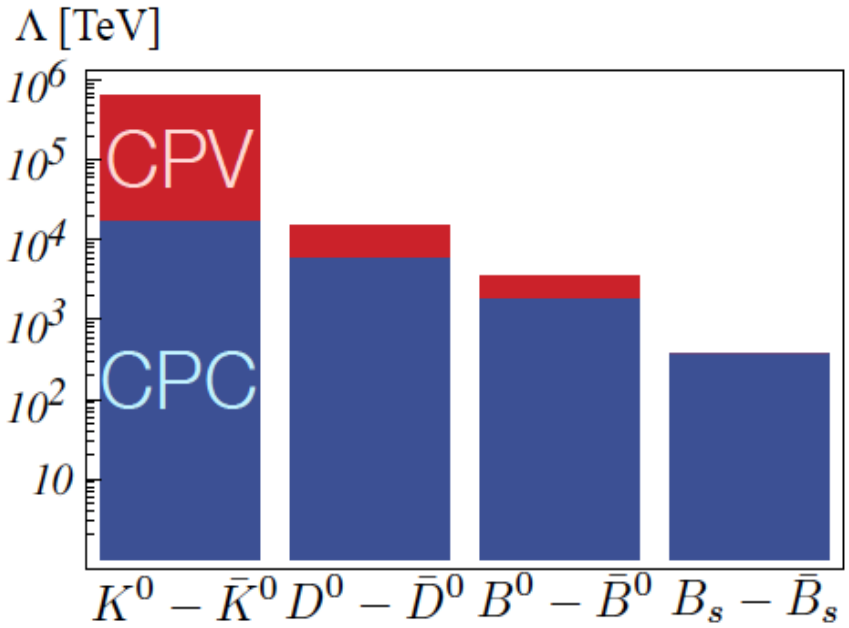
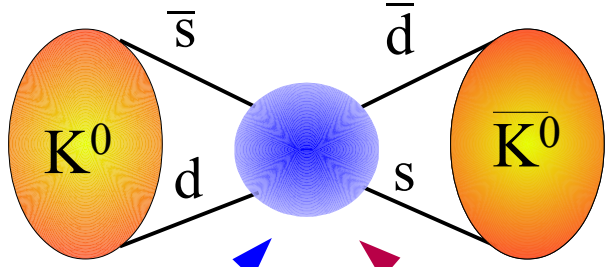
In principle, in the SM-EFT we could expect many violations of the accidental symmetries from the heavy dynamics (→ *new flavor violating effects*).
However, no clear deviations observed so far

The NP flavor puzzle

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





measured precisely

SM amplitude, strongly suppressed by approx. flavor symmetries

contact term $\sim \frac{1}{\Lambda}$

The two flavor puzzles

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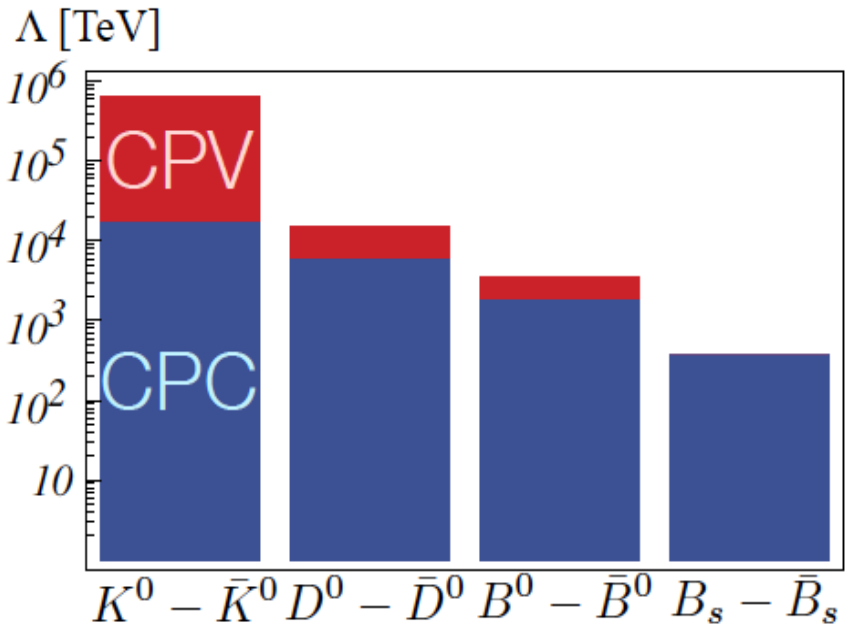
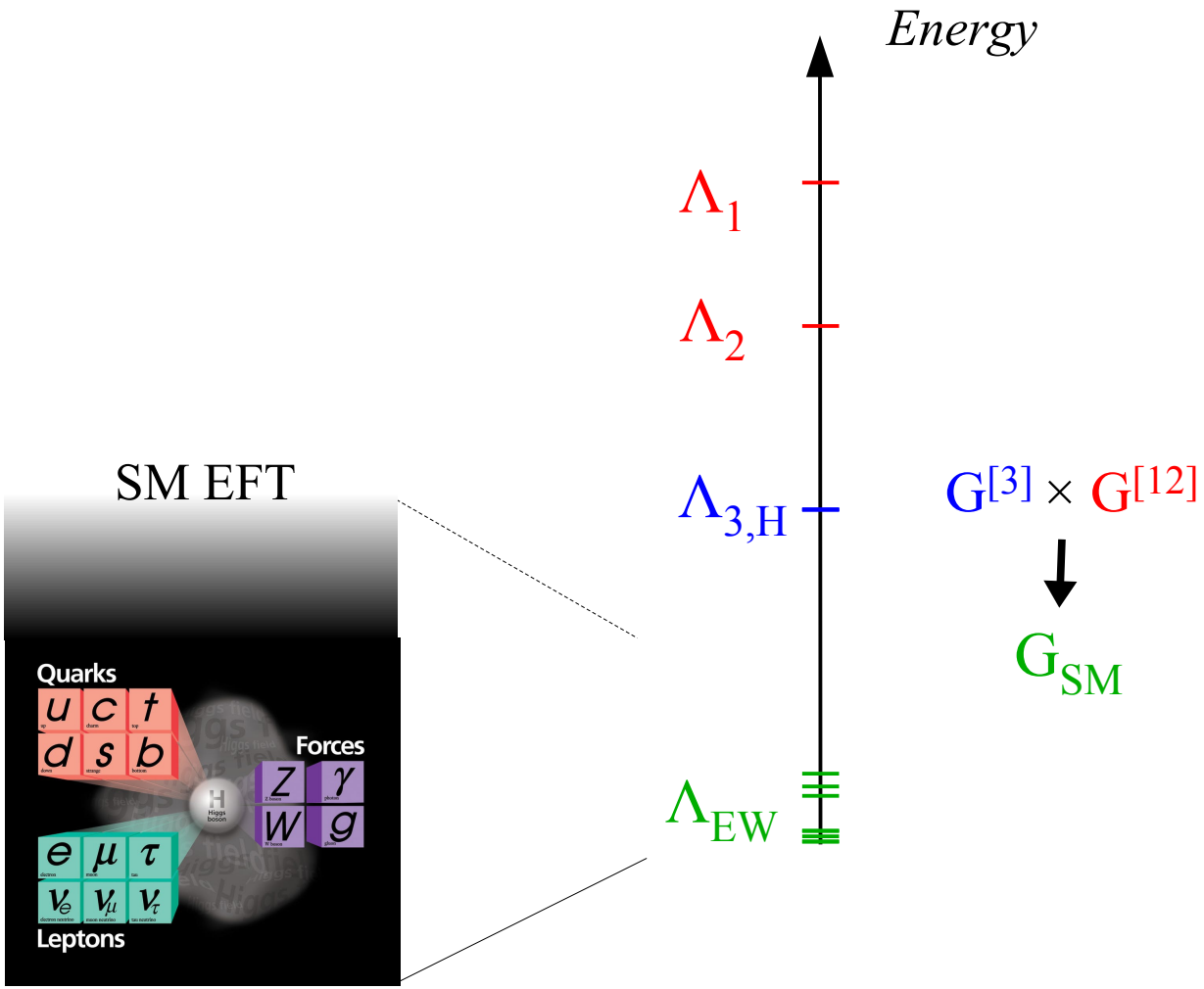


These high scales can be a "mirage"

The only unambiguous message from data is that there are no large breaking of the approximate $U(2)^n$ flavor symmetry at near-by energy scales.

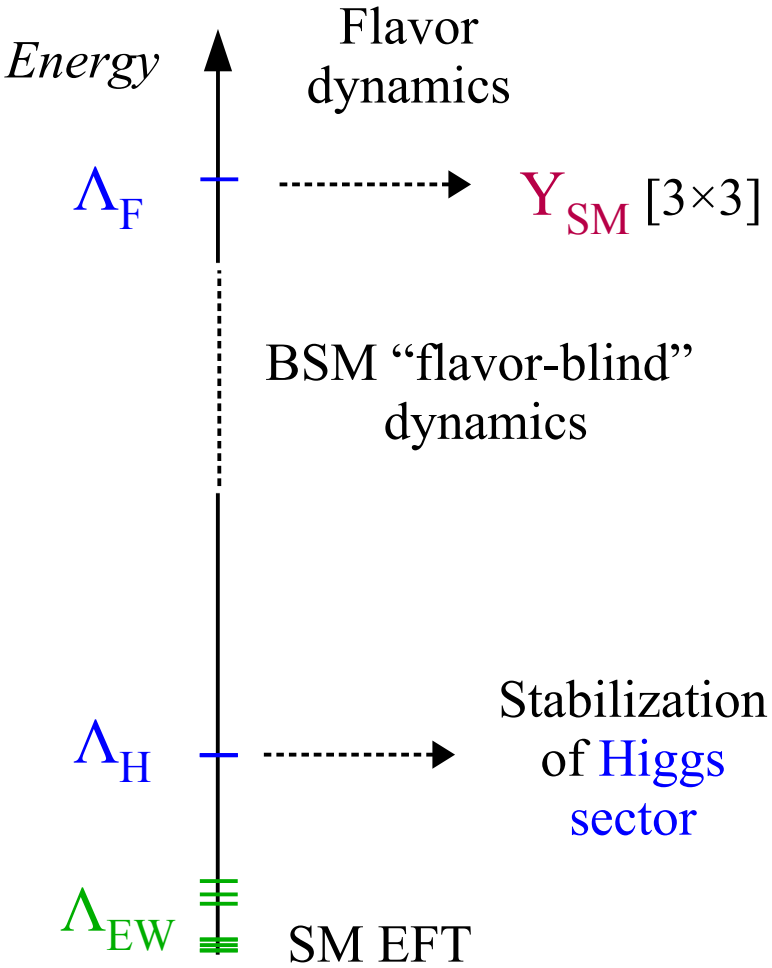
However $U(2)^n$ is not an accidental symmetry of the SM → *indication of specific UV dynamics?*

Flavor non universality & flavor deconstruction



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"

The Yukawa couplings are the only sources of flavor symmetry breaking accessible at low energies

