Flavor Physics: open problems & recent developments

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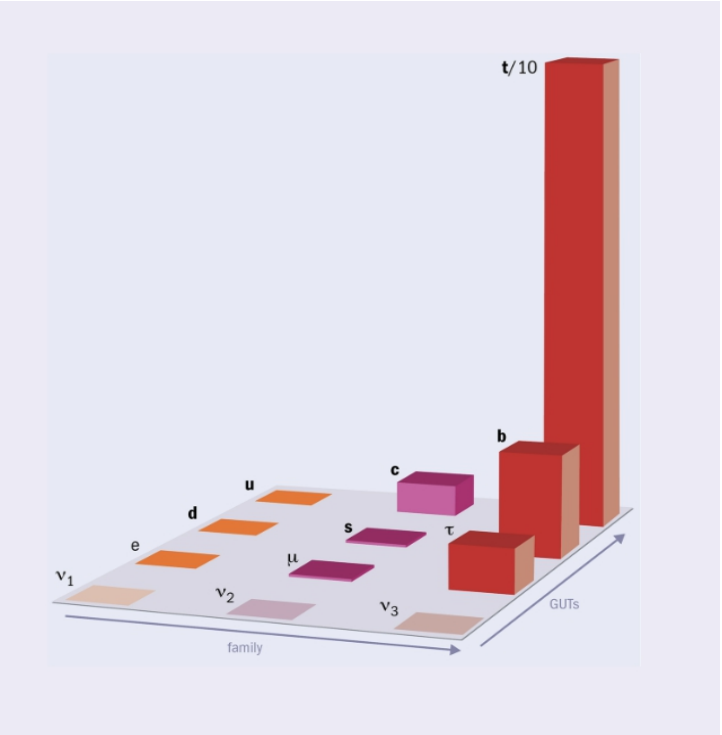
University of Zurich[UZH]

- Introduction: the flavor puzzle
- The flavor structure of the SMEFT
- Flavor non universality & flavor deconstruction
- A look to data & future prospects
- Conclusions

The flavor puzzle



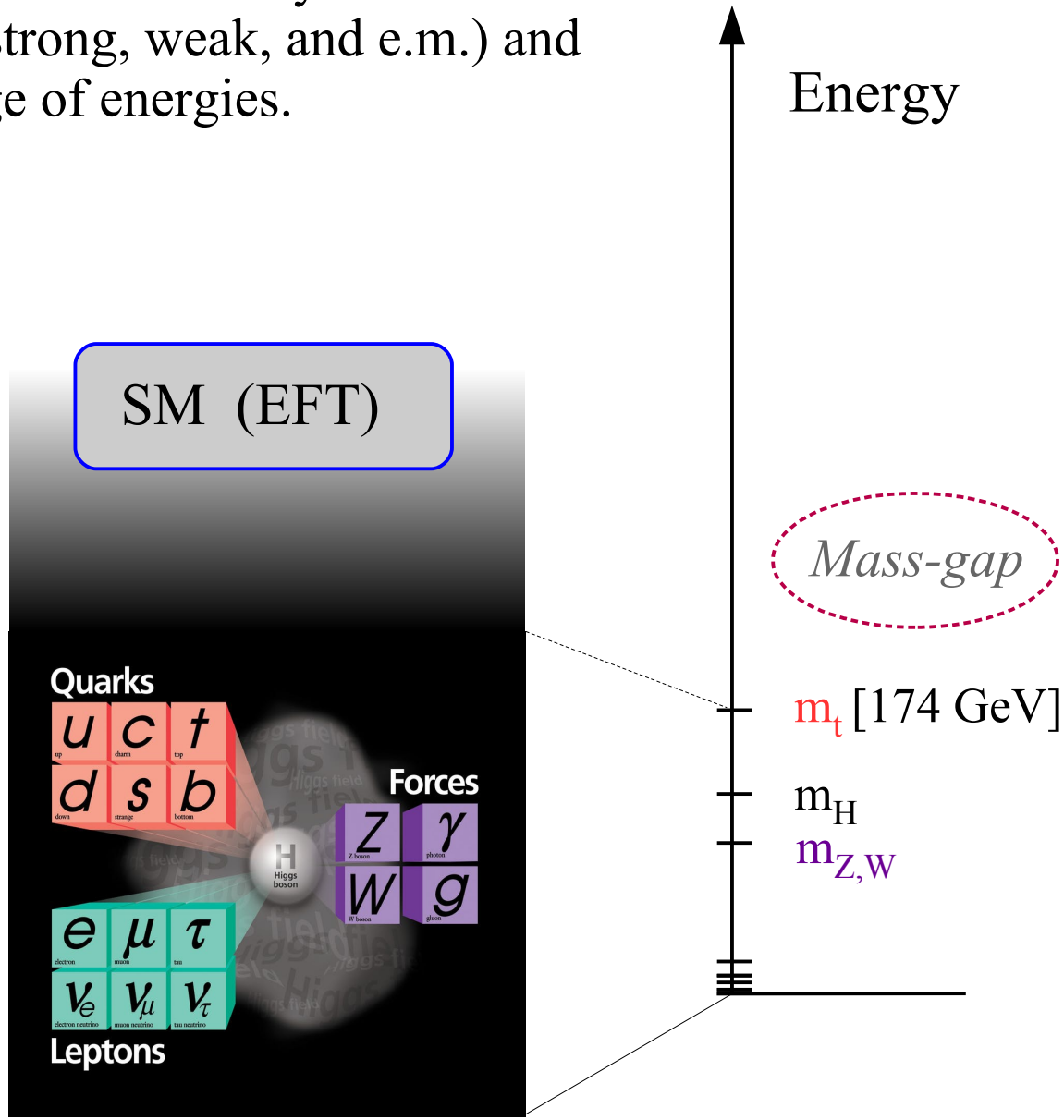
Introduction

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.

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

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

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



Introduction

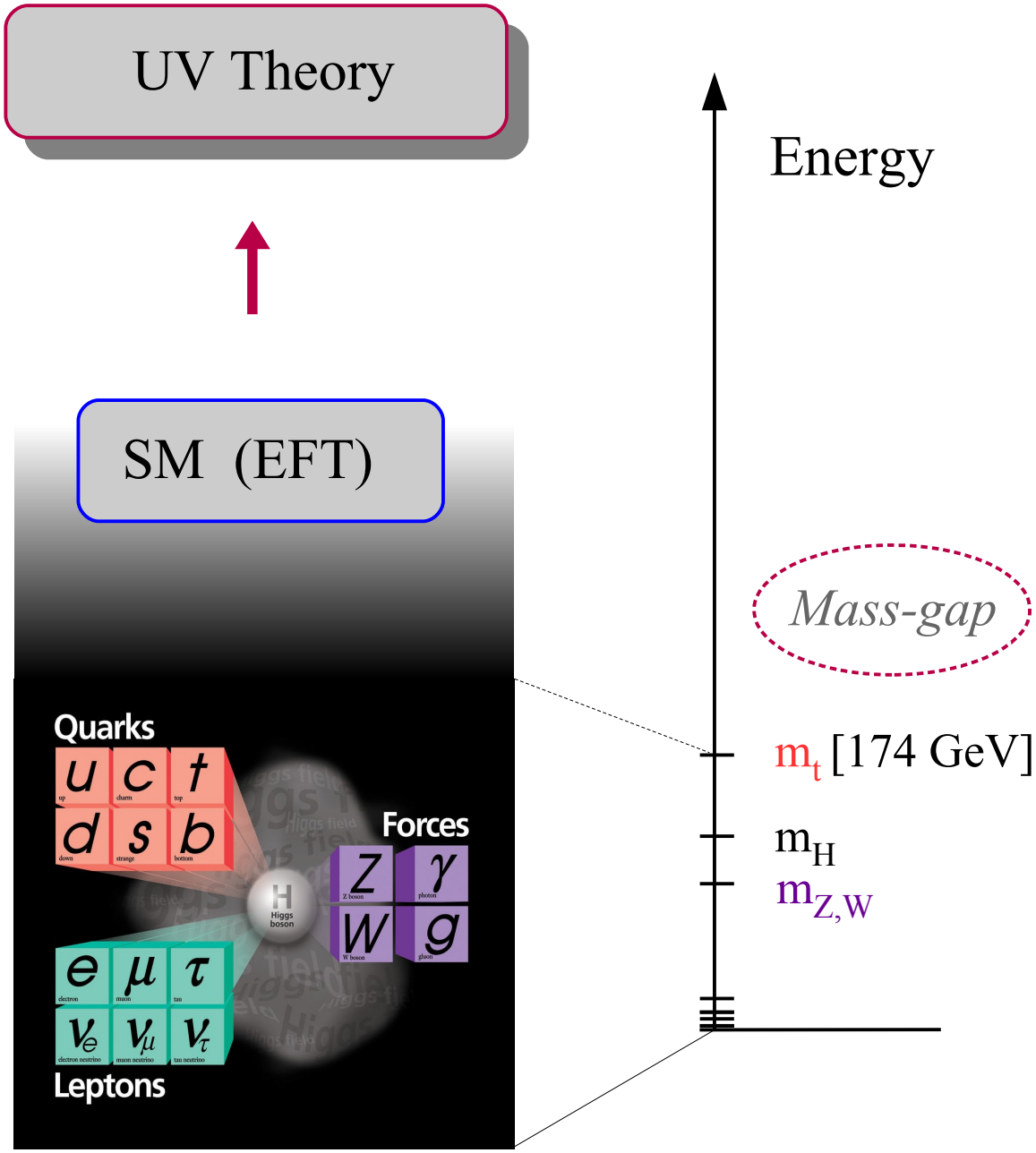
There are several reasons why we think the SM must be extended at high energies:

Electroweak hierarchy problem

Flavor puzzle
U(1) charges
Neutrino masses

Dark-matter
Dark-energy
Inflation

Quantum gravity



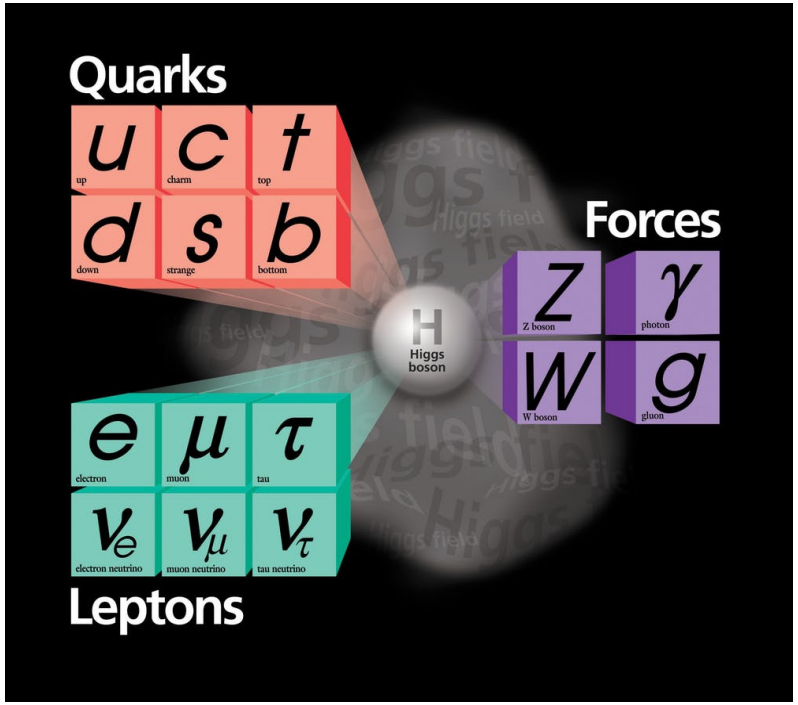
Introduction

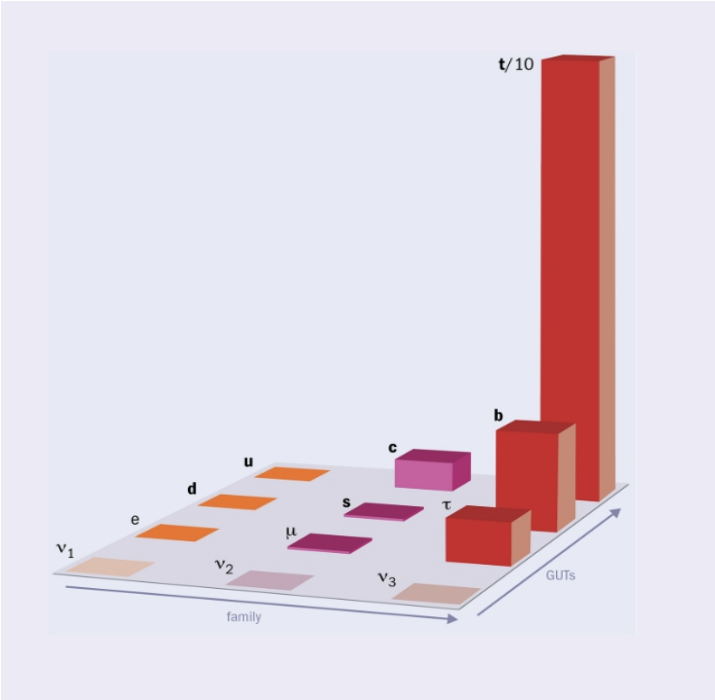
There are several reasons why we think the SM must be extended at high energies:

	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: the flavor puzzle

The "flavor puzzle" is an old problem, that emerged well before the Standard Model (SM) was conceived [*"Who ordered the muon ?"* - I. Rabi (~1950)].

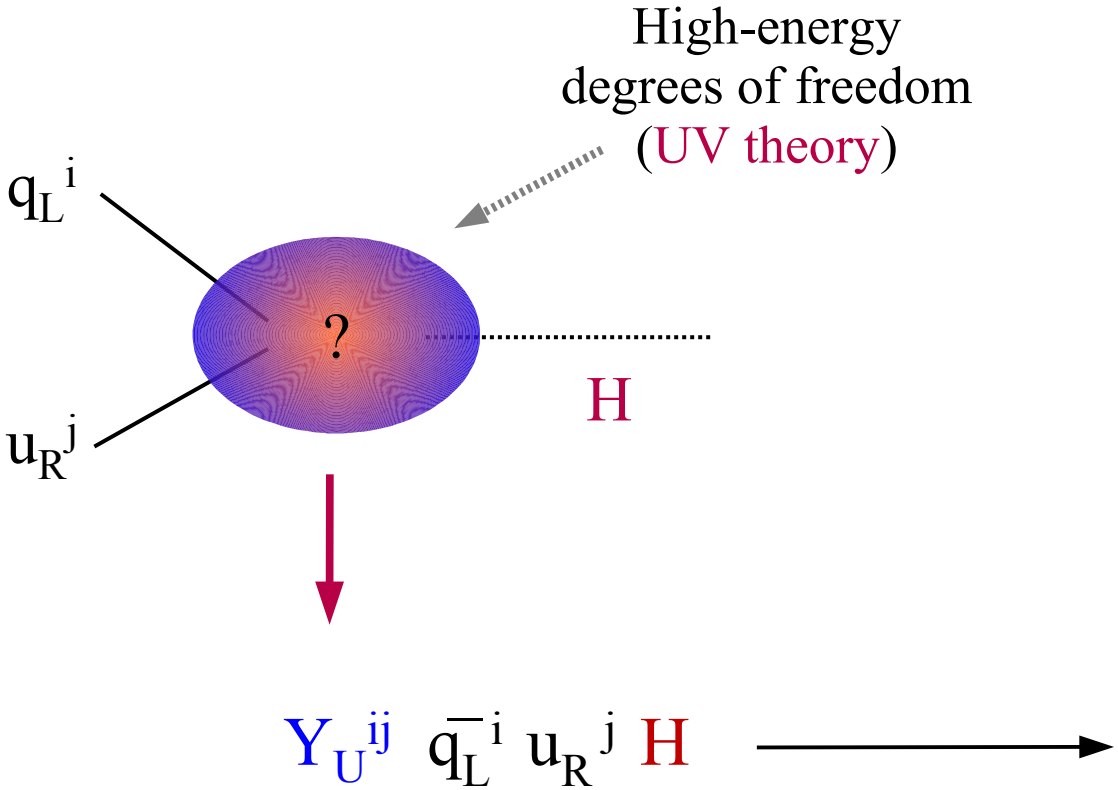


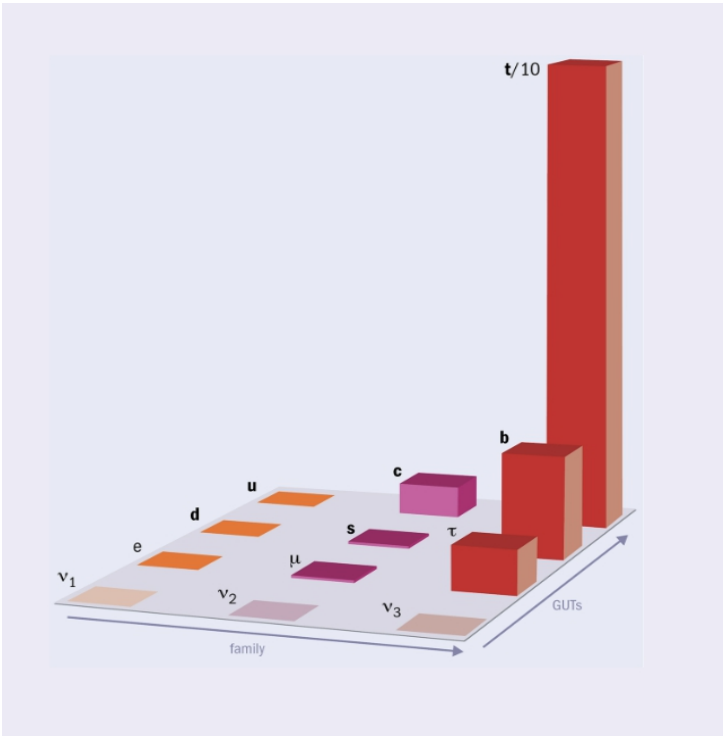


- Why do we have 3 copies of fermions with identical gauge quantum numbers
- What determines their highly non-trivial mass matrices?

