Flavor Physics: open problems & recent developments

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- Introduction
- The flavor structure of the SM-EFT
- Flavor non-universality & flavor deconstruction
- A brief look to current data & future prospects
- Conclusions

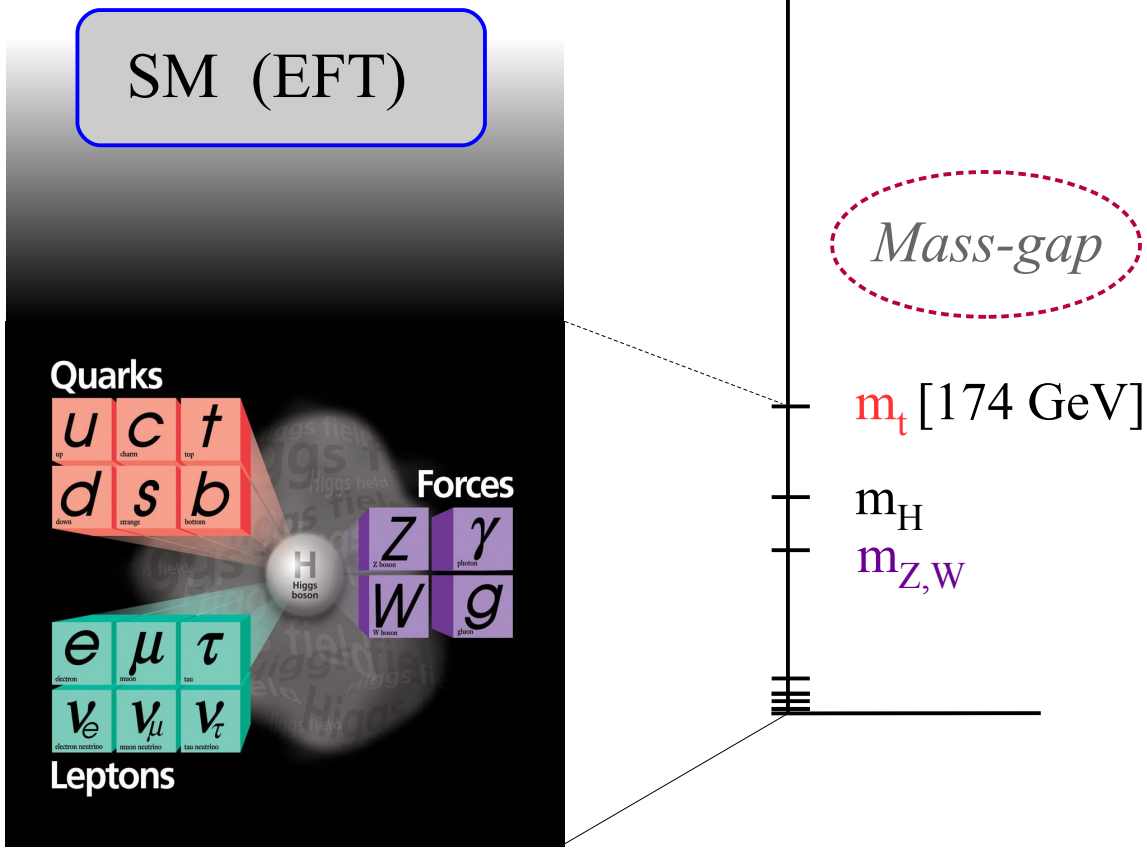
University of Zurich[UZH]

Introduction

Despite all its successes, it is natural to consider the SM as an Effective Field Theory (*as most QFTs in 4D flat space.*), i.e. the low energy limit of a more complete theory, with more degrees of freedom in the UV.

- We identified the *long-range* structure of this EFT...
- … but its UV cut-off is still unknown

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



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

non-trivial properties of the SM-EFT Lagrangian

Dark-matter

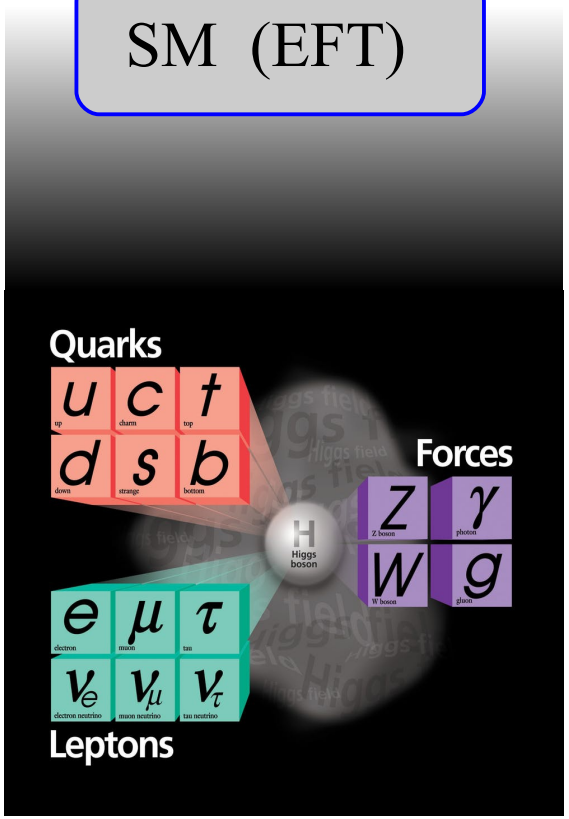
Dark-energy

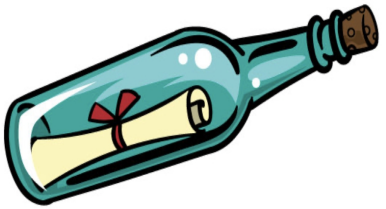
Inflation

Quantum gravity

UV Theory

SM (EFT)





Messages from the UV we need to decode...

The flavor structure of the SM-EFT

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

Large flavor symmetry

Three identical replica of the basic fermion family
$[\psi = Q_L, u_R, d_R, L_L, e_R]$

$\downarrow$

$U(3)^5$ symmetry

E.g.: $Q_L^i \to U^{ij} Q_L^j$

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$U(3)^5$ flavor symmetry

Flavor-degeneracy broken by the Yukawa interaction

Breaking structure which is

- confined to LR terms (by EW symm + d=4)
- *Highly non-generic*

Eg.:

$$Y_U \sim \begin{pmatrix} \sim 10^{-5} & \sim 10^{-4} & 0.003 \\ & 0.005 & 0.04 \\ & & \boxed{1} \end{pmatrix}$$

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

Y_U in the basis where Y_D is diagonal

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"Peculiar" breaking structure: approximate $U(2)^5$ symmetry acting on the light families

Eg.:

$$Y_U \sim \begin{pmatrix} \multicolumn{2}{c}{\overbrace{}^{U(2)_u}} & \\ < 0.01 & & \\ & 0.04 & \\ & & 1 \end{pmatrix} \Big\} U(2)_q$$

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"Peculiar" breaking structure: approximate $U(2)^5$ symmetry acting on the light families

- Neglecting $|Y_{ij}(v)| < 0.1 \quad \rightarrow \quad U(2)_q \times U(2)_u \times U(3)_d \times U(3)_l \times U(3)_e$
- Neglecting $|Y_{ij}(v)| < 0.01 \quad \rightarrow \quad U(2)^5$ [+ a single $U(2)_q$ breaking term $\leftrightarrow |V_{cb}|$]

The flavor structure of the SM-EFT

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A priori, many violations of the *exact & approximate* accidental symmetries of the SM Lagrangian can arise from the higher-dim. ops (contact terms)

Most of the SM-EFT couplings are there to describe how to break such symmetries...

- No flavor symmetry → 2499 free couplings in the SMEFT @ d=6

Jenkins, Manohar, Trott '14

- Exact $U(3)^5$ → 47
- Exact $U(2)^5$ → 120

Faroughi, GI, Wilsh, Yamamoto, '20

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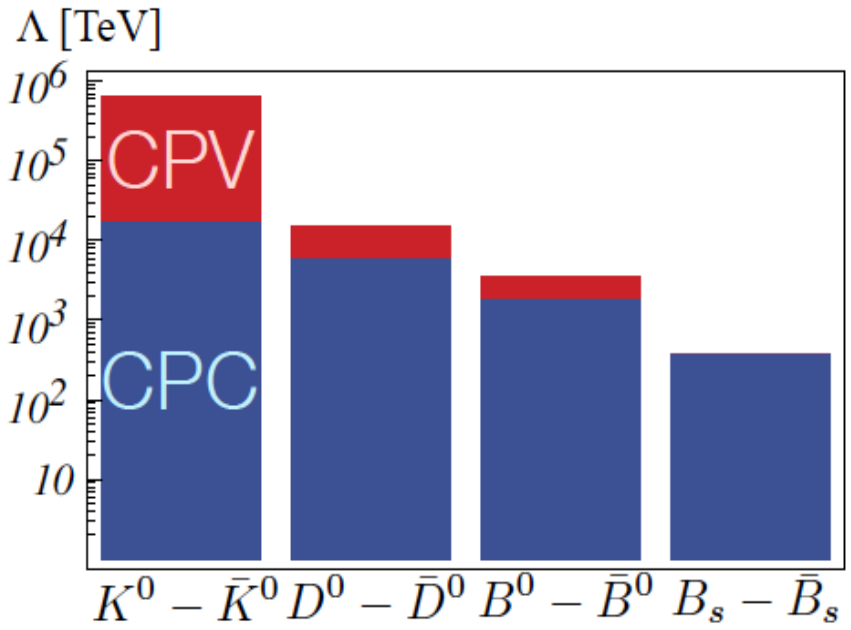
The absence of deviations from the SM predictions are usually translated into stringent bounds on the effective scale of the contact terms.

Eg.:



But these apparently high scales can be a "mirage"...

Only unambiguous message:

No large breaking of the approximate ~U(2)^n flavor symm. at near-by energy scales.

[signal of UV dynamics?]