3 families = "identical copies" up to high energies

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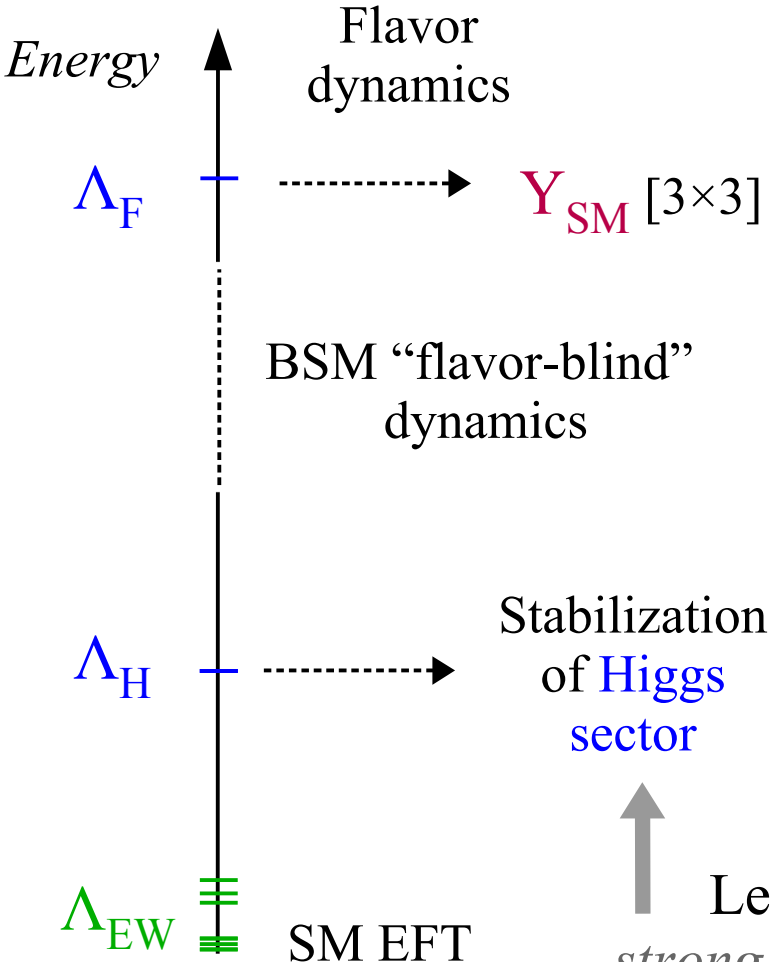

- Concentrate on the Higgs hierarchy problem
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↕

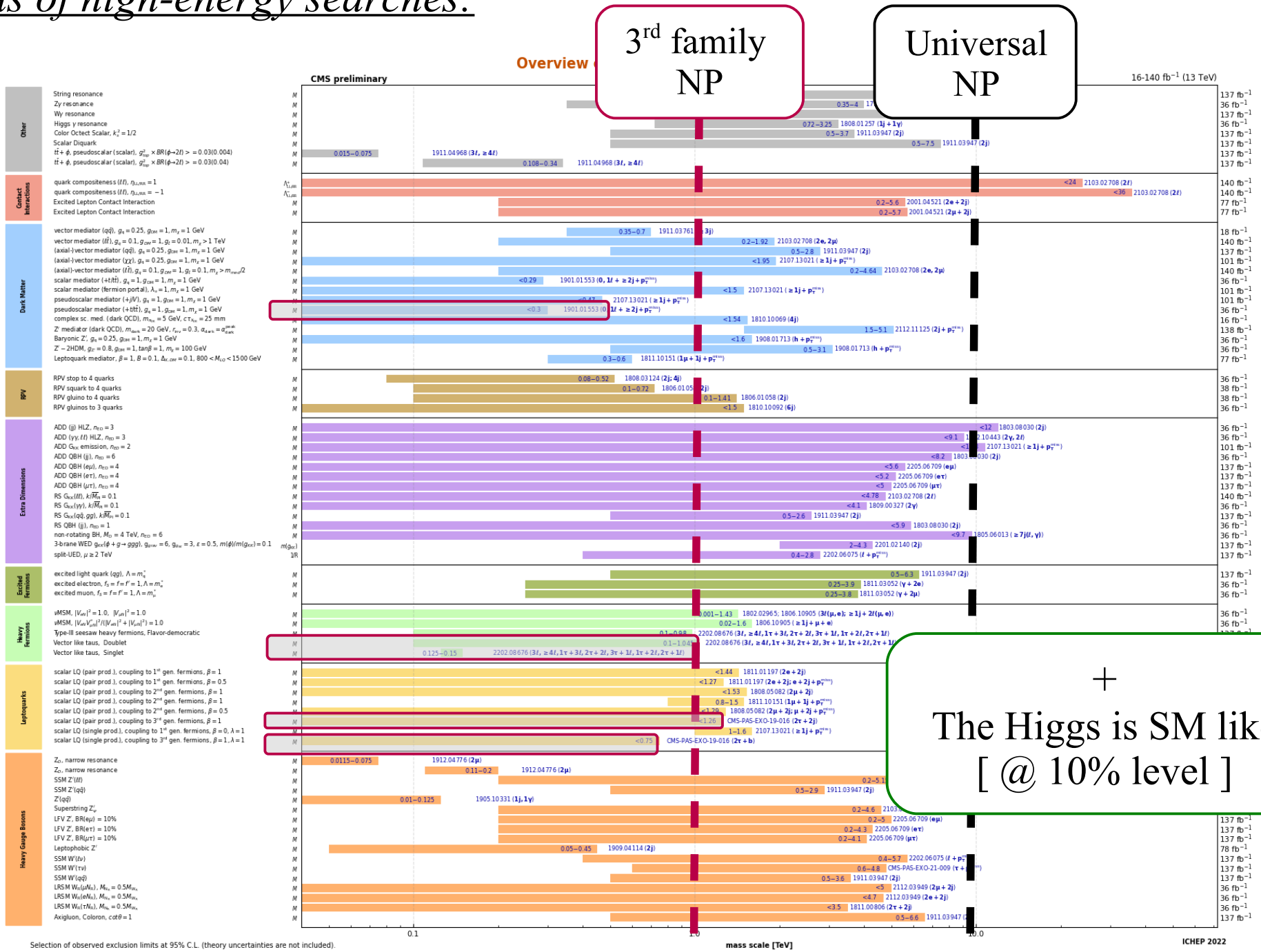
The "MFV paradigm"

↑ 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:



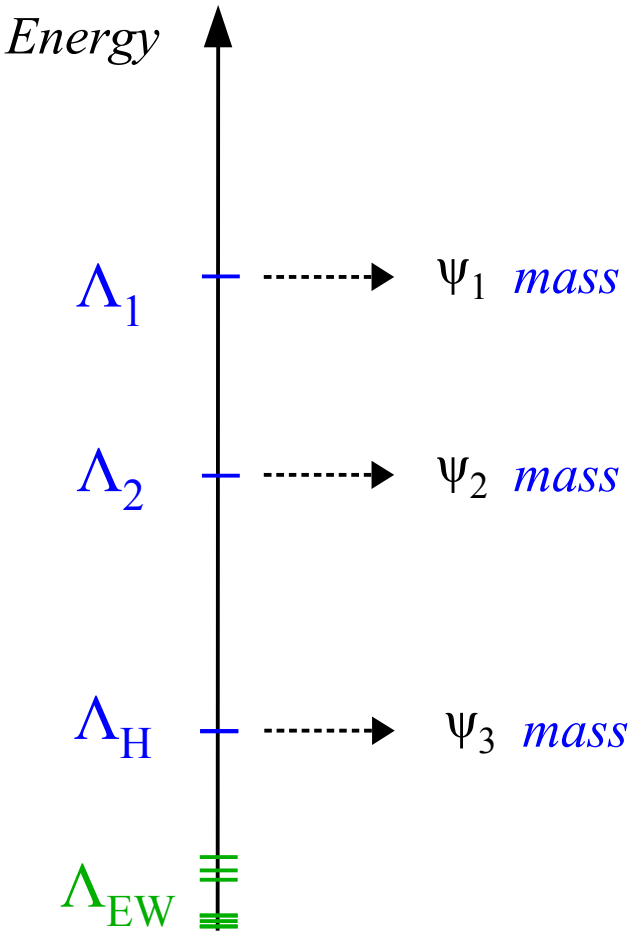
+

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
Davighi & GI '23
Fernandez-Navarro & King '23
Barbieri & GI '24
⋮



Basic idea:

1st & 2nd generations have small masses (+ small coupling to NP) because these are generated by new dynamics at heavier scales

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

Flavor non-universal interactions

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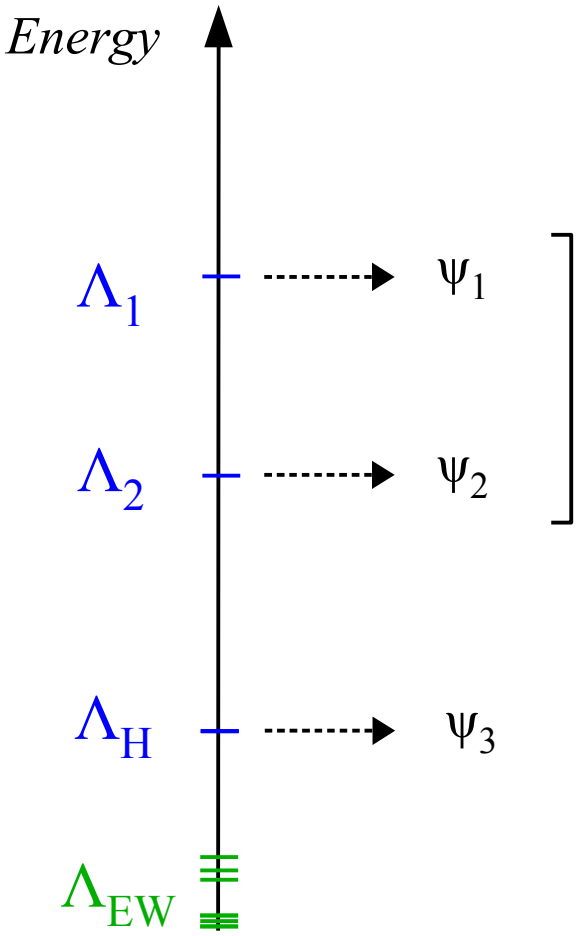

- The 2×2 light block of the Yukawa coupling originates from high-scale physics [→ origin of the *Cabibbo angle*]
- No additional breaking of $U(2)^n$ is mediated at low energies

