Open questions and future prospects in particle physics

Gino Isidori
[*University of Zürich*]

- Introduction
- The SMEFT and its cut-off scale
- A closer look to current New Physics bounds
- Future prospects
- Conclusions

University of Zurich UZH

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Introduction

"Particle physics is the quadrant of nature whose laws can be written in a few lines with absolute precision and the greatest empirical accuracy"

R. Barbieri
[*Lectures on ElectroWeak interactions*]

Introduction

These laws of nature are what we usually refer to as the *Standard Model*

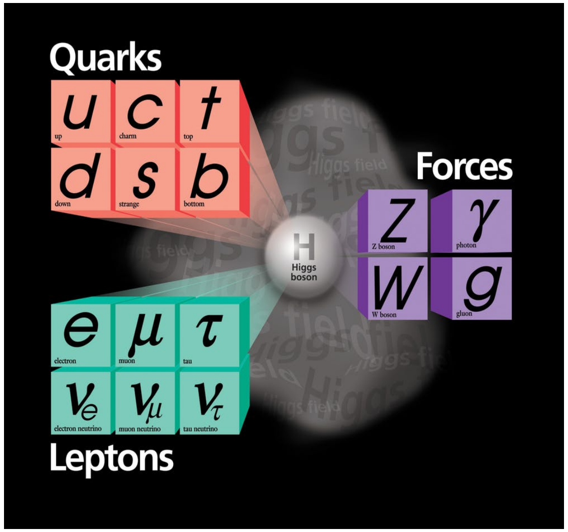
- a Quantum Field Theory [↔ QM + Special Relativity]

based on

- the principle of gauge invariance to describe long-range forces, hence depending on a small set of dimensionless free parameters
- depending on single fundamental energy scale [*Fermi scale*]
- with no intrinsic validity limit [*classical renomalizability*]

⬇

rich phenomenology and unprecedented range of validity in terms of energies/distances [*12 orders of magn. from atomic energy levels to LHC energies*]

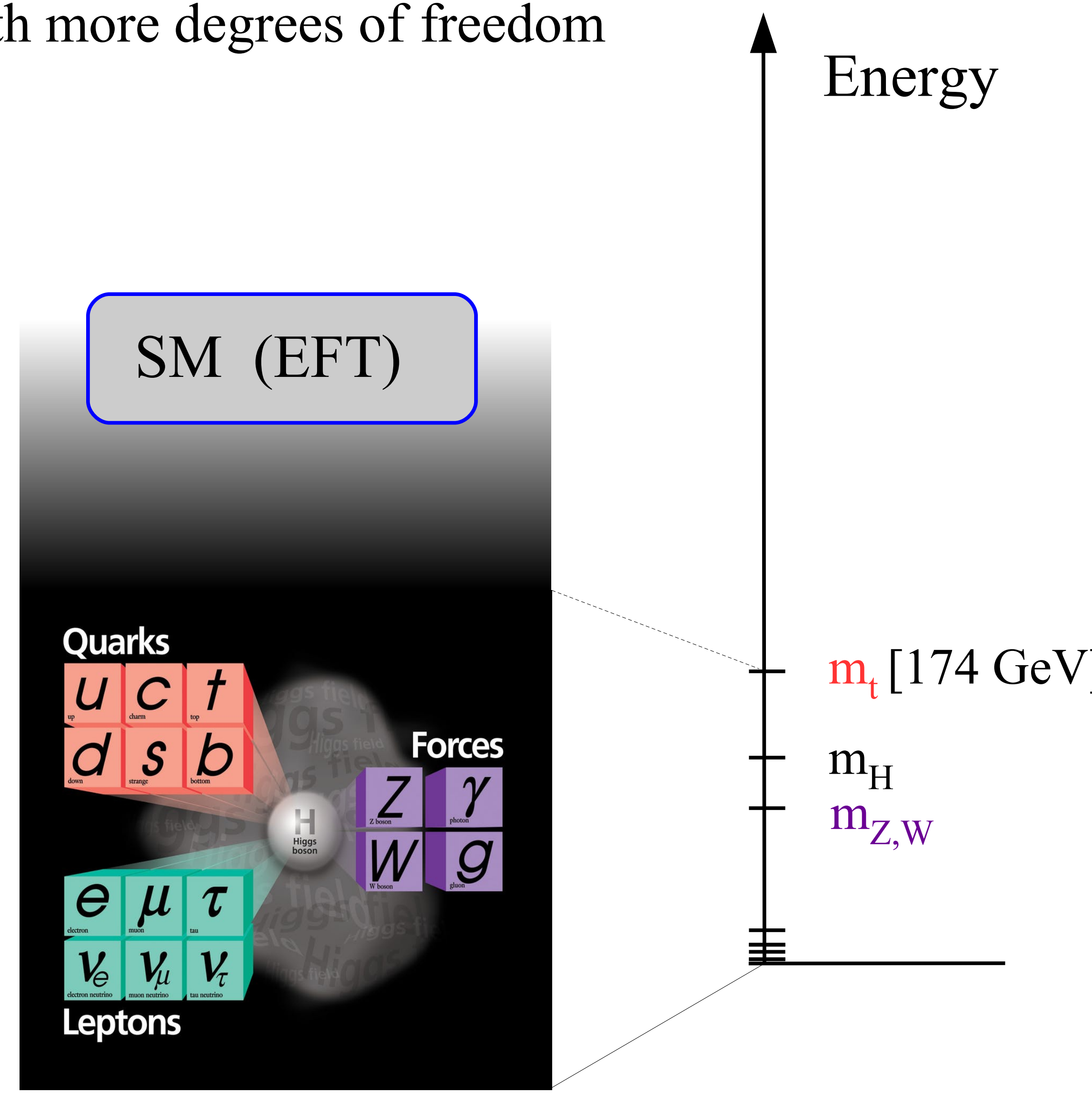


Introduction

Despite all its phenomenological successes, 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

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

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



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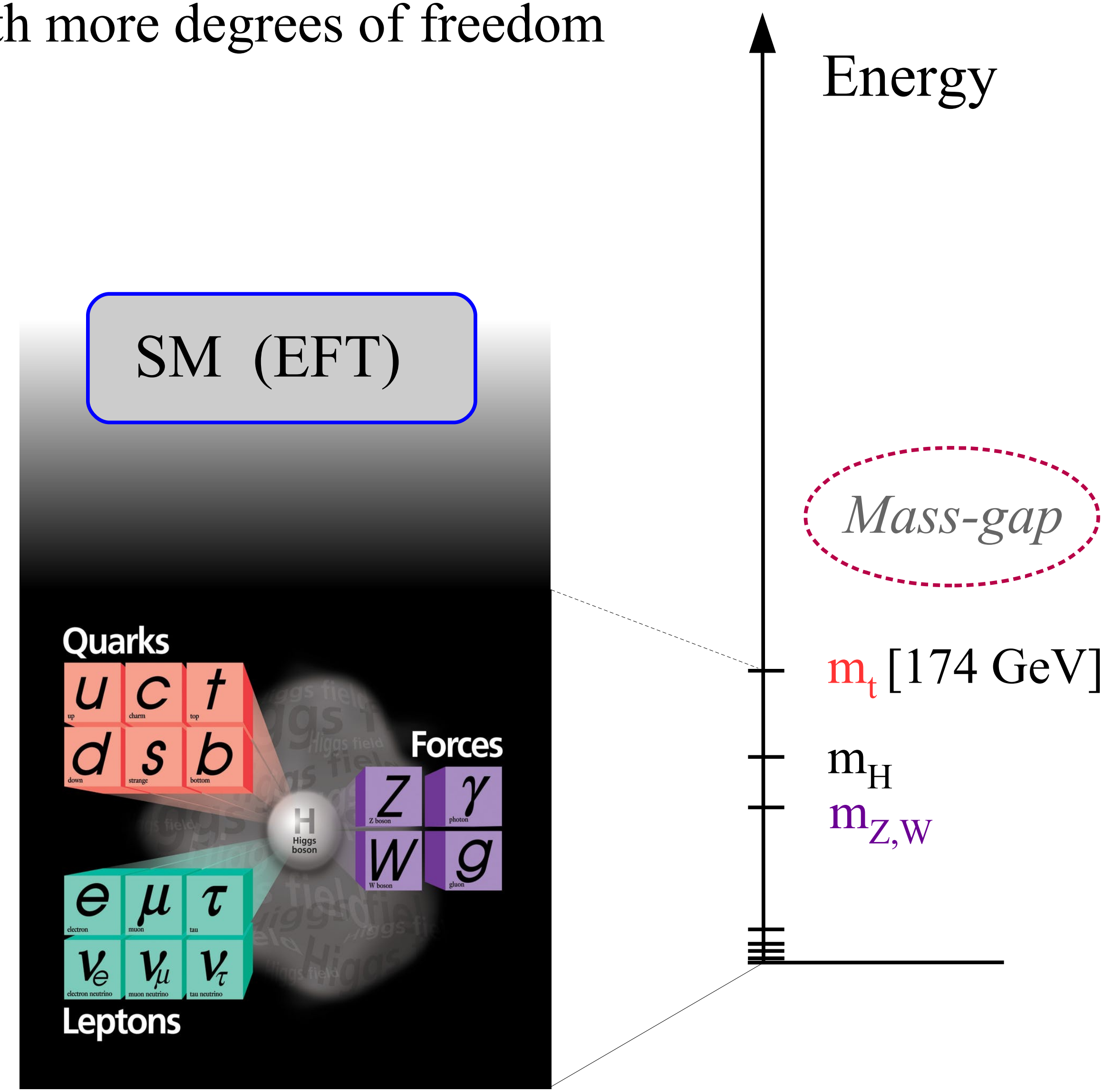
The key message following from run-II LHC results is that there is a mass-gap above the Fermi scale

N.B.: *the existence of a mass gap, albeit not as large, was quite clear even before the LHC started, via EW and flavor physics*



Introduction

While there are no signs of a possible break-down of the general QFT principles (*at least at microscopic level & nearby energies*) there are clear indications that additional (UV) degrees of freedom are needed

Electroweak hierarchy problem

Flavor puzzle
Neutrino masses
U(1) charges

Dark-matter
Dark-energy
Baryon asymmetry
Inflation

Quantum gravity

UV Theory

$\downarrow$

SM (EFT)

Introduction

While there are no signs of a possible break-down of the general QFT principles (*at least at microscopic level & nearby energies*) there are clear indications that additional (UV) degrees of freedom are needed

	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 Neutrino masses U(1) charges	→ *Ad hoc tuning in the model parameters*	

Dark-matter
Dark-energy
Baryon asymmetry
Inflation

→ *Cosmological implementation of the SM*

out of the "quadrant" (in my opinion)

Quantum gravity → *Non compatibility (?) between QFT & GR*

Most useful hints to

- develop the UV completion
- plan new accelerator-based experiments

The SMEFT and the scale of New Physics

The SMEFT and its cut-off scale

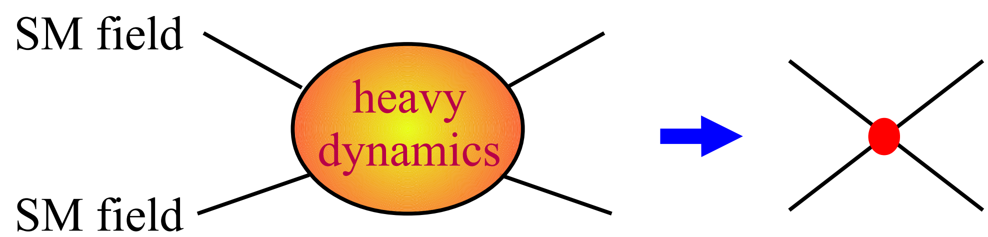
$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(\phi, A_a, \psi_i) + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}(\phi, A_a, \psi_i)$$

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

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

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

"Remnant" of the heavy
dynamics at low energies



What is the value of the Λ
(= *lowest energy threshold for the new dynamics*)
is the "core question" of particle physics

The SMEFT and its cut-off scale

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A clear evidence of a non-vanishing term in the series of higher-dim. ops. (so far the only one...) comes from *Neutrino masses*:

$$\frac{g_\nu^{ij}}{\Lambda_{LN}} (L_L^{T\,i} \sigma_2 \phi)(L_L^{j} \sigma_2 \phi^T)$$

