Hunting for U(2) New Physics with Flavor, Electroweak, and Collider Data

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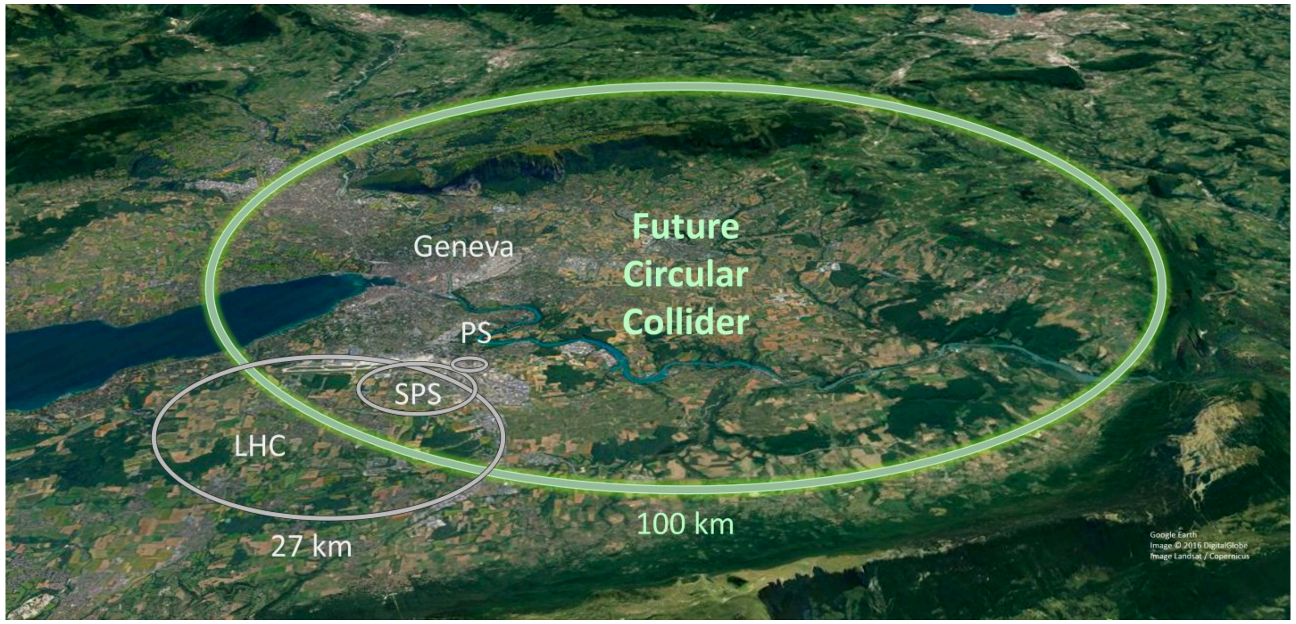

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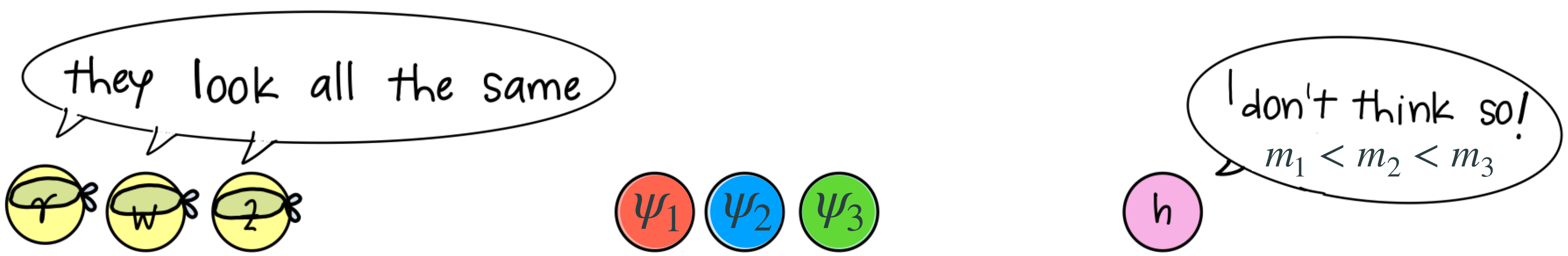
The Higgs and the Flavor Puzzle

- 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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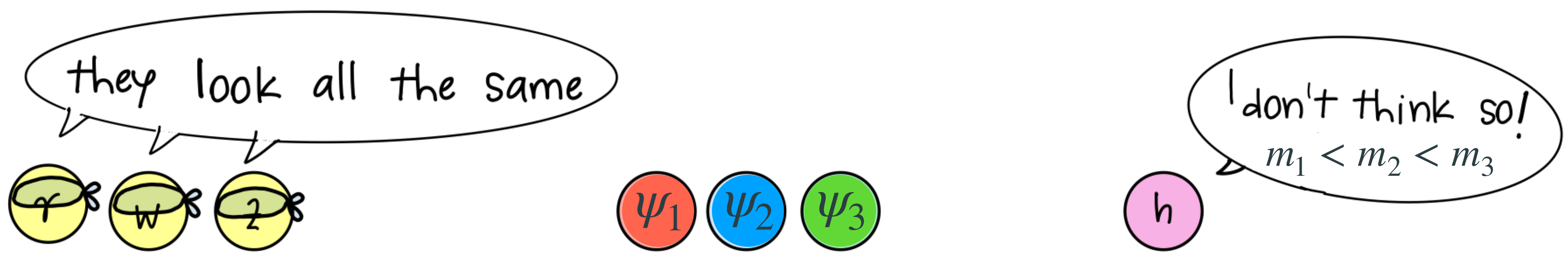

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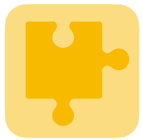

Flavor Puzzle

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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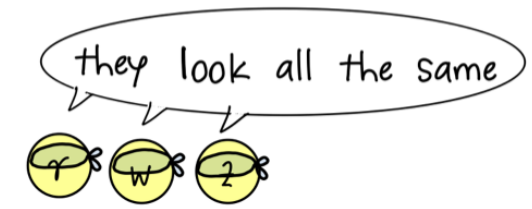

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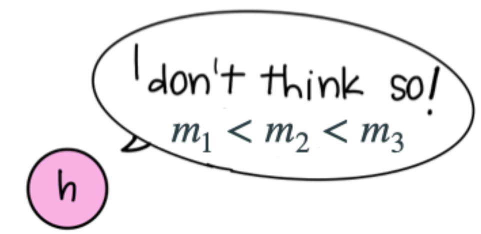
Turn on Yukawas

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



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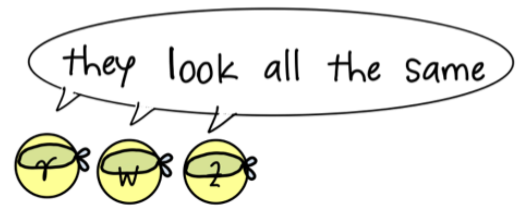

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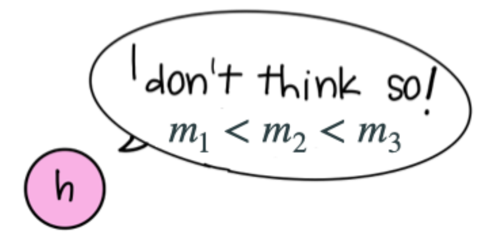

$$\mathcal{G}_F(\mathrm{SM}) = U(1)_B \times U(1)_L$$

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

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

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

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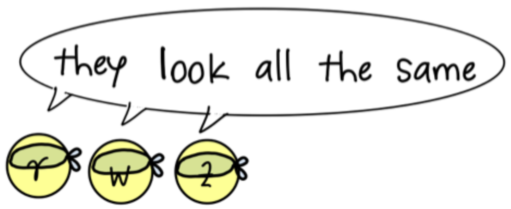

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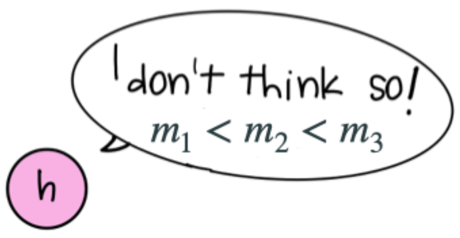

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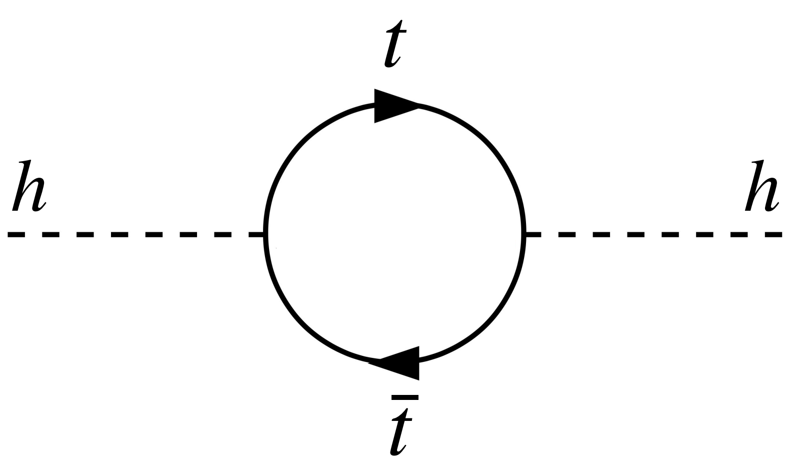
Flavor Puzzle

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

Hints towards NP scale: Nature of the Higgs boson

$\Lambda^2_{\rm NP}$ **Higgs Hierarchy Problem** *Pre-LHC viewpoint: Nature must be natural!*

- The Higgs mass is unstable under quantum corrections- it is quadratically sensitive to NP in the UV. The top Yukawa gives the largest correction:

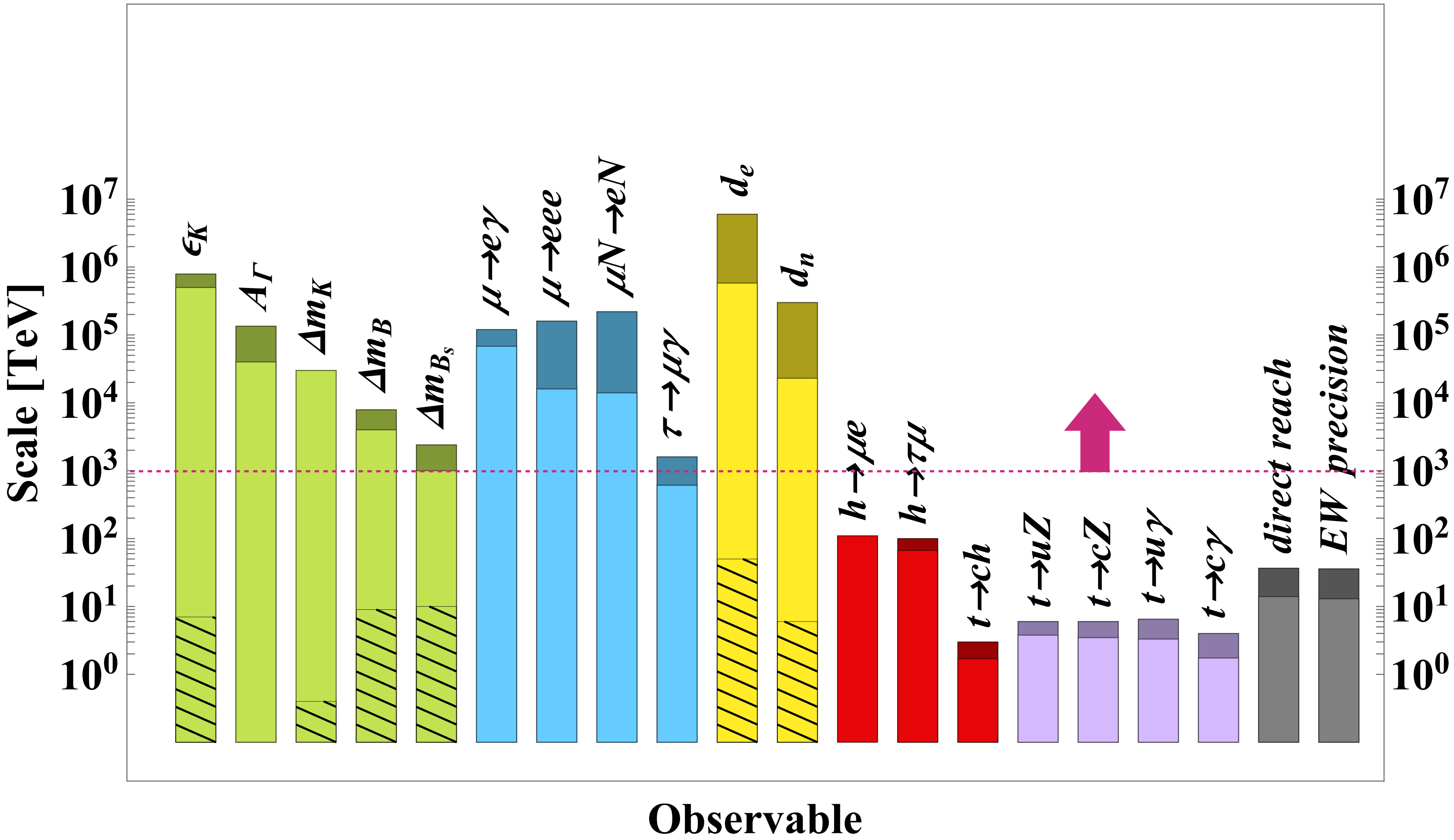


$$\Longrightarrow \qquad \delta m_h^2(\text{top loop}) \approx \frac{3y_t^2}{4\pi^2}\Lambda^2_{\rm NP}$$

- Naturalness principle: Light NP that protects the Higgs mass from large quantum corrections should appear no higher than the TeV scale.

$$\delta m_h^2/m_h^2 \lesssim 1 \qquad \Longrightarrow \qquad \Lambda_{\rm NP} \lesssim 500 \text{ GeV}$$

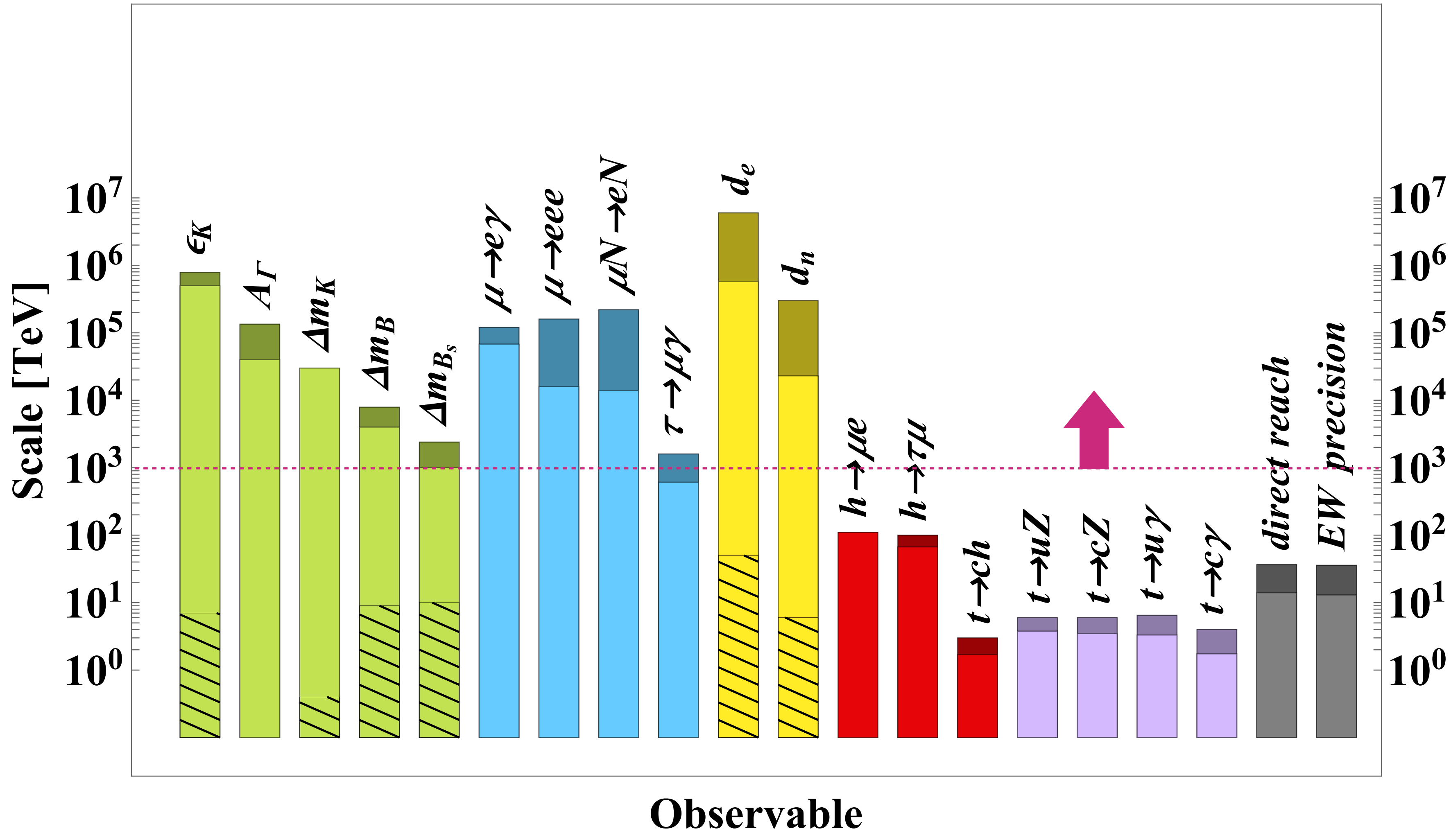
The Flavor Problem of Light New Physics



- Flavor bounds push the scale of flavor anarchic new physics (NP) above 1000 TeV.
- But, to address the EW hierarchy problem, NP must be light. It follows that light NP must have a very specific flavor structure in order to pass flavor bounds.

