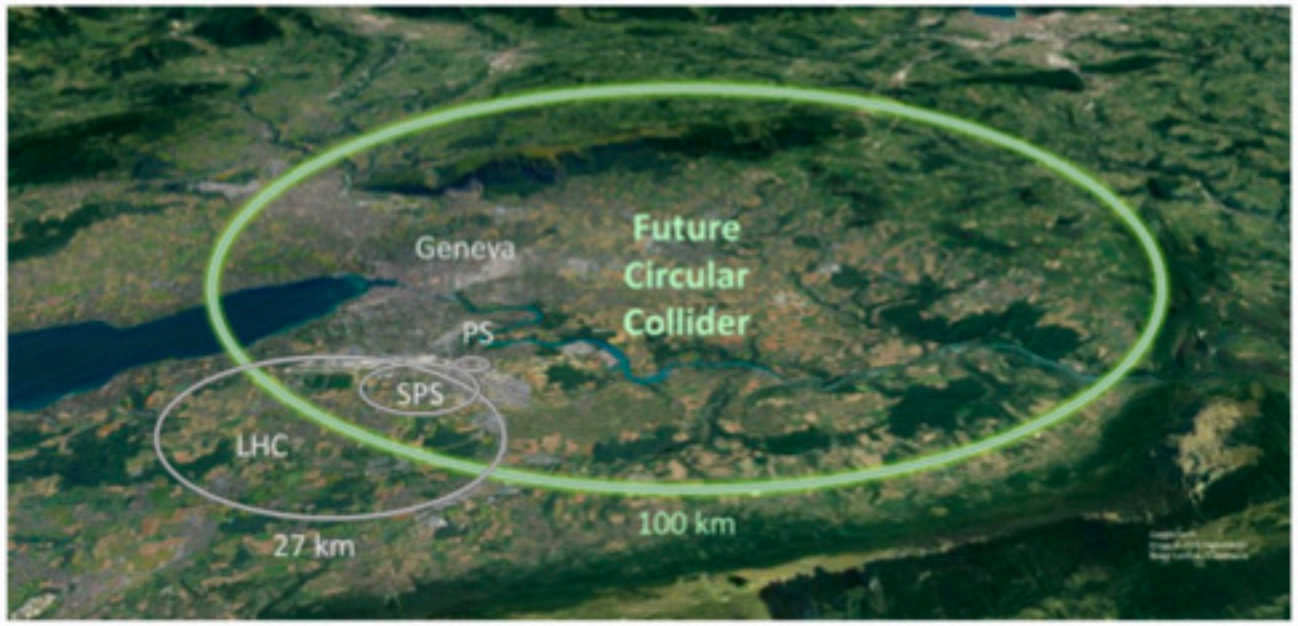
Flavour, Colliders, and the *Z*-pole: Opportunities for probing new physics at FCC-ee

Ben A. Stefanek
King's College London
Theoretical Particle Physics
& Cosmology (TPPC) Group



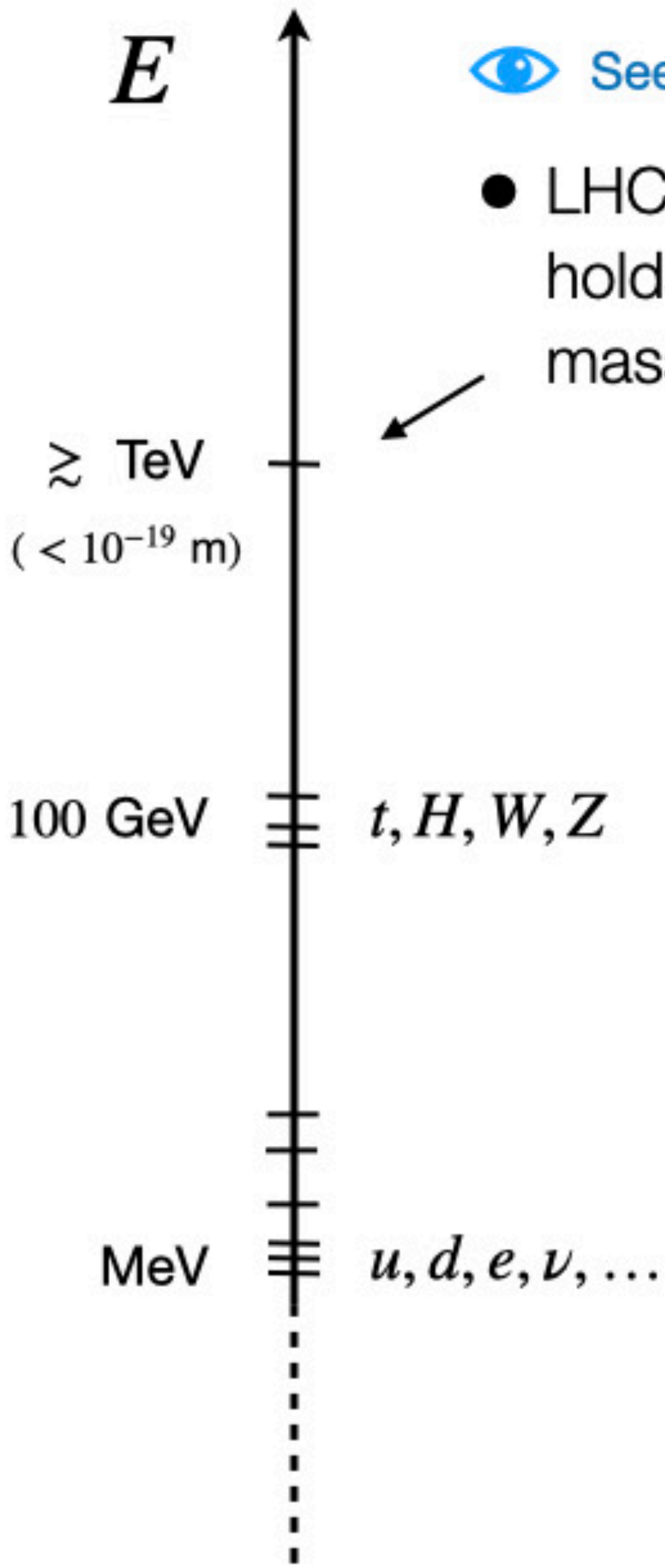
[Based on: Allwicher, Cornella, Isidori, BAS, 2311.00020]