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

Yukawa couplings: $U(3)^5 \rightarrow \sim U(2)^n$ *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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No "QFT solution" to EW hierarchy problem

- "High-scale flavor dynamics" & MFV: the scale of NP is low, but $U(3)^5$ is broken @ high scales

"decoupling" of flavor & EW problems

- "Flavor deconstruction"

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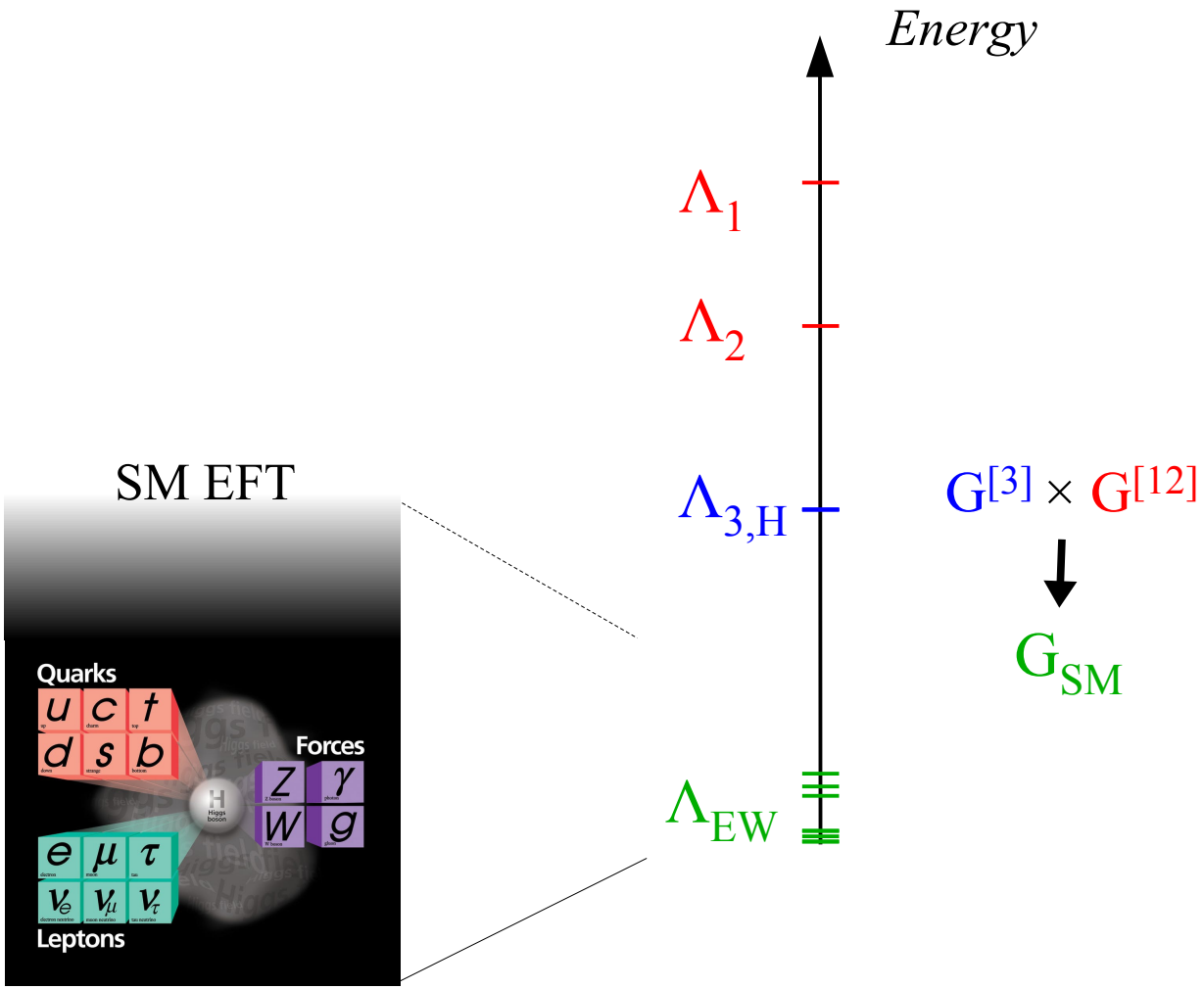
- "High-scale flavor dynamics" & MFV: the scale of NP is low, but $U(3)^5$ is broken @ high scales

  "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

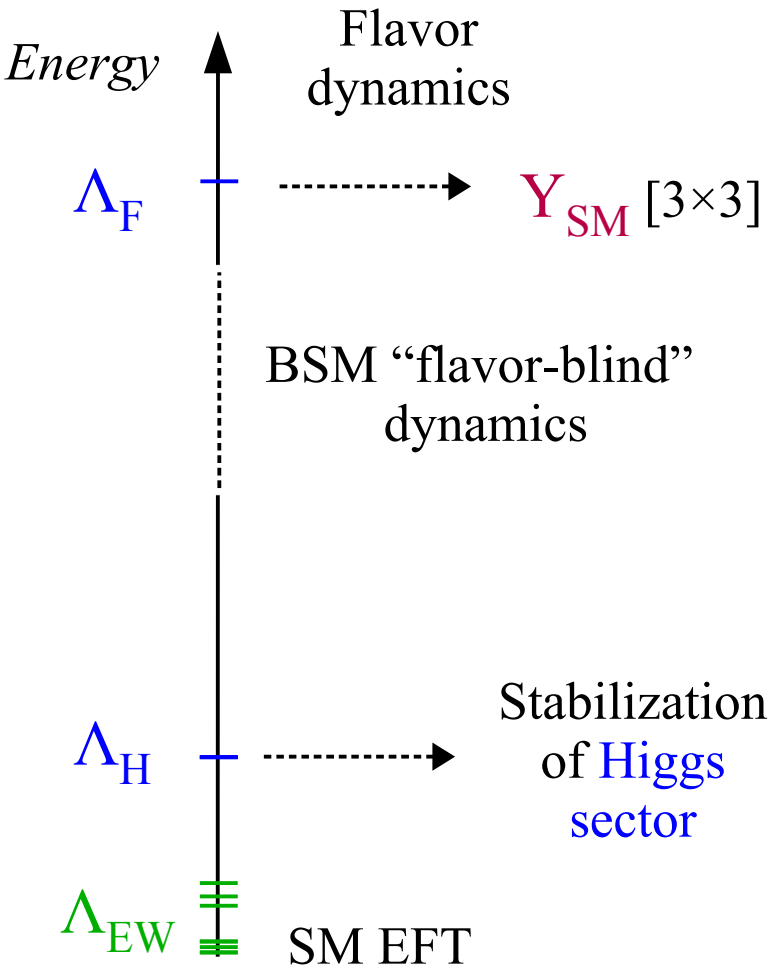
  "interplay" of flavor & EW problems

Flavor non-universality & flavor deconstruction



General considerations about flavor (non) universality

Since the Yukawa couplings are marginal operators, we can assume they originate from high-scale dynamics (→ *"horizontal" flavor symmetries ?*)



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

↕

The "MFV paradigm"

3 families = "identical copies" up to high energies

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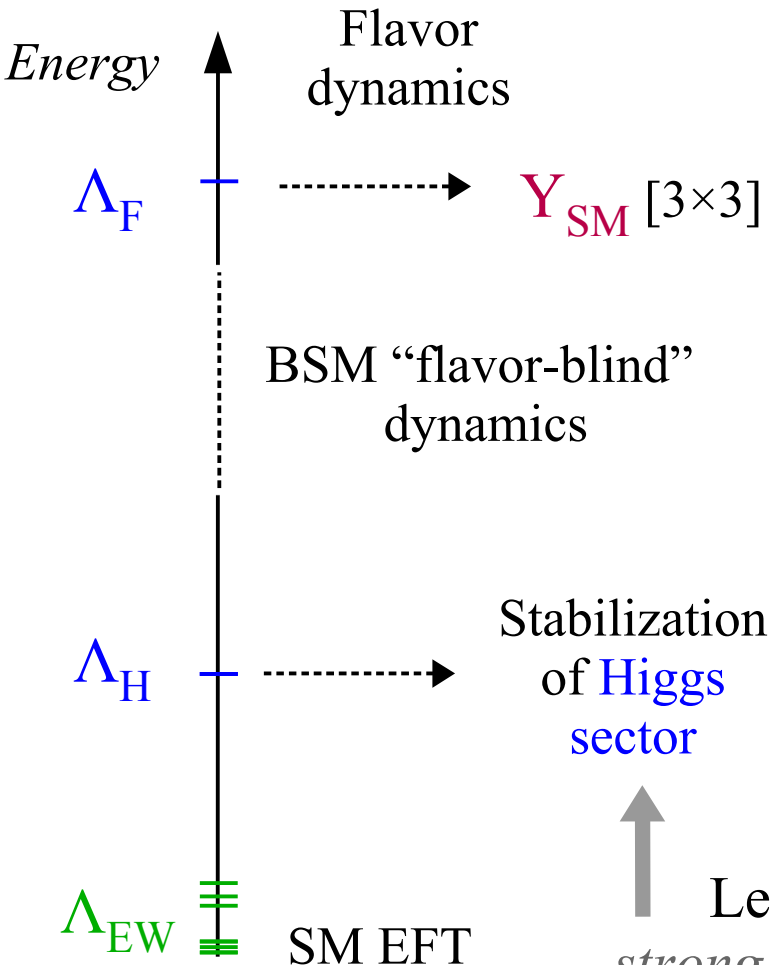

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The "MFV paradigm"

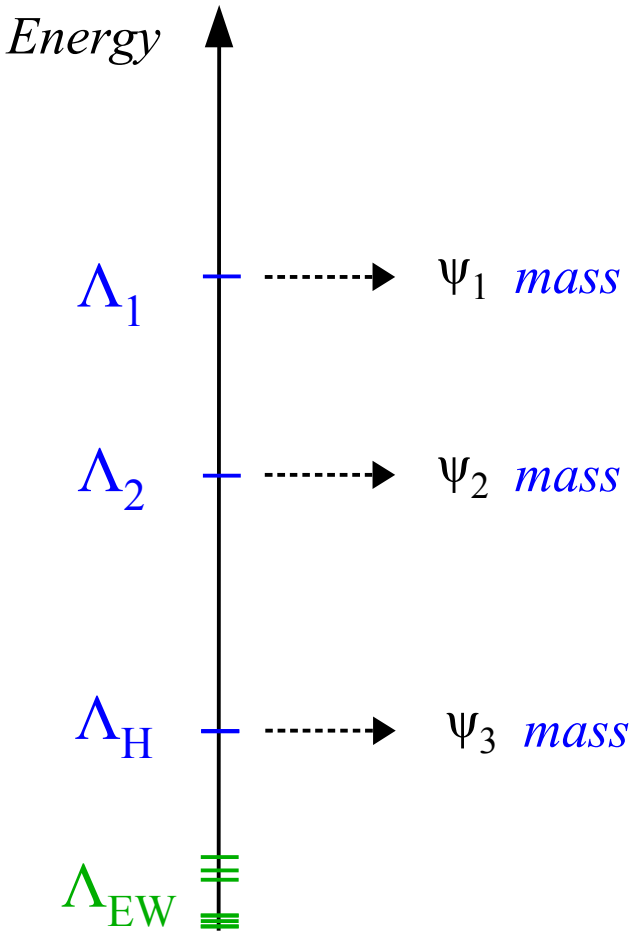
3 families = "identical copies" up to high energies

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

General considerations about flavor (non) universality

A more efficient paradigm to address the flavor puzzles and, possibly, the Higgs hierarchy probem, 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
⋮