[Physics Briefing Book 2020, 1910.11775]

The Flavor Problem of Light New Physics



- It follows that light NP must have a very specific flavor structure in order to pass flavor bounds. *SM Yukawa-like flavor protection?*

Λ^2_{NP} **Higgs Hierarchy Problem** ⟷ **Flavor Puzzle**

Minimal Flavor Violation (MFV)

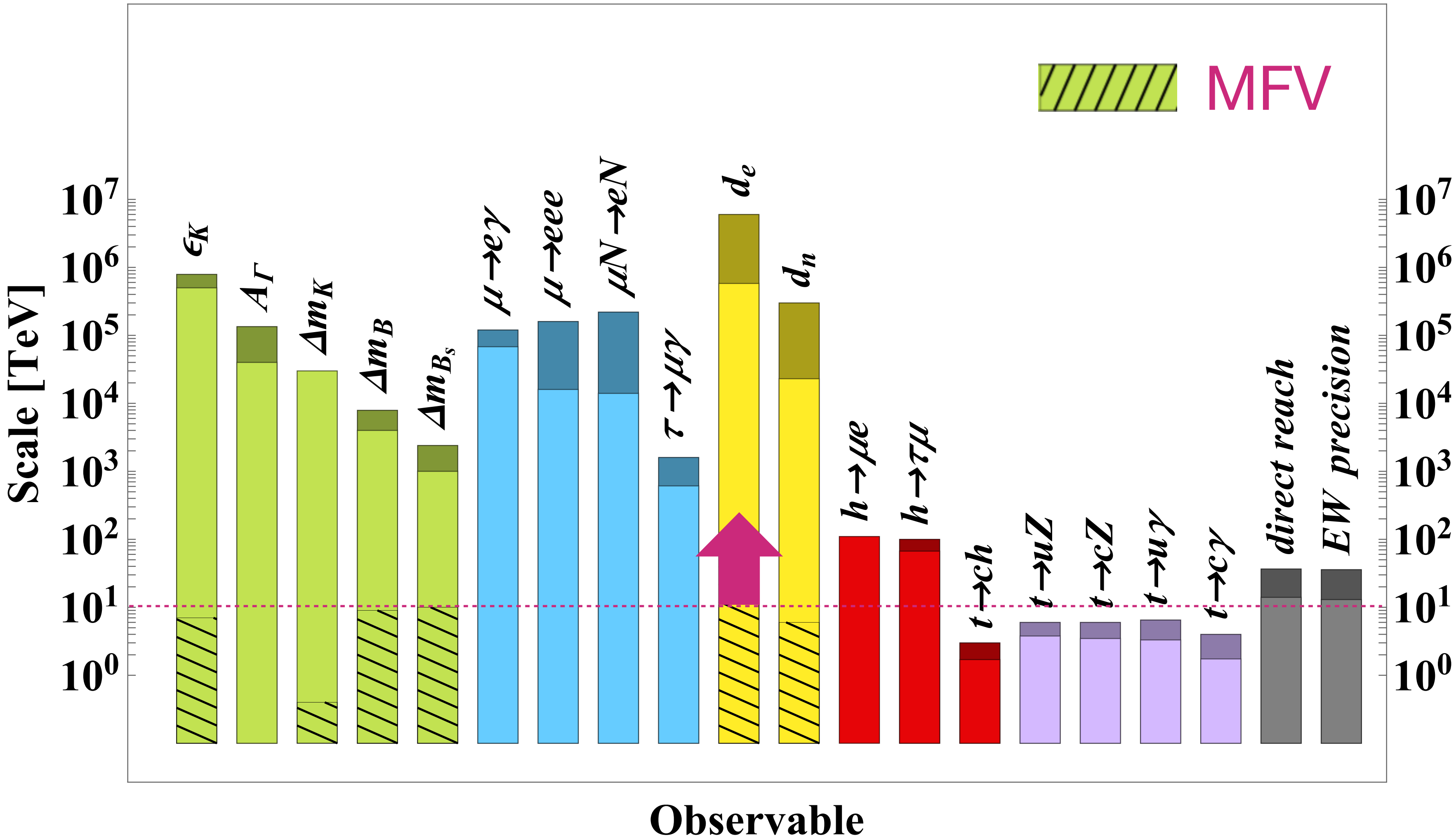
- Key idea: Flavor puzzle probably solved at a high scale. Lightest NP can then be nearly flavor universal. All CP and flavor violation in the NP sector originates from the SM Yukawa couplings.

$$\lambda_{\rm FC} \approx (Y_U Y_U^\dagger)_{\rm FC} \approx y_t^2 \begin{pmatrix} 0 & V_{td}^* V_{ts} & V_{td}^* V_{tb} \\ V_{td} V_{ts}^* & 0 & V_{ts}^* V_{tb} \\ V_{td} V_{tb}^* & V_{ts} V_{tb}^* & 0 \end{pmatrix} \sim \begin{pmatrix} 0 & \lambda^5 & \lambda^3 \\ \lambda^5 & 0 & \lambda^2 \\ \lambda^3 & \lambda^2 & 0 \end{pmatrix}$$

Minimally flavour violating dimension six operator	main observables	Λ [TeV] $-$	$+$	
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	$\epsilon_K, \quad \Delta m_{B_d}$	6.4	5.0	
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4	
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5	
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7	*
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0	*
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6	*
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi, \quad \epsilon'/\epsilon, \ldots$	~ 1		

[G. D'Ambrosio, G.F. Giudice, G. Isidori, A. Strumia, hep-ph/0207036]

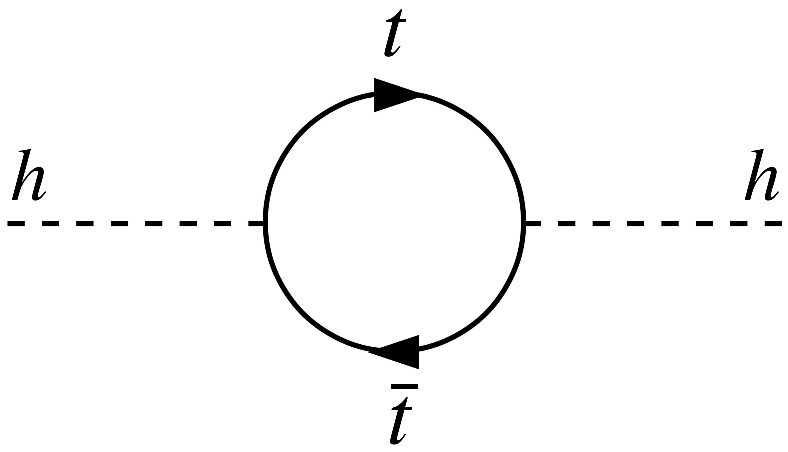
Universal NP + MFV 20 Years Later



- In the case of flavor universal NP + MFV, NP couples to valence quarks!
- For this reason, flavor bounds are still ok, but ***direct searches*** at the LHC push flavor universal NP to the 10 TeV ballpark.

Naturalness Paradigm 20 Years Later

Higgs Hierarchy Problem



$$\Longrightarrow \quad \delta m_h^2(\text{top loop}) \approx \frac{3y_t^2}{4\pi^2}\Lambda_{\text{NP}}^2$$

- Light NP protecting the Higgs mass from large corrections should appear. That didn't happen so far. If NP is almost flavor universal, we now have an experimentally proven "little hierarchy problem":

$$\Lambda_{\text{NP}} \gtrsim 10 \text{ TeV} \quad \Longrightarrow \quad m_h^2/\delta m_h^2 \sim 10^{-3}$$

So, did naturalness fail as a paradigm?

- This seems to be an increasingly common viewpoint. Personal opinion: Indeed, we were too aggressive, but this view is overly pessimistic.

$$m_h^2/\delta m_h^2 \sim 10^{-3} \qquad \text{vs.} \qquad m_h^2/M_P^2 \sim 10^{-34}$$

$(\Lambda_{\text{NP}} \sim 10\ \text{TeV})$ $(\Lambda_{\text{NP}} \sim M_P)$

- Nature seems a bit fine-tuned. However, naturalness arguments still provide the best hope that light NP could be around the corner.
- Can we do better than 10 TeV? To answer this question, we need to ask: Is there a "more natural" flavor protection for NP?

U(2) is the natural successor

- Key idea: New physics is **NOT** flavor universal. In particular, there are 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 hierarchy problem.

- Unlike in the $U(3)$ case, these new interactions see flavor just like the SM Higgs. They could be connected to a low scale solution to the SM flavor puzzle.

[R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone, D. Straub, 1105.2296] [See also: Davighi, Isidori, 2303.01520]

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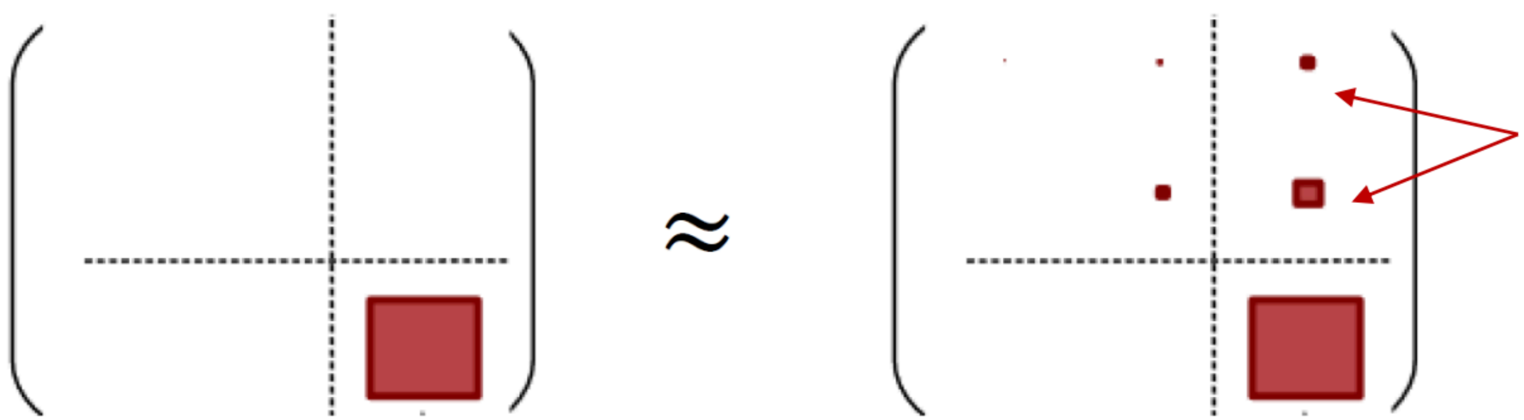
- Unlike in the $U(3)$ case, these new interactions see flavor just like the SM Higgs. They could be connected to a low scale solution to the SM flavor puzzle.
- NP dominantly coupled to the third family quarks (+leptons) enjoys a $U(2)^3$ ($U(2)^5$) flavor symmetry, just like the SM Yukawa couplings.



$U(2)$-breaking effects
Barbieri et al, 1105.2296
Isidori, Straub, 1202.0464
Fuentes-Martin et al, 1909.02519

Exact $U(2)$ limit — Observed Yukawa

NP coupled only to 3rd family — Also small couplings to light families

[R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone, D. Straub, 1105.2296] [See also: Davighi, Isidori, 2303.01520]

U(2) compared with U(3)

Flavor diagonal couplings (direct searches)

- In the exact U(2) limit, we have flavor diagonal, but non-universal NP.

Exact U(3)	Exact U(2)
$\bar{q}_L^a \gamma_\mu q_L^a$	$\bar{q}_L^3 \gamma_\mu q_L^3 + \epsilon\, \bar{q}_L^i \gamma_\mu q_L^i$

- *Key benefit*: Different NP coupling for light families makes it possible to suppress couplings to valence quarks and relax direct search bounds.

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Flavor violating couplings

MFV: Minimally broken U(3)	Minimally broken U(2)
$\bar{q}_L^a \lambda_{\rm FC}^{ab} \gamma_\mu q_L^b$	$\bar{q}_L^i V_q^i \gamma_\mu q_L^3$

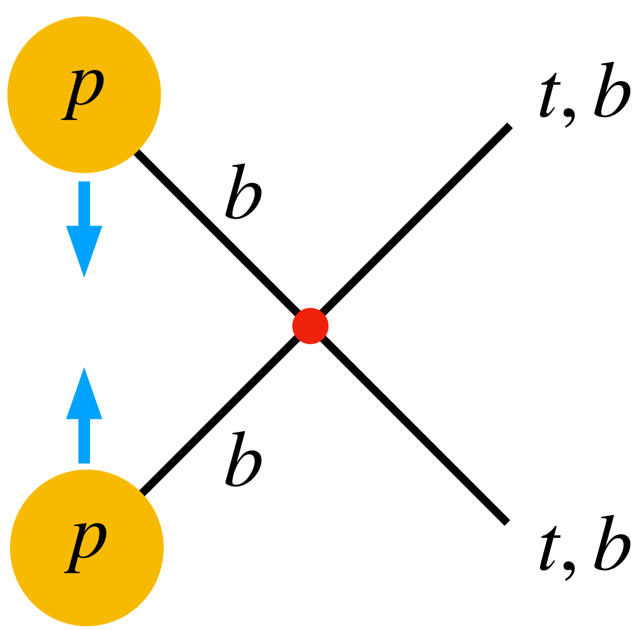
$$V_q \sim \mathcal{O}\begin{pmatrix} V_{td} \\ V_{ts} \end{pmatrix}$$

Model independent pheno of the U(2) hypothesis

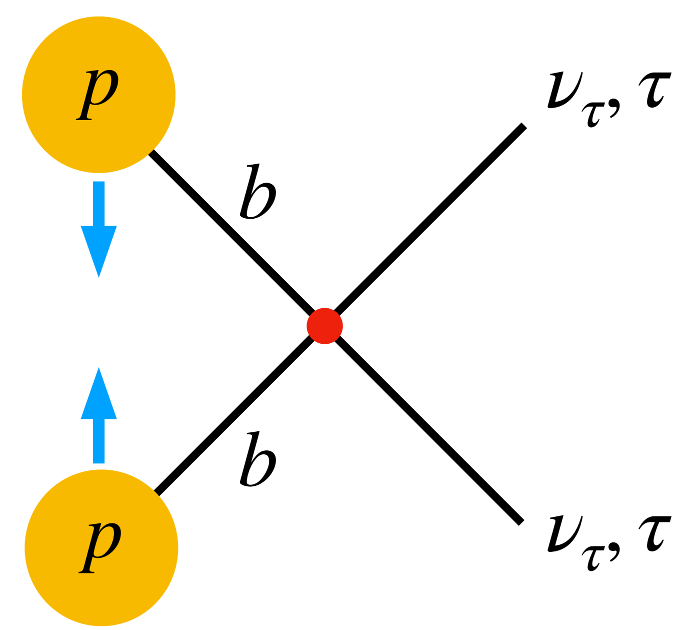
Flavor diagonal couplings: $\bar{q}_L^3\gamma_\mu q_L^3 + \epsilon\,\bar{q}_L^i\gamma_\mu q_L^i + \bar{\ell}_L^3\gamma_\mu \ell_L^3$

- Third family direct searches at the LHC (limit $\epsilon \to 0$)

$\underline{U(2)^3 \text{ (quarks only)}}$



$\underline{U(2)^5 \text{ (also leptons)}}$



- Signals: $t\bar{t}$, $b\bar{b}$ and $t\bar{b}$

Drell-Yan $\tau\bar{\tau}$ and mono-τ + E_T

Model independent pheno of the U(2) hypothesis

Flavor violating couplings: $\bar{q}^i_L V^i_q \gamma_\mu q^3_L\,, \qquad V^T_q \sim \mathcal{O}(V_{td},\, V_{ts})$

- Leading effects: $3 \to i$ transitions: top decays, *B*-physics, tau decays. Focus here on the operators for *B*-physics one can construct together with $\bar{\ell}^3_L \gamma^\mu \ell^3_L$:

U(2)-breaking operator	Process	Example Observables
$(\bar{q}^i_L V^i_q \gamma_\mu q^3_L)^2$	*B*-meson mixing	$\Delta M_{B_s}\,, \Delta M_{B_d}$
$(\bar{q}^i_L V^i_q \gamma_\mu q^3_L)(\bar{\ell}^3_L \gamma^\mu \ell^3_L)$	Neutral current *B*-decays	$B \to K^{(*)} \tau\bar{\tau}\,,\ B \to K^{(*)} \nu_\tau \bar{\nu}_\tau\,,\ B_s \to \tau\bar{\tau}$
$(\bar{q}^i_L V^i_q \gamma_\mu \sigma^I q^3_L)(\bar{\ell}^3_L \gamma^\mu \sigma^I \ell^3_L)$	Charged current *B*-decays	$B \to D^{(*)} \tau\bar{\nu}_\tau\,,\ \Lambda_b \to \Lambda_c \tau\bar{\nu}_\tau\,,\ B_c \to \tau\bar{\nu}_\tau$
$(\bar{q}^i_L V^i_q \gamma^\mu q^3_L)(H^\dagger D_\mu H)$	Neutral current *B*-decays	$B \to K^{(*)} \ell\bar{\ell}\,,\ B \to K^{(*)} \nu_\ell \bar{\nu}_\ell\,,\ B_s \to \ell\bar{\ell}$
$(\bar{q}^i_L V^i_q \sigma_{\mu\nu} H b_R) F^{\mu\nu}$	Neutral current *B*-decays	$B \to X_s \gamma$

How does the Higgs fit into the story?

- To address the EW hierarchy problem, there should be new states coupled to the Higgs and/or top, e.g. SUSY, composite Higgs, etc.