"UV imprint" in the Yukawa couplings

$$Y_U \sim \begin{pmatrix} < 10^{-2} & < 0.1 \\ & \blacksquare \end{pmatrix}$$

$U(2)_u$ ↓ ; $U(2)_q$ ←

Flavor non-universal interactions

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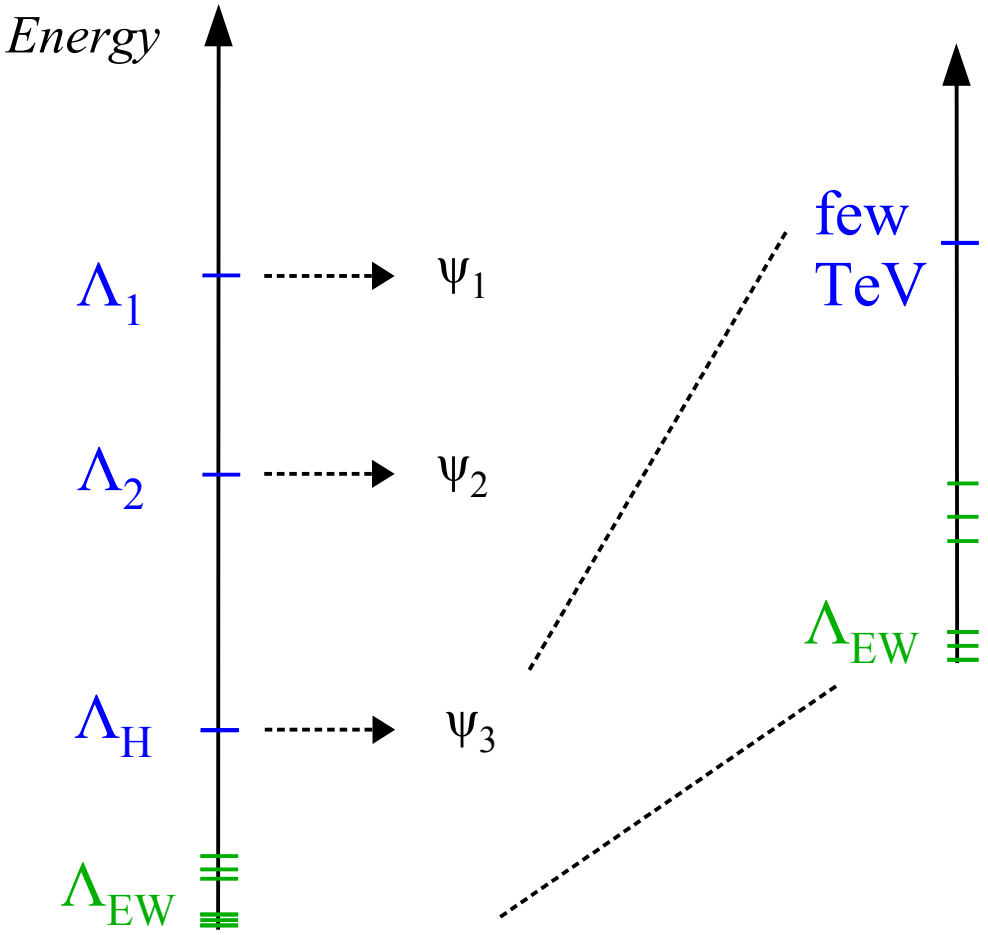
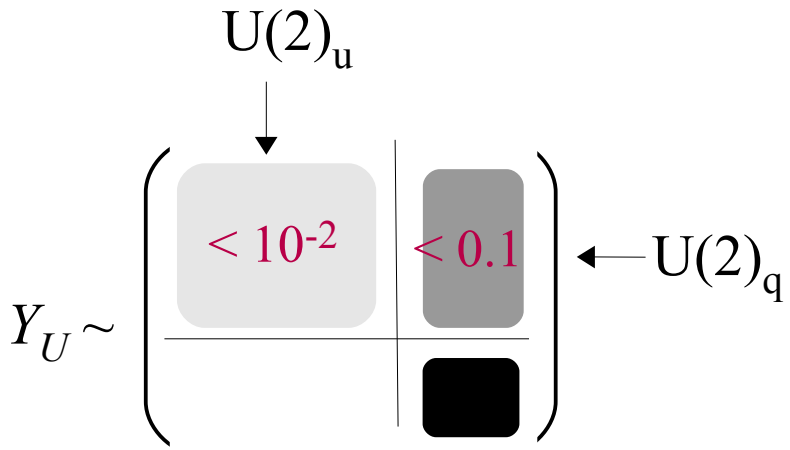


NP coupled mainly to ψ_3

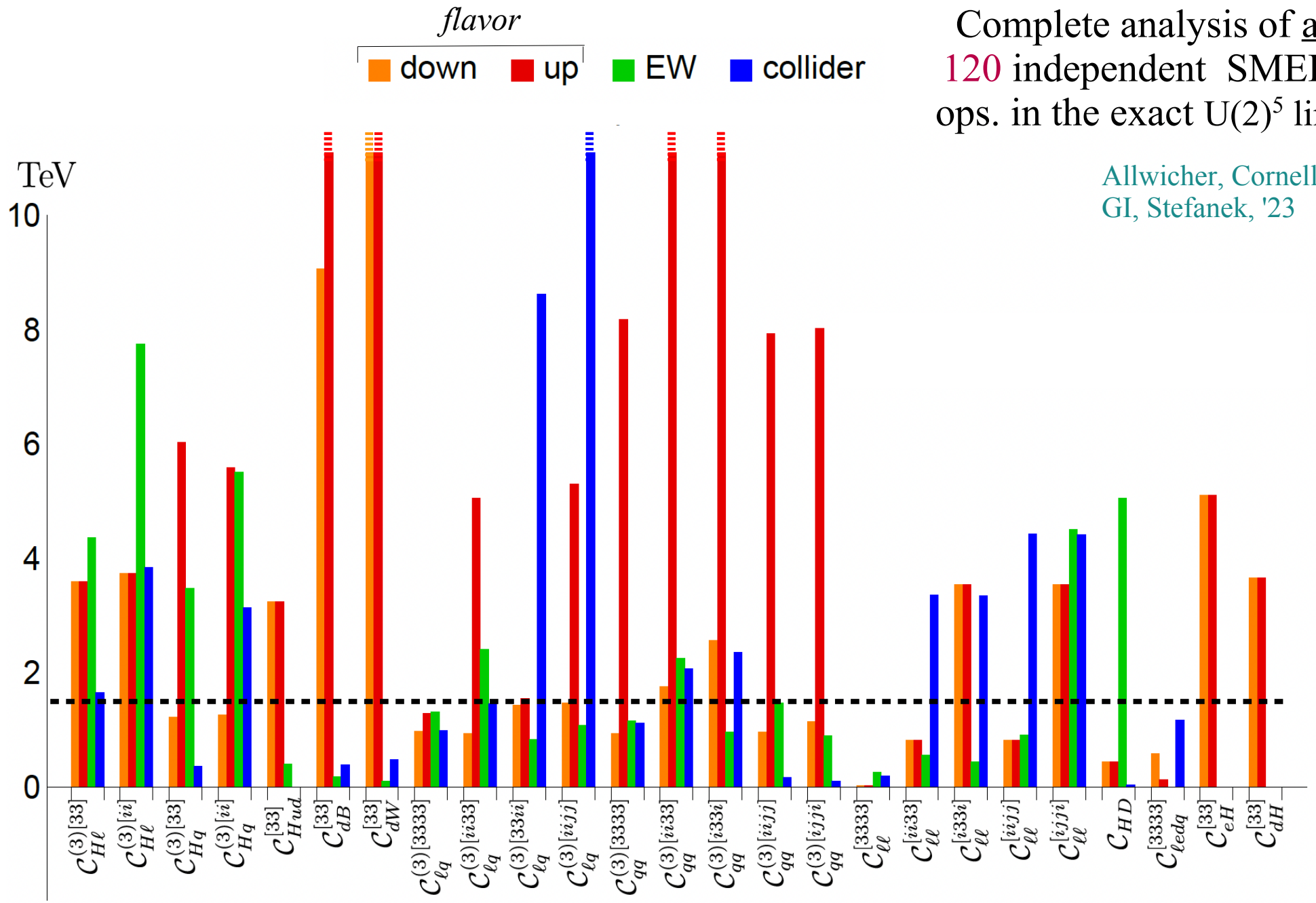
$\psi_{1,2}$ ~ massless [$U(2)^n$ symm.]

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



Effective organizing principle for the flavor structure of the SMEFT

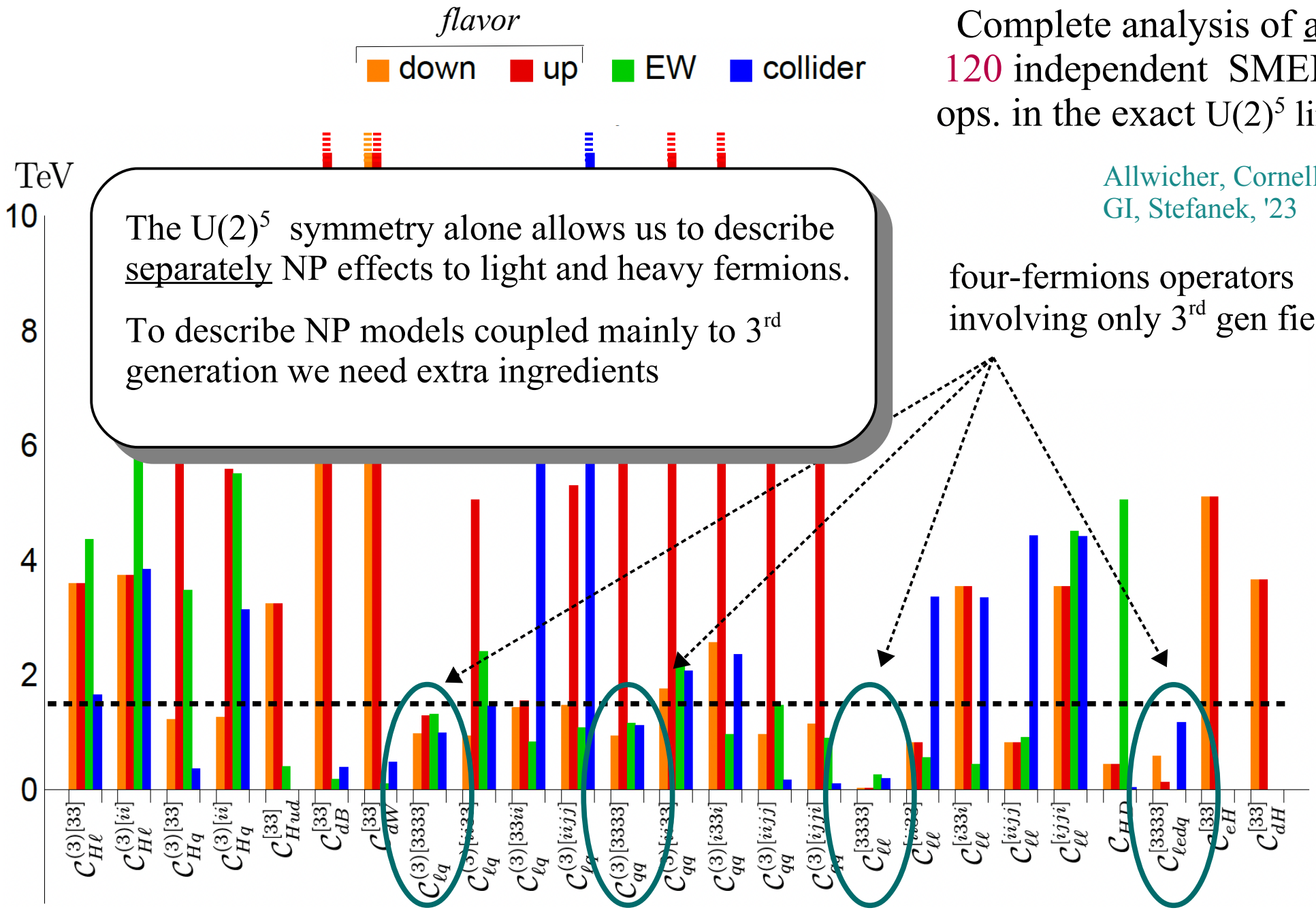
SMEFT bounds in the $U(2)^5$ *symmetric limit:*



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:



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

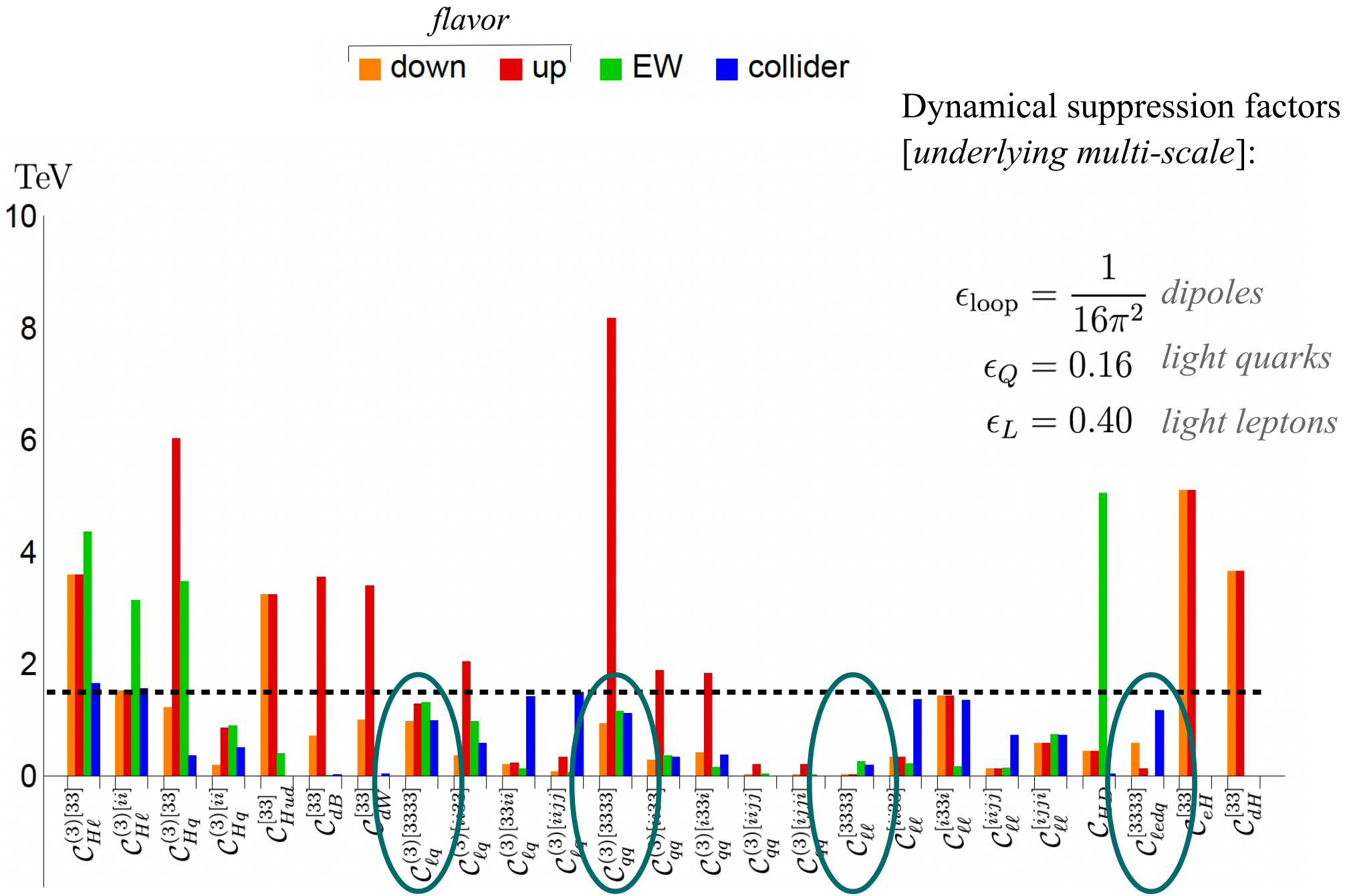
To describe NP models coupled mainly to 3rd generation we need extra ingredients

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

Allwicher, Cornella, GI, Stefanek, '23

four-fermions operators involving only 3rd gen fields

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



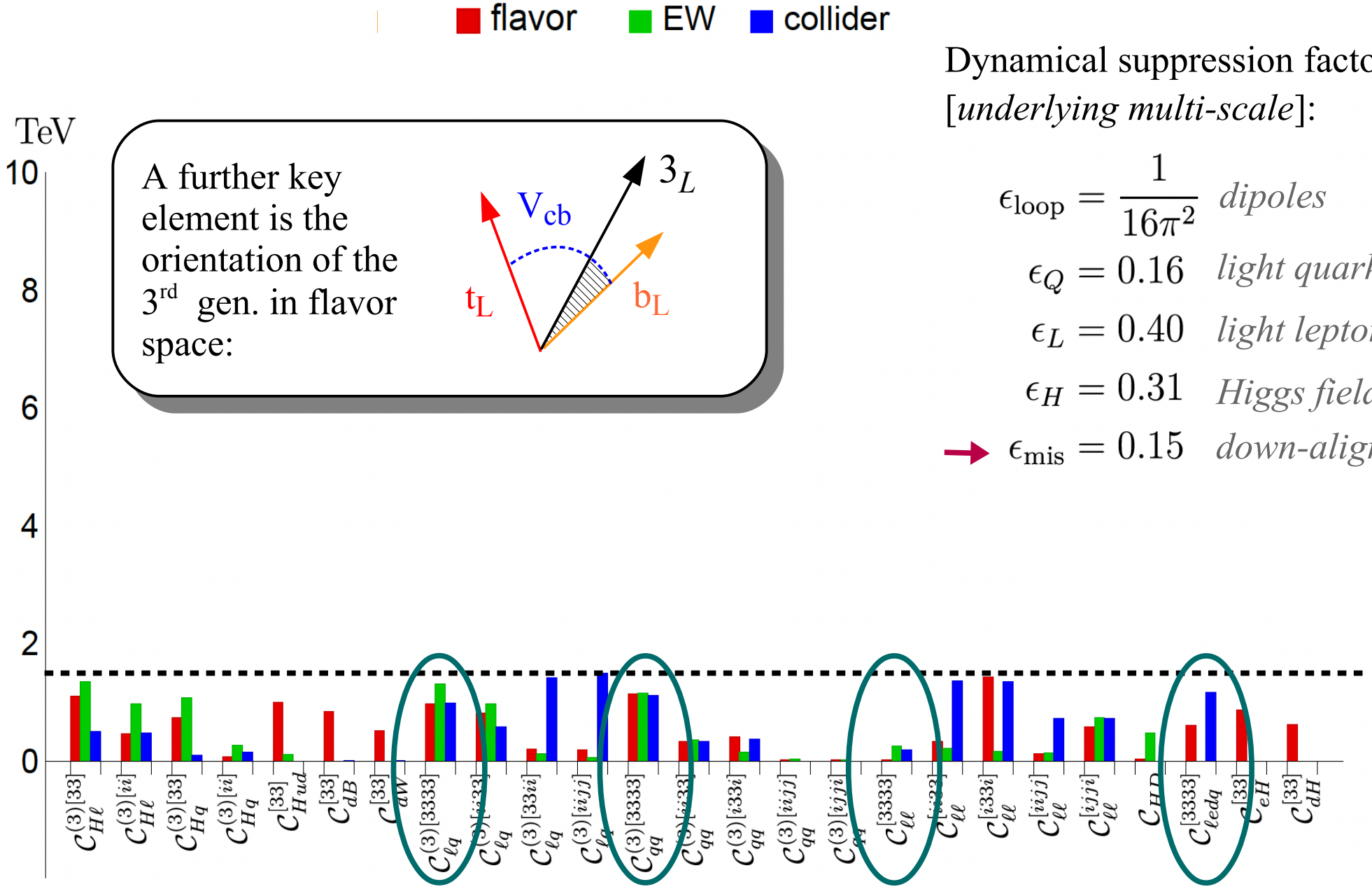
Dynamical suppression factors [*underlying multi-scale*]:

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

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

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

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



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

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

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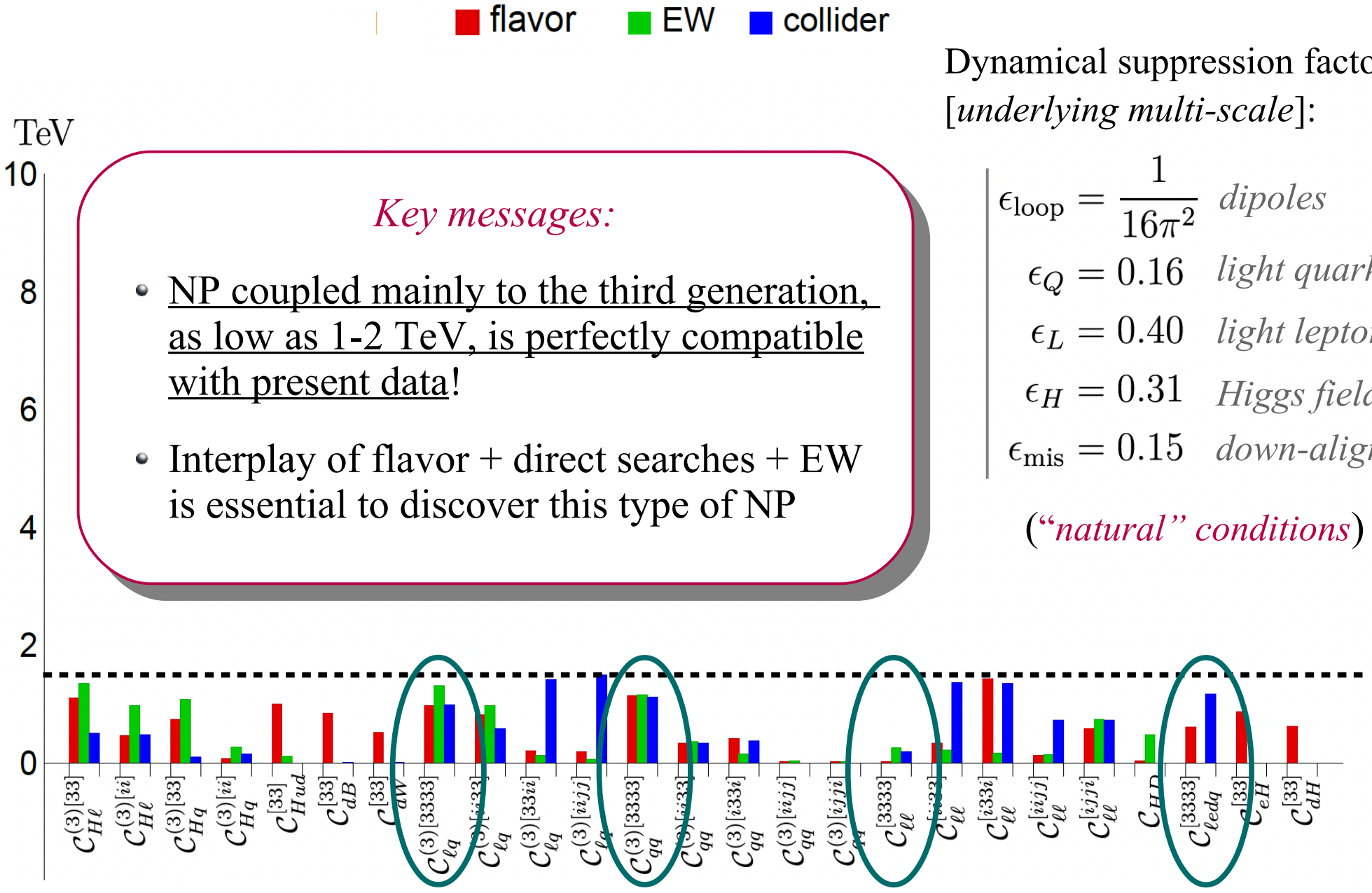

Key messages:

- 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

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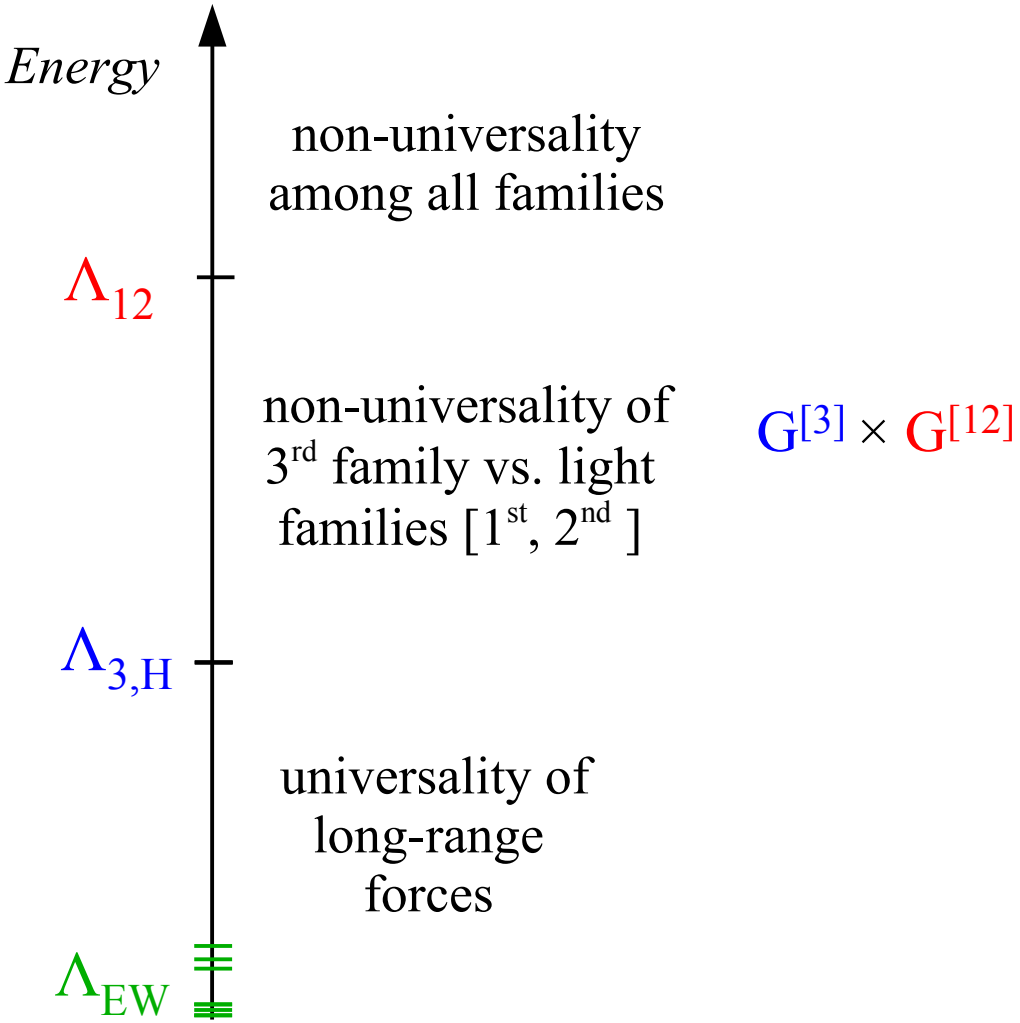
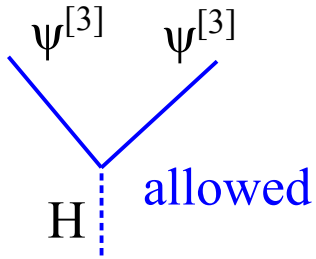
(*"natural" conditions*)

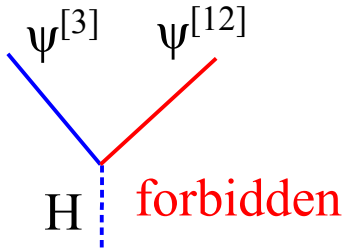
Flavor deconstruction

Going beyond the EFT approach, a consistent way to construct a multi-scale theory with flavor non-universal interactions is via a "*flavor deconstruction*" of the SM gauge symmetries:

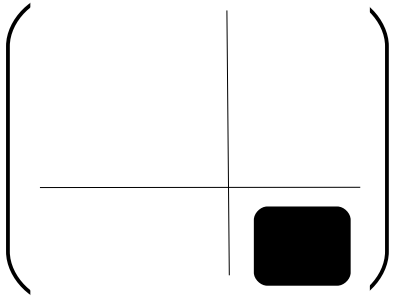


$G^{[3]} \times G^{[12]}$





$Y_U \sim$



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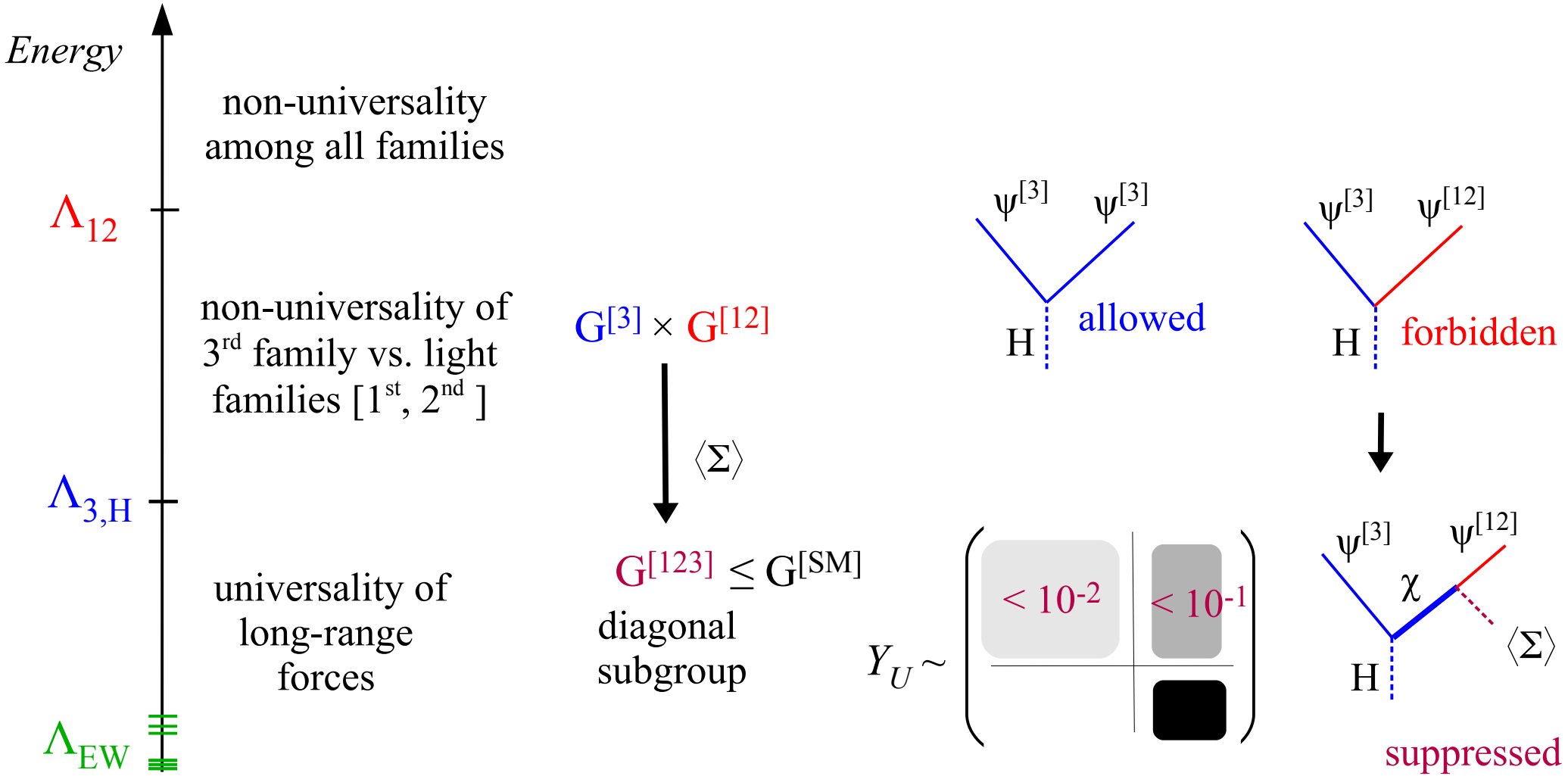

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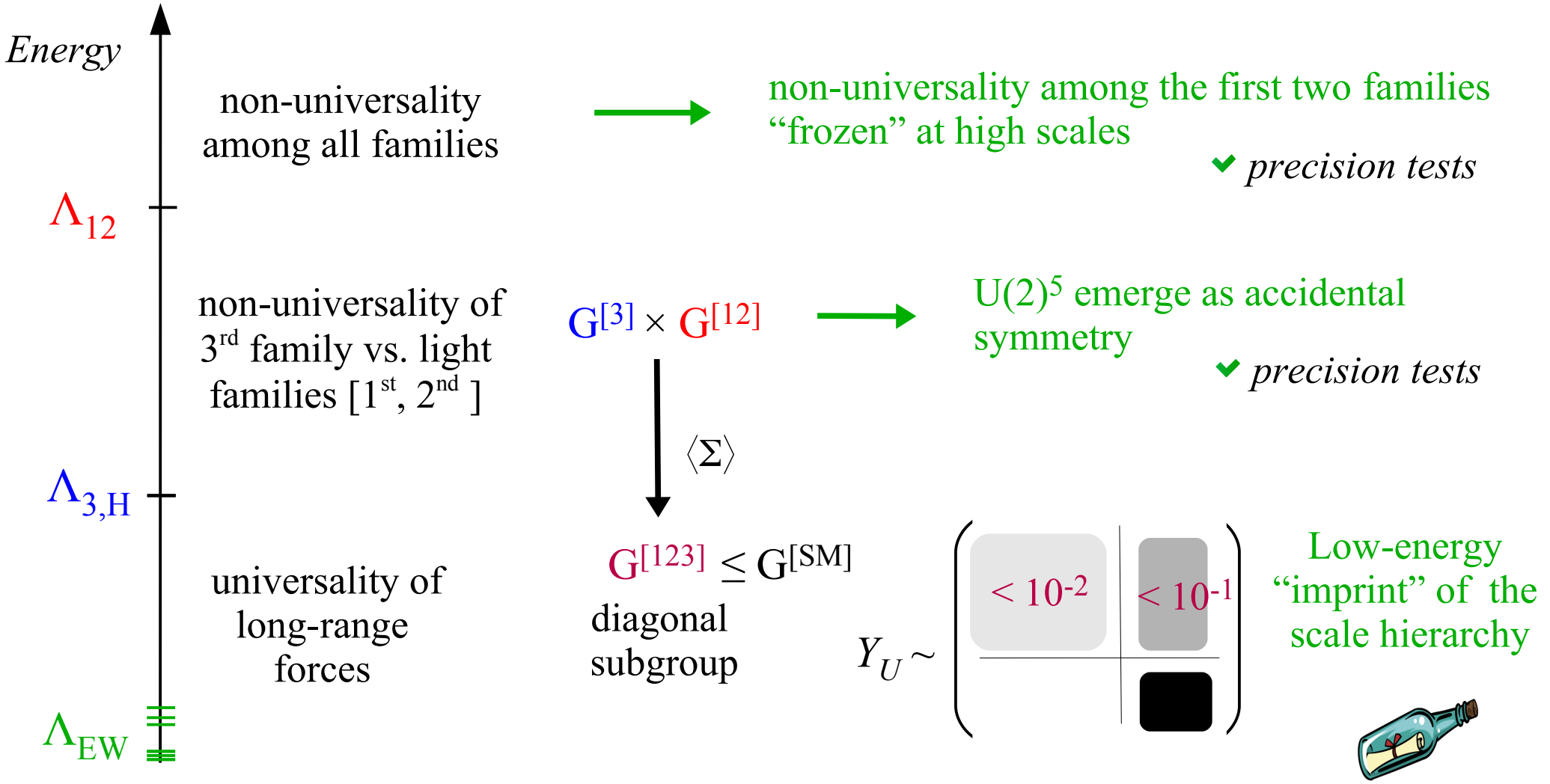

Flavor deconstruction

All possible options have been classified [Davighi & GI '23] → only few choices, if we consider only semi-simple groups [*charge quantization*]. A particularly interesting one is allowing quark-lepton unification a la Pati-Salam for the 3rd gen.