Possible dynamical origin via the see-saw mechanism, where

$$\frac{g_\nu}{\Lambda_{LN}} = \frac{Y_\nu^T Y_\nu}{M_R}$$

$$(m_\nu)^{ij} = \frac{g_\nu^{ij} \langle\phi\rangle^2}{\Lambda_{LN}} \lesssim 0.1 \text{ eV}$$

▶ *The SMEFT and its cut-off scale*

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Unfortunately not very conclusive, given

- lack of clear hypotheses for g_ν $\left[\begin{array}{lcl} y_e & \rightarrow & M_R \sim 2.5 \text{ TeV} \\ y_t \approx 1 & \rightarrow & M_R \sim 3\times 10^{14} \text{ GeV} \end{array}\right.$
- this operator violates total lepton number (accidental *symmetry of SM* → *more later*)

The SMEFT and its cut-off scale

A strong, albeit vague, indication of a nearby energy threshold follows from the ElectroWeak hierarchy problem (↔ *instability of the Higgs mass under quantum corrections*):

$$\mathscr{L}_{\text{Higgs}}\,(\phi, A_a, \psi_i)$$

only d=2 term in the SMEFT

$$\mu^2\ \phi^+\phi \xrightarrow[\text{corrections}]{\text{quantum}} \Lambda^2\ \phi^+\phi$$

N.B.: the quadratic sensitivity of the Higgs mass from the cut-off is not a pure "technical" issue: it implies a quadratic sensitivity to the the new degrees of freedom (*if we assume there is something else beyond the SM – as naturally implied by all the other open issues*)

$$m_H^2\Big|_{M_{NP}} + \text{NP} \rightarrow m_H^2\Big|_{\text{phys}}$$

$$\Delta m_H^2 \sim M^2_{NP}$$

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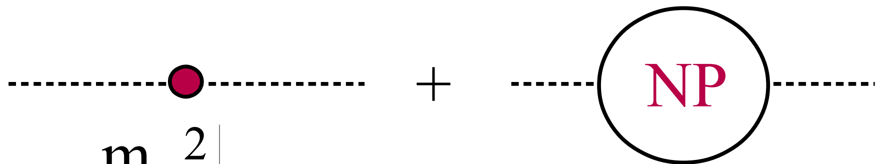

$$m_H^2\big|_{\Lambda} \quad + \quad \Delta m_H^2 \sim \Lambda^2 \quad \rightarrow \quad m_H^2\big|_{\text{phys}}$$

If the Higgs mass (= *overall scale the SM*) is calculable in terms UV dynamics, then new degrees of freedom must show not far from the Fermi scale to "screen it" form its sensitivity to high energies.

A precise estimate of how heavy Λ can be depend on the amount of "fine tuning" we are ready to accept and how strongly NP couples to the Higgs sector.

$$\Delta m_H^2\Big|_{\text{tt-SM}} = \frac{3\,y_t^2}{8\pi^2}\Lambda^2 + \ldots \longrightarrow \frac{(\Delta m_H^2)_{\text{tt-SM}}}{(m_H)_{\text{exp}}} = \frac{\Lambda^2}{(0.5\ \text{TeV})^2}$$

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

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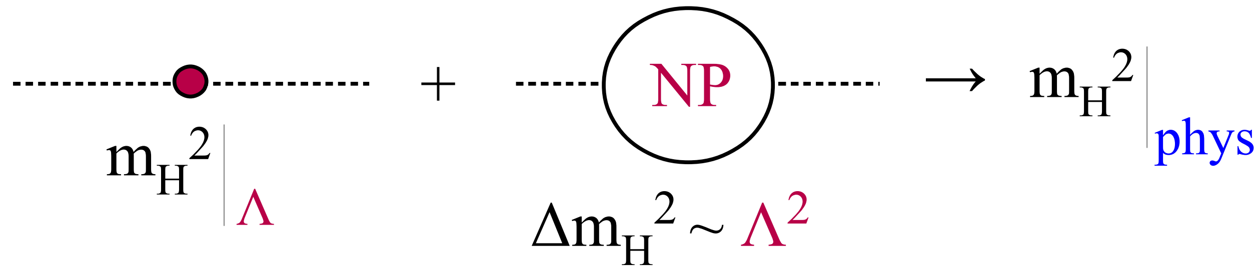

If the Higgs mass (= *overall scale the SM*) is calculable in terms UV dynamics, then new degrees of freedom must show not far from the Fermi scale to "screen it" form its sensitivity to high energies.

Of course we cannot excude the possibilty that m_H is *not calculable* in terms of UV dynamics (*or at least not only*). In such case there is little we can say (*we somehow go "out of the quadrant"*...)

This line of reasoning is motivated by the absence of new physics signals at the LHC and other experiments. As I will argue in the rest of the talk, I think this evidence is not very compelling, given our exploration of the TeV scale is still rather limited

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A closer look to the question of what is the value of Λ reveals more "layers":

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

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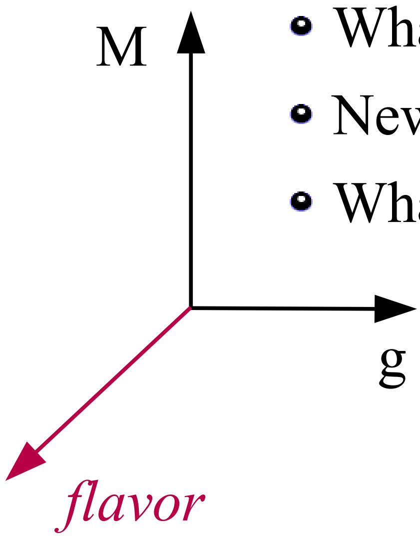

- What is the mass scale of the new d.o.f. ?
- New dynamics weakly or strongly coupled ?
- What is the *flavor structure*?

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

Jenkins, Manohar, Trott '14
Alonso *et al.* '15

Navigating the SMEFT without (consistent) assumptions about its flavor structure leads nowhere!

The SMEFT and its cut-off scale [The flavor puzzle(s)]

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}}(A_a, \psi_i) + \mathscr{L}_{\text{Higgs}}(\phi, A_a, \psi_i)$$

Large flavor symmetry

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

Flavor-degeneracy broken by the Yukawa interaction, which exhibits a "peculiar" breaking structure (large hierarchies)

Eg.: $Y_U \; \overline{Q}_L Y_U U_R \phi_c$

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

$$\begin{array}{cc} \overbrace{\phantom{< 0.01 \quad}}^{U(2)_U} & \\ Y_U \sim \left(\begin{array}{cc|c} & & 0.003 \\ & < 0.01 & 0.04 \\ \hline & & 1 \end{array} \right) & \left.\phantom{\begin{array}{c} 0 \\ 0 \end{array}}\right] U(2)_Q \end{array}$$

The SM flavor puzzle

The SMEFT and its cut-off scale [The flavor puzzle(s)]

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Exact & approximate (*accidental* ?) symmetries

Eg:

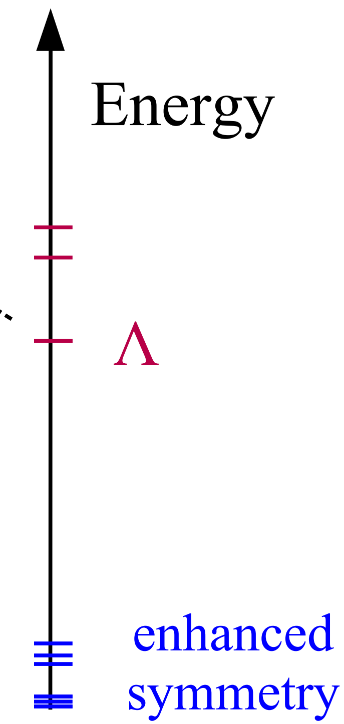
- $U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\mu}$ = (individual) Lepton Flavor [*exact symmetry*]
- $m_u \approx m_d \approx 0 \rightarrow$ Isospin symmetry [*approximate symmetry*]

The SMEFT and its cut-off scale [Accidental symmetries in EFTs]

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

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

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



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

Violations of accidental symmetries

The SMEFT and its cut-off scale [Accidental symmetries in EFTs]

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[SM-2]-EFT

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

Energy

Λ

enhanced symmetry

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

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

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

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

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

The SMEFT and its cut-off scale [Accidental symmetries in EFTs]

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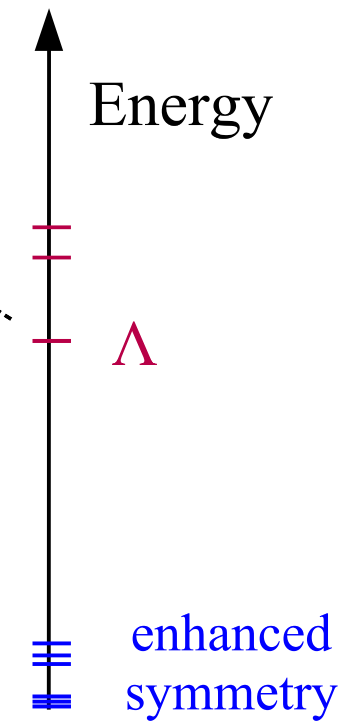

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$$\frac{e^{i\delta}}{\Lambda_{CP}^2} (\bar{s}\,\Gamma\, d)^2$$

SM-3 [KM, '73]:

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

Ellis, Gaillard, Nanopulos, '76

> 1st Key message: beware of high-scale bounds in EFT approaches: they can be a "mirage"...

The SMEFT and its cut-off scale [Accidental symmetries in EFTs]

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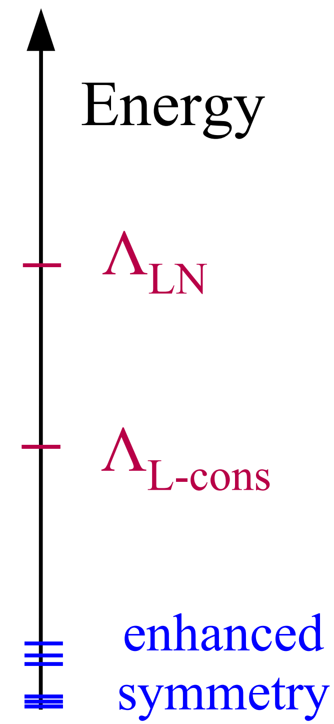

1st Key message: beware of high- scale bounds in EFT approaches: they can be a "mirage"...