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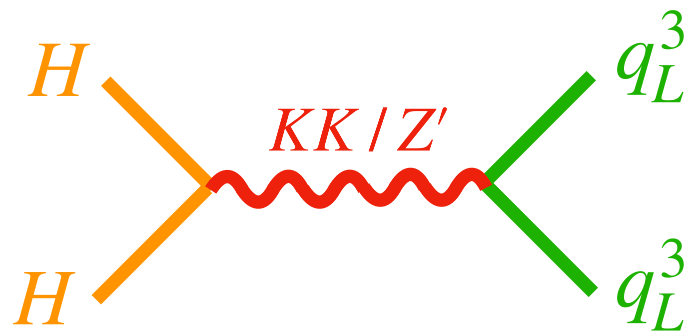

$$C_{Hq}^{(1)[33]}(H^\dagger D_\mu H)(\bar{q}_L^3 \gamma^\mu q_L^3)$$

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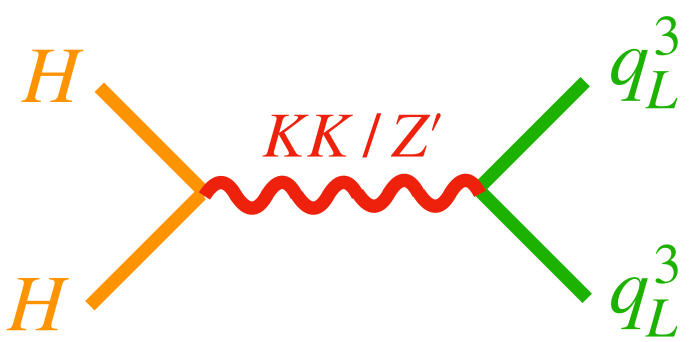

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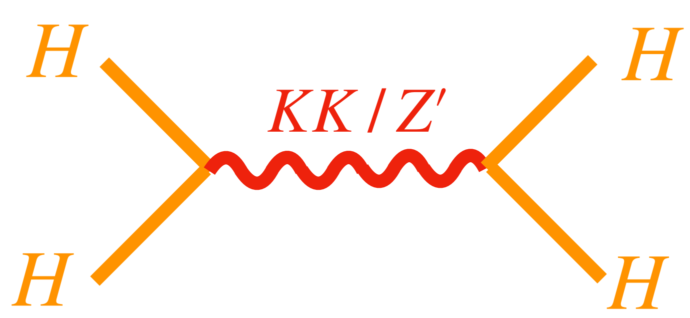

$$C_{HD}\,|H^\dagger D_\mu H|^2$$

EWPT: $C_{HD} \lesssim (5\text{ TeV})^{-2}$

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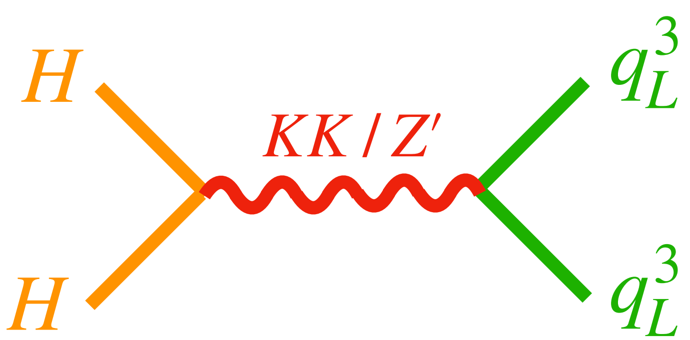
- These well-motivated classes of models generically lead to sizable corrections to EW precision observables (at least in the third-family).

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

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



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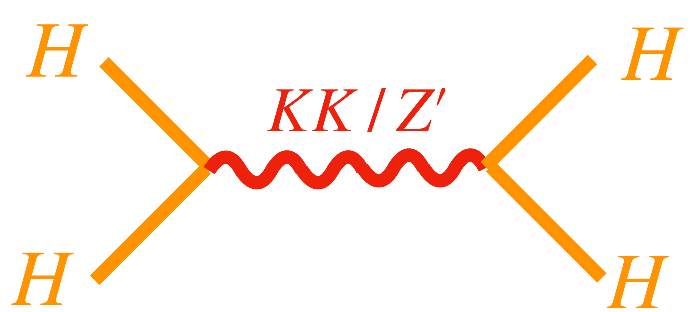

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EWPT are (still) a powerful probe of NP

The 'LEP paradox'

Riccardo Barbieri

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Alessandro Strumia

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

27 Nov 2000

Abstract

Is there a Higgs? Where is it? Is supersymmetry there? Where is it? By discussing these questions, we call attention to the 'LEP paradox', which is how we see the naturalness problem of the Fermi scale after a decade of electroweak precision measurements, mostly done at LEP.

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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 $m_h \approx (100 \div 200)\,\mathrm{GeV}$ and a high cut-off, $\Lambda \gtrsim 5\,\mathrm{TeV}$, 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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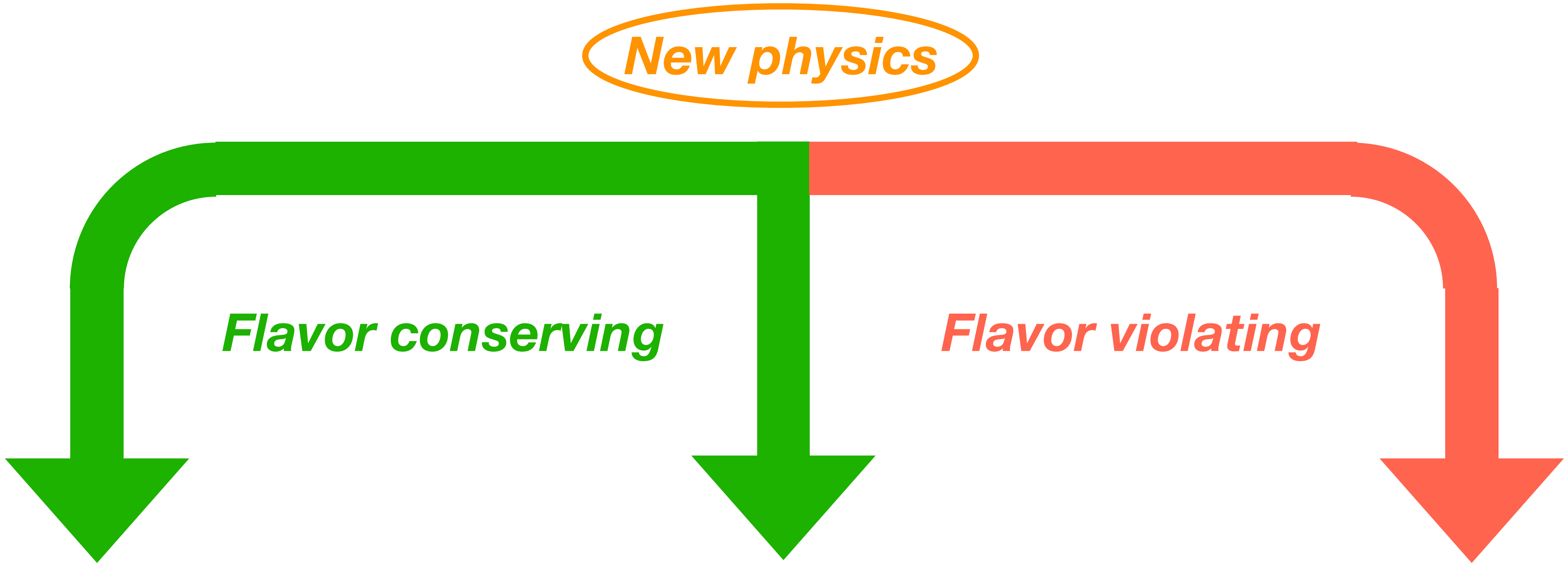
5 Conclusion

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.

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.

All new physics must confront a triad of bounds



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

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

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

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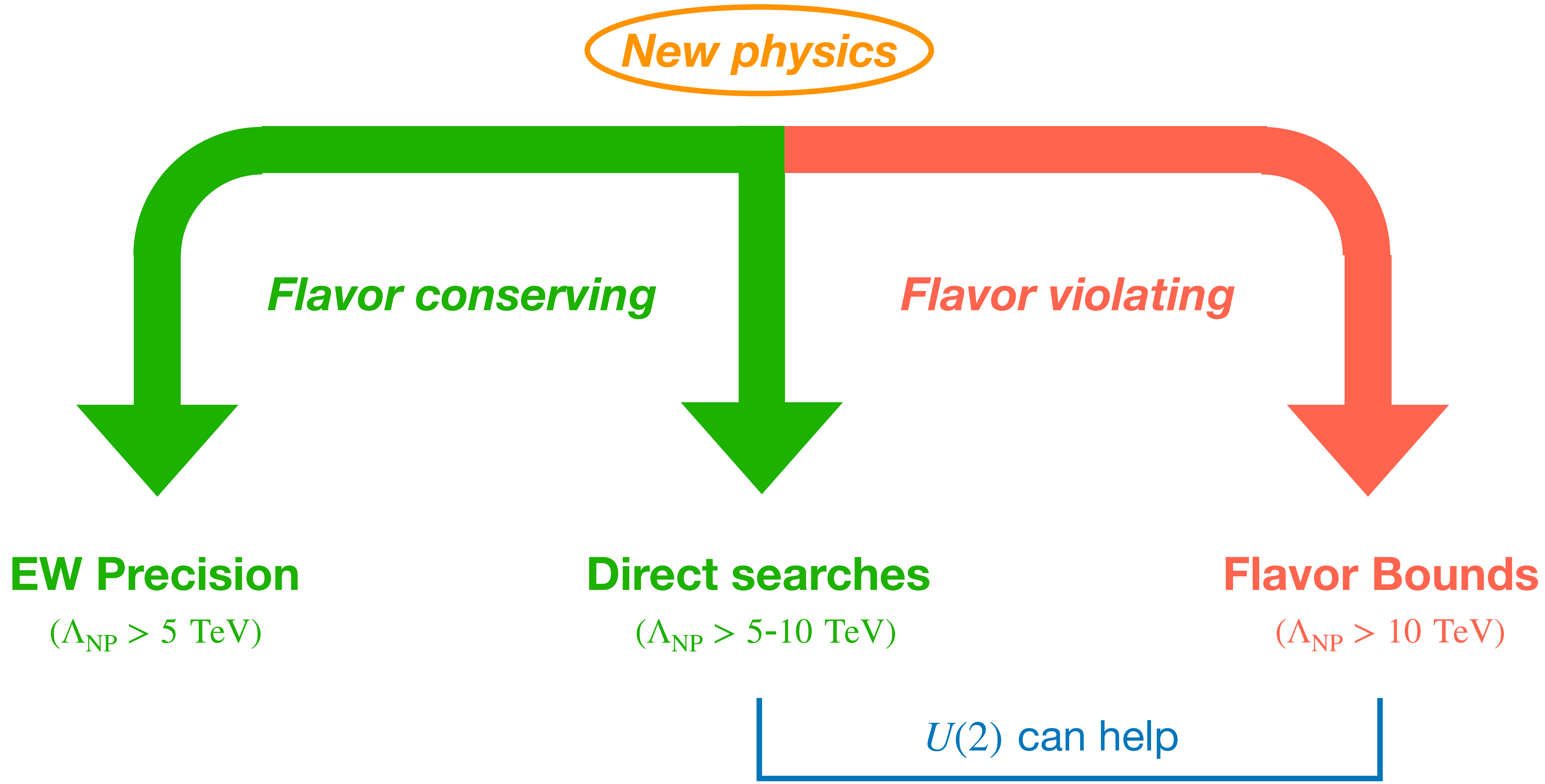

- U(2) helps pass flavor + collider bounds, but is less effective against EWPT.

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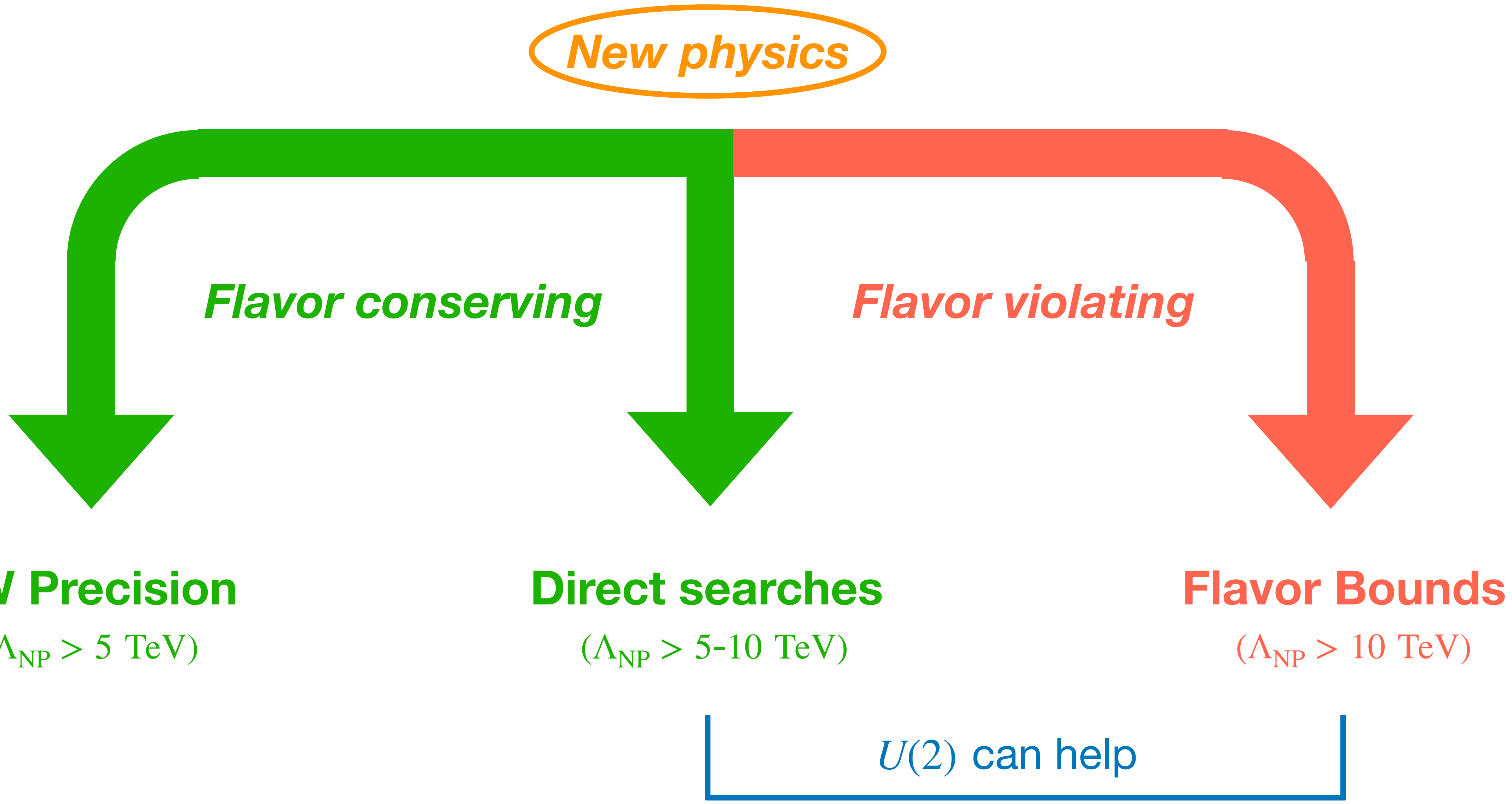

- U(2) helps pass flavor + collider bounds, but is less effective against EWPT.

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	Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1, \Delta^1)$		$\mathcal{O}(V^2, \Delta^1)$		$\mathcal{O}(V^2, \Delta^1 V^1)$		$\mathcal{O}(V^3, \Delta^1 V^1)$	
	$U(2)^5$ [terms summed up to different orders]													
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
$\psi^2 XH$	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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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
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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 $\Lambda_{\rm NP} = 3~\rm TeV$. Using DsixTools 2.0, possible to do this analytically in the WC's beyond LL.
- We then impose $U(2)^5$ flavor symmetry on the high-scale WC's.
- For EWPT and direct searches, which constrain only the flavor-conserving WC's, the exact $U(2)^5$ limit is already sufficient. For example:

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

```
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] -
 0.004 (Cqq1[l, l, p, p] + Cqq1[l, p, p, l]) -
 0.071 Cqq3[l, h, h, l] + 0.009 Cqq3[l, l, h, h] +
 0.089 Cqu1[l, l, h, h] + 0.004 Cqu8[l, l, h, h] +...
```

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

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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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- 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
- Higgs signal strengths + LFU tests in τ-decays

[V. Bresó-Pla, A. Falkowski, M. González-Alonso, 2103.12074]

[L. Allwicher, G. Isidori, J. M. Lizana, N. Selimovic, BAS, 2302.11584]

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]

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 enter the EW fit.
- Including RGE, we have 120 of 124, 38 with bounds $\gtrsim 1$ TeV.

