Flavor, Colliders, and the Z-pole: Opportunities for probing new physics

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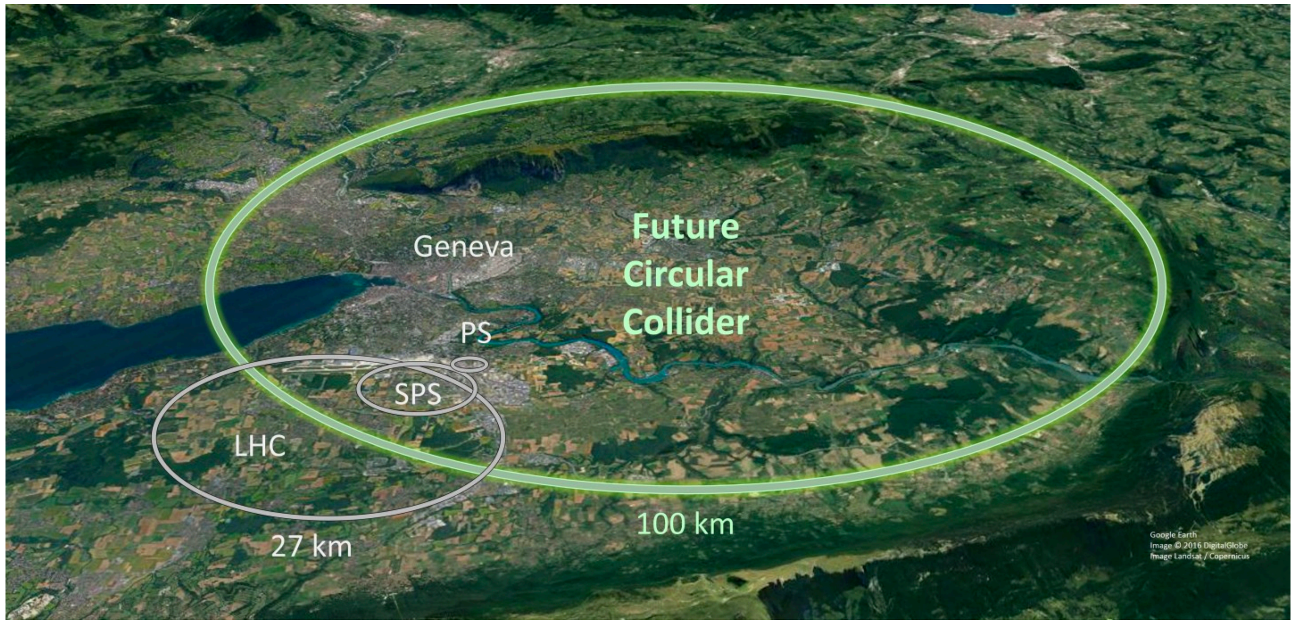
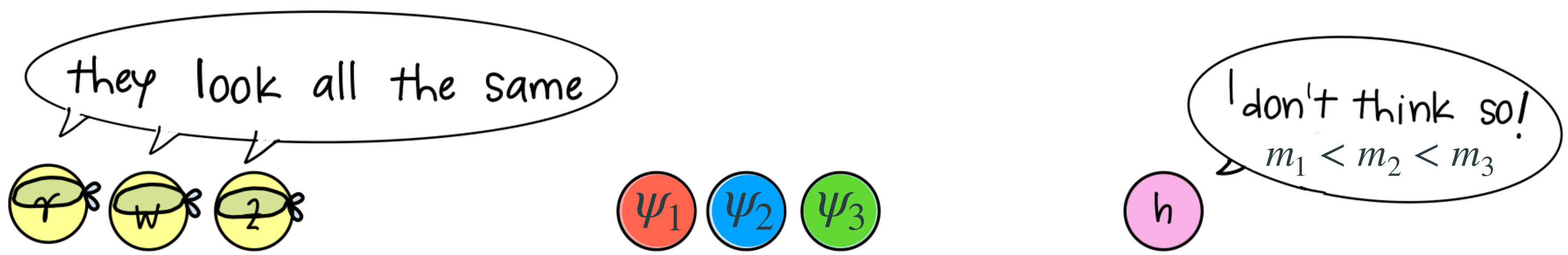


Second ECFA Workshop
e^+e^- Higgs/EW/Top Factories
Ariston Hotel, Paestum, Italy
October 11, 2023

The Higgs and the Flavor Puzzle

- Standard Model (SM) gauge sector is *flavor blind!*

$$\mathcal{G}_F\,(\text{gauge}) = U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$$



- The Higgs, the last piece of the SM discovered in 2012, strongly disagrees! Yukawas with Higgs are the only source of flavor violation in the SM, with a very hierarchical pattern that does not look accidental- *SM flavor puzzle*.

[Credit for cool drawings: Claudia Cornella]

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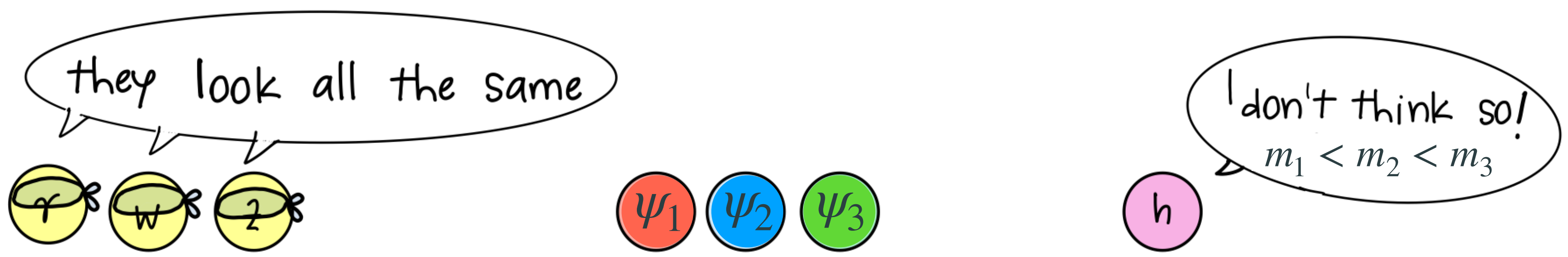

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Flavor Puzzle

Is there a connection between the nature of the Higgs boson and the SM flavor puzzle? Clues toward the structure and scale of new physics (NP)?

[Credit for cool drawings: Claudia Cornella]

Hints of NP structure: Flavor symmetries of the SM

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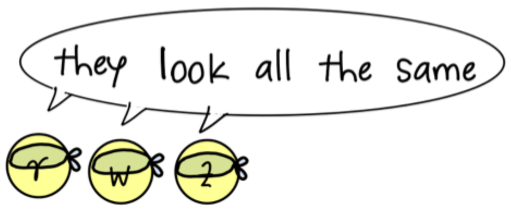
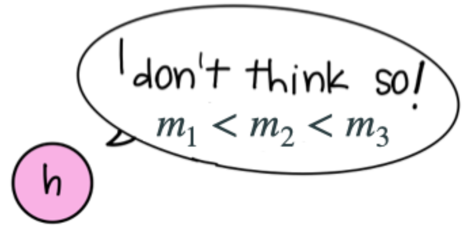


Turn on Yukawas

$$Y_{ij}\bar{\Psi}^i_L H \Psi^j_R$$



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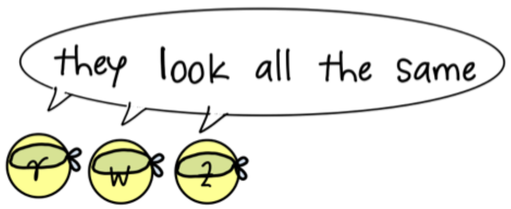

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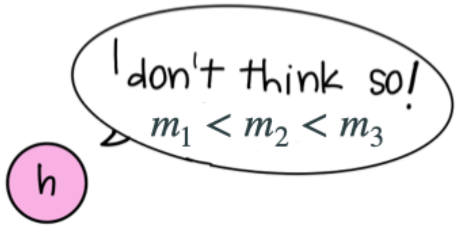

$$\mathcal{G}_F(\text{SM}) = U(1)_B \times U(1)_L$$

- But, since the light family Yukawa couplings are very small:

$$\mathcal{G}_F(\text{SM}) \approx U(2)^5 \equiv U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e$$

$U(2)^5$ is a good accidental approximate symmetry of the SM!

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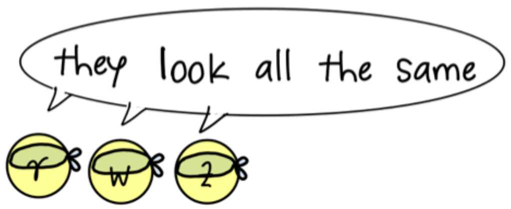

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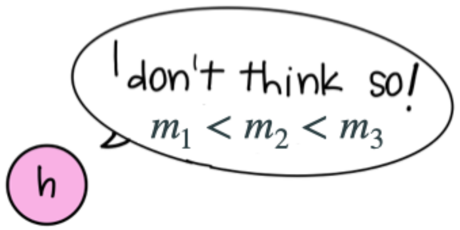

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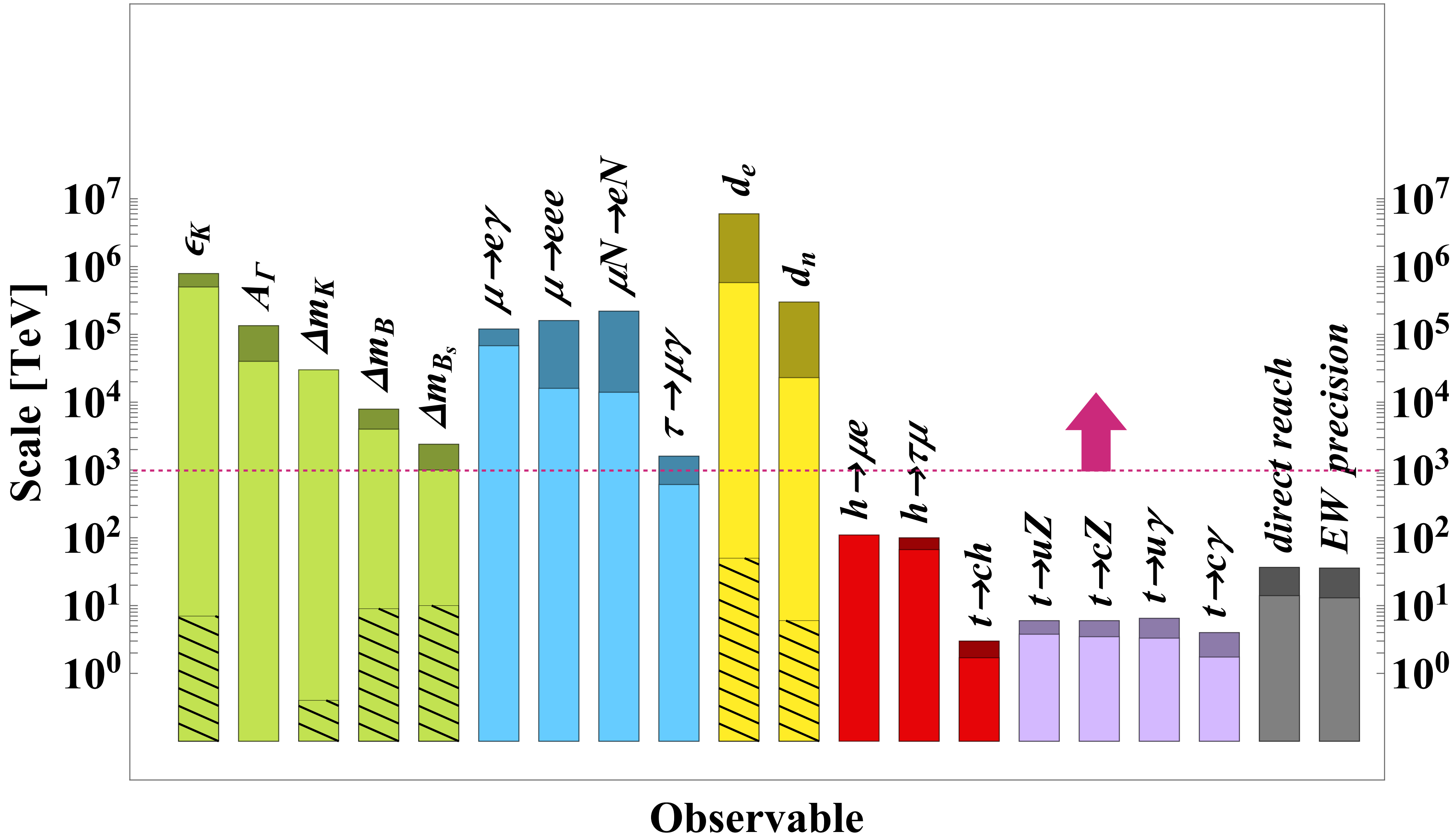
Flavor Puzzle

Perhaps this is not an accident- maybe there is NP responsible for this pattern that follows the same structure….

Hints of NP structure: Data

[Physics Briefing Book 2020, 1910.11775]



- No deviations in ***flavor data:*** the accidental approximate symmetries of the SM should also be good symmetries of NP. High scales could be a mirage, but one unambiguous message is that there cannot be any large breaking of $U(2)^5$ at nearby energy scales.

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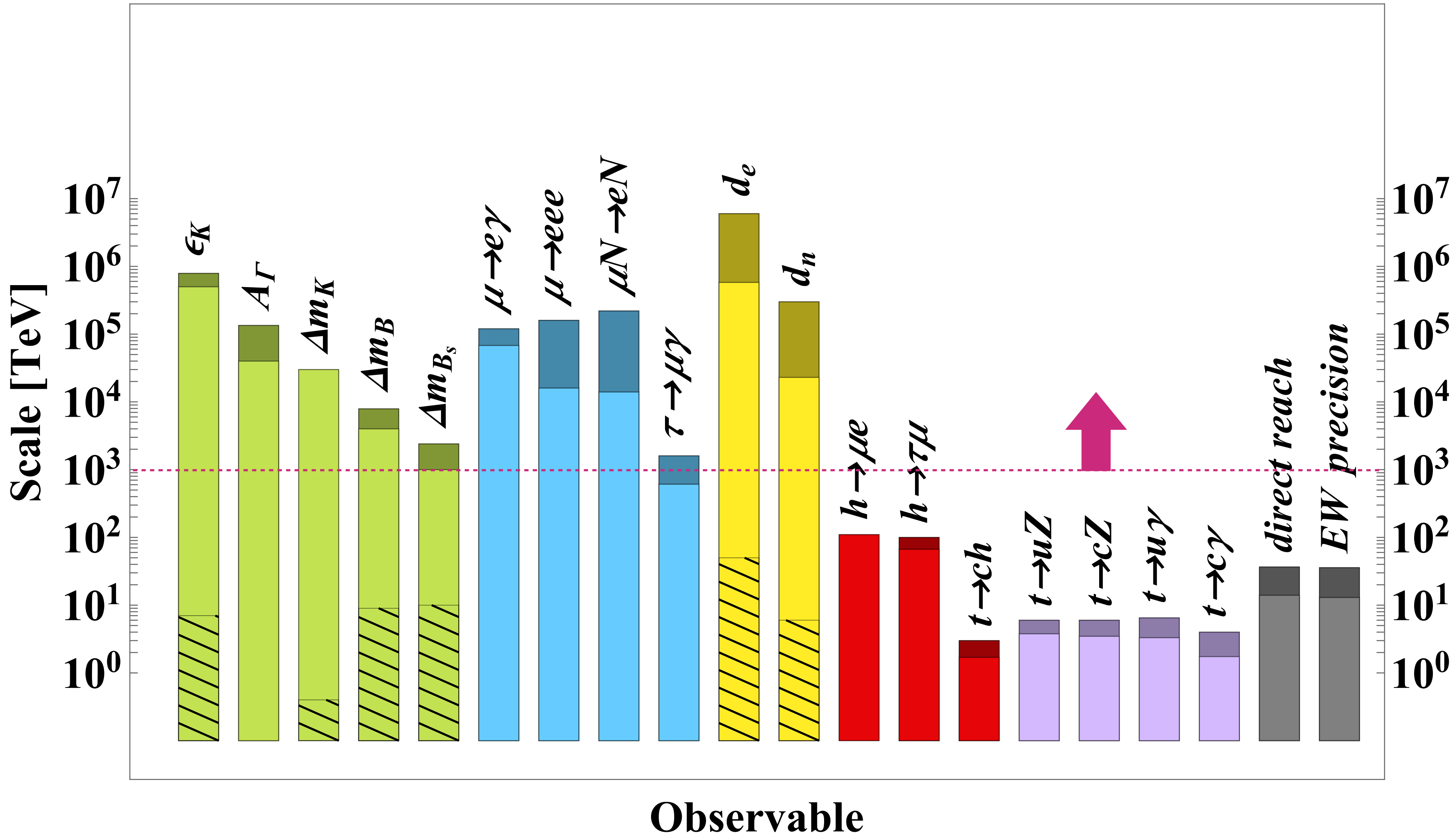