Introduction: the flavor puzzle

Fermion masses are the results of the Yukawa interactions → Inescapable link between Higgs and flavor, whose origin can be addressed only beyond the SM…





"Message from the UV"
that we need to "decode"

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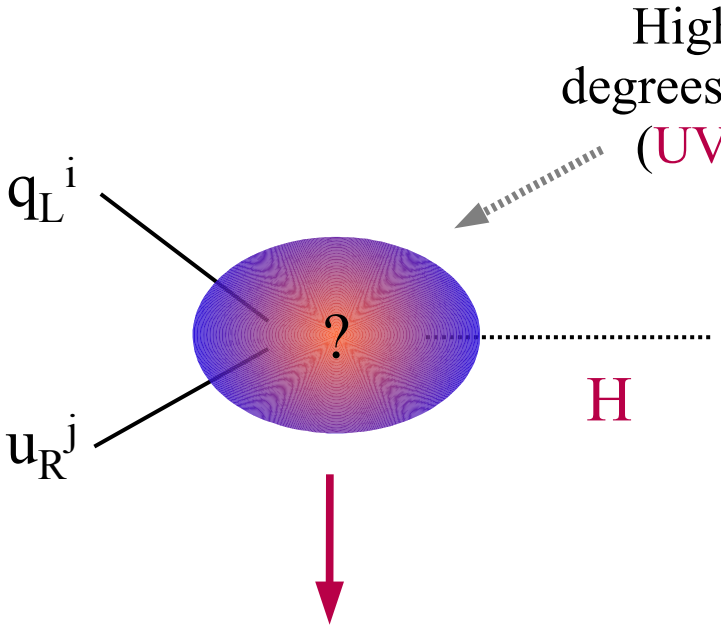

Contrary to gauge interactions, which are "protected" by gauge symmetries [*universal couplings controlled only by field charges*] the Yukawa interactions provide more information about UV dynamics

The UV dynamics responsible for the Higgs-fermion couplings is not universal among generations

Introduction: the flavor puzzle

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E.g.:

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

Y_U in the basis where Y_D is diagonal

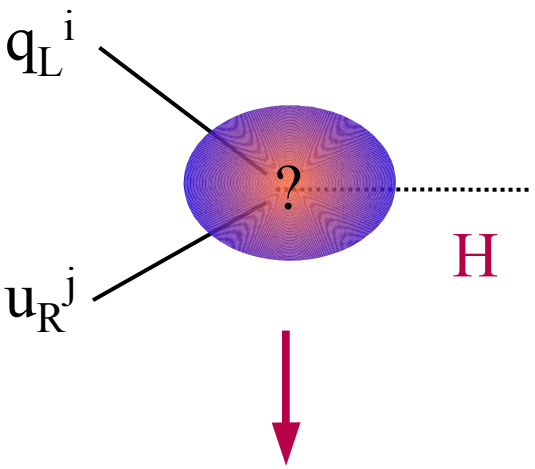
$$y_u = \frac{\sqrt{2}\, m_u}{\langle H \rangle} \approx 10^{-5}$$

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

The UV dynamics responsible for the Higgs-fermion couplings is not universal among generations & exhibits a strongly hierarchical pattern

Introduction: the flavor puzzle

On general grounds, the flavor non-universal dynamics in the UV should give rise to new effective flavor-violating contact interactions



$$Y_U \sim \begin{pmatrix} < 0.01 & < 0.1 \\ \cdot & 1 \end{pmatrix}$$

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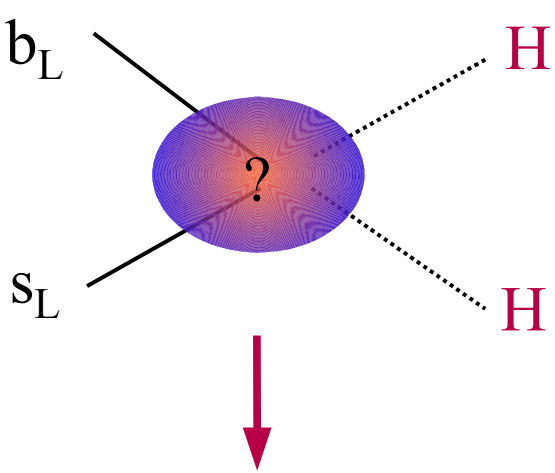
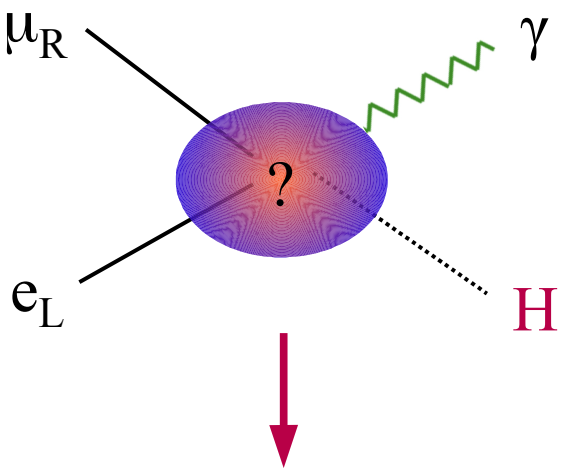


$B_s \to \mu\mu$



$\mu \to e\gamma$

Strength of the contact interaction ~ C_{eff}/Λ^2

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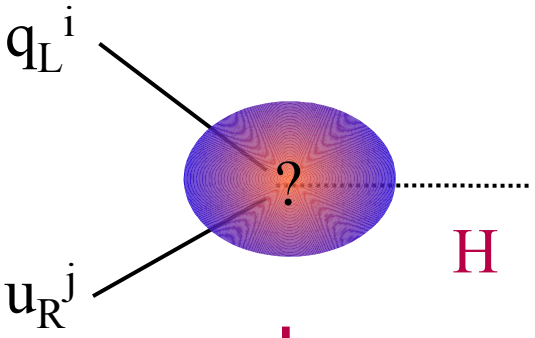

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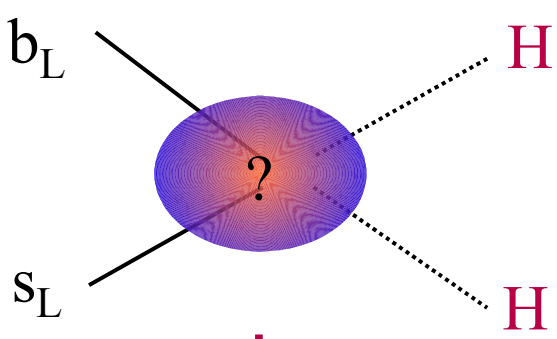

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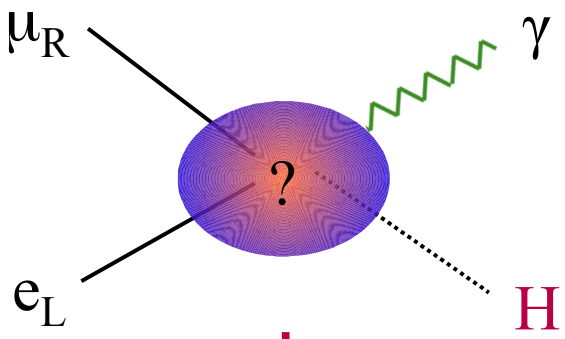


$\mu \to e\gamma$

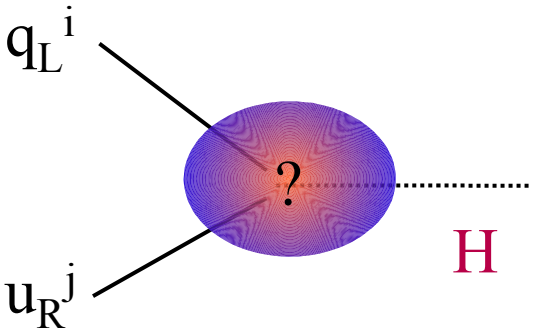
Strength of the contact interaction ~ C_{eff}/Λ^2

At present we do not see any of these effects.

This is often expressed in terms of bounds on Λ exceeding the TeV scale by several orders of magnitude

Introduction: the flavor puzzle

The two faces of the flavor puzzle:



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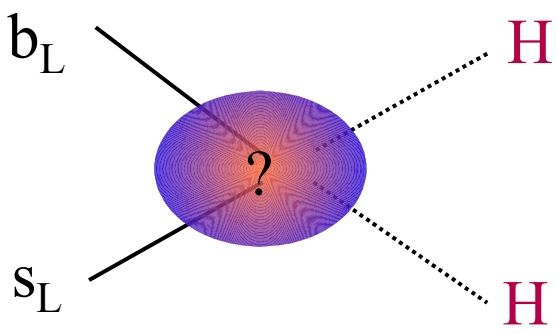
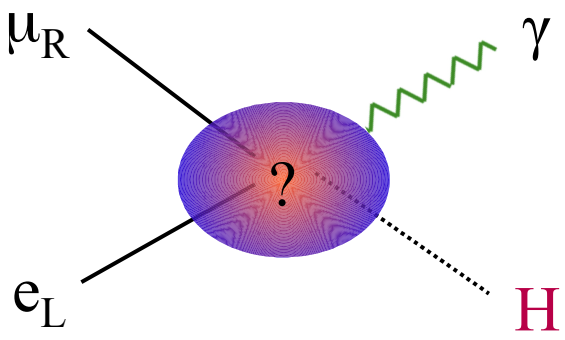
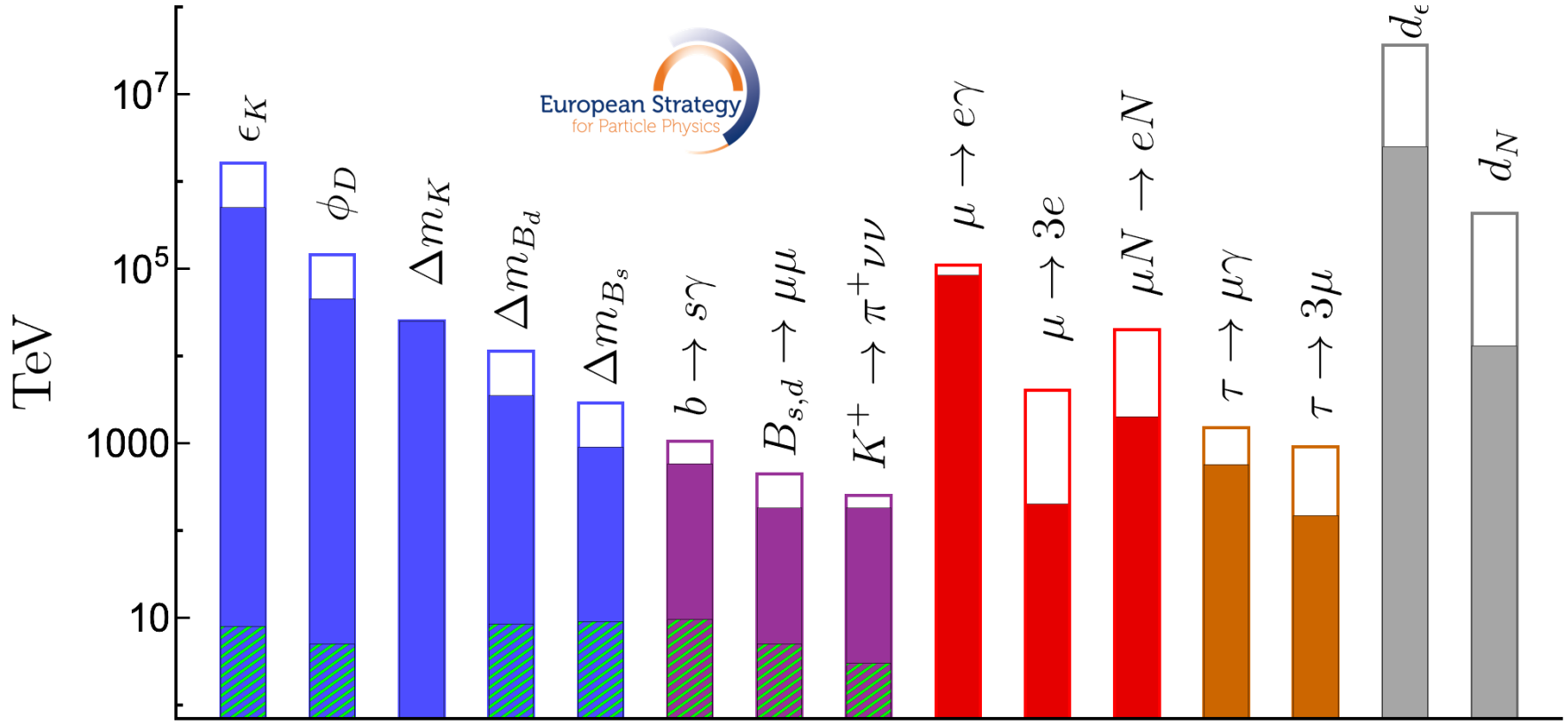




Strength of the contact interaction ~ C_{eff}/Λ^2

- *Which is the origin of this peculiar structure?*
- *Why we do not see other signs of flavor non-universality?*
- *Is there a connection between these two problems?*

The flavor structure of the SMEFT



The flavor structure of the SMEFT

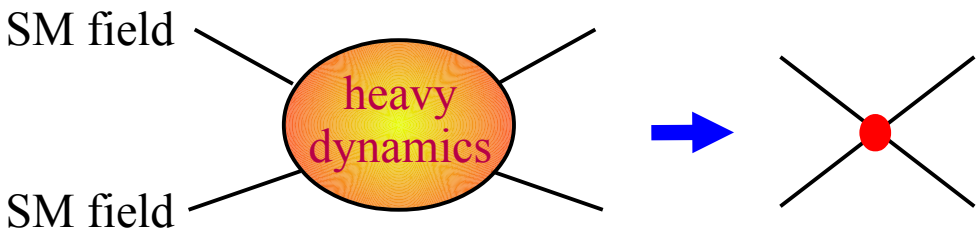
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

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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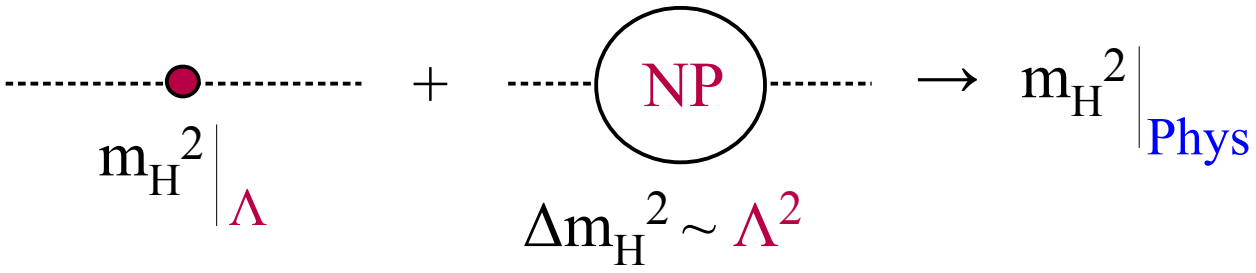
What is the cut-off scale Λ of the SMEFT?

UV Theory

SM (EFT)

A useful (*but somewhat vague*) indication follows from the Electroweak hierarchy problem ($\leftrightarrow$ *instability of the Higgs mass under quantum corrections*):



→ (*some*) New Physics (*coupled at least to* H & t) in the TeV domain

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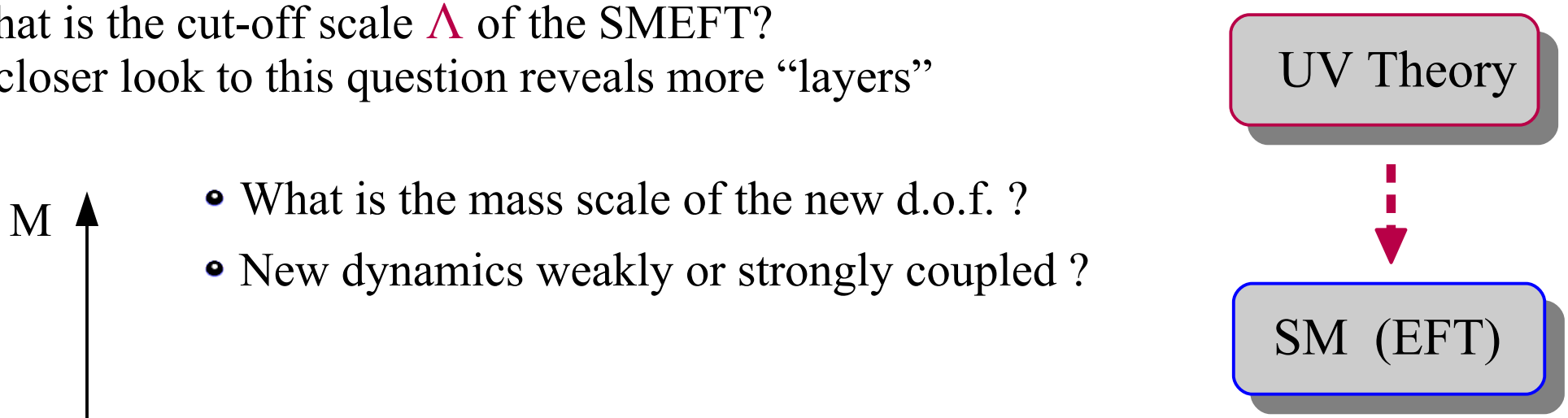
A closer look to this question reveals more "layers"



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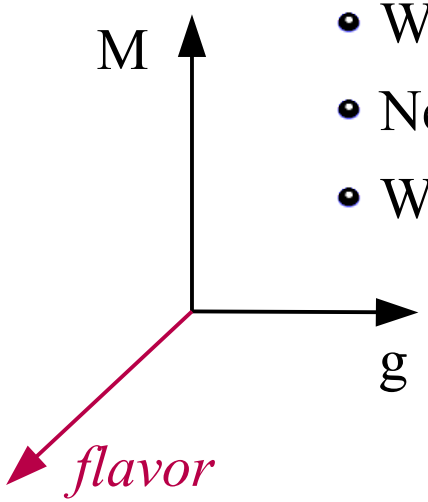
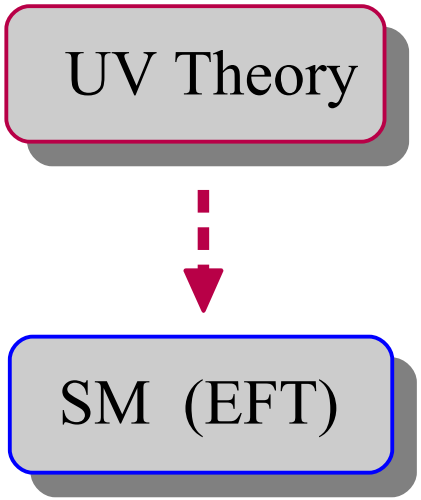


- What is the mass scale of the new d.o.f. ?
- New dynamics weakly or strongly coupled ?
- What is the *flavor structure*?