2nd Key message: accidental global symmetries allows make a consistent "partition" of the EFT operators

E.g.: even if $\Lambda_{LN} \sim 10^{14}$ TeV (Weinberg op. for ν masses) is consistent to consider d=6 ops preserving LN characterized by $\Lambda_{L\text{-cons}} \ll \Lambda_{LN}$

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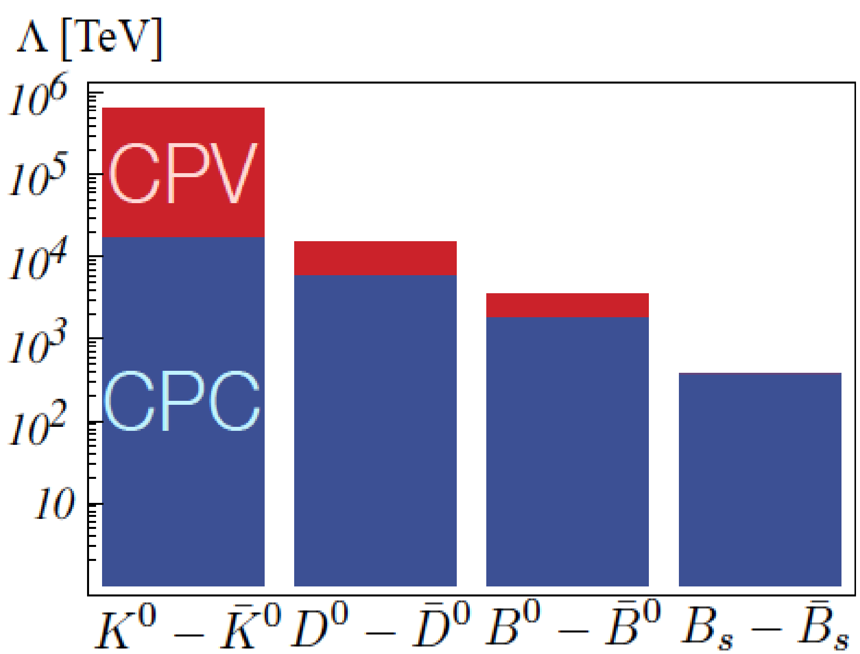
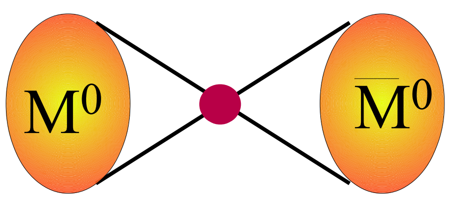
In principle, in the SMEFT we could expect many violations of the accidental SM symmetries, but we have observed none so far

↓

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

The NP flavor puzzle





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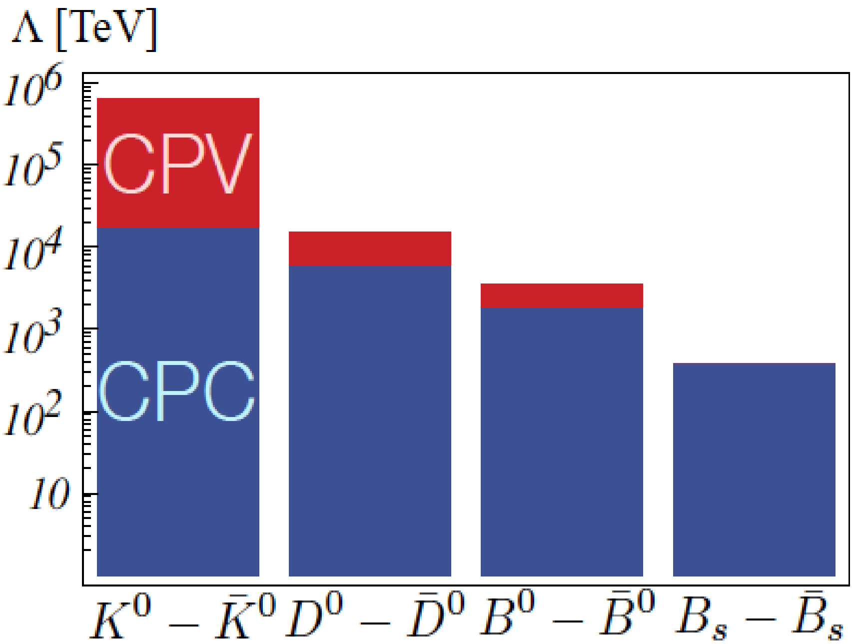
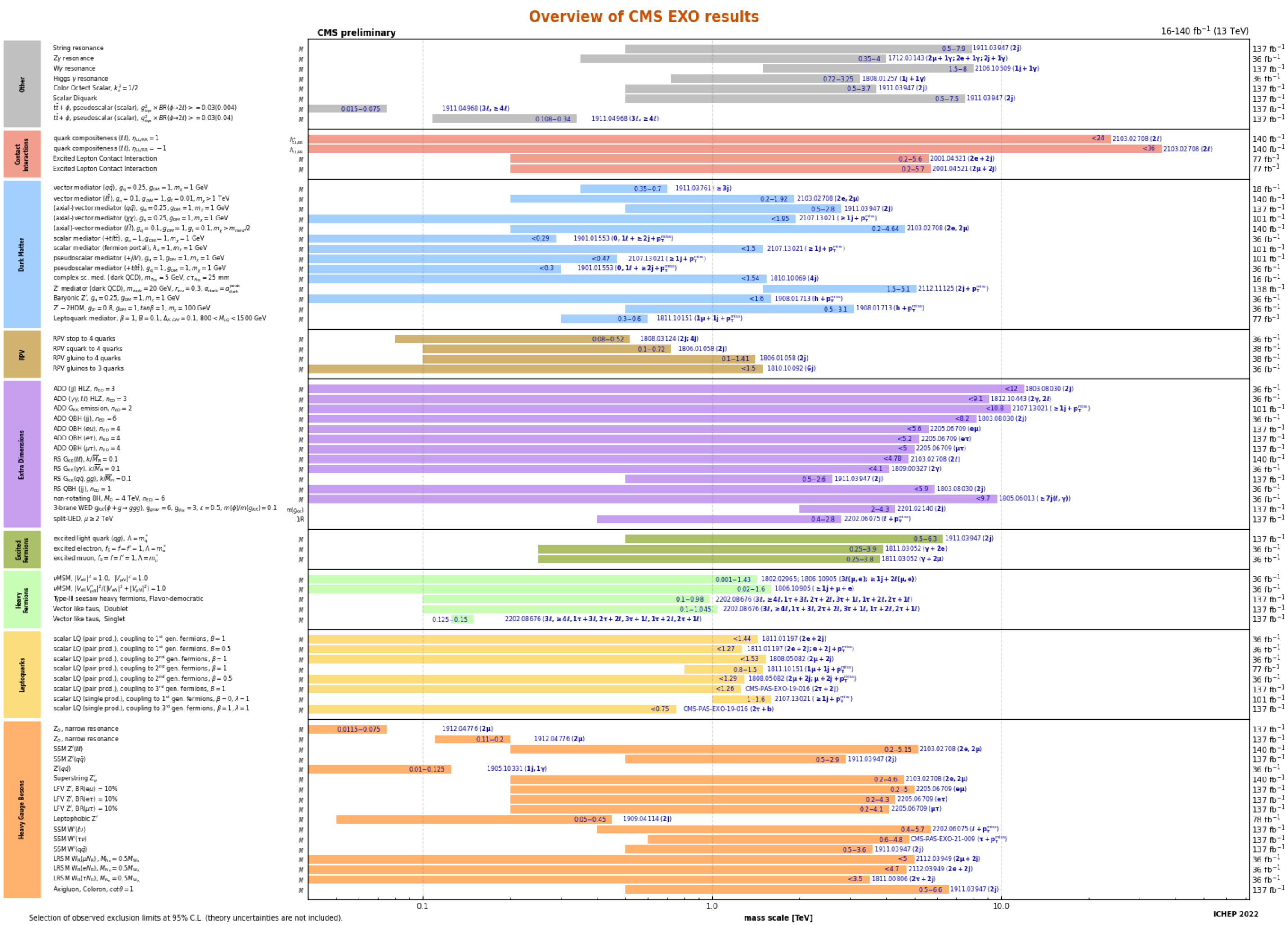


From what we just discussed, it is clear these high scales can well be a "mirage"

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

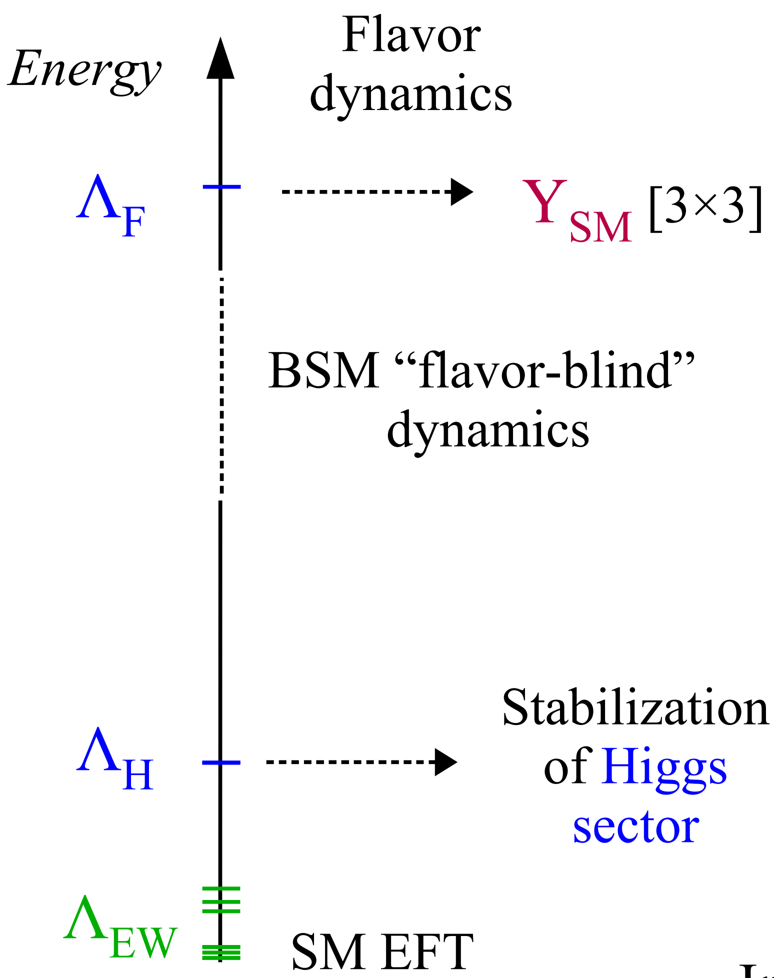
Note, however, that $U(2)^n$ is not an accidental symmetry of the SM [→ *indication of specific UV dynamics*]

A closer look to current New Physics bounds



A closer look to current NP bounds

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 EW hierarchy problem
- Postpone the flavor problem to higher scales

↕

The "MFV paradigm"

The Yukawa couplings are the unique sources of flavor symmetry breaking

[GIM & CKM suppression as in SM]

⬇

In the SMEFT with MFV the bounds effective scales from flavor-violating processes lowered to ~ TeV

A closer look to current NP bounds

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Energy

Flavor dynamics

Λ_F ⟶ Y_{SM} [3×3]

BSM "flavor-blind" dynamics

Λ_H ⟶ Stabilization of Higgs sector

Λ_{EW} SM EFT

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

↕

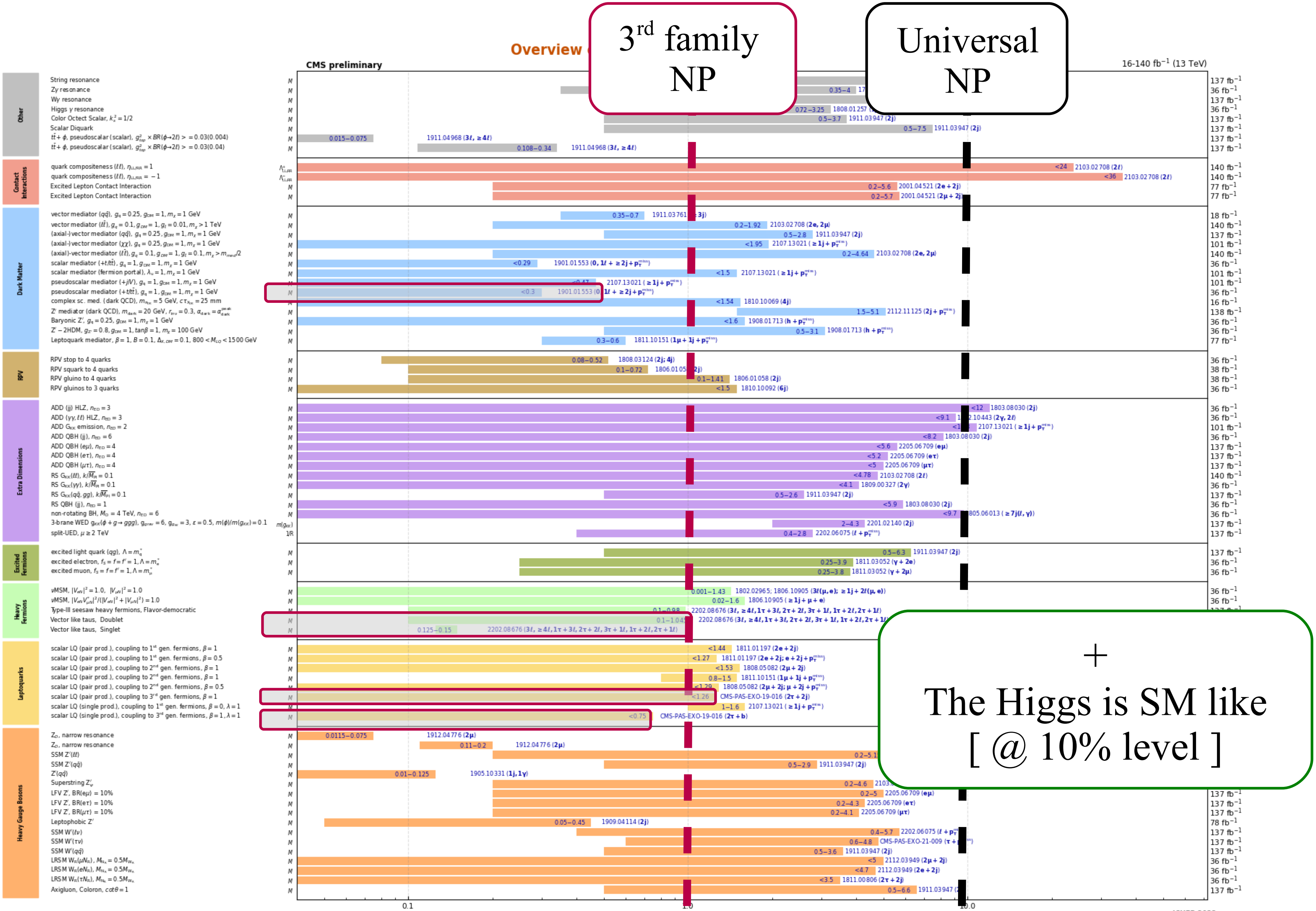
The "MFV paradigm"