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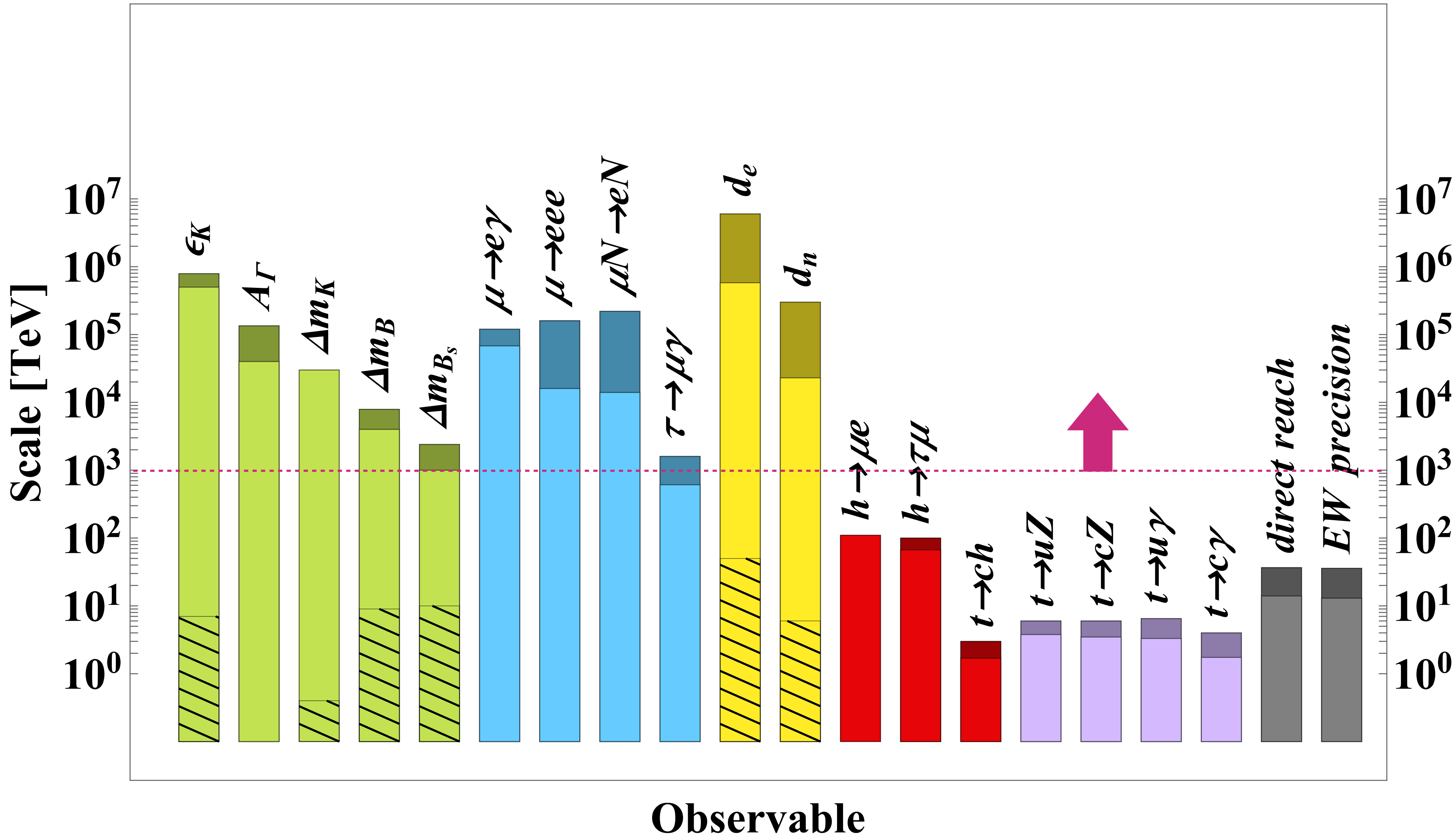

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- Similarly, ***direct searches at the LHC*** tell us that NP does not couple strongly to valence quarks at nearby energy scales.
- Interestingly, these two hints point toward a coherent hypothesis for the structure of NP.

The hypothesis of (dominantly) third-family NP

- Key idea: New physics is **NOT** flavor universal- there could be new flavor non-universal interactions at the TeV scale coupled dominantly to the third family. NP coupled to Higgs & top is what we need to address the EW hierarchy problem.

[R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone, D. Straub, 1105.2296]

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- These new interactions see flavor just like the SM Higgs. They could be connected to a low scale solution to the SM flavor puzzle. (see e.g. Davighi and BAS, arXiv: 2305.16280)

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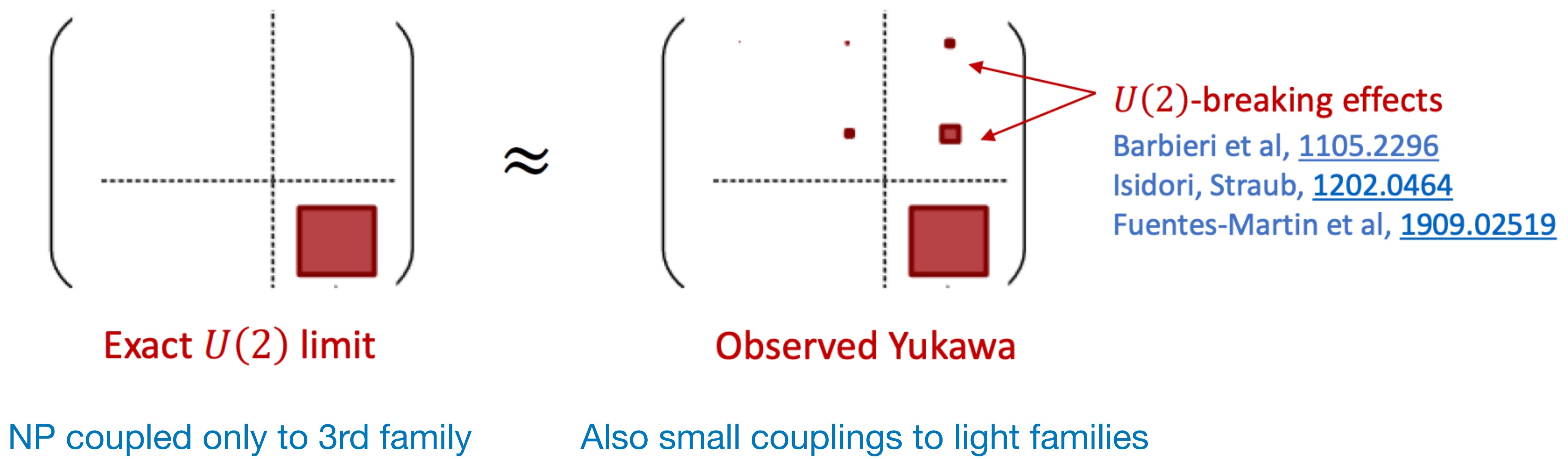
- These new interactions see flavor just like the SM Higgs. They could be connected to a low scale solution to the SM flavor puzzle. (see e.g. Davighi and BAS, arXiv: 2305.16280)
- NP dominantly coupled to the third family quarks (+ leptons) enjoys an approximate $U(2)^3$ ($U(2)^5$) flavor symmetry, just like the SM Yukawa couplings.



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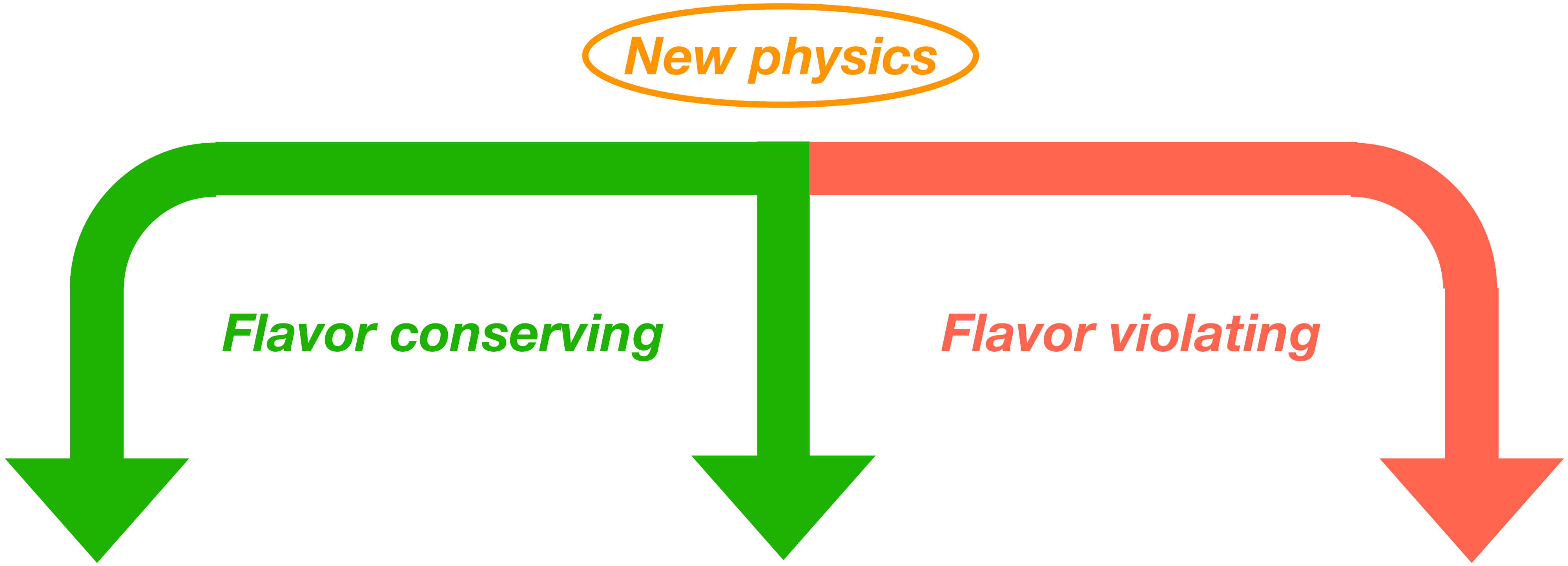
All new physics must confront a triad of bounds



EW Precision
($\Lambda_{NP} > 5$ TeV)

Direct searches
($\Lambda_{NP} > 5\text{-}10$ TeV)

Flavor Bounds
($\Lambda_{NP} > 10$ TeV)

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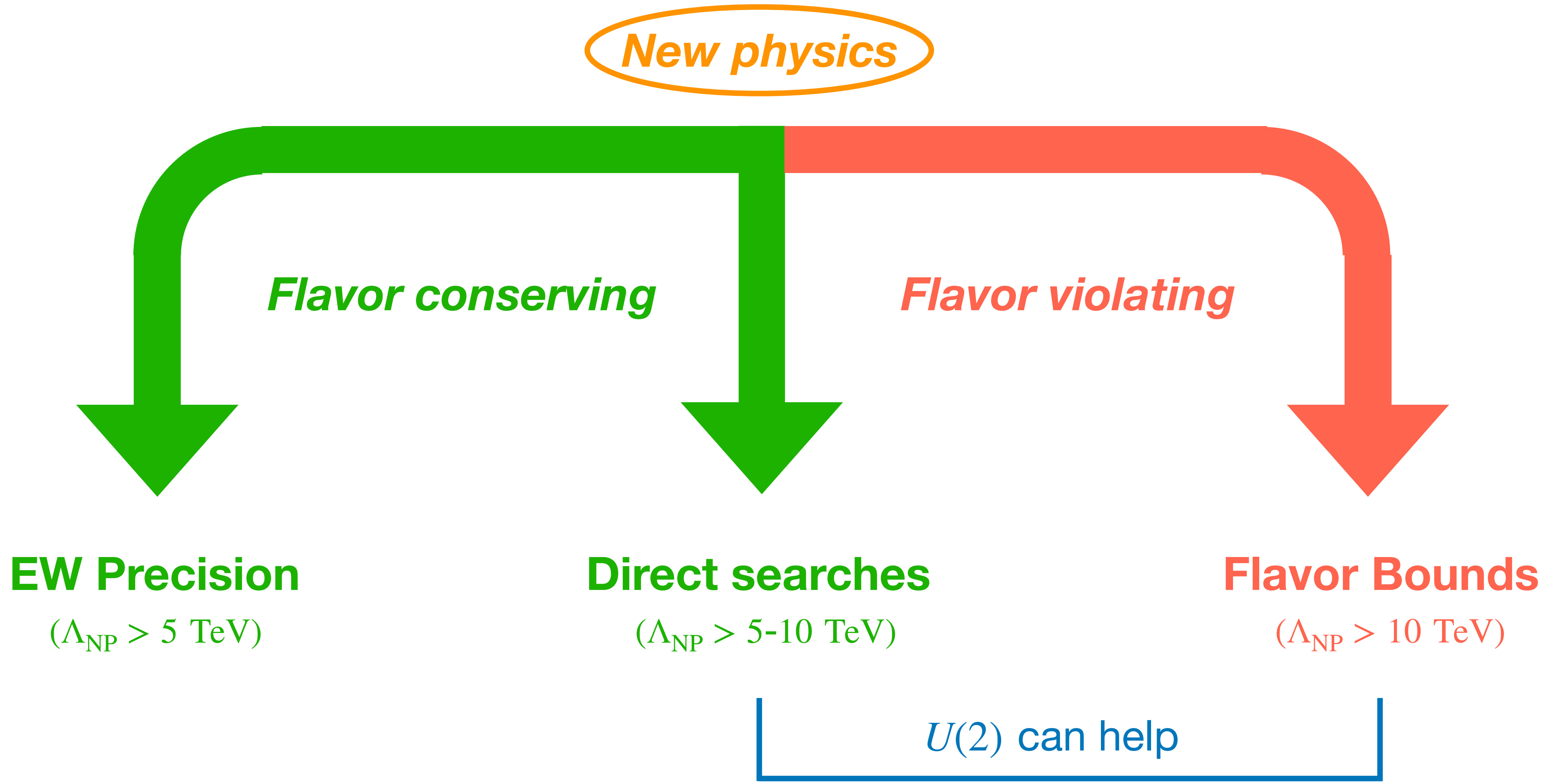

- U(2) helps pass flavor + collider bounds, but is less effective against EWPT.

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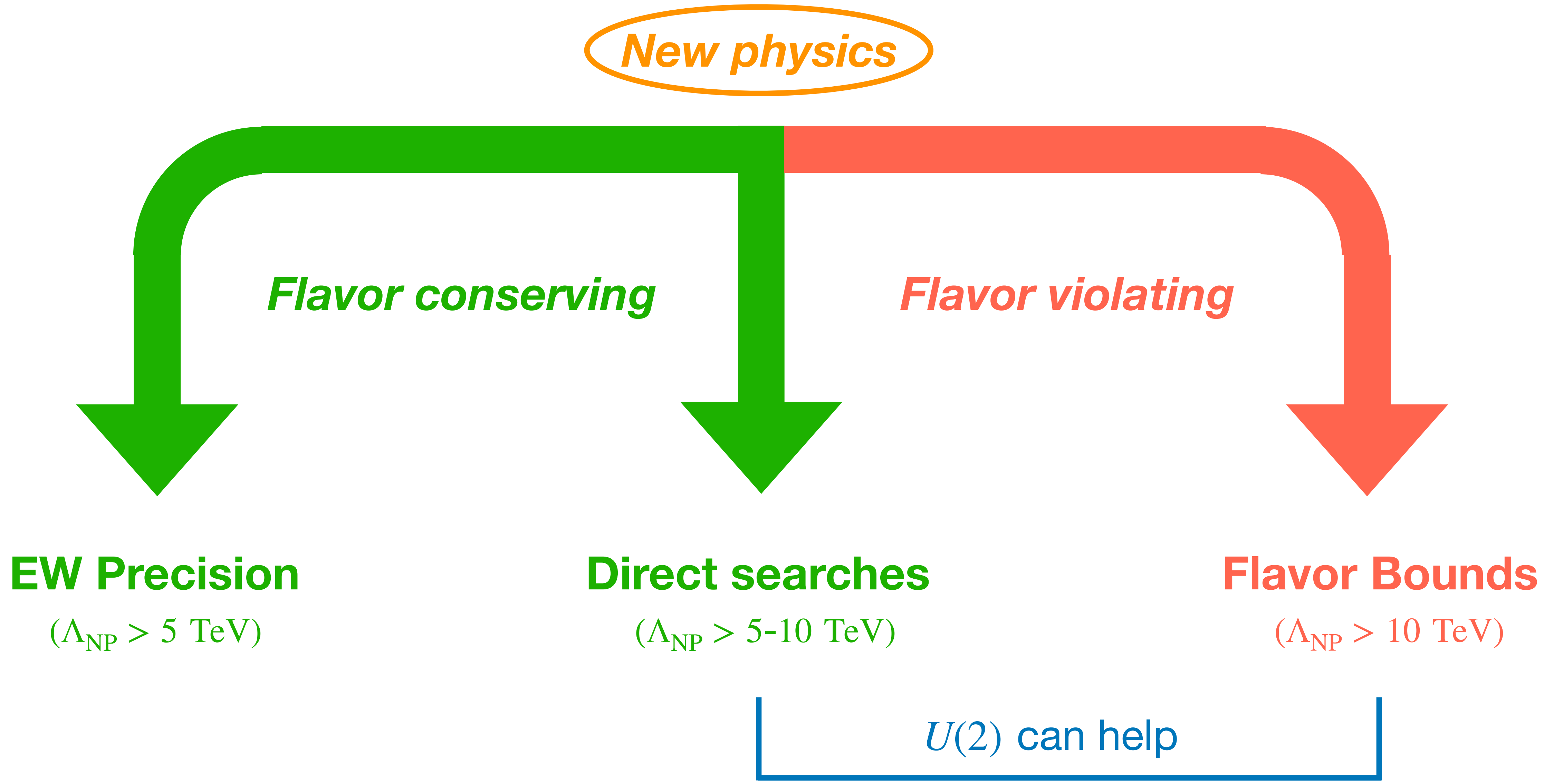

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A future EW precision machine is ideal to test the U(2) hypothesis!

SMEFT in the Exact U(2) Limit

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

Operators	$U(2)^5$ [terms summed up to different orders] Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1, \Delta^1)$		$\mathcal{O}(V^2, \Delta^1)$		$\mathcal{O}(V^2, \Delta^1 V^1)$		$\mathcal{O}(V^3, \Delta^1 V^1)$	
Class 1–4	9	6	9	6	9	6	9	6	9	6	9	6	9	6
$\psi^2 H^3$	3	3	6	6	6	6	9	9	9	9	12	12	12	12
$\psi^2 X H$	8	8	16	16	16	16	24	24	24	24	32	32	32	32
$\psi^2 H^2 D$	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 $\mathcal{O}(V^3, \Delta^1 V^1)$. Notations as in Table 1.