No RGE

#	Wilson Coef.	$[\text{Obs}]_{\text{bound}}$	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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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
22	Ceu[l, l, h, h]	σ_{had}	2.08	2.41	-15.9
23	CHq1[l]	R_c	1.94	1.9	2.1
24	CHd[l]	R_τ	1.71	1.68	1.8
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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28	Clu[h, h, h, h]	R_τ	1.36	1.59	-16.9
29	Clq3[h, h, h, h]	R_τ	1.32	1.47	-11.4
30	CHd[h]	R_b	1.31	1.29	1.5
31	Cqu1[h, h, h, h]	Γ_Z	1.25	1.2	4.
32	Cuu[h, h, h, h]	A_b^{FB}	1.24		
33	Cqe[h, h, h, h]	R_τ	1.2	1.41	-17.5
34	Ceu[h, h, h, h]	R_τ	1.18	1.38	-16.9
35	Cqq3[h, h, h, h]	m_W	1.16	0.77	33.6
36	Clq3[l, l, p, p]	σ_{had}	1.08	1.09	-0.9
37	Cuu[l, l, h, h]	R_τ	1.07	1.27	-18.7
38	Cqq3[l, h, h, l]	R_τ	0.95	1.26	-32.6

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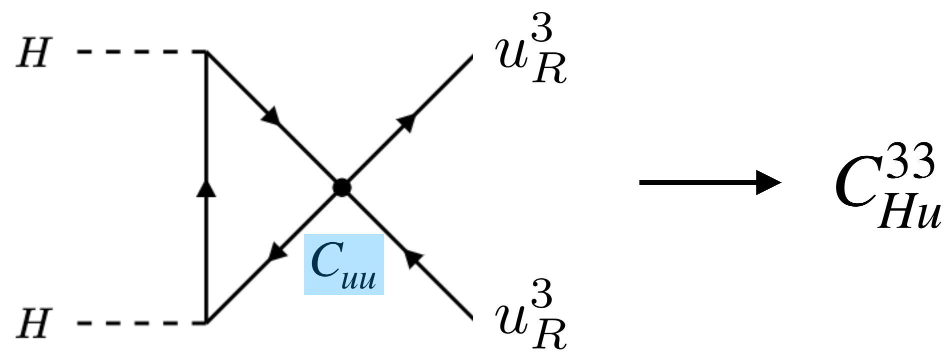
LL
RGE



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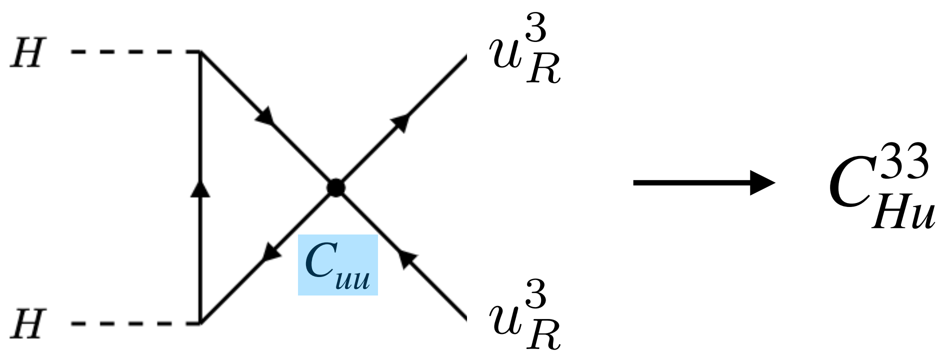
38	Cqq3[l, h, h, l]	R_τ	0.95	1.26	-32.6

[Allwicher, Cornella, Isidori, BAS, to appear]
[Allwicher, Isidori, Lizana, Selimovic, BAS, 2302.11584]

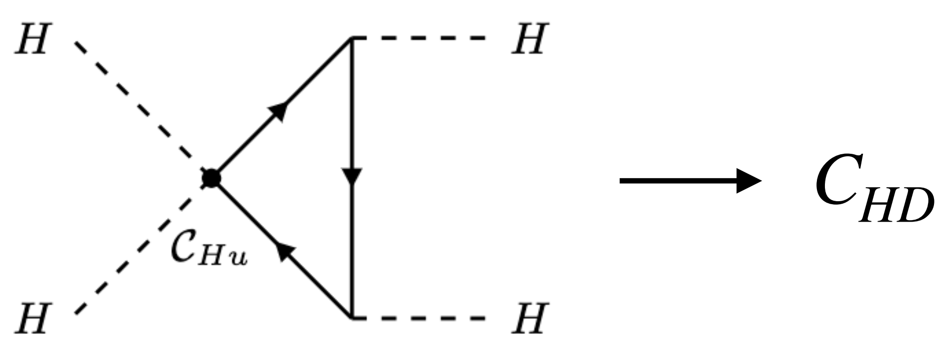
Bounds from EWPT

- Including RGE, we have 120 of 124, 38 with bounds $\gtrsim 1$ TeV.
- Resummation is important, even from $\Lambda_{\rm NP} = 3$ TeV.

LL RGE



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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#	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
22	Ceu[l, l, h, h]	σ_{had}	2.08	2.41	-15.9
23	CHq1[l]	R_c	1.94	1.9	2.1
24	CHd[l]	R_τ	1.71	1.68	1.8
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
27	Clq1[h, h, h, h]	R_τ	1.43	1.63	-14.
28	Clu[h, h, h, h]	R_τ	1.36	1.59	-16.9
29	Clq3[h, h, h, h]	R_τ	1.32	1.47	-11.4
30	CHd[h]	R_b	1.31	1.29	1.5
31	Cqu1[h, h, h, h]	Γ_Z	1.25	1.2	4.
32	Cuu[h, h, h, h]	A_b^{FB}	1.24		
33	Cqe[h, h, h, h]	R_τ	1.2	1.41	-17.5
34	Ceu[h, h, h, h]	R_τ	1.18	1.38	-16.9
35	Cqq3[h, h, h, h]	m_W	1.16	0.77	33.6
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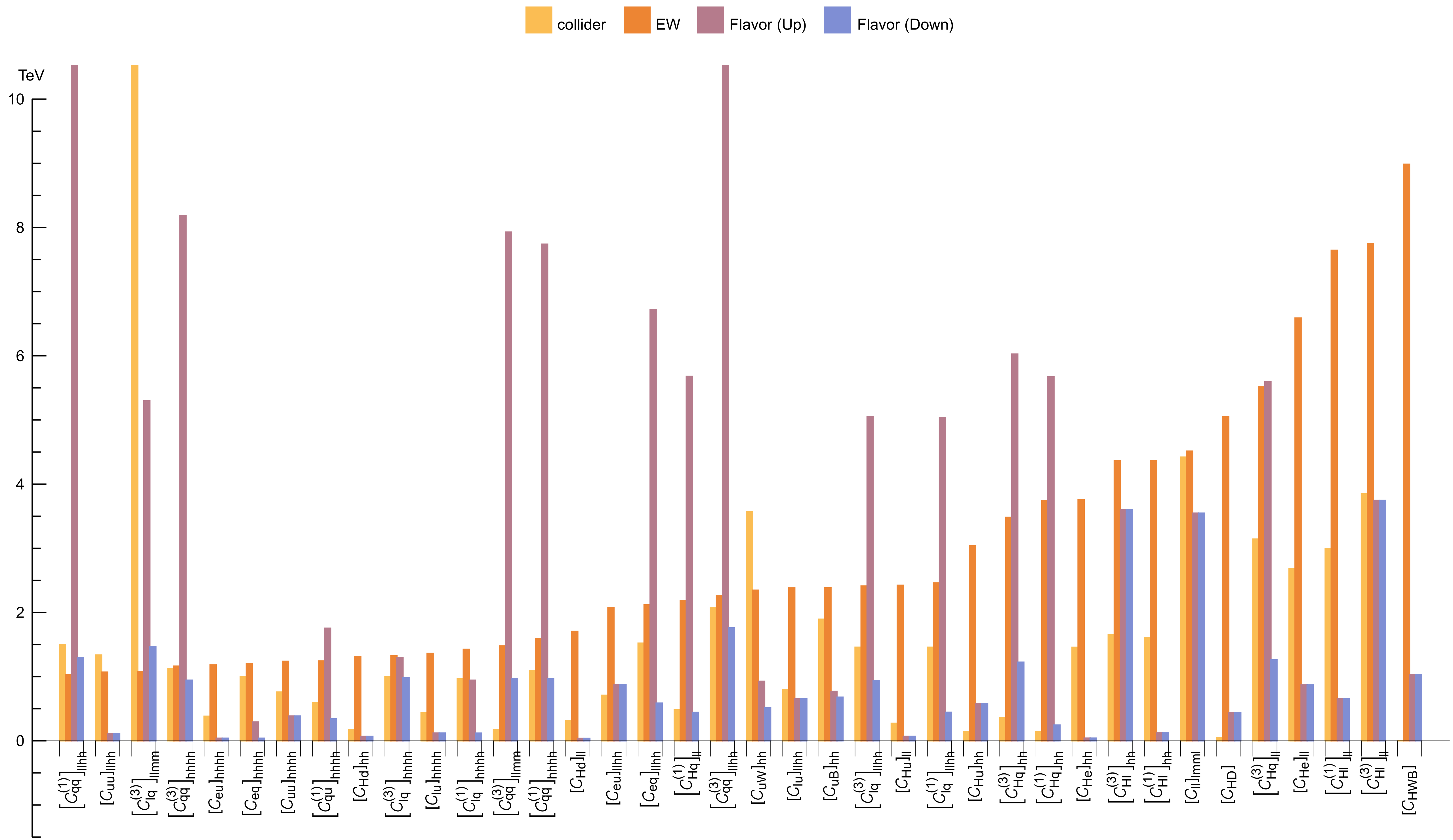
Bounds: EWPT + Flavor + Direct Searches



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- In total, EW dominates in 42 of 124 bounds.

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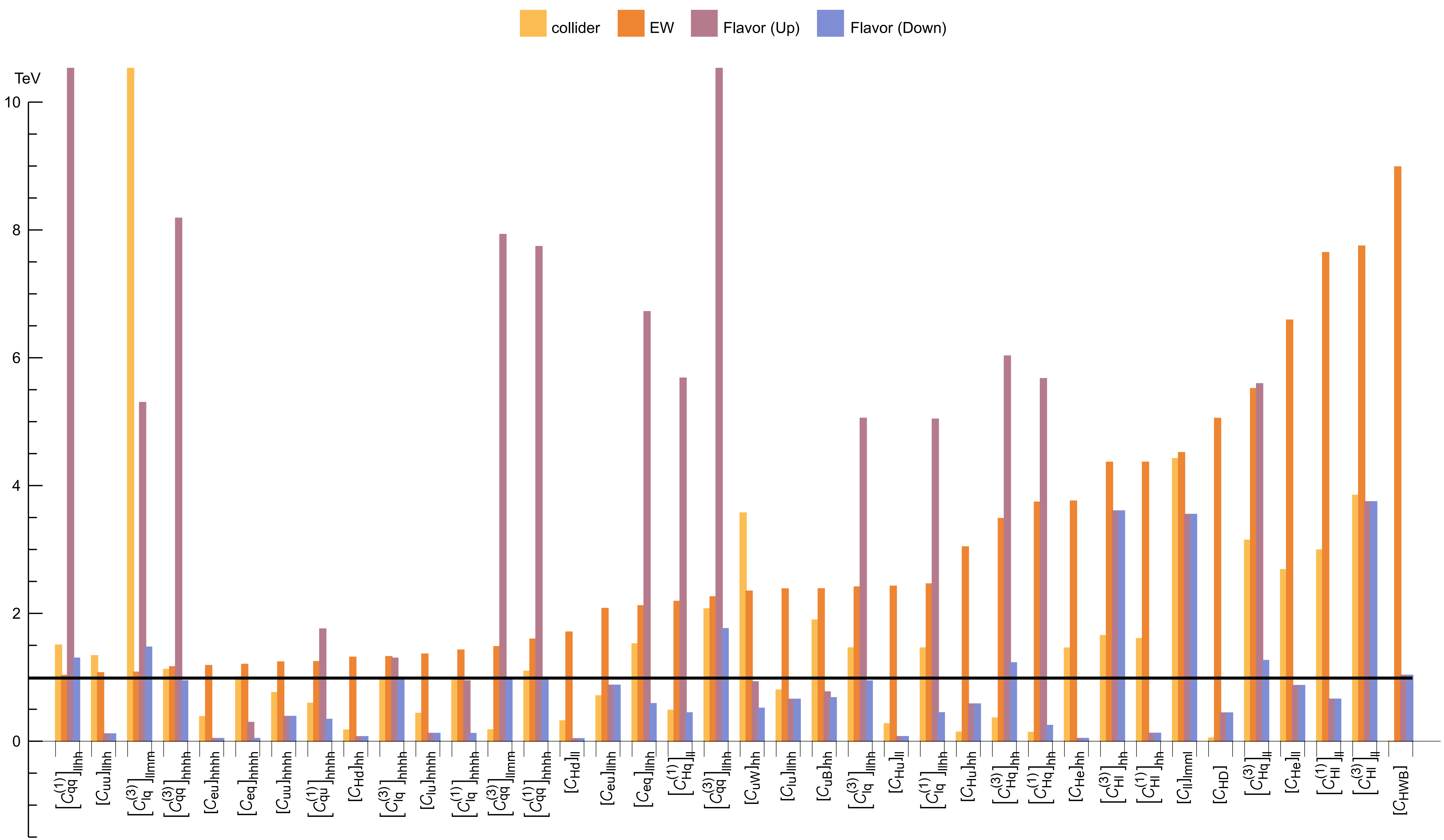

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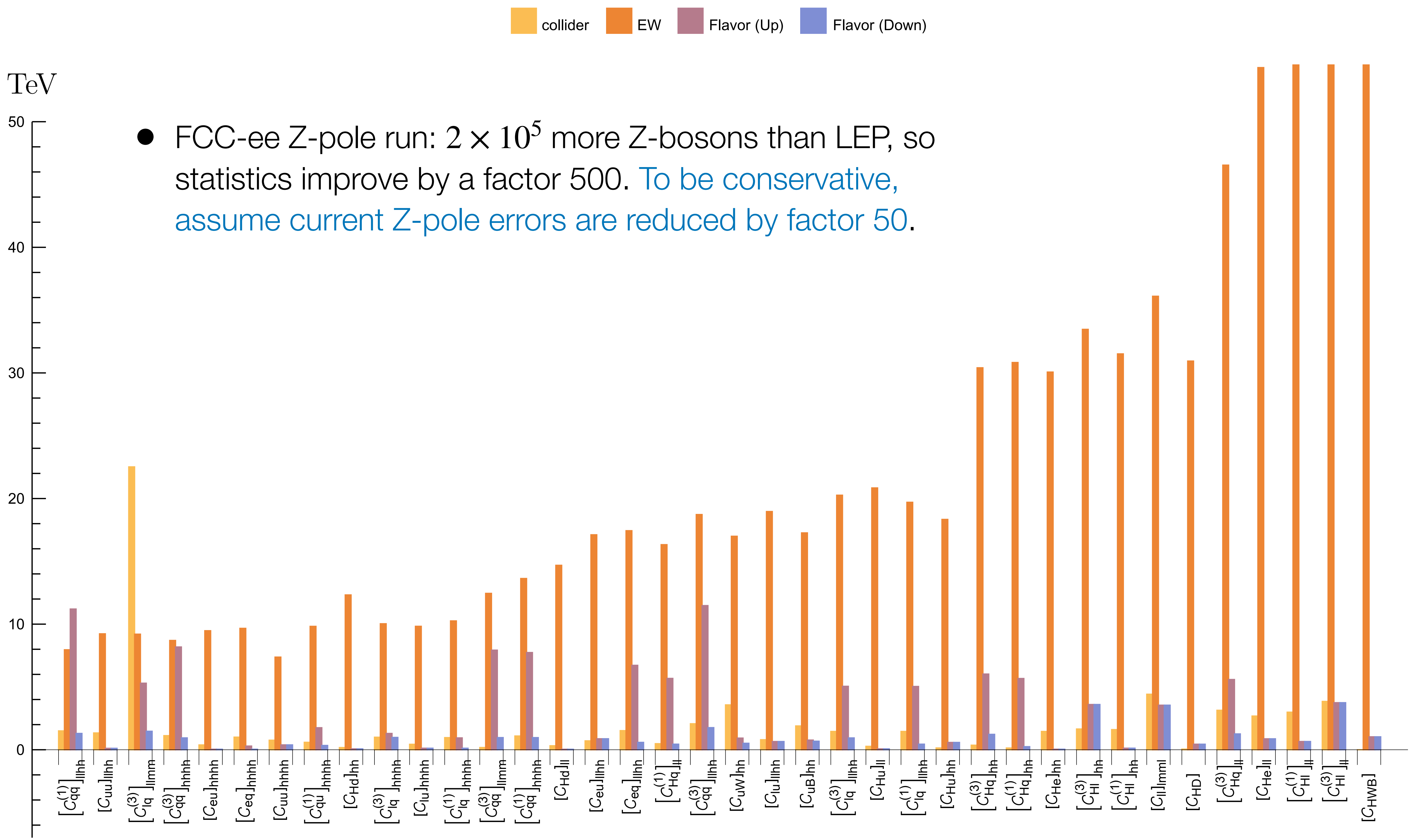
Projection: FCC-ee + Flavor + Direct Searches

- FCC-ee Z-pole run: 2×10^5 more Z-bosons than LEP, so statistics improve by a factor 500. To be conservative, assume current Z-pole errors are reduced by factor 50.



