New physics and flavor: current insights and future prospects

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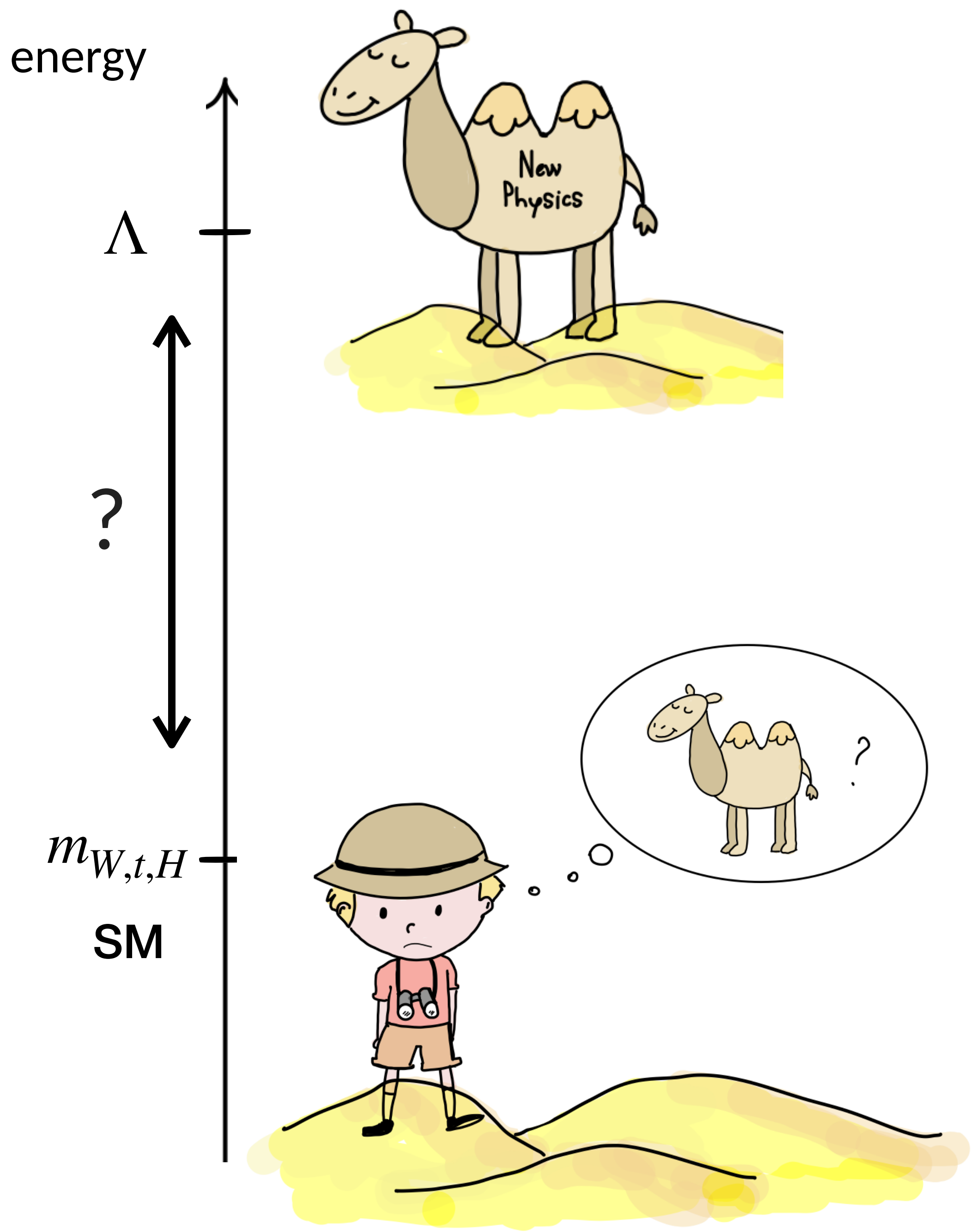
October 3rd, 2024 || Laboratori Nazionali di Frascati

The scale of new physics

No direct evidence of BSM.
We are facing a **mass gap**.

How large?



The scale of new physics, in theory

- The **Higgs mass** is **unstable** under quantum corrections.
  If there's nothing else, its naive scale is the **Planck** mass.

  In the SM, the largest contribution comes from the top.

  To keep the Higgs mass at its measured value, need some **NP coupled to** the **Higgs** and **top** around the **TeV scale**.

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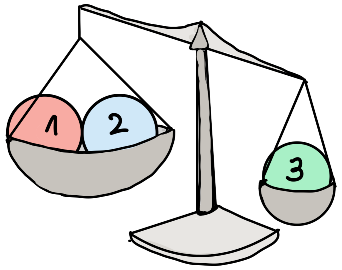
- If the **flavor puzzle** is linked to the hierarchy problem (involving the 3rd family), then the solution could also emerge around the TeV scale.



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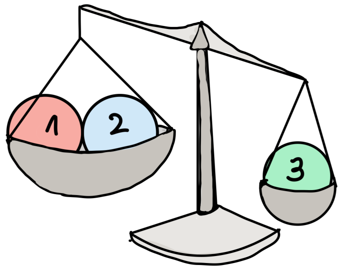

- Challenges like dark matter, dark energy, inflation, and baryon asymmetry are more difficult to link directly to a specific scale accessible by colliders.

The scale of new physics, from data

Without direct evidence of New Physics, we rely on the **SMEFT**

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_{i=1}^{N_5} C_i^{(5)} O_i^{(5)} + \frac{1}{\underbrace{\Lambda^2}_{\text{NP scale}}}\sum_{i=1}^{N_6} \underbrace{C_i^{(6)}}_{\text{unknown Wilson coefficients}} \underbrace{O_i^{(6)}}_{\text{higher-dimensional operators}} + \mathcal{O}\left(\frac{E^3}{\Lambda^3}\right)$$

which gives a **model-independent**, efficient framework to constrain (any) heavy BSM affecting **different sectors & energy regimes**.

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NP scale

unknown
Wilson coefficients

higher-dimensional
operators

which gives a **model-independent**, efficient framework to constrain (any) heavy BSM affecting **different sectors & energy regimes**.

In practice:

- use data (EW precision, flavor, collider…) to constrain the C_i
- interpret constraints as lower bounds on an **effective NP scale** $\Lambda^i_{\mathrm{eff}} = \frac{\Lambda}{\sqrt{C_i}} \sim \frac{M}{g}$

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An **example** from the past:

In the 1970s, the “SM” had two quark families, & CP was an accidental symmetry. CPV in K mixing suggested a huge NP scale…

$$\frac{1}{\Lambda_{\mathrm{CP}}^2}(\bar{s}\,\Gamma\, d\,)^2 \;\Rightarrow\; \Lambda_{\mathrm{CP}} \sim 10^4\,\mathrm{TeV}$$

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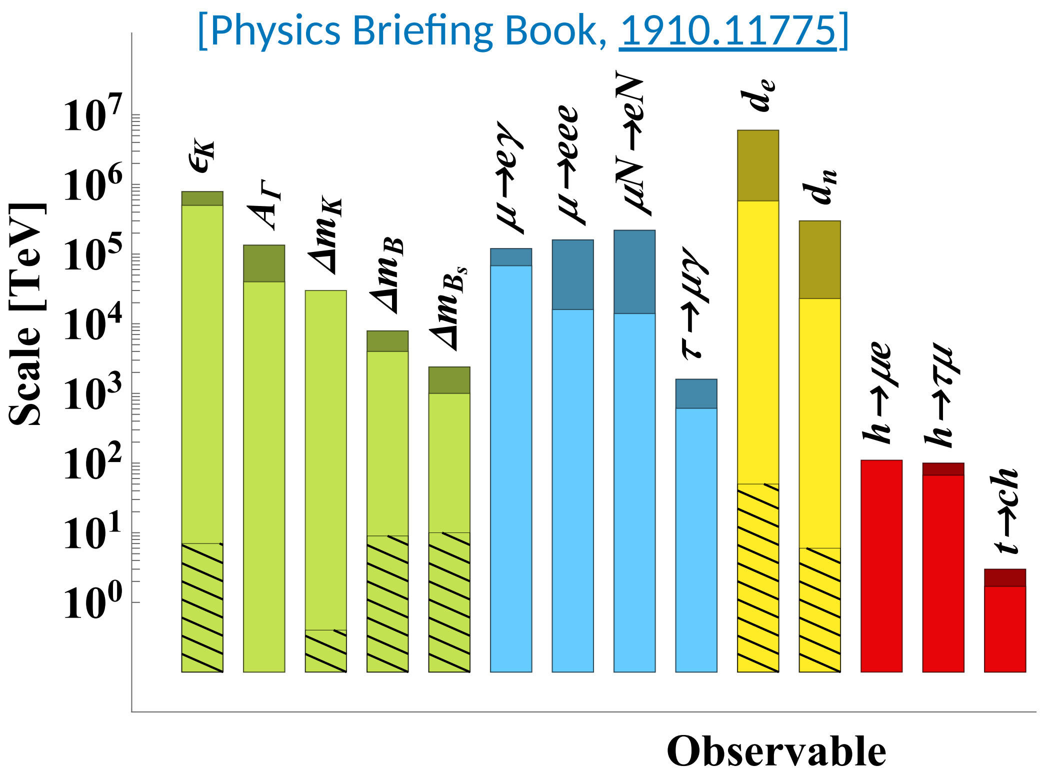
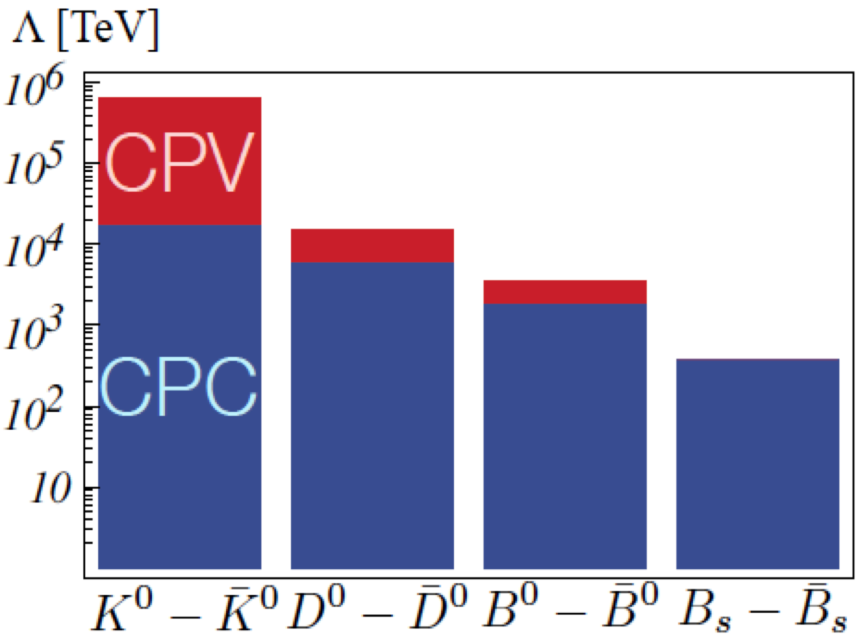
…but the real scale was much lower, because CP is a good approximate symmetry also with 3 generations (broken only by weak interactions)!

The importance of flavor assumptions, today

Similar caution is needed when interpreting **SMEFT** bounds today:
with O(1) NP couplings, bounds on flavor-violating operators point to huge scales…



[Physics Briefing Book, 1910.11775]



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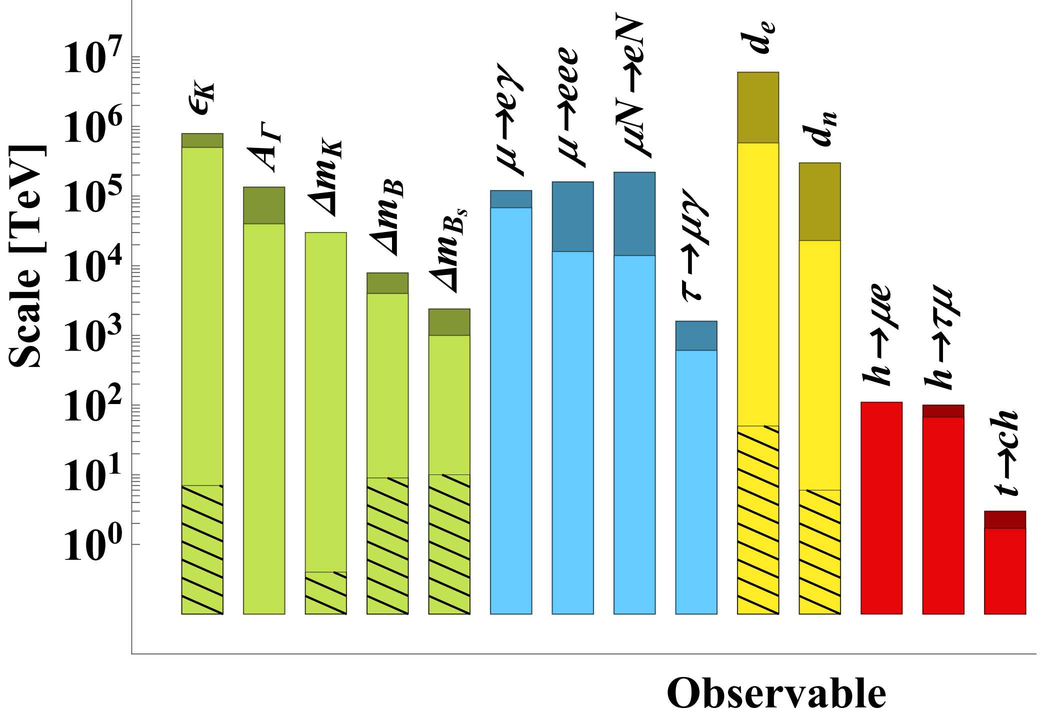

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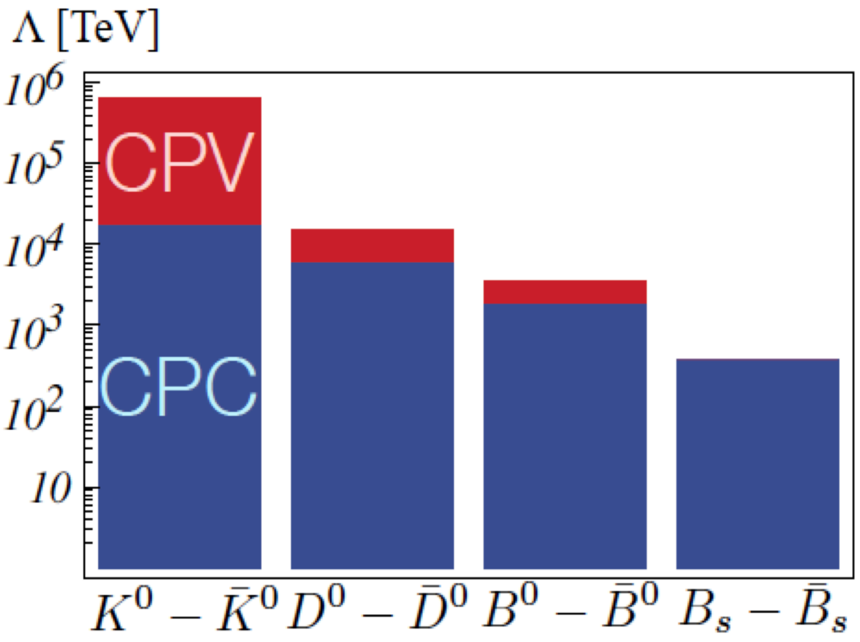

….but in realistic models [with a flavor structure!] these couplings can be suppressed, and give much looser constraints!

⇒ Making **educated assumptions about the NP structure** and translating them into selection rules in the SMEFT can provide a more informative interpretation of bounds.