7th FCC Physics Workshop
LAPP Annecy
January 30th, 2024

Searching for New Physics (NP) beyond the SM

See Joe Davighi's talk

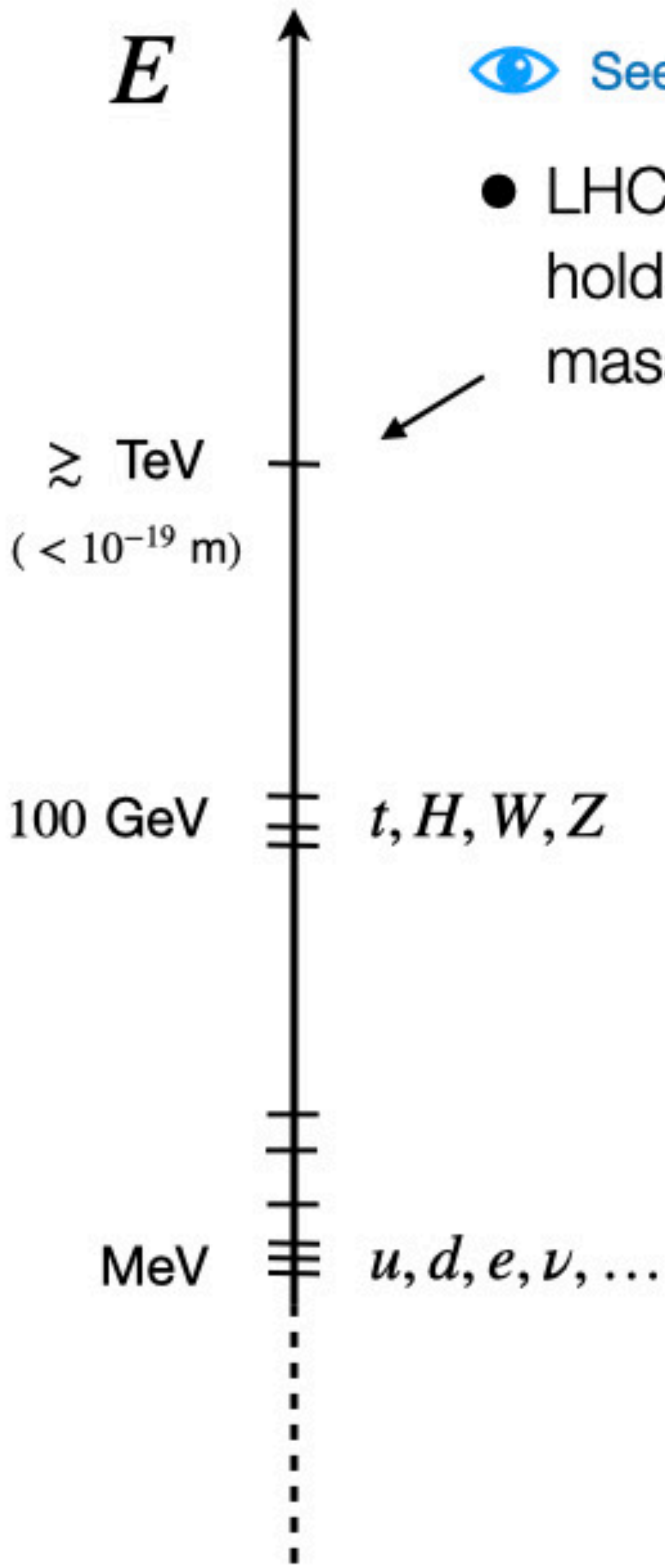
- LHC data tells us that the SM holds at least to here. Facing a mass gap, but not for the first time!