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

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

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- Focus on the 124 CP-even independent WC's in the exact $U(2)^5$ limit. Makes an exhaustive phenomenological analysis tractable.

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

Pheno analysis: Our procedure

- WC's entering observables are run up to a reference high scale of $\Lambda_{\mathrm{NP}} = 3\ \mathrm{TeV}$. We then impose $U(2)^5$ flavor symmetry on the high-scale WC's, e.g:

$$[C_{Hq}^{(1)}]_{11}(\mu_{\mathrm{EW}}) \rightarrow$$

```
0.906 CHq1[l] - 0.022 Cqq1[l, h, h, l] -
 0.189 Cqq1[l, l, h, h] - 0.004 Cqq1[l, l, p, p] -
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[J. Fuentes-Martin, P. Ruiz-Femenia, A. Vicente, J. Virto, arXiv:2010.16341]

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- For EWPT and direct searches, which constrain only the flavor-conserving WC's, the exact $U(2)^5$ limit is already sufficient.

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- Flavor-violating effects taken into account by considering the cases where the $U(2)^5$ basis corresponds to the 1) down-quark mass basis and 2) up-quark mass basis.

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- Flavor-violating effects taken into account by considering the cases where the $U(2)^5$ basis corresponds to the 1) down-quark mass basis and 2) up-quark mass basis.

- We then construct a likelihood as a function of the high-scale $U(2)^5$ invariants and switch on one at a time to obtain bounds.

[J. Fuentes-Martin, P. Ruiz-Femenia, A. Vicente, J. Virto, arXiv:2010.16341]

Pheno analysis: Our observables

EW Precision

- W-pole observables
- Z-pole observables

[V. Bresó-Pla, A. Falkowski, M. González-Alonso, 2103.12074]
[L. Allwicher, G. Isidori, J. M. Lizana, N. Selimovic, BAS, 2302.11584]

- Higgs signal strengths + LFU tests in τ-decays

Direct searches

- LHC Drell-Yan $pp \to \ell\ell$ and mono-lepton $pp \to \ell\nu$
- LHC 4-quark observables
- LEP 4-lepton $ee \to \ell\ell$

[L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, 2207.10756]

[Ethier, Magni, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang, 2105.00006]

HighPT

Flavor Bounds

- $\Delta F = 1$ ($B \to X_s \gamma$, $B \to K\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$, $B \to K^{(*)}\mu^+\mu^-$, $B_{s,d} \to \mu^+\mu^-$)
- $\Delta F = 2$ ($B_{s,d}$-mixing, K-mixing, D-mixing)
- Charged-current B-decays (R_D, R_{D*}, $B_{u,c} \to \tau\nu$)

Bounds from EWPT

- With no RGE, only 16 of 124 operators constrained on the Z-pole.
- Including RGE, we have 120 of 124, 38 with bounds $\gtrsim 1$ TeV.

No RGE

#	Wilson Coef.	$[\mathrm{Obs}]_{\mathrm{bound}}$	Λ_{bound} [TeV]
1	cHWB	A_b^{FB}	9.63
2	CHl1[l]	σ_{had}	8.07
3	CHl3[l]	A_b^{FB}	7.96
4	CHe[l]	σ_{had}	6.93
5	cHD	A_b^{FB}	5.74
6	CHq3[l]	R_τ	5.73
7	CHl1[h]	R_τ	4.57
8	CHl3[h]	R_τ	4.48
9	Cll[l, p, p, l]	A_b^{FB}	4.43
10	CHe[h]	R_τ	3.97
11	CHq3[h]	R_b	3.43
12	CHq1[h]	R_b	3.43
13	CHu[l]	R_τ	2.58
14	CHq1[l]	R_c	2.07
15	CHd[l]	R_τ	1.81
16	CHd[h]	R_b	1.4

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12	CHq1[h]	R_b	3.43
13	CHu[l]	R_τ	2.58
14	CHq1[l]	R_c	2.07
15	CHd[l]	R_τ	1.81
16	CHd[h]	R_b	1.4

#	Wilson Coef.	$[\text{Obs}]_{\text{bound}}$	Λ_{bound} [TeV]	Λ_{bound} [TeV] (LL)	$\Delta_{\text{Full-LL}}$ (%)
1	cHWB	A_b^{FB}	8.98	8.78	2.2
2	CHl3[l]	σ_{had}	7.75	7.64	1.4
3	CHl1[l]	σ_{had}	7.65	7.51	1.8
4	CHe[l]	σ_{had}	6.6	6.48	1.8
5	CHq3[l]	R_τ	5.56	5.48	1.4
6	cHD	A_b^{FB}	5.05	4.71	6.7
7	Cll[l, p, p, l]	A_b^{FB}	4.52	4.52	0.
8	CHl1[h]	R_τ	4.37	4.3	1.6
9	CHl3[h]	R_τ	4.36	4.3	1.4
10	CHe[h]	R_τ	3.76	3.68	2.1
11	CHq1[h]	Γ_Z	3.74	4.34	-16.
12	CHq3[h]	R_b	3.48	3.53	-1.4
13	CHu[h]	A_b^{FB}	3.04	3.99	-31.3
14	Clq1[l, l, h, h]	σ_{had}	2.46	2.87	-16.7
15	CHu[l]	R_τ	2.43	2.39	1.6