Flavor symmetries to the rescue

Use **accidental symmetries** of the SM as **guidance.**

The SM has an approximate $U(2)^5$ flavor symmetry:

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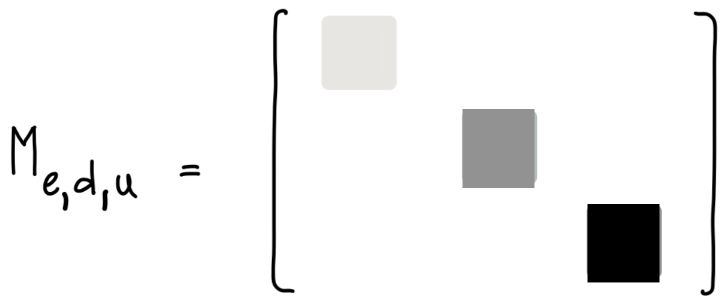
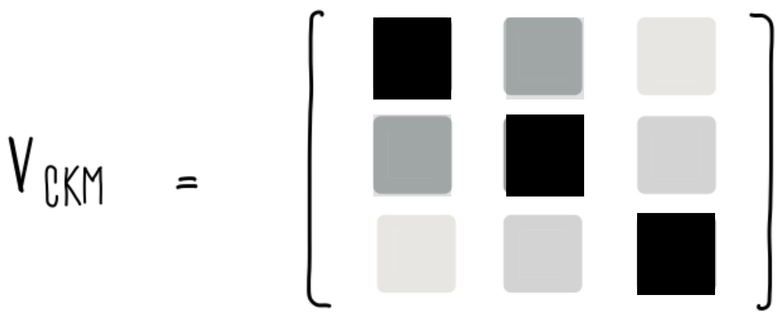




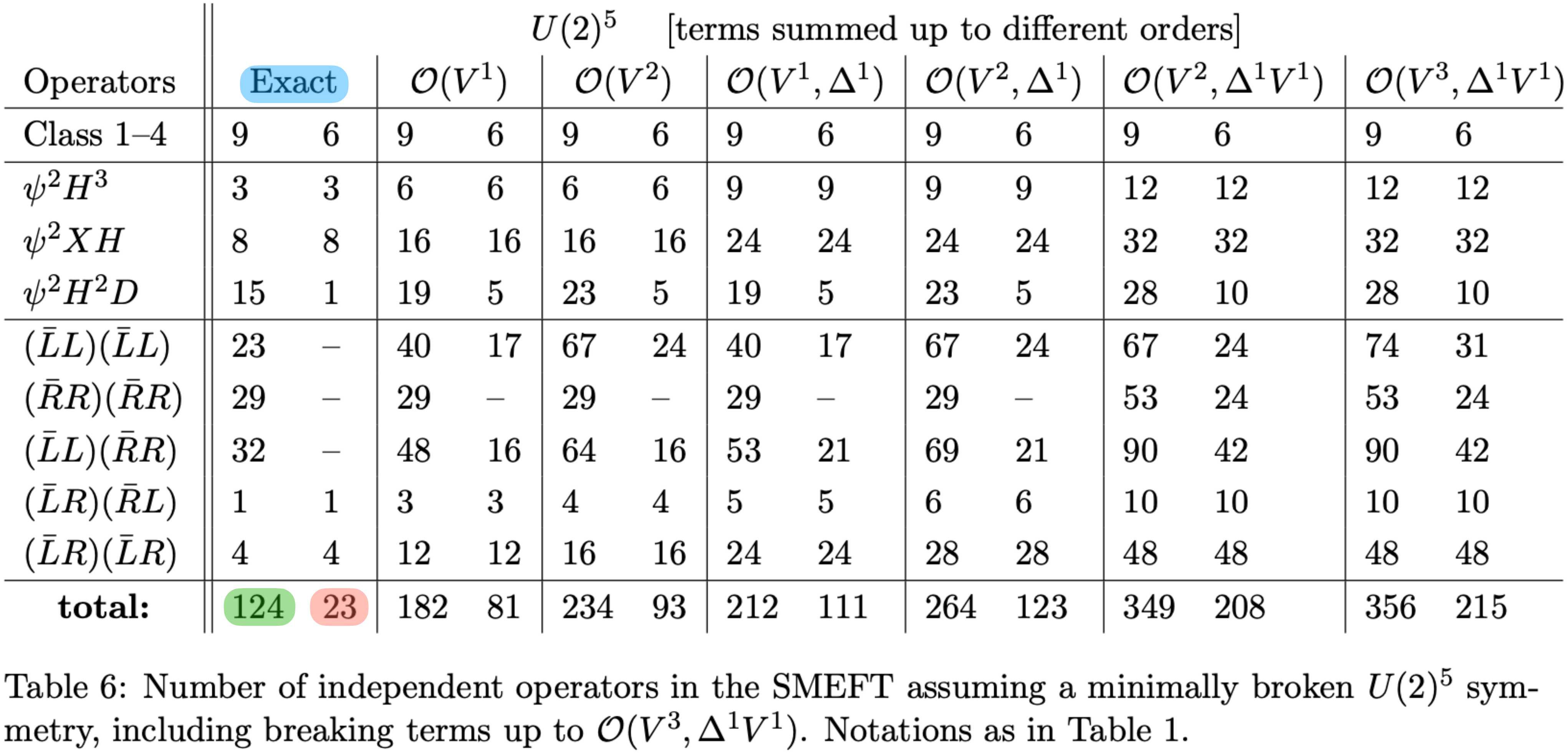
What flavor data tells us that NP does to:
there is **no large breaking** of U(2)^5 at **nearby** scales!

As long as it respects U(2), NP can exist at lower scales.

The U(2)-symmetric SMEFT

$U(2)^5$ is an **efficient organising principle**:

- The SMEFT with 3 generations has 1350 + 1149 = 2499 independent WCs at dim-6.
- In the exact $U(2)^5$ limit, this is reduced to 124 + 23 = 147 independent WCs.



$U(2)^5$ [terms summed up to different orders]

Operators	Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1V^1)$		$\mathcal{O}(V^3,\Delta^1V^1)$	
Class 1–4	9	6	9	6	9	6	9	6	9	6	9	6	9	6
ψ^2H^3	3	3	6	6	6	6	9	9	9	9	12	12	12	12
ψ^2XH	8	8	16	16	16	16	24	24	24	24	32	32	32	32
ψ^2H^2D	15	1	19	5	23	5	19	5	23	5	28	10	28	10
$(\bar{L}L)(\bar{L}L)$	23	–	40	17	67	24	40	17	67	24	67	24	74	31
$(\bar{R}R)(\bar{R}R)$	29	–	29	–	29	–	29	–	29	–	53	24	53	24
$(\bar{L}L)(\bar{R}R)$	32	–	48	16	64	16	53	21	69	21	90	42	90	42
$(\bar{L}R)(\bar{R}L)$	1	1	3	3	4	4	5	5	6	6	10	10	10	10
$(\bar{L}R)(\bar{L}R)$	4	4	12	12	16	16	24	24	28	28	48	48	48	48
total:	124	23	182	81	234	93	212	111	264	123	349	208	356	215

Table 6: Number of independent operators in the SMEFT assuming a minimally broken $U(2)^5$ symmetry, including breaking terms up to $\mathcal{O}(V^3,\Delta^1V^1)$. Notations as in Table 1.

[D. A. Faroughy, G. Isidori, F. Wilsch, K. Yamamoto, arXiv:2005.05366]

The U(2)-symmetric SMEFT, universal

Without additional assumptions, $U(2)^5$ is close in spirit to **Minimal Flavor Violation**:

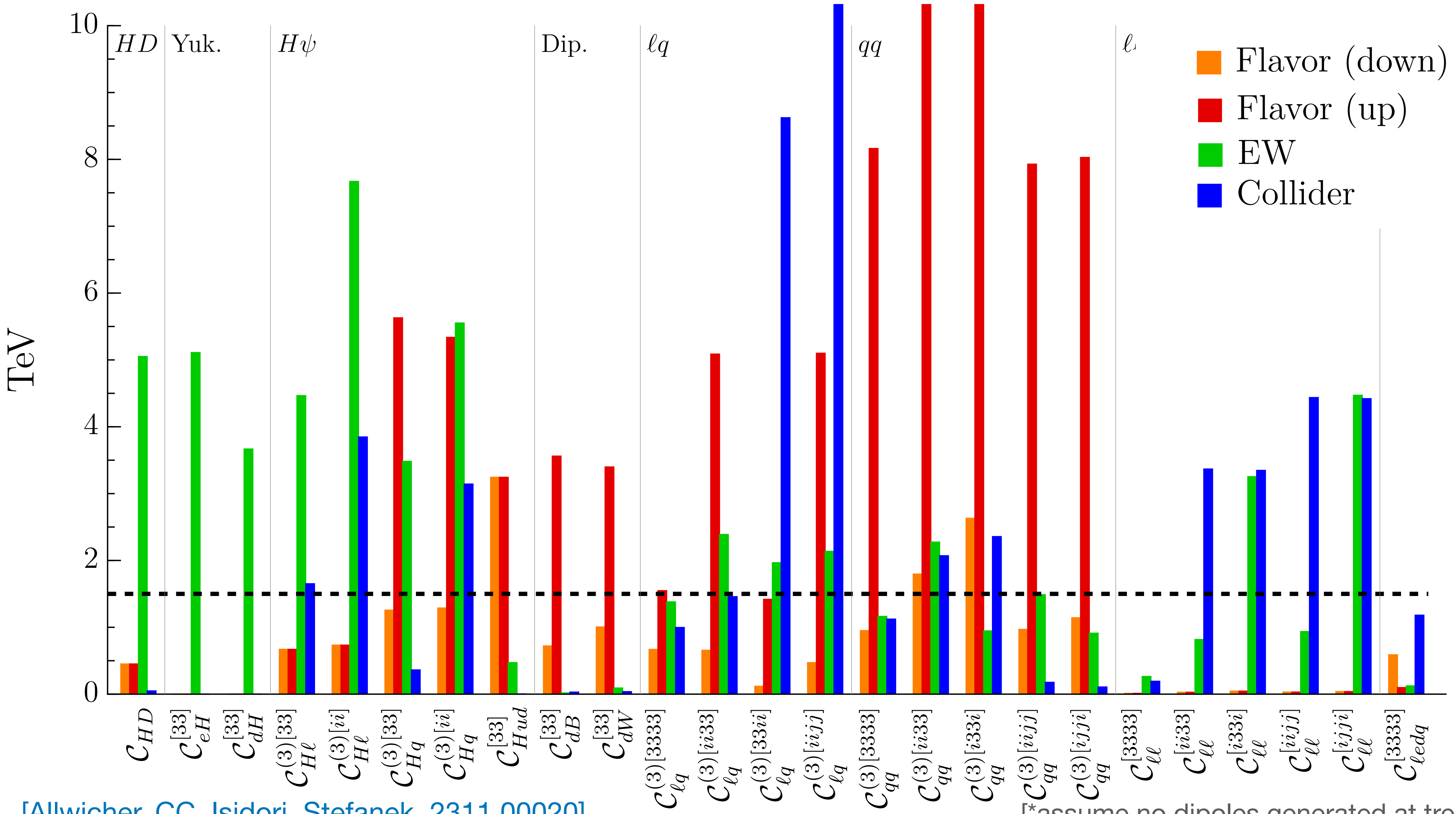
- Yukawas couplings are the only sources of flavor violation, NP is to a good approximation **flavor-universal**

- by construction, CKM-like suppression on flavor-changing processes, but flavor-diagonal couplings to valence quarks are not suppressed $\Rightarrow$ LHC data pushes the scale of MFV NP to scales $\gtrsim$ **10 TeV**.

The U(2)-symmetric SMEFT, universal: bounds

complementarity:

1/3 of the bounds are dominated by EWPO, 1/3 by collider, 1/3 by flavor



[Allwicher, CC, Isidori, Stefanek, 2311.00020]

[*assume no dipoles generated at tree level]

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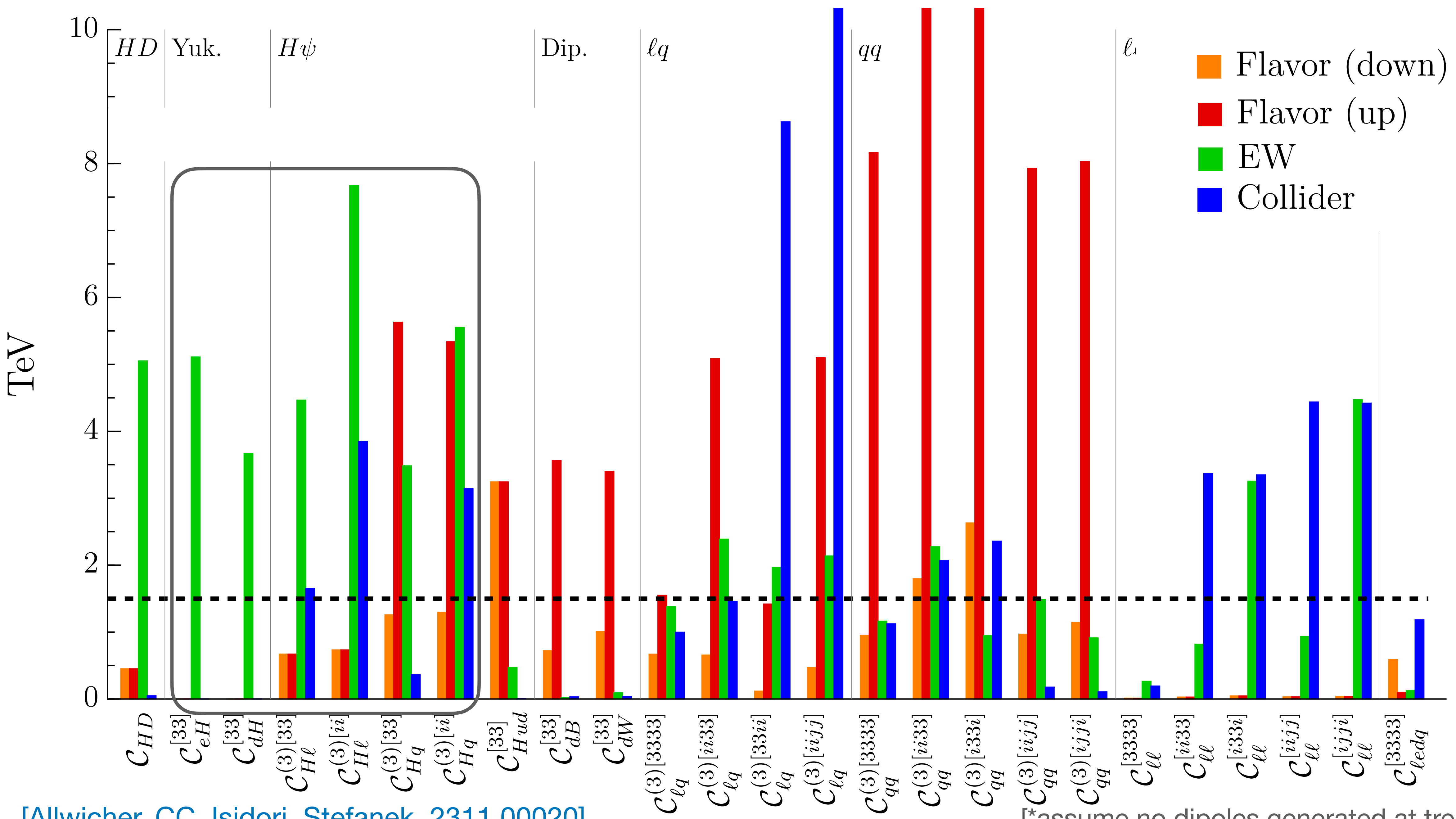
EW: • LEP dominates: 5 -10 TeV bounds for operators entering EWPOs at tree level.