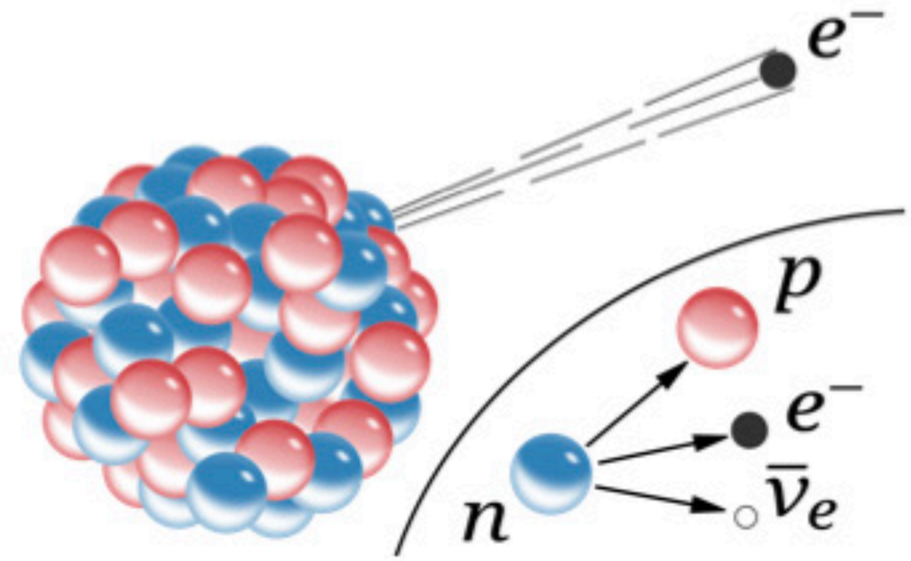


Searching for New Physics (NP) beyond the SM

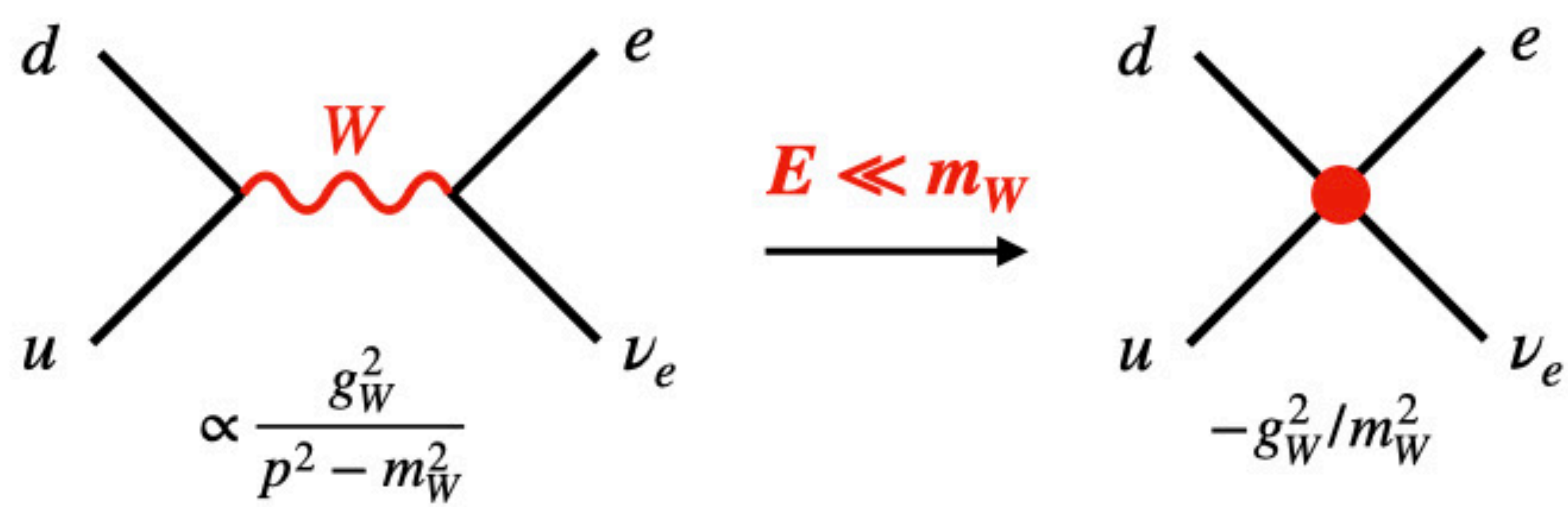
See Joe Davighi's talk

- LHC data tells us that the SM holds at least to here. Facing a mass gap, but not for the first time!