16	Clq3[l, l, h, h]	A_b^{FB}	2.41	2.72	-12.9
17	Clu[l, l, h, h]	σ_{had}	2.39	2.81	-17.6
18	CuB[h]	A_b^{FB}	2.38	2.79	-17.2
19	CuW[h]	A_b^{FB}	2.35	2.67	-13.6
20	Cqq3[l, l, h, h]	R_b	2.28	2.61	-14.5
21	Cqe[h, h, l, l]	σ_{had}	2.12	2.47	-16.5
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23	CHq1[l]	R_c	1.94	1.9	2.1
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25	Cqq1[h, h, h, h]	R_b	1.6	1.75	-9.4
26	Cqq3[l, l, p, p]	R_τ	1.49	1.5	-0.7
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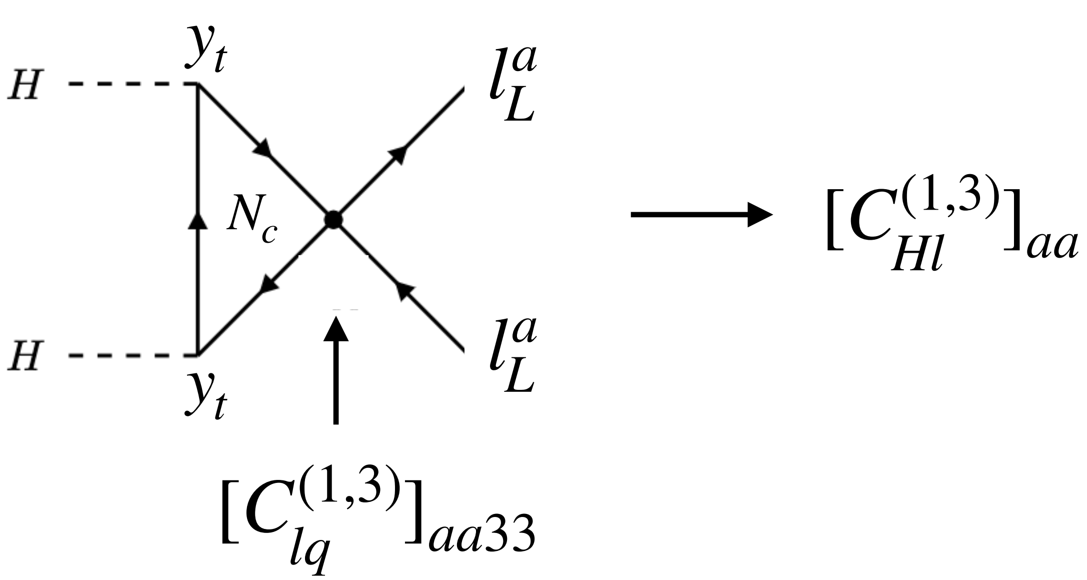
Bounds from EWPT

- With no RGE, only 16 of 124 operators constrained on the Z-pole.
- Including RGE, we have 120 of 124, 38 with bounds $\gtrsim 1$ TeV.
- Important effects come from operators w/ third-family quarks running strongly with y_t into operators directly constrained on the Z-pole:



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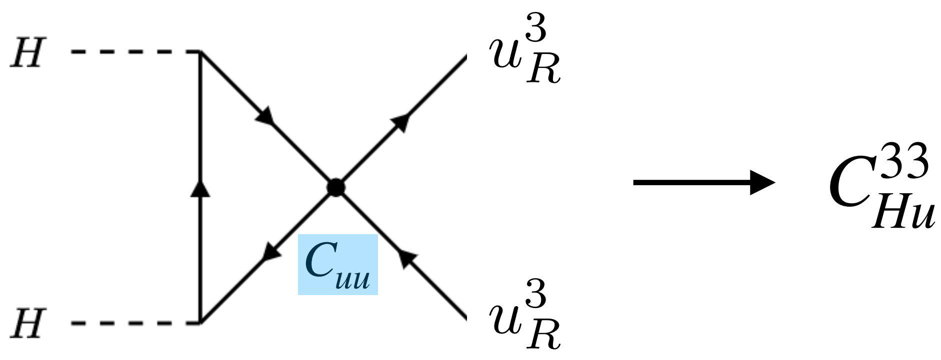

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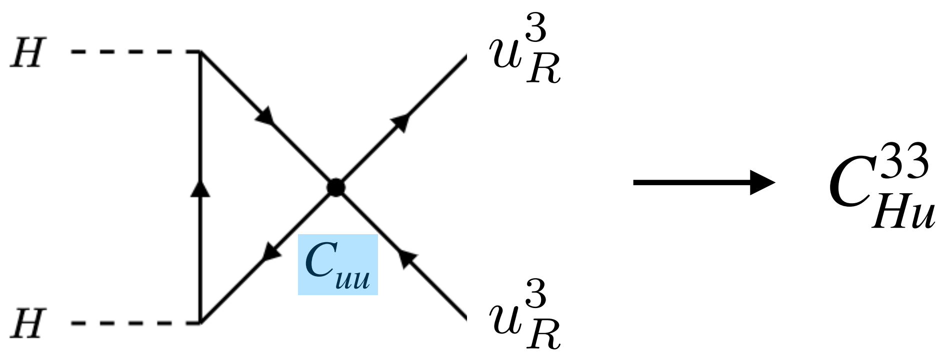
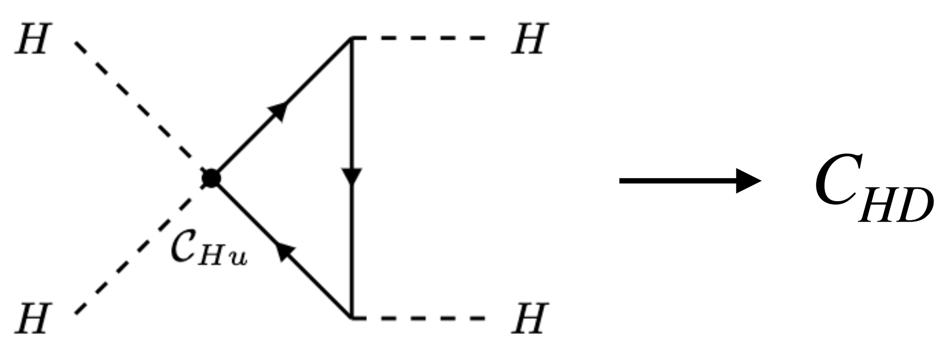


NLL RGE



$$[\mathcal{C}_{HD}]^{\rm NLL} \approx \frac{4N_c^2\, y_t^4}{(16\pi^2)^2}\, \mathcal{C}_{uu} \log^2\left(\frac{\mu^2}{\Lambda_{\rm NP}^2}\right)$$

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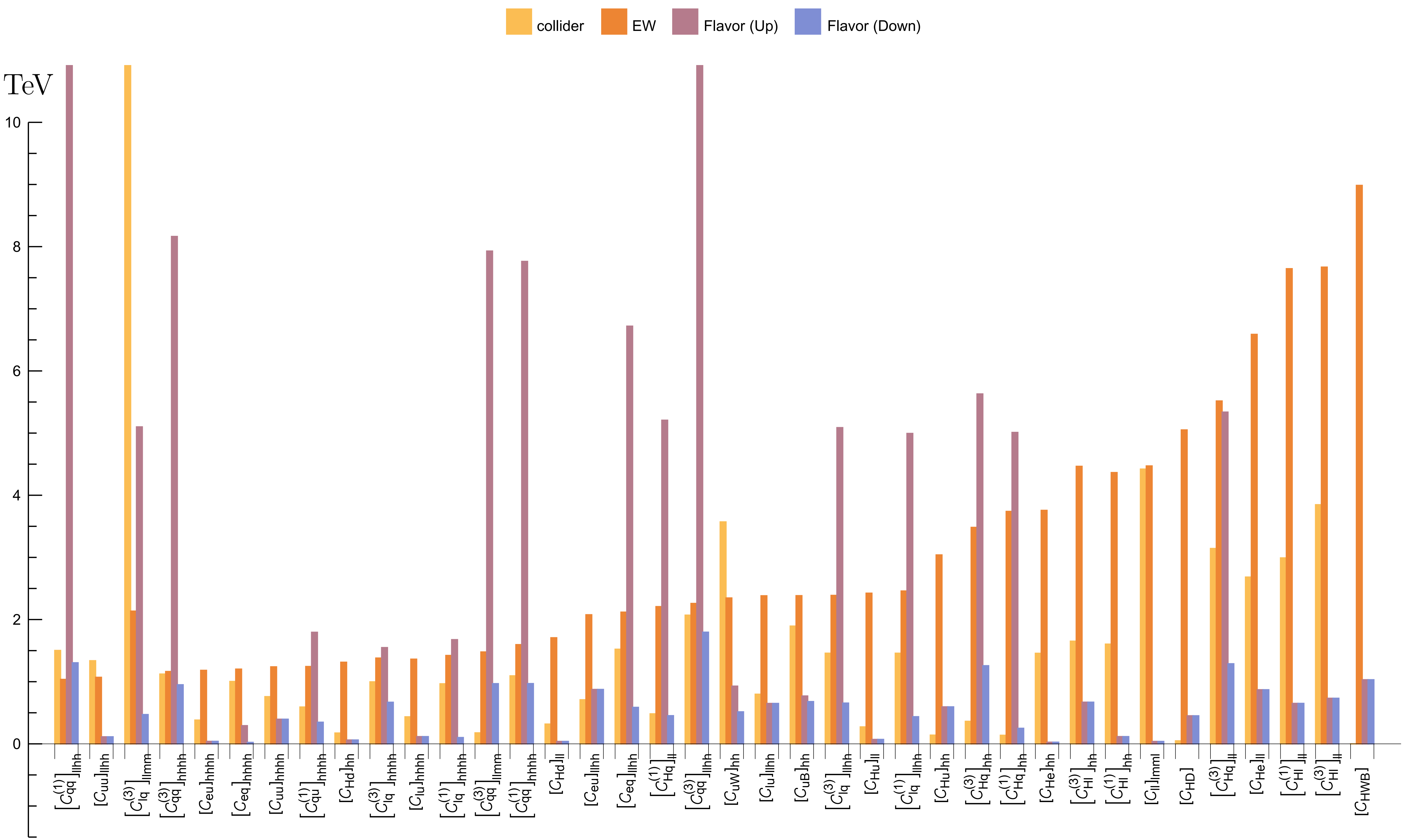

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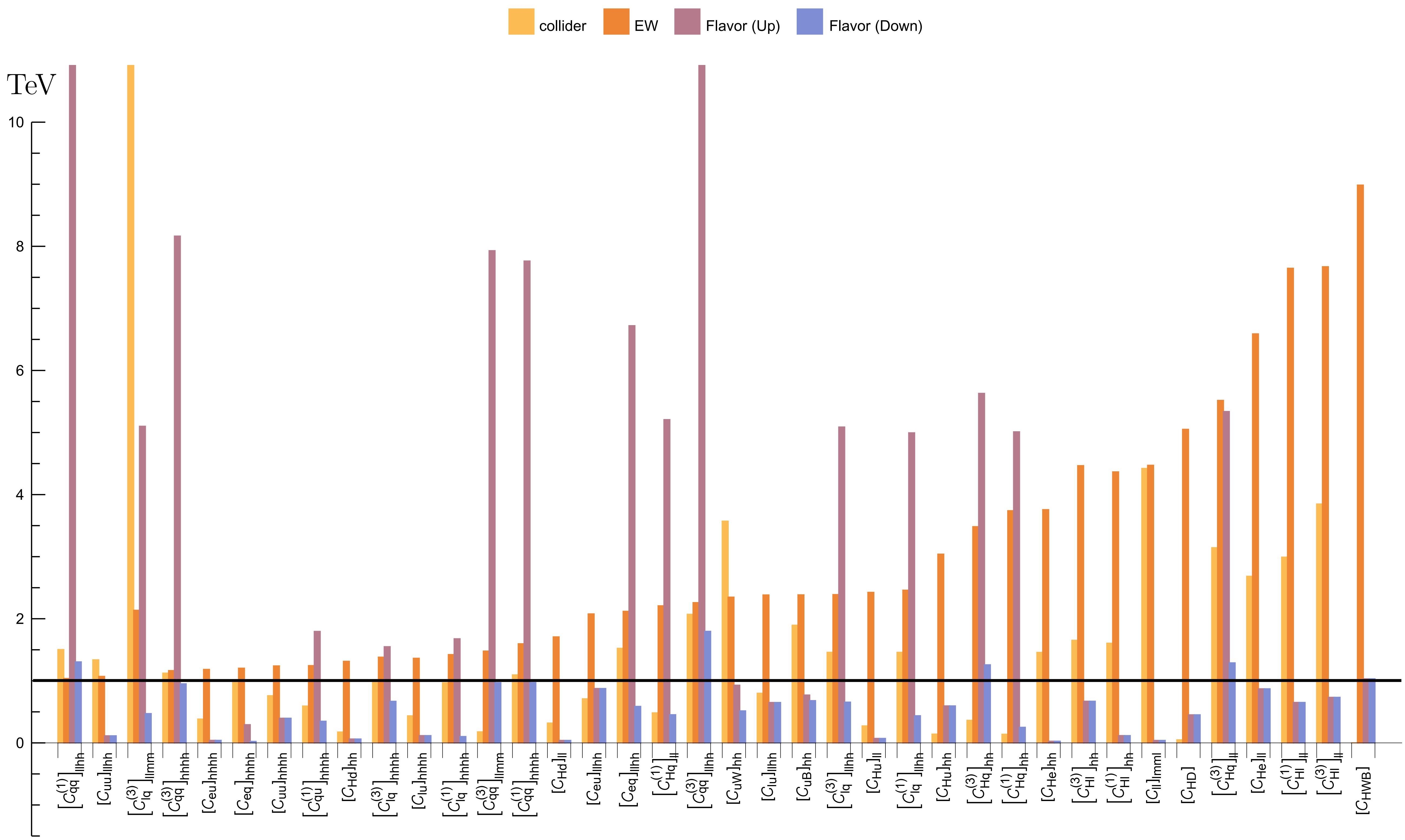

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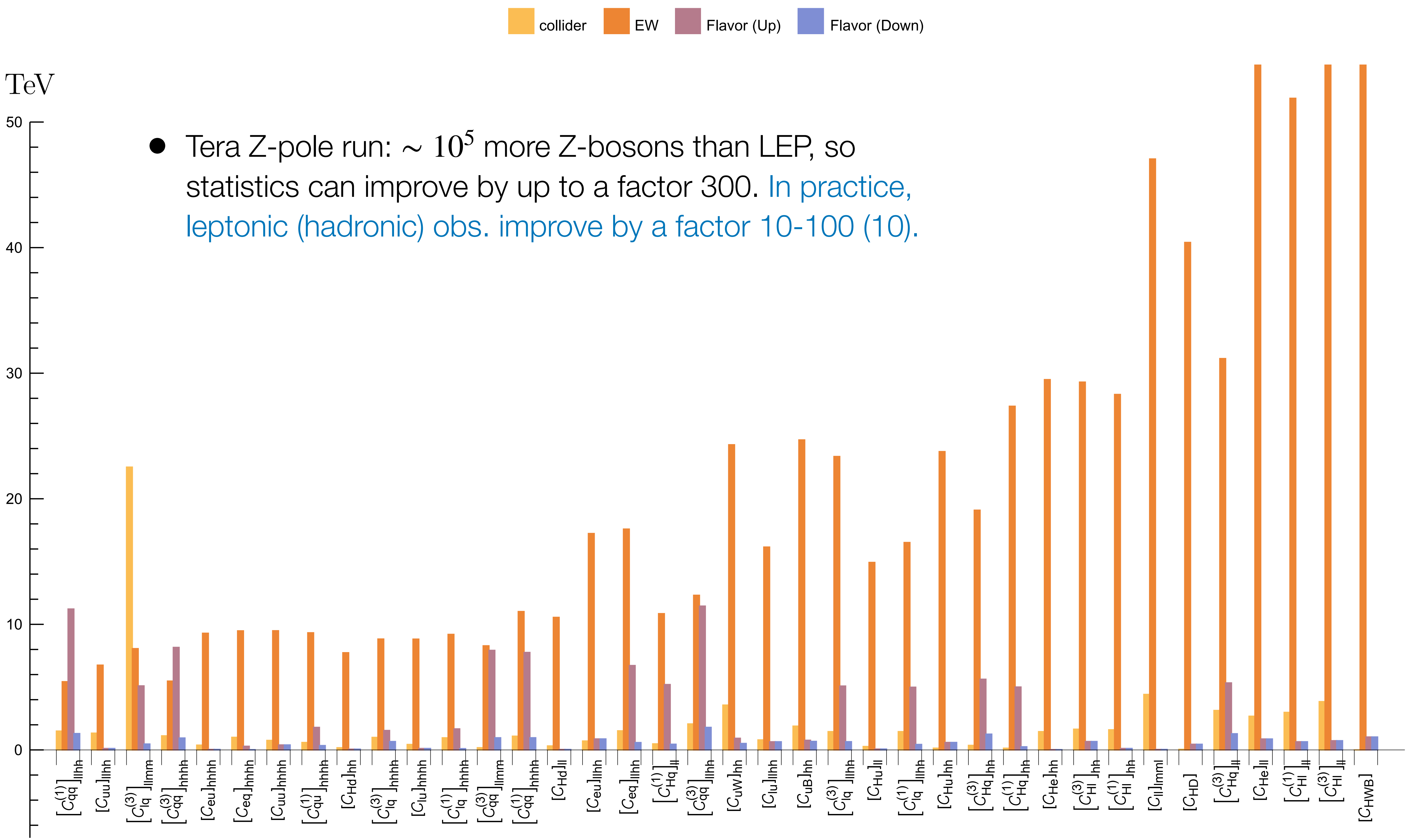

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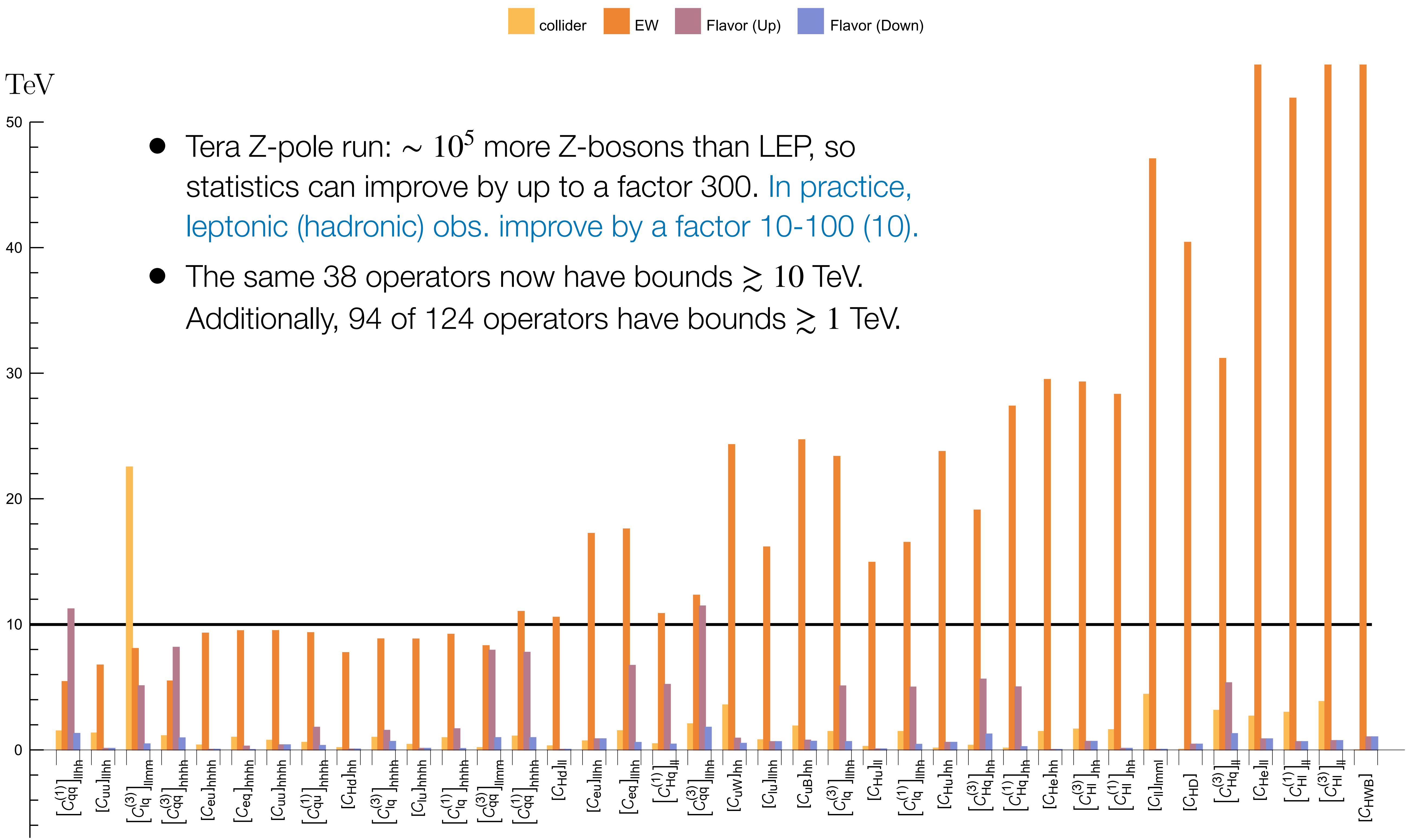

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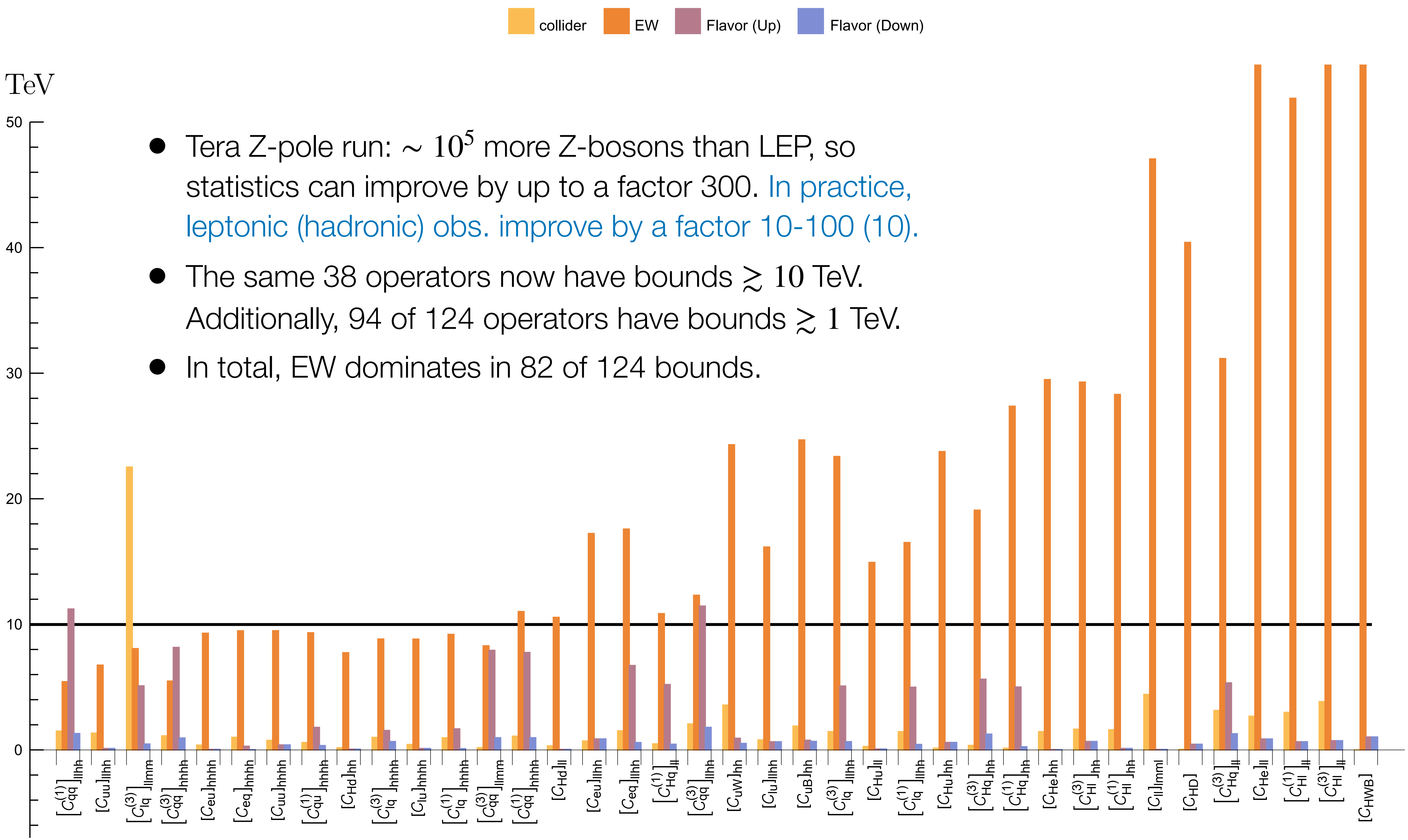

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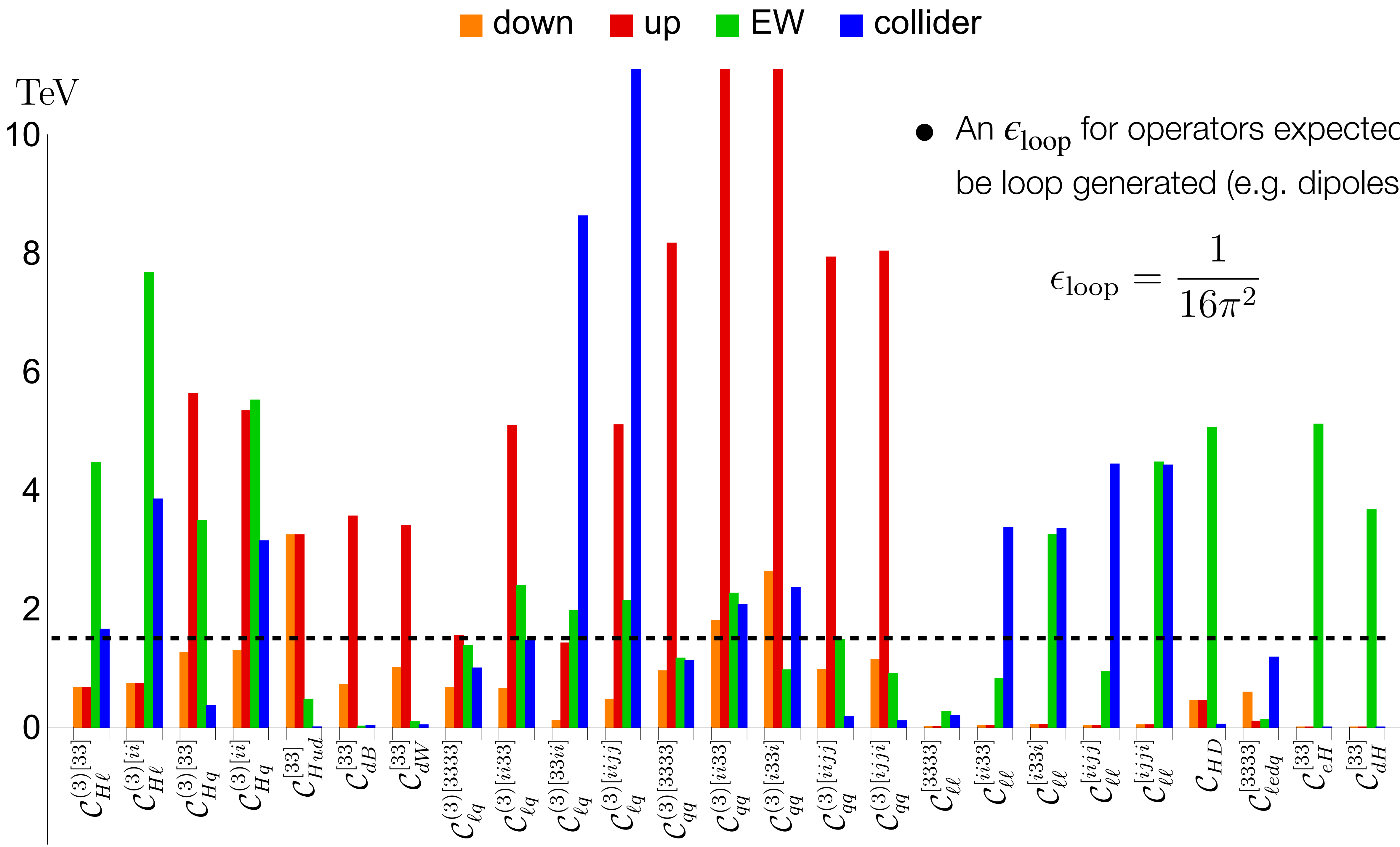
NP coupled to the light families: Bounds O(5-10) TeV



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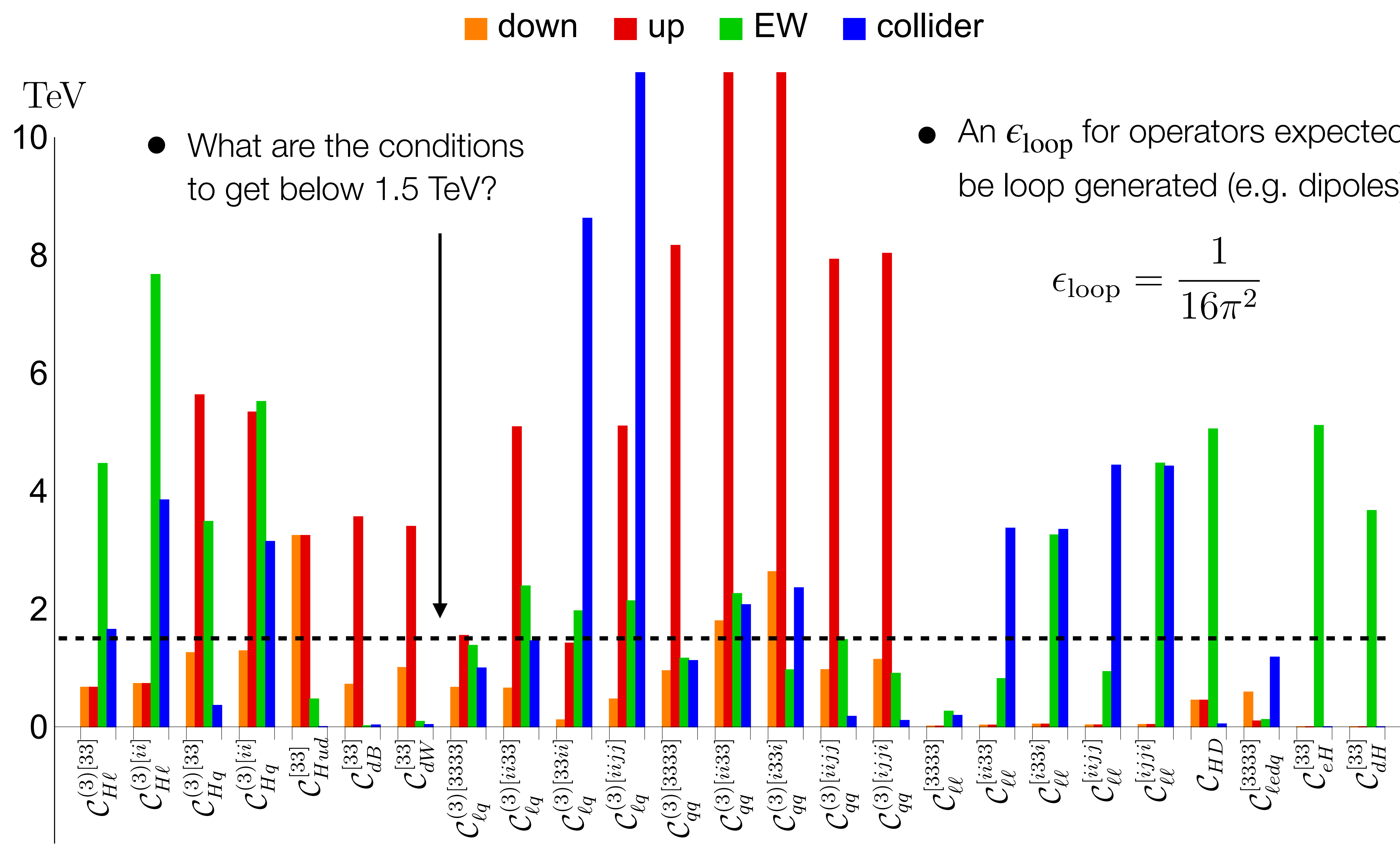

- What are the conditions to get below 1.5 TeV?

- An ϵ_{loop} for operators expected to be loop generated (e.g. dipoles).

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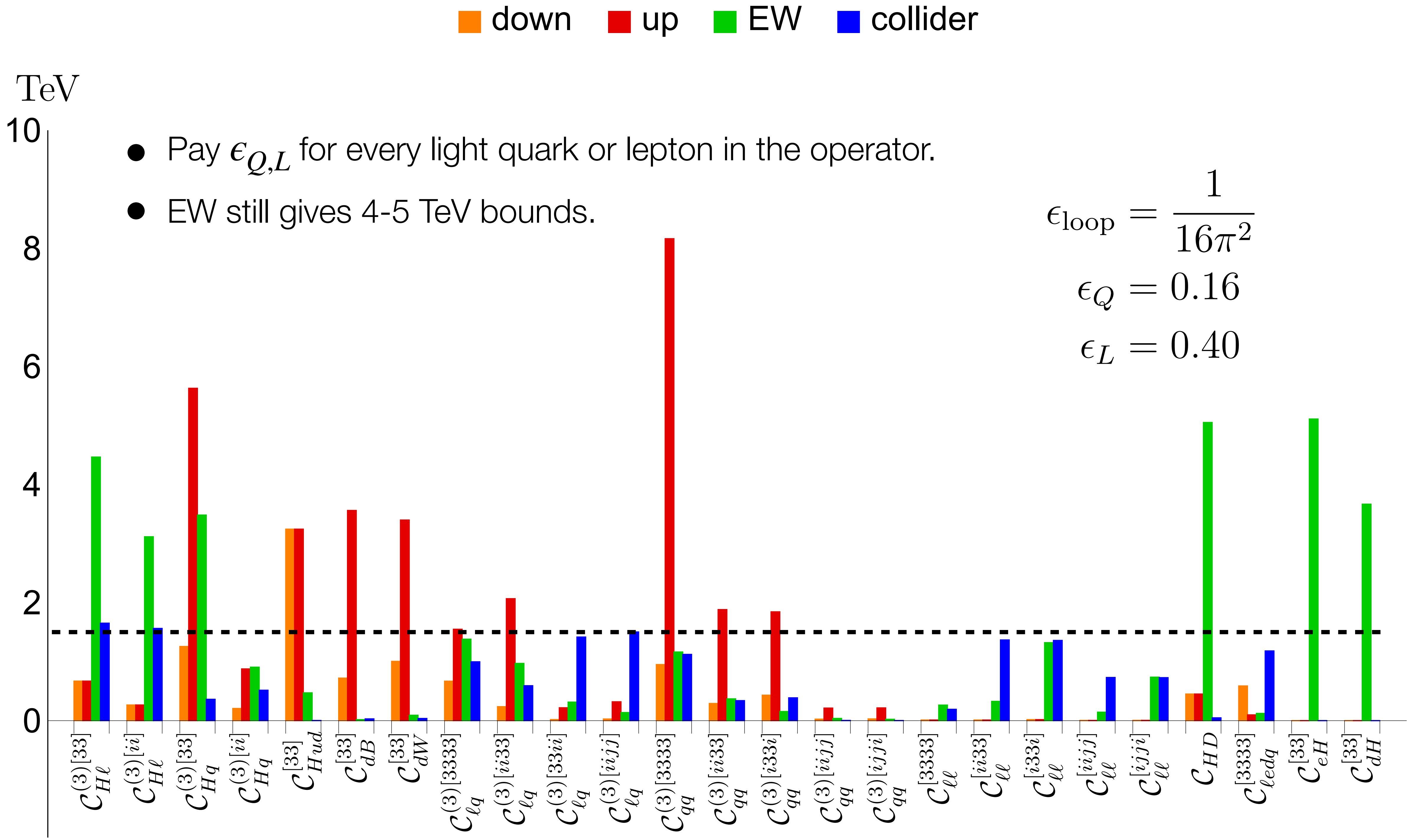
Hypothesis of dominantly third-family NP



- Pay $\epsilon_{Q,L}$ for every light quark or lepton in the operator.
- EW still gives 4-5 TeV bounds.

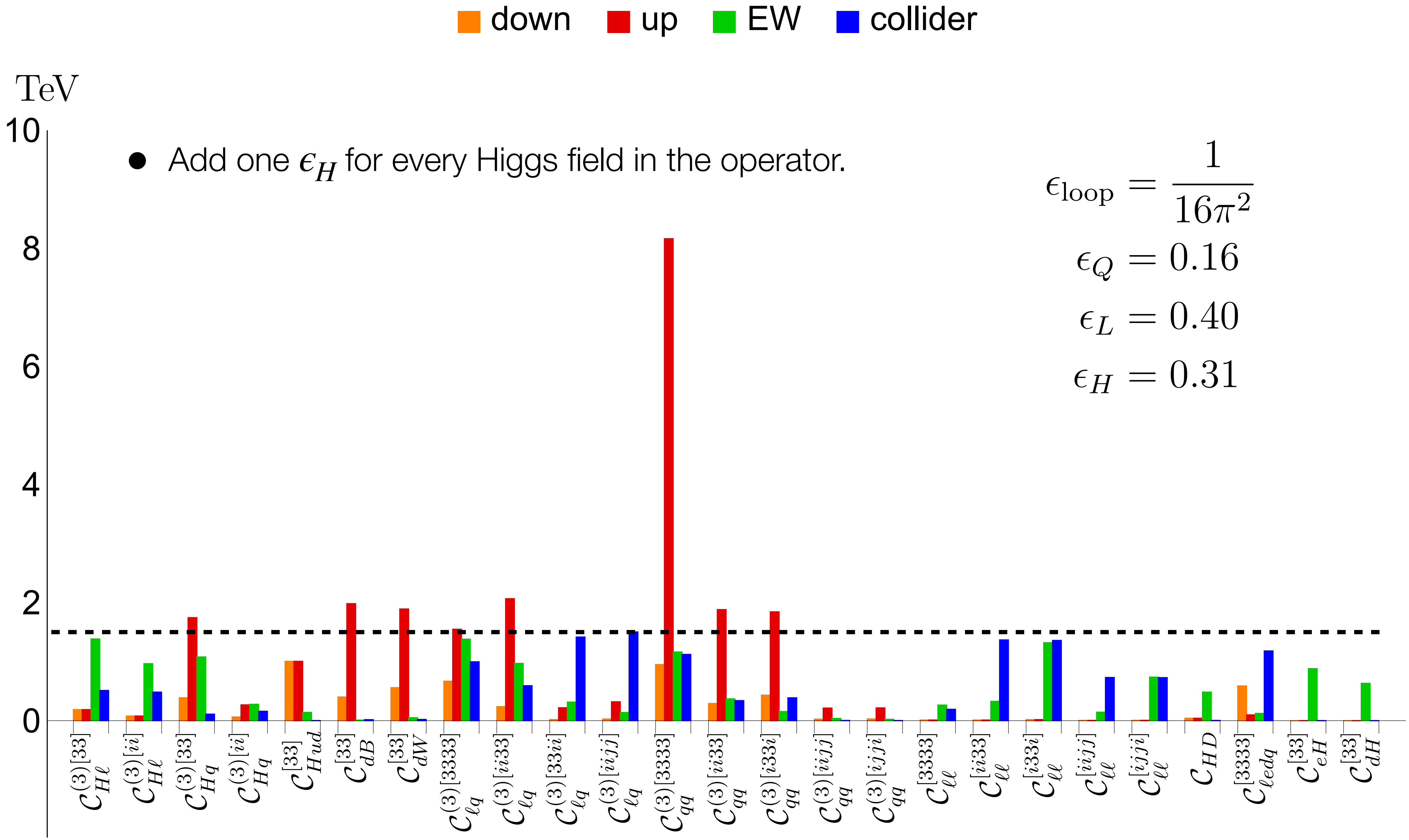
$$\epsilon_{\text{loop}} = \frac{1}{16\pi^2}$$

$$\epsilon_Q = 0.16$$

$$\epsilon_L = 0.40$$

[Allwicher, Cornella, Isidori, BAS, to appear]

Third-family NP: Higgs couplings

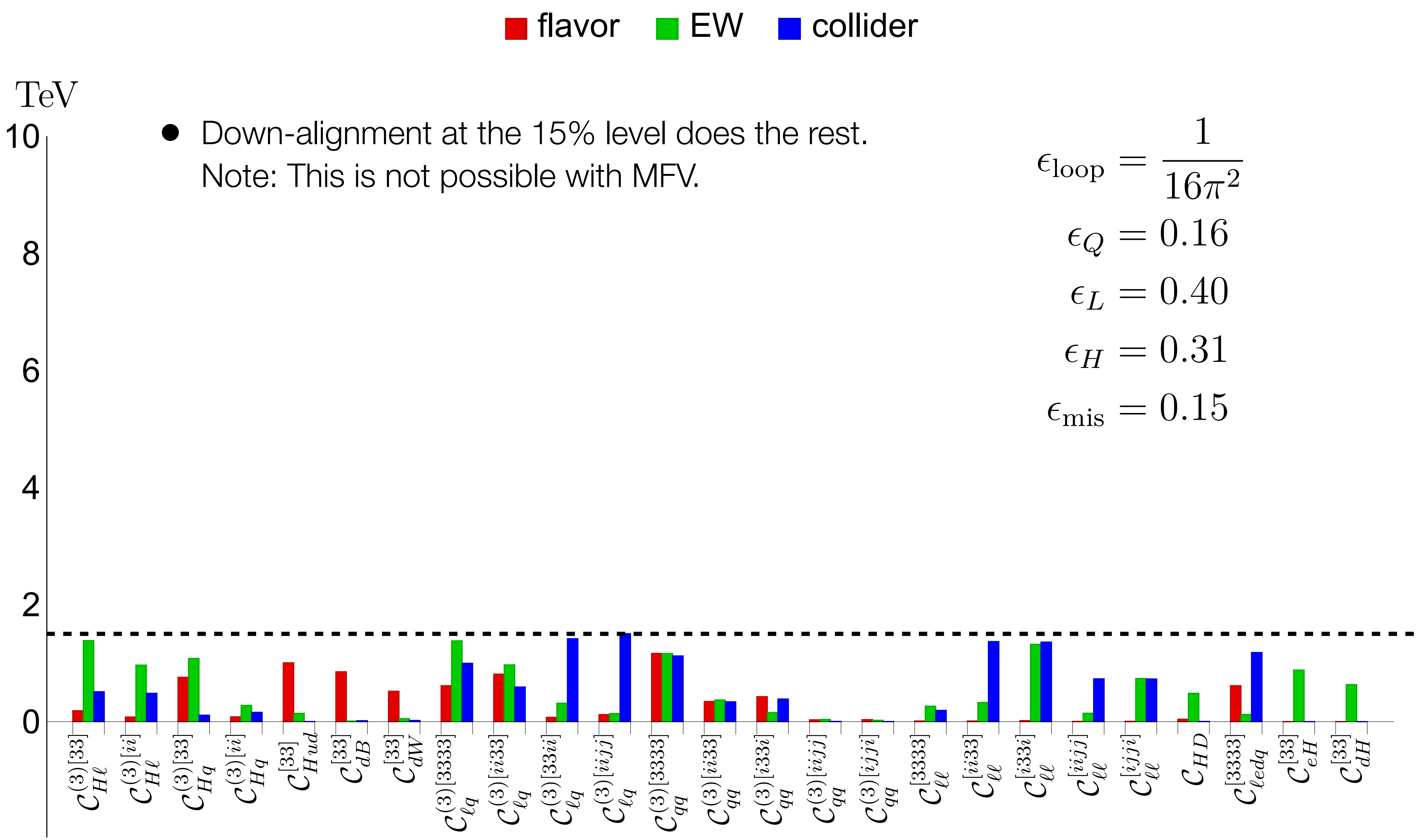


- Add one ϵ_H for every Higgs field in the operator.

$$\epsilon_{\rm loop} = \frac{1}{16\pi^2}$$
$$\epsilon_Q = 0.16$$
$$\epsilon_L = 0.40$$
$$\epsilon_H = 0.31$$

[Allwicher, Cornella, Isidori, BAS, to appear]

Third-family NP: Flavor alignment



- Down-alignment at the 15% level does the rest.
  Note: This is not possible with MFV.

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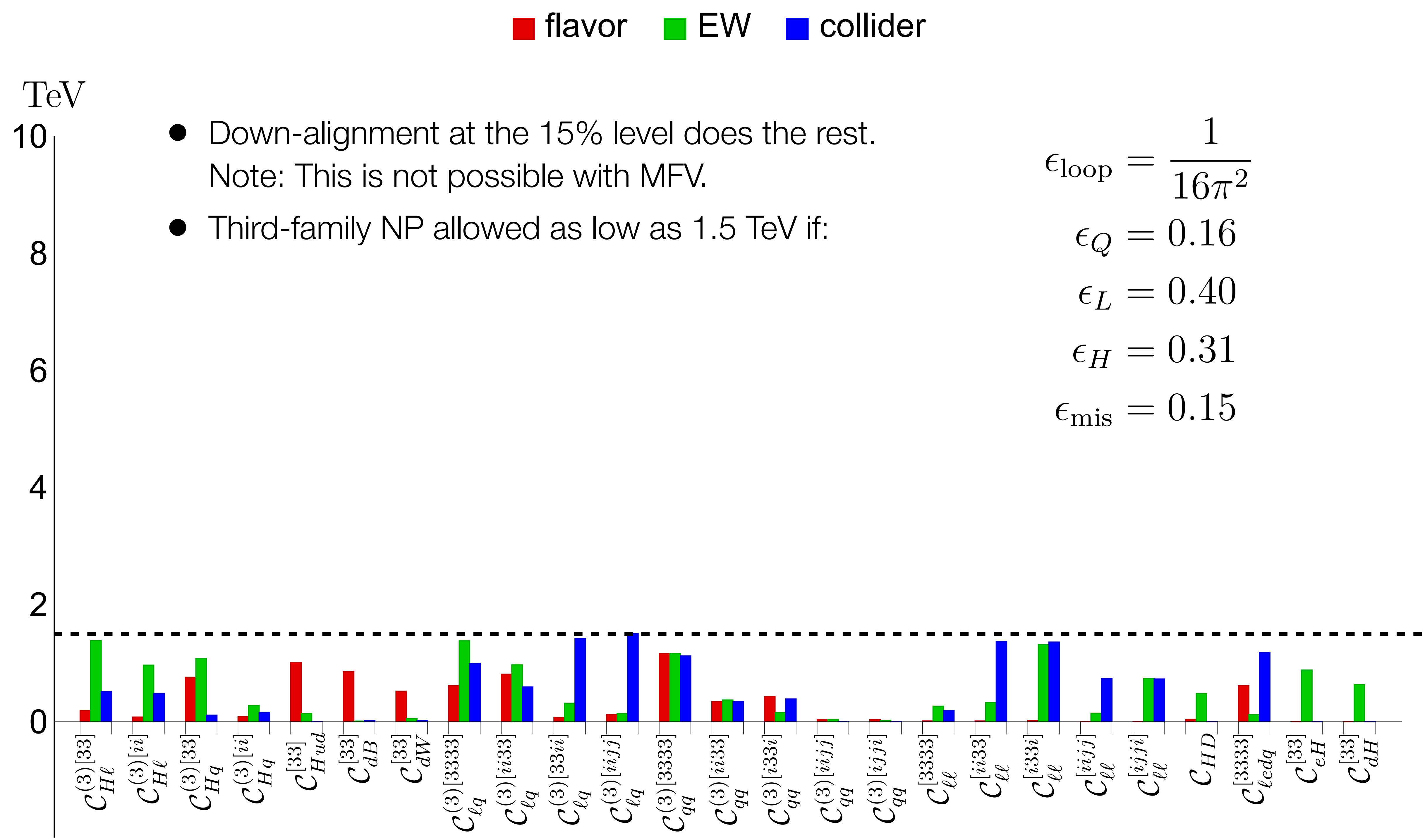

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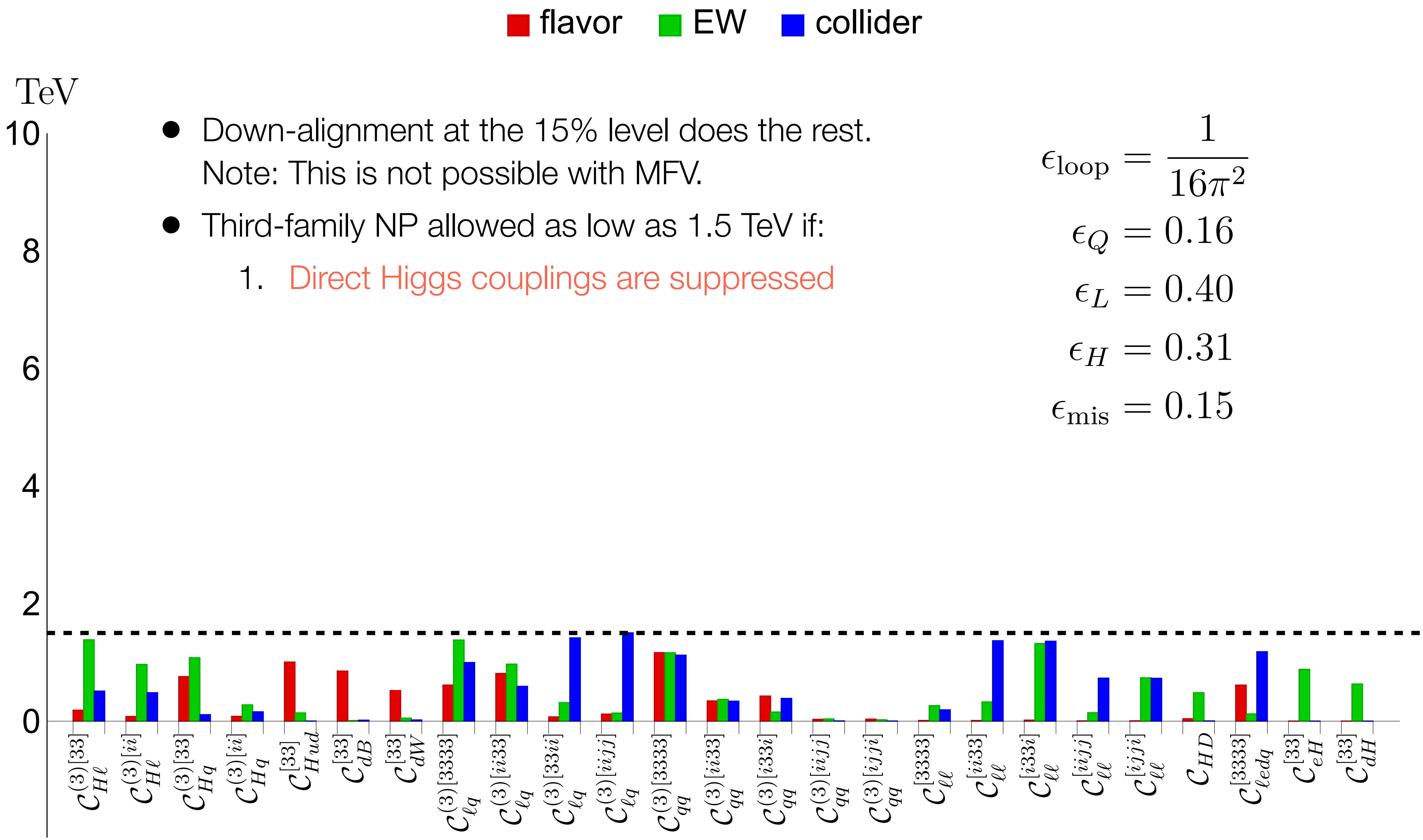

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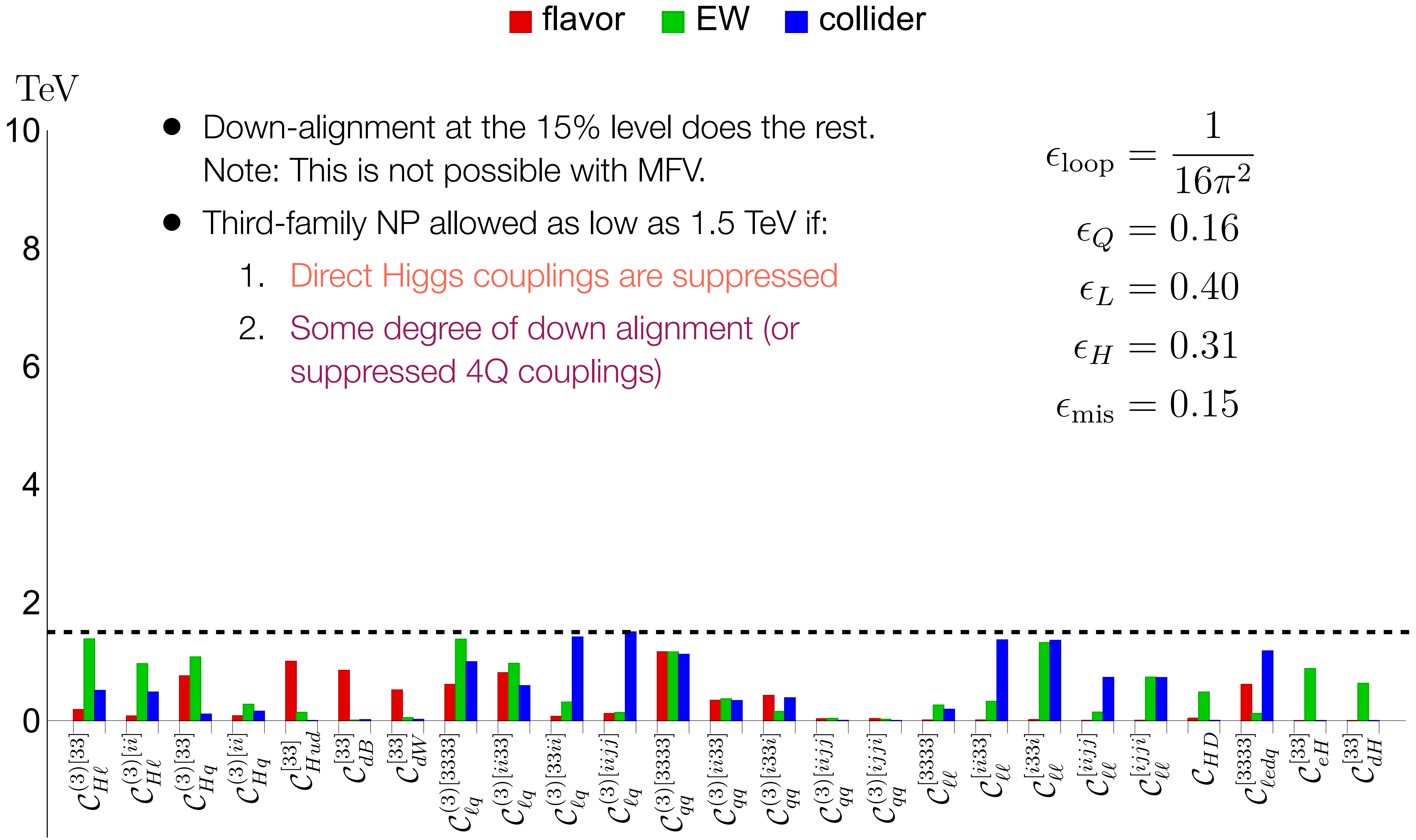

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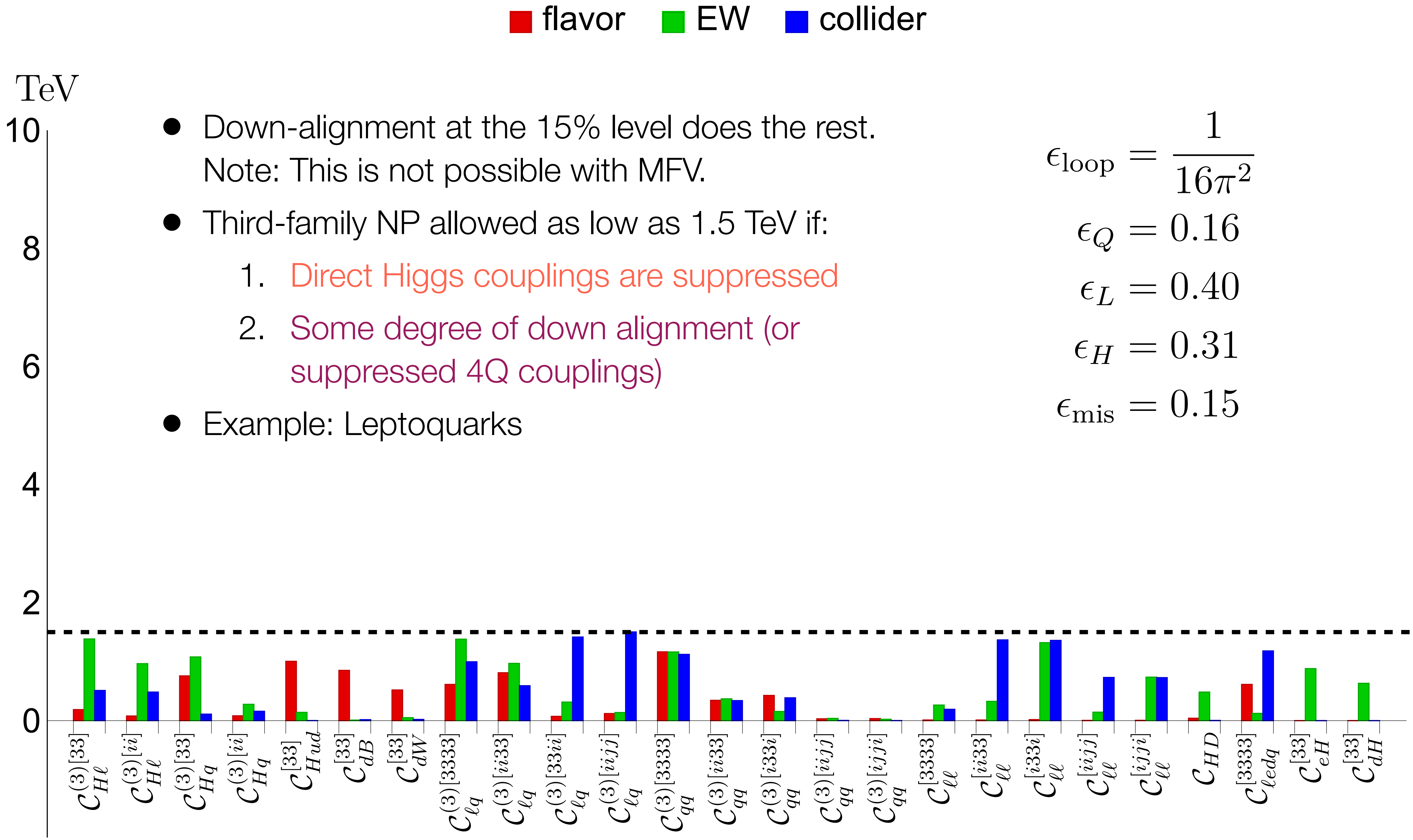

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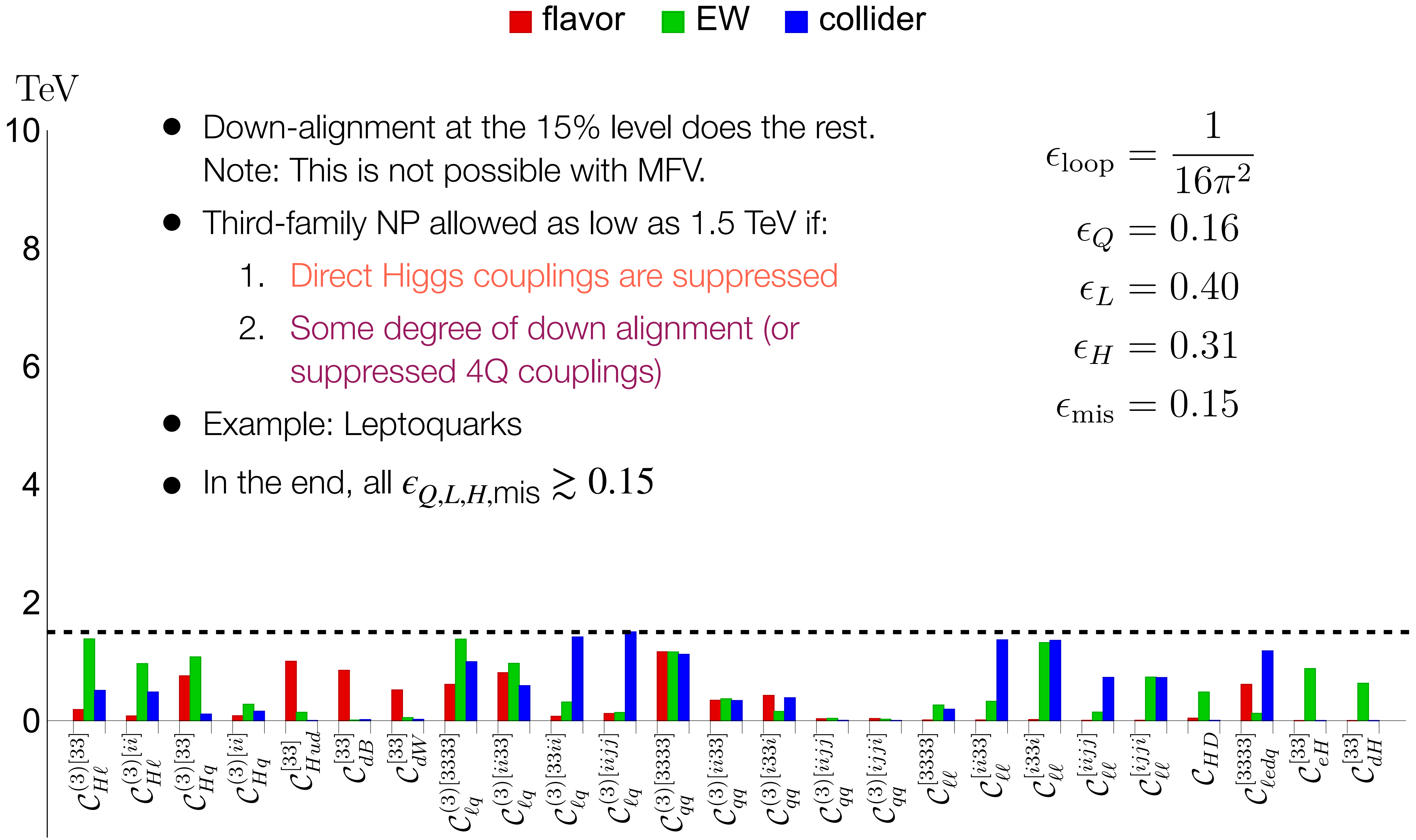

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- In the end, all $\epsilon_{Q,L,H,\text{mis}} \gtrsim 0.15$

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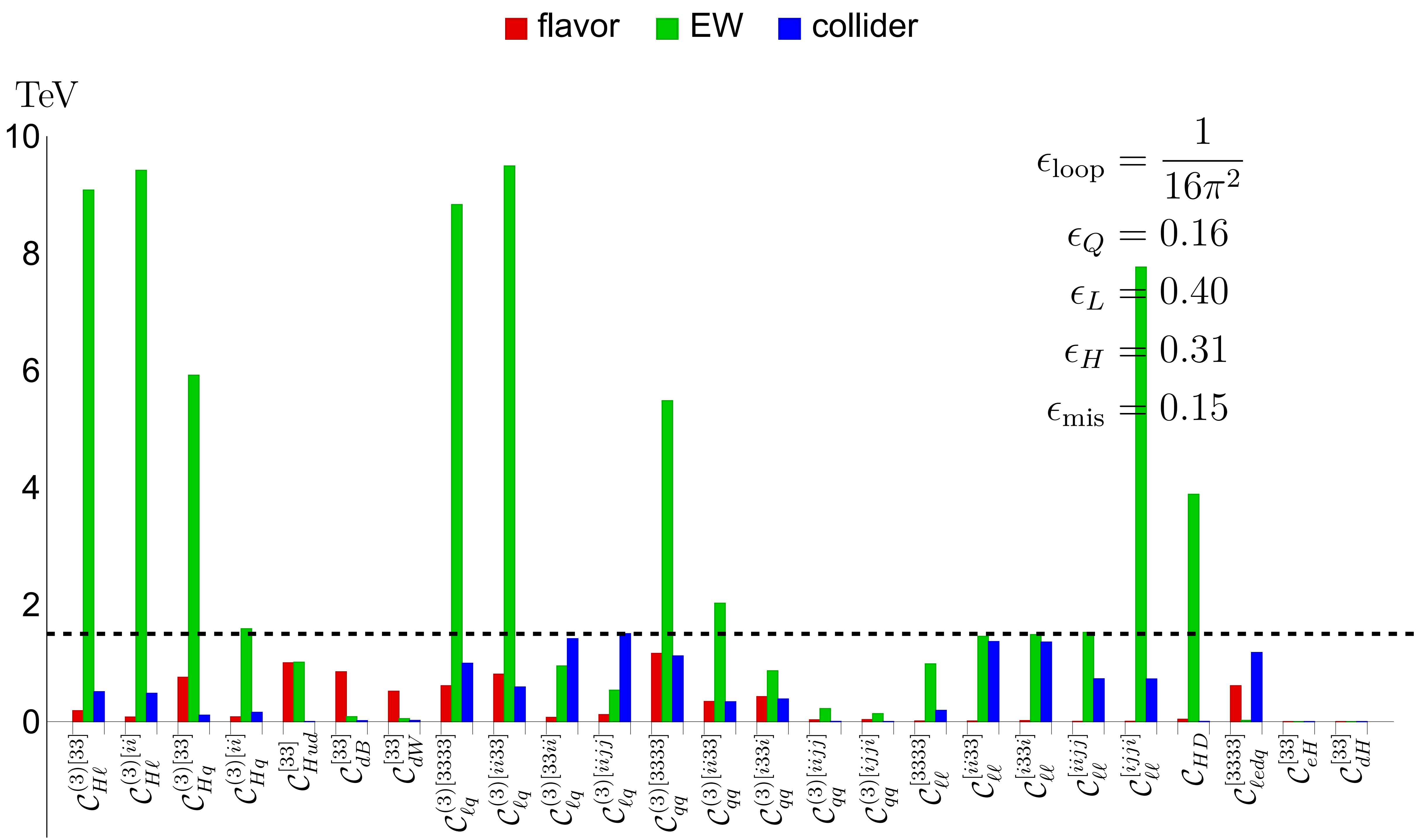

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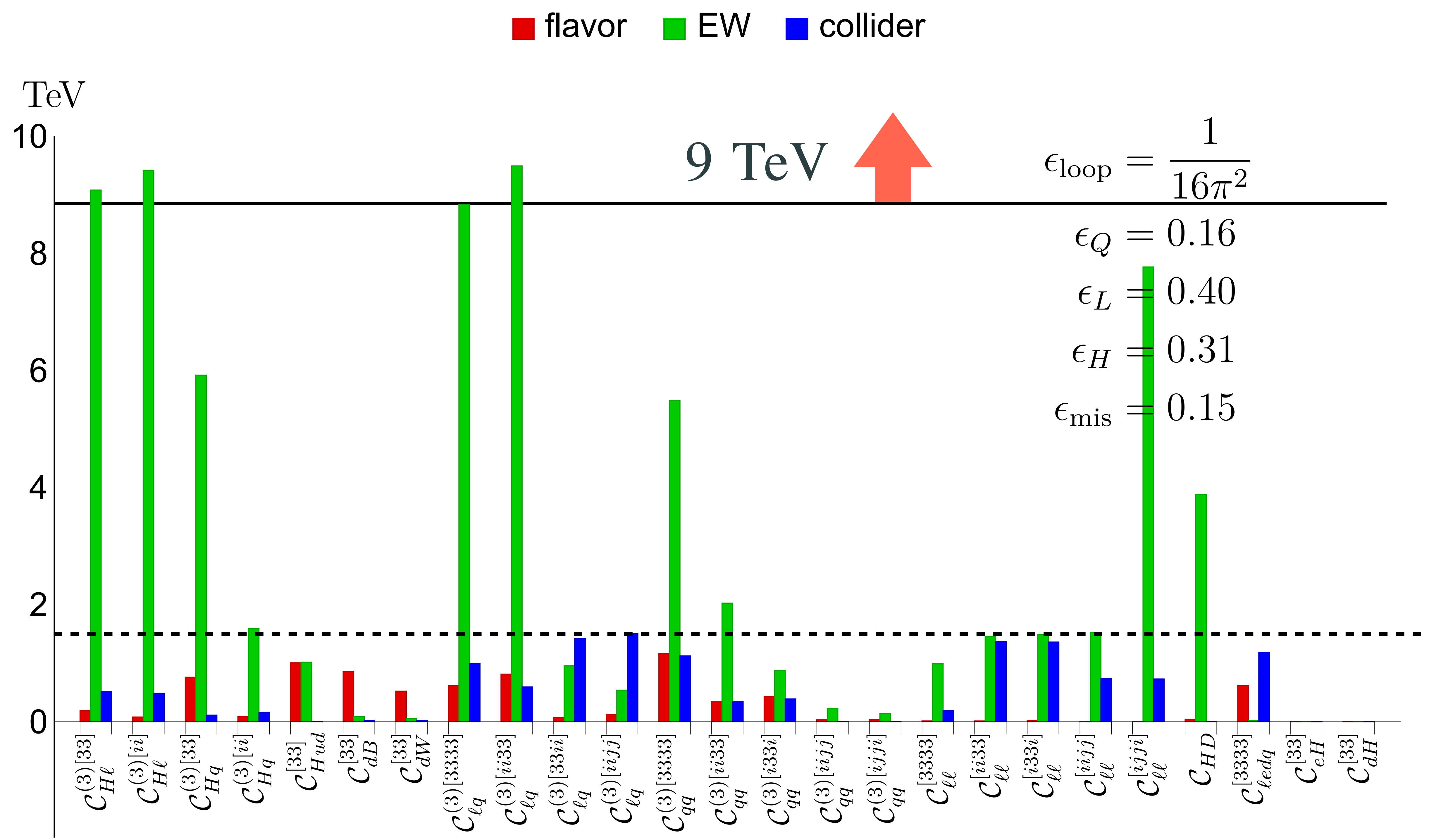

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Backup Slides

How does the Higgs fit into the story?