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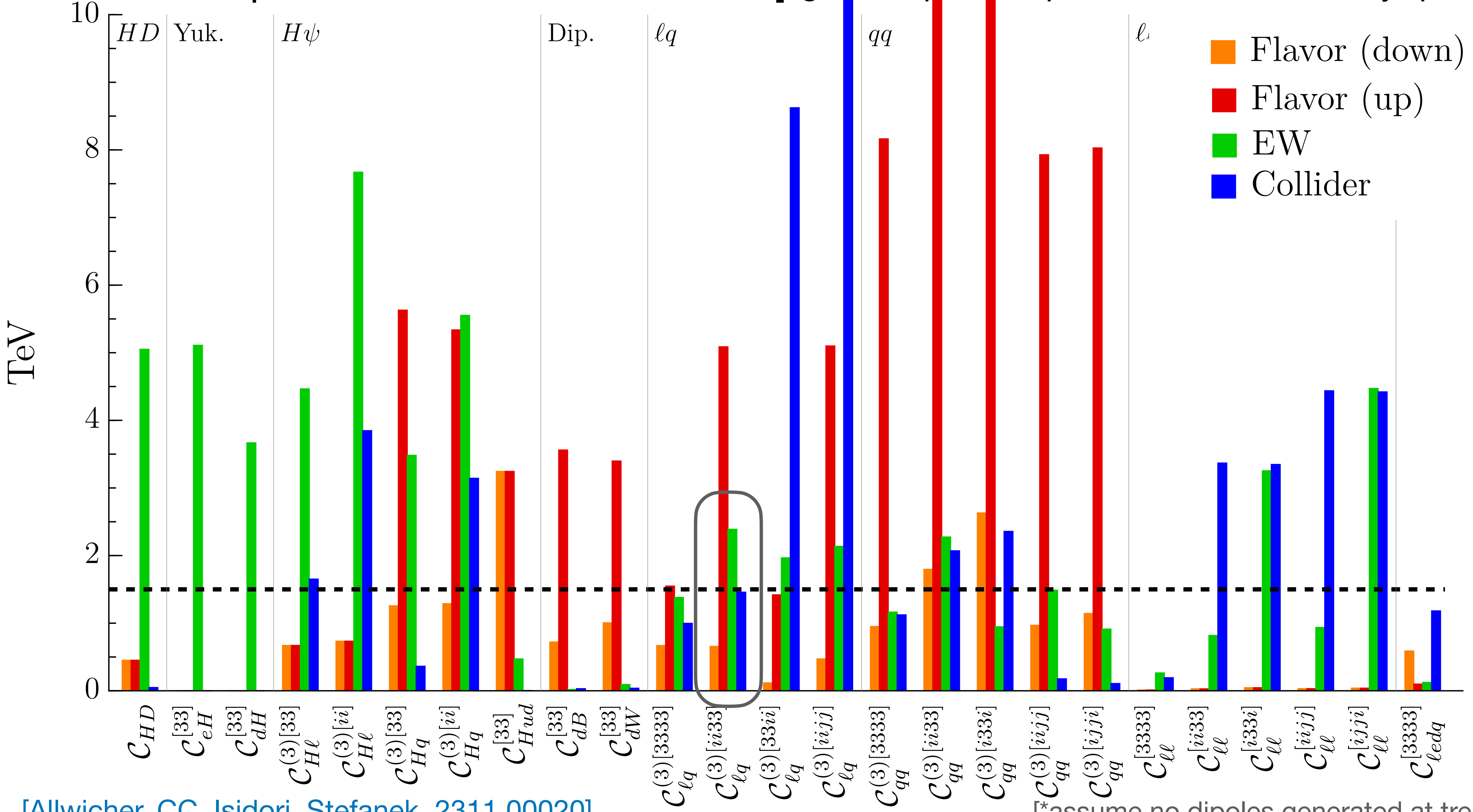
The U(2)-symmetric SMEFT, bounds

EW:
- LEP dominates: 5 -10 TeV bounds for operators entering EWPOs at tree level.
- Significant constraints on operators entering EWPO at one loop, sometimes competitive with direct searches. [eg semileptonic operators with 3rd family quarks]



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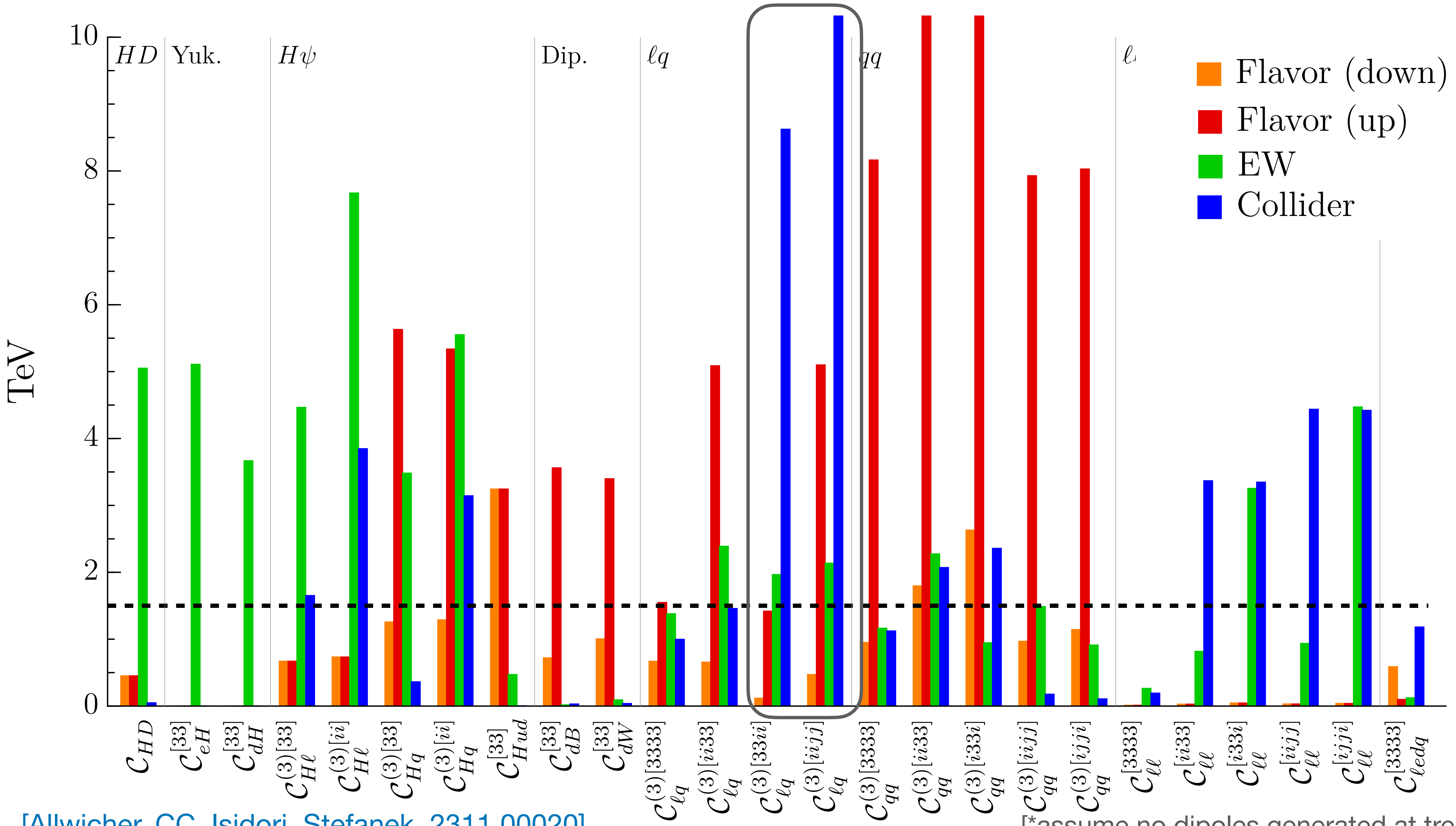
Collider:
- strongest bounds (~8 TeV) from Drell-Yan on ops. with light quarks



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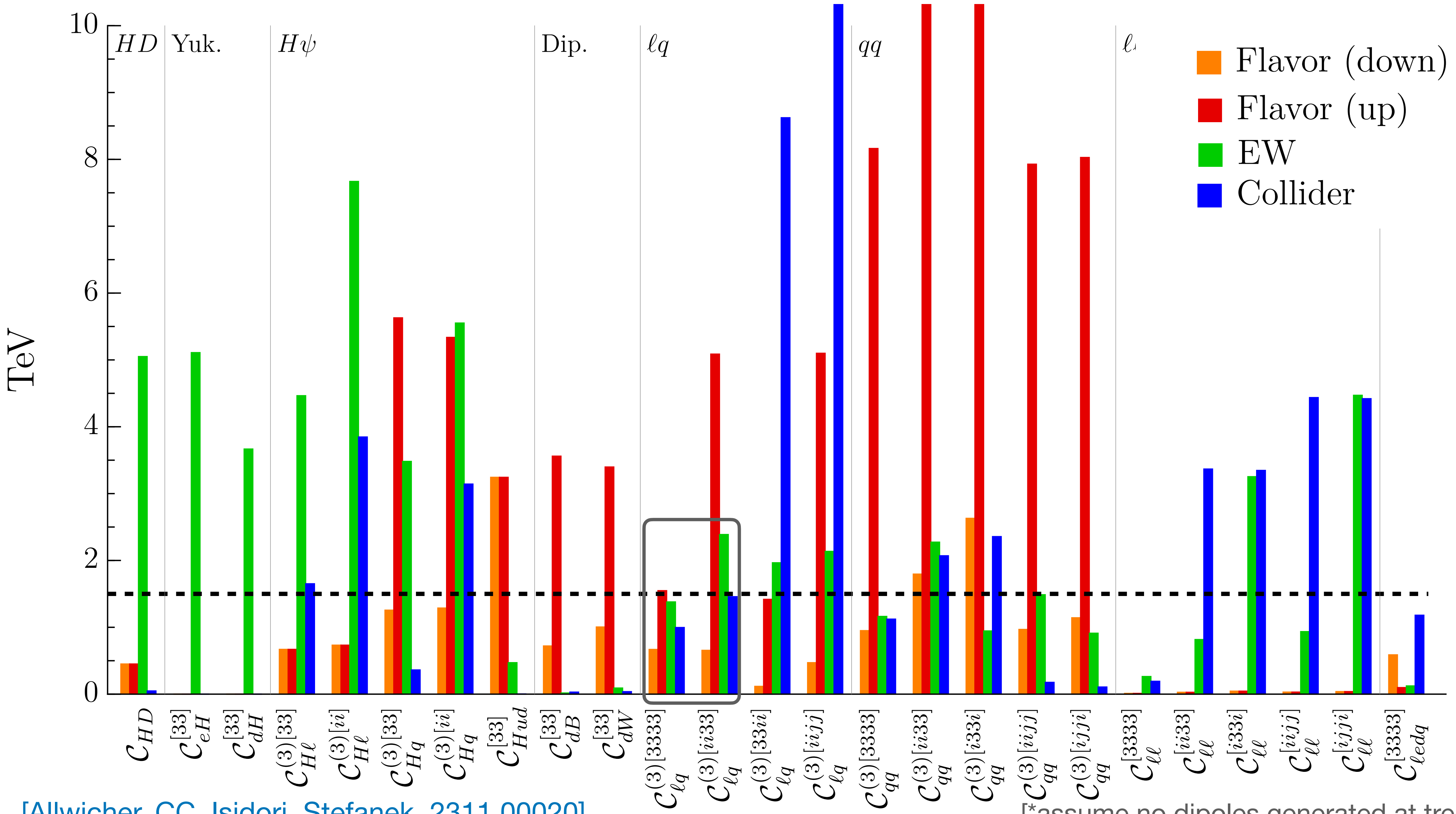
- 3rd family sees milder constraints (~1 TeV) due to proton composition



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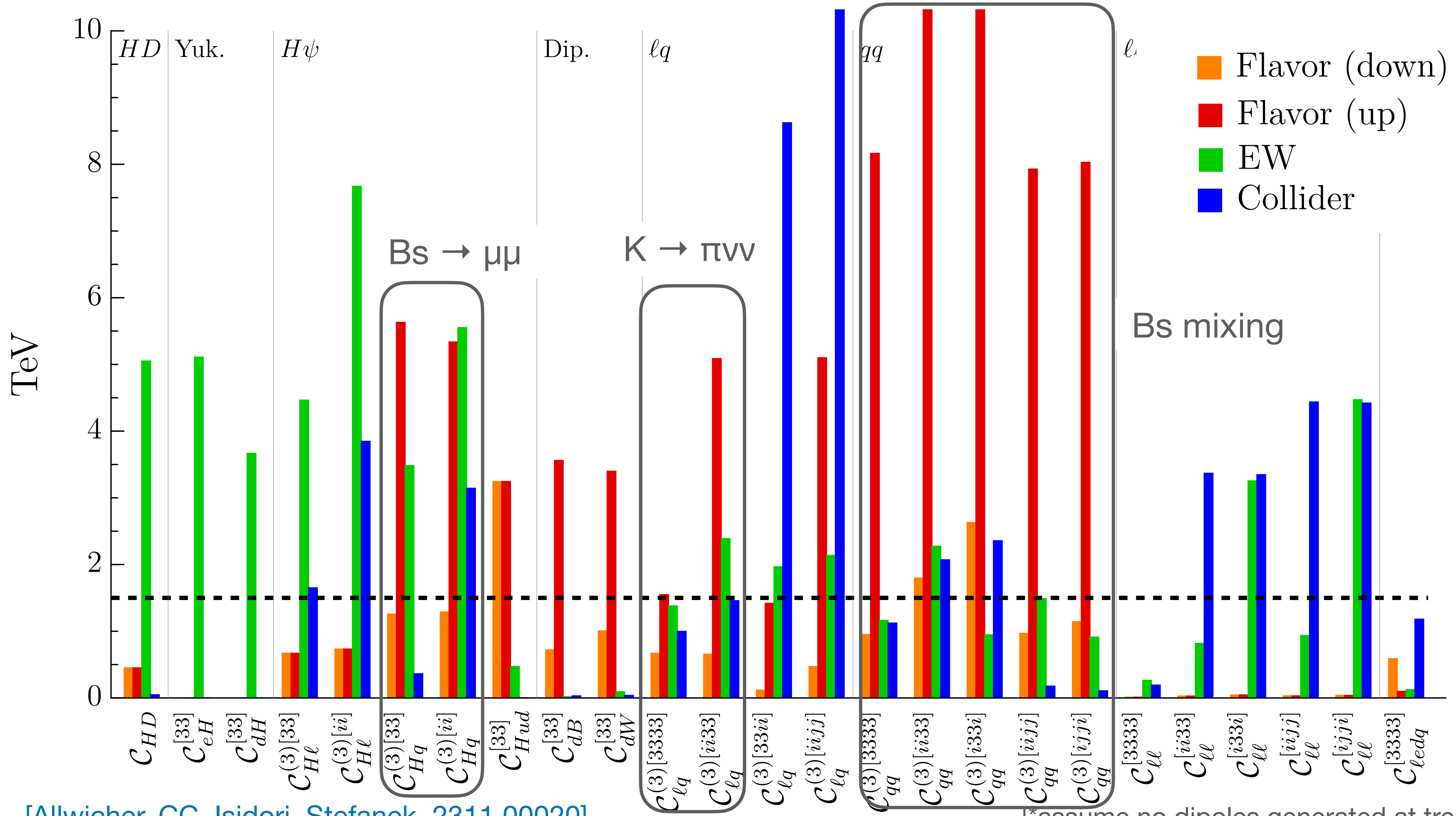
Flavor: • up-aligned: strongest bounds (~10 TeV) from B_s mixing, $B_s \to \mu^+\mu^-$, $K \to \pi\nu\nu$.



$B_s \to \mu\mu$

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B_s mixing

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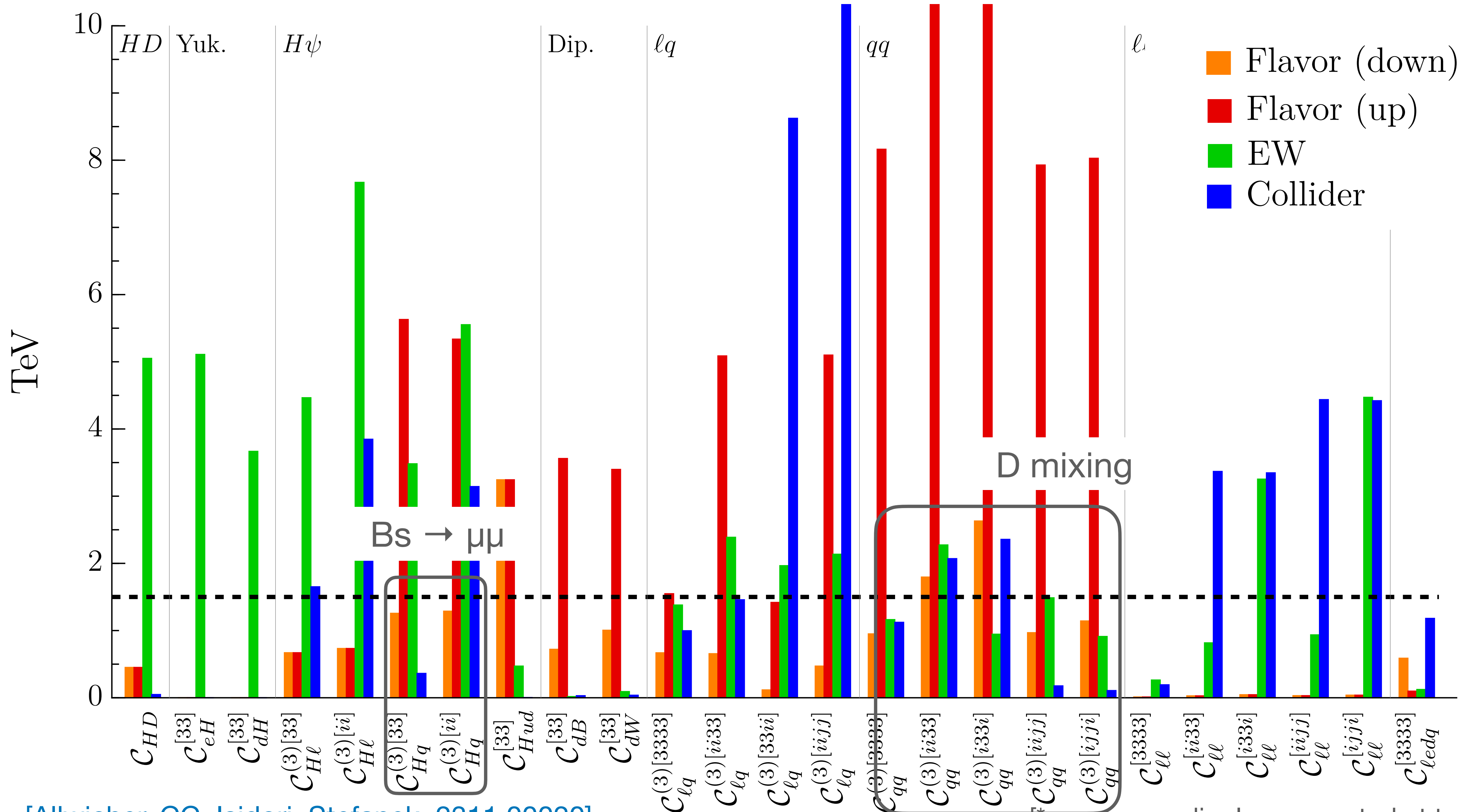
- down aligned: milder constraints (~few TeV) dominated by D mixing & $B_s \to \mu^+\mu^-$