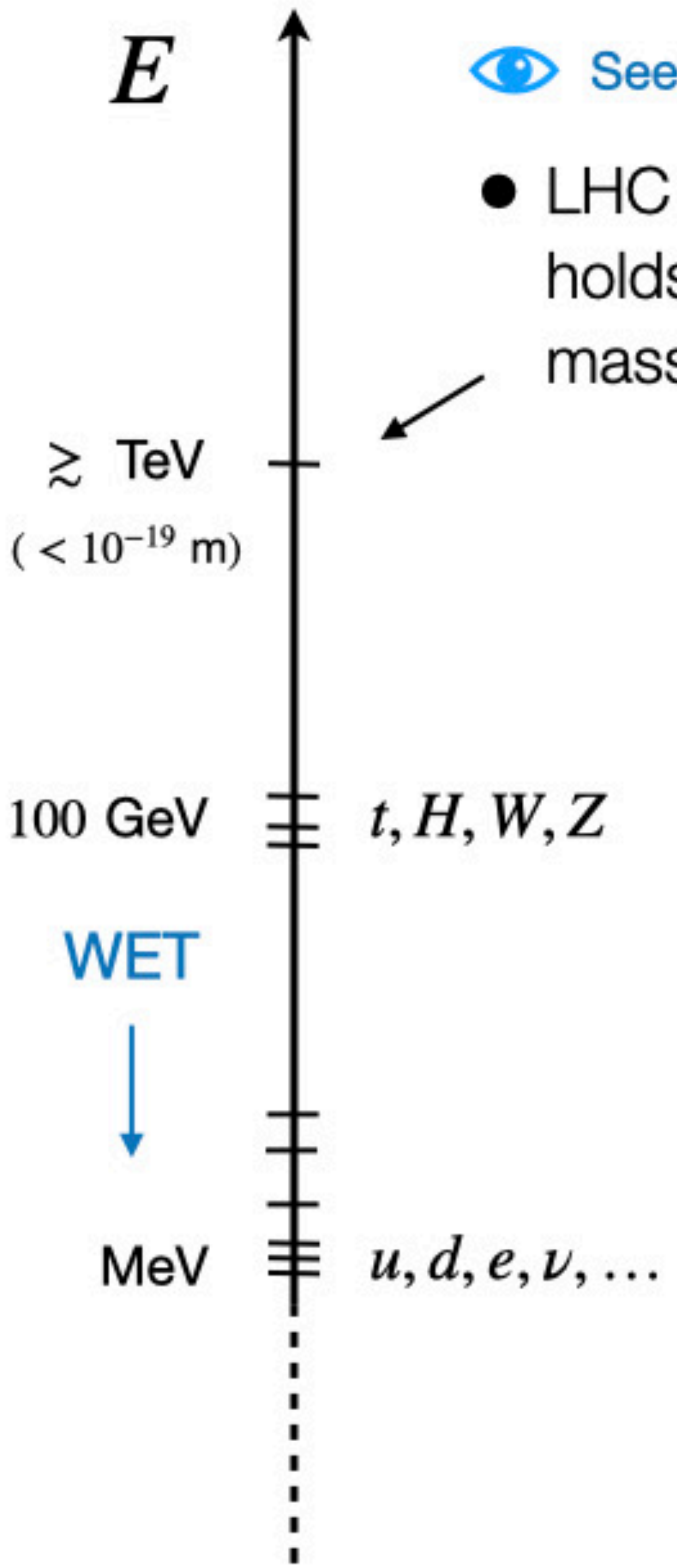




Fermi Theory [$E \ll m_W$]