SM (Yukawa) sector → flavor is highly non trivial

- No flavor symmetry → 2499 free couplings in the SMEFT @ d=6
- Exact $U(3)^5$ → 47

Jenkins, Manohar, Trott '14

The flavor structure of the SMEFT

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Large flavor symmetry

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

$$\psi^i \to U^{ij}\, \psi^j$$

$$\psi = Q_L\,,\, u_R,\, d_R,\, L_L,\, e_R$$

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Large flavor symmetry

Flavor-degeneracy broken by the Yukawa interaction

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$$y_{ij}\, \psi_L{}^i\, \psi'_R{}^j\, H \;\to\; m_{ij}\, \psi_L{}^i\, \psi'_R{}^j$$

"Peculiar" breaking structure

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

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"Peculiar" breaking structure

Exact & approximate (*accidental* ?) symmetries

How are these symmetries broken in the whole SMEFT ?

The flavor structure of the SMEFT

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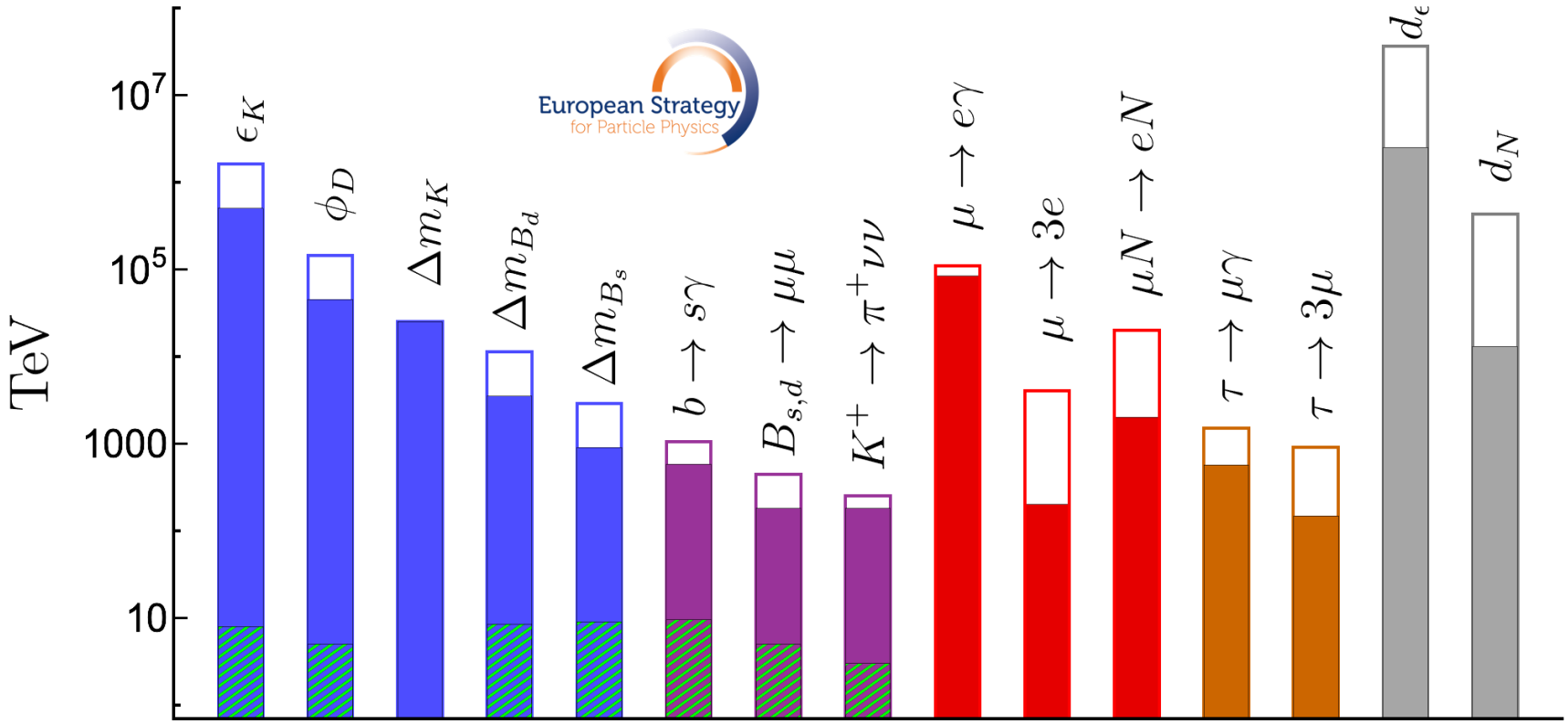
In principle, we could expect many violations of the accidental symmetries from heavy dynamics. However, no clear deviations observed so far → stringent bounds on the *effective scale* of possible new flavor violating interactions



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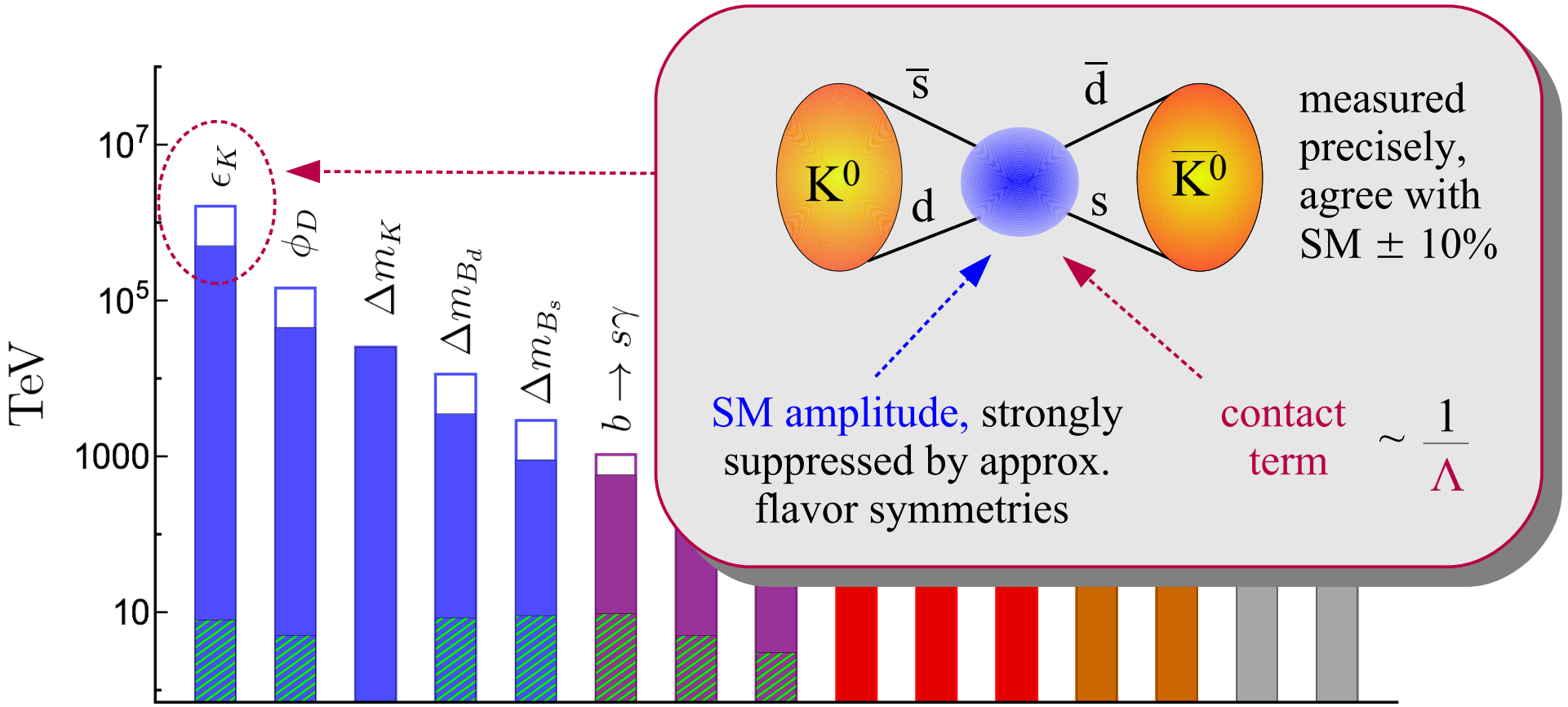

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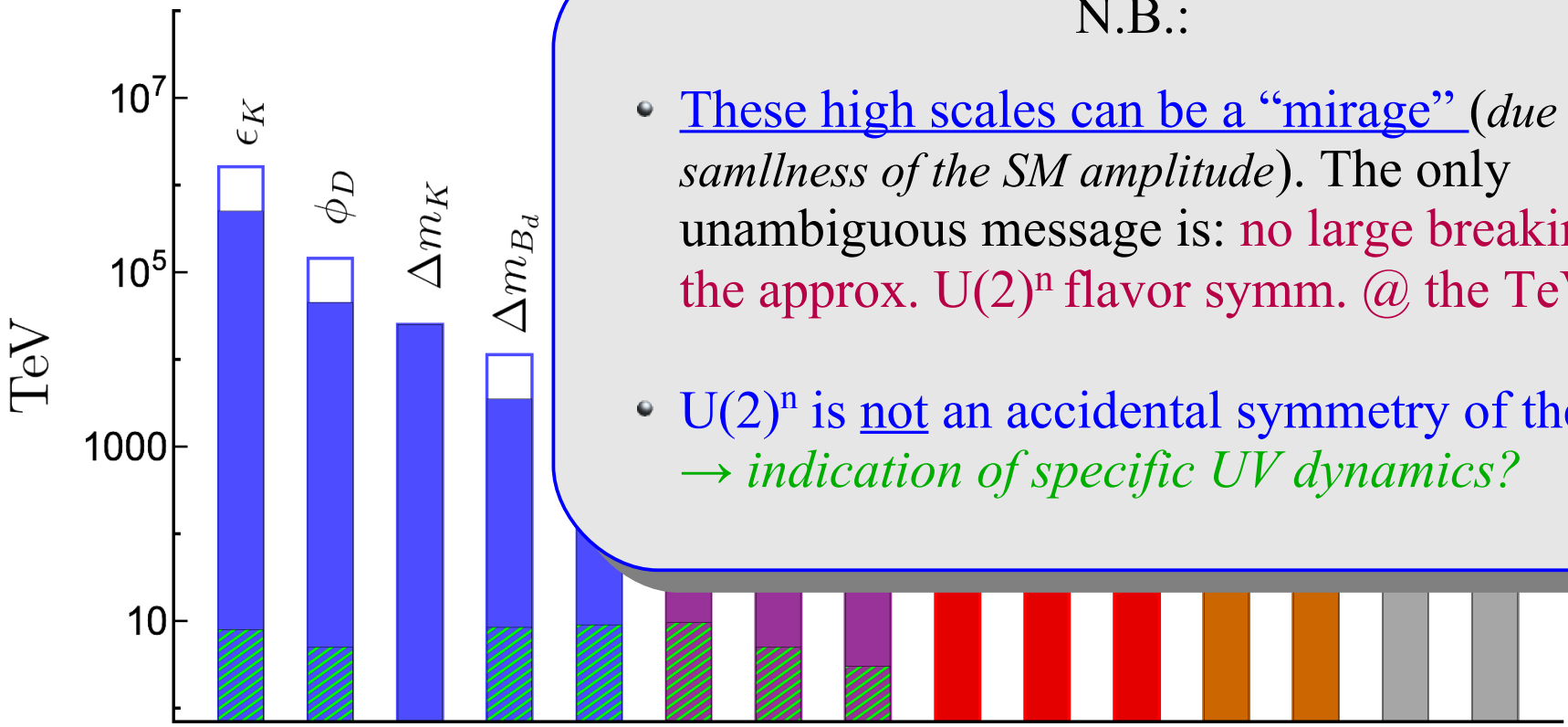

N.B.:

- These high scales can be a "mirage" (*due to the samllness of the SM amplitude*). The only unambiguous message is: no large breaking of the approx. $U(2)^n$ flavor symm. @ the TeV scale
- $U(2)^n$ is not an accidental symmetry of the SM → *indication of specific UV dynamics?*

The flavor structure of the SMEFT

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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 additional symmetry breaking terms

3 classes of "interpretations"

- "Simplicity": the scale of NP is high ($> 10^5$ TeV)
  → no way to test the origin of the Y's
- "High-scale flavor dynamics" & MFV
- "Flavor deconstruction"

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"decoupling" of flavor & EW problems

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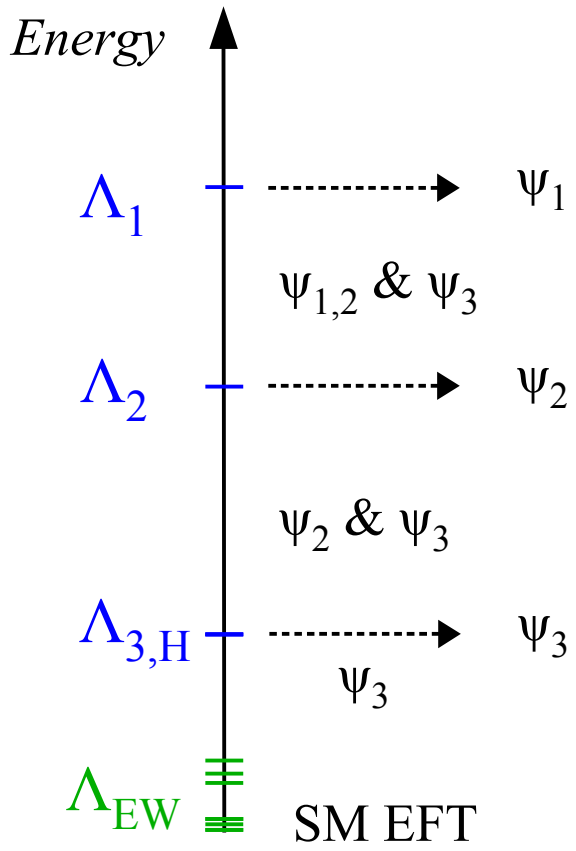
  "decoupling" of flavor & EW problems

- "Flavor deconstruction": the scale of NP is low & $U(2)^n$ emerges as accidental symm. from flavor non-universal gauge interactions @ nearby scales

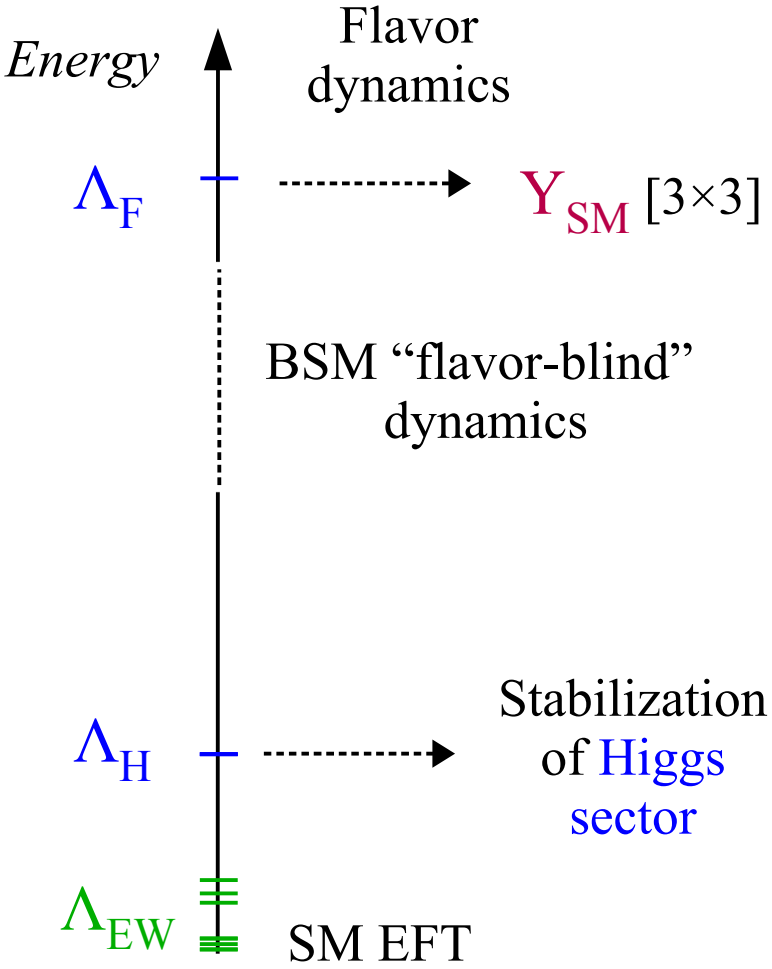
  "interplay" of flavor & EW problems

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"