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~~

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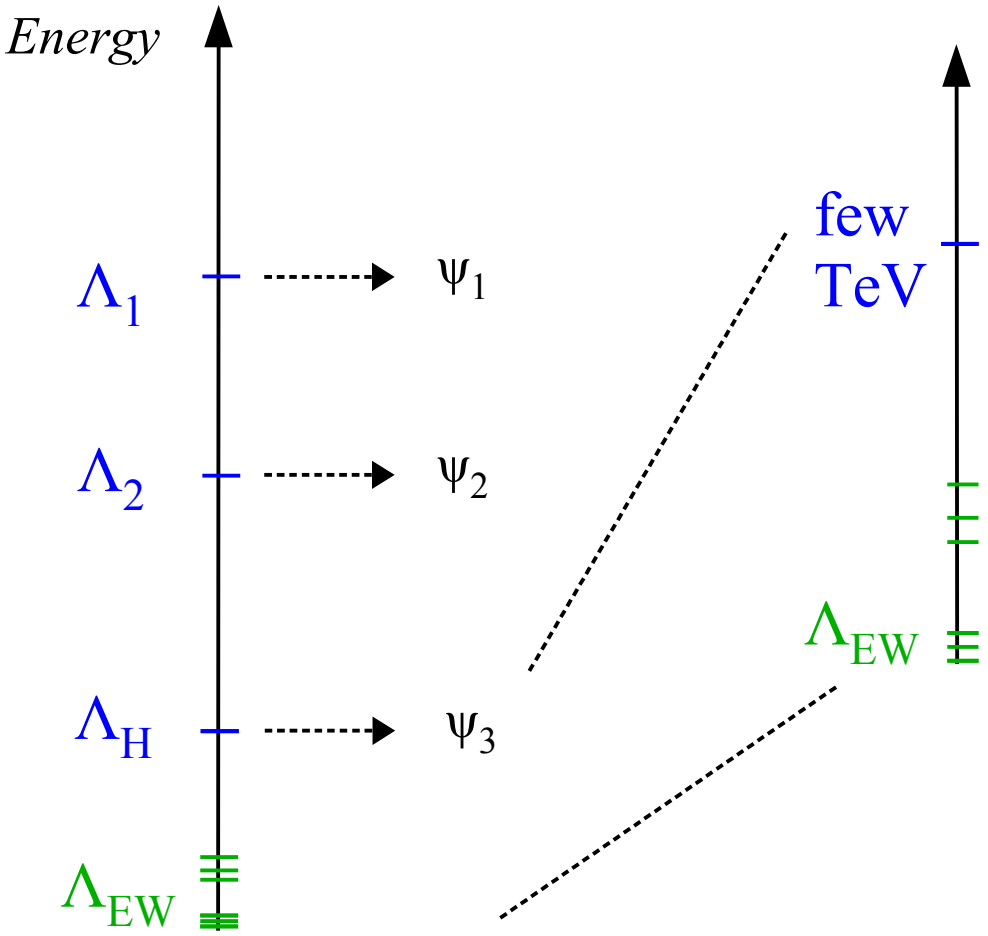
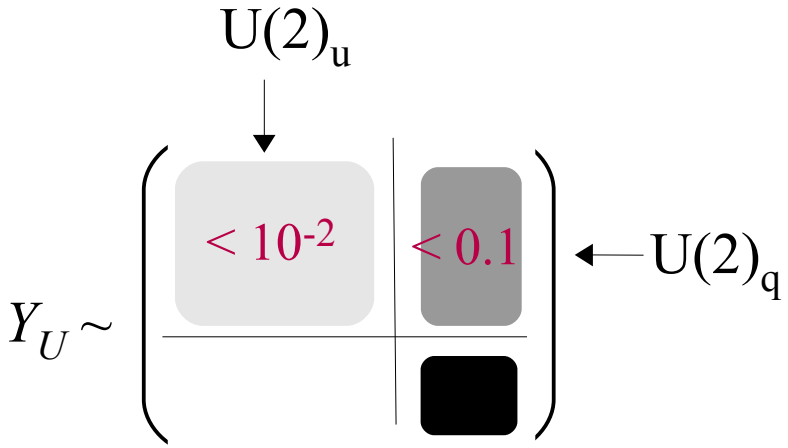


NP coupled mainly to ψ_3

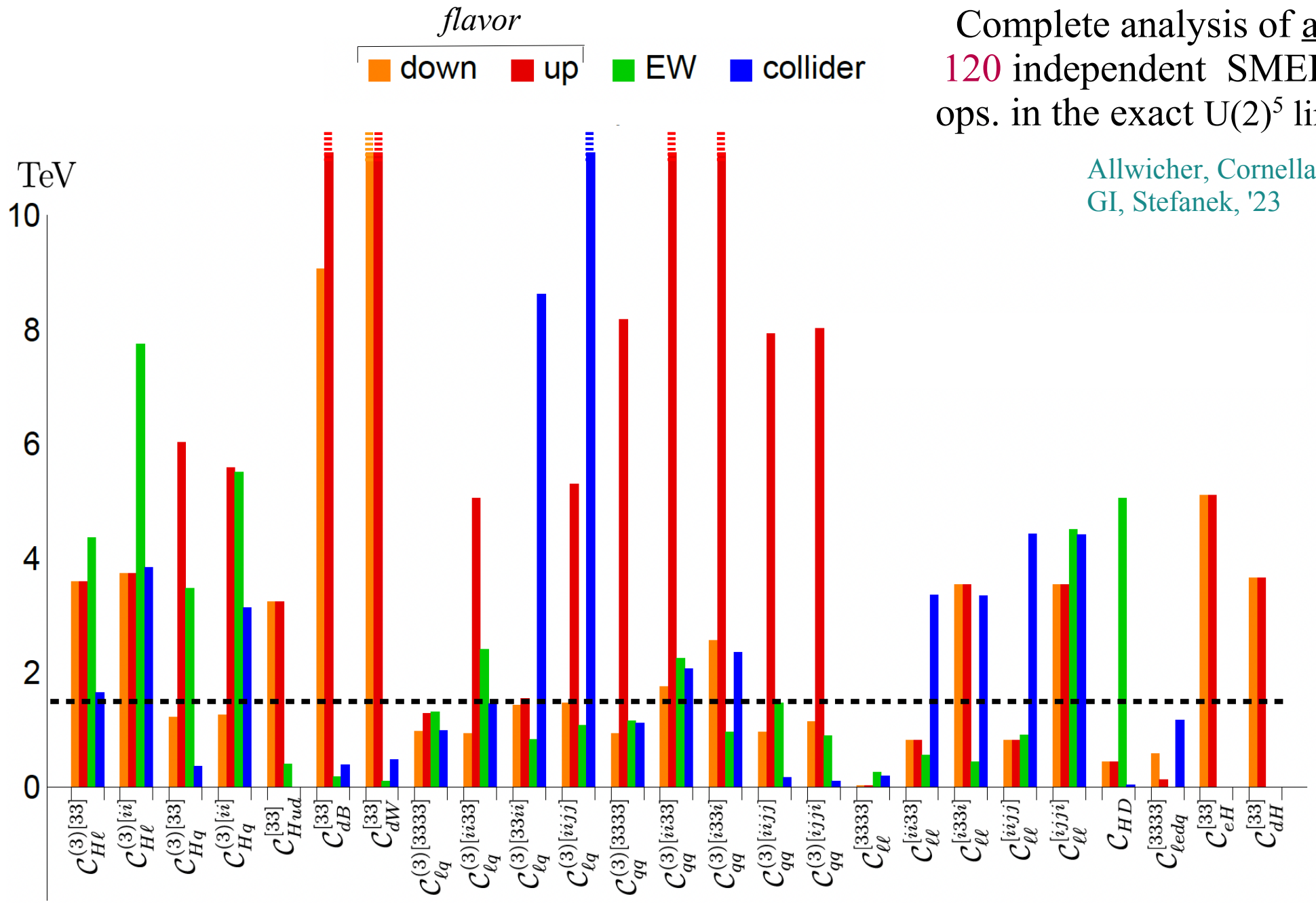
$\psi_{1,2}$ ~ massless [$U(2)^n$ symm.]

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



Effective organizing principle for the flavor structure of the SMEFT

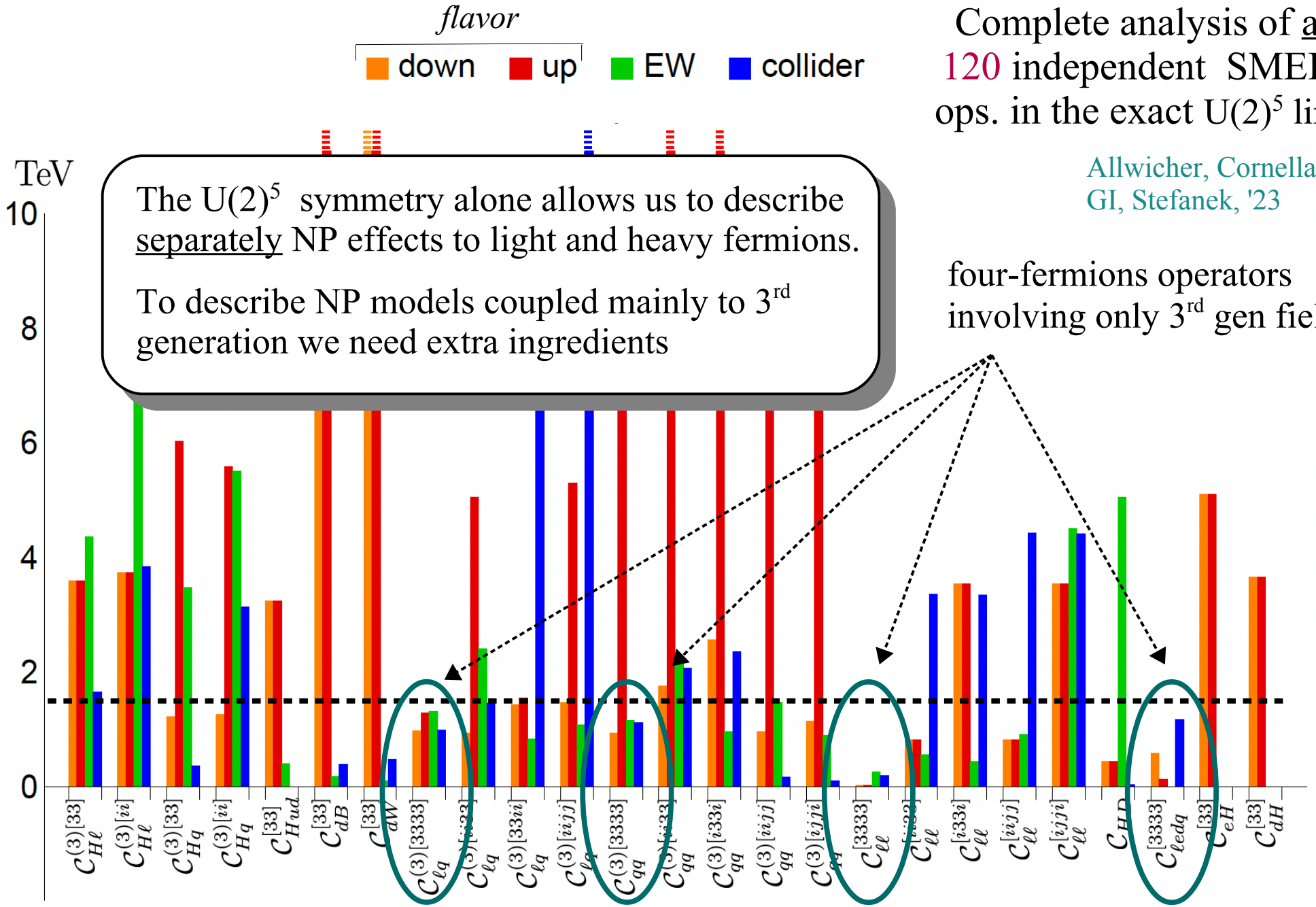
General considerations about flavor (non) universality



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

Allwicher, Cornella, GI, Stefanek, '23

General considerations about flavor (non) universality



General considerations about flavor (non) universality

flavor EW collider

naive scaling underlying multi-scale EFT hypothesis:

TeV

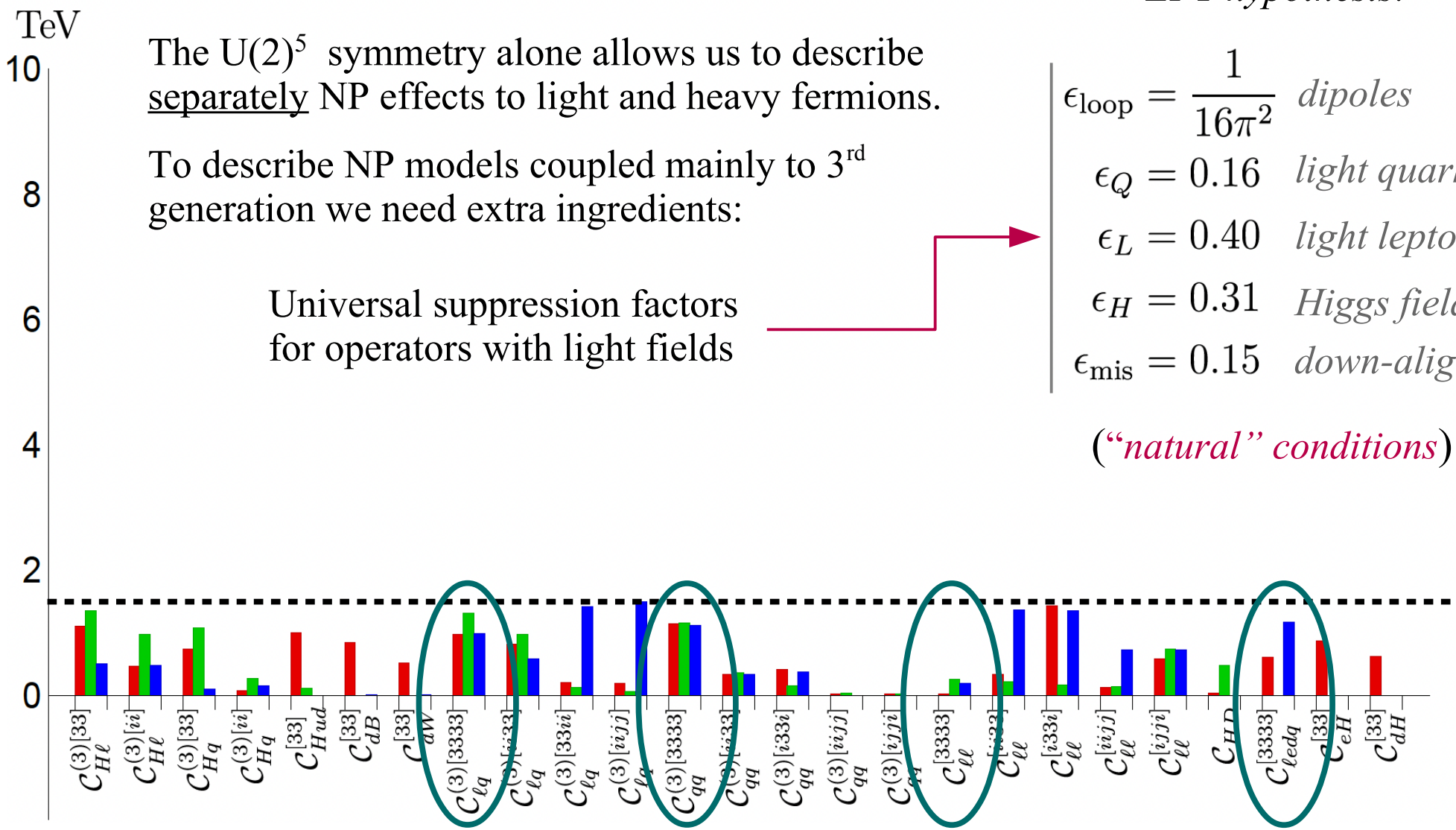
The $U(2)^5$ symmetry alone allows us to describe separately NP effects to light and heavy fermions.

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

Universal suppression factors for operators with light fields

$$\epsilon_{\rm loop} = \frac{1}{16\pi^2} \quad \textit{dipoles}$$
$$\epsilon_Q = 0.16 \quad \textit{light quarks}$$
$$\epsilon_L = 0.40 \quad \textit{light leptons}$$
$$\epsilon_H = 0.31 \quad \textit{Higgs fields}$$
$$\epsilon_{\rm mis} = 0.15 \quad \textit{down-align.}$$

(*"natural" conditions*)



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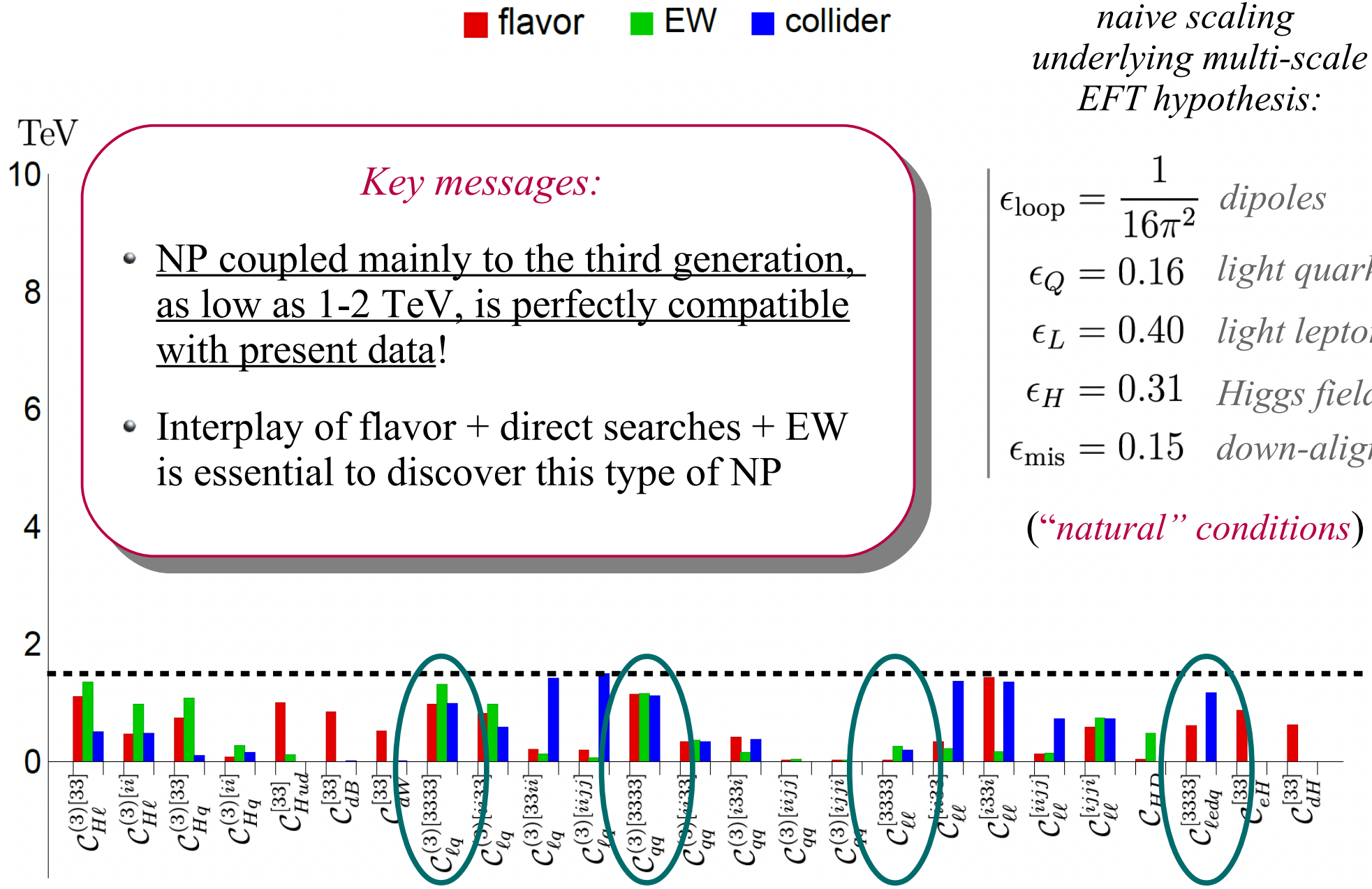

Key messages:

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

- Basic idea:

Arkani-Hamed, Cohen, Georgi '01
Craig, Green, Katz, '11
...

$$G^{[1]} \times G^{[2]} \rightarrow G^{[12]}$$

flavor non-univ. groups acting on single families

flavor univ. group acting on both families

General model-building features:

- The symmetry breaking pattern is very general: any scalar rep. (provided $R_{[1]}, R_{[2]} \neq 1$) breaks to the diagonal subgroup → flavor universality emerges "naturally" at low energies

Michel & Radicati '68
Craig, Garcia-Garcia, Sutherland '17

- Flavor hierarchies obtained without the need of peculiar choices for the "flavor charges" [e.g. U(1) charges as in Froggatt & Nielsen]

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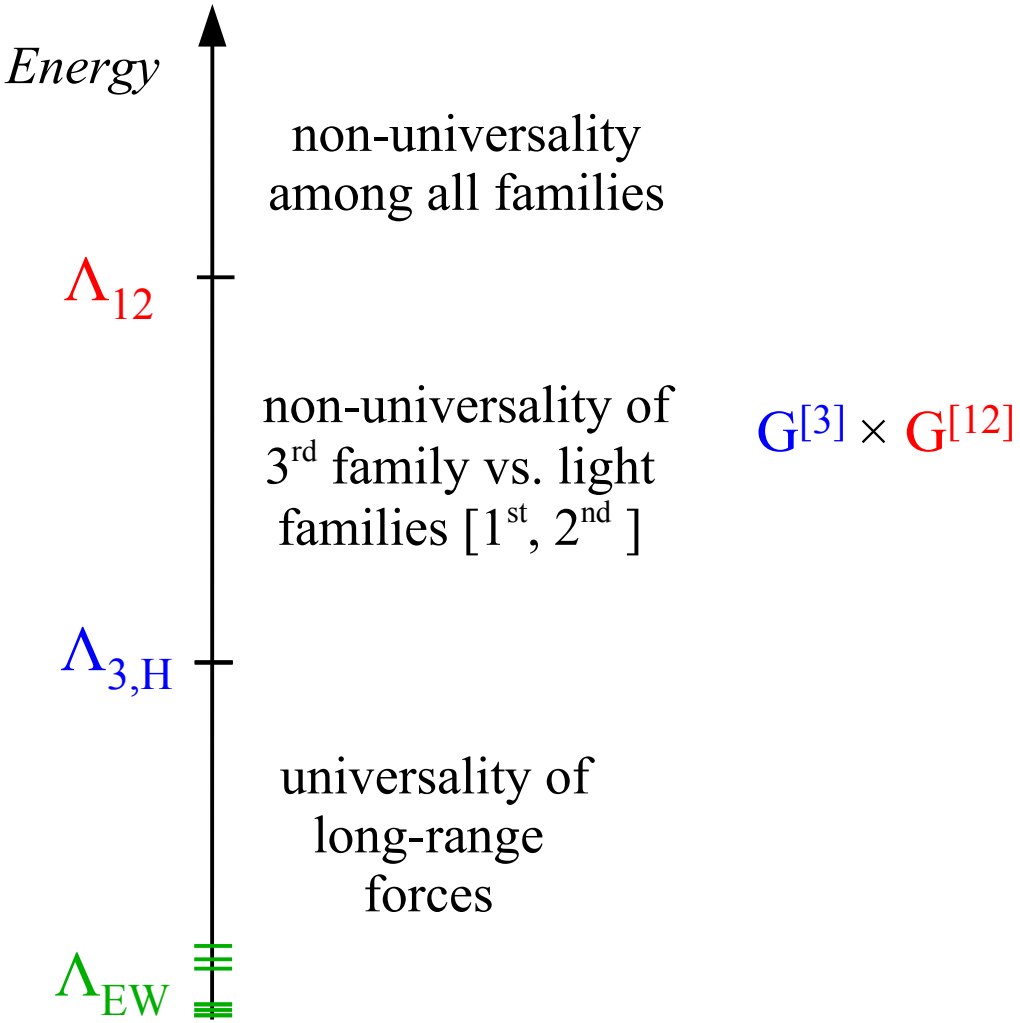
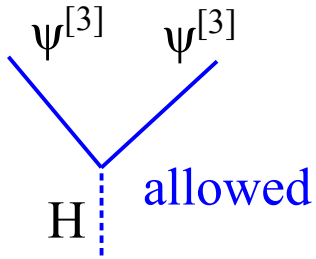
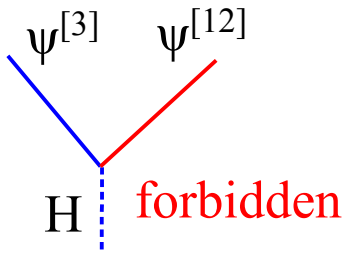
Davighi & GI '23, Davighi & Stefanek '23
Navarro & King '22 & '23
Barbieri & GI '24