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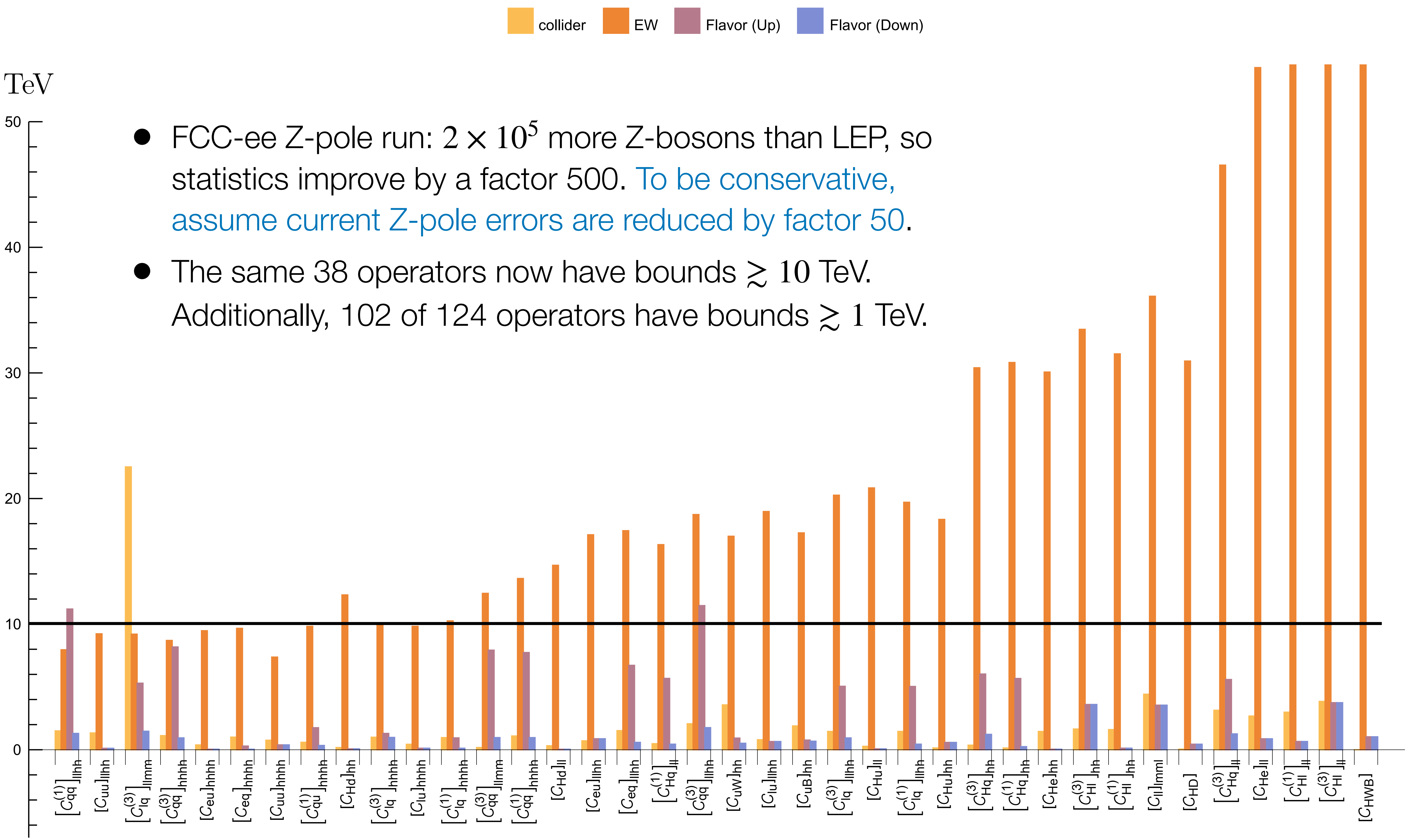

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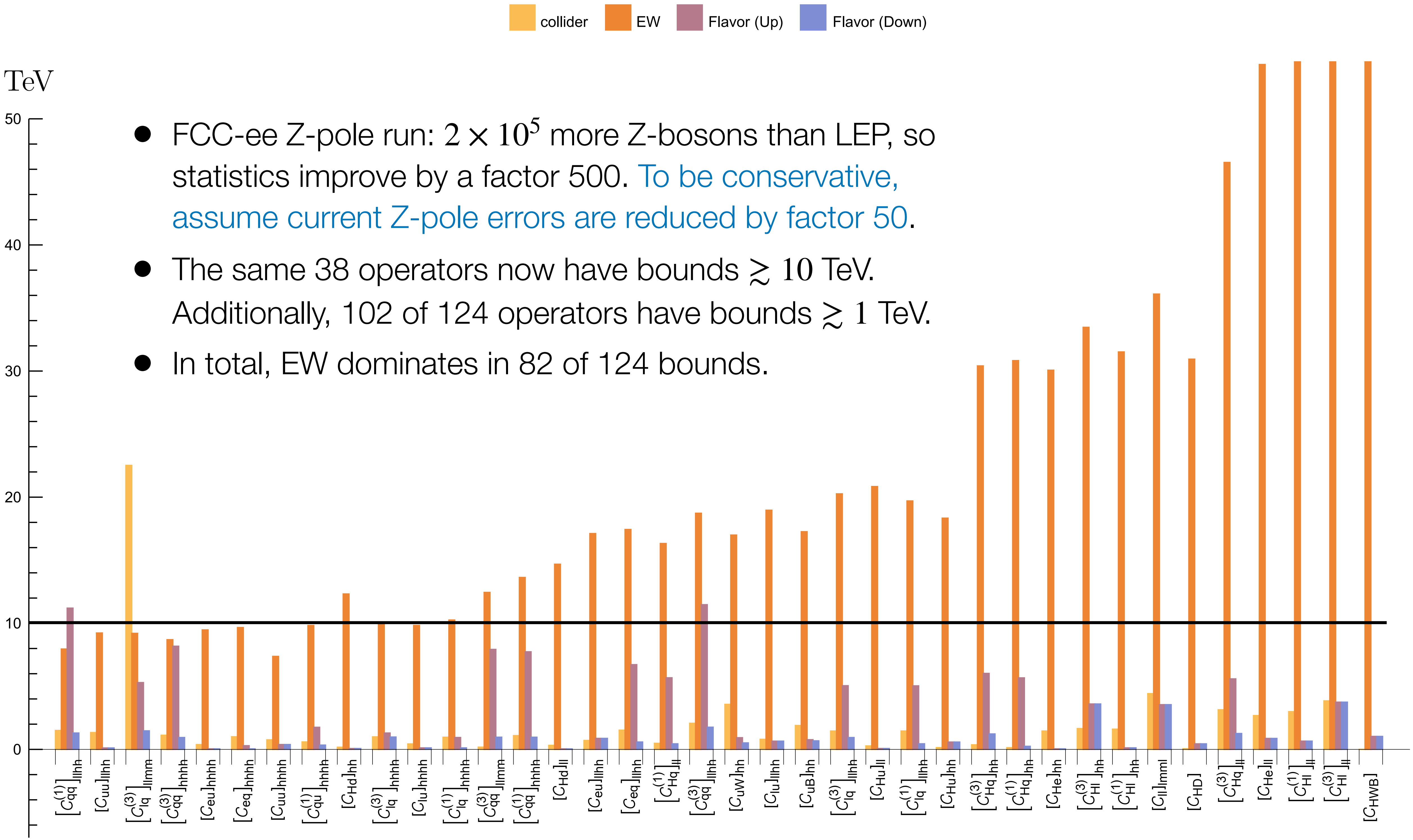
- In total, EW dominates in 82 of 124 bounds.



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Plenty of room for third-family NP (currently)

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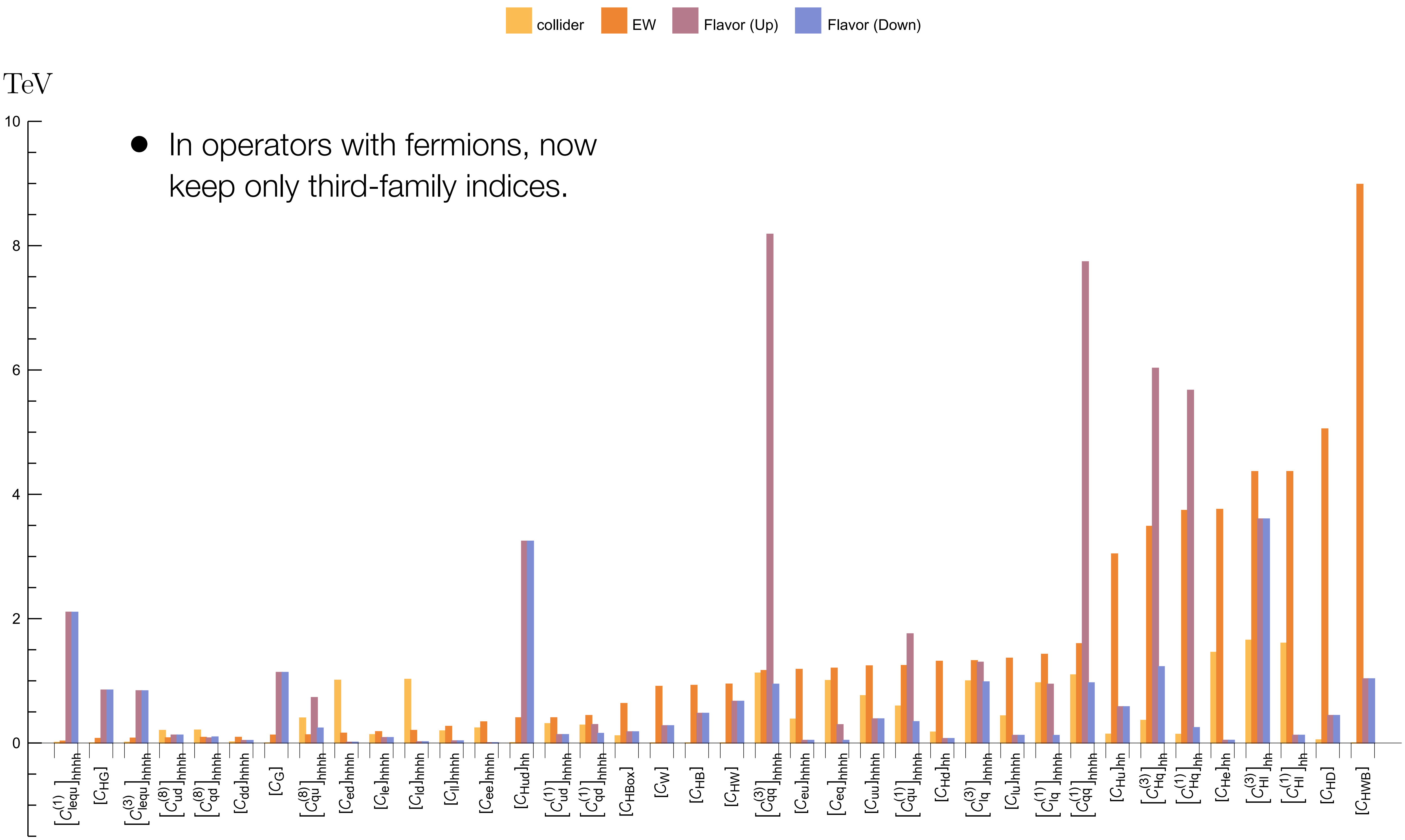

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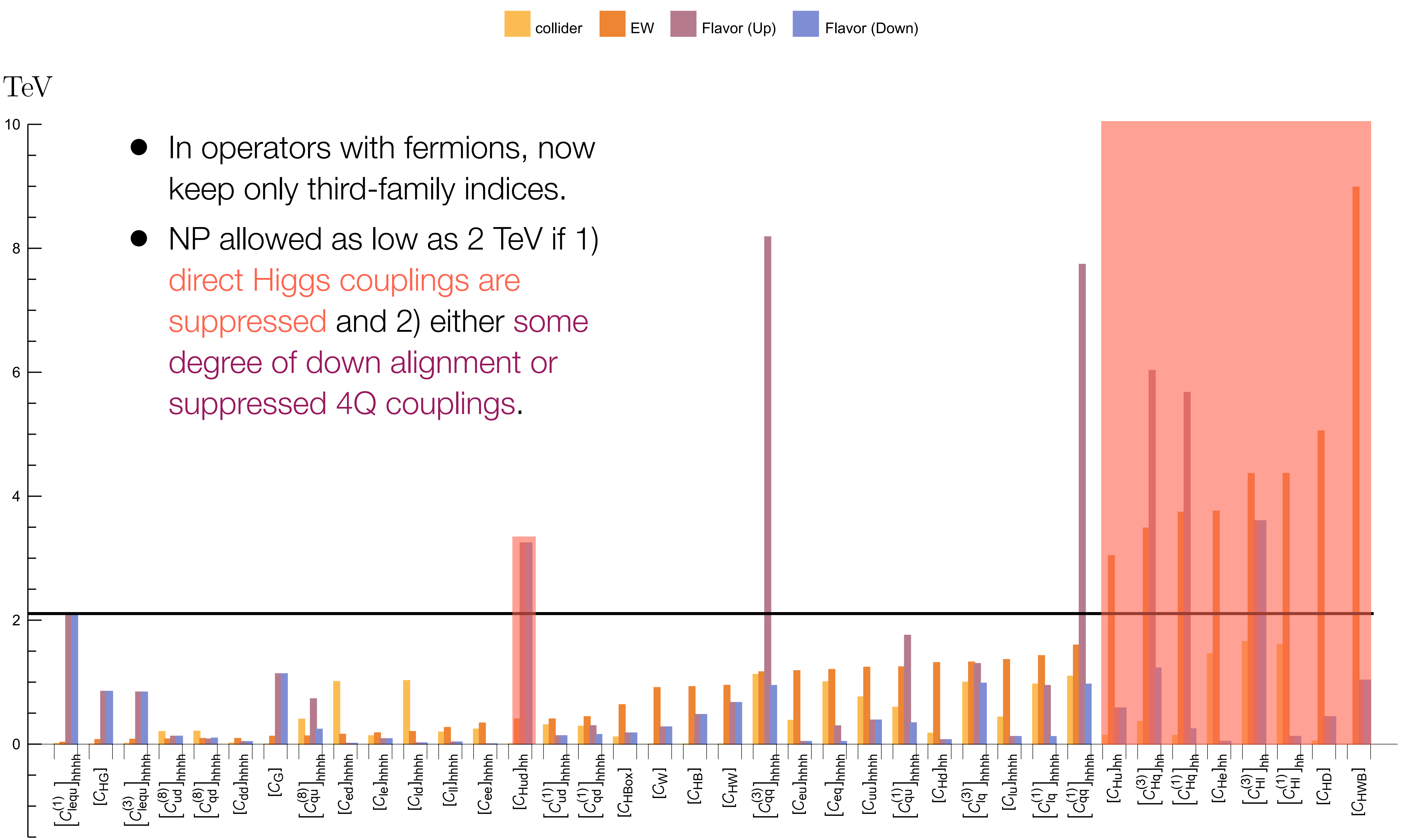

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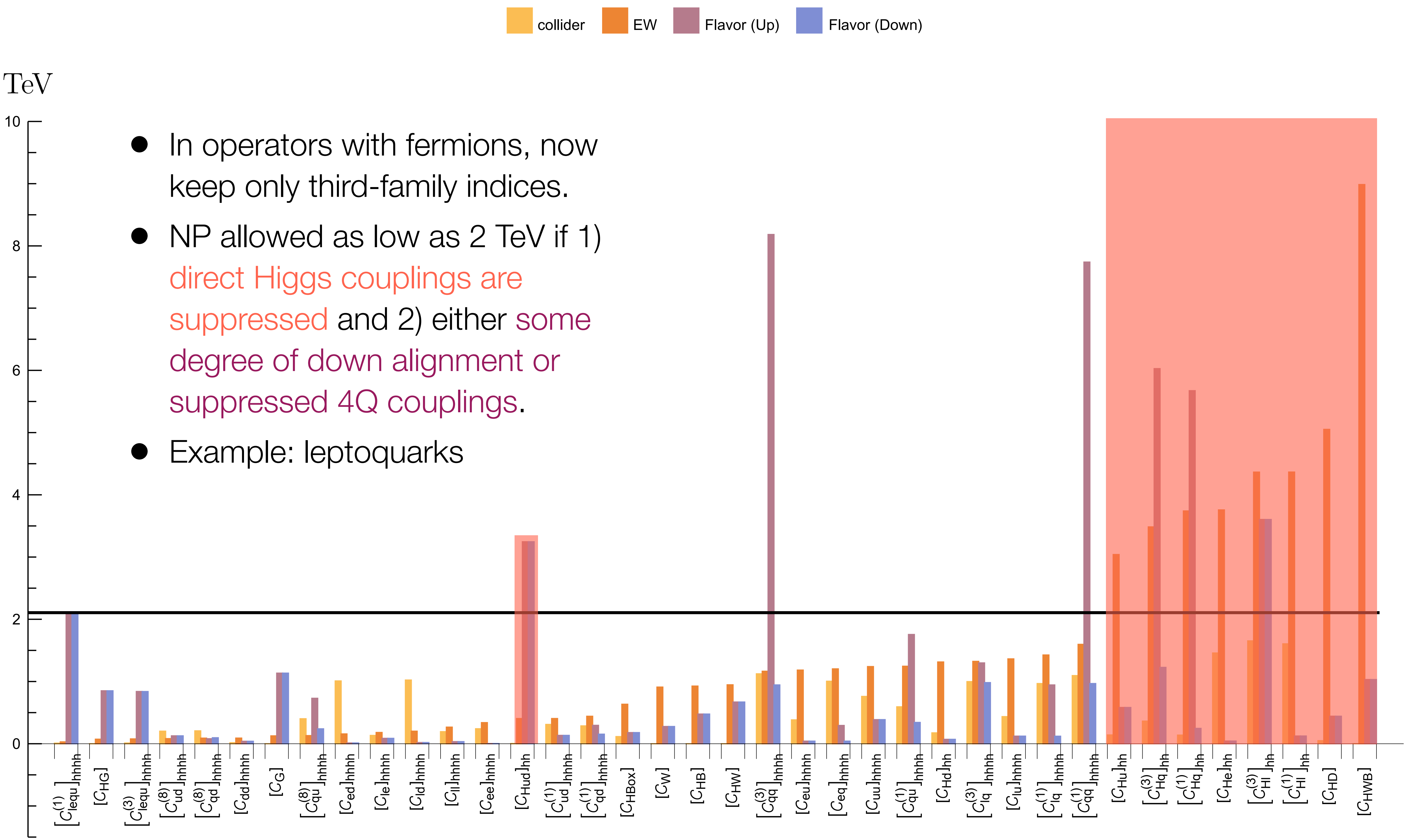
- Example: leptoquarks



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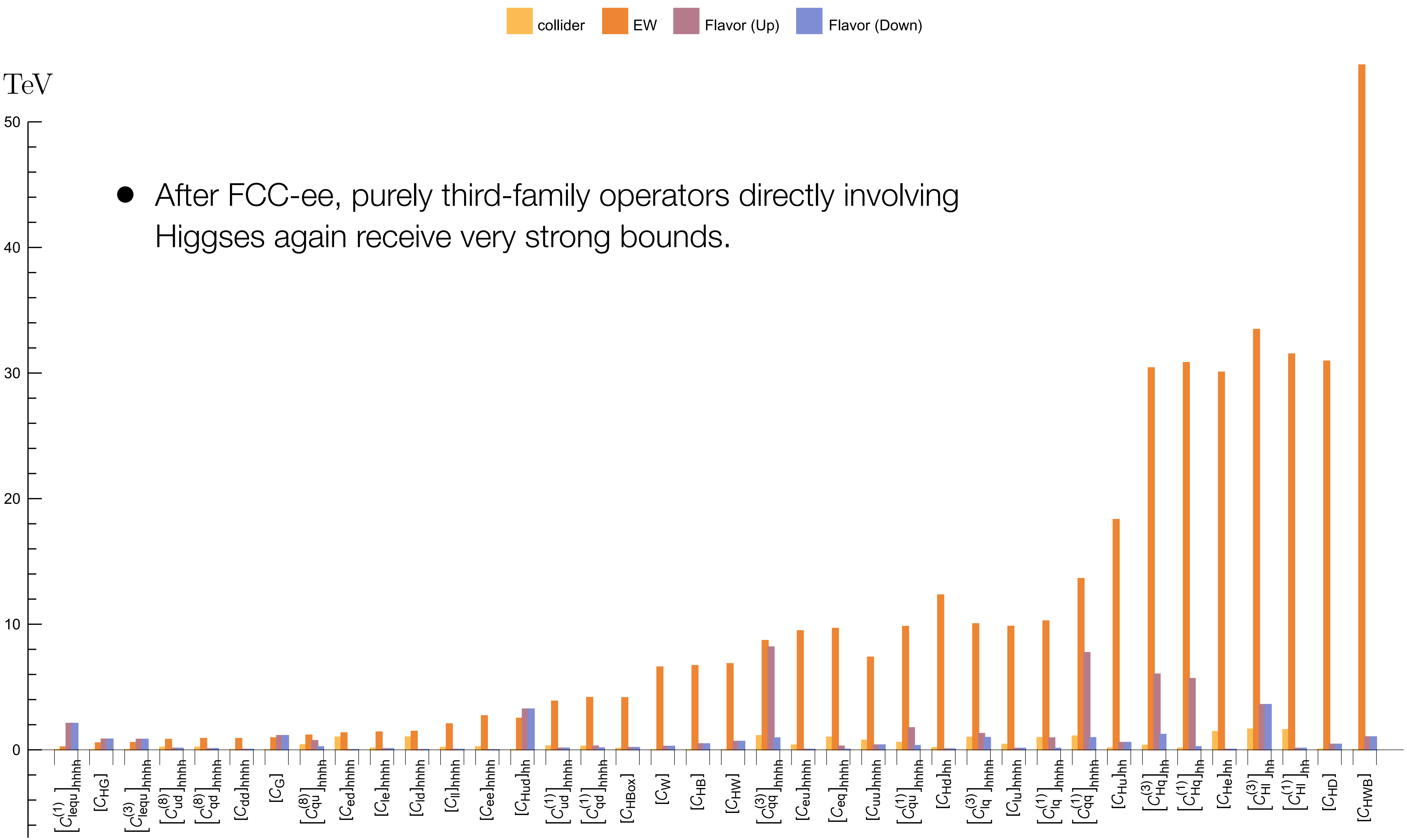
FCC-ee will push third-family NP above 10 TeV!