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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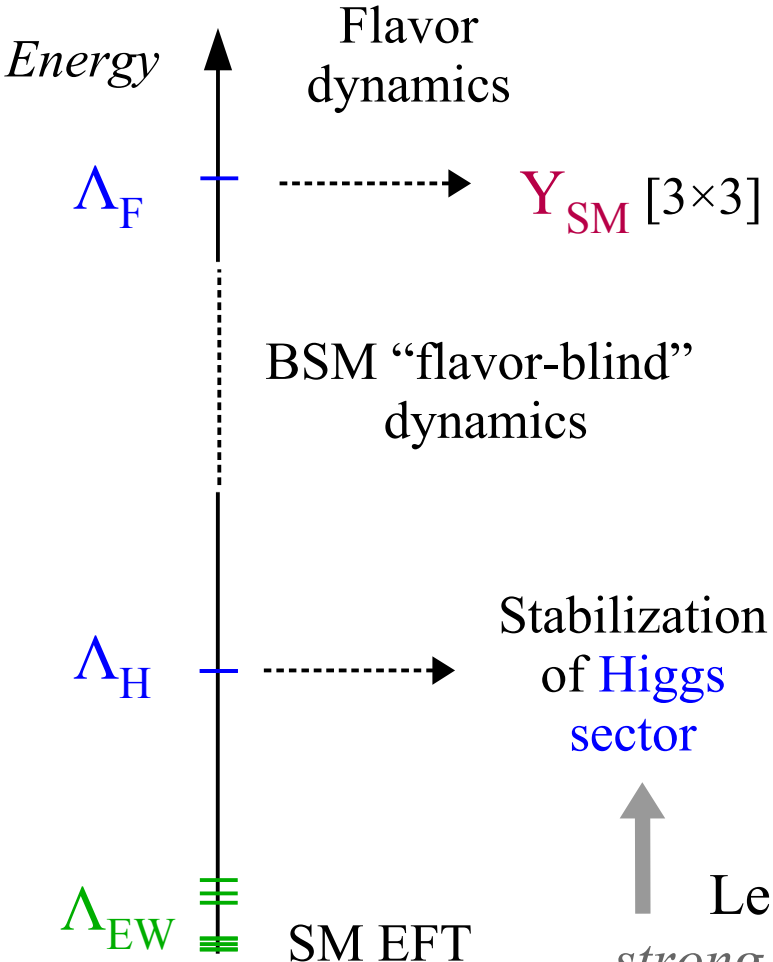

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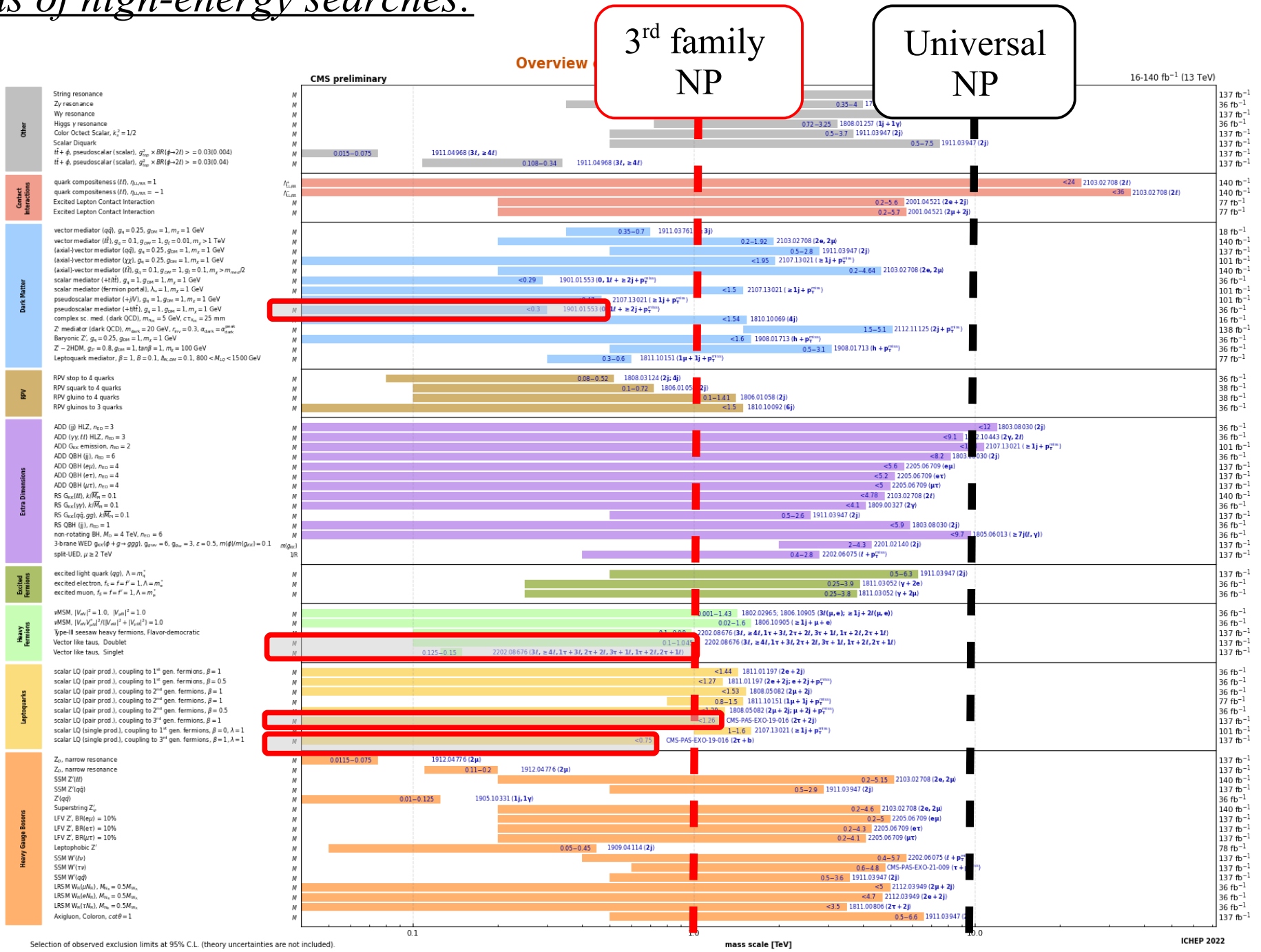
The "MFV paradigm"

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

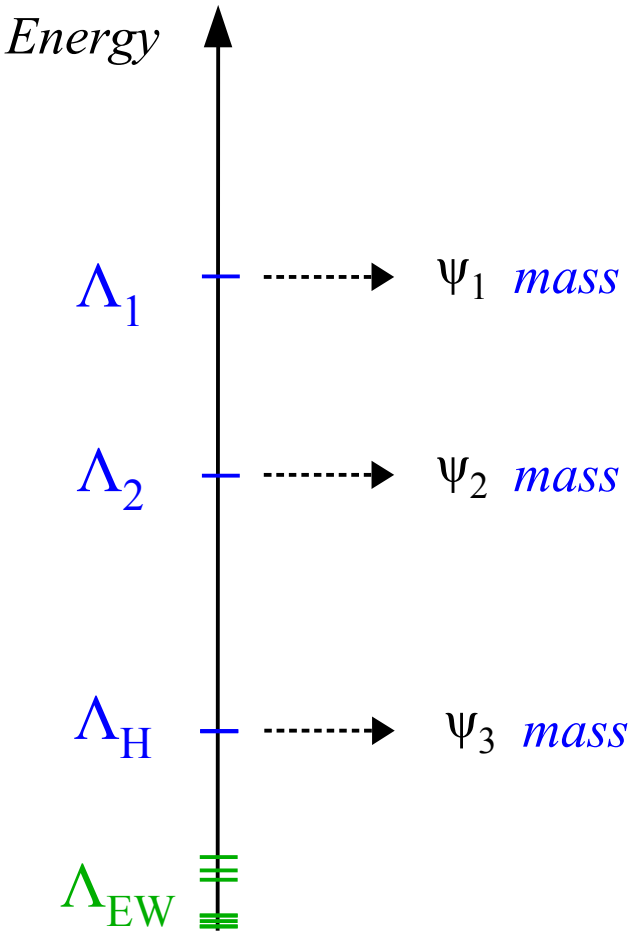
Status of high-energy searches:



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
Barbieri & GI '24
⋮



Basic idea:

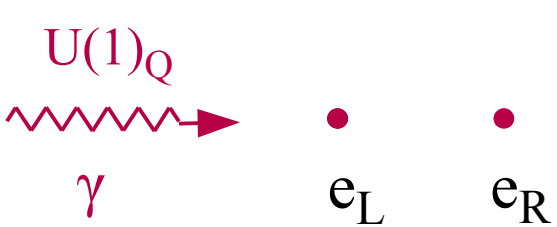
1st & 2nd generations have small masses (+ small coupling to NP) because these are generated by new dynamics at heavier scales

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

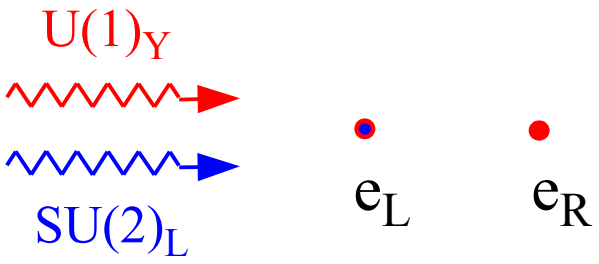
Flavor non-universal interactions

To better appreciate the change of perspective, consider the following analogy:

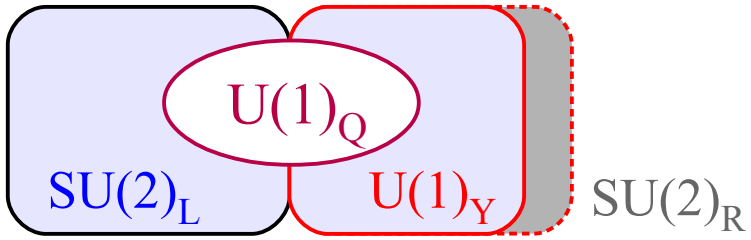
In the low-energy limit of the SM (= QED×QCD) we observe perfect universality of LH and RH gauge couplings. However, we know this is a low-energy artifact:



Low energies



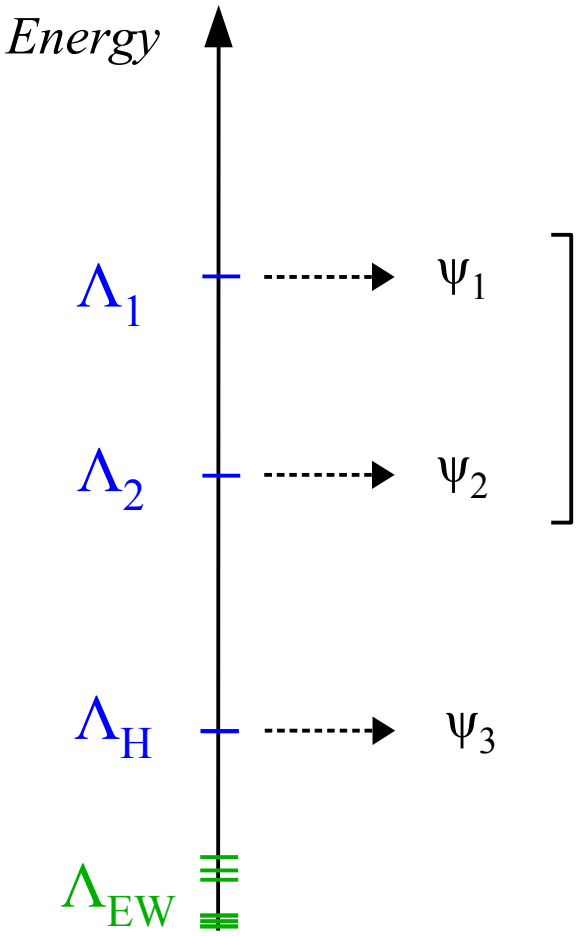
High energies



In a similar fashion, the flavor universality of all SM gauge interactions could be a low-energy artifact...

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



- 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

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

$U(2)_u$

Flavor non-universal interactions

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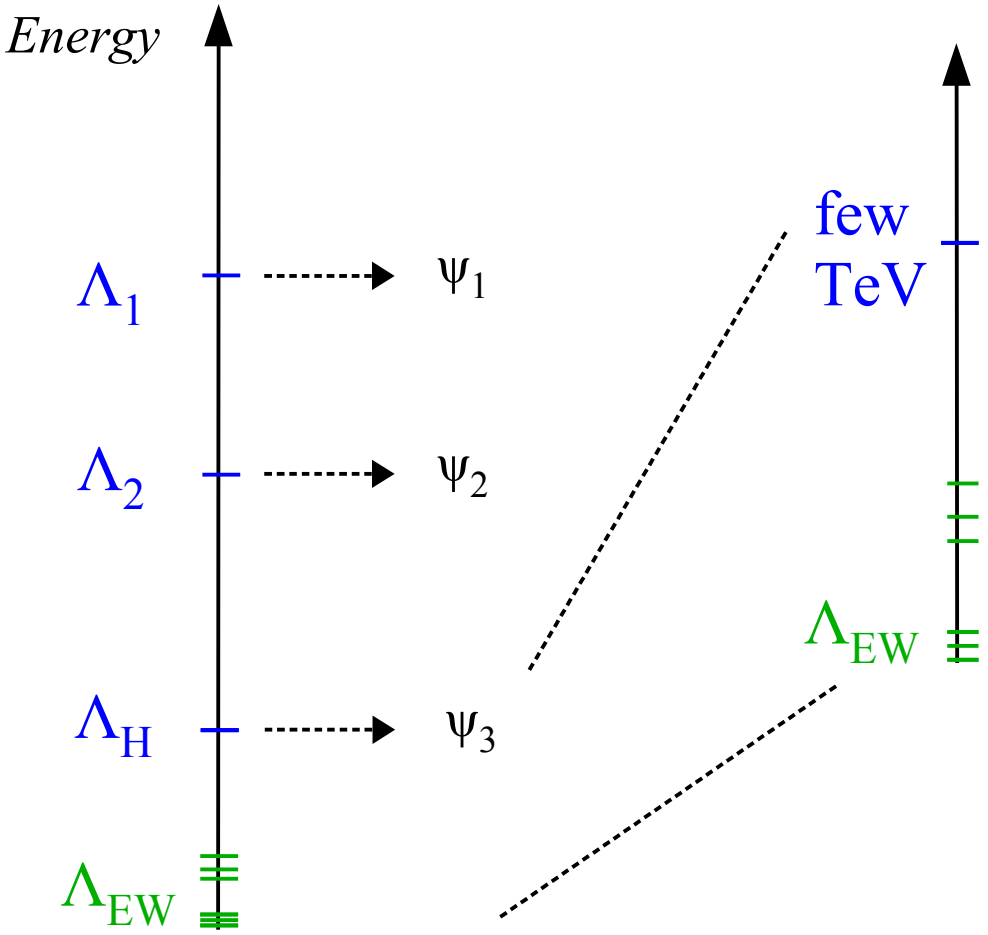
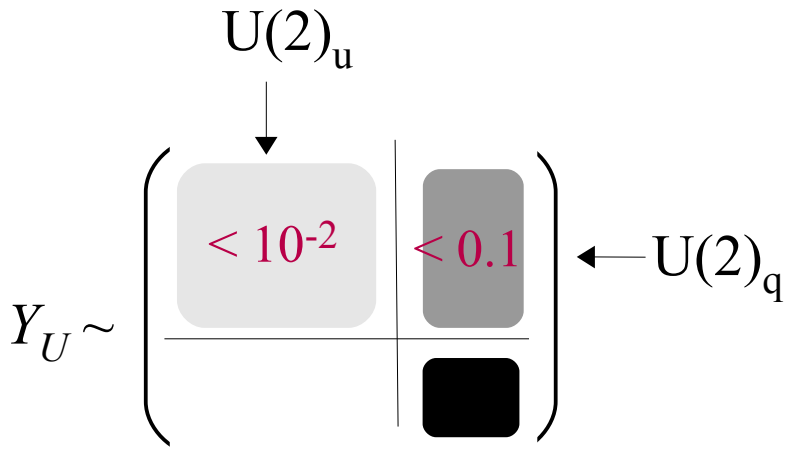


NP coupled mainly to ψ_3

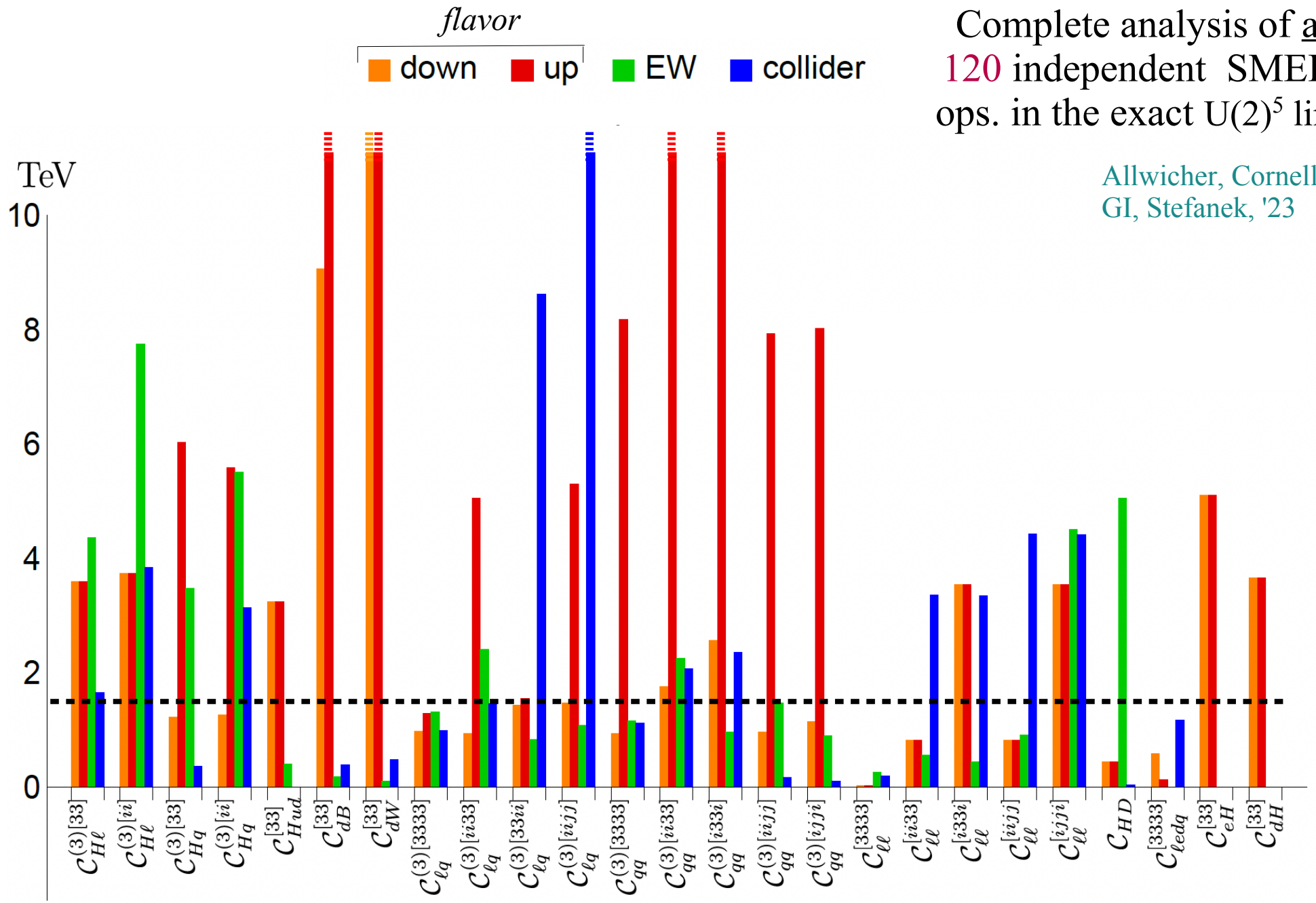
$\psi_{1,2}$ ~ massless [$U(2)^n$ symm.]