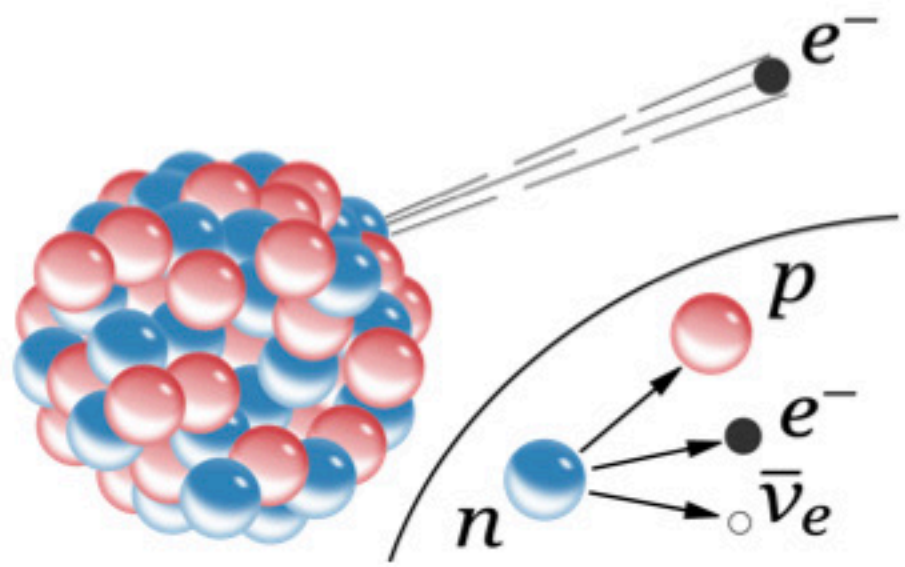


Searching for New Physics (NP) beyond the SM

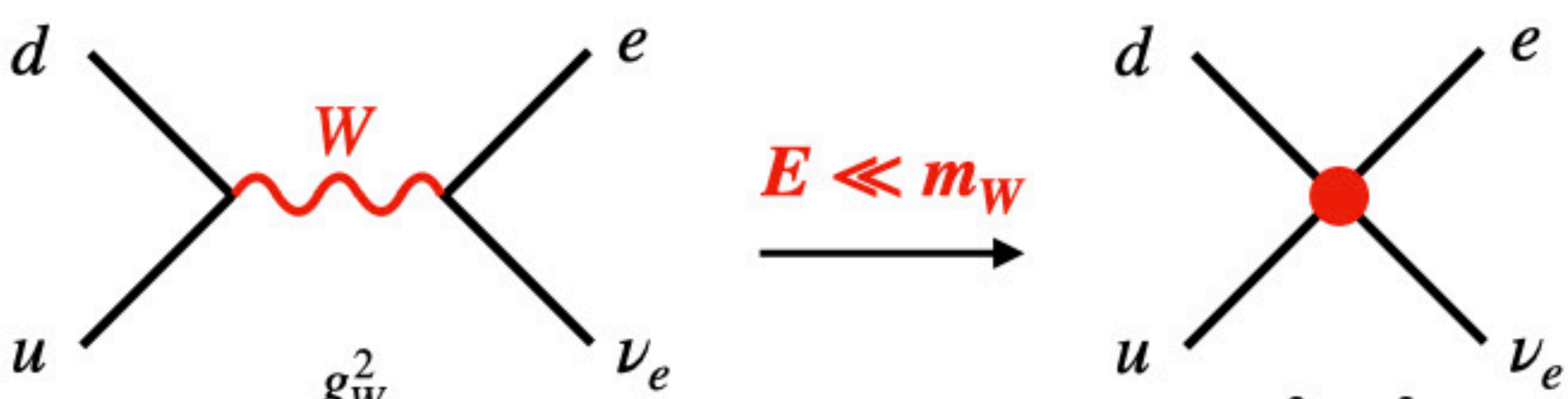


See Joe Davighi's talk

- LHC data tells us that the SM holds at least to here. Facing a mass gap, but not for the first time!



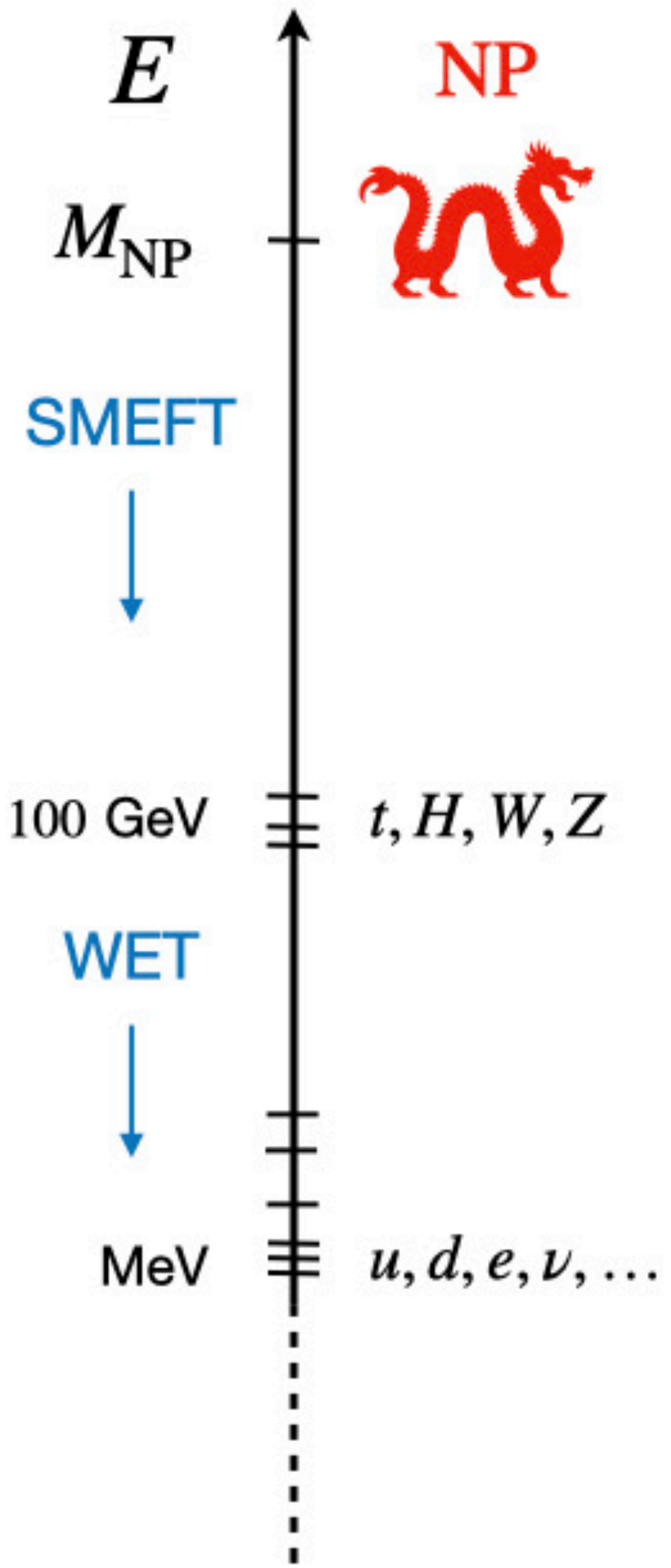
Fermi Theory [$E \ll m_W$]