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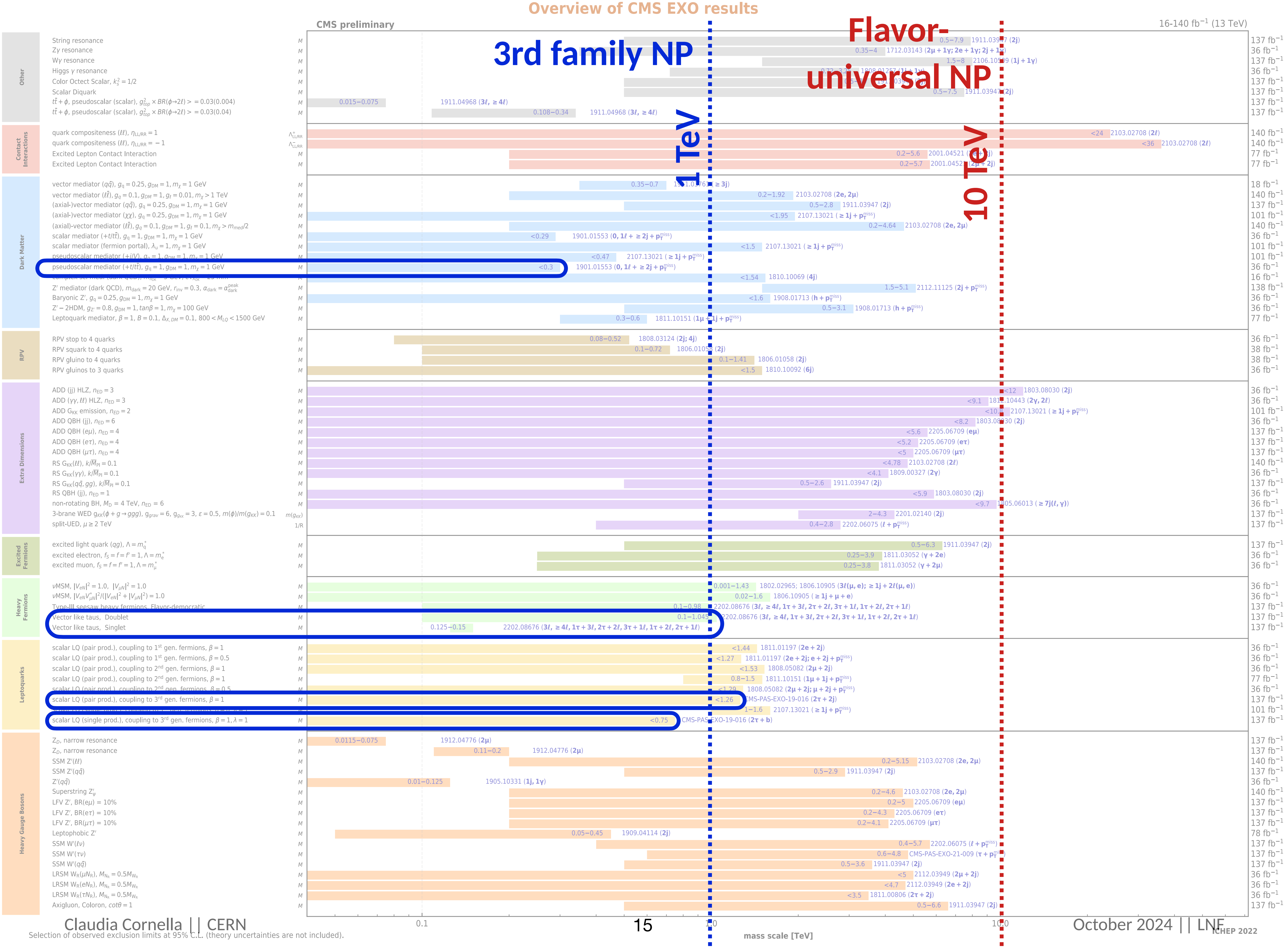
$U(2)^n$ allows to place a clear distinction between light & 3rd families, and can thus host **flavor-non-universal NP**, specifically NP **coupling dominantly** to the **3rd family**

Different NP couplings for light families make it possible to suppress couplings to valence quarks and relax direct search bounds to 1 TeV.

3rd family NP

Flavor-universal NP

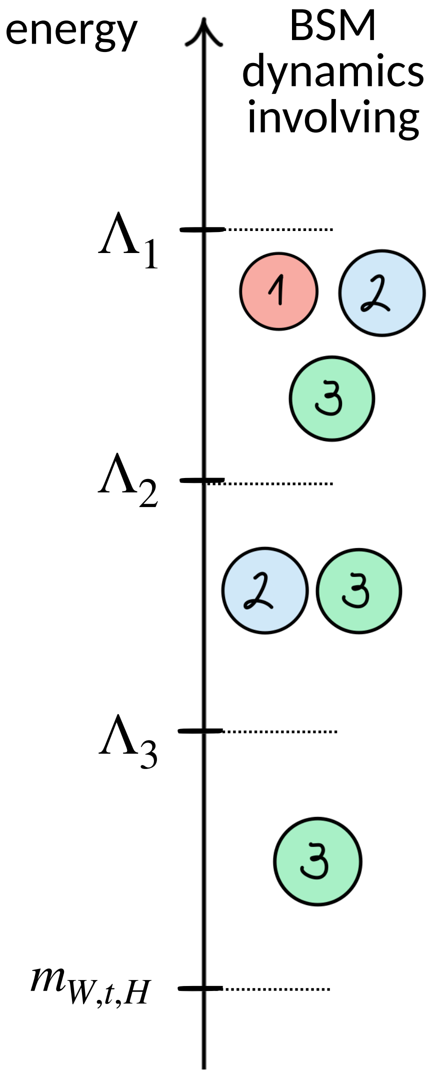


1 TeV

10 TeV

Flavor non-universality: the bigger picture

Key idea: The U(2) symmetry in the Yukawas and in the NP couplings has a single dynamical origin & is a remnant of a more fundamental difference.



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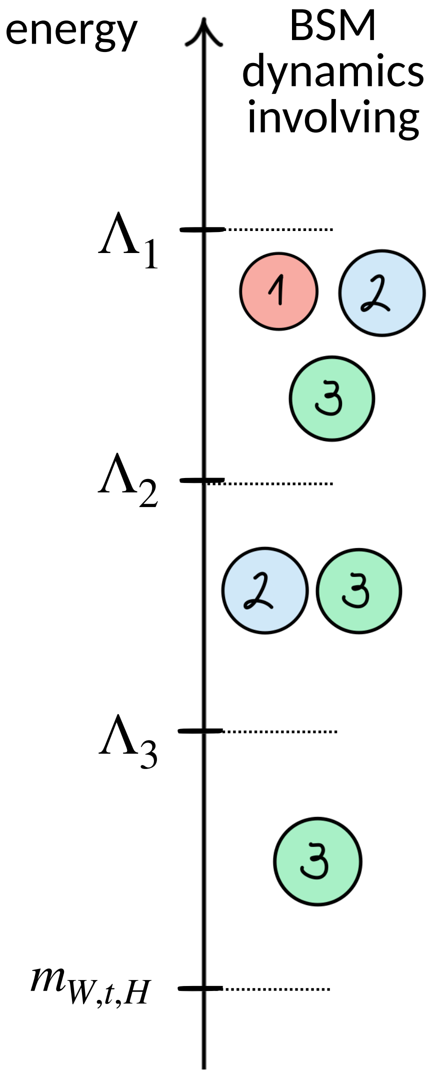

At high energies, the 3 **families** are **intrinsically different** objects.

Non-universal forces acting on the i-th SM family have characteristic scales $\Lambda_1 \gg \Lambda_2 \gg \Lambda_3 \gg m_W$.

The **flavor universality** of SM gauge interactions is an accidental **low-energy property**.

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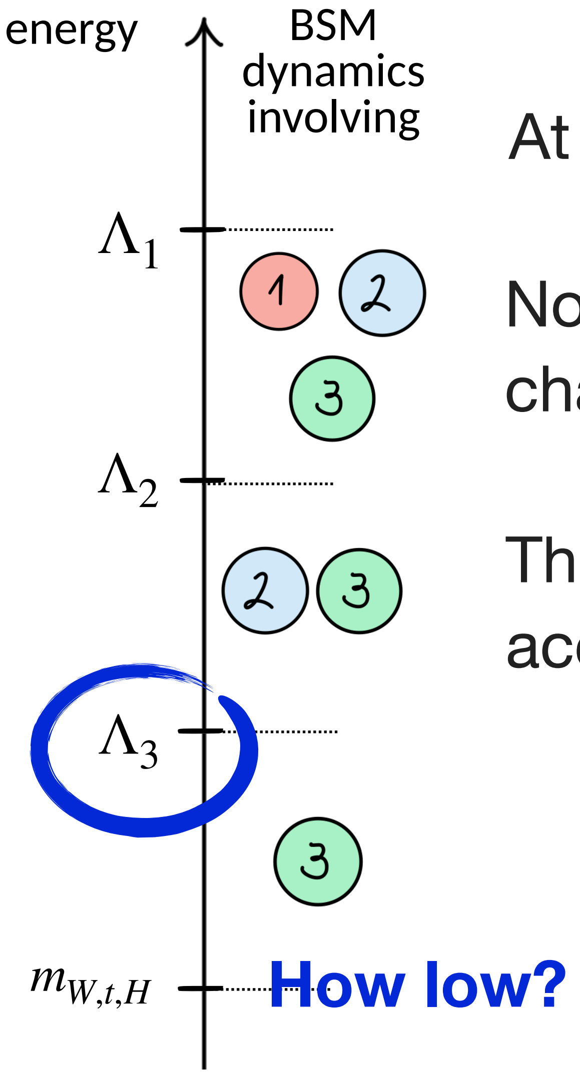

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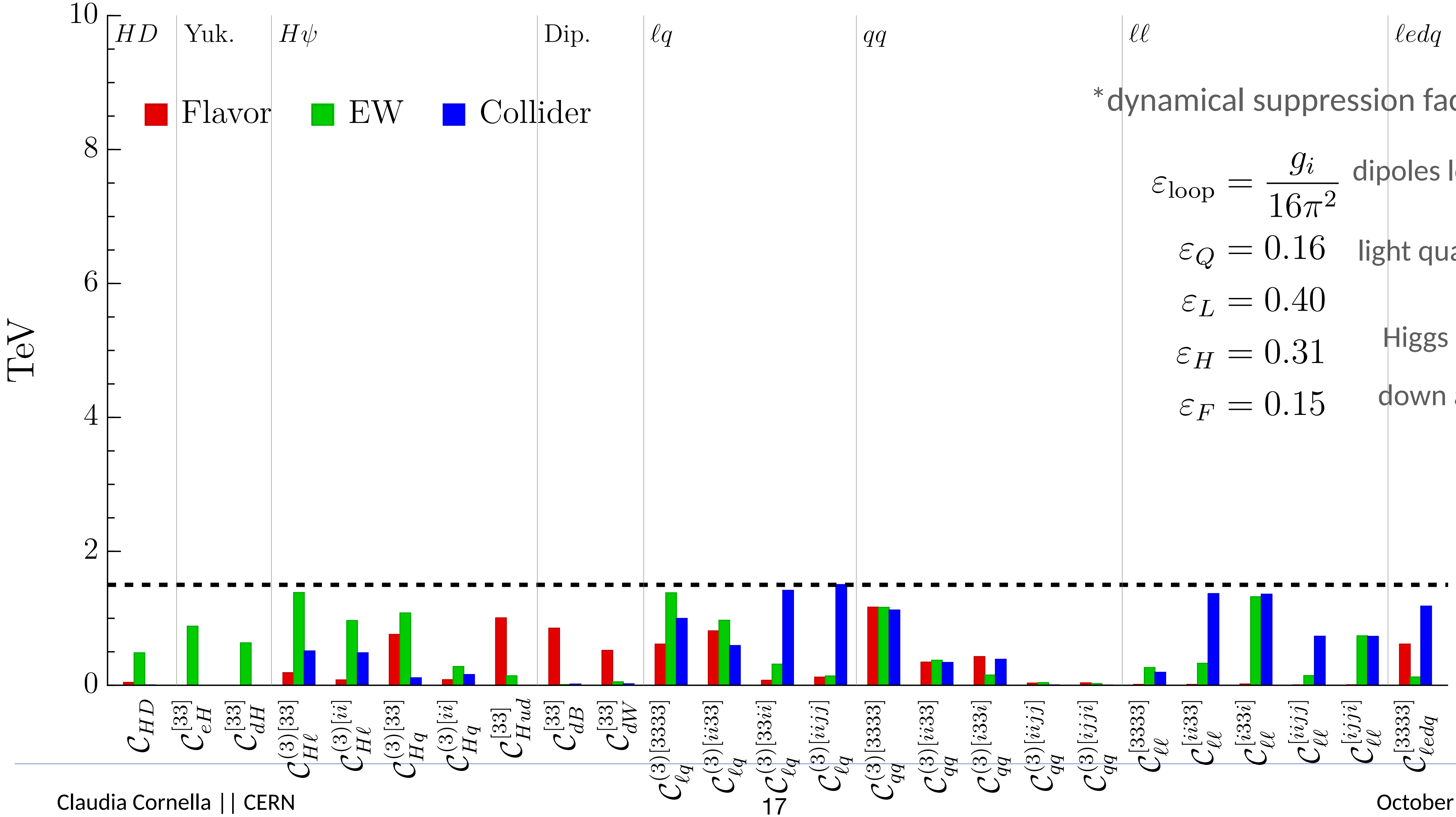
With **current data,** NP mainly coupled to the 3rd family can exist at scales as low as **1-2 TeV** under conditions* that are radiatively stable and simple to realise.



*dynamical suppression factors:

$\varepsilon_{\text{loop}} = \frac{g_i}{16\pi^2}$ dipoles loop induced

$\varepsilon_Q = 0.16$ light quarks & leptons

$\varepsilon_L = 0.40$

$\varepsilon_H = 0.31$ Higgs

$\varepsilon_F = 0.15$ down alignment

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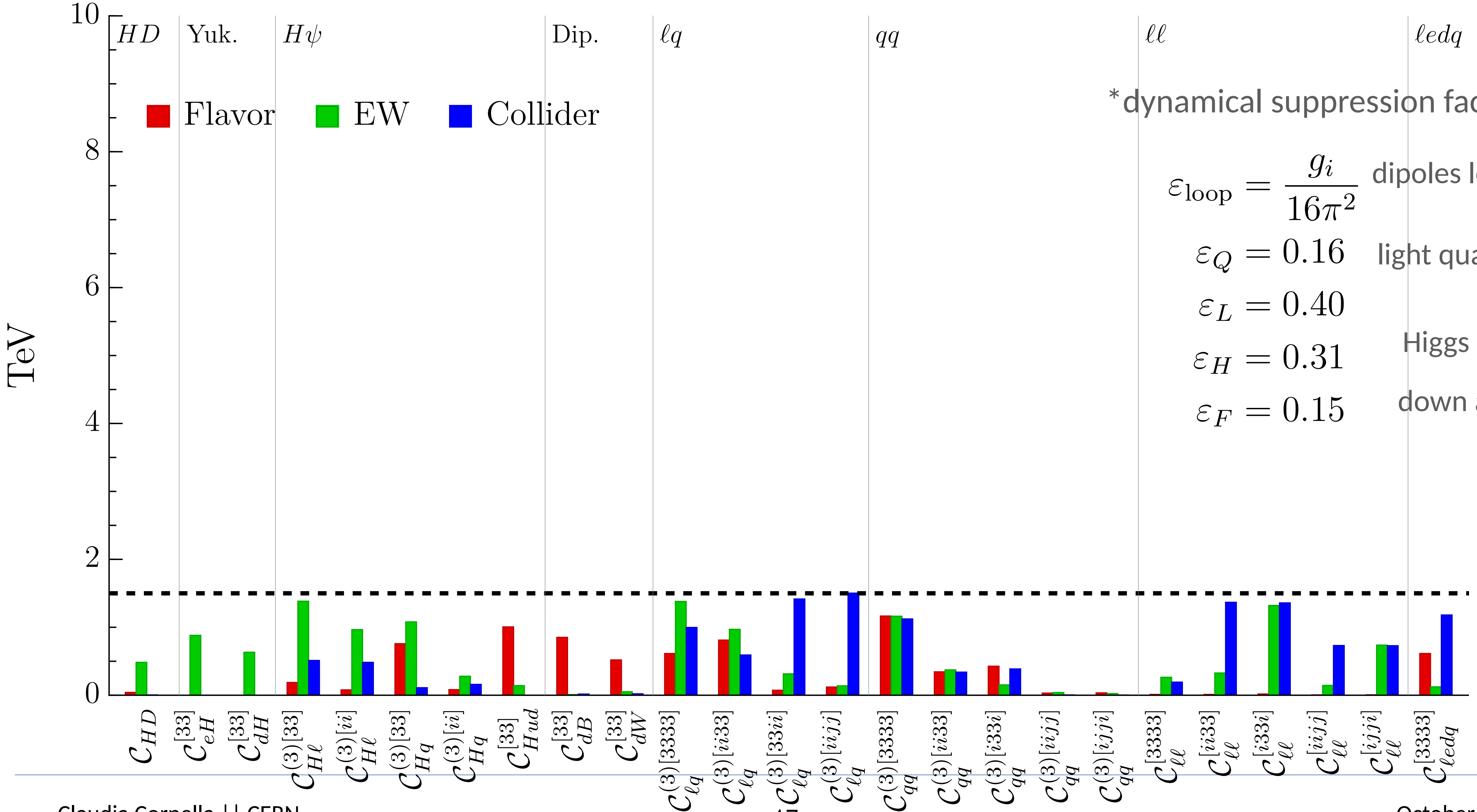
⇒ 3rd family NP is the closest motivated target for experimental exploration.