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

strong bounds on NP coupled universally to all families

worsening of the Higgs hierarchy problem

A closer look to current NP bounds

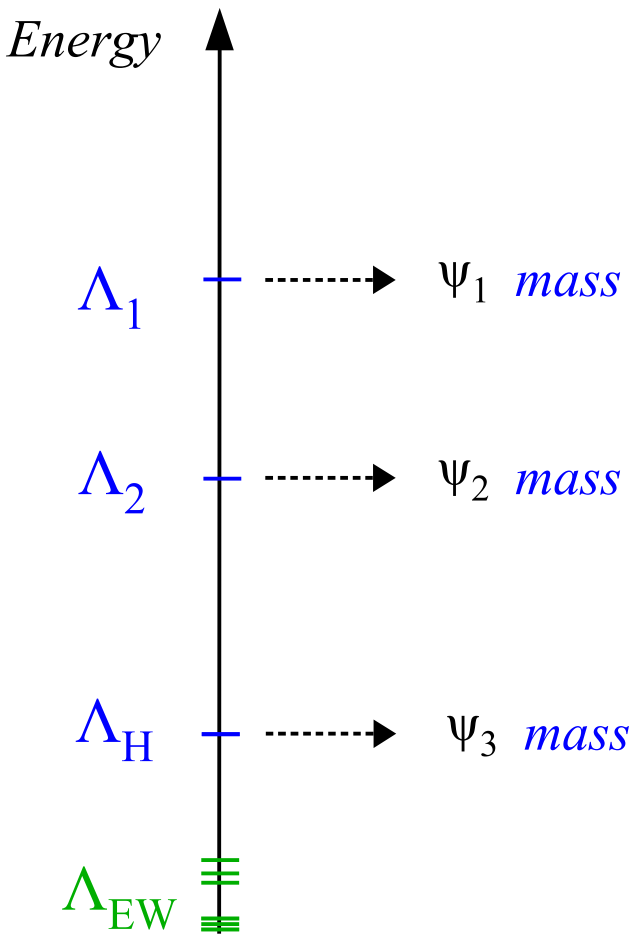


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

A closer look to current NP bounds

A more efficient paradigm to address both flavor puzzles and, possibly, also the EW hierarchy problem, is a *multi-scale* UV with *flavor non-universal* interactions

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



Basic idea:

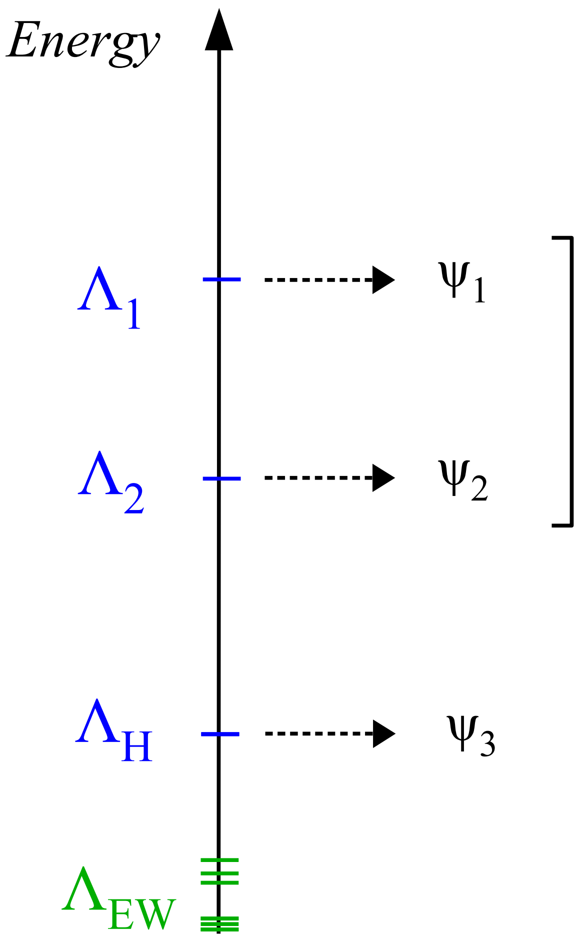
1st & 2nd generations have small masses (+ small coupling to NP) because these are generated by new dynamics at heavier scales

⬇

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

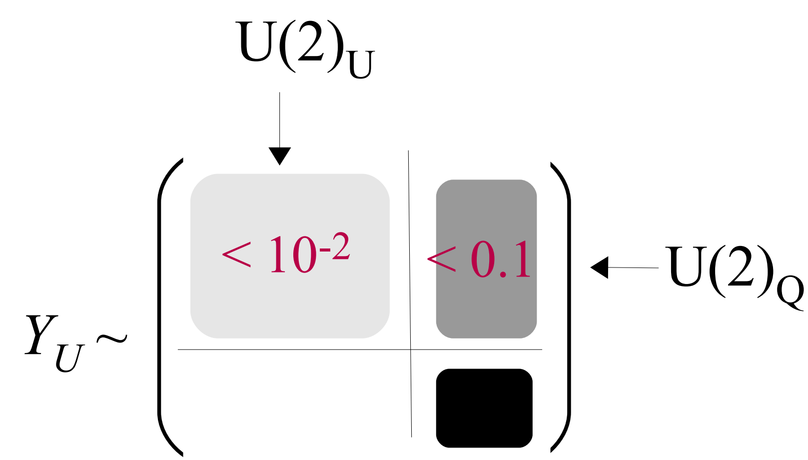
▶ *A closer look to current NP bounds*

A more efficient paradigm to address both flavor puzzles and, possibly, also the EW hierarchy problem, 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



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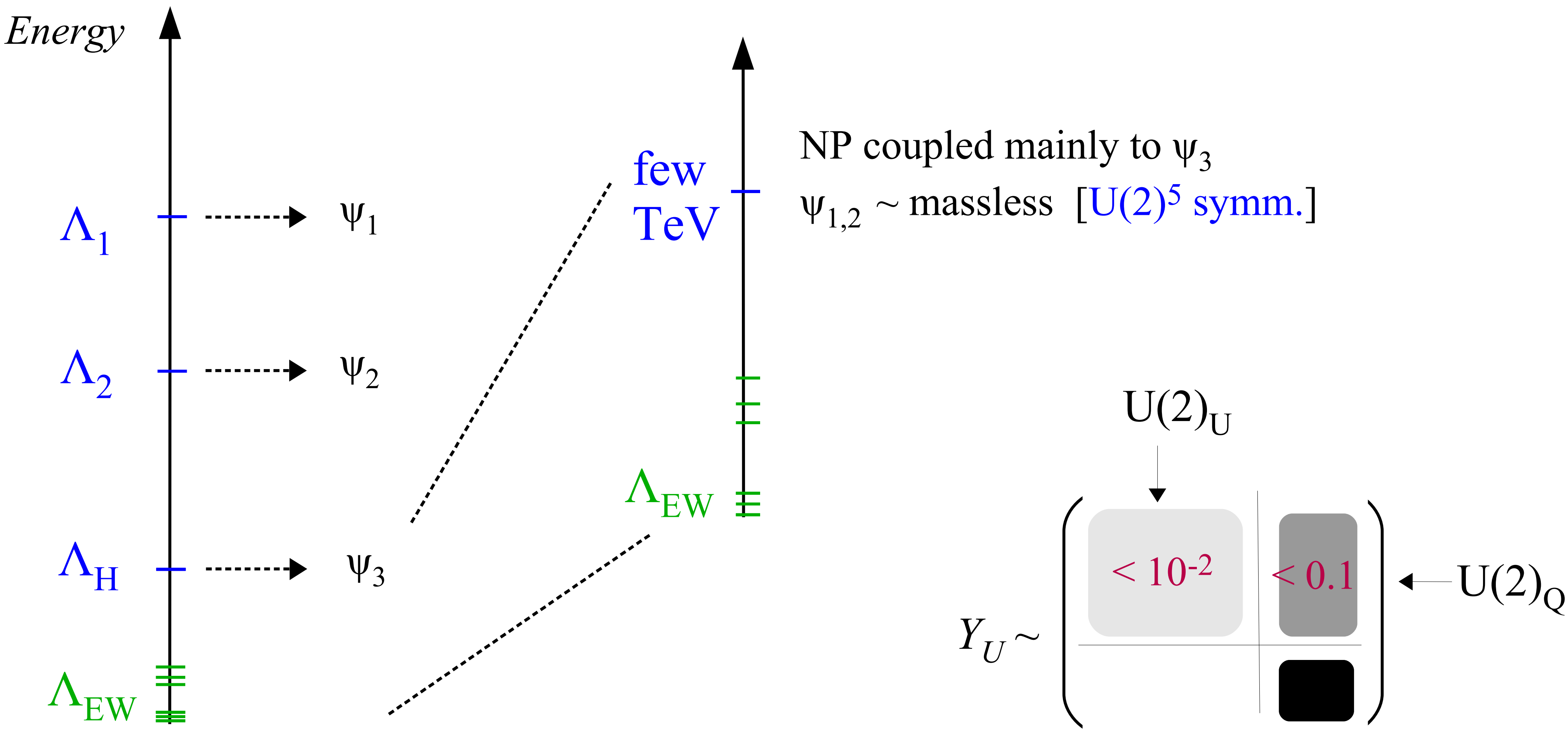
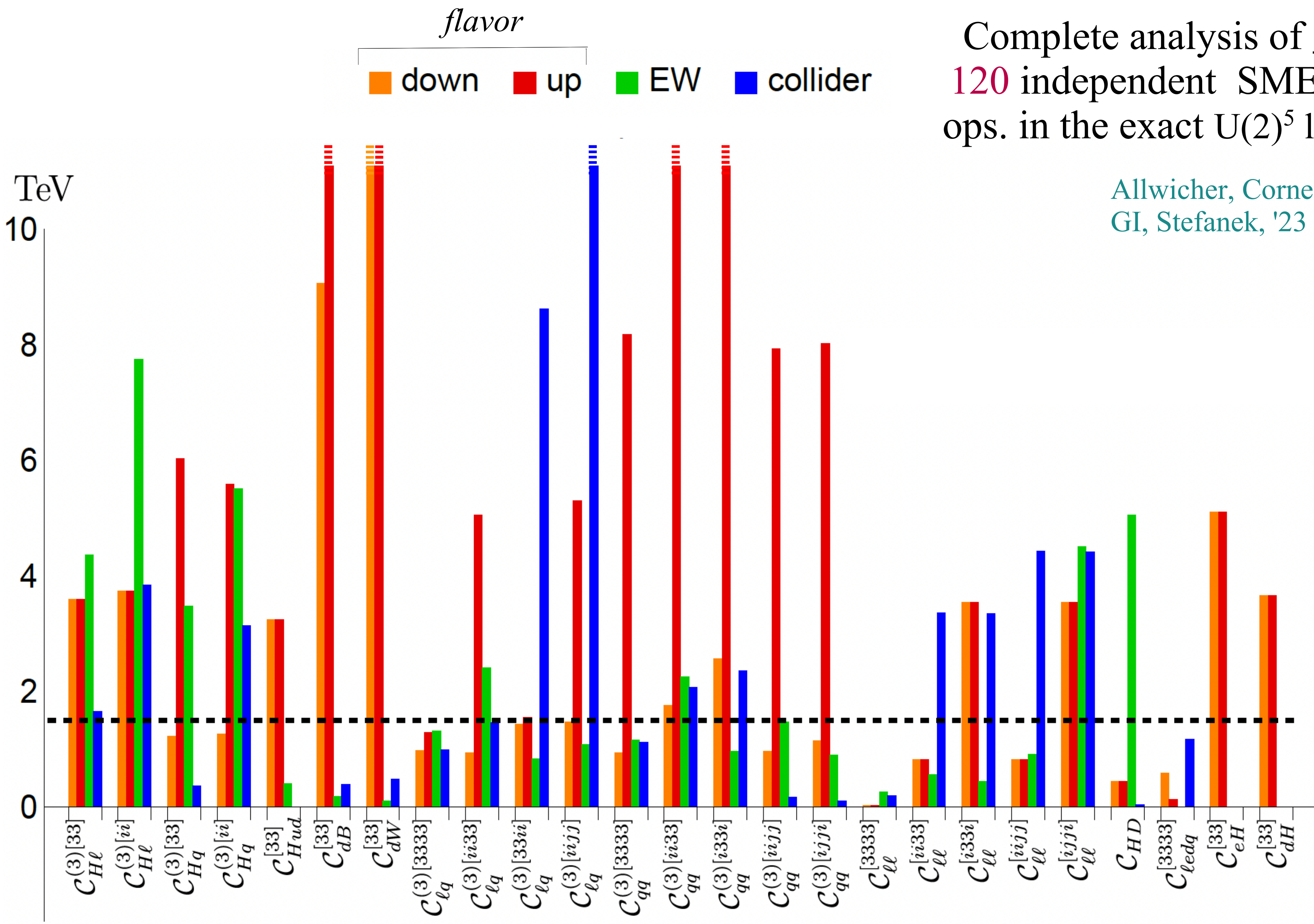