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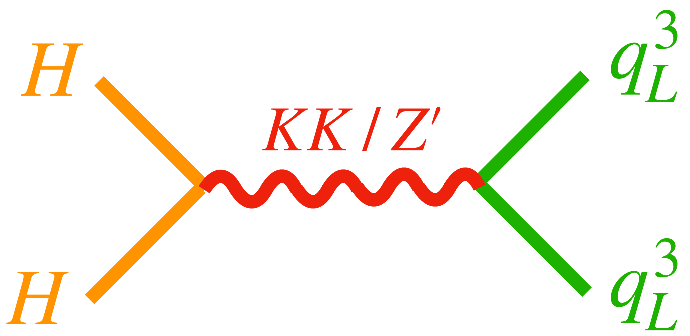

$$C_{Hq}^{(1)[33]}(H^\dagger D_\mu H)(\bar{q}_L^3 \gamma^\mu q_L^3)$$

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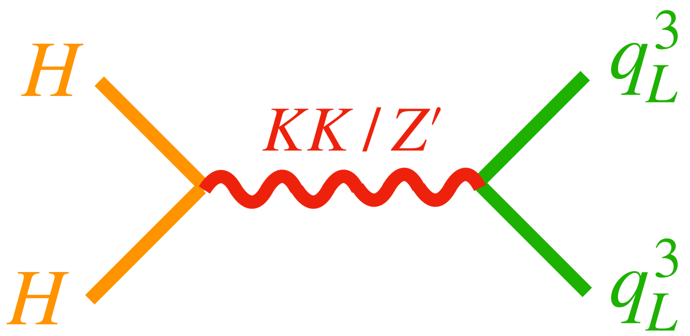

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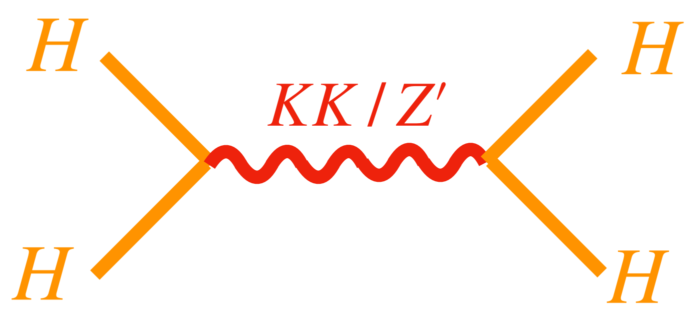

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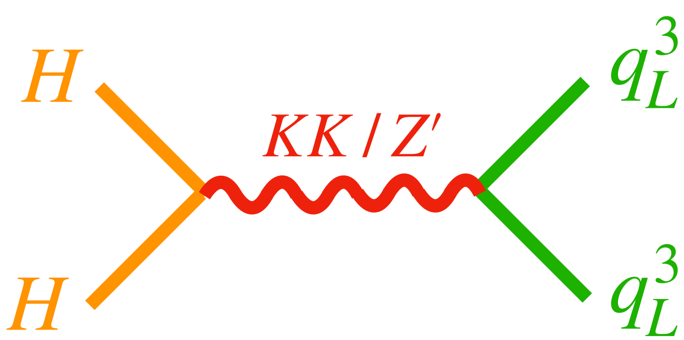
Both operators are $U(2)^5$ preserving!

Difficult for NP to hide once the Higgs is brought into the game!



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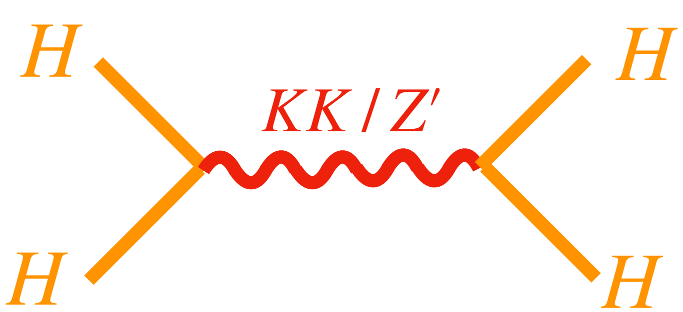

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The 'LEP paradox'

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Alessandro Strumia

Dipartimento di Fisica, Università di Pisa and INFN, Pisa, Italia

27 Nov 2000

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A straight interpretation of the results of the EWPT, mostly performed at LEP in the last decade, gives rise to an apparent paradox. The EWPT indicate both a light Higgs mass $m_h \approx (100 \div 200)\,\text{GeV}$ and a high cut-off, $\Lambda \gtrsim 5\,\text{TeV}$, with the consequence of a top loop correction to m_h largely exceeding the preferred value of m_h itself. The well known naturalness problem of the Fermi scale has gained a pure 'low energy' aspect. At present, supersymmetry at the Fermi scale is the only way we know of to attach this problem.

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This way of looking at the data may be too naive. As we said, in EWPT the SM with a light Higgs and a large cut-off can at least be faked by a fortuitous cancellation. In any case the point is not to replace direct searches for supersymmetry or for any other kind of new physics. Rather, we wonder if a better theoretical focus on the LEP paradox might be not without useful consequences. Its solution, we think, is bound to give us some surprise, in a way or another.

Collider Constraints on 4Q operators

Class	DoF	$t\bar{t}$	$t\bar{t}V$	t	tV	$t\bar{t}Q\bar{Q}$	h (μ_i^f, Run-I)	h (μ_i^f, Run-II)	h (STXS, Run-II)	VV
2-heavy-2-light	$c_{Qq}^{1,8}$	✓	✓			✓	✓	✓	✓	
	$c_{Qq}^{1,1}$	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	$c_{Qq}^{3,8}$	✓	✓	(✓)	(✓)	✓	✓	✓	✓	
	$c_{Qq}^{3,1}$	(✓)	(✓)	✓	✓	✓	(✓)	(✓)	(✓)	
	c_{tq}^{8}	✓	✓			✓	✓	✓	✓	
	c_{tq}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{tu}^{8}	✓	✓			✓	✓	✓	✓	
	c_{tu}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{Qu}^{8}	✓	✓			✓	✓	✓	✓	
	c_{Qu}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{td}^{8}	✓	✓			✓	✓	✓	✓	
	c_{td}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{Qd}^{8}	✓	✓			✓	✓	✓	✓	
	c_{Qd}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
4-heavy	c_{QQ}^{1}					✓				
	c_{QQ}^{8}					✓				
	c_{Qt}^{1}					✓				
	c_{Qt}^{8}					✓				
	c_{tt}^{1}					✓				
4-lepton	c_{ll}			✓	✓		✓	✓	✓	✓
2-fermion +bosonic	$c_{t\varphi}$						✓	✓	✓	
	c_{tG}	✓	✓			✓	✓	✓	✓	
	$c_{b\varphi}$						✓	✓	✓(b)	
	$c_{c\varphi}$						✓	✓		
	$c_{\tau\varphi}$						✓	✓		
	c_{tW}	✓		✓	✓		✓	✓		
	c_{tZ}		✓		✓		✓	✓		
	$c_{\varphi Q}^{(3)}$		✓(b)	✓	✓		✓(b)	✓(b)	✓(b)	
	$c_{\varphi Q}^{(-)}$		✓		✓		✓	✓	✓(b)	
	$c_{\varphi t}$		✓		✓		✓	✓		
	$c_{\varphi l_i}^{(1)}$						✓	✓		✓
	$c_{\varphi l_i}^{(3)}$			✓	✓		✓	✓	✓	✓
	$c_{\varphi e}$						✓	✓		✓
	$c_{\varphi \mu}$						✓	✓		
	$c_{\varphi \tau}$						✓	✓		
	$c_{\varphi q}^{(3)}$		✓	✓	✓		✓	✓	✓	✓
	$c_{\varphi q}^{(-)}$		✓		✓		✓	✓	✓	✓
	$c_{\varphi u}$		✓		✓		✓	✓	✓	✓
	$c_{\varphi d}$		✓		✓		✓	✓	✓	✓

[Ethier, Magni, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang, 2105.00006]

Hermitian bi-fermion operators

coeff.	$\Lambda_{\text{flav.}}^{\text{down}}$	$\Lambda_{\text{flav.}}^{\text{up}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$	$\Lambda_{\text{all}}^{\text{down}}$	Obs.	$\Lambda_{\text{all}}^{\text{up}}$	Obs.