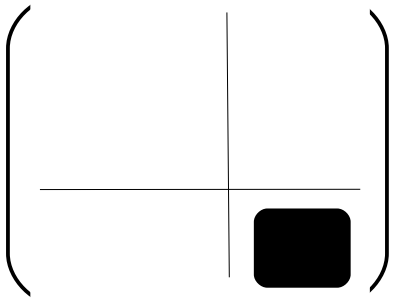


$G^{[3]} \times G^{[12]}$





$Y_U \sim$



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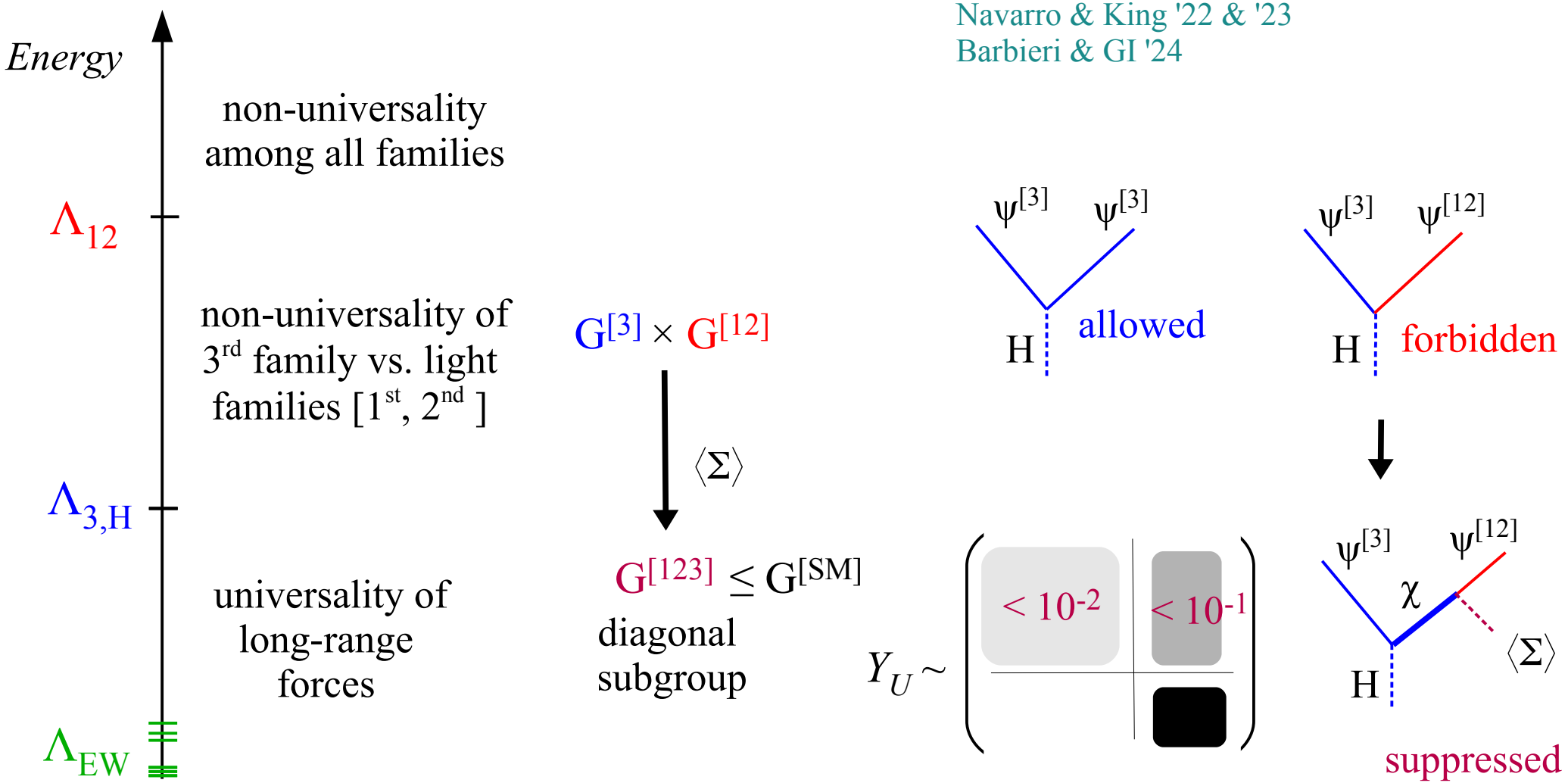

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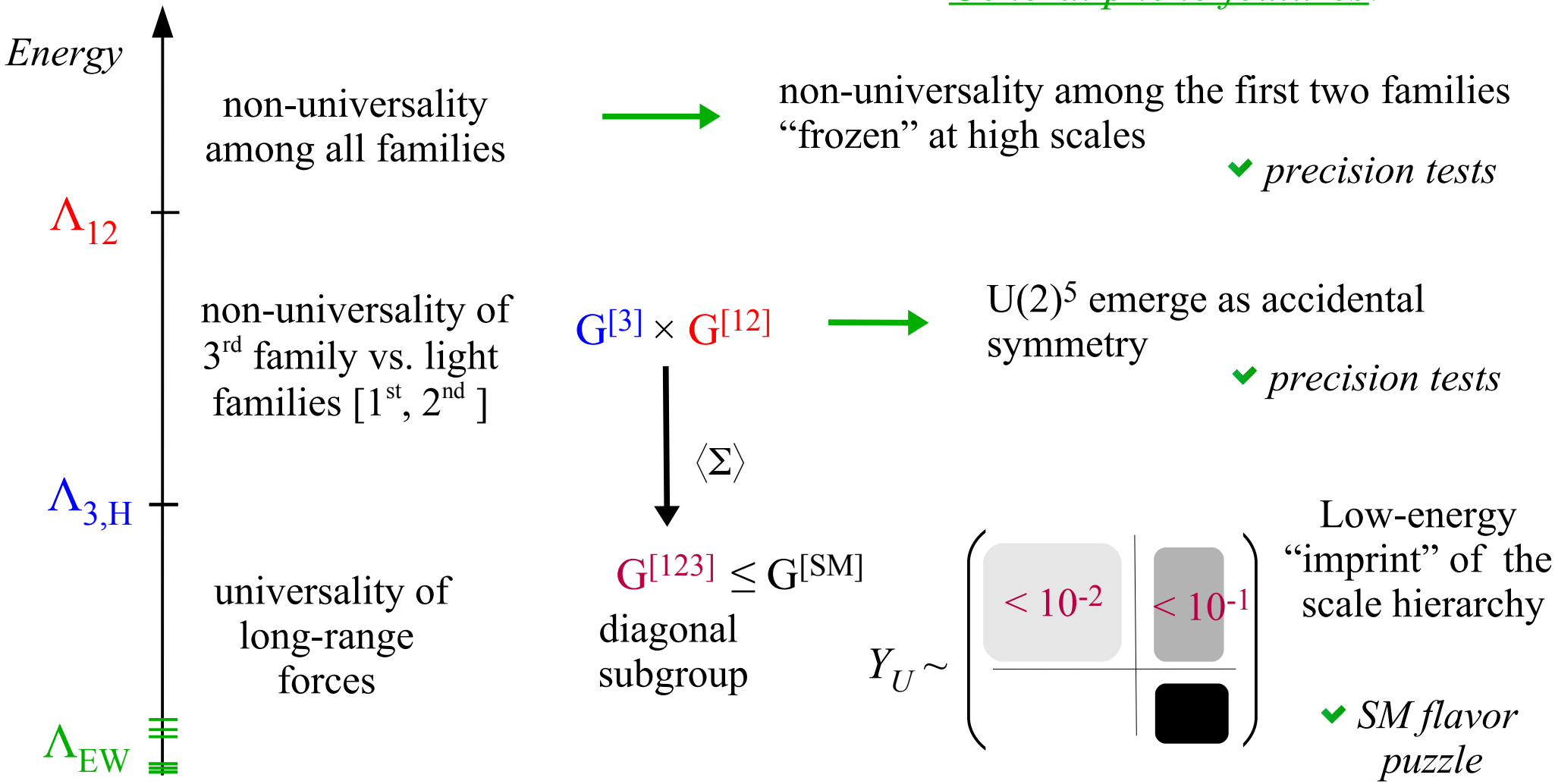
General pheno features:



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

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

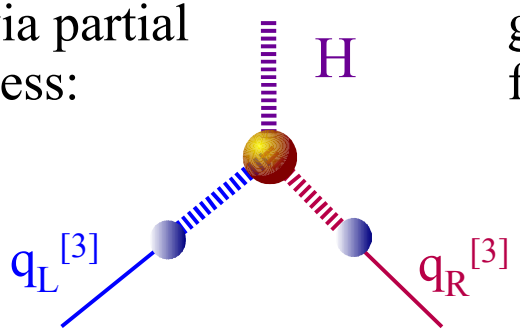
Minimal Composite Higgs:

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

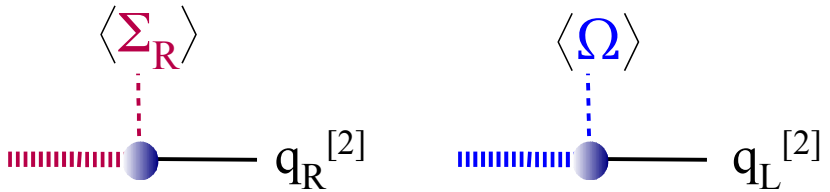
Flavor Deconstruction of Hypercharge:

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

3rd 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:



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 (*unambiguos 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

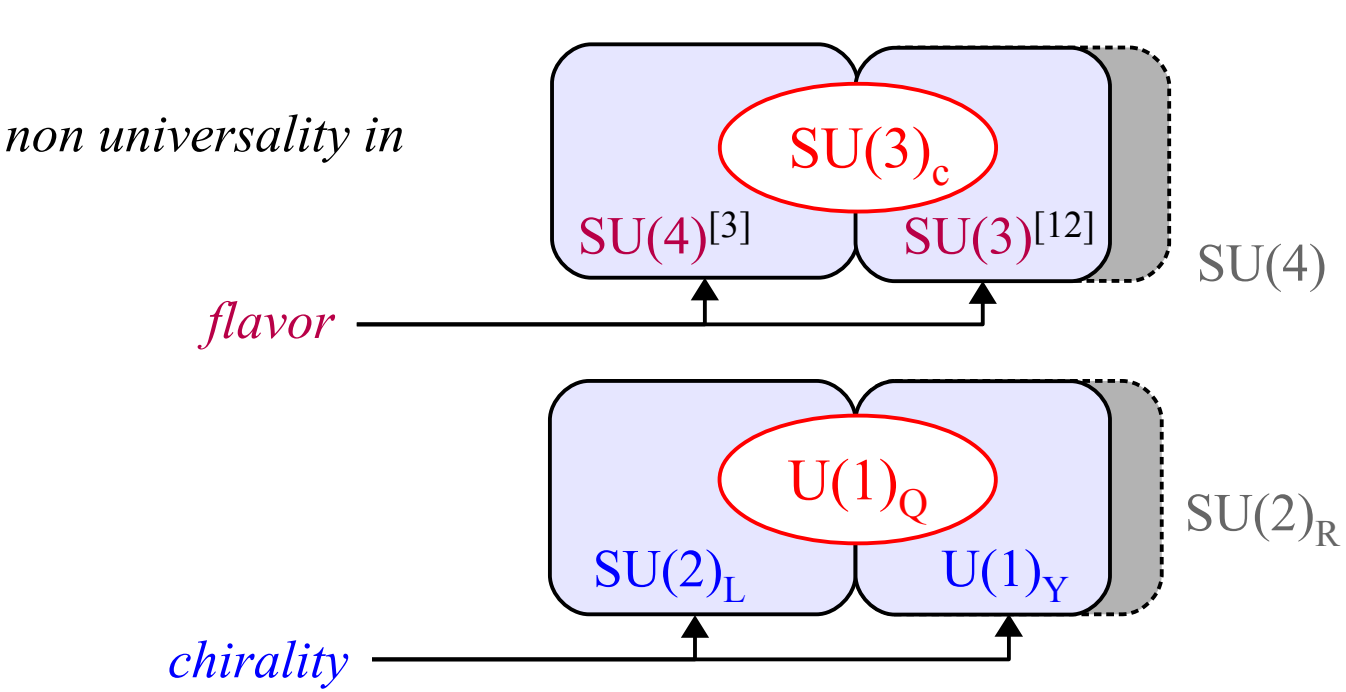
→ talk by M Pesut on Thu.