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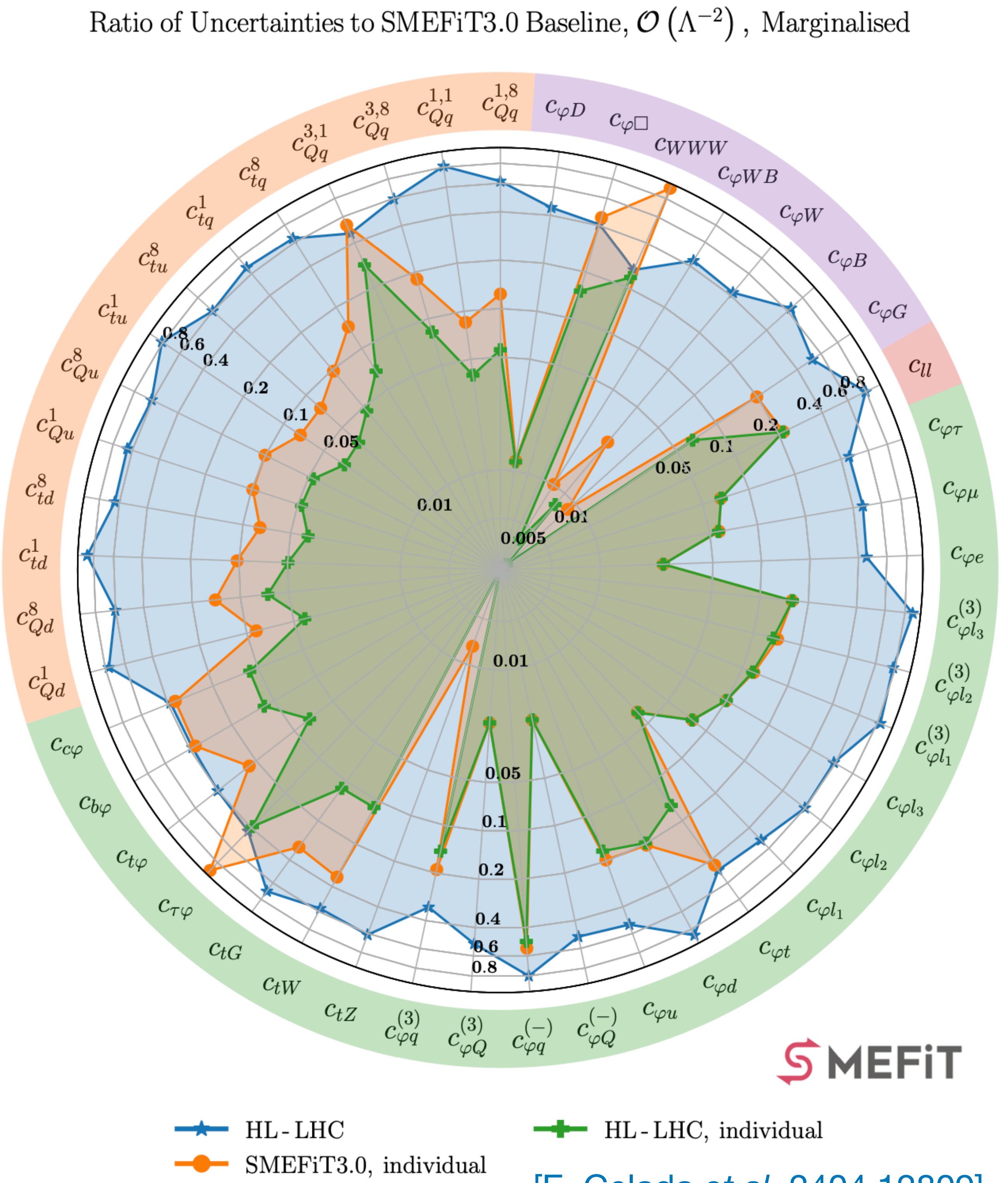
The near future, at high pT

HL-LHC [here: CMS & ATLAS EXPERIMENT]

improvement in SMEFT Wilson coefficients bounds ranging from 20% to a factor 4

For semileptonic operators [Drell-Yan!] the expected improvement is ~4, so 2 in the NP scale probed


Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-2}\right)$, Marginalised

[E. Celada *et al*, 2404.12809]

The near future, at low pT

Currently,

- collected 1/2 of the Belle dataset, many ongoing analyses
- luminosity is not ramping up as well as planned

- run 3 ongoing, getting ready for upgrade 2
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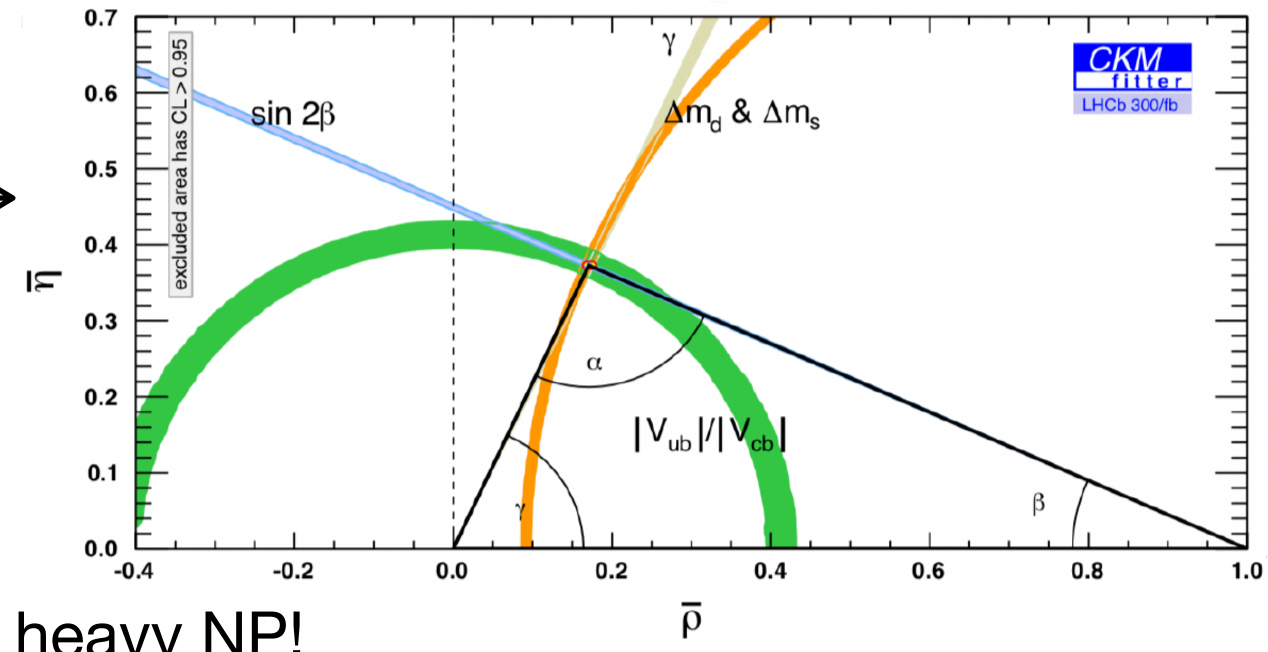
In the **next 15 years**, LHCb & Belle II should collect ~**100x** the **B mesons** they have now.

Among other, this means:

- CKM matrix elements <1%
- observe **CPV in B$_s$**
- measure CPV in **charm** precisely



! Important progress, as B$_s$ and D mixing are already leading constraints on flavored heavy NP!

The near future, at low pT

Another observable leading current constraints is **$B_s \to \mu^+\mu^-$**

- theoretically very clean.
- current precision at LHCb is~15% (systematics ~ 4%).
  With 100 fb^{-1}, the statistical uncertainty could match the systematics.

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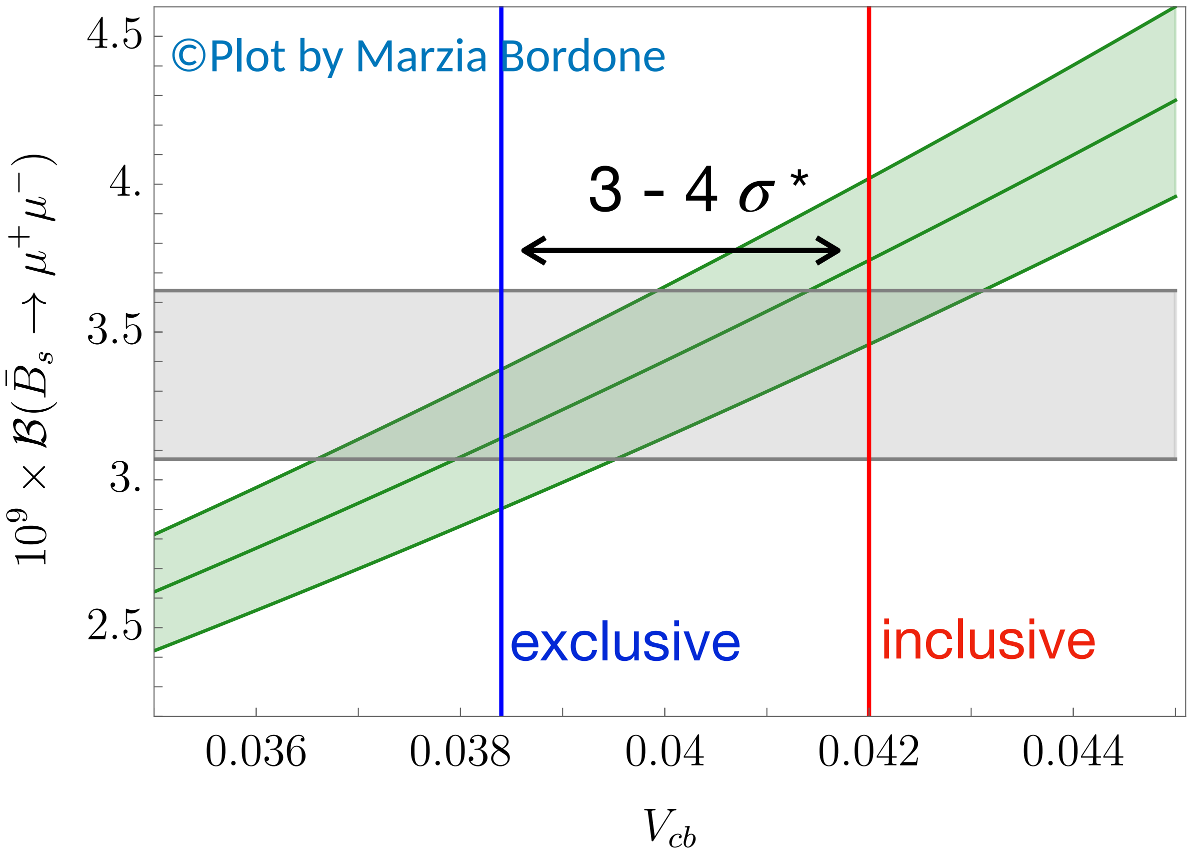
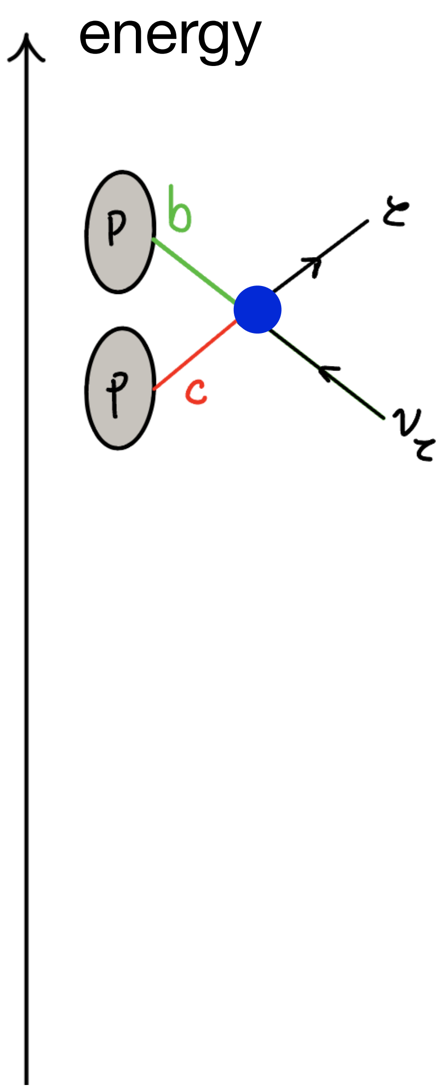
Resolving the **V_{cb} puzzle** is crucial for leveraging this improved precision:



Inclusive consistent across various datasets,

less consensus in the exclusive from $B \to D^*$.
Work in progress to understand the tensions.

Probing 3rd-family new physics



- processes like pp → ττ, pp → τ + missing energy, $t\bar{t}$, $b\bar{b}$….
- energy enhancement in tails helps overcome pdf suppression.

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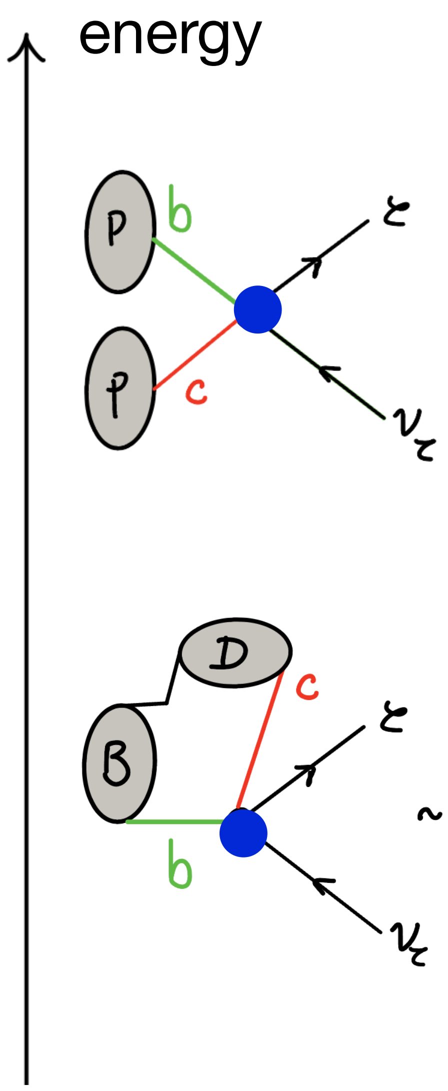

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- rare transitions between 3rd and light families: **B** & **tau** physics
- here focus on **semileptonic** transitions:

neutral currents $b \to s(d)\ell\ell^{(\prime)},\ b \to s(d)\nu\nu$

charged currents $b \to c(u)\ell\nu$

Probing 3rd-family new physics in neutral currents

- Probing $b \to s\tau\tau$ directly is experimentally very challenging:
  Even with full LHCb and Belle II dataset, the bounds will exceed the SM by $10^{2\text{-}3}$.