$\mathcal{C}_{H\ell}^{(1)[33]}$	0.1	0.1	4.4	1.6	4.3	R_τ	4.3	R_τ
$\mathcal{C}_{H\ell}^{(1)[ii]}$	0.7	0.7	7.6	3.	7.8	σ_{had}	7.8	σ_{had}
$\mathcal{C}_{H\ell}^{(3)[33]}$	0.7	0.7	4.5	1.7	4.4	R_τ	4.4	R_τ
$\mathcal{C}_{H\ell}^{(3)[ii]}$	0.7	0.7	7.7	3.8	7.7	σ_{had}	7.7	σ_{had}
$\mathcal{C}_{He}^{[33]}$	-	-	3.8	1.5	3.7	R_τ	3.7	R_τ
$\mathcal{C}_{He}^{[ii]}$	0.9	0.9	6.6	2.7	6.7	σ_{had}	6.7	σ_{had}
$\mathcal{C}_{Hq}^{(1)[33]}$	0.3	5.	3.7	0.1	3.7	Γ_Z	5.1	$B_s \to \mu\mu$
$\mathcal{C}_{Hq}^{(1)[ii]}$	0.5	5.2	1.9	0.5	2.	R_c	5.4	$B_s \to \mu\mu$
$\mathcal{C}_{Hq}^{(3)[33]}$	1.3	5.6	3.5	0.4	3.4	R_b	5.5	$B_s \to \mu\mu$
$\mathcal{C}_{Hq}^{(3)[ii]}$	1.3	5.3	5.6	3.1	5.7	R_τ	7.7	Γ_Z
$\mathcal{C}_{Hd}^{[33]}$	-	-	1.3	0.2	1.3	R_b	1.3	R_b
$\mathcal{C}_{Hd}^{[ii]}$	-	-	1.7	0.3	1.7	R_τ	1.7	R_τ
$\mathcal{C}_{Hu}^{[33]}$	0.6	0.6	3.	0.1	3.1	A_b^{FB}	3.1	A_b^{FB}
$\mathcal{C}_{Hu}^{[ii]}$	-	-	2.4	0.3	2.4	R_τ	2.4	R_τ

Table 2. Hermitian ψ^2 operators

Non-hermitian bi-fermion operators

coeff.	$\Lambda^{\text{down}}_{\text{flav.}}$	$\Lambda^{\text{up}}_{\text{flav.}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$	$\Lambda^{\text{down}}_{\text{all}}$	Obs.	$\Lambda^{\text{up}}_{\text{all}}$	Obs.
$\mathcal{C}^{[33]}_{eH}$	-	-	5.1	-	5.1	$H \to \tau\tau$	5.1	$H \to \tau\tau$
$\mathcal{C}^{[33]}_{uH}$	-	-	0.2	-	0.2	$H \to \tau\tau$	0.2	$H \to \tau\tau$
$\mathcal{C}^{[33]}_{dH}$	-	-	3.7	-	3.7	$H \to bb$	3.7	$H \to bb$
$\mathcal{C}^{[33]}_{Hud}$	3.2	3.2	0.5	-	3.2	$B \to X_s\gamma$	3.2	$B \to X_s\gamma$
$\mathcal{C}^{[33]}_{eB}$	-	-	0.2	1.2	1.2	$pp \to \tau\tau$	1.2	$pp \to \tau\tau$
$\mathcal{C}^{[33]}_{uB}$	0.7	0.8	2.4	1.9	2.7	A_b^{FB}	2.7	A_b^{FB}
$\mathcal{C}^{[33]}_{dB}$	15.2	74.8	0.4	0.7	15.2	$B \to X_s\gamma$	74.8	$B \to X_s\gamma$
$\mathcal{C}^{[33]}_{eW}$	-	-	1.	1.9	1.8	$pp \to \tau\nu$	1.8	$pp \to \tau\nu$
$\mathcal{C}^{[33]}_{uW}$	0.5	0.9	2.3	3.6	3.7	QuarkDipoles	3.8	QuarkDipoles
$\mathcal{C}^{[33]}_{dW}$	15.7	53.	1.4	0.6	15.7	$B \to X_s\gamma$	53.	$B \to X_s\gamma$
$\mathcal{C}^{[33]}_{uG}$	0.1	0.3	0.5	2.7	2.7	QuarkDipoles	2.7	QuarkDipoles
$\mathcal{C}^{[33]}_{dG}$	4.	25.5	0.3	-	4.	$B \to X_s\gamma$	25.5	$B \to X_s\gamma$

Table 3. Non-hermitian ψ^2 operators

Scalar and Tensor operators

coeff.	$\Lambda_{\text{flav.}}^{\text{down}}$	$\Lambda_{\text{flav.}}^{\text{up}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$	$\Lambda_{\text{all}}^{\text{down}}$	Obs.	$\Lambda_{\text{all}}^{\text{up}}$	Obs.
$\mathcal{C}_{\ell edq}^{[3333]}$	0.6	-	0.1	1.2	1.1	$pp \to \tau\tau$	1.2	$pp \to \tau\tau$
$\mathcal{C}_{quqd}^{(1)[3333]}$	1.8	5.5	1.7	0.4	2.2	$B \to X_s\gamma$	5.5	$B \to X_s\gamma$
$\mathcal{C}_{quqd}^{(8)[3333]}$	1.	5.1	0.7	0.2	1.	$B \to X_s\gamma$	5.1	$B \to X_s\gamma$
$\mathcal{C}_{\ell equ}^{(1)[3333]}$	-	-	2.1	-	2.1	$H \to \tau\tau$	2.1	$H \to \tau\tau$
$\mathcal{C}_{\ell equ}^{(3)[3333]}$	-	-	0.8	-	0.8	$H \to \tau\tau$	0.8	$H \to \tau\tau$

Table 4. Non-hermitian ψ^4 operators

LLLL vector operators

coeff.	$\Lambda^{\rm down}_{\rm flav.}$	$\Lambda^{\rm up}_{\rm flav.}$	$\Lambda_{\rm EW}$	$\Lambda_{\rm coll.}$	$\Lambda^{\rm down}_{\rm all}$	Obs.	$\Lambda^{\rm up}_{\rm all}$	Obs.
$\mathcal{C}_{\ell\ell}^{[3333]}$	-	-	0.3	0.2	0.3	$\sigma_{\rm had}$	0.3	$\sigma_{\rm had}$
$\mathcal{C}_{\ell\ell}^{[ii33]}$	-	-	0.8	3.4	3.3	$(e^+e^-\to\mu^+\mu^-)_{\rm FB}$	3.3	$(e^+e^-\to\mu^+\mu^-)_{\rm FB}$
$\mathcal{C}_{\ell\ell}^{[i33i]}$	-	-	3.3	3.3	4.2	$(e^+e^-\to\mu^+\mu^-)_{\rm FB}$	4.2	$(e^+e^-\to\mu^+\mu^-)_{\rm FB}$
$\mathcal{C}_{\ell\ell}^{[iijj]}$	-	-	0.9	4.4	4.4	$(e^+e^-\to\mu^+\mu^-)_{\rm FB}$	4.4	$(e^+e^-\to\mu^+\mu^-)_{\rm FB}$
$\mathcal{C}_{\ell\ell}^{[ijji]}$	-	-	4.5	4.4	4.9	$A_b^{\rm FB}$	4.9	$A_b^{\rm FB}$