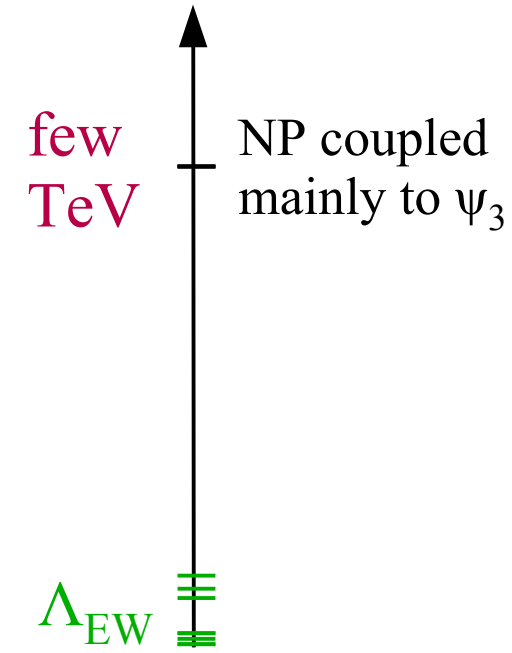
Flavor deconstruction & *quark-lepton unification*

All deconstructed versions of the SM gauge group compatible with
I) semi-simple embedding in the UV + 1I) 3rd family non-univ. @ TeV scale
have been classified → general expectation: quark-lepton unification a la Pati-Salam for the 3rd gen:

Bordone *et al.* '17
Greljo, Stefanek '18
Fuentes-Martin & Stangl '20
Davighi & GI '23

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





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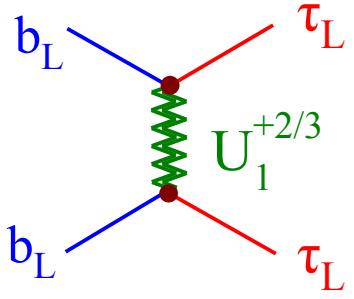
$$SU(4)^{[3]}\times SU(3)^{[12]} \times G_{EW} \longrightarrow SU(3) \times SU(2)_L \times U(1)_Y$$

vector leptoquark

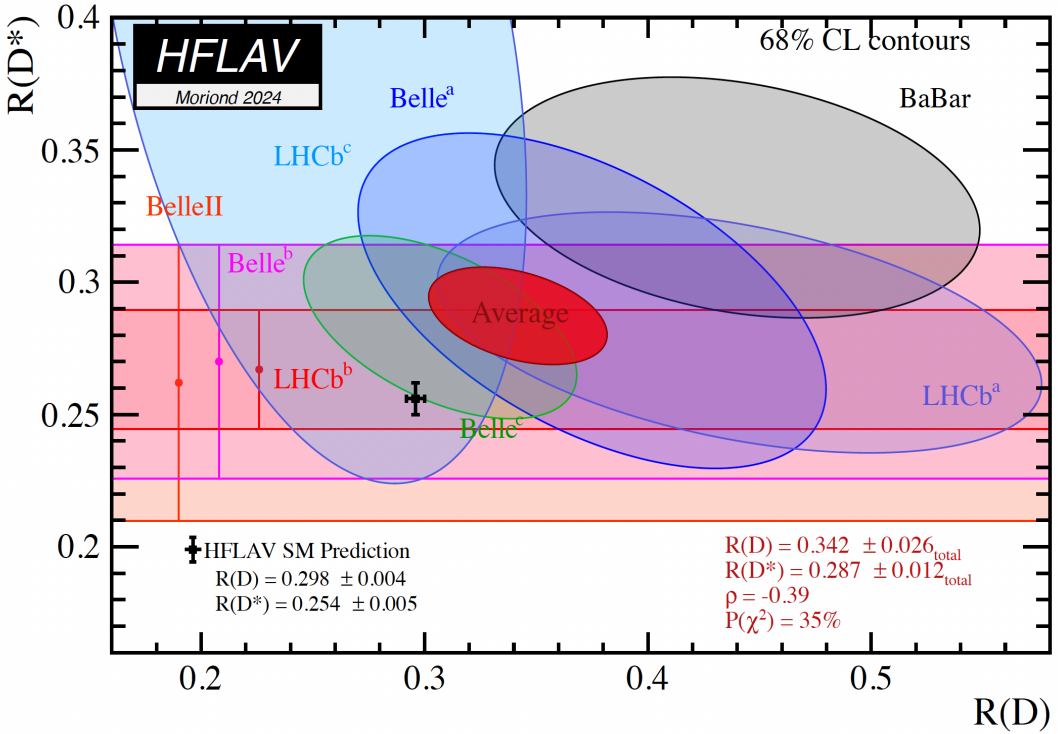


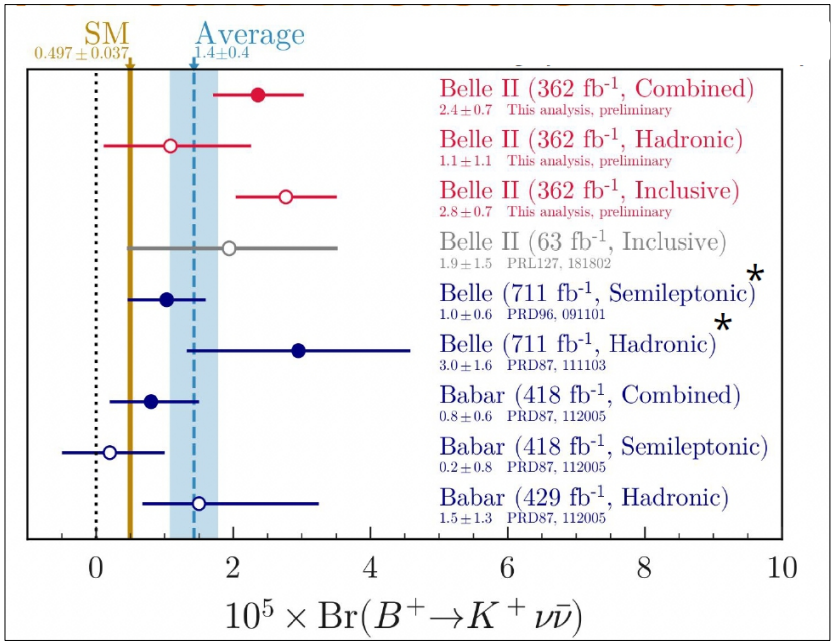
- Explain charge quantization
- Might explain some existing tensions in B-physics data

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

B-L generator

A brief look to current data & future prospects





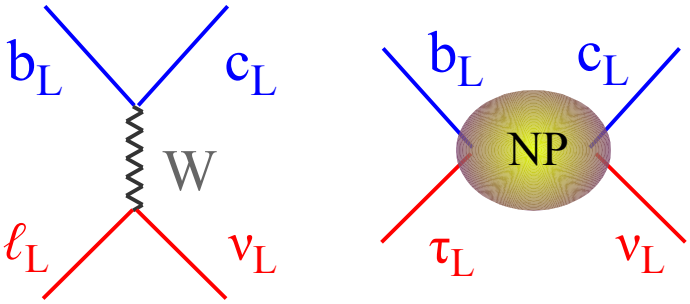
A brief look to current data & future prospects

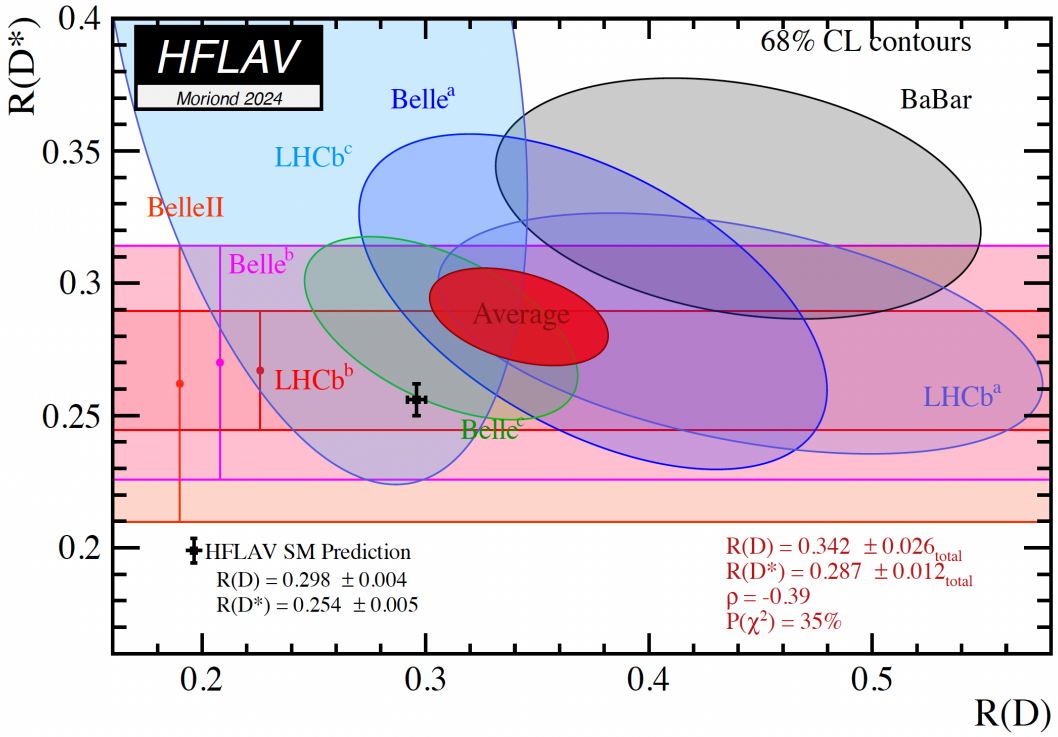
The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements (*with different degree of model-dependence*)