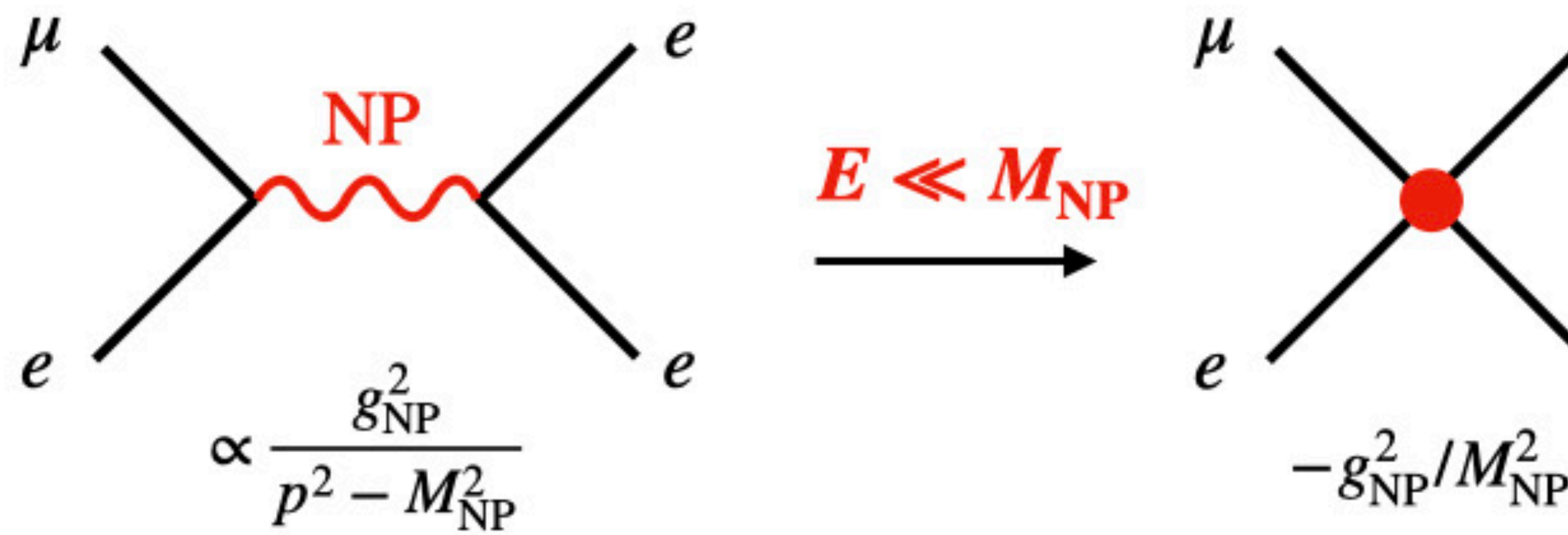
$\propto \dfrac{g_W^2}{p^2 - m_W^2}$ $\qquad$ $-g_W^2/m_W^2$

$$\mathscr{L}_{\text{WET}} = \mathscr{L}_{\text{QED}} + \mathscr{L}_{\text{QCD}} - \frac{g_W^2}{m_W^2}(\bar{u}_L \gamma_\mu d_L)(\bar{e}_L \gamma^\mu \nu_L) + \ldots$$