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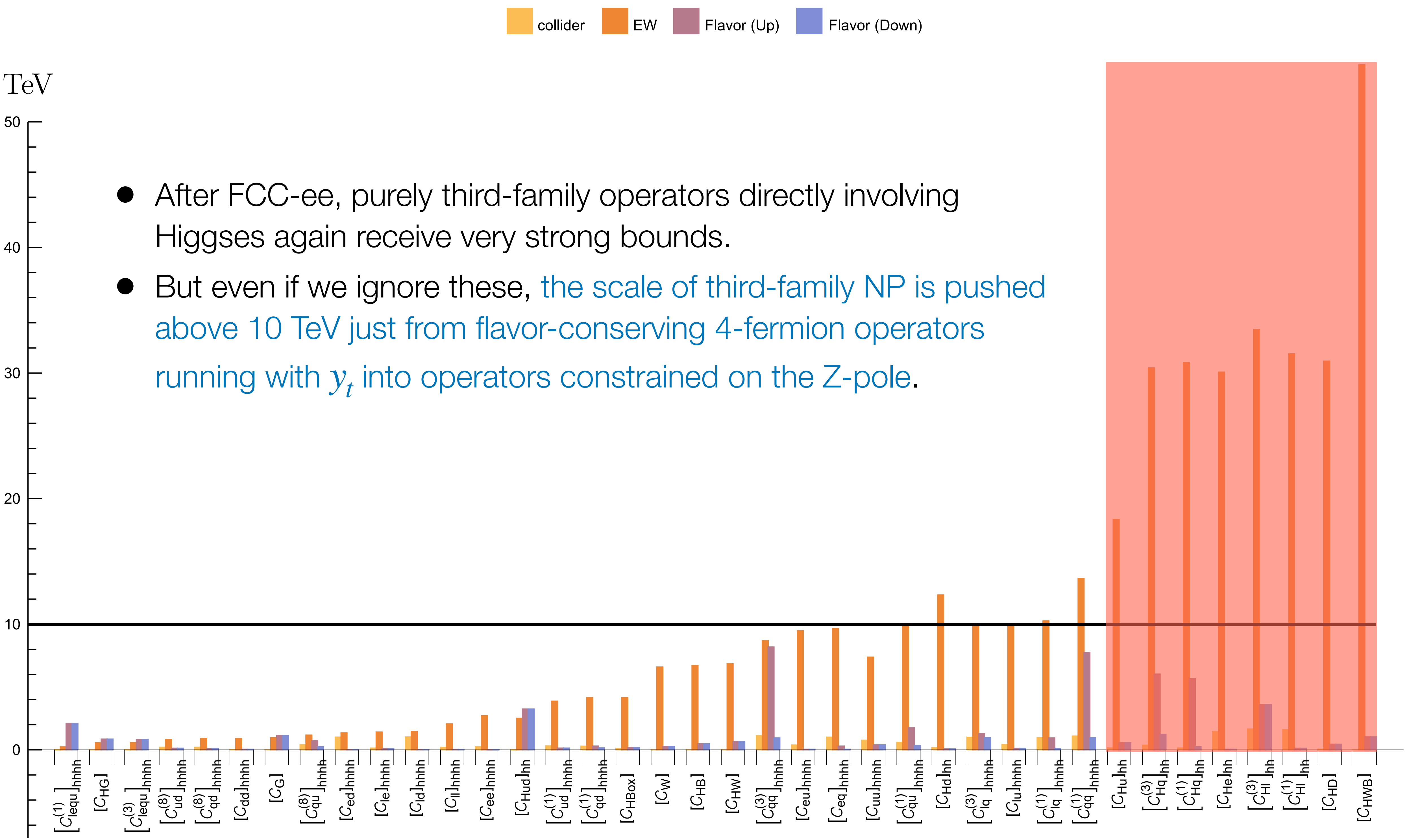

- After FCC-ee, purely third-family operators directly involving Higgses again receive very strong bounds.
- But even if we ignore these, the scale of third-family NP is pushed above 10 TeV just from flavor-conserving 4-fermion operators running with y_t into operators constrained on the Z-pole.

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

Part 2

How does it work in a particular UV model?

Deconstructed Hypercharge: A model of flavor

[J. Davighi and BAS, arXiv: 2305.16280]

[See also G. Isidori, 2308.11612]

Deconstructed Hypercharge: A model of flavor

- Extend the SM based on the concept of flavor deconstruction: the hypothesis that the SM gauge interactions are manifestly flavor non-universal in the UV.

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SSB at ~ few TeV ↓ *massive Z'*

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**Gauging realizes an accidental, exact $U(2)^5$ flavor symmetry!*

[J. Davighi and BAS, arXiv: 2305.16280] [See also G. Isidori, 2308.11612]

Deconstructed Hypercharge: Minimally-broken U(2)

**Light Yukawas via a heavy Higgs*

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**Small mixing of Higgses after DH SSB:*

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**Small CKM mixing at dim-5 via a VLQ doublet:* $\mathscr{L}_{d=5} \supset \dfrac{y_\pm \lambda_q^i}{m_Q} \bar{q}_L^i \Phi_q H_3 \psi_R^\pm$

[J. Davighi and BAS, arXiv: 2305.16280]

Deconstructed Hypercharge: Gauge interactions

Z' gauge coupling to Fermion and Higgs currents

$\tan\theta = g_{12}/g_3$

$$g_\psi^{ij} = g_Y Y_\psi \,\mathrm{diag}(-\tan\theta, -\tan\theta, \cot\theta)\,, \qquad g_H = g_Y Y_H \cot\theta$$

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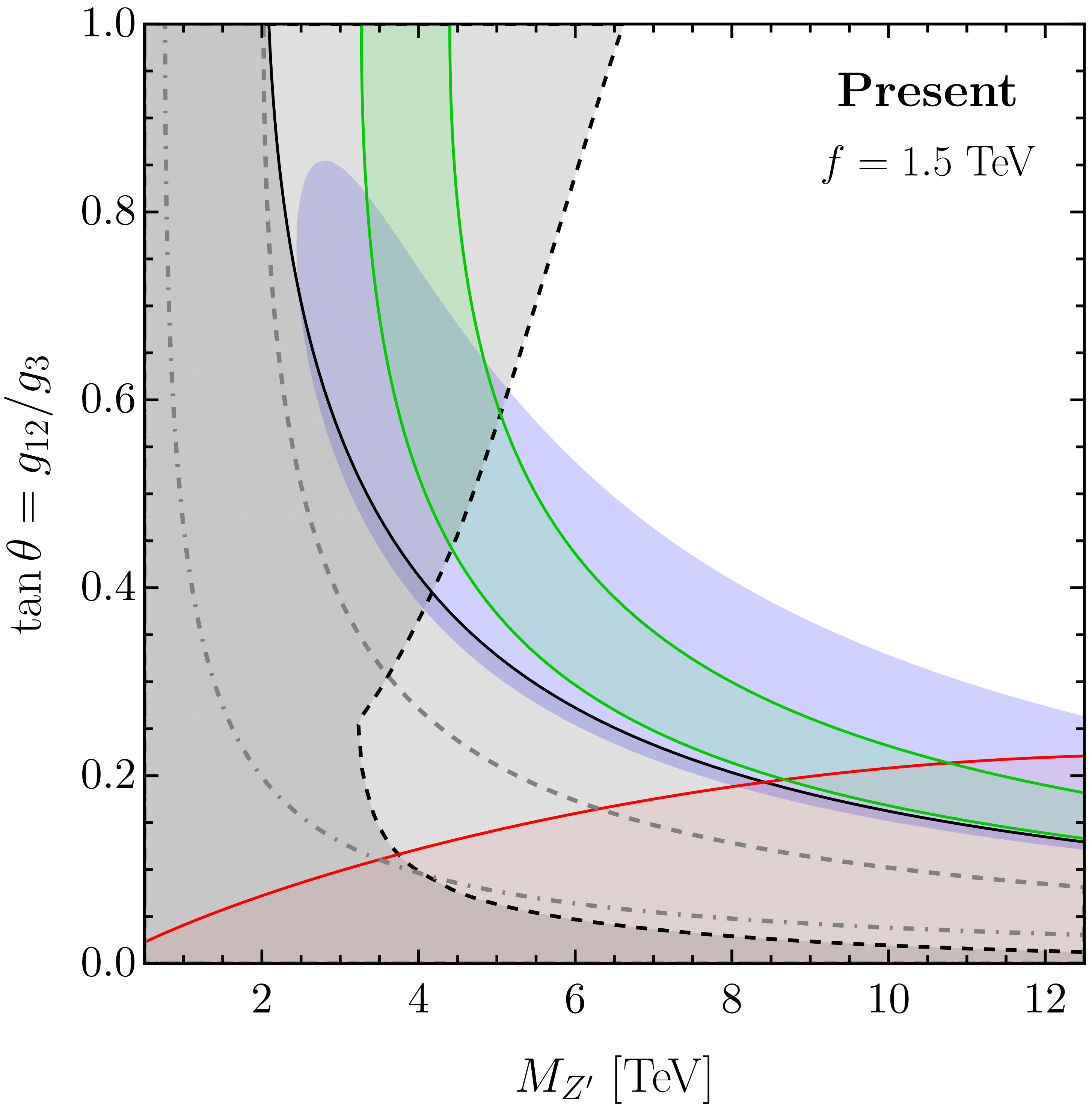
- If flavor violation occurs only in the left-handed sector (e.g. minimally-broken $U(2)$), then quark-flavor violating observables are always suppressed by powers of $g_Y Y_q$. As a consequence, the DH model easily passes flavor bounds.

[J. Davighi and BAS, arXiv: 2305.16280]

Deconstructed Hypercharge vs. the Bound Triad



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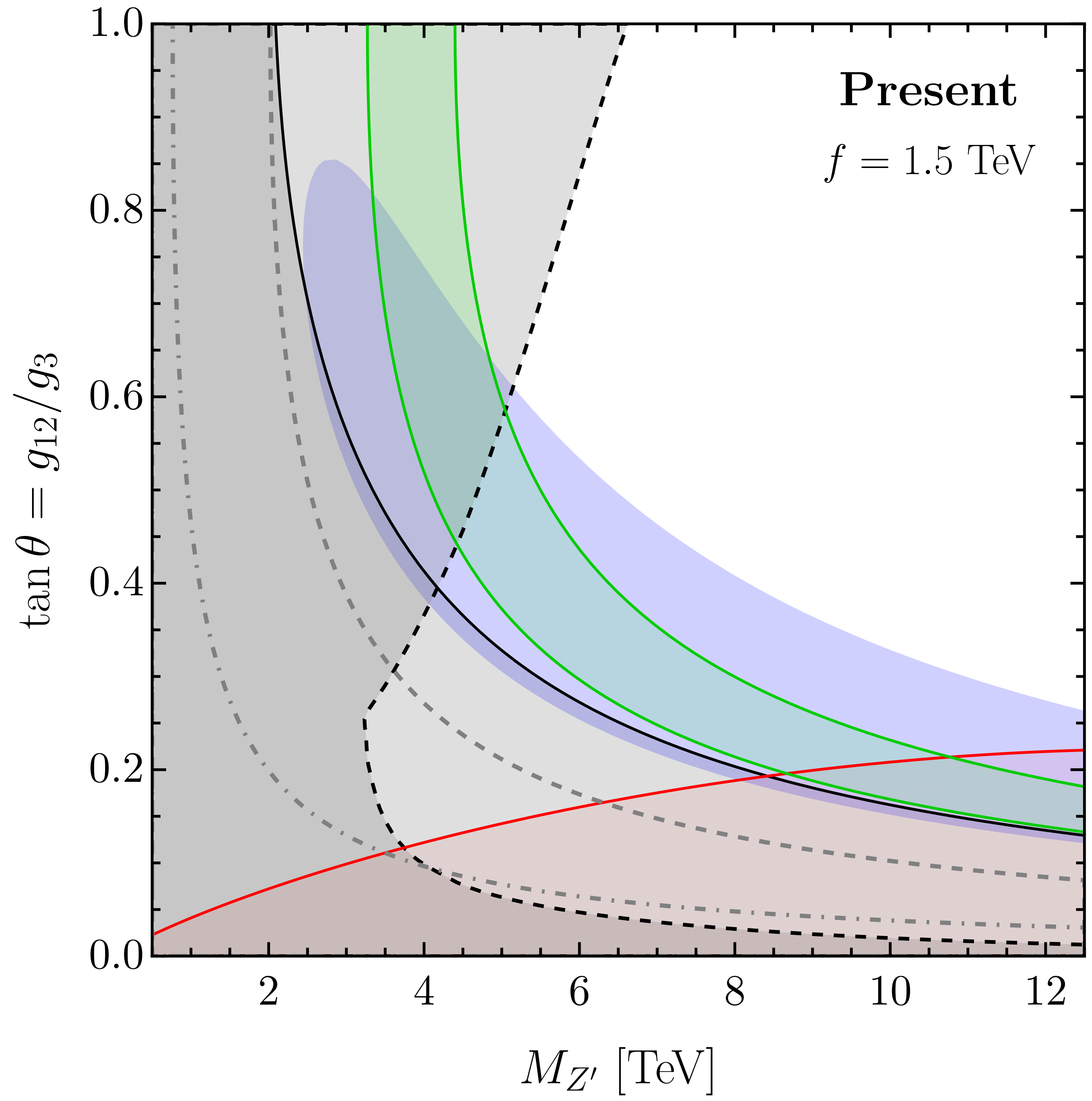

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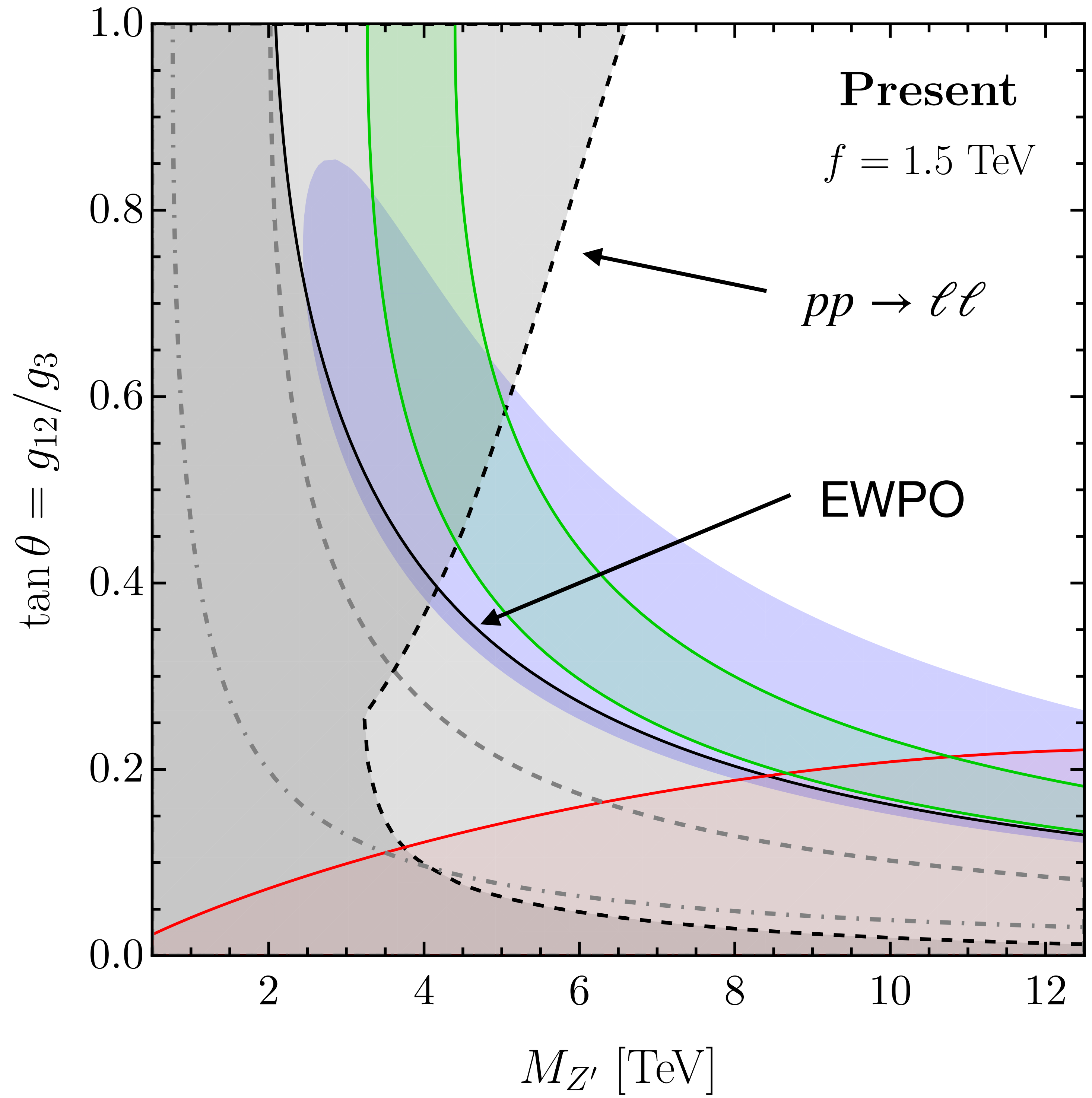