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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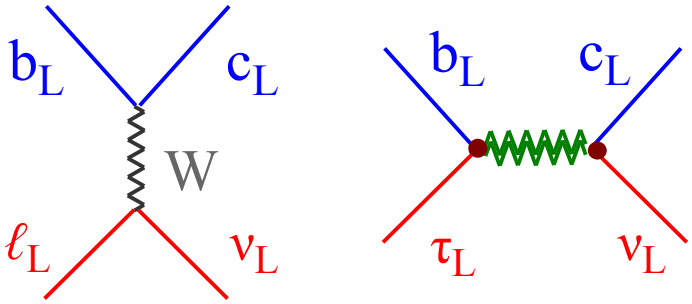
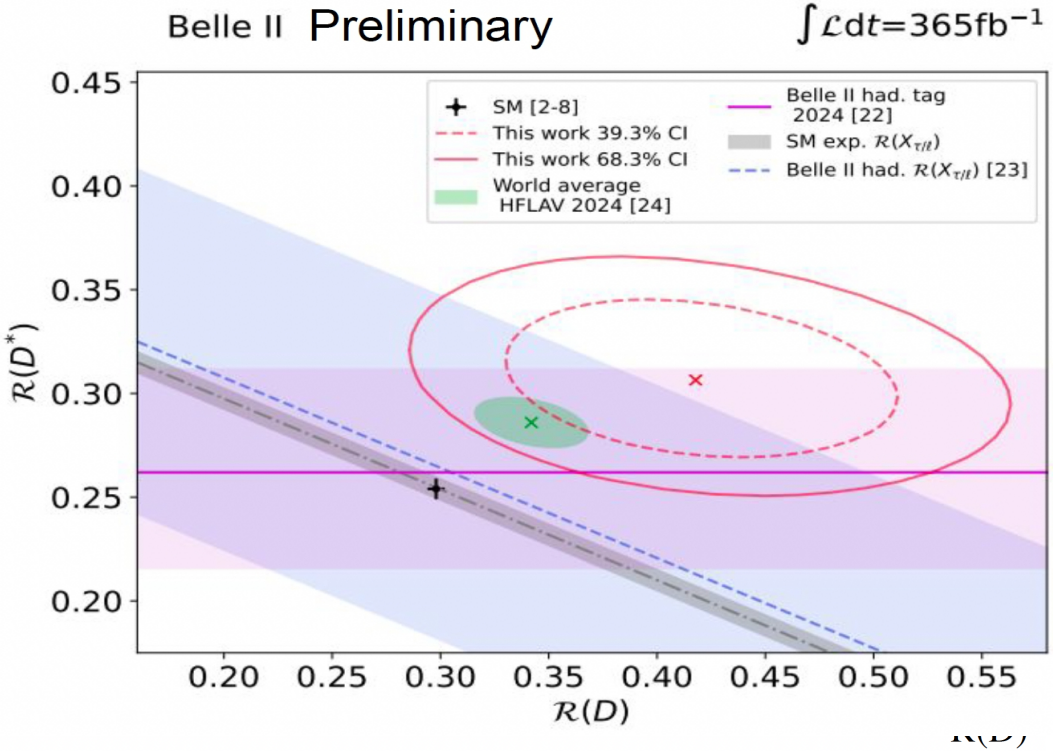


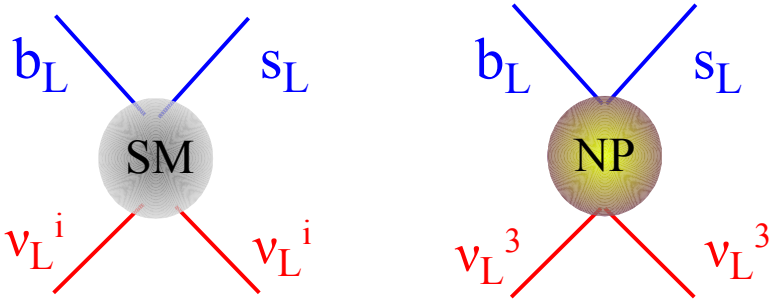


→ *The vector LQ of 3rd gen. quark-lepton unification is an ideal candidate to describe current data*

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*)

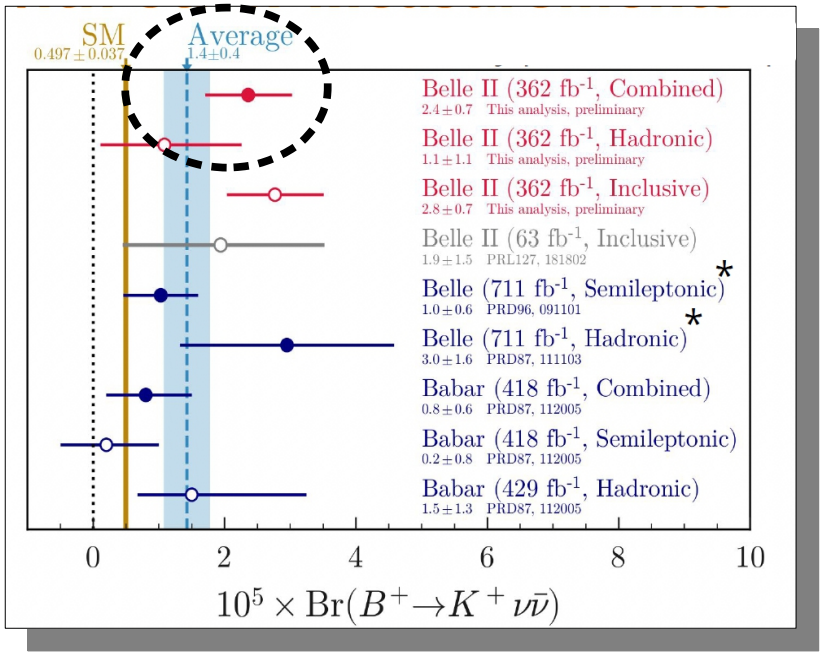
E.g.: II) Deviations from SM in $b\to s\nu\nu$ rates [3rd gen. ν in the final state]



identical for all neutrino species

relevant only for 3rd gen. neutrinos

Belle-II '2023



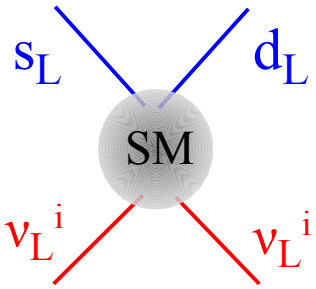
Unambiguous prediction of O(50%) enhancement of $B(B\to K\nu\nu)$ in the model with vector LQ – given excess in R(D).

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

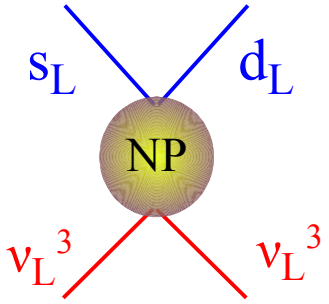
A brief look to current data & future prospects

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



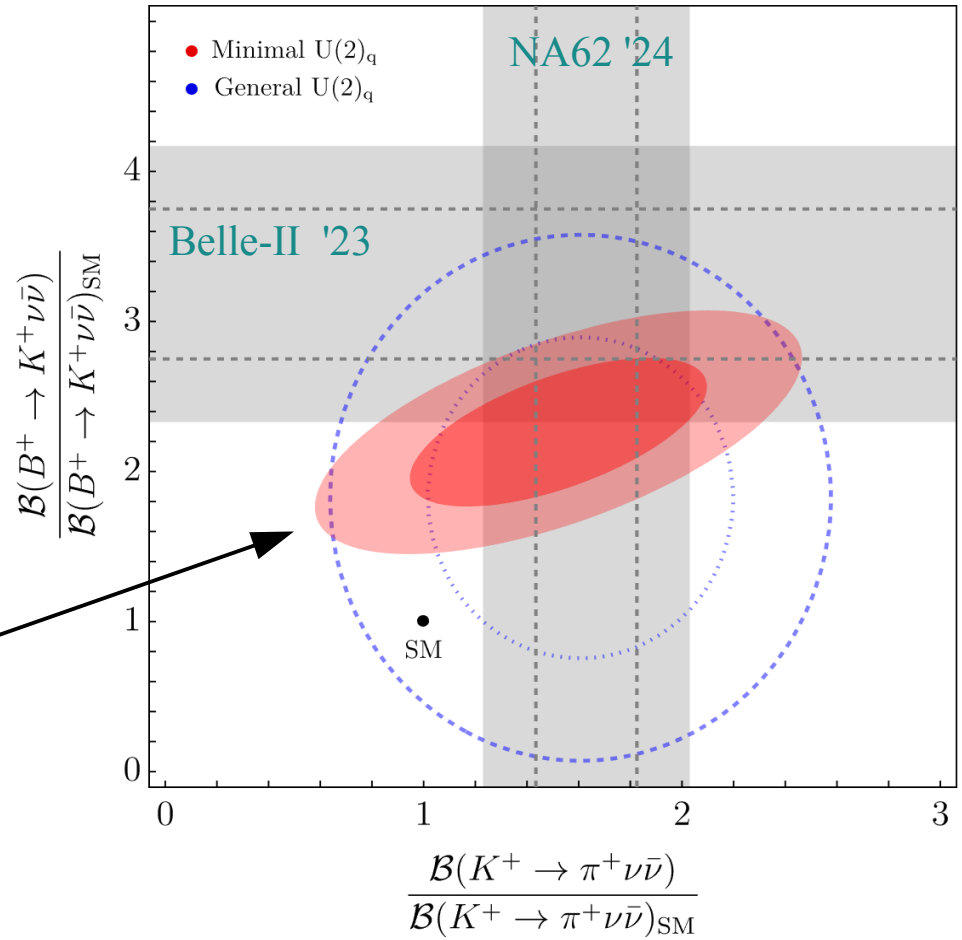
identical for all neutrino species



relevant only for 3rd gen. neutrinos

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

Bordone *et al.* '24



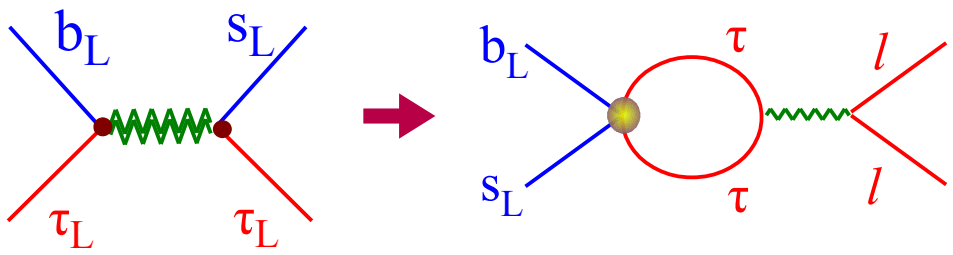
A brief look to current data & future prospects