	CURRENT BOUND	PROJECTIONS	SM PREDICTION
$BR(B^+ \to K^+\tau^+\tau^-)$	$< 2.25 \cdot 10^{-3}$ @ 90% CL Babar	$< 6.5 \cdot 10^{-5}$ @ 90% CL Belle 2 $5ab^{-1}$	$(1.4 \pm 0.2) \cdot 10^{-7}$
$BR(B_s \to \tau^+\tau^-)$	$< 6.8 \cdot 10^{-3}$ @ 95% CL LHCb	$< 5 \cdot 10^{-4}$ @ 95% CL LHCb 300 fb^{-1}	$(7.73 \pm 0.49) \cdot 10^{-7}$

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  Even with full LHCb and Belle II dataset, the bounds will exceed the SM by 10^{2-3} .

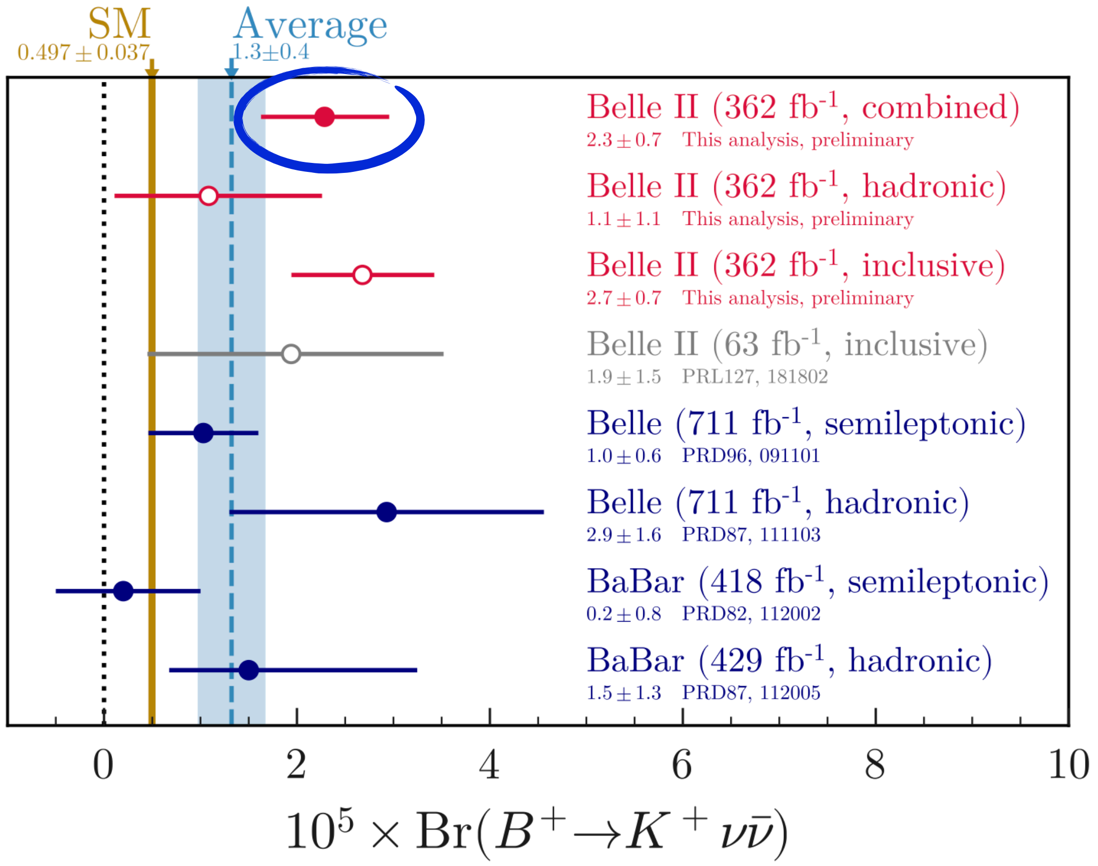
	CURRENT BOUND	PROJECTIONS	SM PREDICTION
$BR(B^+ \to K^+\tau^+\tau^-)$	$< 2.25 \cdot 10^{-3}$ @ 90% CL Babar	$< 6.5 \cdot 10^{-5}$ @ 90% CL Belle 2 5ab^{-1}	$(1.4 \pm 0.2) \cdot 10^{-7}$
$BR(B_s \to \tau^+\tau^-)$	$< 6.8 \cdot 10^{-3}$ @ 95% CL LHCb	$< 5 \cdot 10^{-4}$ @ 95% CL LHCb 300 fb^{-1}	$(7.73 \pm 0.49) \cdot 10^{-7}$

- Currently the only accessible FCNC directly sensitive to 3rd family leptons is $B \to K\nu\bar{\nu}$

  First evidence by Belle II,
  combined result 2.7σ above the SM

  Work ongoing on $K^{*0,+}$ and K_S modes.

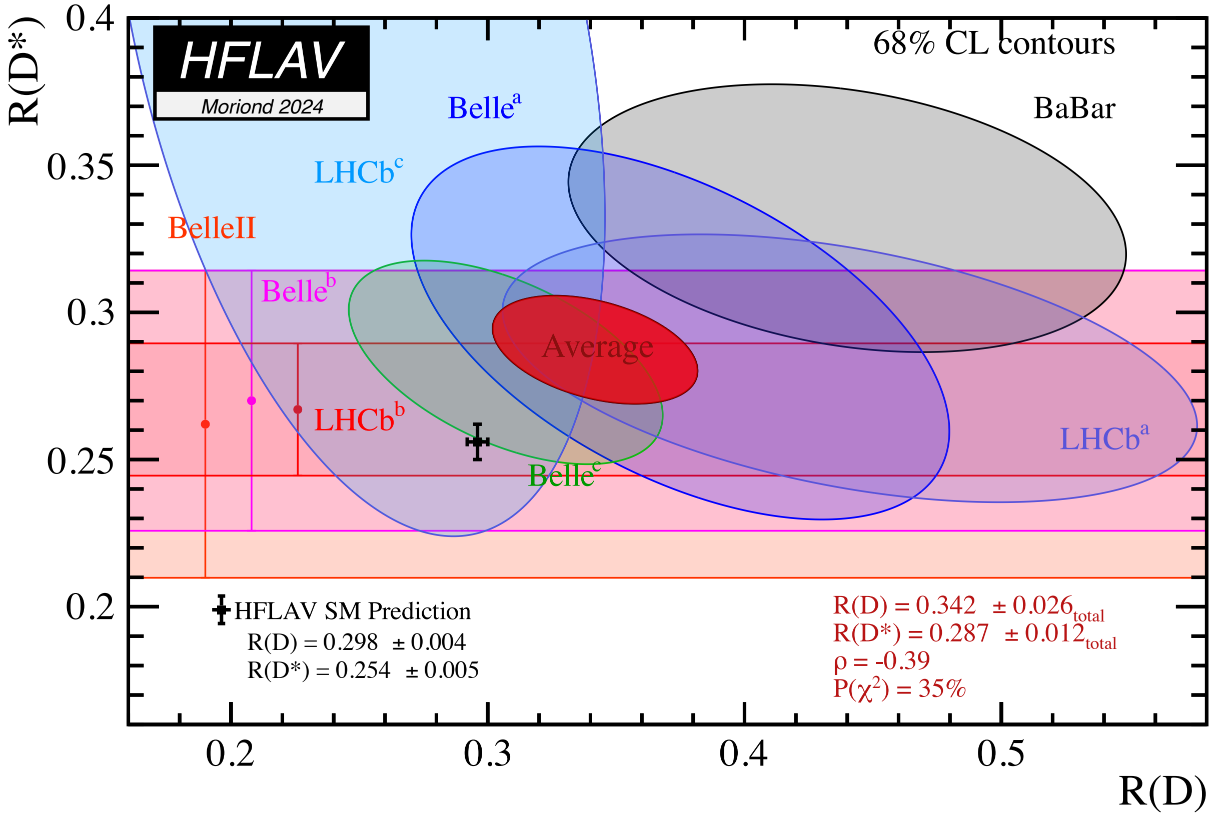
  Final goal is 10% precision.



Probing 3rd-family new physics in charged currents

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})} \quad [\ell = e, \mu]$$

Current status



$\sim 10\,\%$ enhancement [tau mode]

$\approx 3\,\sigma$ tension w.r.t. SM

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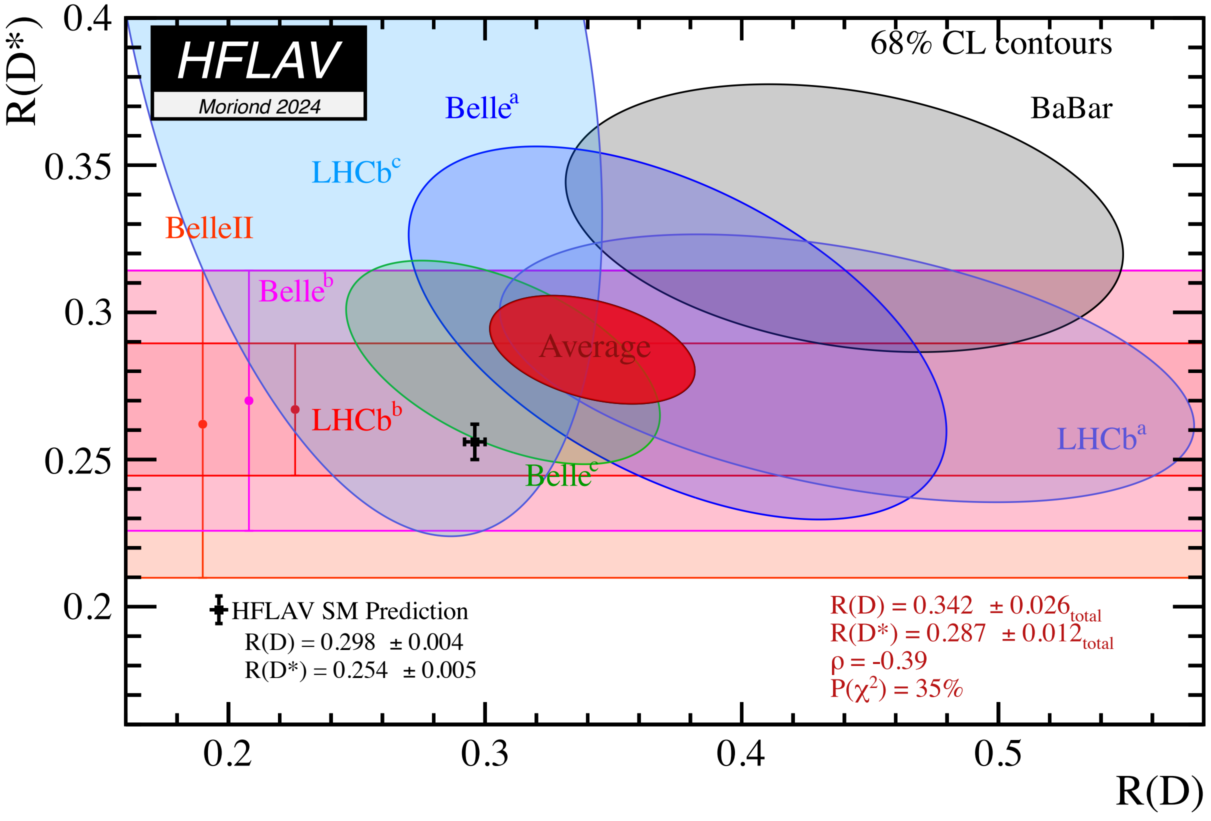

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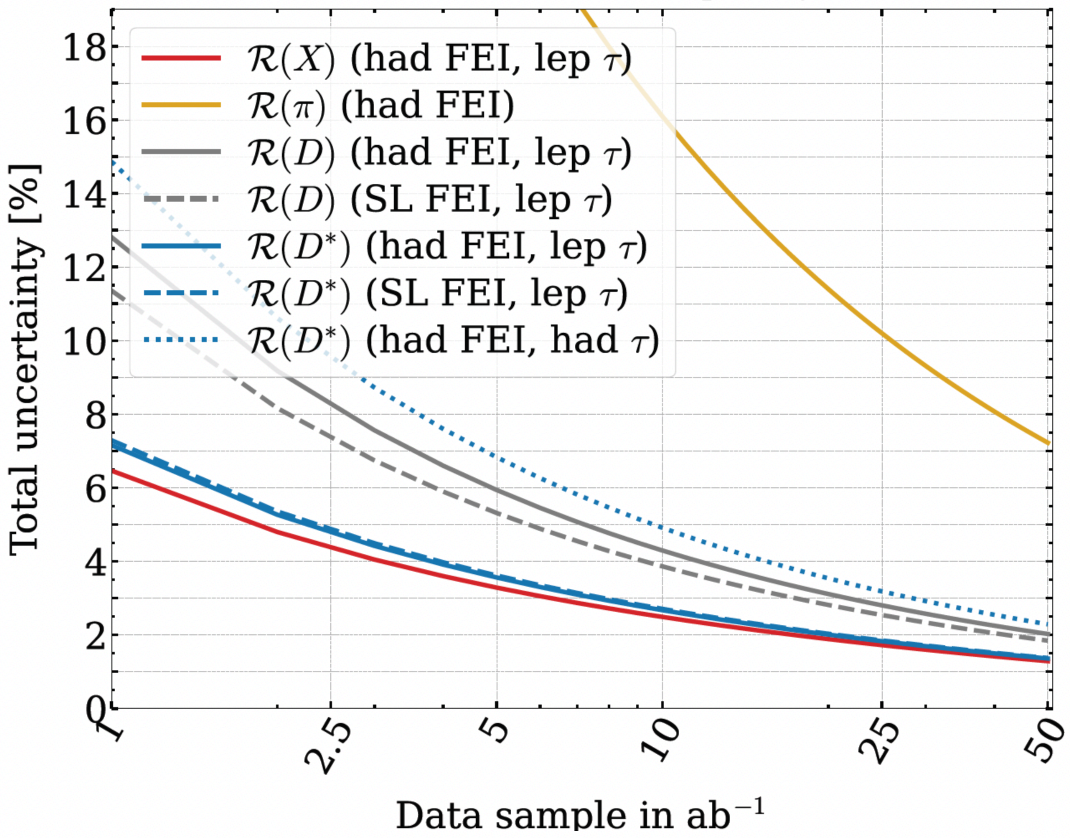
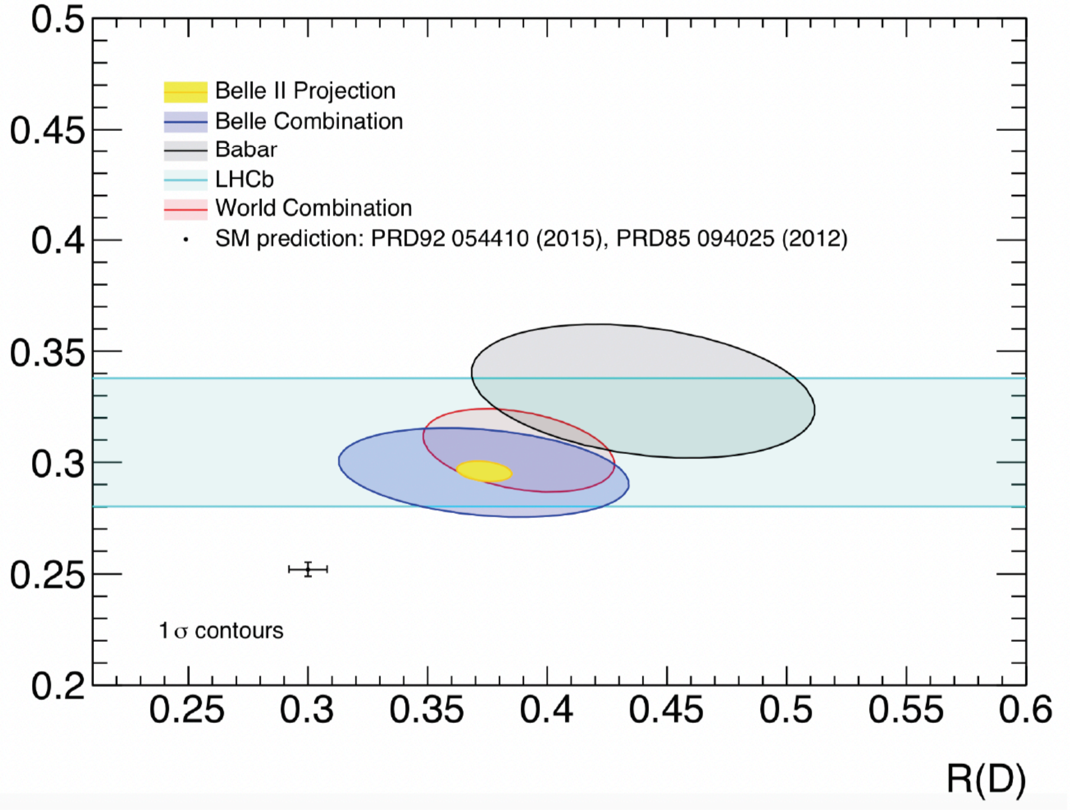
Belle II projections