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

$$\downarrow$$

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

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

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

✔ Explain charge quantization

$$SU(4) \sim \left[\begin{array}{c|c} SU(3)_C & 0 \\ \hline 0 & 0 \end{array}\right] + \left[\begin{array}{c|c} 0 & LQ \\ \hline LQ & \end{array}\right] + \left[\begin{array}{c|c} \frac{1}{3} & 0 \\ \hline 0 & -1 \end{array}\right]$$

B-L generator

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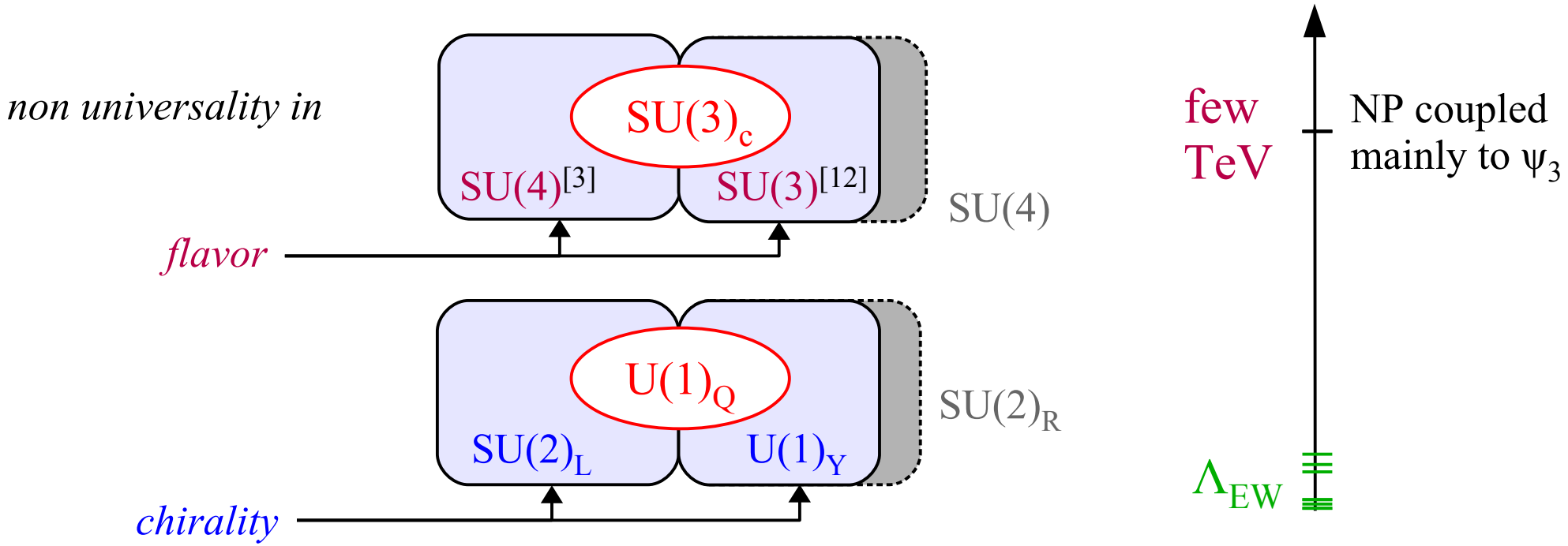

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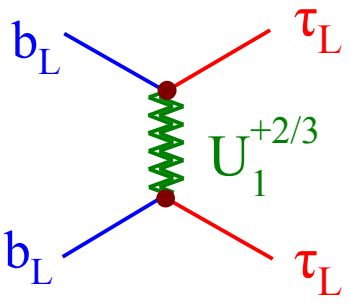
vector leptoquark

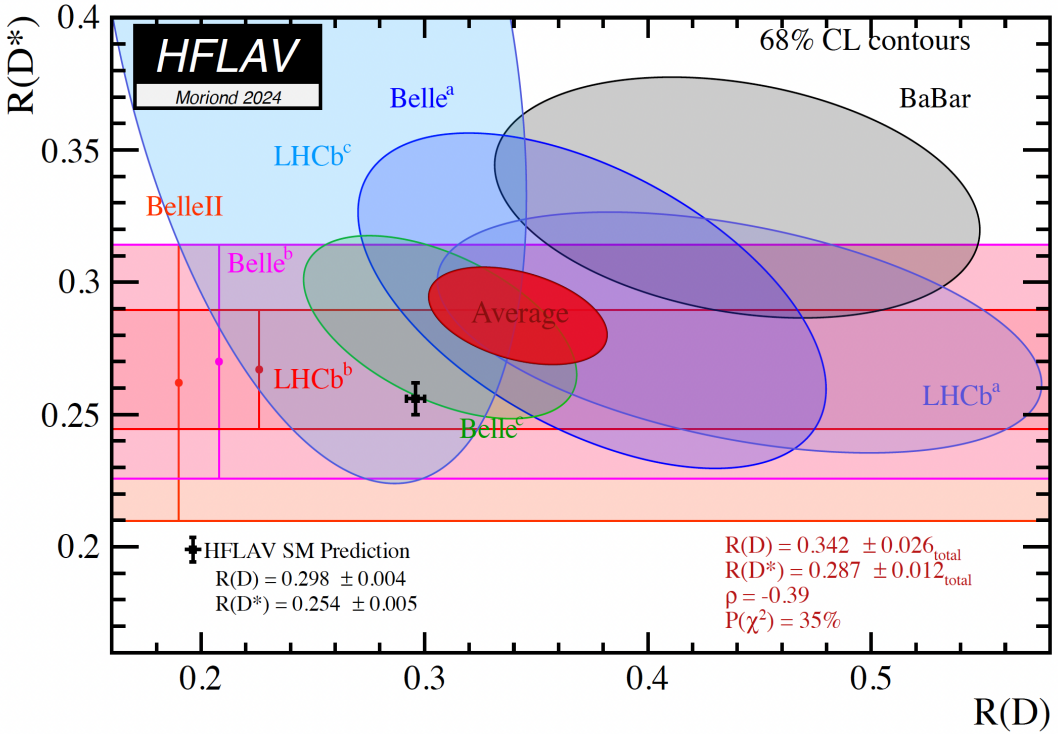


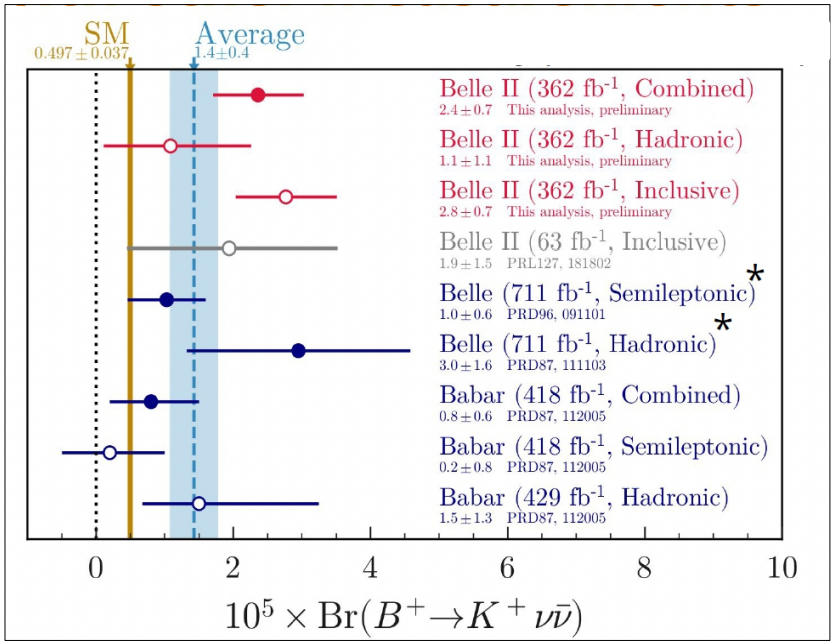
- ✔ Explain charge quantization
- ✔ Might explain some existing tensions in B-physics data

$$SU(4) \sim \begin{bmatrix} SU(3)_C & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & LQ \\ LQ & \end{bmatrix} + \begin{bmatrix} \frac{1}{3} & 0 \\ 0 & -1 \end{bmatrix}$$

B-L generator

A brief look to current data & future prospects





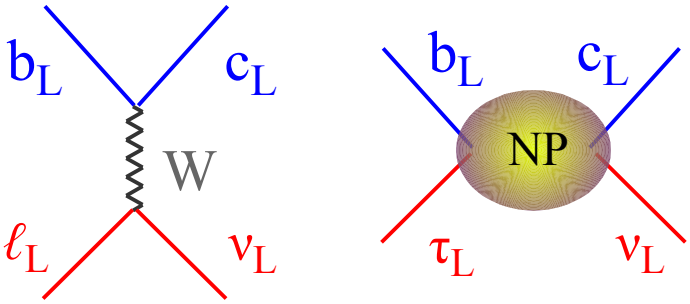
A brief look to current data & future prospects

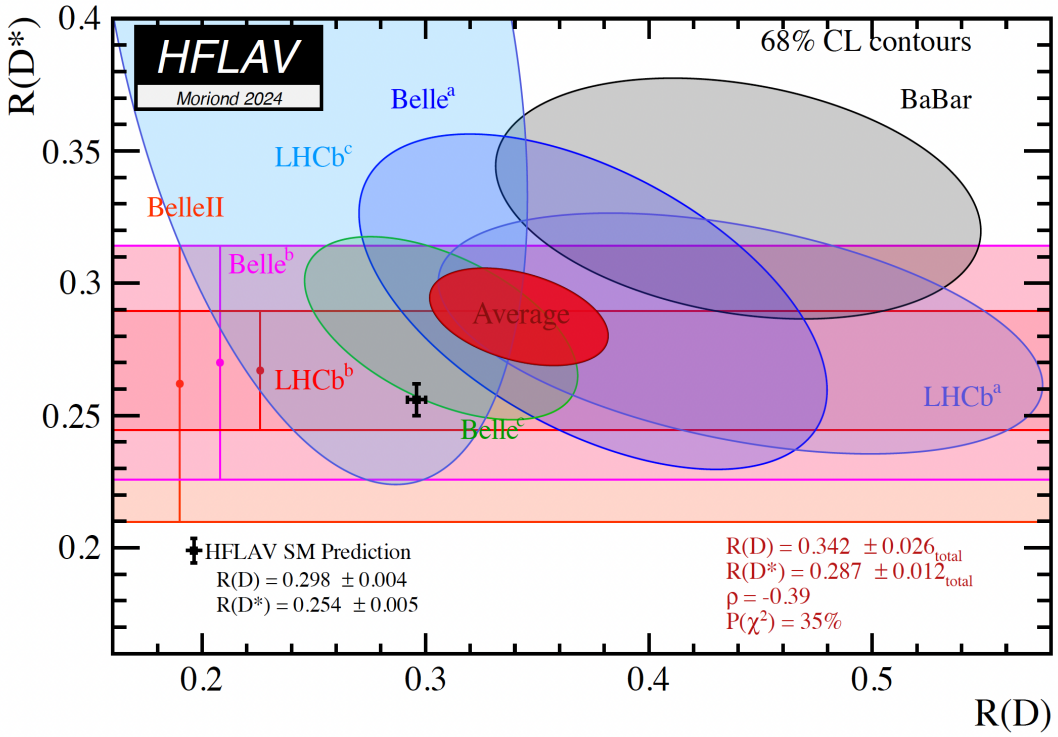
The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements (*with different degree of model-dependence*)