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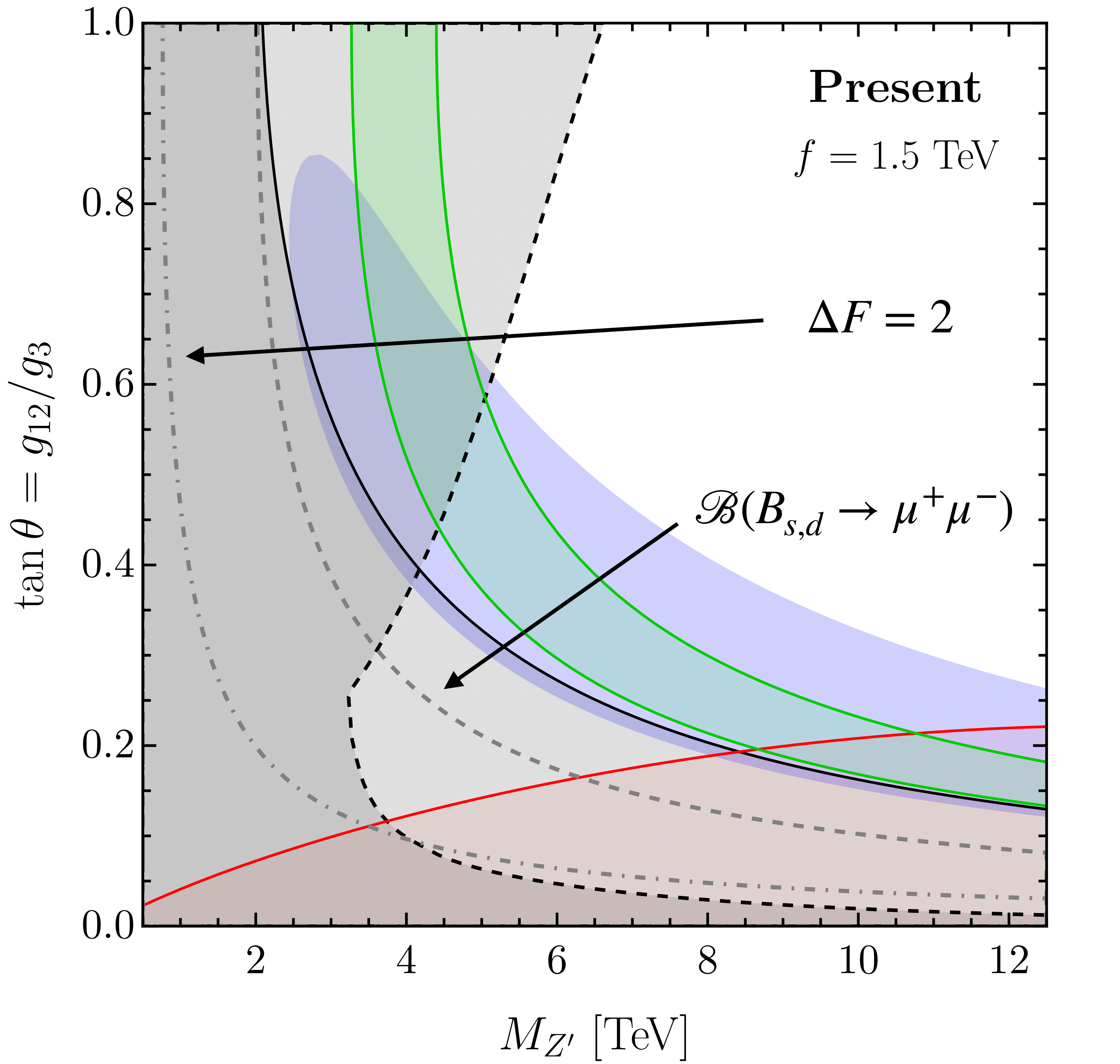

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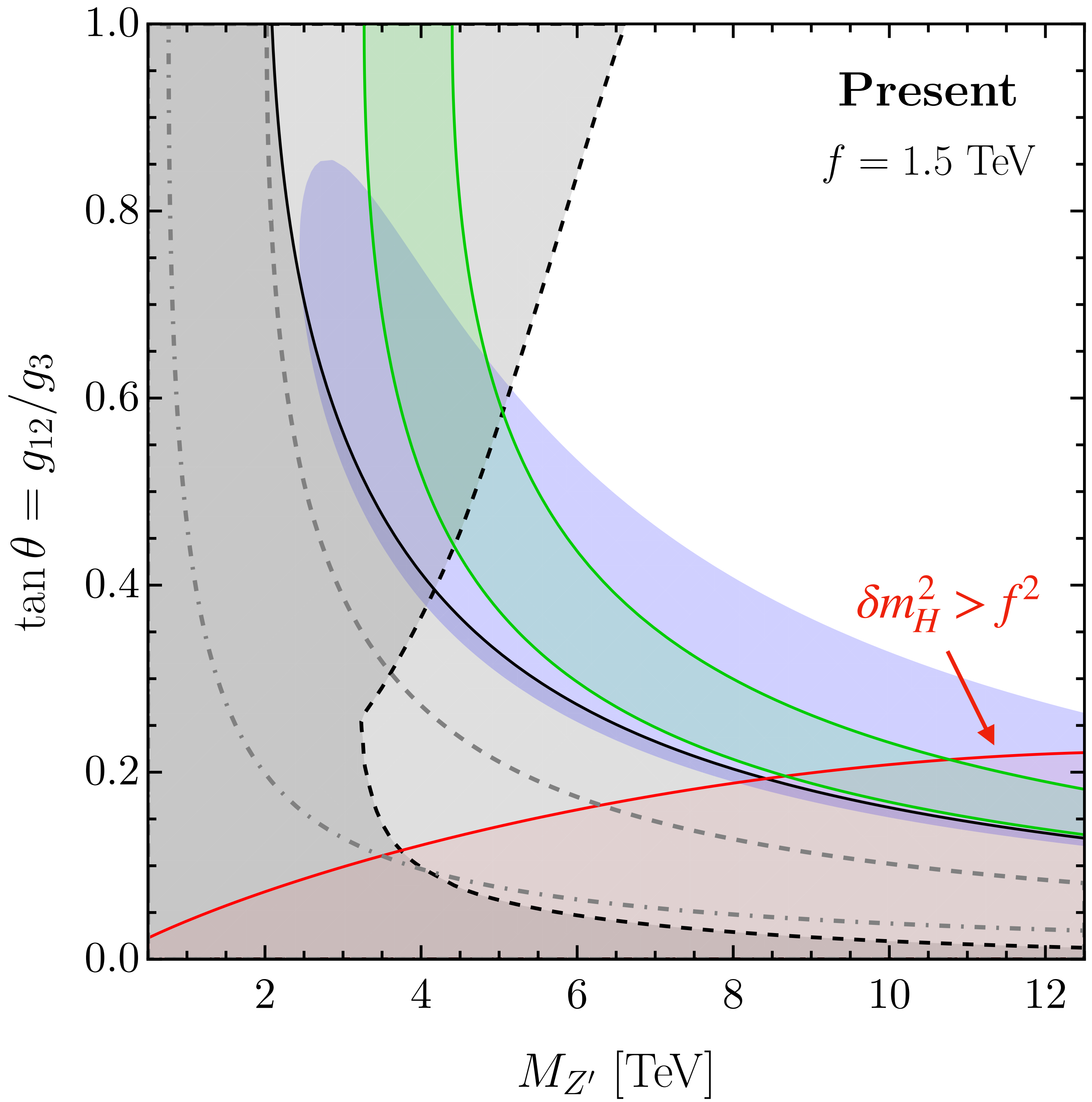

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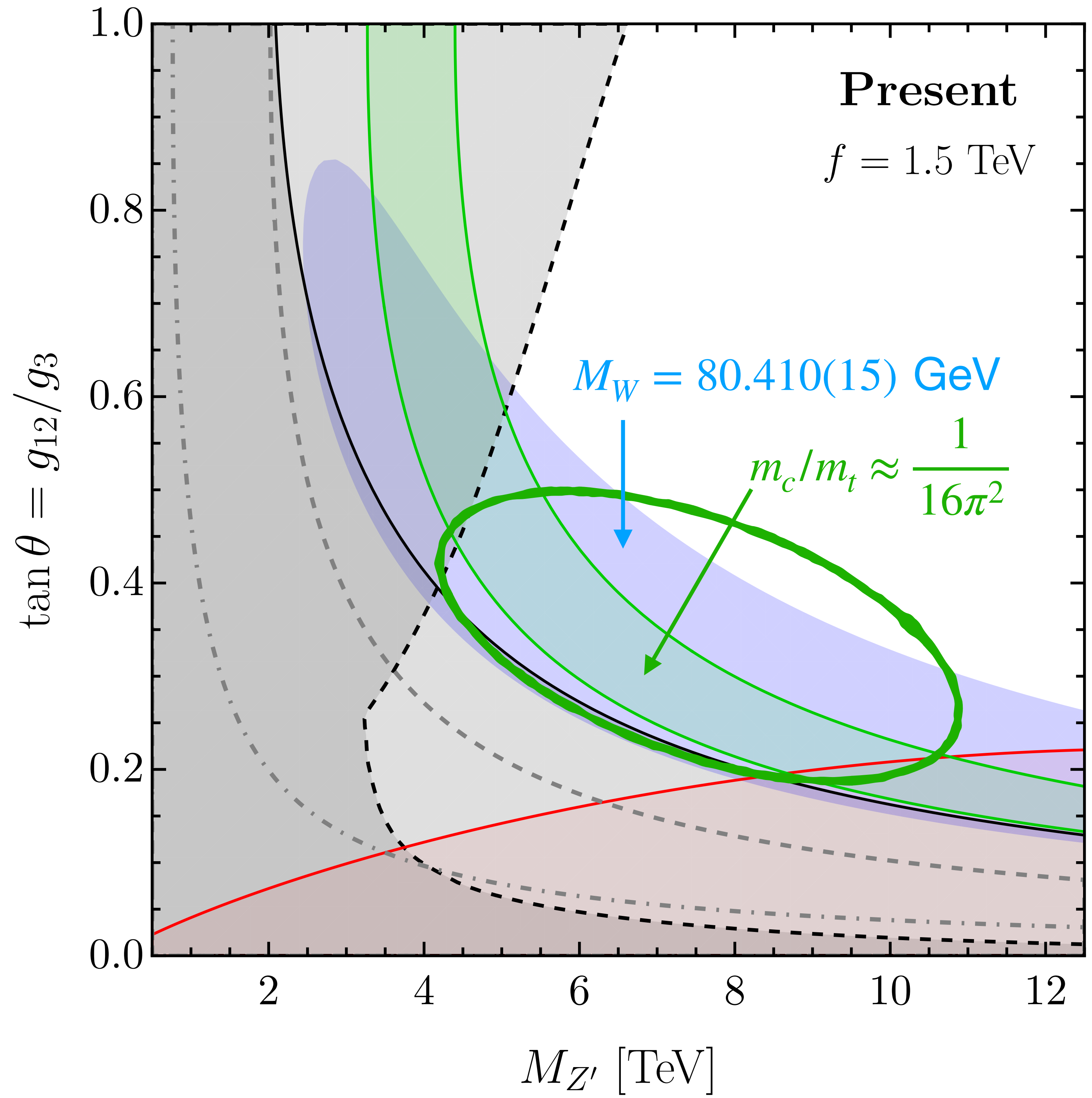


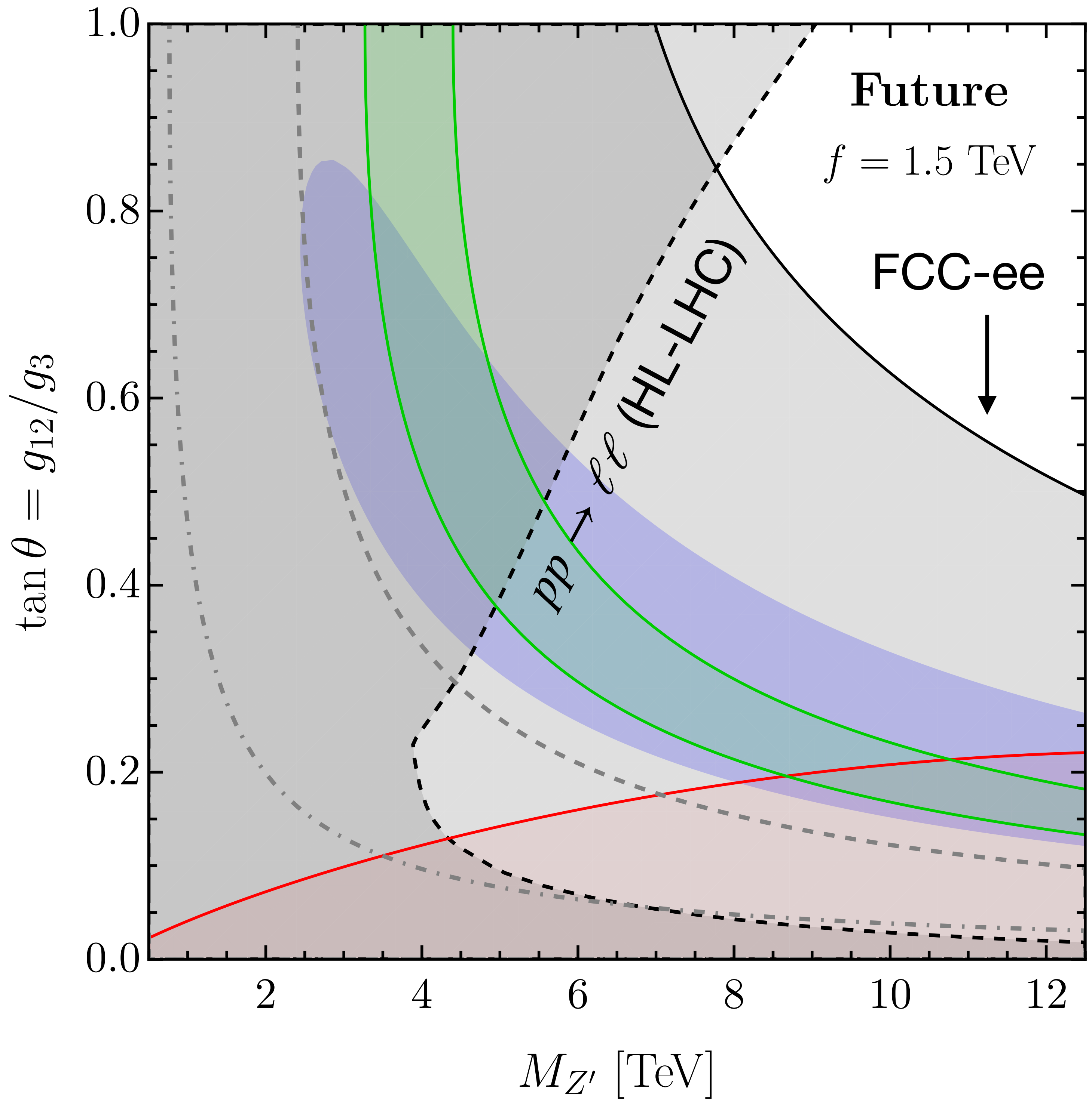
[J. Davighi and BAS, arXiv: 2305.16280]

Deconstructed Hypercharge: Fully probed by FCC-ee

- We also give projections for current and future exps.
- HL-LHC with 3/ab of int. lum.
- FCC-ee (assuming EWPO errors improve by only a factor of 10)

Key take-away:

FCC-ee easily has the reach to fully probe the model! We expect it to be the case for any low-scale model with direct NP couplings to the Higgs.