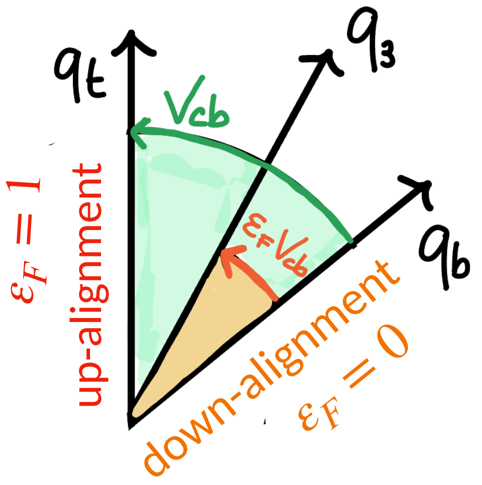


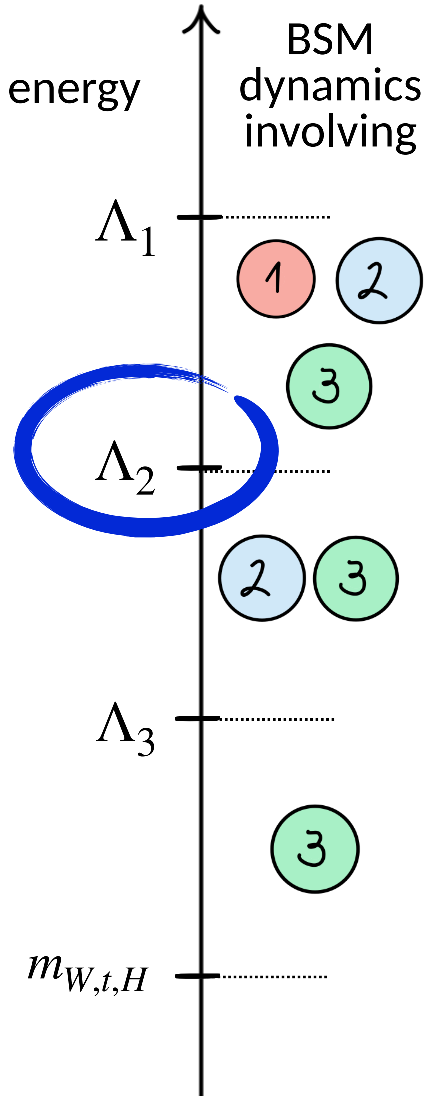


Probing 3rd-family new physics with kaons

Rare kaon decays (s → d FCNCs)

- complementary to b → s in determining the orientation of 3rd family in flavor space
- allow us to probe $U(2)_{q,d}$ breaking in the 21 sector, related to the “next threshold”, Λ_2
- For NP modes with a CKM-like structure, typically correlated with $B \to K\nu\bar{\nu}$





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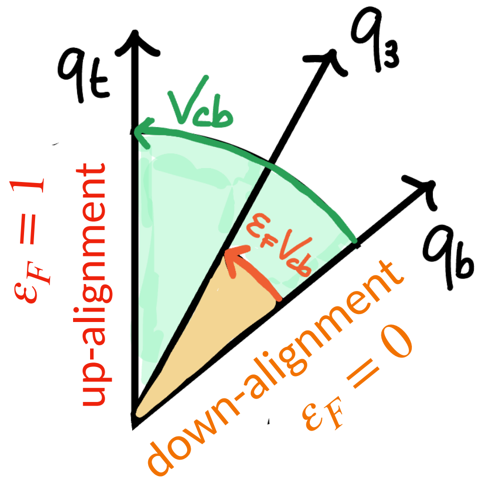
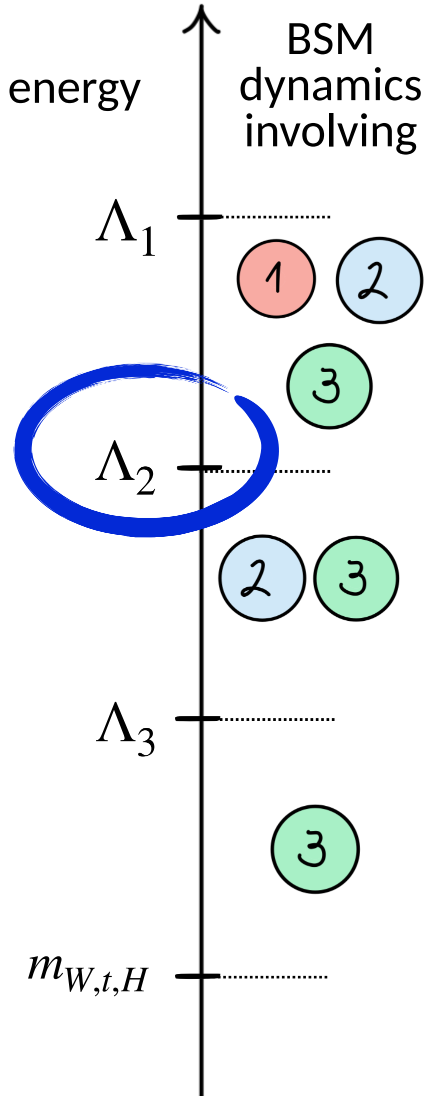
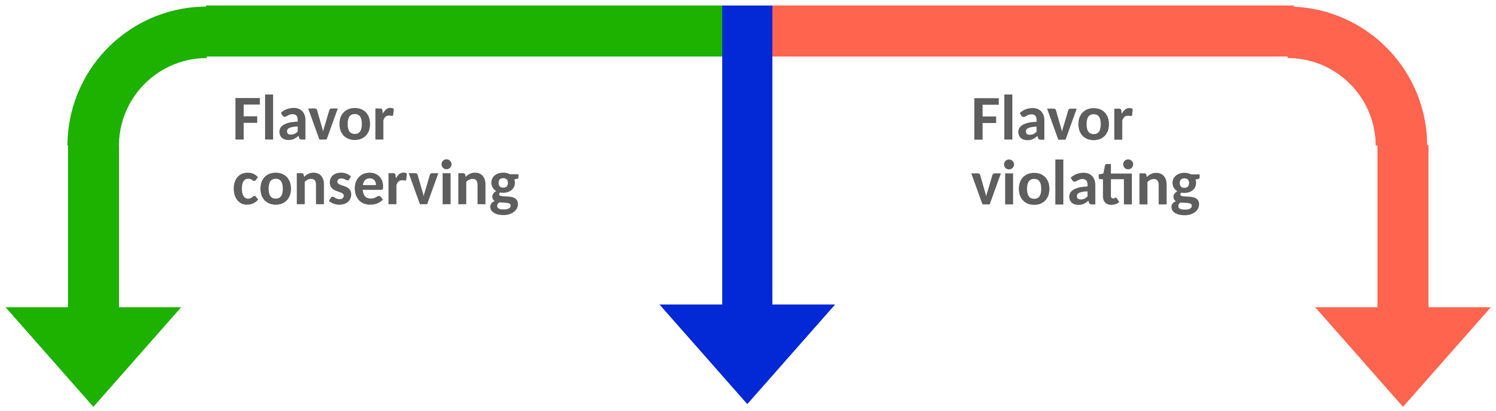




$\boldsymbol{K^+ \to \pi^+\nu\bar{\nu}}$ is special:

- only rare K decay from which short distance information is accessible
- sole opportunity to get a clean B vs K comparison in the same transition, if similar precision (~10%) is achieved

Electroweak Precision as a Flavor Probe



New physics

©Ben Stefanek

Flavor conserving

Flavor violating

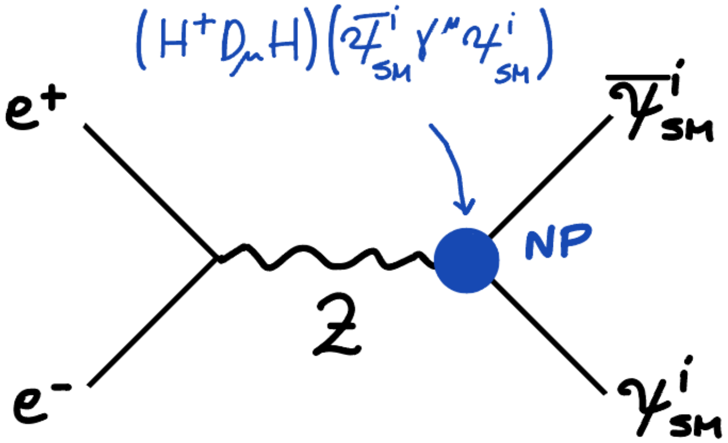
EW Precision

Direct searches

Flavor Bounds

3rd family NP is “**protected**” against direct searches at the LHC & flavor bounds, but not against **EW precision tests.**

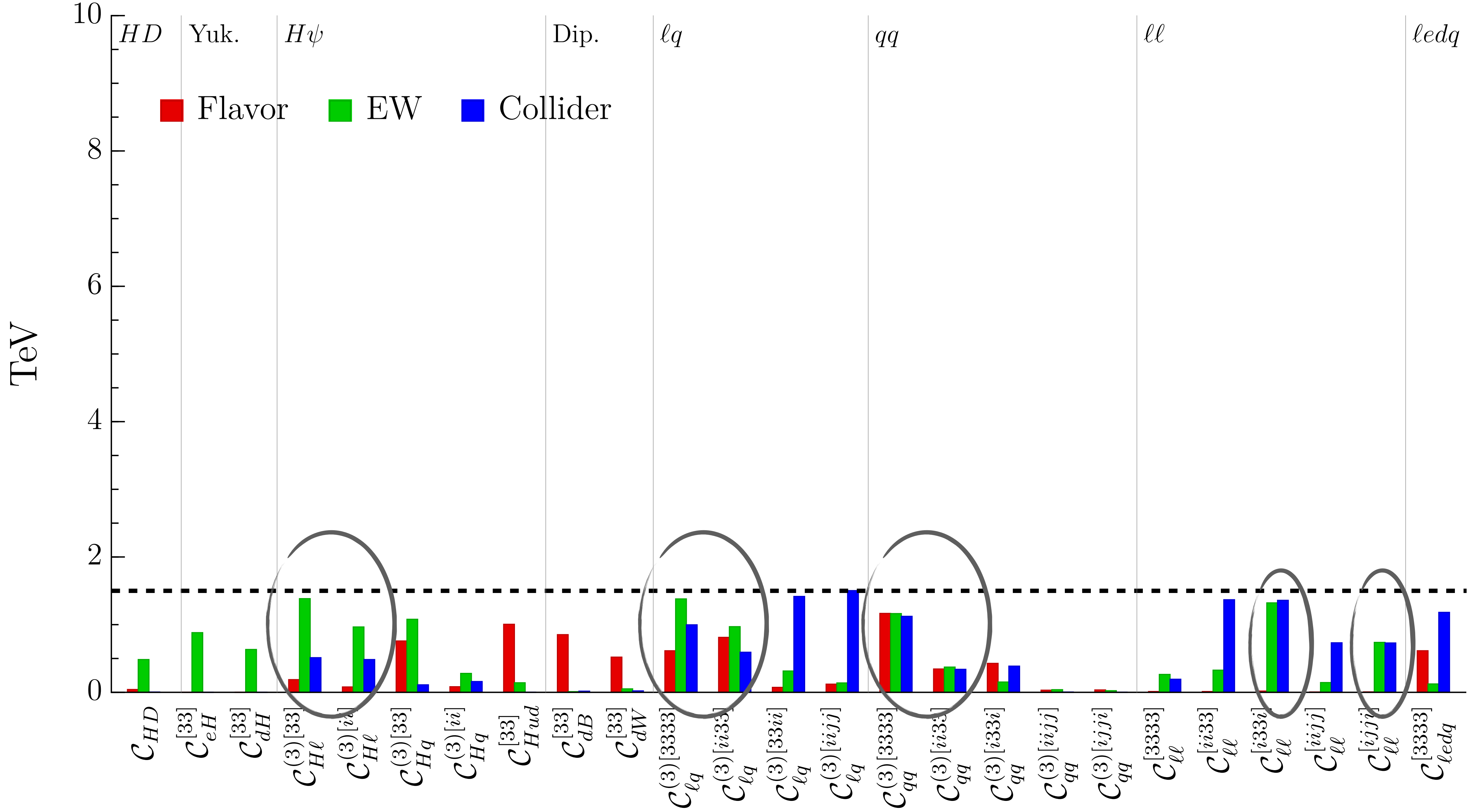
At a Z factory, we can use the flavor blindness of the SM gauge interactions to indirectly probe NP coupled to **any** generation.



⇒ EWPT are powerful probes of flavor non-universality

Perspectives at Tera-Z: EW precision tests

LEP bounds have a strength **comparable** to current **direct searches** for operators involving mostly the 3rd generation:



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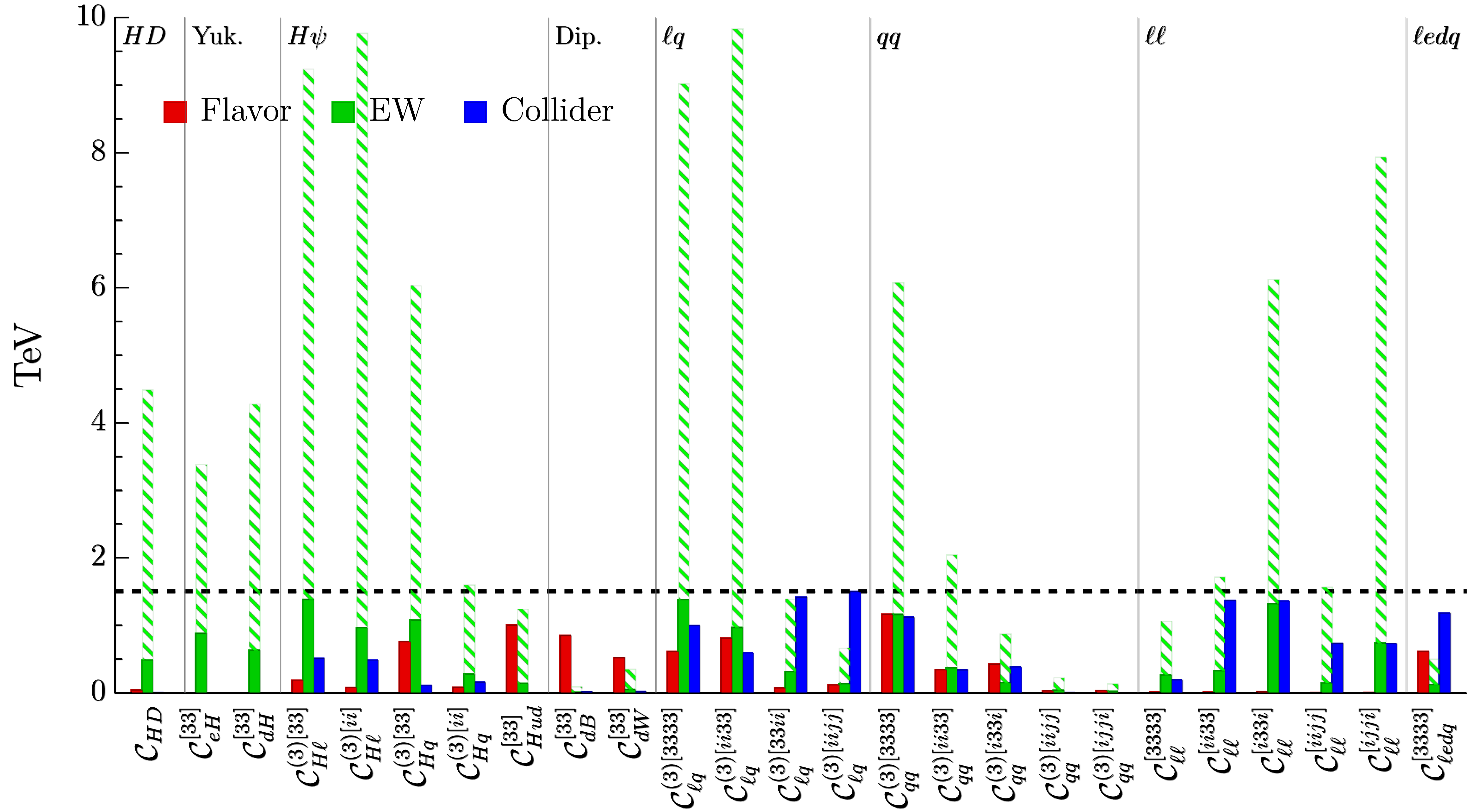
….with $\approx 10^5$ more Z bosons than LEP,
a tera-Z machine could probe 3rd-family NP **up to ~ 10 TeV**!