Effective organizing principle for the flavor structure of the SMEFT

A closer look to current NP bounds [SMEFT bounds in the $U(2)^5$ 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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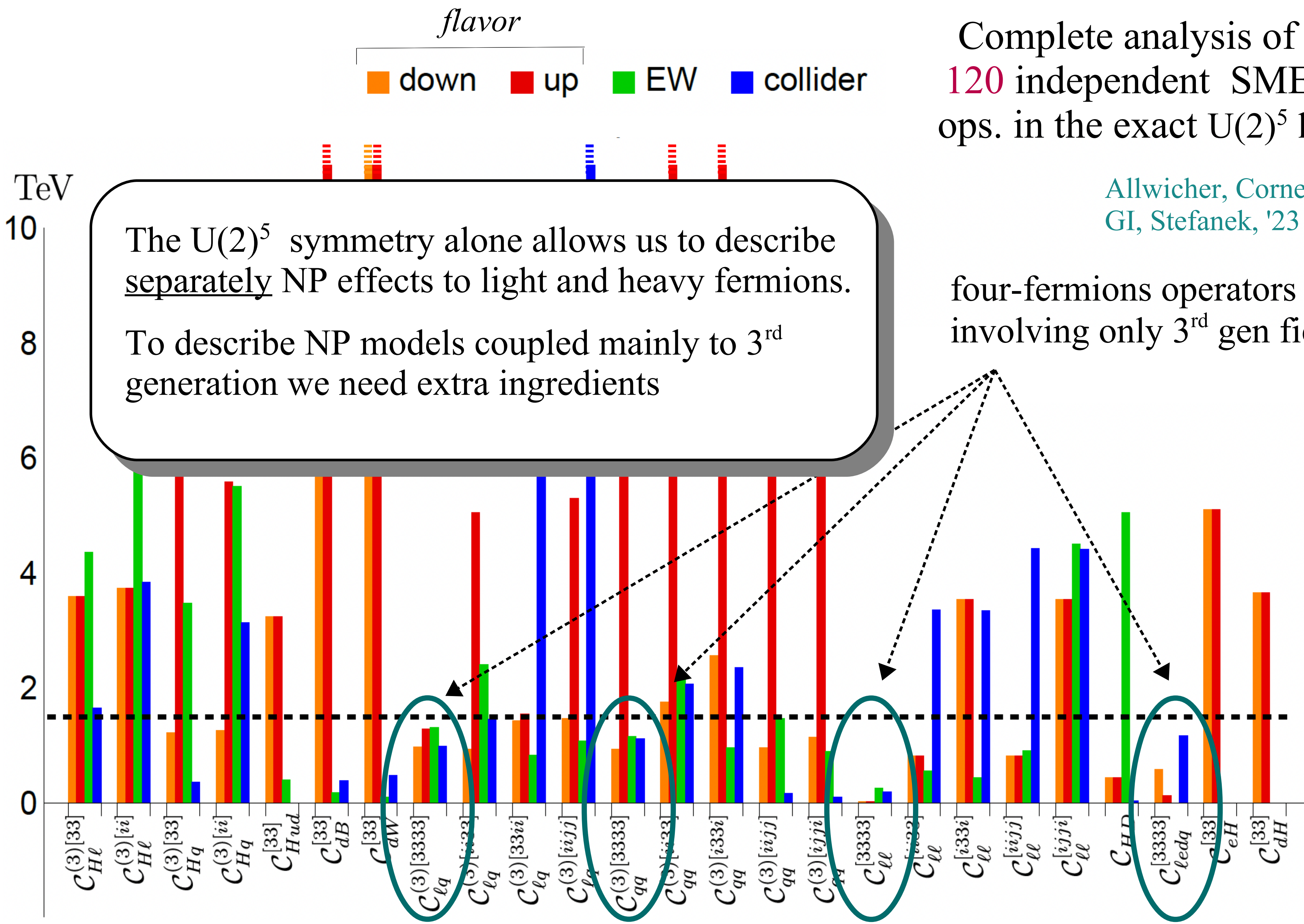
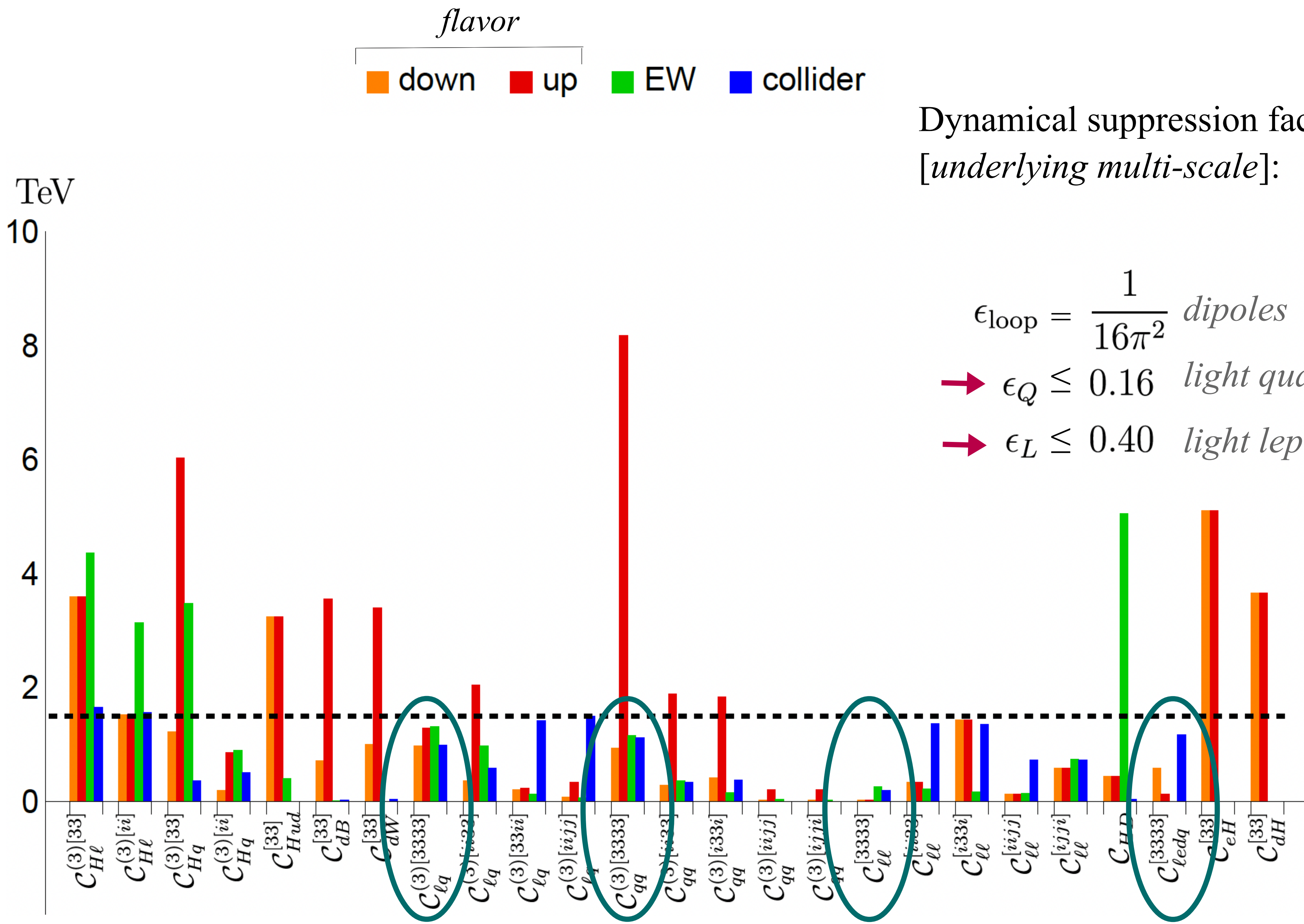


The U(2)^5 symmetry alone allows us to describe separately NP effects to light and heavy fermions.