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



Effective organizing principle for the flavor structure of the SMEFT

[I] *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

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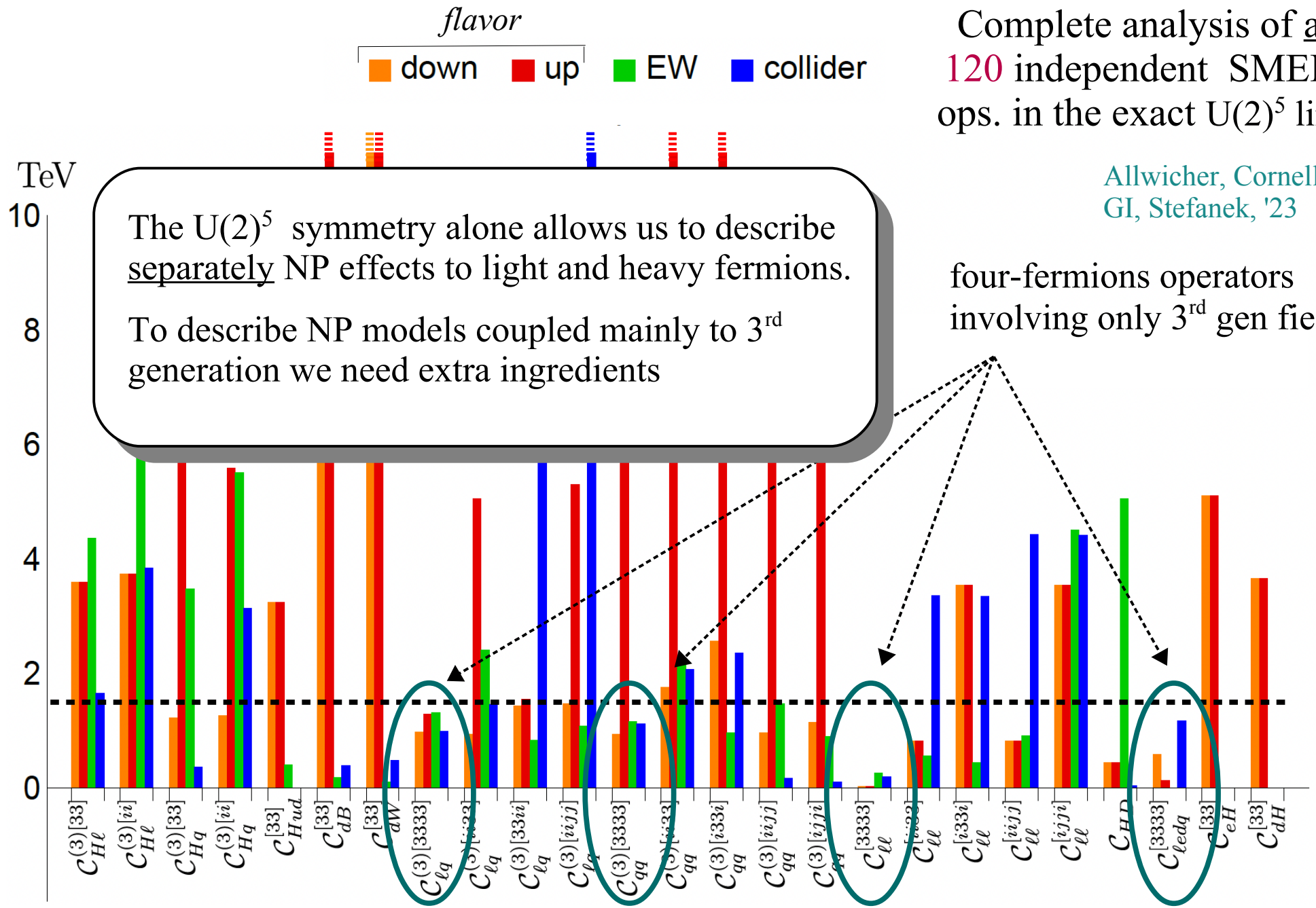

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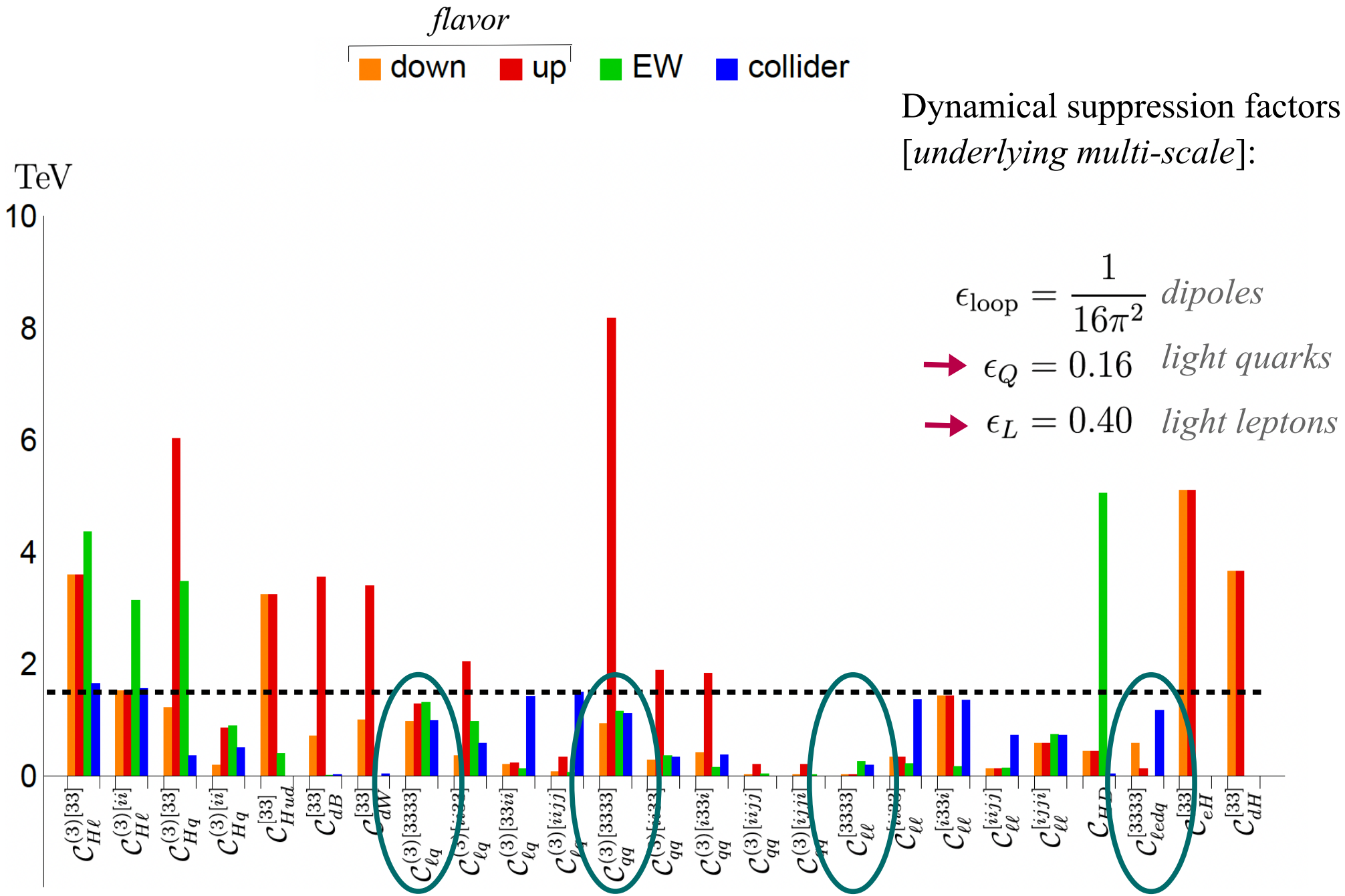

Dynamical suppression factors [*underlying multi-scale*]:

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

→ $\epsilon_Q = 0.16$ *light quarks*

→ $\epsilon_L = 0.40$ *light leptons*

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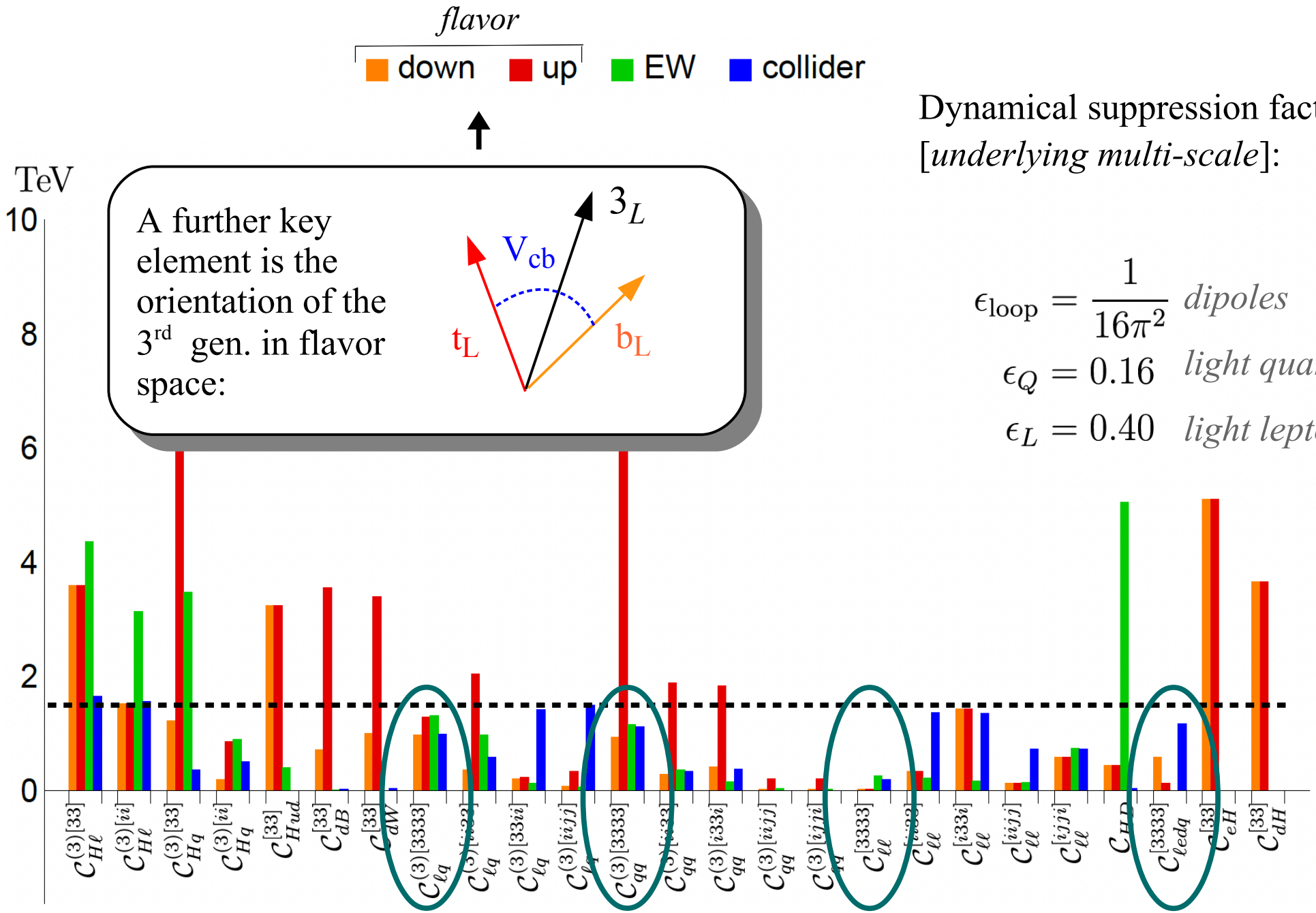

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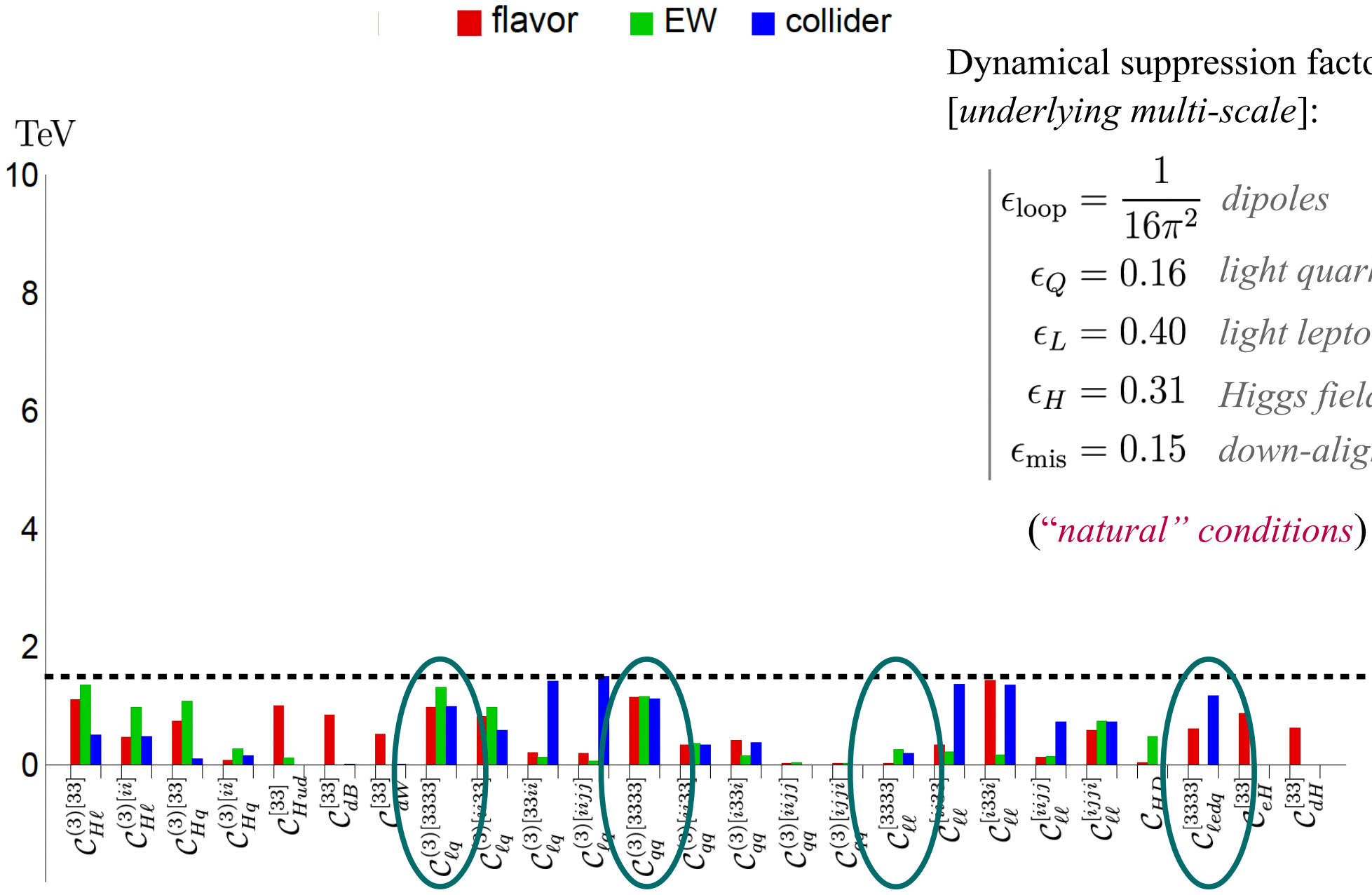