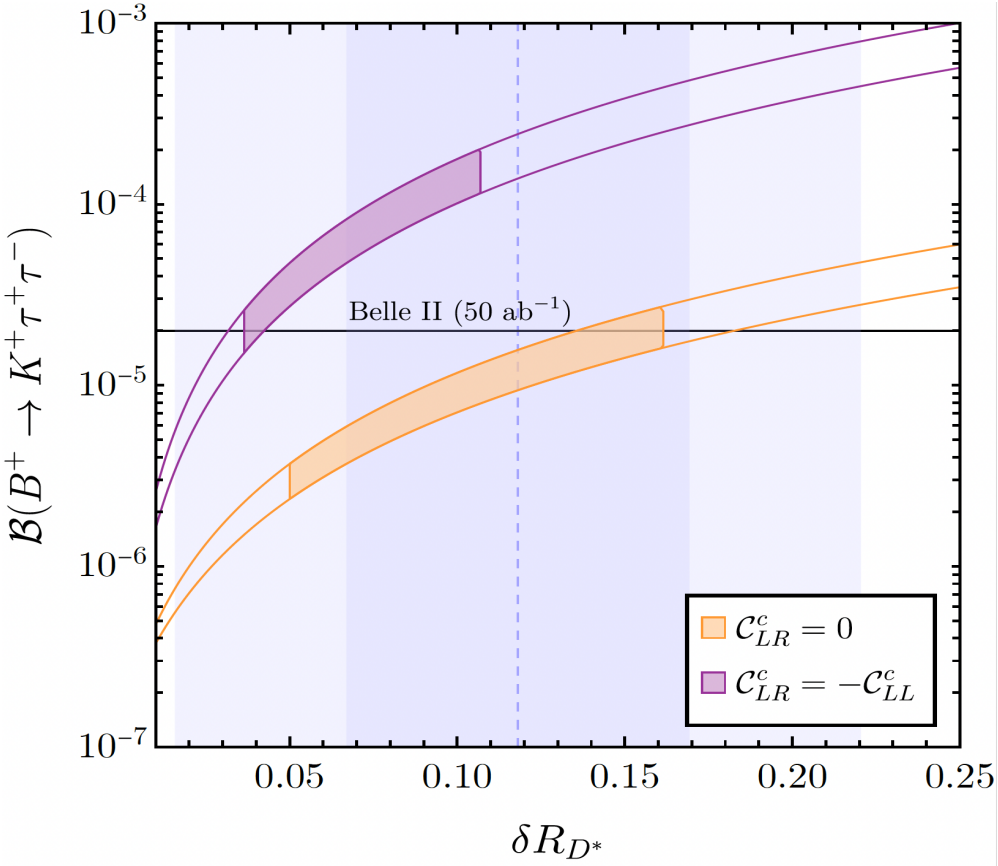
The idea of flavor non-universal interactions – with a 1st layer of new physics already at the TeV scale – has several interesting implications for various low-energy measurements (*with different degree of model-dependence*)

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

$b\to s\tau\tau$ 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 $b\to sll$ via RGE effects (*could explain current tensions..*)

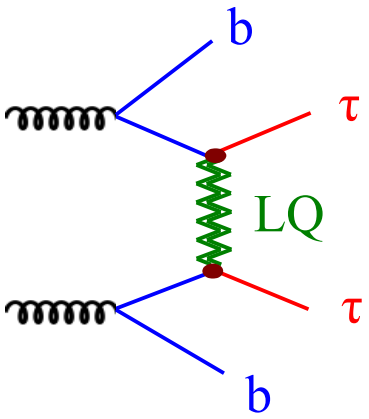




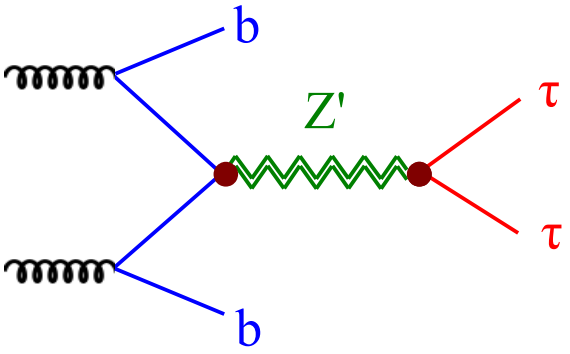
A brief look to current data & future prospects

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

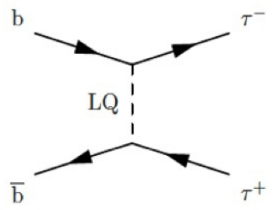


A brief look to current data & future prospects

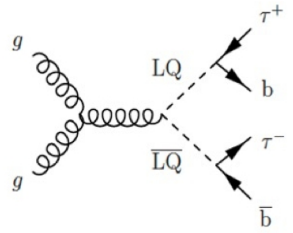
Aurelio Juste [*Moriond EW* '23]

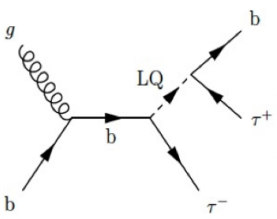
LQ-b-τ: Comparison of recent results

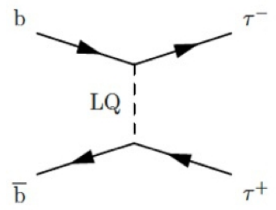
Including interference w/ SM bkg



Neglecting interference w/ SM bkg

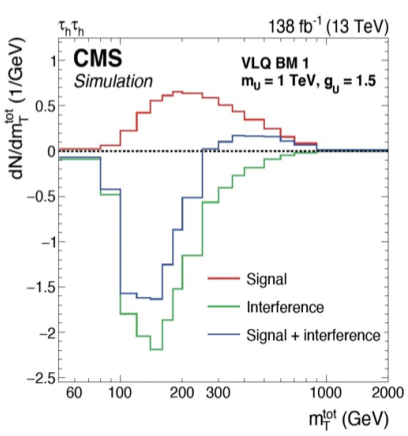


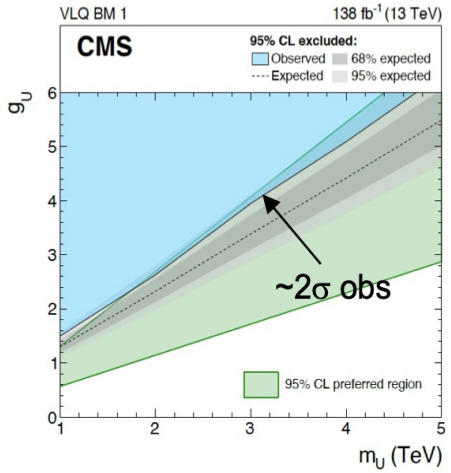




Caveat: BR=1 (CMS) vs BR=0.5 (ATLAS)

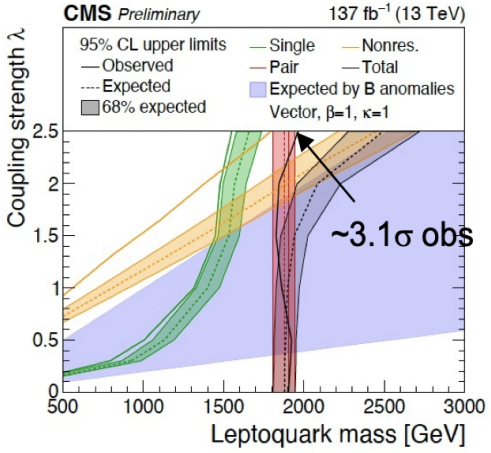
[CMS-HIG-21-001]



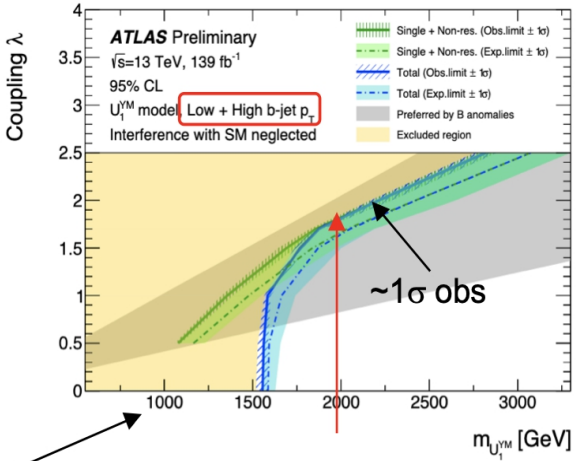


Shown at Moriond EW 2022

[CMS-PAS-EXO-19-016]



[EXOT-2022-39]

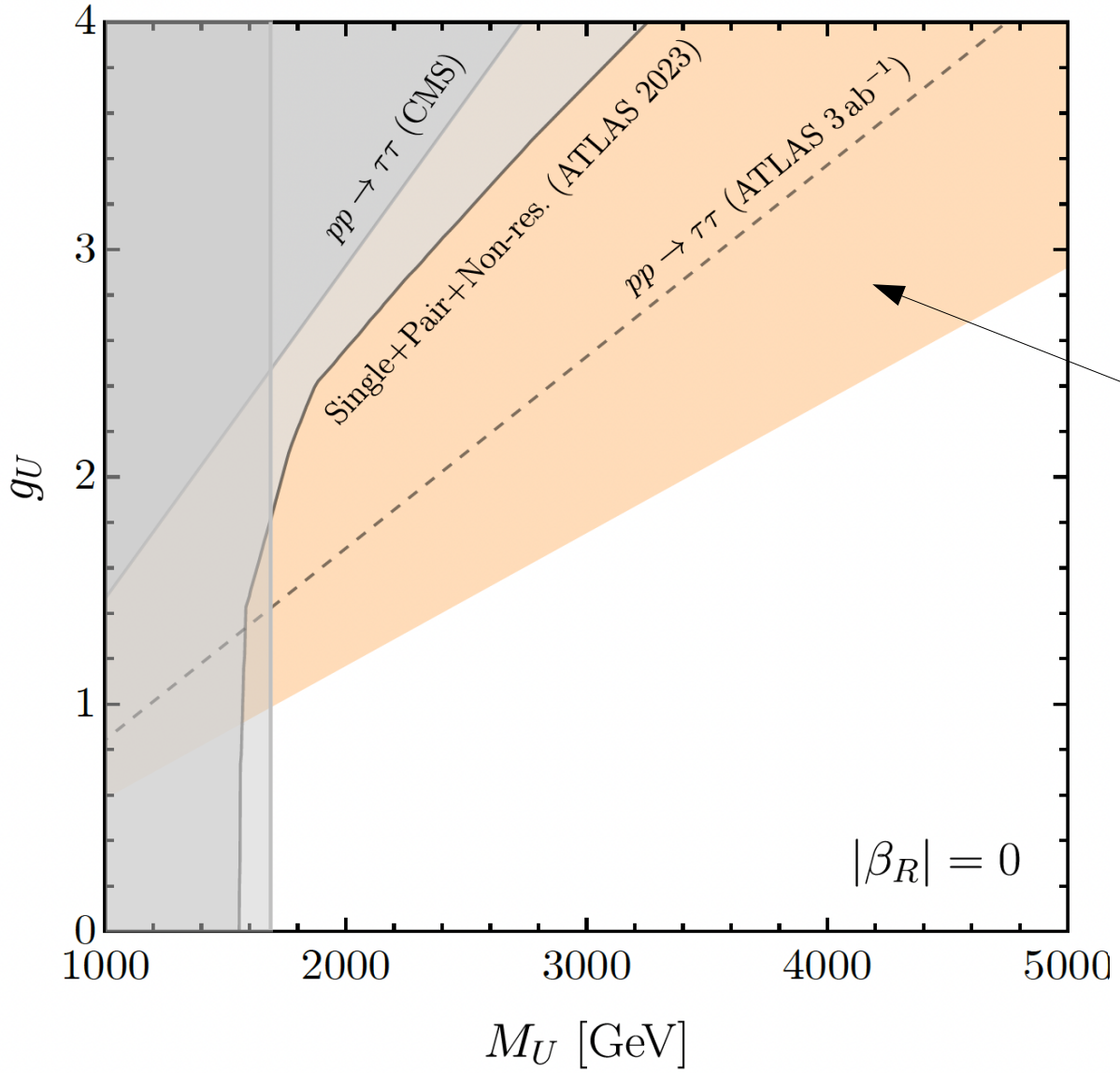


Large improvement in sensitivity when adding low b-jet p_T category

Need to clarify interference issue for future interpretations

A brief look to current data & future prospects

Leptoquark search in $pp \to \tau\bar{\tau}$ (+ b-jets)



Updated preferred region by b → c low-energy data

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 renewed perspective toward 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.

- 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 (mainly Belle-II & LHCb-II) and @ HL-LHC