$\mathcal{C}_{qq}^{(1)[3333]}$	1.	7.8	1.6	1.1	1.7	Γ_Z	7.6	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(1)[ii33]}$	1.3	11.2	0.9	1.5	1.7	FourQuarksTop	11.3	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(1)[i33i]}$	2.5	11.3	0.7	1.6	2.6	$B_s\to\mu\mu$	11.3	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(1)[iijj]}$	0.9	8.1	0.4	-	0.9	${\rm Im}(C_D)$	8.1	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(1)[ijji]}$	1.1	8.1	0.5	-	1.	${\rm Im}(C_D)$	8.1	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(3)[3333]}$	1.	8.2	1.2	1.1	1.5	m_W	8.2	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(3)[ii33]}$	1.8	11.5	2.3	2.1	3.	R_b	11.3	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(3)[i33i]}$	2.6	11.2	0.9	2.4	3.1	$B_s\to\mu\mu$	11.3	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(3)[iijj]}$	1.	7.9	1.5	0.2	1.5	R_τ	7.9	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(3)[ijji]}$	1.1	8.	0.9	0.1	1.2	$K^+\to\pi^+\nu\bar\nu$	8.	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{\ell q}^{(1)[3333]}$	0.1	1.7	1.4	1.	1.4	R_τ	1.6	$K^+\to\pi^+\nu\bar\nu$
$\mathcal{C}_{\ell q}^{(1)[ii33]}$	0.4	5.	2.5	1.5	2.5	$\sigma_{\rm had}$	5.1	$B_s\to\mu\mu$
$\mathcal{C}_{\ell q}^{(1)[33ii]}$	-	1.6	0.3	3.4	3.4	$pp\to\tau\tau$	3.4	$pp\to\tau\tau$
$\mathcal{C}_{\ell q}^{(1)[iijj]}$	0.5	5.	0.5	5.4	5.4	$pp\to\mu\mu$	5.6	$pp\to\mu\mu$
$\mathcal{C}_{\ell q}^{(3)[3333]}$	0.7	1.5	1.4	1.	1.6	R_τ	1.6	$K^+\to\pi^+\nu\bar\nu$
$\mathcal{C}_{\ell q}^{(3)[ii33]}$	0.7	5.1	2.4	1.5	2.5	$A_b^{\rm FB}$	5.	$B_s\to\mu\mu$
$\mathcal{C}_{\ell q}^{(3)[33ii]}$	0.1	1.4	2.	8.6	8.8	$pp\to\tau\nu$	8.7	$pp\to\tau\nu$
$\mathcal{C}_{\ell q}^{(3)[iijj]}$	0.5	5.1	2.1	22.5	22.5	$pp\to\mu\nu$	23.7	$pp\to\mu\nu$

Table 5. Four-fermion $(\bar LL)(\bar LL)$ terms

RRRR vector operators

coeff.	$\Lambda^{\rm down}_{\rm flav.}$	$\Lambda^{\rm up}_{\rm flav.}$	$\Lambda_{\rm EW}$	$\Lambda_{\rm coll.}$	$\Lambda^{\rm down}_{\rm all}$	Obs.	$\Lambda^{\rm up}_{\rm all}$	Obs.
$\mathcal{C}_{ee}^{[3333]}$	-	-	0.3	0.2	0.3	R_τ	0.3	R_τ
$\mathcal{C}_{ee}^{[ii33]}$	-	-	0.7	3.2	3.2	$(e^+e^-\to\mu^+\mu^-)_{\rm FB}$	3.2	$(e^+e^-\to\mu^+\mu^-)_{\rm FB}$
$\mathcal{C}_{ee}^{[iijj]}$	-	-	0.8	4.2	4.2	$(e^+e^-\to\mu^+\mu^-)_{\rm FB}$	4.2	$(e^+e^-\to\mu^+\mu^-)_{\rm FB}$
$\mathcal{C}_{uu}^{[3333]}$	0.4	0.4	1.2	0.8	1.3	$A_b^{\rm FB}$	1.3	$A_b^{\rm FB}$
$\mathcal{C}_{uu}^{[ii33]}$	0.1	0.1	1.1	1.3	1.4	FourQuarksTop	1.4	FourQuarksTop
$\mathcal{C}_{uu}^{[i33i]}$	-	-	0.5	1.3	1.4	FourQuarksTop	1.4	FourQuarksTop
$\mathcal{C}_{uu}^{[iijj]}$	-	-	0.3	-	0.3	R_τ	0.3	R_τ
$\mathcal{C}_{uu}^{[ijji]}$	-	-	0.3	-	0.3	R_τ	0.3	R_τ
$\mathcal{C}_{dd}^{[3333]}$	-	-	-	-	-	R_b	-	R_b
$\mathcal{C}_{dd}^{[ii33]}$	-	-	0.1	-	0.1	R_τ	0.1	R_τ
$\mathcal{C}_{dd}^{[i33i]}$	-	-	-	-	-	Γ_Z	-	Γ_Z
$\mathcal{C}_{dd}^{[iijj]}$	-	-	0.2	-	0.2	R_τ	0.2	R_τ
$\mathcal{C}_{dd}^{[ijji]}$	-	-	0.1	-	0.1	R_τ	0.1	R_τ
$\mathcal{C}_{eu}^{[3333]}$	-	-	1.2	0.4	1.2	R_τ	1.2	R_τ
$\mathcal{C}_{eu}^{[ii33]}$	0.9	0.9	2.1	0.7	2.2	$\sigma_{\rm had}$	2.2	$\sigma_{\rm had}$
$\mathcal{C}_{eu}^{[33ii]}$	-	-	0.3	2.8	2.8	$pp\to\tau\tau$	2.8	$pp\to\tau\tau$
$\mathcal{C}_{eu}^{[iijj]}$	-	-	0.6	7.4	7.4	$pp\to ee$	7.4	$pp\to ee$
$\mathcal{C}_{ed}^{[3333]}$	-	-	0.2	1.	1.	$pp\to\tau\tau$	1.	$pp\to\tau\tau$
$\mathcal{C}_{ed}^{[ii33]}$	-	-	0.3	1.5	1.5	$pp\to\mu\mu$	1.5	$pp\to\mu\mu$
$\mathcal{C}_{ed}^{[33ii]}$	-	-	0.2	2.8	2.8	$pp\to\tau\tau$	2.8	$pp\to\tau\tau$
$\mathcal{C}_{ed}^{[iijj]}$	-	-	0.4	4.4	4.4	$pp\to\mu\mu$	4.4	$pp\to\mu\mu$
$\mathcal{C}_{ud}^{(1)[3333]}$	0.1	0.1	0.4	0.3	0.4	R_b	0.4	R_b
$\mathcal{C}_{ud}^{(1)[ii33]}$	-	-	0.1	-	0.1	R_τ	0.1	R_τ
$\mathcal{C}_{ud}^{(1)[33ii]}$	-	-	0.5	1.2	1.2	FourQuarksTop	1.2	FourQuarksTop
$\mathcal{C}_{ud}^{(1)[iijj]}$	-	-	0.2	-	0.2	R_τ	0.2	R_τ
$\mathcal{C}_{ud}^{(8)[3333]}$	0.1	0.1	-	0.2	0.2	FourQuarksBottom	0.2	FourQuarksBottom
$\mathcal{C}_{ud}^{(8)[ii33]}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{ud}^{(8)[33ii]}$	-	-	0.1	0.7	0.7	FourQuarksTop	0.7	FourQuarksTop