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

four-fermions operators involving only 3rd gen fields

A closer look to current NP bounds [SMEFT bounds in the $U(2)^5$ limit]



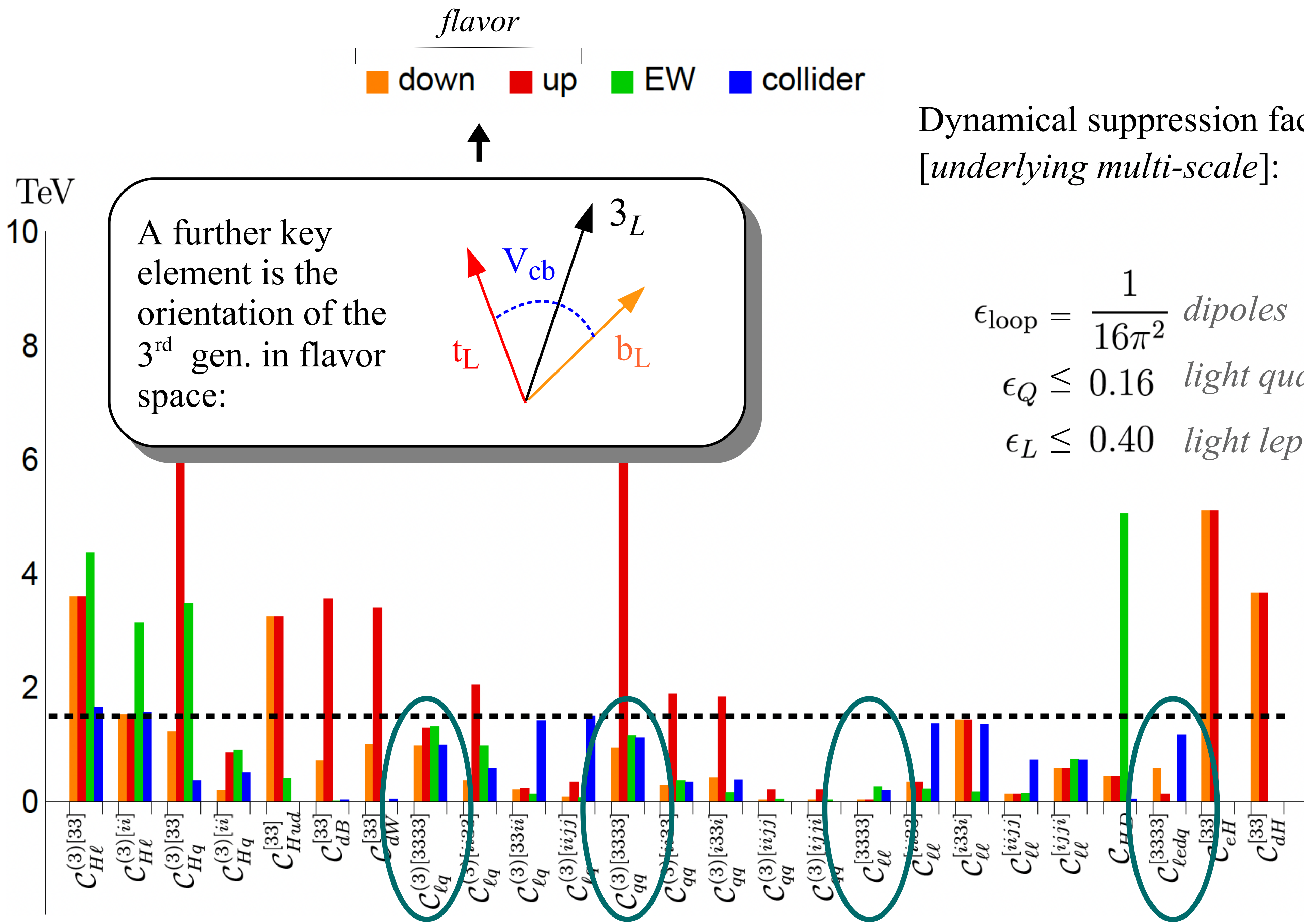
Dynamical suppression factors [*underlying multi-scale*]:

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

$\epsilon_Q \leq 0.16$ *light quarks*

$\epsilon_L \leq 0.40$ *light leptons*

A closer look to current NP bounds [SMEFT bounds in the $U(2)^5$ limit]



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

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

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

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

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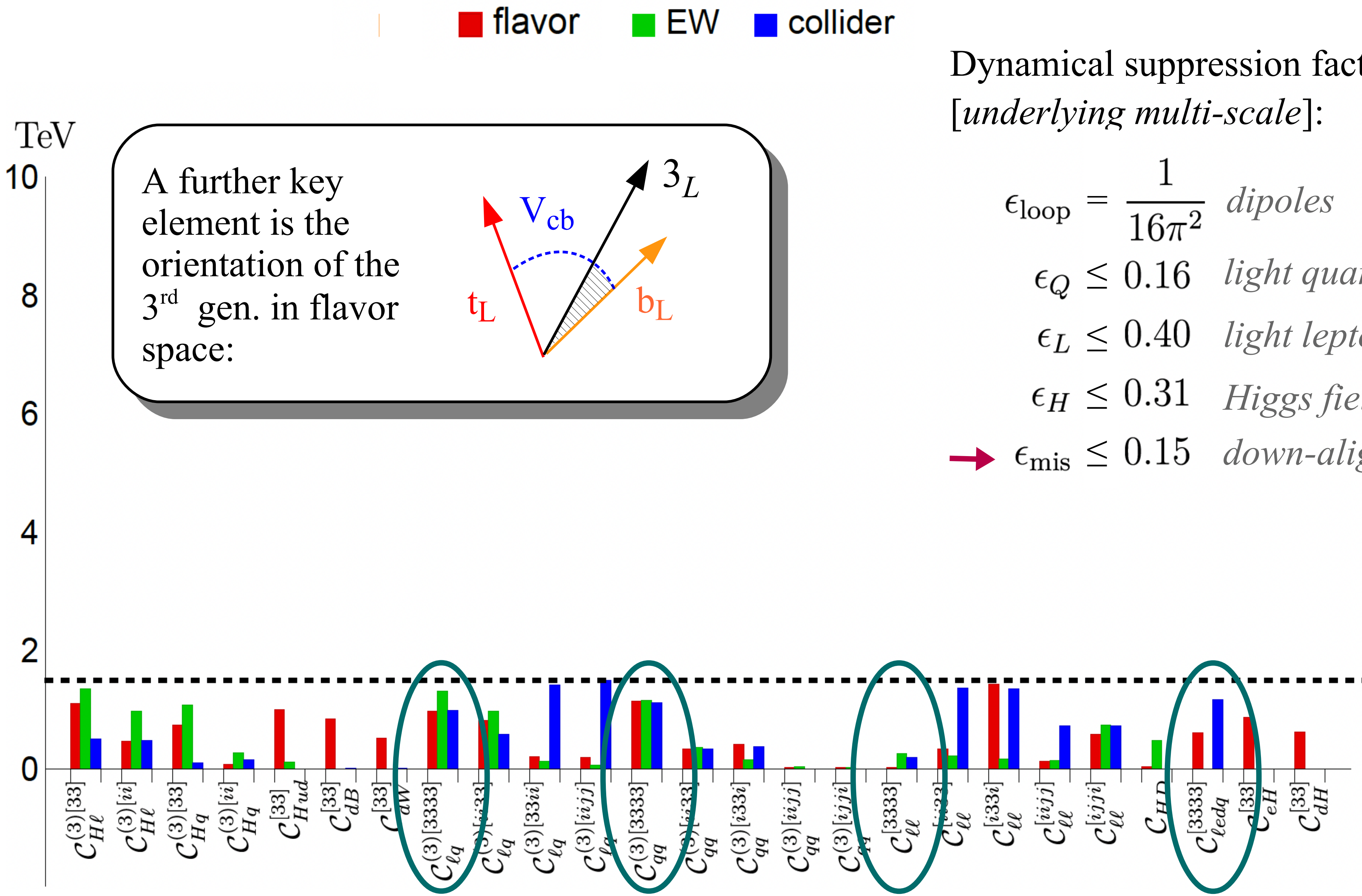

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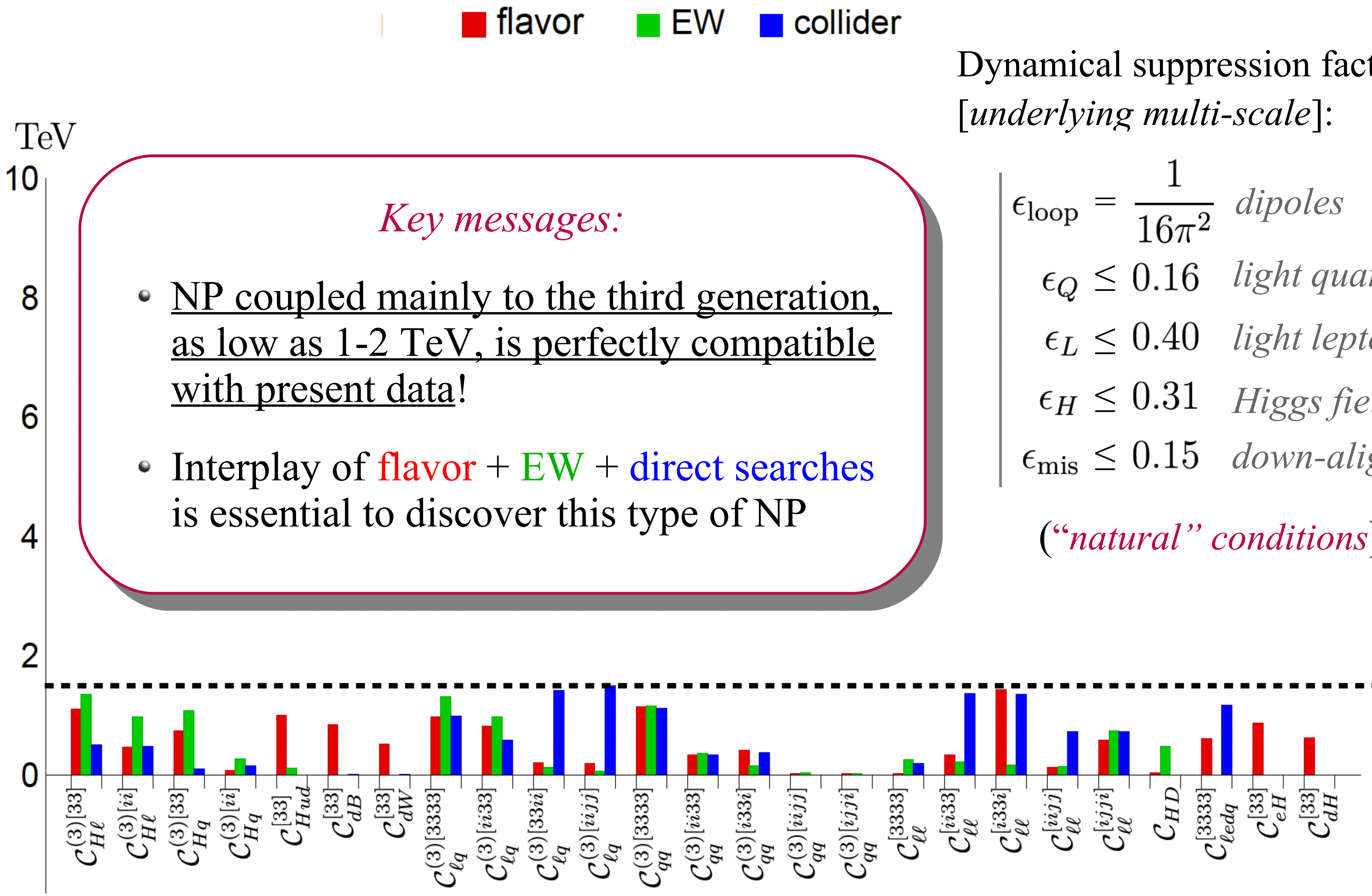

Key messages:

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

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(*"natural" conditions*)

Future prospects

"It is very difficult to make predictions, especially about the future"

[attributed to Niels Bohr]

▸ *Future prospects* [On the relevance of indirect NP searches]

In the last 50 years, all the discoveries at the High-Energy frontier [c, b, t, H] were anticipated by indirect indications from flavor and EW observables

A posteriori... it is also easy to admit that LEP & B-factories where clearly indicating a light Higgs and a mass gap above the SM spectrum.

Hard to expect a discovery at High Energies without indirect clues at low energies...

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

$$\Downarrow$$

$$A(\psi_i \to \psi_j + X) = A_0 \left[\frac{c_{SM}}{M_W^2} + \frac{c_i}{\Lambda^2} \right] \qquad (\textit{EW \& falvor obs.})$$

Future prospects [On the relevance of indirect NP searches]

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Can we agree on that?

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- Given current bounds on Λ do not exceed 1-2 TeV for a wide class of motivated modes, assuming no NP up to very high energies is nonsense...