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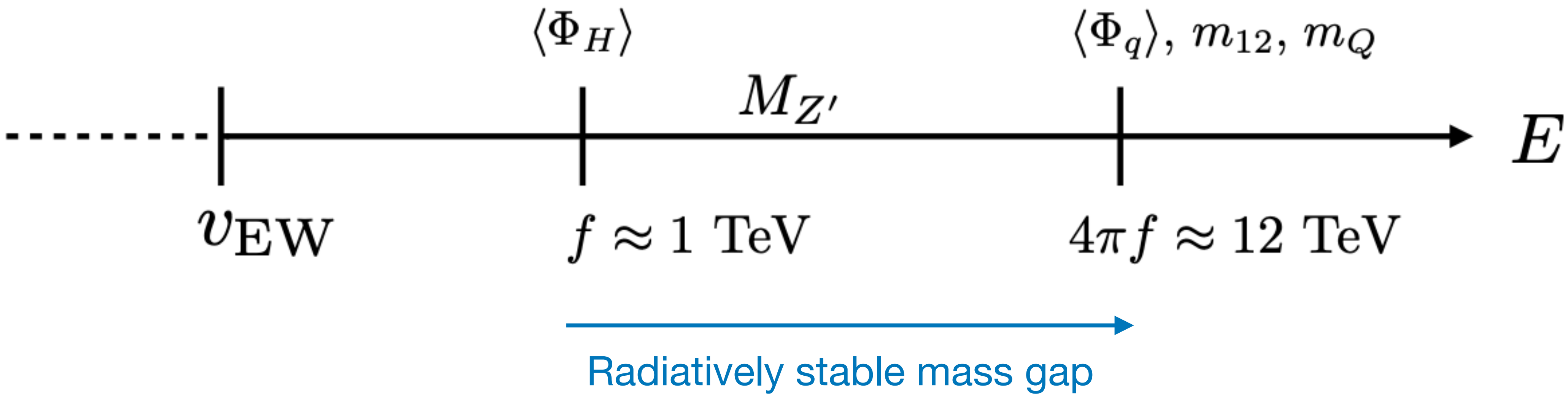
Backup Slides

Deconstructed Hypercharge: Scale Setup



Z' gauge boson mass: $$M_{Z'}^2 = \frac{2 g_Y^2}{\sin^2 2\theta} \left[\langle \Phi_H \rangle^2 + \frac{1}{9} \langle \Phi_q \rangle^2 \right]$$

Gauge Higgs mass corrections: $$\delta M_{H_l}^2 (Z') = \frac{g_Y^2 Y_H^2}{16\pi^2} \frac{M_{Z'}^2}{\tan^2 \theta} \left[1 + 3 \log \frac{\mu^2}{M_{Z'}^2} \right]$$

VLF Higgs mass corrections: $$\delta M_{H_l}^2 (\mathrm{VLF}) = -\frac{N_c}{8\pi^2} |y_{H\psi}|^2 M_\psi^2 \left[1 + \log \frac{\mu^2}{M_\psi^2} \right]$$

Scalar Higgs mass corrections: $$\delta M_{H_l}^2 (\lambda_{hl}) = -\frac{\lambda_{hl}}{8\pi^2} M_{H_h}^2 \left[1 + \log \frac{\mu^2}{M_{H_h}^2} \right]$$

[J. Davighi and BAS, arXiv: 2305.16280]

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]

Higgs 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.
$\mathcal{C}^{(1)[33]}_{H\ell}$	0.1	0.1	4.4	1.6	4.3	R_τ	4.3	R_τ
$\mathcal{C}^{(1)[ii]}_{H\ell}$	0.7	0.7	7.6	3.	7.8	σ_{had}	7.8	σ_{had}
$\mathcal{C}^{(3)[33]}_{H\ell}$	3.6	3.6	4.4	1.7	4.9	R_τ	4.9	R_τ
$\mathcal{C}^{(3)[ii]}_{H\ell}$	3.7	3.7	7.7	3.8	7.9	σ_{had}	7.9	σ_{had}
$\mathcal{C}^{[33]}_{He}$	-	-	3.8	1.5	3.7	R_τ	3.7	R_τ
$\mathcal{C}^{[ii]}_{He}$	0.9	0.9	6.6	2.7	6.7	σ_{had}	6.7	σ_{had}
$\mathcal{C}^{(1)[33]}_{Hq}$	0.2	5.7	3.7	0.1	3.7	Γ_Z	5.	$B_s \to \mu\mu$
$\mathcal{C}^{(1)[ii]}_{Hq}$	0.4	5.7	2.2	0.5	2.2	R_c	5.2	$B_s \to \mu\mu$
$\mathcal{C}^{(3)[33]}_{Hq}$	1.2	6.	3.5	0.4	3.4	R_b	5.4	$B_s \to \mu\mu$
$\mathcal{C}^{(3)[ii]}_{Hq}$	1.3	5.6	5.5	3.1	5.7	R_τ	7.6	$B_s \to \mu\mu$
$\mathcal{C}^{[33]}_{Hd}$	-	-	1.3	0.2	1.3	R_b	1.3	R_b
$\mathcal{C}^{[ii]}_{Hd}$	-	-	1.7	0.3	1.7	R_τ	1.7	R_τ
$\mathcal{C}^{[33]}_{Hu}$	0.6	0.6	3.	0.1	3.1	A_b^{FB}	3.1	A_b^{FB}
$\mathcal{C}^{[ii]}_{Hu}$	-	-	2.4	0.3	2.4	R_τ	2.4	R_τ
$\mathcal{C}^{[33]}_{Hud}$	3.2	3.2	0.4	-	3.2	$B \to X_s\gamma$	3.2	$B \to X_s\gamma$

3H and Dipole 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.
$\mathcal{C}_{eH}^{[33]}$	5.1	5.1	-	-	5.1	$H \to \tau\tau$	5.1	$H \to \tau\tau$
$\mathcal{C}_{uH}^{[33]}$	0.2	0.2	-	-	0.2	$H \to \tau\tau$	0.2	$H \to \tau\tau$
$\mathcal{C}_{dH}^{[33]}$	3.7	3.7	-	-	3.7	$H \to bb$	3.7	$H \to bb$

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.
$\mathcal{C}_{eB}^{[33]}$	0.1	0.1	0.2	1.2	1.2	$pp \to \tau\tau$	1.2	$pp \to \tau\tau$
$\mathcal{C}_{uB}^{[33]}$	0.7	0.8	2.4	1.9	2.7	A_b^{mFB}	2.7	A_b^{mFB}
$\mathcal{C}_{dB}^{[33]}$	15.2	74.8	0.3	0.7	15.2	$B \to X_s\gamma$	74.8	$B \to X_s\gamma$
$\mathcal{C}_{eW}^{[33]}$	1.	1.	0.2	1.9	1.8	$pp \to \tau\nu$	1.8	$pp \to \tau\nu$
$\mathcal{C}_{uW}^{[33]}$	0.5	0.9	2.3	3.6	3.7	4Q	3.8	4Q
$\mathcal{C}_{dW}^{[33]}$	15.7	53.	0.1	0.6	15.7	$B \to X_s\gamma$	53.	$B \to X_s\gamma$
$\mathcal{C}_{uG}^{[33]}$	0.2	0.3	0.5	2.6	2.6	4Q	2.6	4Q
$\mathcal{C}_{dG}^{[33]}$	4.	25.5	-	-	4.	$B \to X_s\gamma$	25.5	$B \to X_s\gamma$

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	$pp \to \tau\tau$
$\mathcal{C}_{quqd}^{(1)[3333]}$	2.2	5.5	-	0.4	2.2	$B \to X_s\gamma$	5.5	$B \to X_s\gamma$
$\mathcal{C}_{quqd}^{(8)[3333]}$	1.	5.1	-	0.2	1.	$B \to X_s\gamma$	5.1	$B \to X_s\gamma$
$\mathcal{C}_{\ell equ}^{(1)[3333]}$	2.1	2.1	-	-	2.1	$H \to \tau\tau$	2.1	$H \to \tau\tau$
$\mathcal{C}_{\ell equ}^{(3)[3333]}$	0.8	0.8	-	-	0.8	$H \to \tau\tau$	0.8	$H \to \tau\tau$

LLLL vector 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.
$\mathcal{C}_{\ell\ell}^{[3333]}$	-	-	0.3	0.2	0.3	σ_{had}	0.3	σ_{had}
$\mathcal{C}_{\ell\ell}^{[ii33]}$	0.8	0.8	0.6	3.4	3.4	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$	3.4	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$\mathcal{C}_{\ell\ell}^{[i33i]}$	3.5	3.5	0.4	3.3	4.6	$(g_\tau/g_\mu)_\tau$	4.6	$(g_\tau/g_\mu)_\tau$
$\mathcal{C}_{\ell\ell}^{[iijj]}$	0.8	0.8	0.9	4.4	4.4	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$	4.4	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$\mathcal{C}_{\ell\ell}^{[ijji]}$	3.5	3.5	4.5	4.4	5.1	A_b^{mFB}	5.1	A_b^{mFB}
$\mathcal{C}_{qq}^{(1)[3333]}$	1.	7.7	1.6	1.1	1.7	Γ_Z	7.6	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(1)[ii33]}$	1.3	11.2	1.	1.5	1.7	4Q	11.2	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(1)[i33i]}$	2.4	11.3	0.7	1.6	2.5	$B_s \to \mu\mu$	11.3	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(1)[iimm]}$	0.9	8.1	0.4	-	0.9	$\text{Im}(C_D)$	8.1	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(1)[immi]}$	1.1	8.1	0.5	-	1.	$\text{Im}(C_D)$	8.1	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(3)[3333]}$	0.9	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	1.	2.4	3.	$B_s \to \mu\mu$	11.3	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(3)[iimm]}$	1.	7.9	1.5	0.2	1.5	R_τ	7.9	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(3)[immi]}$	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	0.9	1.4	1.	1.4	R_τ	1.6	R_τ
$\mathcal{C}_{\ell q}^{(1)[ii33]}$	0.4	5.	2.5	1.5	2.5	σ_{had}	5.1	$B_s \to \mu\mu$
$\mathcal{C}_{\ell q}^{(1)[33ii]}$	0.2	0.9	0.3	3.4	3.4	$pp \to \tau\tau$	3.5	$pp \to \tau\tau$
$\mathcal{C}_{\ell q}^{(1)[iimm]}$	0.4	5.1	0.5	5.4	5.4	$pp \to \mu\mu$	5.6	$pp \to \mu\mu$
$\mathcal{C}_{\ell q}^{(3)[3333]}$	1.	1.3	1.3	1.	1.4	R_τ	1.8	R_τ
$\mathcal{C}_{\ell q}^{(3)[ii33]}$	0.9	5.1	2.4	1.5	2.6	A_b^{mFB}	5.	$B_s \to \mu\mu$
$\mathcal{C}_{\ell q}^{(3)[33ii]}$	1.4	1.6	0.8	8.6	9.	$pp \to \tau\nu$	9.	$pp \to \tau\nu$
$\mathcal{C}_{\ell q}^{(3)[iimm]}$	1.5	5.3	1.1	22.5	22.4	$pp \to \mu\nu$	23.7	$pp \to \mu\nu$

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	4Q	1.4	4Q
$\mathcal{C}_{uu}^{[i33i]}$	-	-	0.5	1.3	1.4	4Q	1.4	4Q
$\mathcal{C}_{uu}^{[iijj]}$	-	-	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	4Q	1.2	4Q
$\mathcal{C}_{ud}^{(1)[iimm]}$	-	-	0.2	-	0.2	R_τ	0.2	R_τ
$\mathcal{C}_{ud}^{(8)[3333]}$	0.1	0.1	-	0.2	0.2	4Q	0.2	4Q
$\mathcal{C}_{ud}^{(8)[ii33]}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{ud}^{(8)[33ii]}$	-	-	0.1	0.7	0.7	4Q	0.7	4Q
$\mathcal{C}_{ud}^{(8)[iimm]}$	-	-	-	-	-	-	-	-

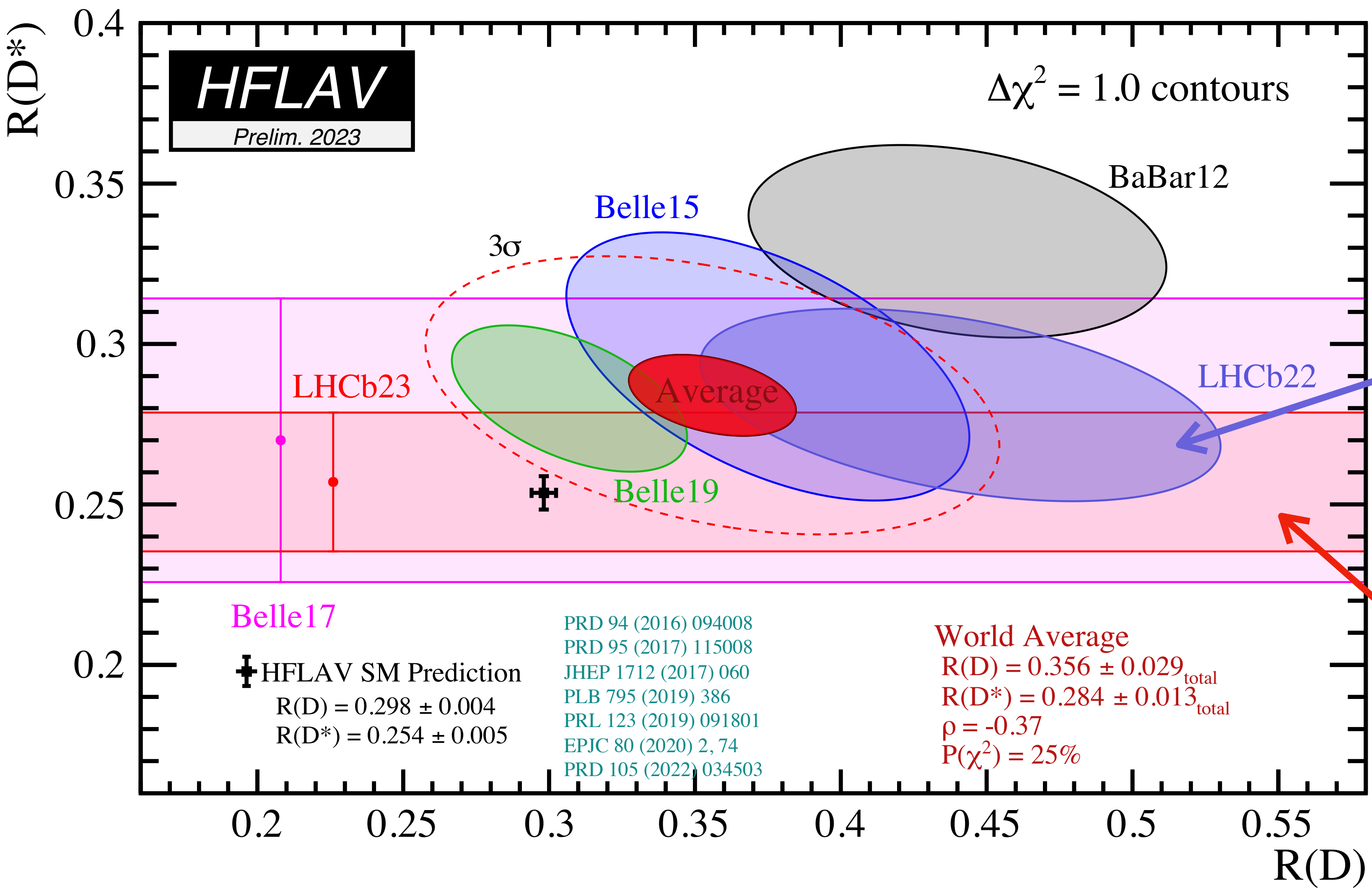
LLRR vector operators

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.
$\mathcal{C}_{\ell e}^{[3333]}$	-	-	0.2	0.1	0.2	A_τ	0.2	A_τ
$\mathcal{C}_{\ell e}^{[ii33]}$	-	-	0.4	2.	1.9	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$	1.9	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$\mathcal{C}_{\ell e}^{[i33i]}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{\ell e}^{[iijj]}$	-	-	0.5	3.8	3.8	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$	3.8	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$\mathcal{C}_{\ell u}^{[3333]}$	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	σ_{had}	2.3	σ_{had}
$\mathcal{C}_{\ell u}^{[i33i]}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{\ell u}^{[iijj]}$	-	-	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	$pp \to \mu\mu$
$\mathcal{C}_{\ell d}^{[i33i]}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{\ell d}^{[iijj]}$	-	-	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	σ_{had}	6.7	$B_s \to \mu\mu$
$\mathcal{C}_{eq}^{[i33i]}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{eq}^{[iijj]}$	-	-	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	0.7	1.6	1.6	4Q	2.1	$B_s \to \mu\mu$
$\mathcal{C}_{qu}^{(1)[i33i]}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{qu}^{(1)[iimm]}$	-	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	4Q	0.7	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qu}^{(8)[ii33]}$	0.3	0.7	0.2	1.2	1.2	4Q	1.2	4Q
$\mathcal{C}_{qu}^{(8)[i33i]}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{qu}^{(8)[iimm]}$	-	0.1	-	-	-	R_τ	0.1	C_9^{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	-	0.1	R_τ	0.3	$B_s \to \mu\mu$
$\mathcal{C}_{qd}^{(1)[i33i]}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{qd}^{(1)[iimm]}$	-	0.4	0.2	-	0.2	R_τ	0.4	$B_s \to \mu\mu$
$\mathcal{C}_{qd}^{(8)[3333]}$	-	-	-	0.2	0.2	4Q	0.2	4Q
$\mathcal{C}_{qd}^{(8)[ii33]}$	0.1	-	-	-	0.1	$B \to X_s\gamma$	-	$B \to X_s\gamma$
$\mathcal{C}_{qd}^{(8)[i33i]}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{qd}^{(8)[iimm]}$	-	-	-	-	-	R_τ	-	$\lvert C_{Bs}\rvert$

Bosonic 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.
$\mathcal{C}_H$	-	-	-	-	-	-	-	-
$\mathcal{C}_{H\Box}$	0.2	0.2	0.6	0.1	0.6	A_b^{FB}	0.6	A_b^{FB}
$\mathcal{C}_{HD}$	0.4	0.4	5.1	-	5.	A_b^{FB}	5.	A_b^{FB}
$\mathcal{C}_{HG}$	0.9	0.9	-	-	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}
$\mathcal{C}_{H\tilde{G}}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{H\tilde{B}}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{H\tilde{W}}$	-	-	-	-	-	-	-	-
$\mathcal{C}_{H\tilde{W}B}$	-	-	-	-	-	-	-	-
$\mathcal{C}_G$	1.1	1.1	0.1	-	1.1	$B \to X_s\gamma$	1.1	$B \to X_s\gamma$
$\mathcal{C}_{\tilde{G}}$	-	-	-	-	-	-	-	-
$\mathcal{C}_W$	0.3	0.3	0.9	-	0.9	A_b^{FB}	0.9	A_b^{FB}
$\mathcal{C}_{\tilde{W}}$	-	-	-	-	-	-	-	-

Anomalies in $b \to c$ semi-leptonics: R_D and R_{D*}



$$R_{D^{(*)}} = \frac{\mathscr{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathscr{B}(B \to D^{(*)}\ell\bar{\nu})}$$

$$[\ell = e, \mu]$$

2022 LHCb $\tau \to \mu$: first joint measurement of R_D & R_{D*} at a hadron collider. Only Run 1 data. [LHCb, 2302.02886]

New! 2023 LHCb $\tau \to$ had: R_{D*} with Run 1 + partial Run 2 data. Hadronic taus.

- Theoretically clean. Measurements by Babar, Belle, LHCb in good agreement.
- Enhancement of $\sim 10\,\%$ over SM due to excess in tau mode: $B \to D^{(*)}\tau\bar{\nu}_\tau$.
- Combined, $3.2\,\sigma$ tension w.r.t SM. Measurement of $R_{\Lambda_c}/R_{\Lambda_c}^{\rm SM} = 0.73 \pm 0.23$ reduces tension slightly. [LHCb, 2201.03497]