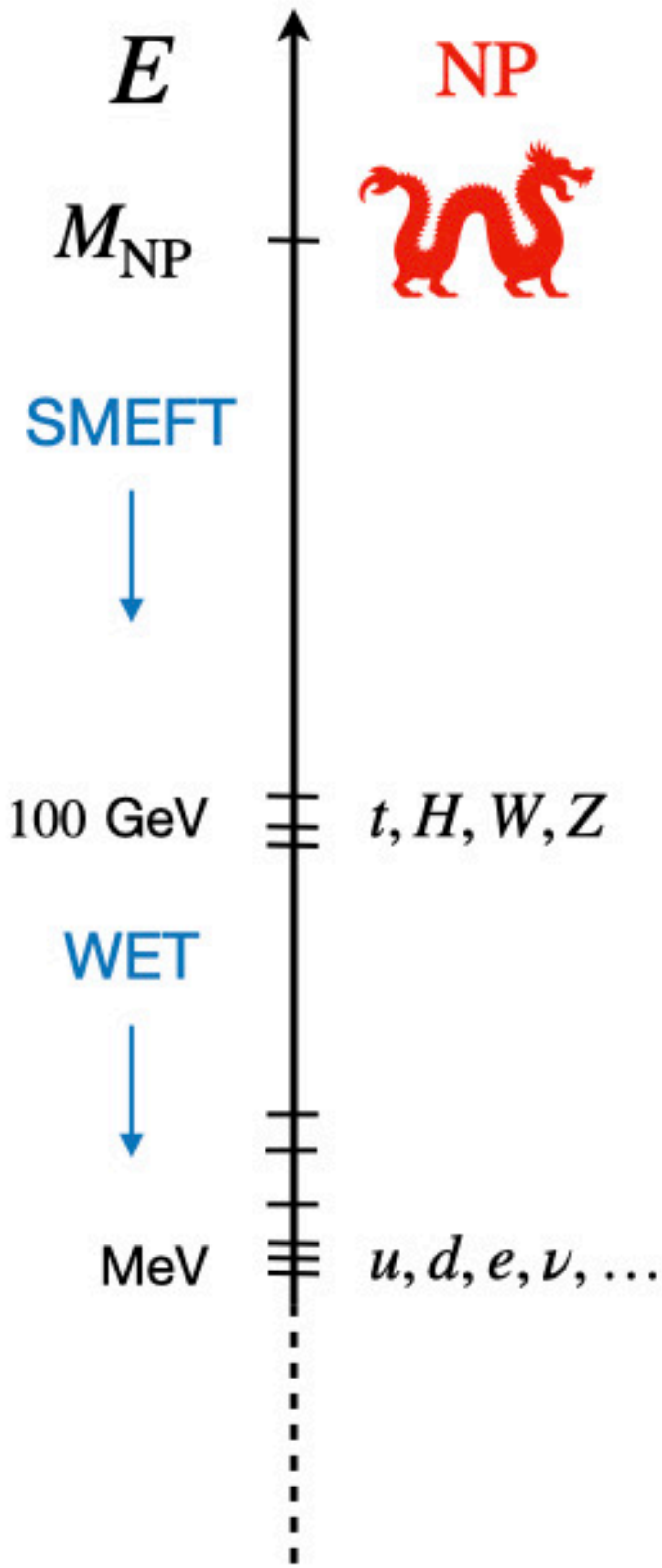
The SM as an Effective Field Theory



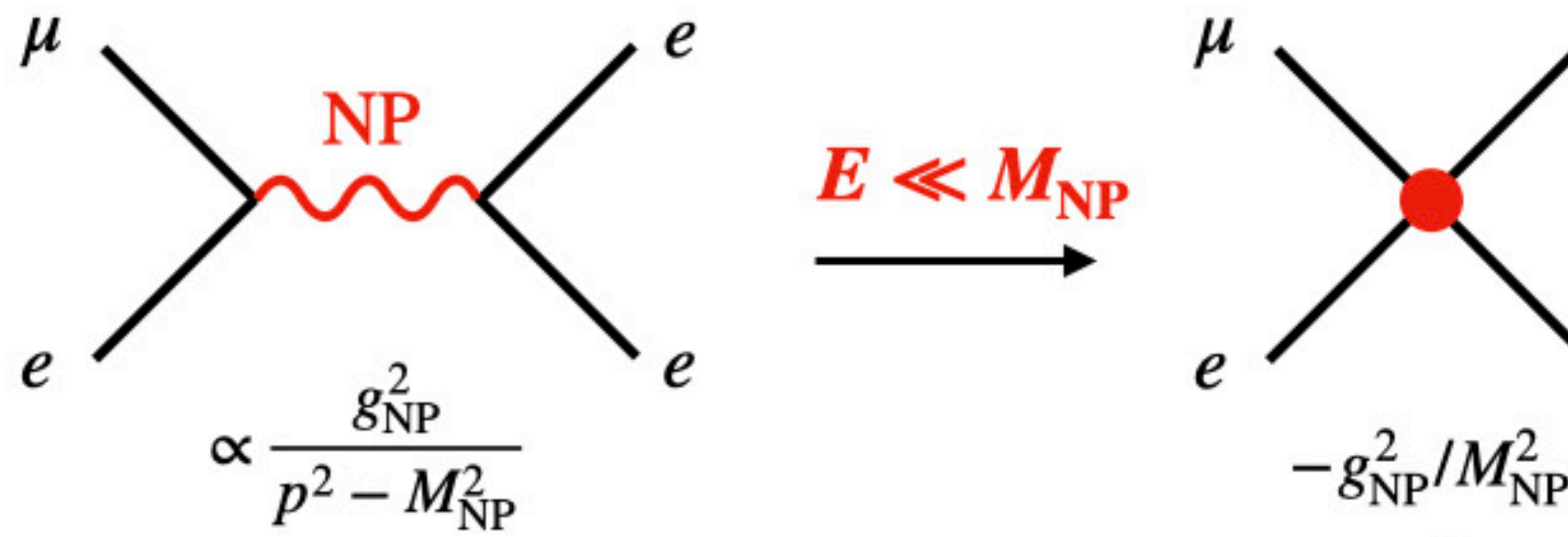
- The same can be done for the SM! Indeed, the modern view of the SM is that it is yet another effective field theory.