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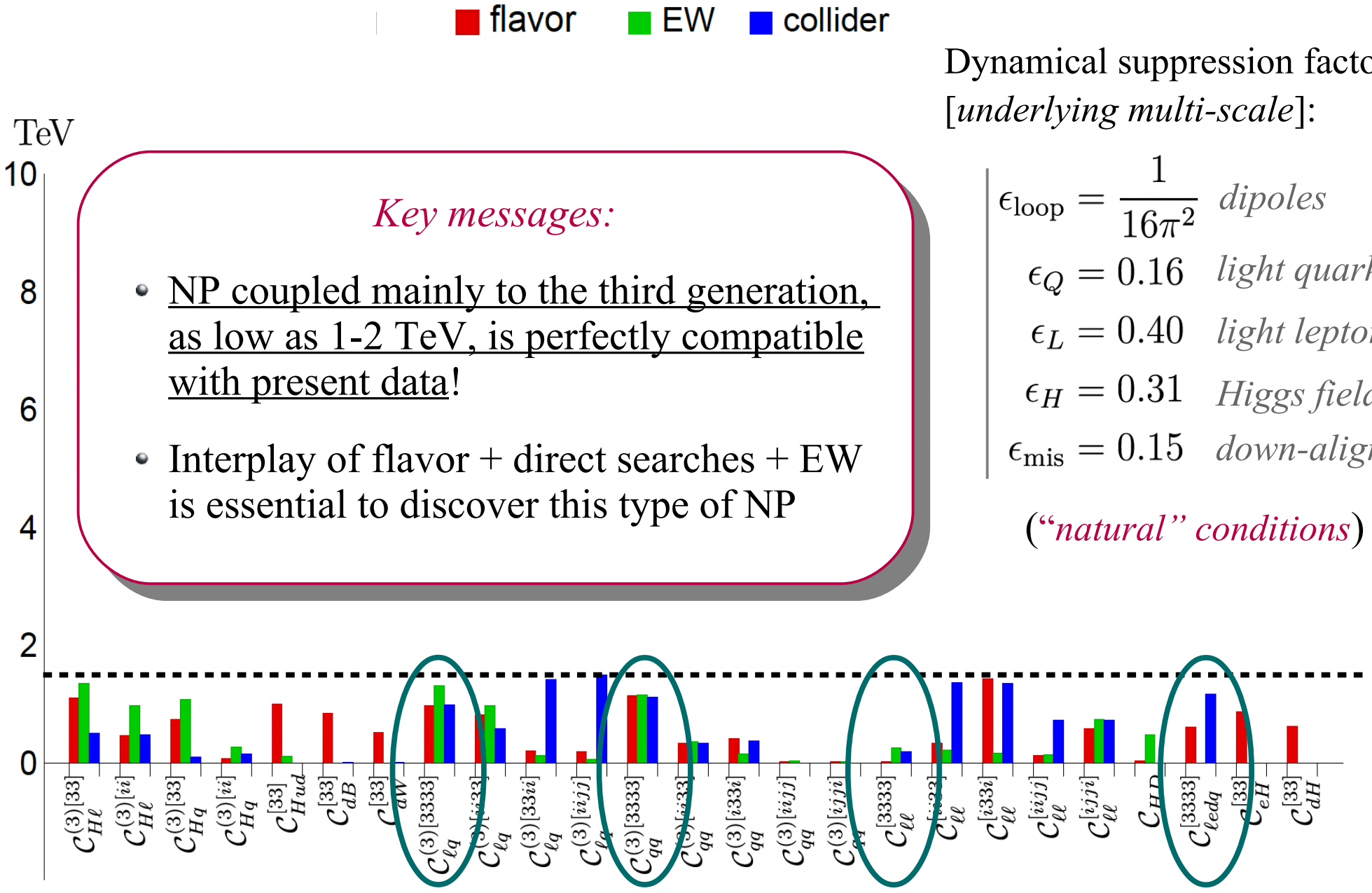

Key messages:

- 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

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

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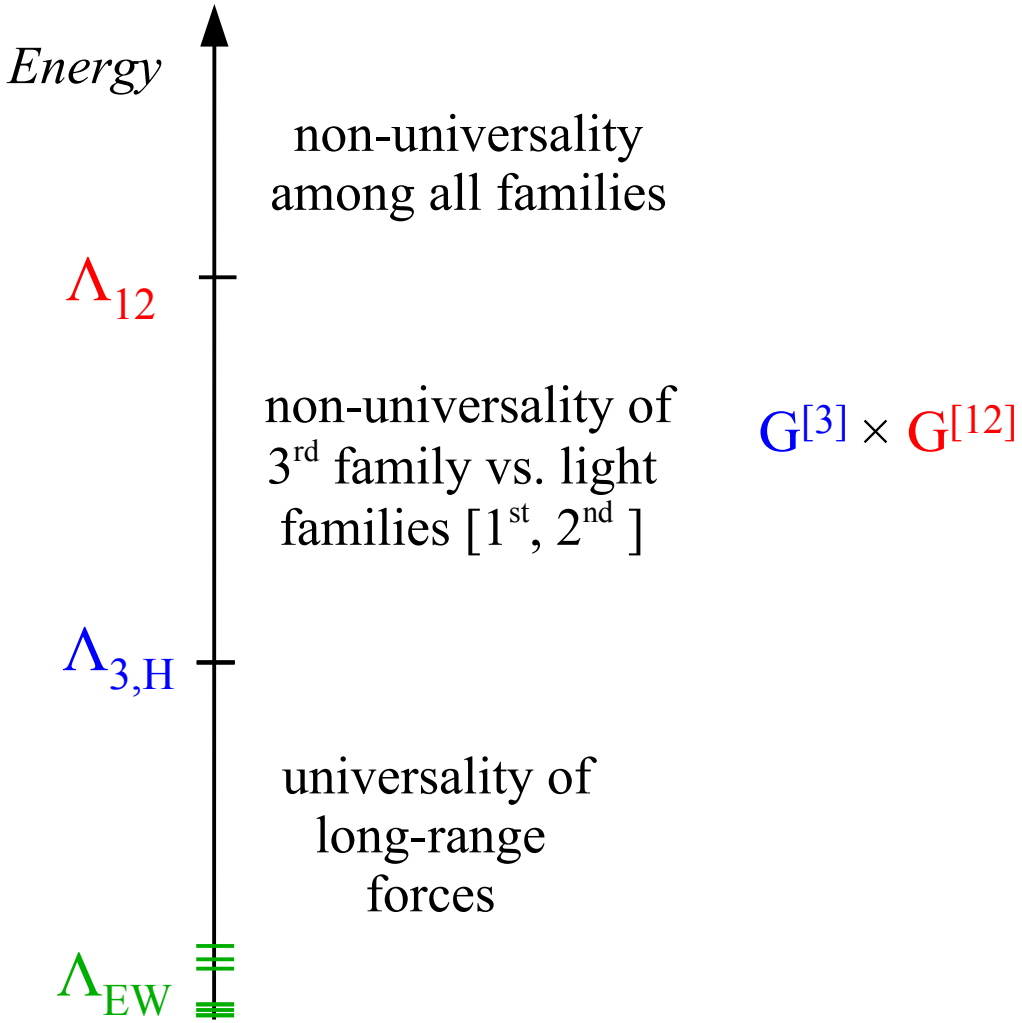
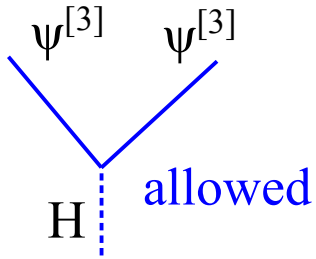
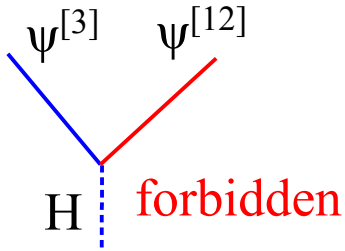
Going beyond the EFT approach, a consistent way to construct a multi-scale theory with flavor non-universal interactions is via a "*flavor deconstruction*" of the SM gauge symmetries:

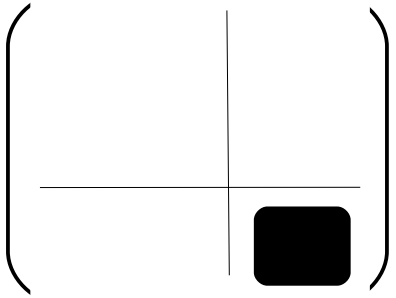


$G^{[3]} \times G^{[12]}$





$Y_U \sim$



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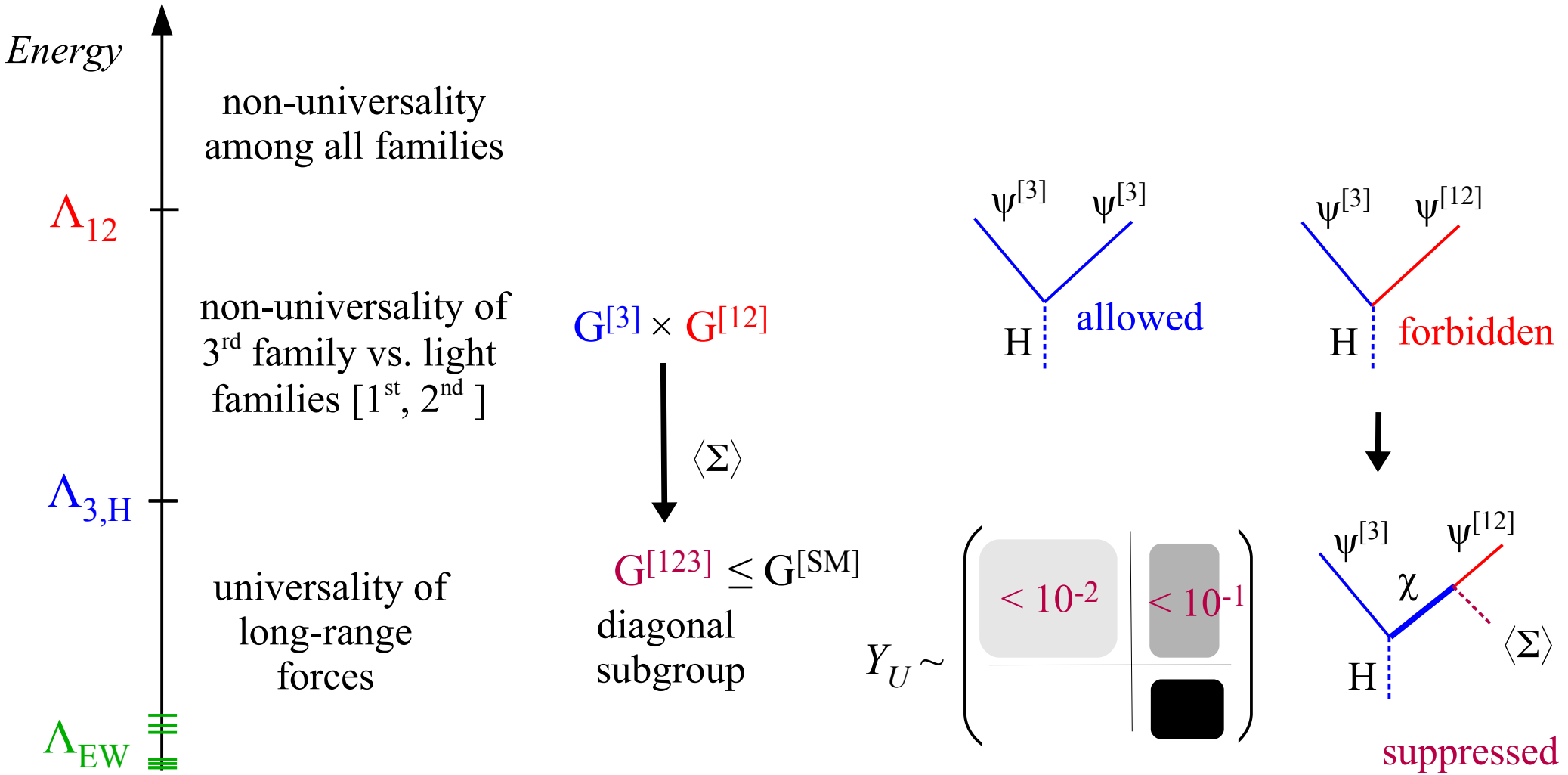

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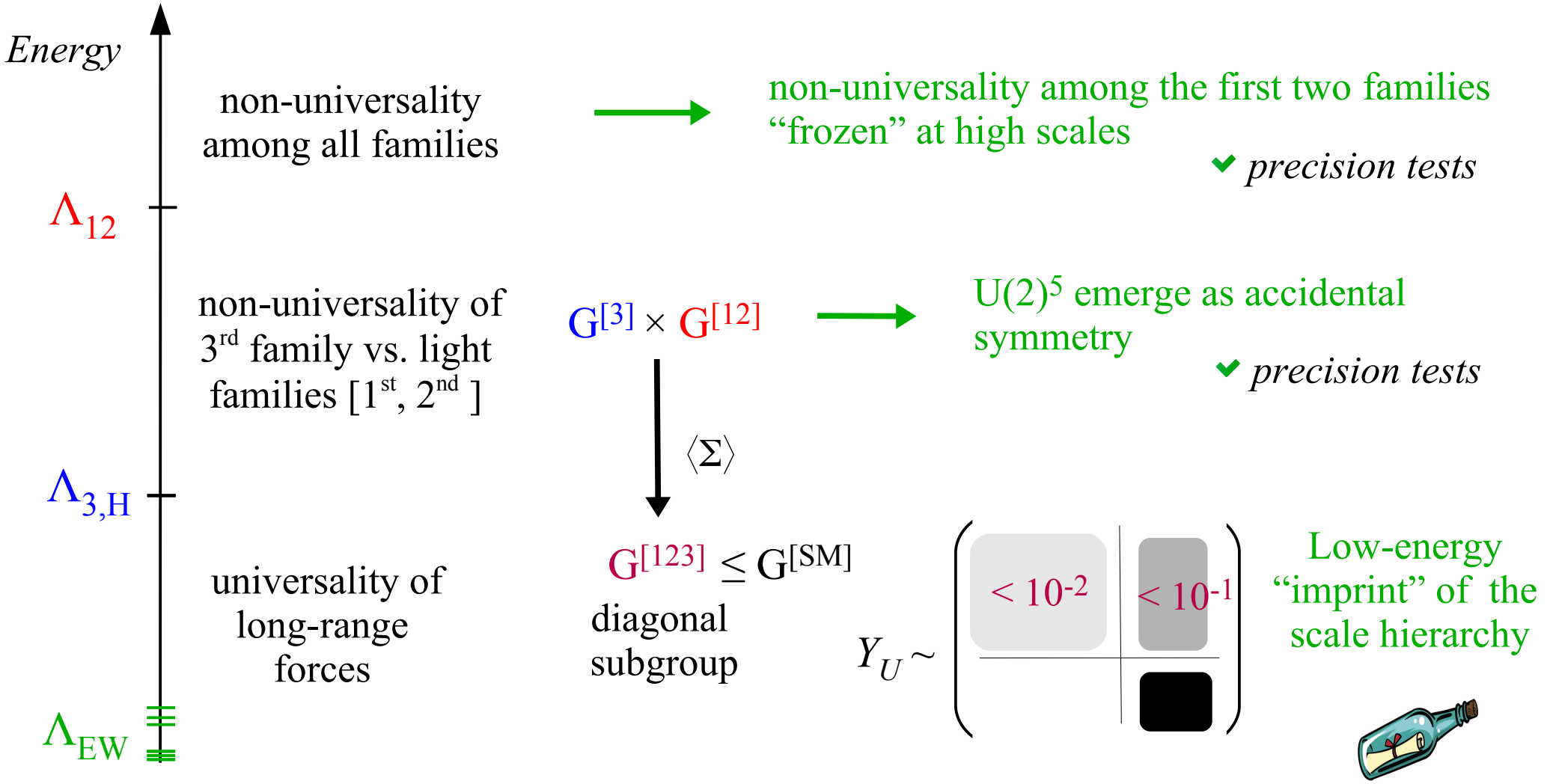

[III] *Flavor deconstruction & quark-lepton unification*

All possible options have been classified (*not many consistent choices*).

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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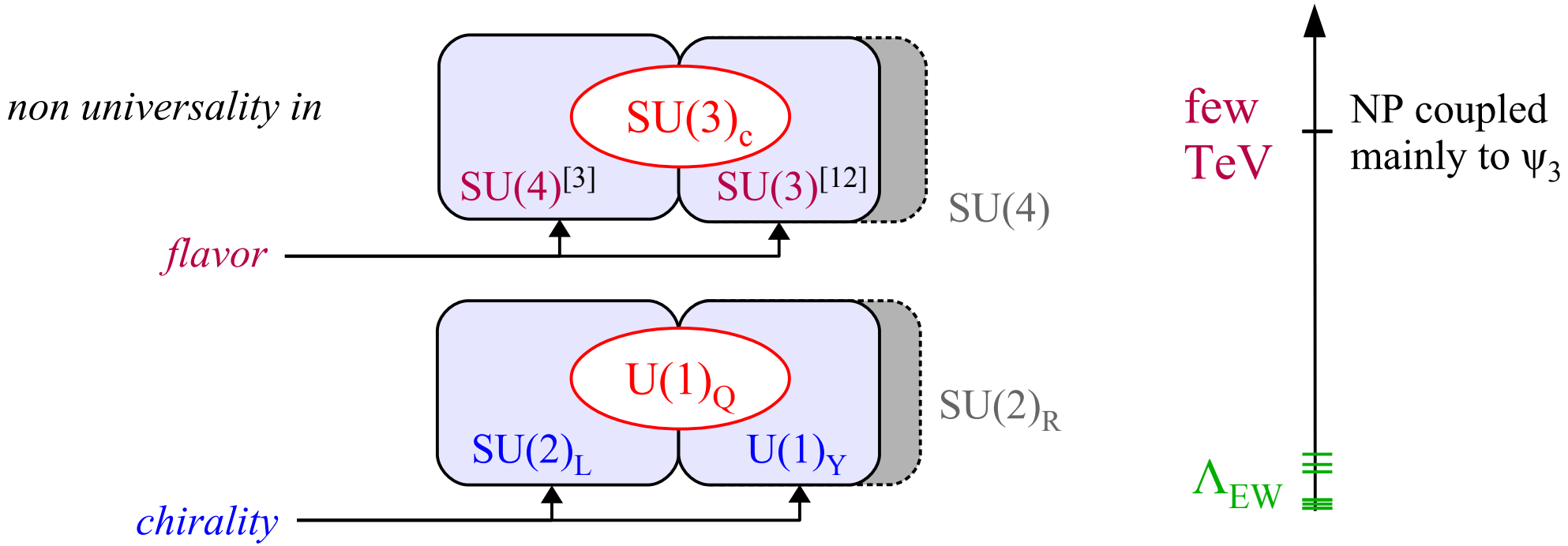

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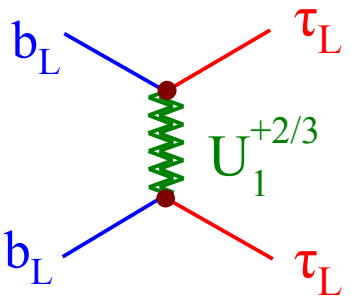
$$SU(4)^{[3]} \times SU(3)^{[12]} \times G_{EW} \;\longrightarrow\; SU(3) \times SU(2)_L \times U(1)_Y$$

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

- [IV] *Flavor deconstruction & partial compositeness*

The FD hypothesis alone does not address the EW hierarchy problem. However, it provides some basic ingredients (*"light" new states coupled to Higgs and 3rd gen.*) which can help to address it → interesting specific advantage when merged to Higgs compositeness