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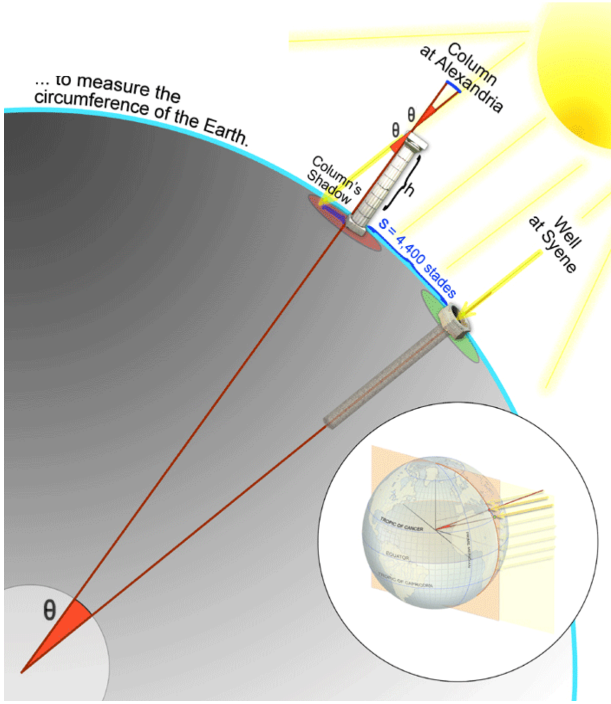

- Given current bounds on Λ do not exceed 1-2 TeV for a wide class of motivated modes, assuming no NP up to very high energies is nonsense...
- On the other hand, emabarking into a new high-energy effort without a clear clue of where NP could be, is a very high risk I'm not sure is worth to undertake (*Colombo would have never started his travel wothout an estimate of earth's radius...*)

▸ *Future prospects* [On the physics case of FCC-ee]

The FCC-ee offers a unique opportunity in this respect with the huge statistics @ the Z pole:

$$A(\psi_i \rightarrow \psi_j + X) = A_0 \left[\frac{c_{SM}}{M_W^2} + \frac{c_{NP}}{\Lambda^2} \right]$$

Λ_{NP}		→	$20 \times \Lambda_{NP}$	
c_{NP}	N_Z [LEP]		$0.002 \times c_{NP}$	$3\times10^5 N_Z$ [FCC-ee]

For th. clean observables (pure stat. error) determined by Z decays

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Λ_{NP} c_{NP}	$b\bar{b}$, $\tau\bar{\tau}$ [Belle]	→	$5.6 \times \Lambda_{NP}$ $0.03 \times c_{NP}$	$10^3 \times$ $b\bar{b}$, $\tau\bar{\tau}$ [FCC-ee]

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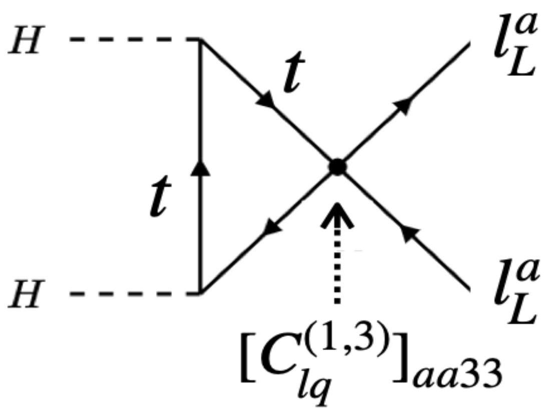
highly boosted b & τ

For $b\bar{b}$ & $\tau\bar{\tau}$ pairs we have to take into account also Belle-II (~ 50 × Belle), & LHCb

But...
→ LHCb is poor on missing-energy modes (*virtually all tau decays..*)
→ At Belle-II there are no B_s, and b & τ have a very small boost

▸ Future prospects [On the physics case of FCC-ee]

Such level of precison on EW physics leads to an unprecedented level of precision to a wide class of NP (*in particular NP coupled mainly to 3rd gen.*) via RG effects.



$$\dashrightarrow \quad [C_{Hl}^{(1,3)}]_{aa} \quad \Rightarrow \quad Z \to ll$$

Garosi, Marzocca, Sanchez, Stanzione, 23
Allwicher, Cornella, GI, Stefanek, '23
Allwicher, McCullough, Renner, '24
...

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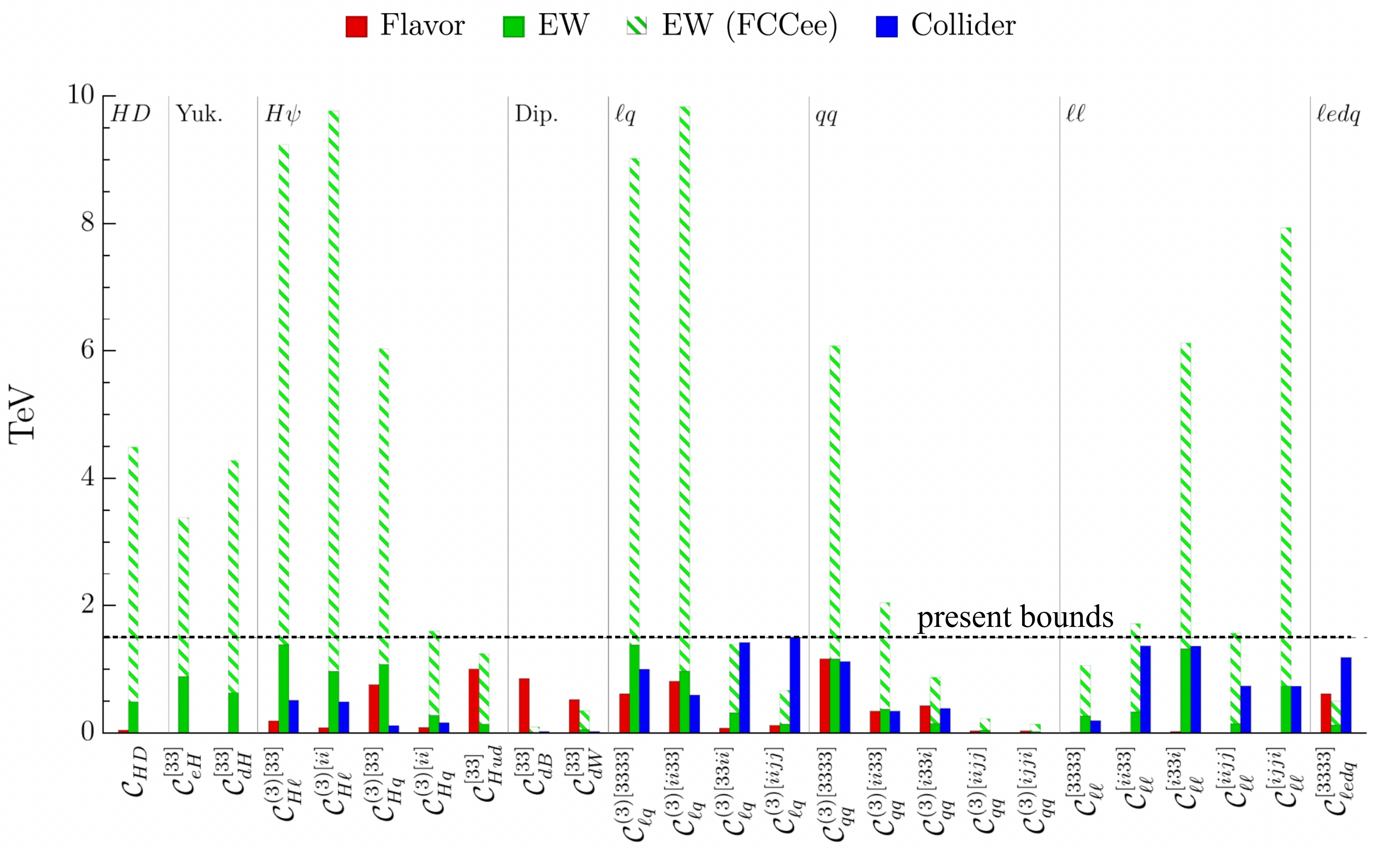

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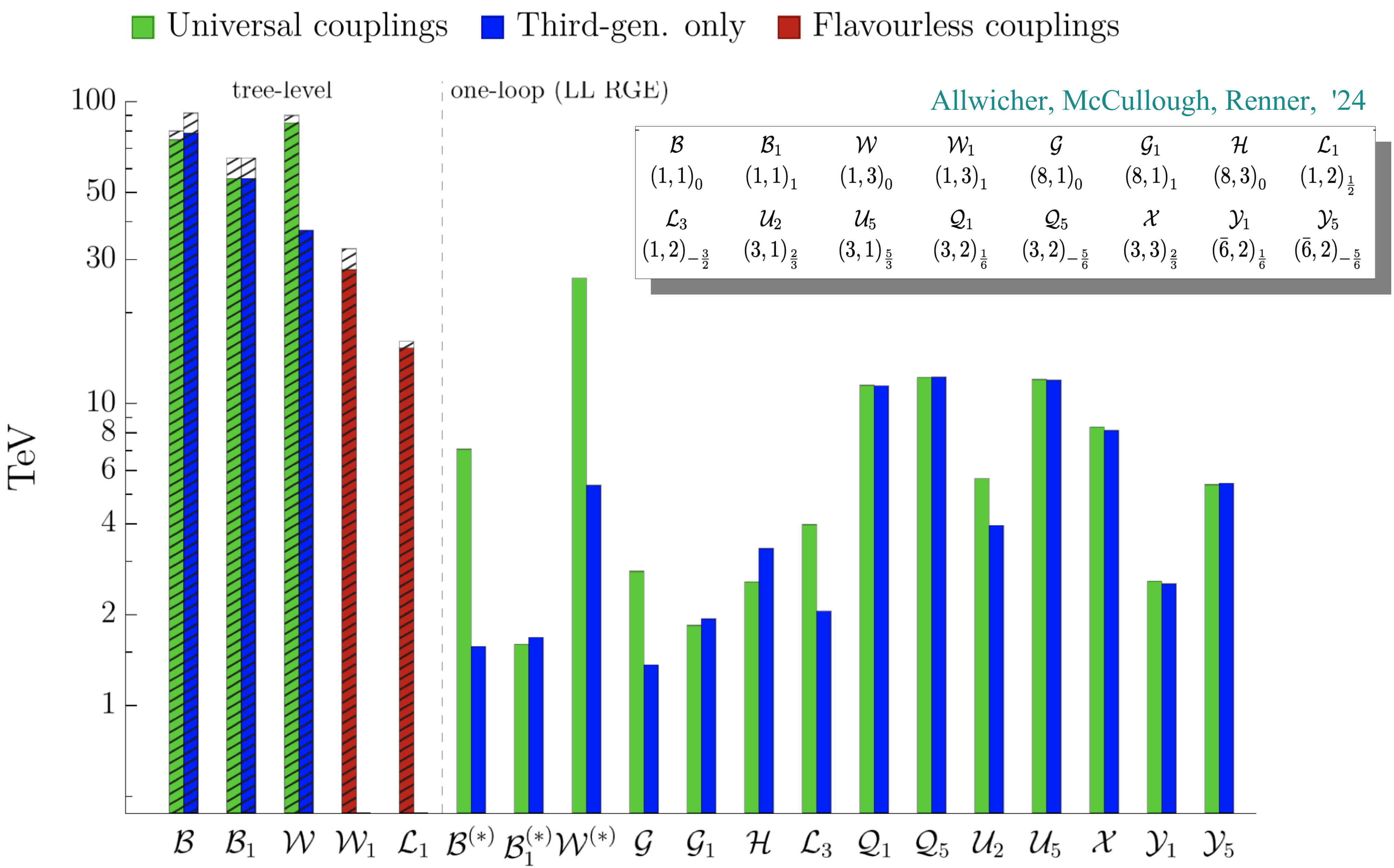


Future prospects [On the physics case of FCC-ee]

And of course we should not forget the Higgs program of FCC-ee...

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

$\to O(\frac{v^2}{f^2})$ in composite Higgs models

Test of Higgs compositness and, more-generally,
of fine-tuning in the Higgs secotr, at the per-mill level

Conclusions

- How large is the mass gap above the SM spectrum?
  No clear answer so far, but premature to think this gap is very large.

- Giving up the prejudice of flavor universality, reveals a wide class of well-motivated models with
  - *new degrees of freedom in the TeV domain, as suggested by the EW hierarchy problem*
  - *able to addresses both "flavor problems"*

- In this class of models, NP could be around the corner and might show up at HL-LHC and/or in near-future flavor-physics experiments.
  However, FCC-ee would be the ideal machine to thoroughly explore this option.