$\mathcal{C}_{ud}^{(8)[iijj]}$	-	-	-	-	-	-	-	-

Table 6. Four-fermion $(\bar{R}R)(\bar{R}R)$ terms

LLRR vector operators

coeff.	$\Lambda^{\rm down}_{\rm flav.}$	$\Lambda^{\rm up}_{\rm flav.}$	$\Lambda_{\rm EW}$	$\Lambda_{\rm coll.}$	$\Lambda^{\rm down}_{\rm all}$	Obs.	$\Lambda^{\rm up}_{\rm all}$	Obs.
$\mathcal{C}_{\ell e}^{[3333]}$	-	-	0.2	0.1	0.2	A_τ	0.2	A_τ
$\mathcal{C}_{\ell e}^{[ii33]}$	-	-	0.4	2.	1.9	$(e^+e^- \to \mu^+\mu^-)_{\rm FB}$	1.9	$(e^+e^- \to \mu^+\mu^-)_{\rm FB}$
$\mathcal{C}_{\ell e}^{[33ii]}$	-	-	0.3	1.9	2.	$(e^+e^- \to \mu^+\mu^-)_{\rm FB}$	2.	$(e^+e^- \to \mu^+\mu^-)_{\rm FB}$
$\mathcal{C}_{\ell e}^{[iijj]}$	-	-	0.5	3.8	3.8	$(e^+e^- \to \mu^+\mu^-)_{\rm FB}$	3.8	$(e^+e^- \to \mu^+\mu^-)_{\rm FB}$
$\mathcal{C}_{\ell u}^{[3333]}$	0.1	0.1	1.4	0.4	1.3	R_τ	1.3	R_τ
$\mathcal{C}_{\ell u}^{[ii33]}$	0.7	0.7	2.4	0.8	2.3	$\sigma_{\rm had}$	2.3	$\sigma_{\rm had}$
$\mathcal{C}_{\ell u}^{[33ii]}$	-	-	0.4	3.1	3.1	$pp \to \tau\tau$	3.1	$pp \to \tau\tau$
$\mathcal{C}_{\ell u}^{[iijj]}$	-	-	0.7	5.2	5.2	$pp \to \mu\mu$	5.2	$pp \to \mu\mu$
$\mathcal{C}_{\ell d}^{[3333]}$	-	-	0.2	1.	1.	$pp \to \tau\tau$	1.	$pp \to \tau\tau$
$\mathcal{C}_{\ell d}^{[ii33]}$	-	-	0.3	1.5	1.5	$pp \to \mu\mu$	1.5	$pp \to \mu\mu$
$\mathcal{C}_{\ell d}^{[33ii]}$	-	-	0.3	3.	3.	$pp \to \tau\tau$	3.	$pp \to \tau\tau$
$\mathcal{C}_{\ell d}^{[iijj]}$	-	-	0.5	4.7	4.7	$pp \to \mu\mu$	4.7	$pp \to \mu\mu$
$\mathcal{C}_{eq}^{[3333]}$	-	0.3	1.2	1.	1.3	R_τ	1.2	R_τ
$\mathcal{C}_{eq}^{[ii33]}$	0.6	6.7	2.1	1.5	2.2	$\sigma_{\rm had}$	6.7	$B_s \to \mu\mu$
$\mathcal{C}_{eq}^{[33ii]}$	-	0.3	0.2	3.7	3.7	$pp \to \tau\tau$	3.7	$pp \to \tau\tau$
$\mathcal{C}_{eq}^{[iijj]}$	-	-	0.4	6.	6.	$pp \to \mu\mu$	6.	$pp \to \mu\mu$
$\mathcal{C}_{qu}^{(1)[3333]}$	0.3	1.8	1.2	0.6	1.3	Γ_Z	1.7	$B_s \to \mu\mu$
$\mathcal{C}_{qu}^{(1)[ii33]}$	0.3	1.8	0.6	1.6	1.6	FourQuarksTop	2.1	$B_s \to \mu\mu$
$\mathcal{C}_{qu}^{(1)[33ii]}$	-	0.6	0.8	1.4	1.4	FourQuarksTop	1.2	FourQuarksTop
$\mathcal{C}_{qu}^{(1)[iijj]}$	-	0.6	0.2	-	0.2	R_τ	0.6	$\lvert C_{Bd}\rvert$
$\mathcal{C}_{qu}^{(8)[3333]}$	0.2	0.7	0.1	0.4	0.4	FourQuarksTop	0.7	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qu}^{(8)[ii33]}$	0.3	0.7	0.1	1.2	1.2	FourQuarksTop	1.2	FourQuarksTop
$\mathcal{C}_{qu}^{(8)[33ii]}$	-	0.1	0.2	0.8	0.8	FourQuarksTop	0.8	FourQuarksTop
$\mathcal{C}_{qu}^{(8)[iijj]}$	-	0.1	-	-	-	R_τ	0.1	$C_9^{\rm U}$
$\mathcal{C}_{qd}^{(1)[3333]}$	0.2	0.3	0.4	0.3	0.3	R_b	0.3	R_b
$\mathcal{C}_{qd}^{(1)[ii33]}$	-	0.3	0.1	-	-	R_τ	0.3	$B_s \to \mu\mu$
$\mathcal{C}_{qd}^{(1)[33ii]}$	-	0.4	0.6	1.3	1.2	FourQuarksTop	1.1	FourQuarksTop
$\mathcal{C}_{qd}^{(1)[iijj]}$	-	0.4	0.2	-	0.2	R_τ	0.4	$B_s \to \mu\mu$
$\mathcal{C}_{qd}^{(8)[3333]}$	-	-	-	0.2	0.2	FourQuarksBottom	0.2	FourQuarksBottom
$\mathcal{C}_{qd}^{(8)[ii33]}$	0.1	-	-	-	0.1	$B \to X_s\gamma$	-	$B \to X_s\gamma$
$\mathcal{C}_{qd}^{(8)[33ii]}$	-	-	0.1	0.7	0.7	FourQuarksTop	0.7	FourQuarksTop
$\mathcal{C}_{qd}^{(8)[iijj]}$	-	-	-	-	-	R_τ	-	$\lvert C_{Bs}\rvert$

Table 7. Four-fermion $(\bar{L}L)(\bar{R}R)$ terms

Bosonic operators

coeff.	$\Lambda^{\text{down}}_{\text{flav.}}$	$\Lambda^{\text{up}}_{\text{flav.}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$	$\Lambda^{\text{down}}_{\text{all}}$	Obs.	$\Lambda^{\text{up}}_{\text{all}}$	Obs.
$\mathcal{C}_{H}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{H\Box}$	0.2	0.2	0.6	0.1	0.6	A_b^{FB}	0.6	A_b^{FB}
$\mathcal{C}_{HD}$	0.5	0.5	5.1	-	5.	A_b^{FB}	5.	A_b^{FB}
$\mathcal{C}_{HG}$	0.8	0.8	0.4	-	0.9	$B \to X_s\gamma$	0.9	$B \to X_s\gamma$
$\mathcal{C}_{HB}$	0.5	0.5	0.9	-	0.9	A_b^{FB}	0.9	A_b^{FB}
$\mathcal{C}_{HW}$	0.7	0.7	0.9	-	1.	A_b^{FB}	1.	A_b^{FB}
$\mathcal{C}_{HWB}$	1.	1.	9.	-	9.	A_b^{FB}	9.	A_b^{FB}
$\mathcal{C}_{G}$	1.1	1.1	0.1	-	1.1	$B \to X_s\gamma$	1.1	$B \to X_s\gamma$
$\mathcal{C}_{W}$	0.3	0.3	0.9	-	0.9	A_b^{FB}	0.9	A_b^{FB}

Table 8. CP-conserving bosonic operators