Fuentes-Martin & Stangl '20
Fuentes-Martin *et al.* '22

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Fuentes-Martin & Stangl '20
Fuentes-Martin *et al.* '22

Toy example [Covone, GI, Pesut '24]:

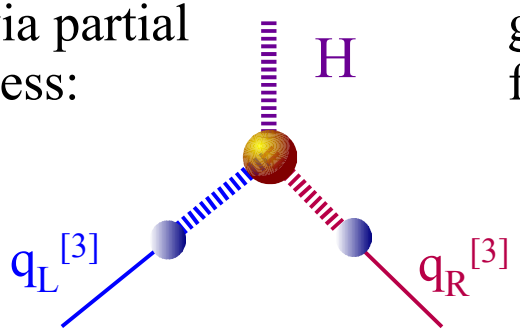
Minimal Composite Higgs:

$$\mathrm{Sp}(4) \xrightarrow{\;H \sim (2,2)\;} \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R^{[3]}$$

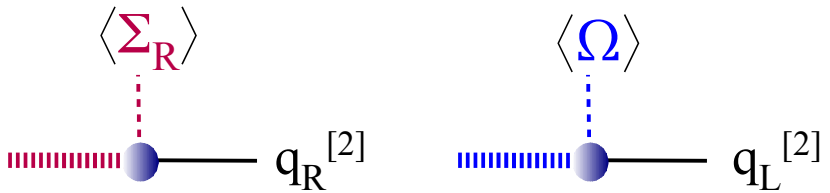
Flavor Deconstruction of Hypercharge:

$$\mathrm{SU}(2)_R^{[3]} \times \mathrm{U}(1)_{B\text{-}L}^{[3]} \times \mathrm{U}(1)_Y^{[12]} \xrightarrow{\;\langle\Sigma_R\rangle,\ \langle\Omega\rangle\;} \mathrm{U}(1)_Y$$

3^{rd} family Yukawa couplings via partial compositeness:



Light Yukawas suppressed → higher-dim ops. generated by heavy (elementary) dynamics (e.g. VL fermions) above the compositeness scale:



[IV] *Flavor deconstruction & partial compositeness*

An interesting feature emerges when computing explicitly the radiatively-induced Higgs potential:

$$V(h) = \Delta V_f(h) + \Delta V_A(h) \approx c_0 - c_1 \sin^2\left(\frac{h}{2F}\right) + c_2 \sin^4\left(\frac{h}{2F}\right)$$

$$\left.\frac{c_1}{F^4}\right|_{\text{phys.}} = \frac{m_h^2}{F^2} \lesssim 0.06$$

Unavoidable ~ 1% tuning
[given current bounds on F ($\gtrsim 0.7$ TeV)]

$$\left.\frac{c_2}{F^4}\right|_{\text{phys.}} = \frac{2m_h^2}{v^2} \approx \frac{1}{2}$$

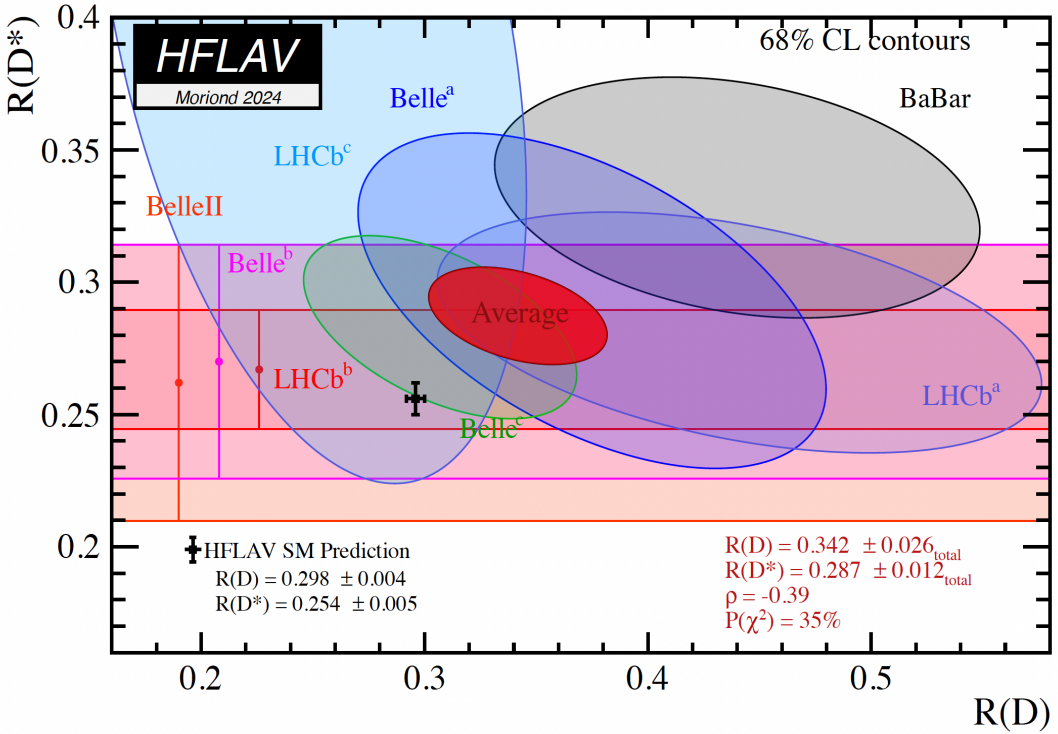
requires light top partners
(*as in ordinary CH*)

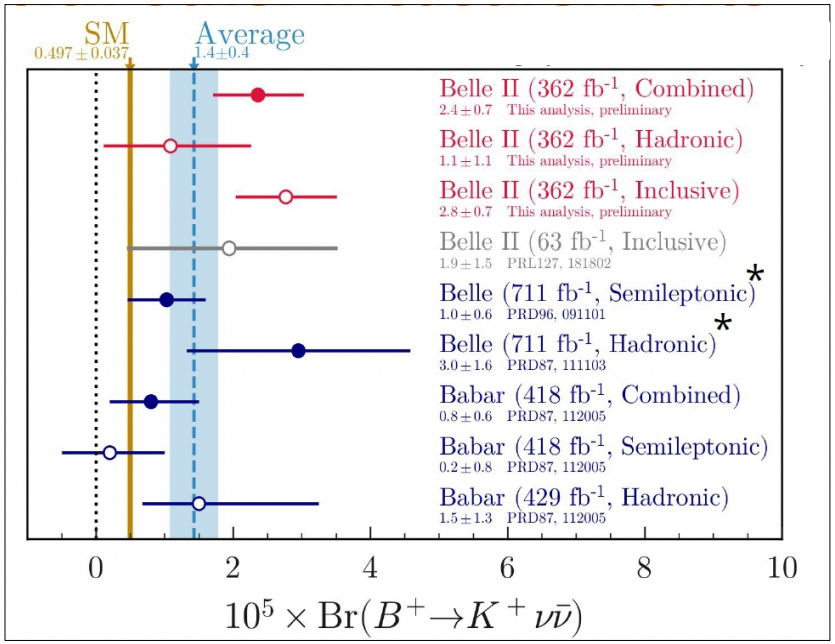
- O(1) model-independent fermion contribution (controlled by y_t)
- Possible cancellation from the gauge sector (unambiguous *opposite sign*) if

$$g_R^{[3]} \gtrsim 1 \;\; \& \;\; g_R \langle \Sigma_R \rangle < M_\rho$$

The cancellation occurs in the "natural" parameter space dictated by the flavor-deconstruction hypothesis

A brief look to current data & future prospects





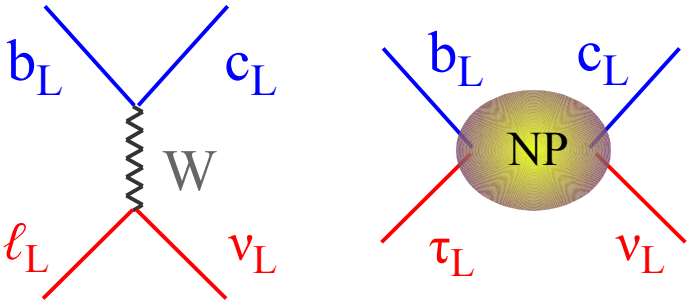
A brief look to current data & future prospects

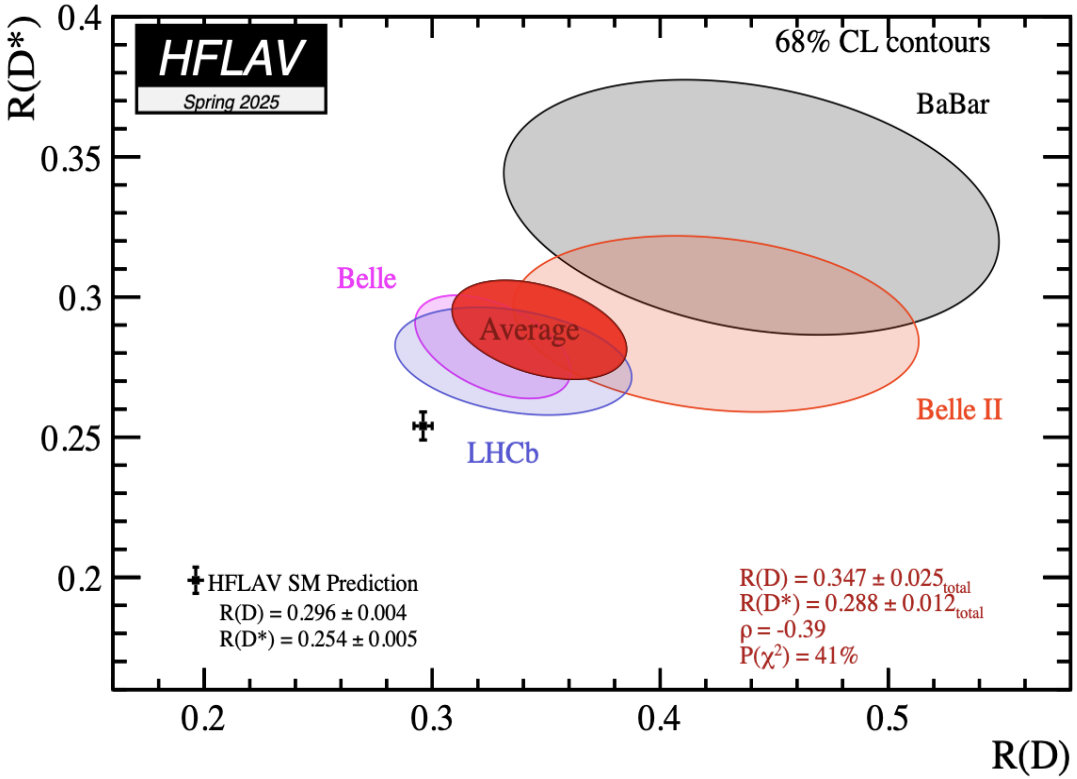
The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements (*with different degree of model-dependence*)

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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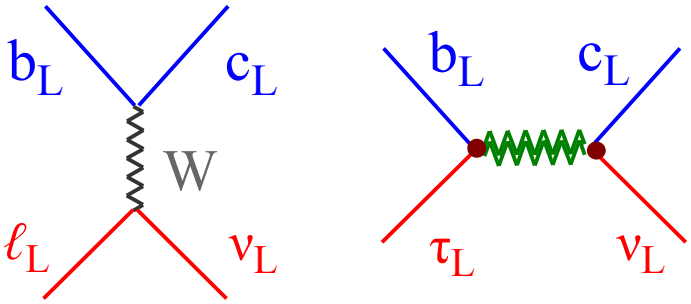

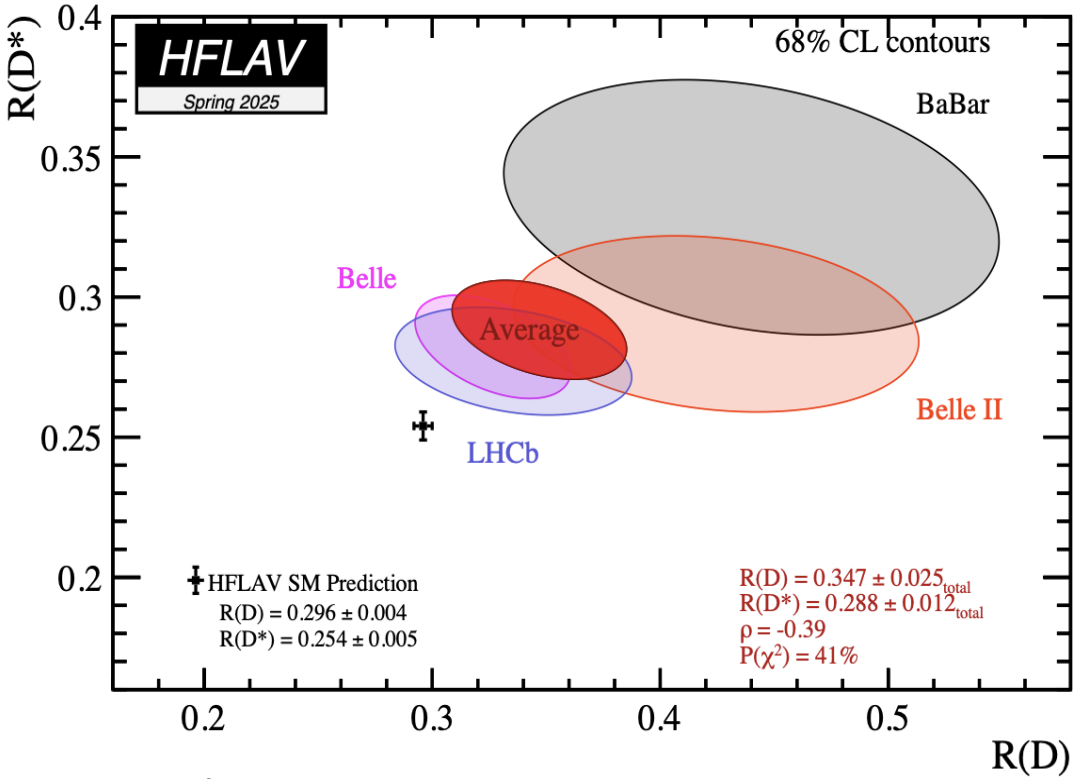

→ *The vector LQ of 3rd gen. quark-lepton unification is an ideal candidate to describe current data*

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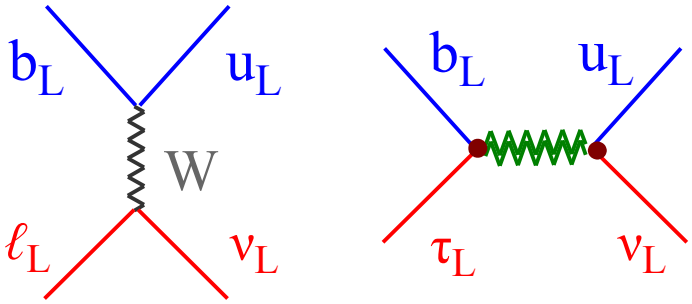
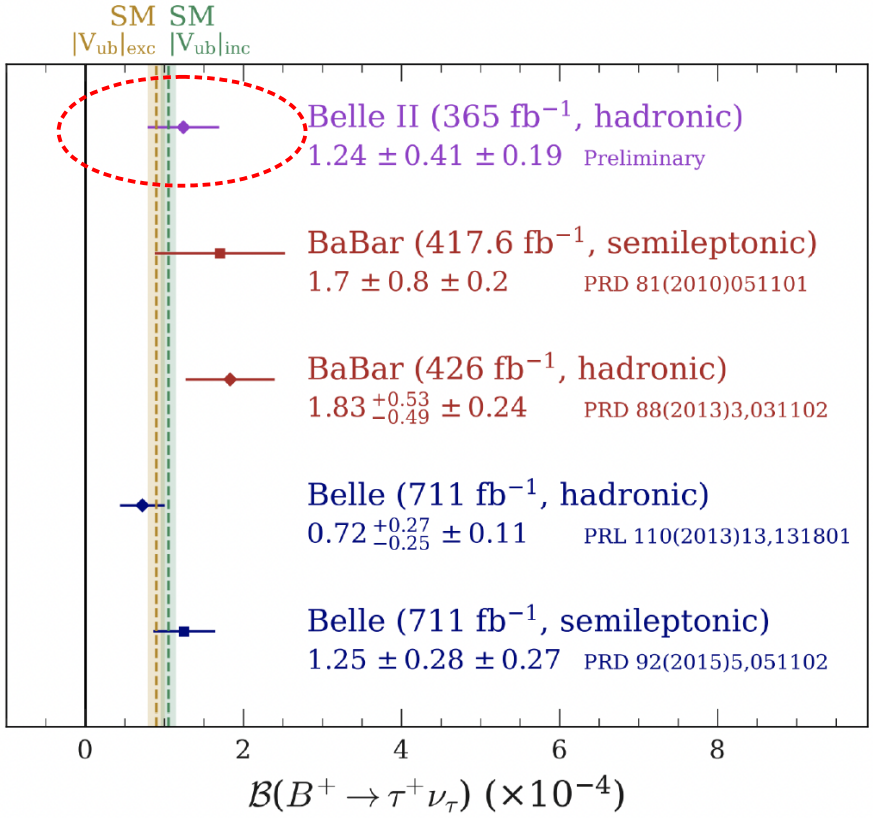
E.g.: I) Lepton universality violations in $b\to c\tau\nu$... & $b\to u\tau\nu$ decays

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

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





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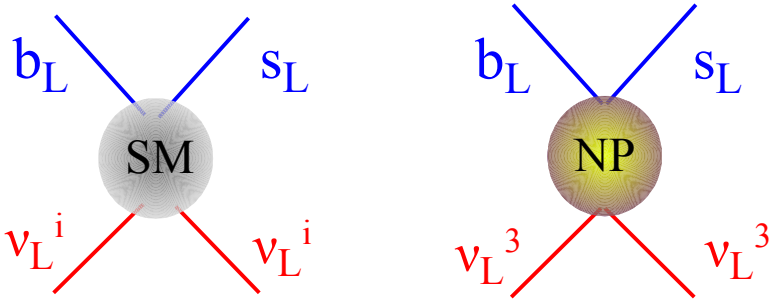
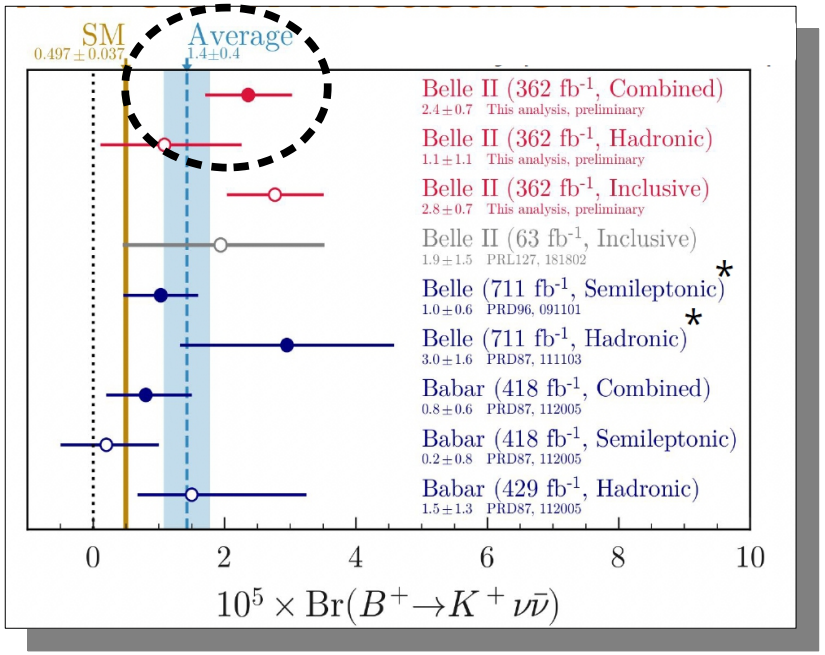
E.g.: II) Deviations from SM in $b\to s\nu\nu$ rates [3rd gen. ν in the final state]



identical for all neutrino species

relevant only for 3rd gen. neutrinos

Belle-II '2023



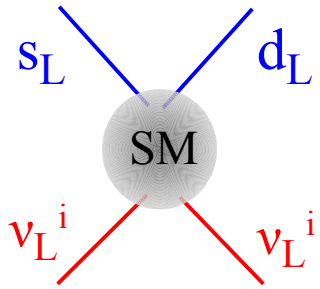
Unambiguous prediction of O(50%) enhancement of $B(B\to K\nu\nu)$ in the model with vector LQ – given excess in R(D).