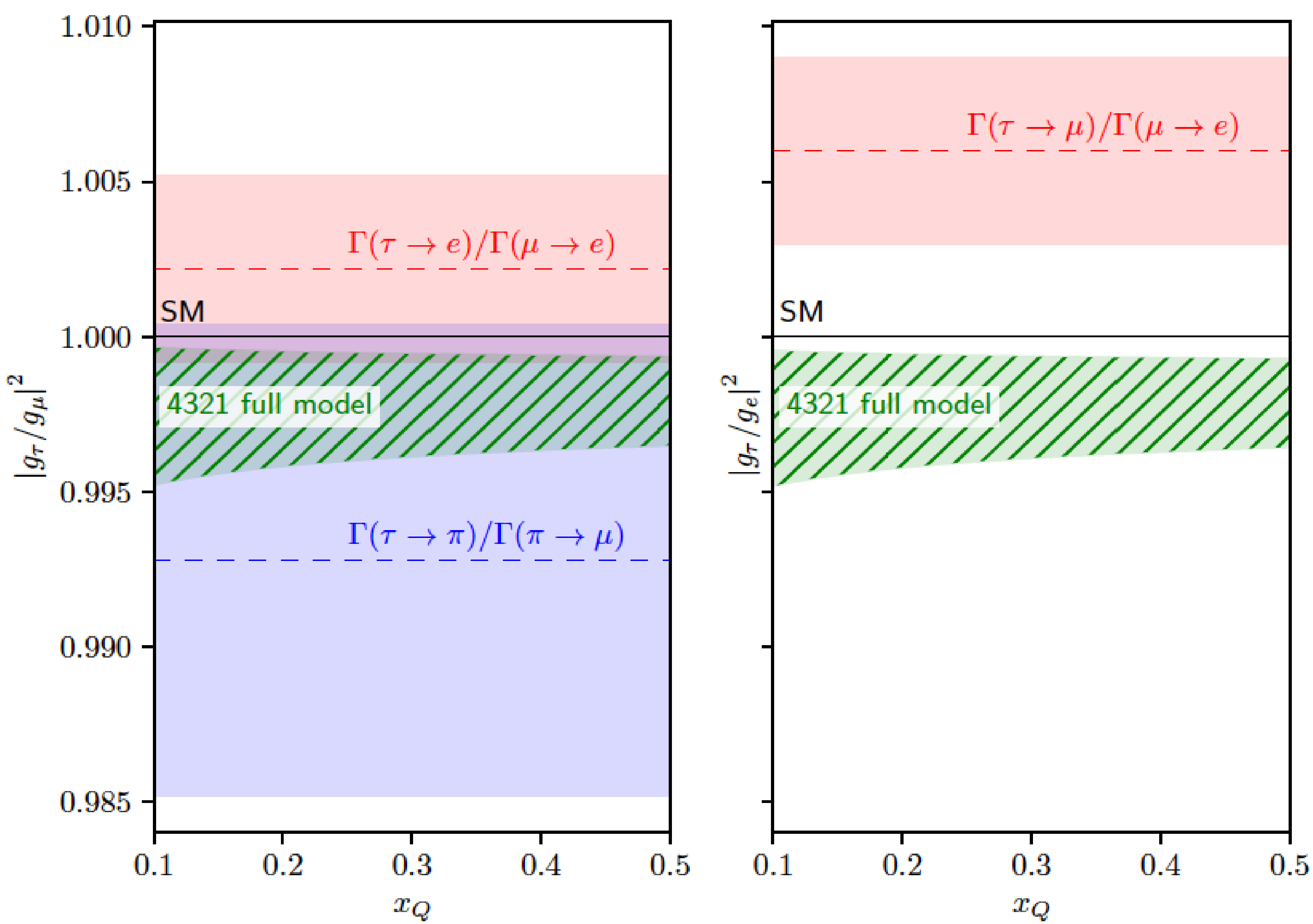
- More generally, the combined potential on EW, flavor, and Higgs physics of FCC-ee provides a very efficient strategy to determine where the next energy threshold lies.

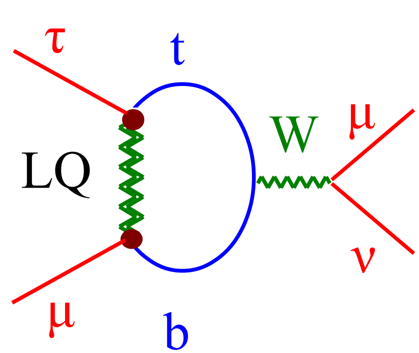
Highlights of FCC-ee in tau & b physics

E.g.: (I) LFU tests in tau decays

LFU violations in tau decays expected in models addressing exisitng tension in b → cτν decays

Allwicher *et al.* '21, '22





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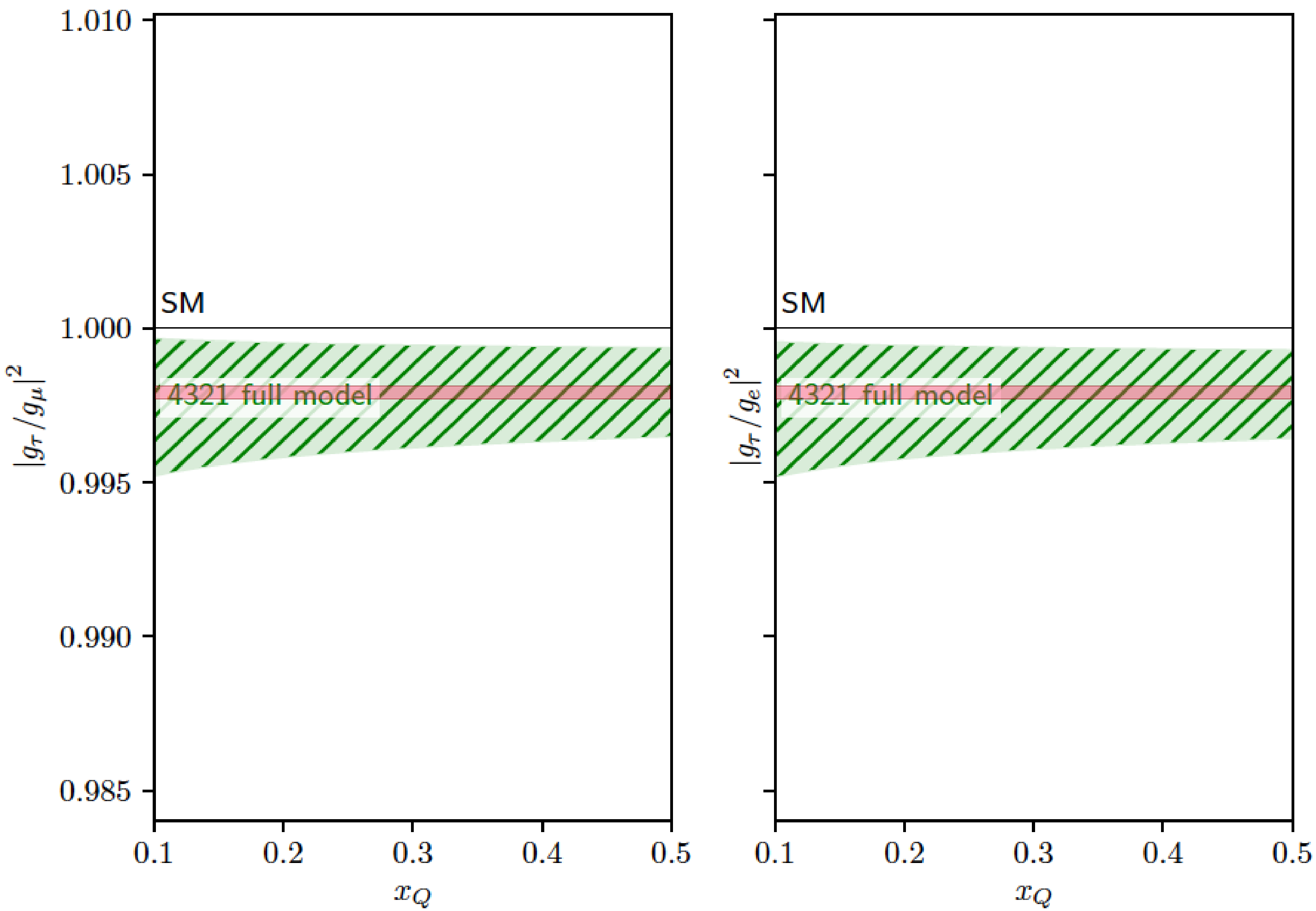

4321 model

hypothetical 3σ bands with Γ(τ→μνν) & Γ(τ→eνν) @ 2×10^{-4}

Highlights of FCC-ee in tau & b physics

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Cornella *et al.* '21

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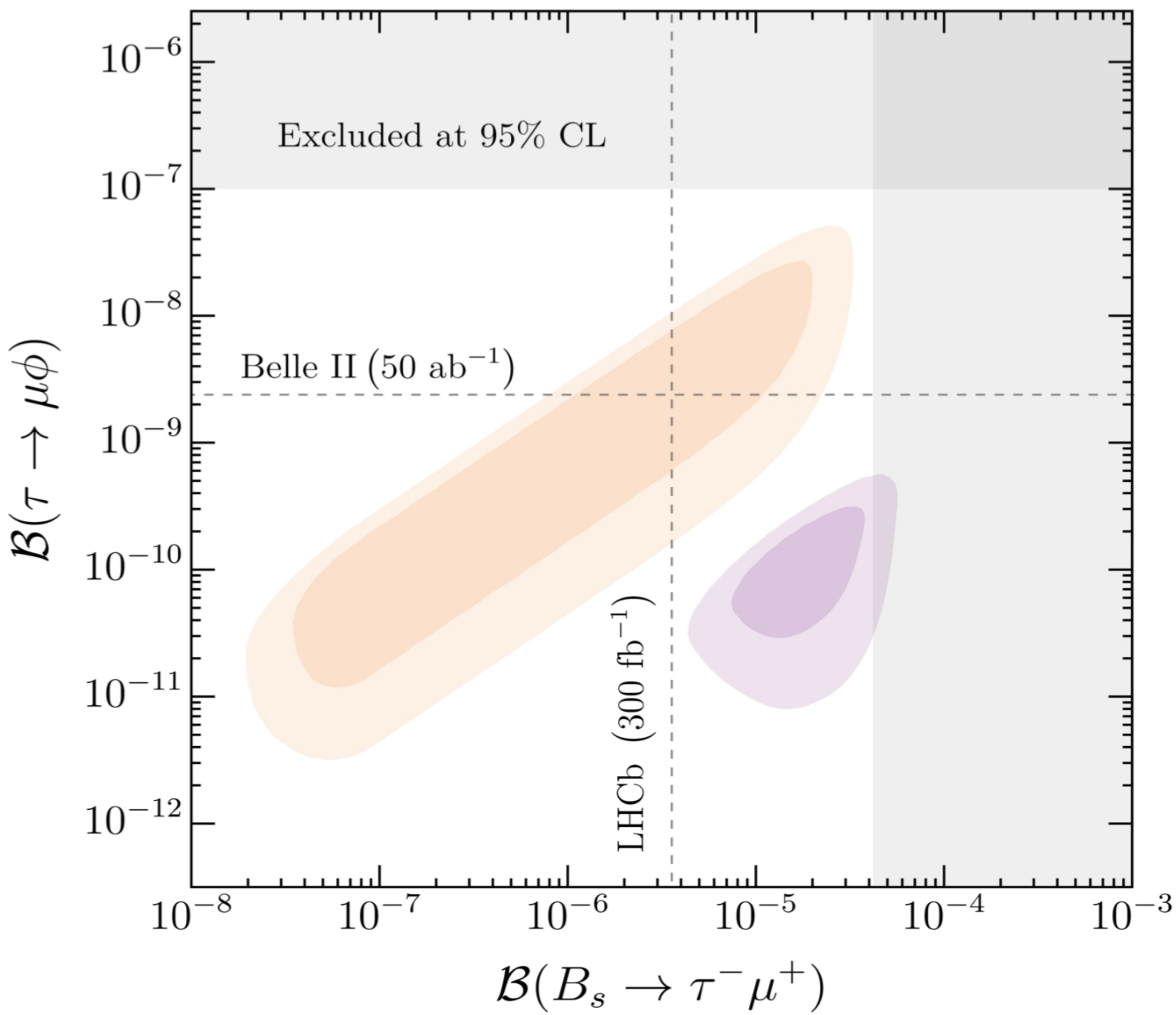

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