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

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

X = D or D*





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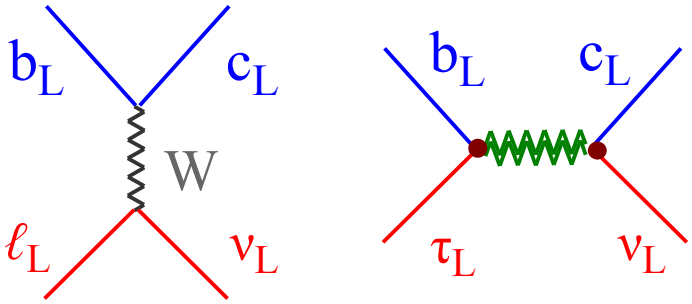
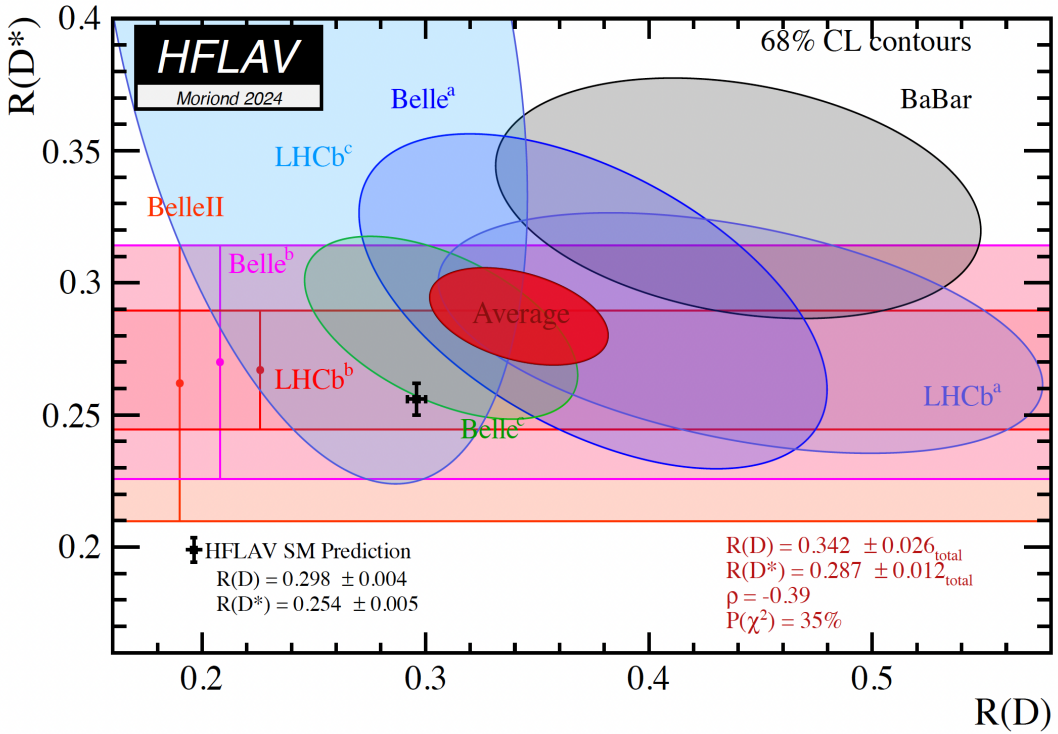




→ *The vector LQ of 3rd gen. quark-lepton unification is an ideal candidate to describe current data*

very interesting for Belle-II (1)

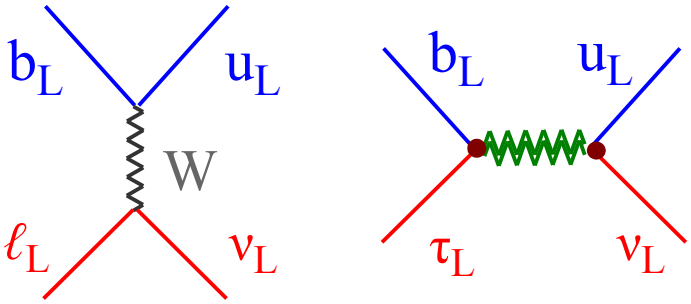
A brief look to current data & future prospects

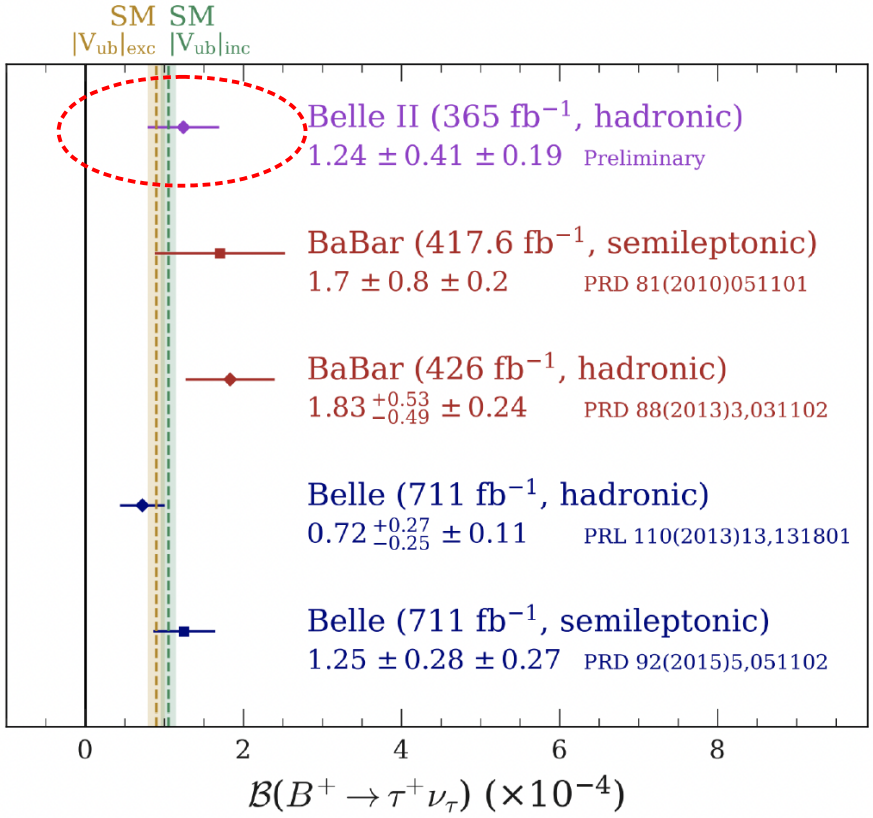
The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements (*with different degree of model-dependence*)

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

$b\to u\,\tau\nu$ decays are more suppressed ($|V_{ub}| \ll |V_{cb}|$) but could allow an extremely clean LFU test via purely leptonic modes

$$R_u^{\tau/\mu} = \frac{\Gamma(B\to\tau\nu)}{\Gamma(B\to\mu\nu)}$$



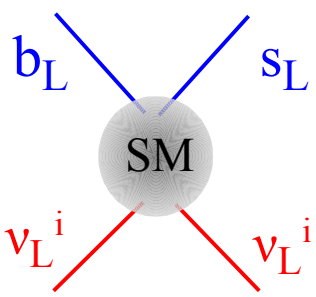


very interesting for Belle-II (2)

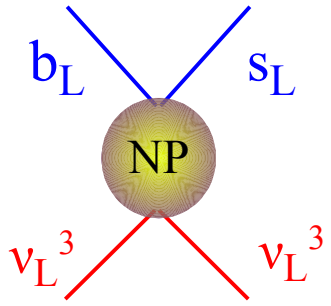
A brief look to current data & future prospects

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]

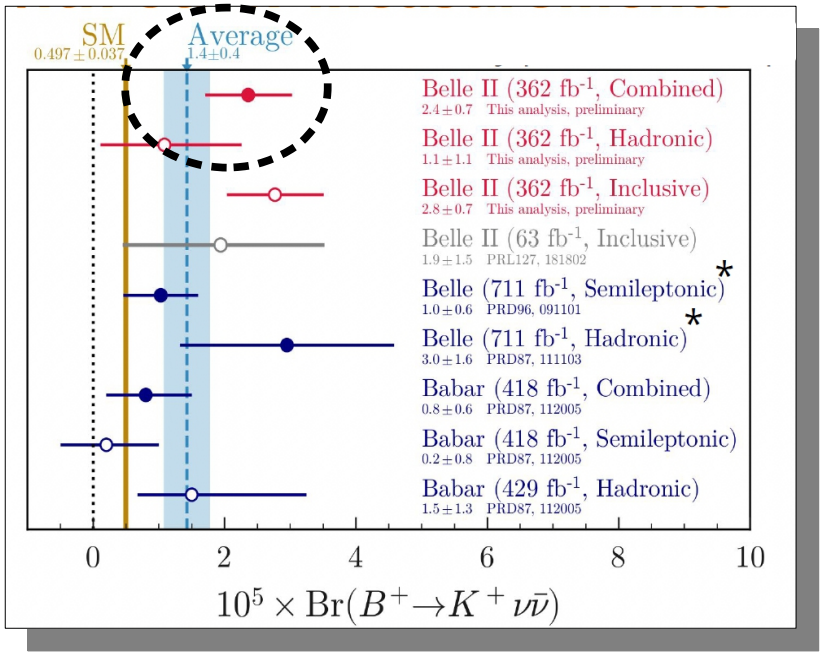


identical for all neutrino species



relevant only for 3rd gen. neutrinos

Belle-II '2023



Unambiguous prediction of O(50%) enhancement of B($B\to K\nu\nu$) in the model with vector LQ – given excess in R(D).