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

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



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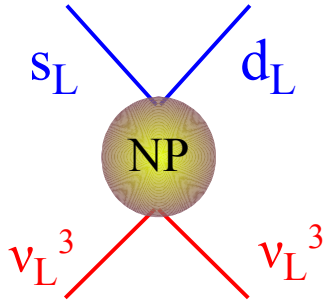
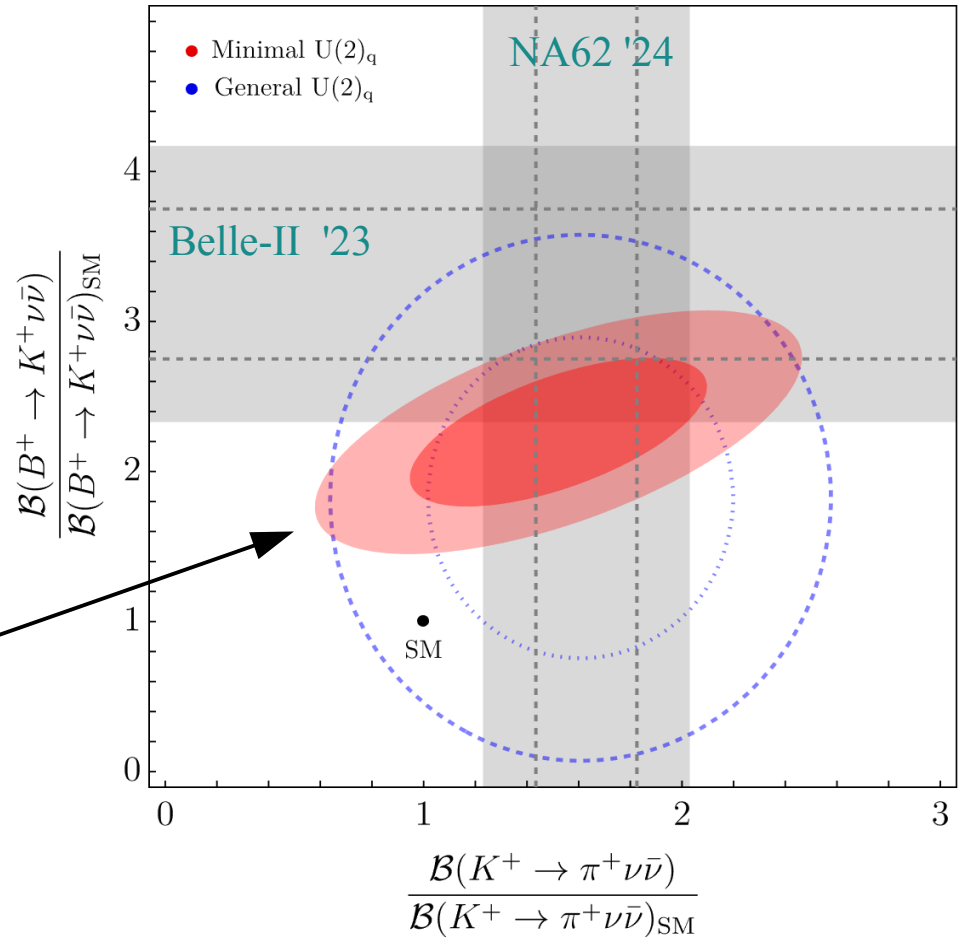


relevant only for 3rd gen. neutrinos

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

Bordone *et al.* '24



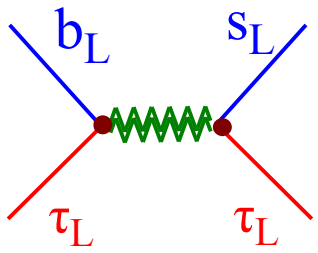
A brief look to current data & future prospects

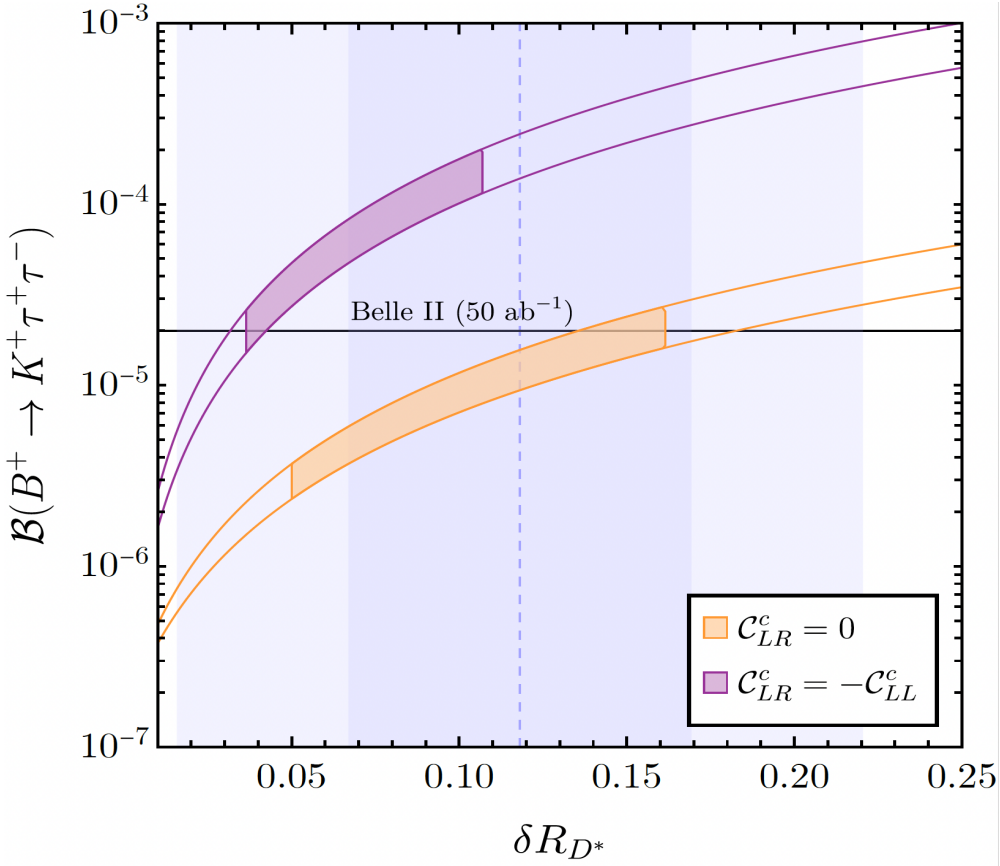
The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements (*with different degree of model-dependence*)

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

$b\to s\tau\tau$ are affected by the LQ already at the tree-level (contrary $b\to s\nu\nu$)

- huge effect compared to SM in $b\to s\tau\tau$ (consistent with data)





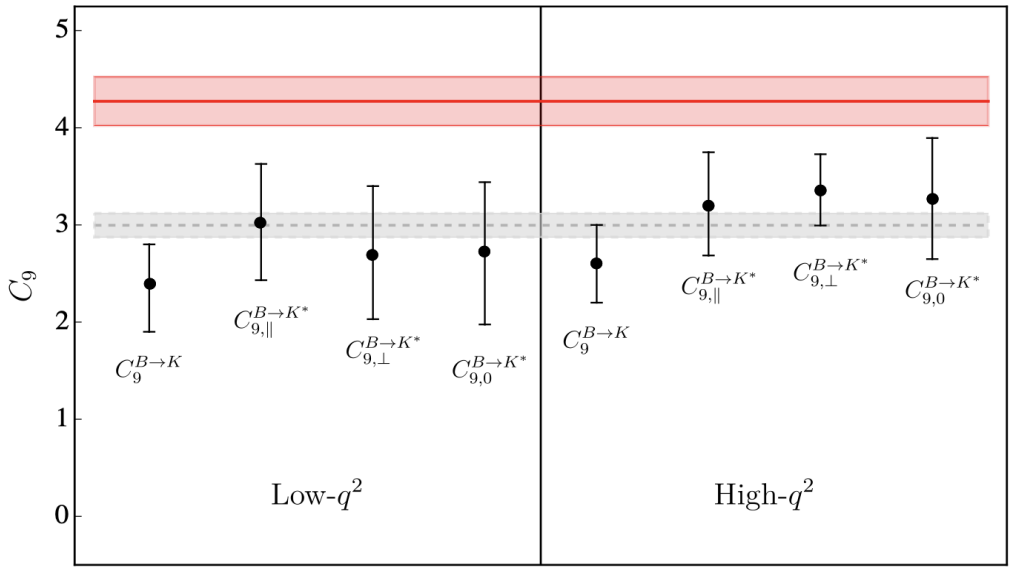
A brief look to current data & future prospects

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*)

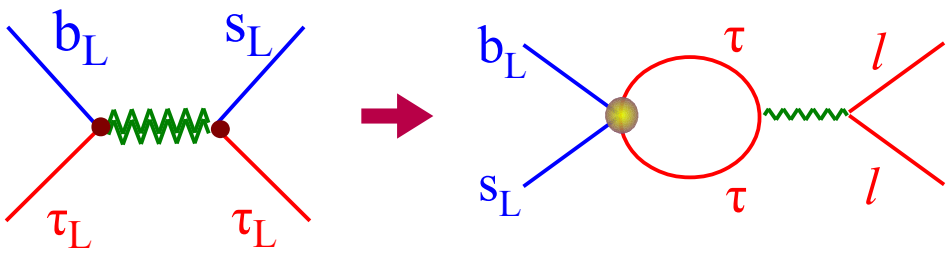
E.g.: III) Potential large enhancement of $b\to s\tau\tau$ rates

$b\to s\tau\tau$ are affected by the LQ already at the tree-level (contrary $b\to s\nu\nu$)

- huge effect compared to SM in $b\to s\tau\tau$ (consistent with data)
- O(10%) effect in $b\to sll$ @ 1-loop could explain persisting tension(s) in $B\to K^{(*)}\mu\mu$ & $B_s\to\phi\mu\mu$



Bordone, GI, Macler, Tinari'24
GI, Tinari, Polonski, '24-'25

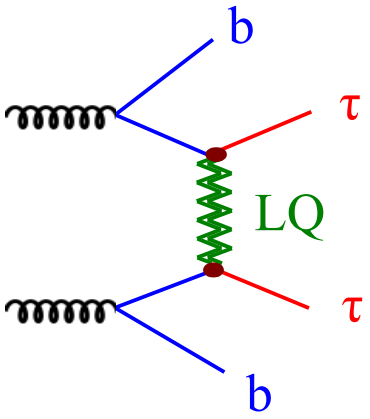


Unambiguous prediction of magnitude & sign consistent with excess in R(D)

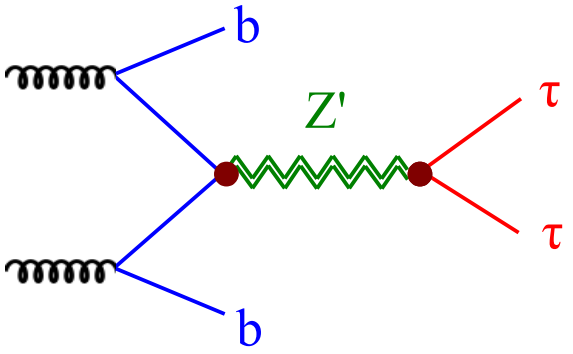
A brief look to current data & future prospects

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 & high-enegery measurements

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



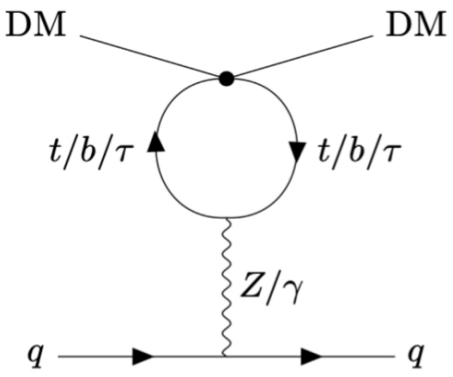
and / or

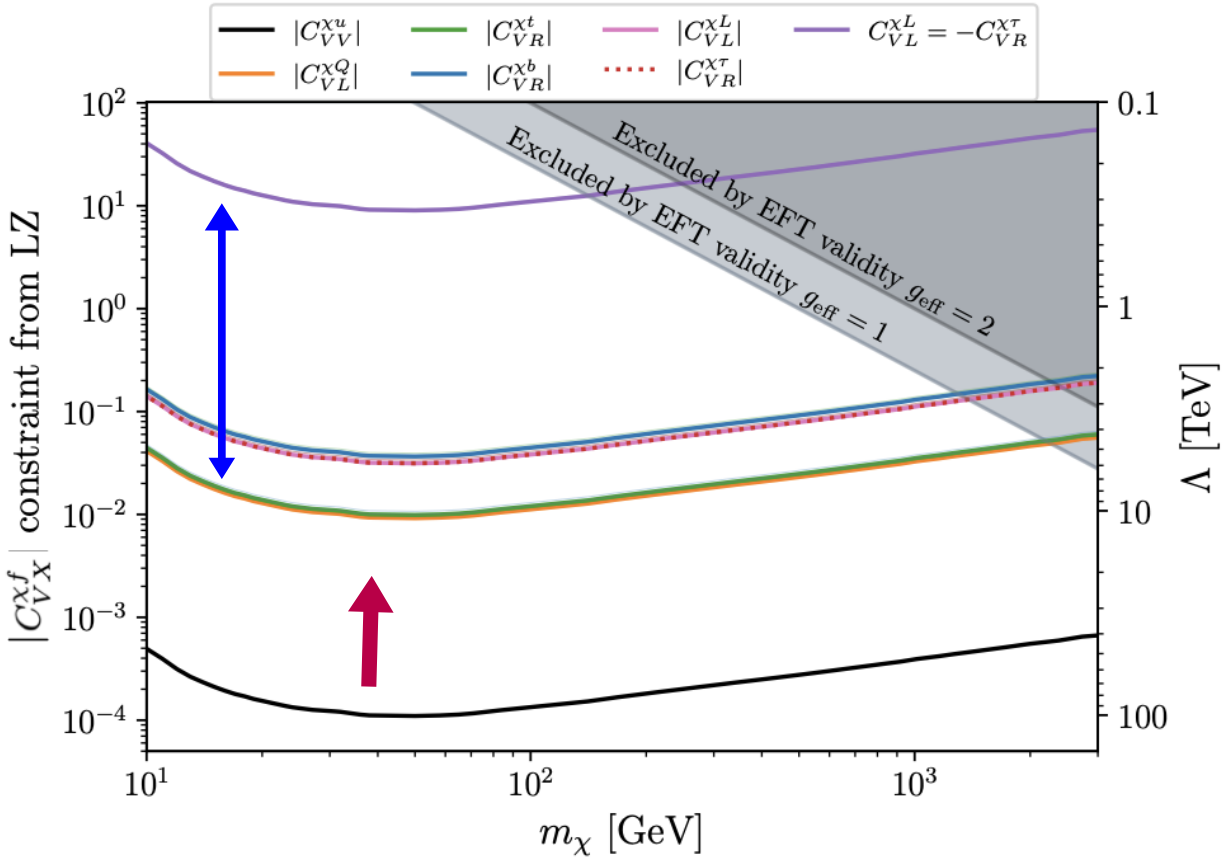


A brief look to current data & future prospects

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 & high-enegery measurements, but could even have implications for DM searches

DM coupled mainly to 3rd gen. leads to weaker bounds from direct searches [1-loop suppression] → TeV-scale WIMP-type back in business





Demetriou, GI, Piazza, Pinsard '25

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: general paradigm to consistently interpret the structure of the SMEFT, in connection with present data.

- Still a lot of work to be done on the model-building side to construct realistic models addressing both the origin of the flavor and the EW hierarchy problem...

- 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 (Belle-II, NA62, LHCb) & at high energies (LHC run-3)