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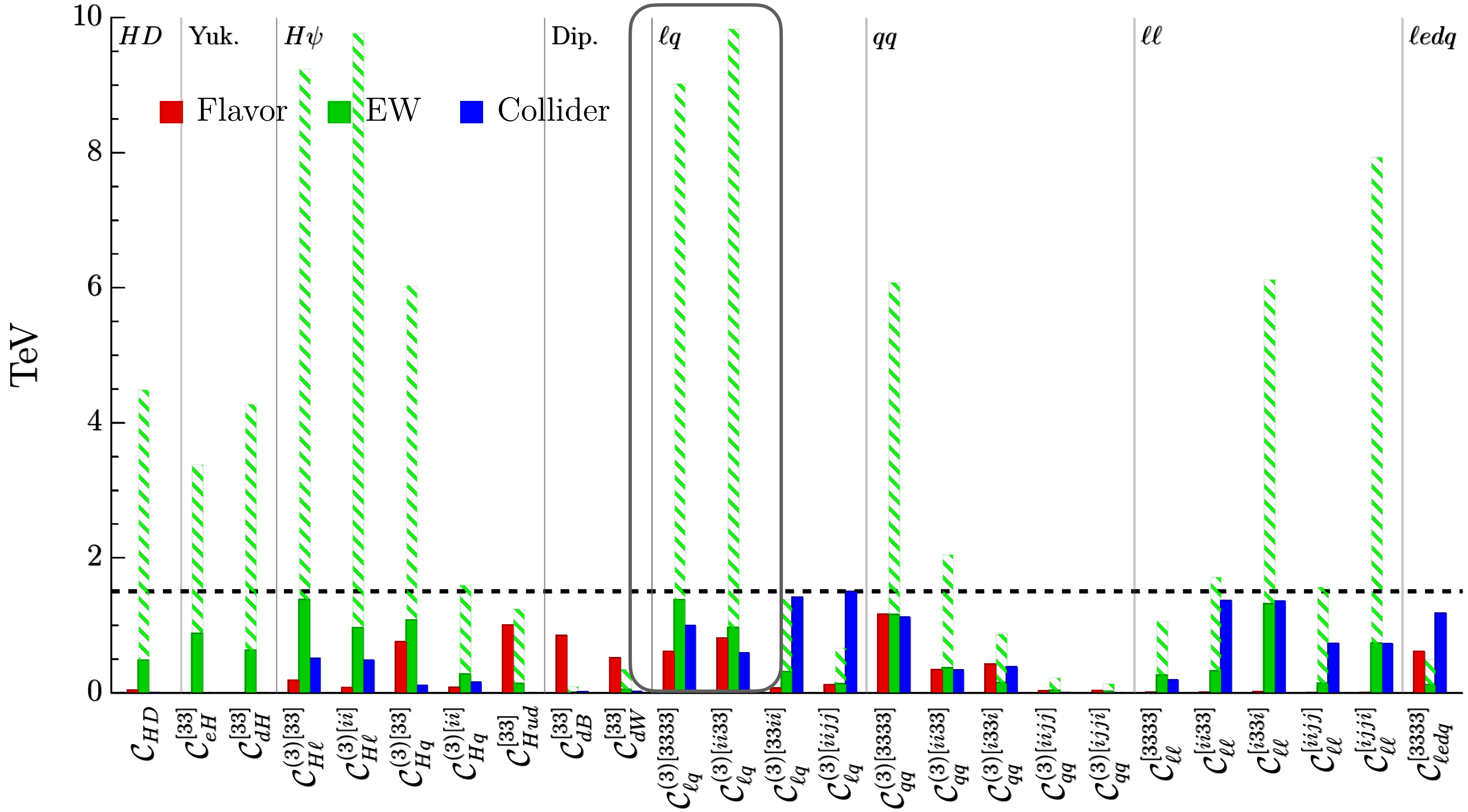

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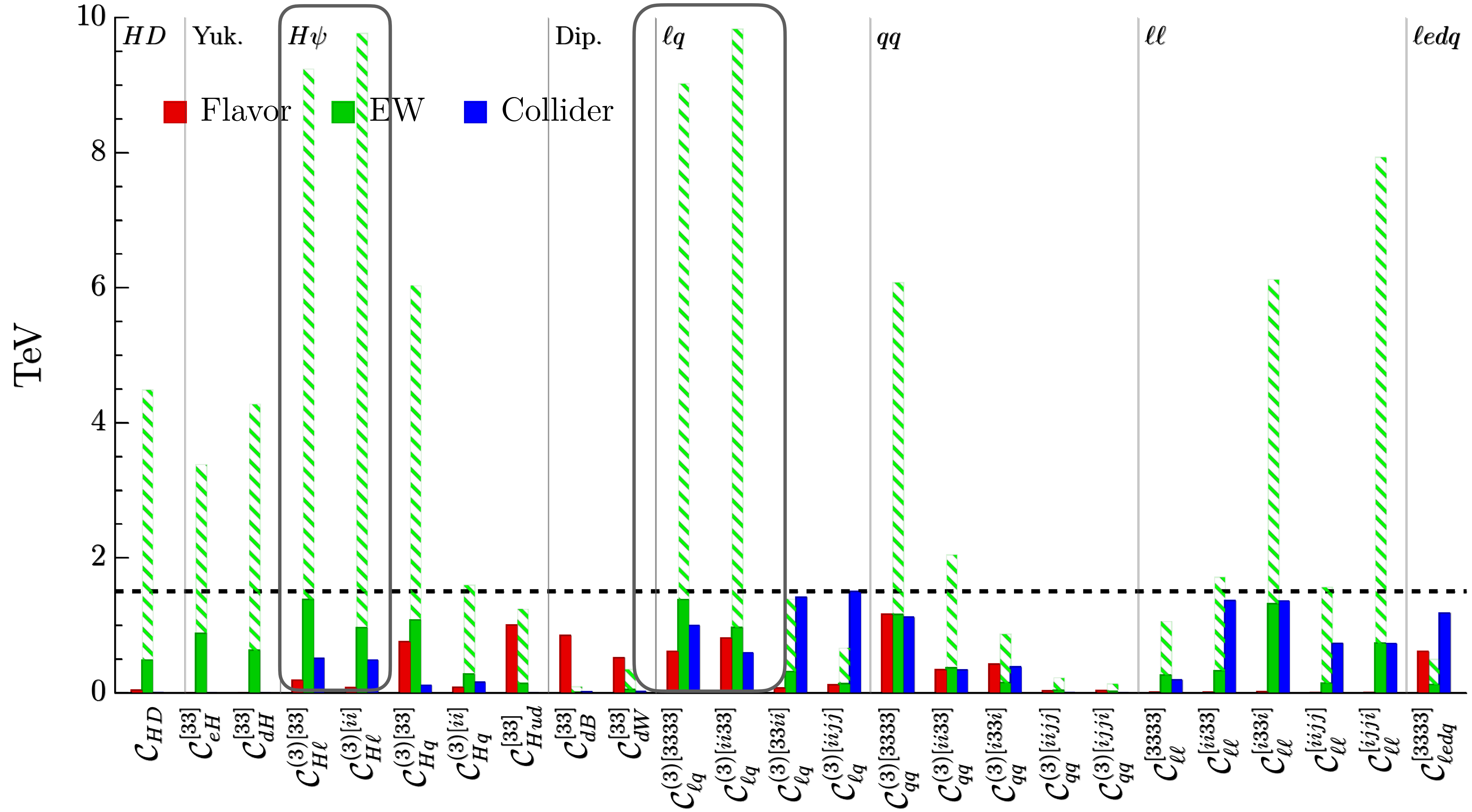

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For flavor universal NP,

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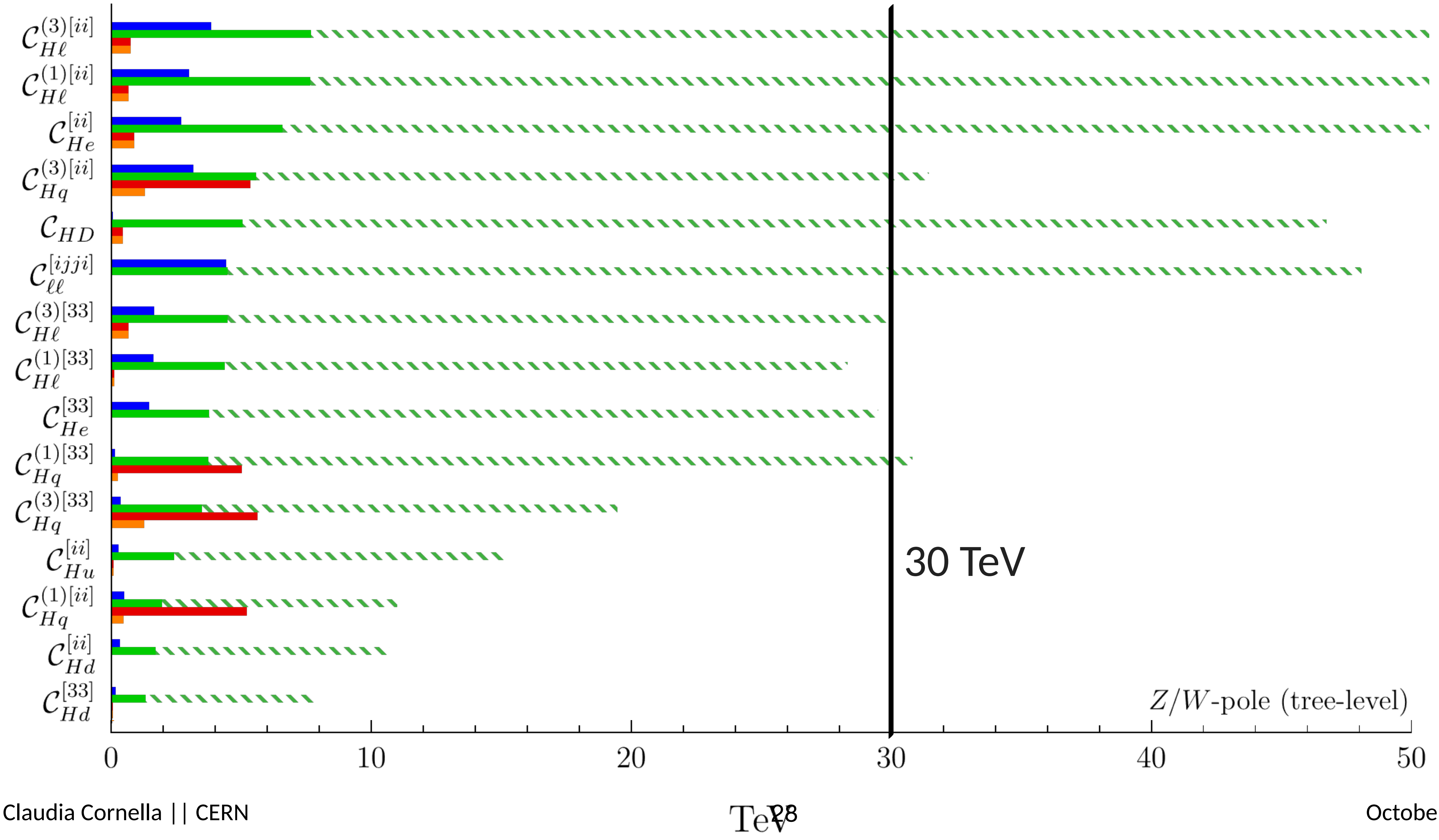
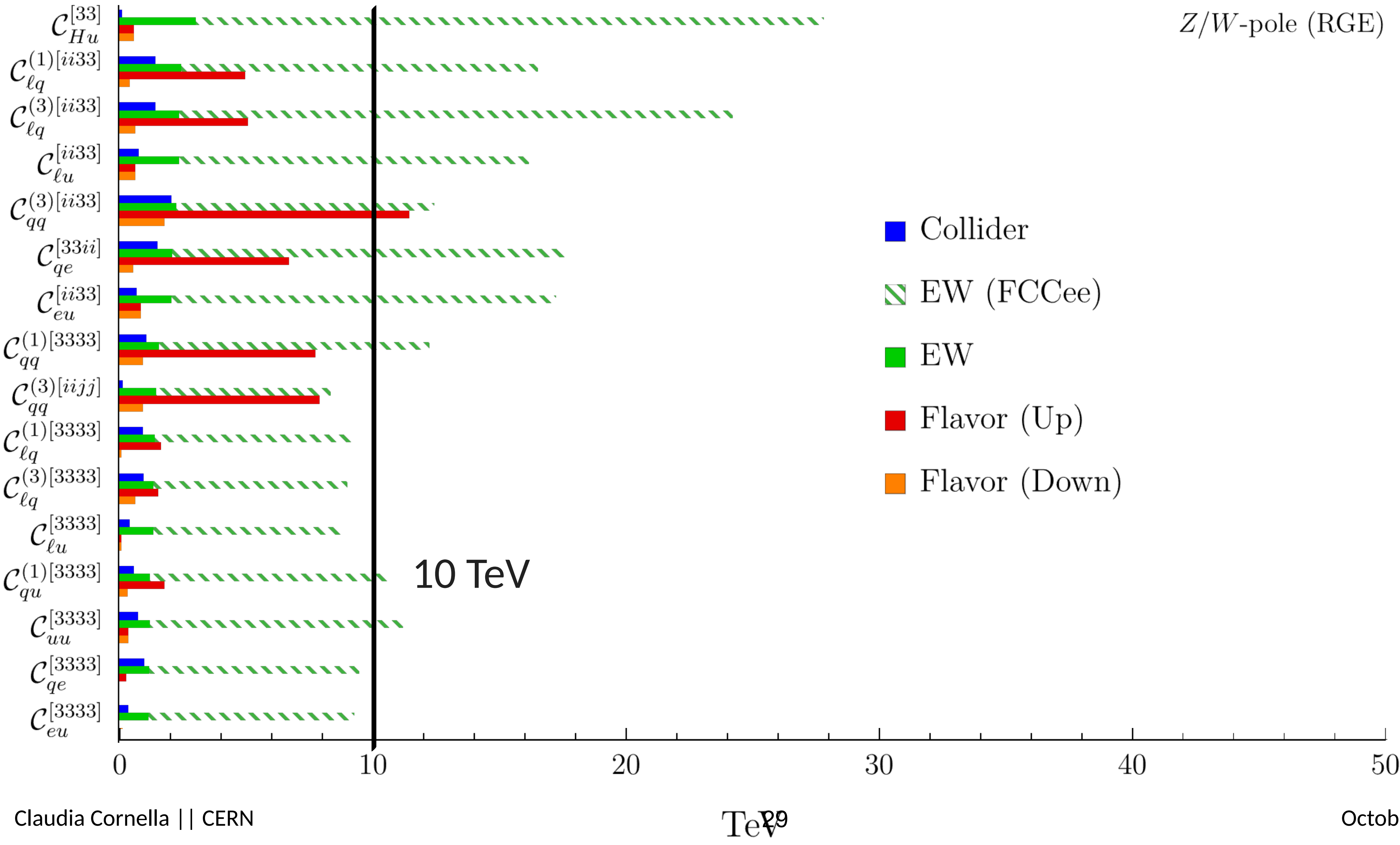


Perspectives at Tera-Z: EW precision tests

For flavor universal NP,

- operators entering Z-pole observables at tree-level get bounds of 30-50 TeV
- 4-fermion operators involving third-family quarks get bounds ~ 10 TeV



Perspectives at Tera-Z: heavy flavours

A tera-Z machine is a powerful **heavy-flavor factory**. For **FCC-ee:**

Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B^0_s/\overline{B}^0_s$	$B^+_c/\overline{B}^-_c$	$\Lambda_b/\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

[FCC Snowmass Summary, 2203.06520]

Clean environment and **boosted** topologies are **advantages** with respect to Belle II & LHCb, and will allow for major advancement in B & tau physics.

Among others:

- precise measurements of $b \to s\tau\tau$ & $b \to s\nu\nu$, incl. $b \to d$ counterpart
- access to heavier b-hadrons: B_c , B_s , Λ_b
- LFU tests in τ decays at the 10^{-4} level

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Disclaimer: no dedicated studies yet, just personal thoughts!

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In any case, I think that **any direct or indirect discovery at a 100 TeV collider would almost certainly be preceded by an anomaly indirect precision measurements** e.g. at a tera-Z machine (EWPT or flavor observables).

If I could choose, I'd rather not skip e+e-.

Conclusions

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Looking forward, a tera-Z machine like FCC-ee is ideal in testing these scenarios

- unprecedentedly precise **EWPT** that cannot be bypassed by flavor symmetries
- major advancements in **tau** and **B physics**, with access to new channels

If we firmly establish **any** anomaly, it will help design a future hadron collider, potentially creating a no-lose situation for **FCChh**.