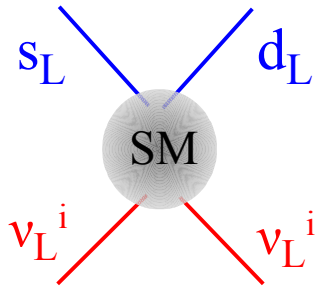
Fuentes-Martin, GI, Konig, Selimovic, '20

very interesting for Belle-II (3)

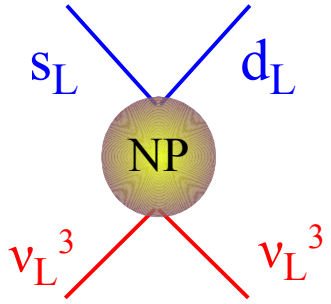
A brief look to current data & future prospects

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... & s→dνν rates



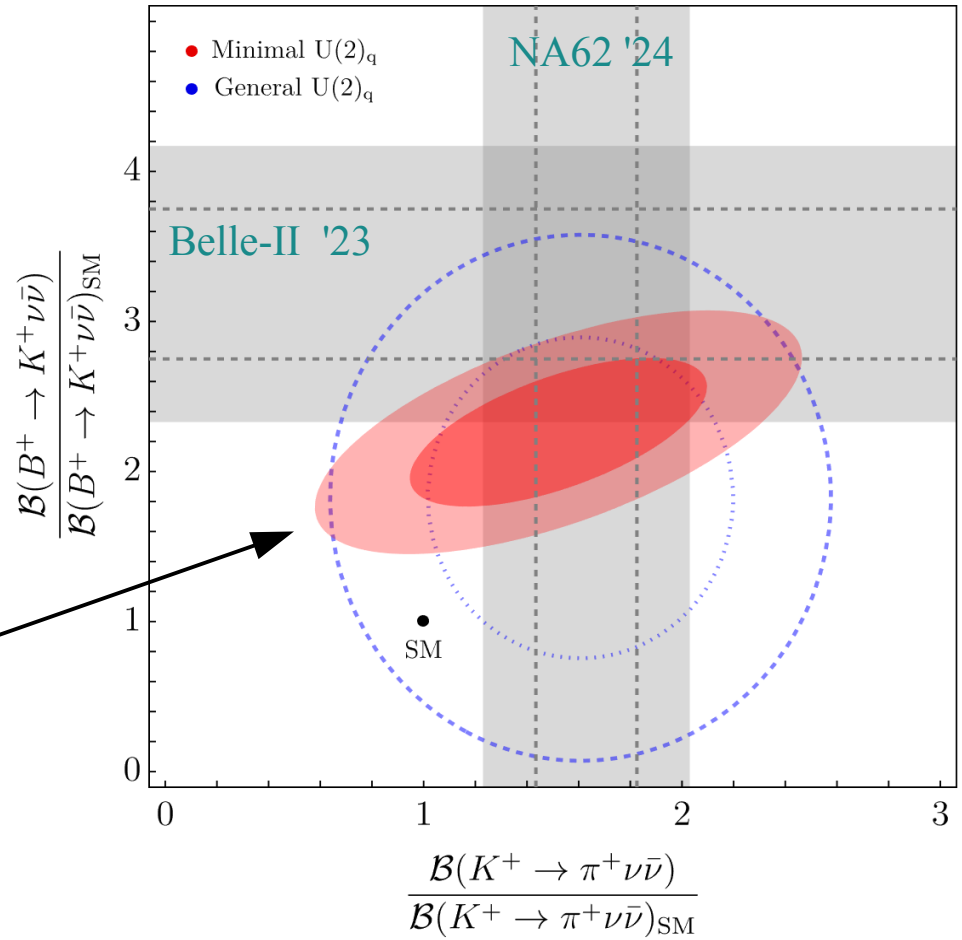
identical for all neutrino species



relevant only for 3rd gen. neutrinos

Close correlation of non-standard effects in B(B→Kνν) & B(K→πνν)

Bordone *et al.* '24

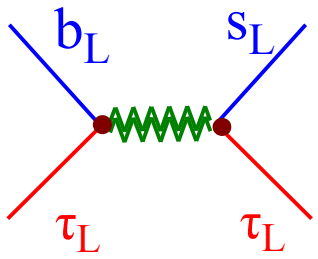


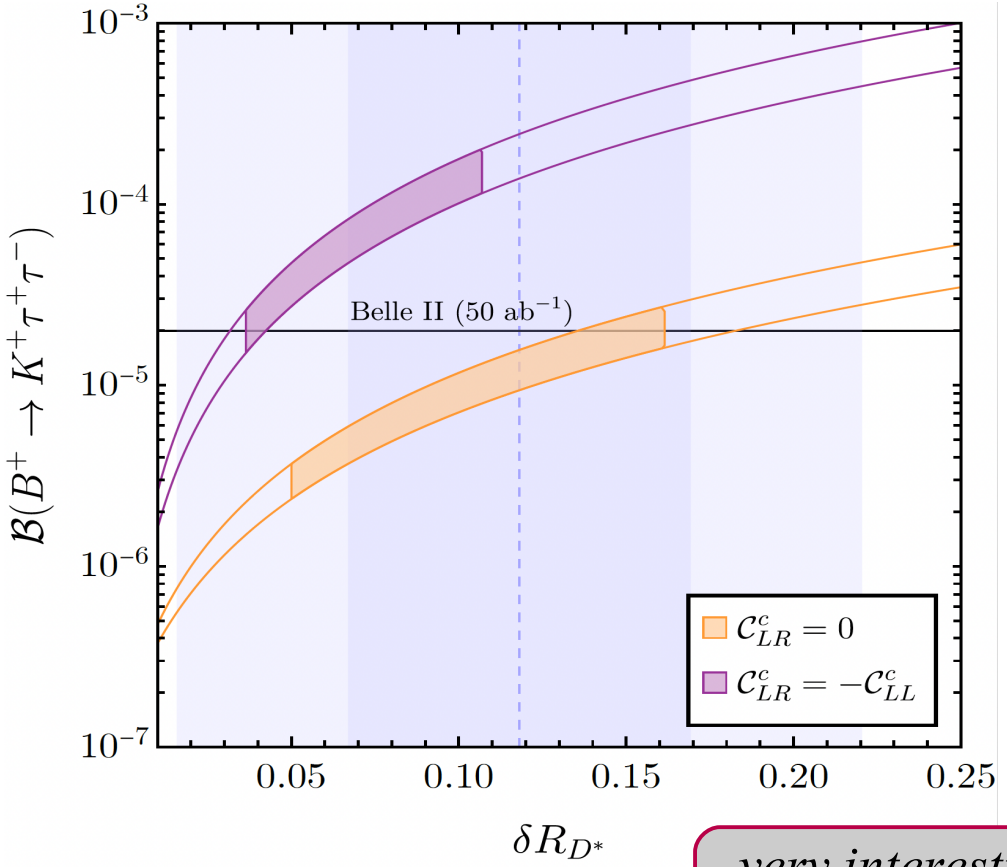
A brief look to current data & future prospects

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.: III) Potential large enhancement of $b\to s\tau\tau$ rates

$b\to s\nu\nu$ rates are affected at the LQ exchange already at the tree-level (contrary $b\to s\nu\nu$) and involve only 3rd gen. leptons → possible huge effect compared to SM



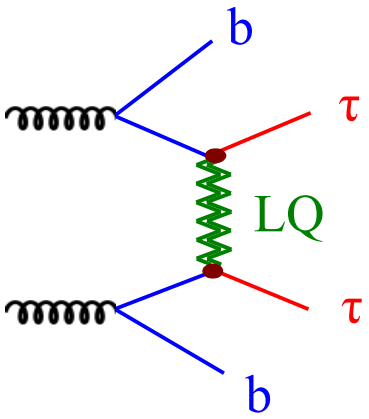


very interesting for Belle-II (4)

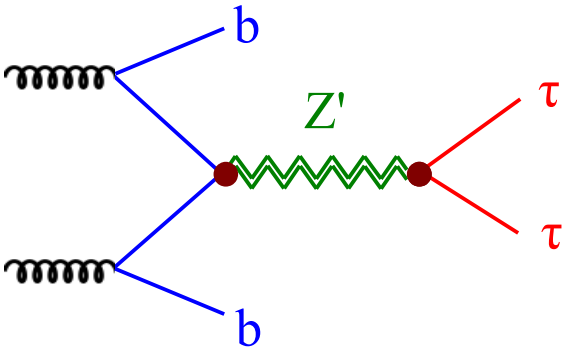
A brief look to current data & future prospects

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



and / or

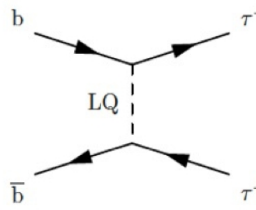


A brief look to current data & future prospects

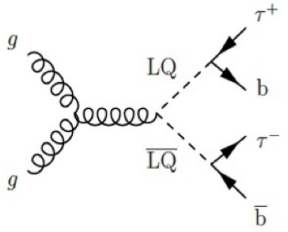
Aurelio Juste [*Moriond EW* '23]

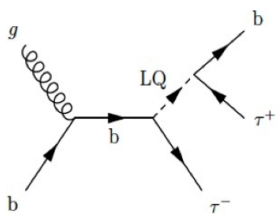
LQ-b-τ: Comparison of recent results

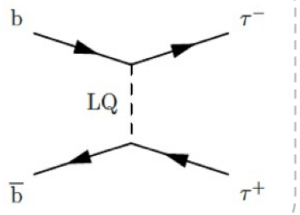
Including interference w/ SM bkg



Neglecting interference w/ SM bkg

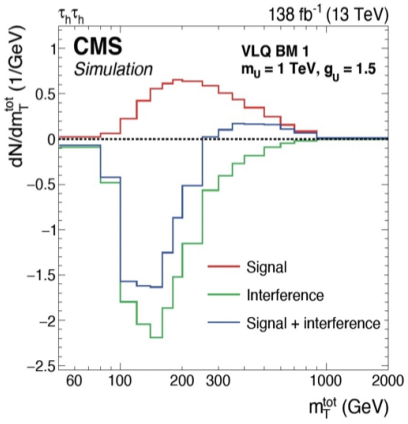


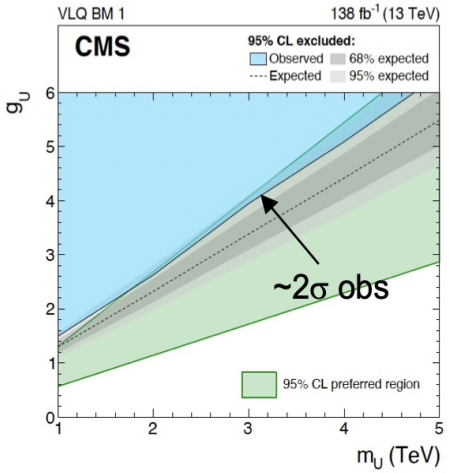




Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

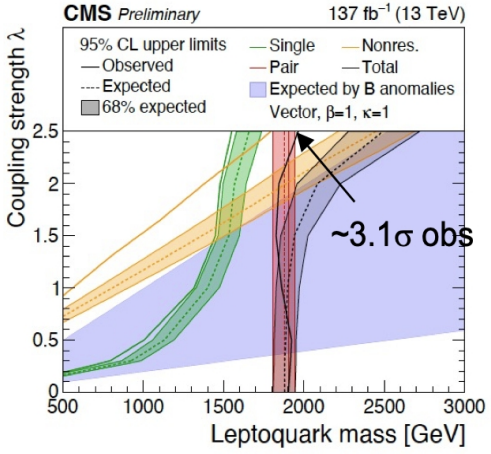
[CMS-HIG-21-001]



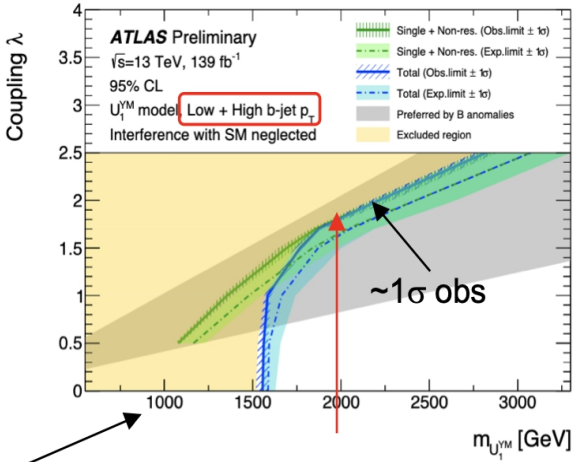


Shown at Moriond EW 2022

[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

- 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 → very interesting opportunities for near-future exp. in flavor physics (key role for Belle-II) & at high energies (LHC run-3)