The SM as an Effective Field Theory

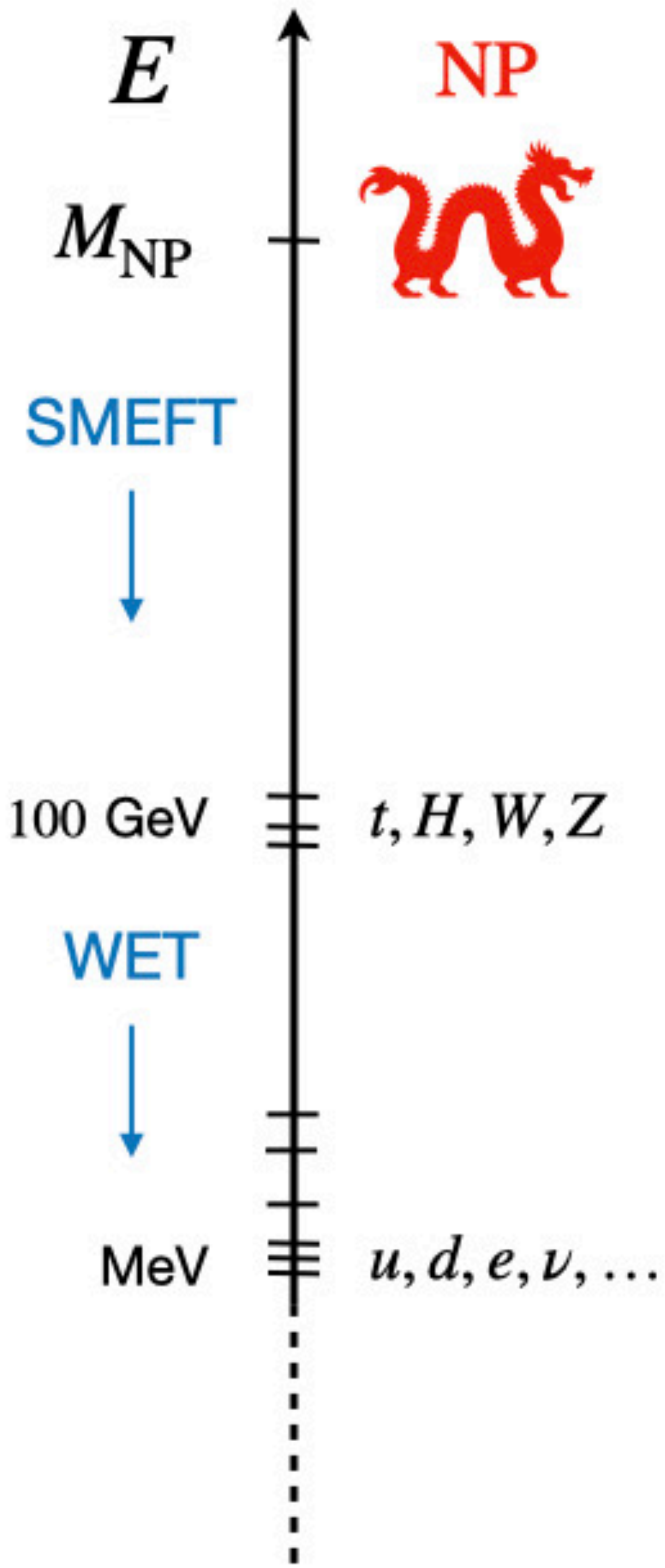


- The same can be done for the SM! Indeed, the modern view of the SM is that it is yet another effective field theory.

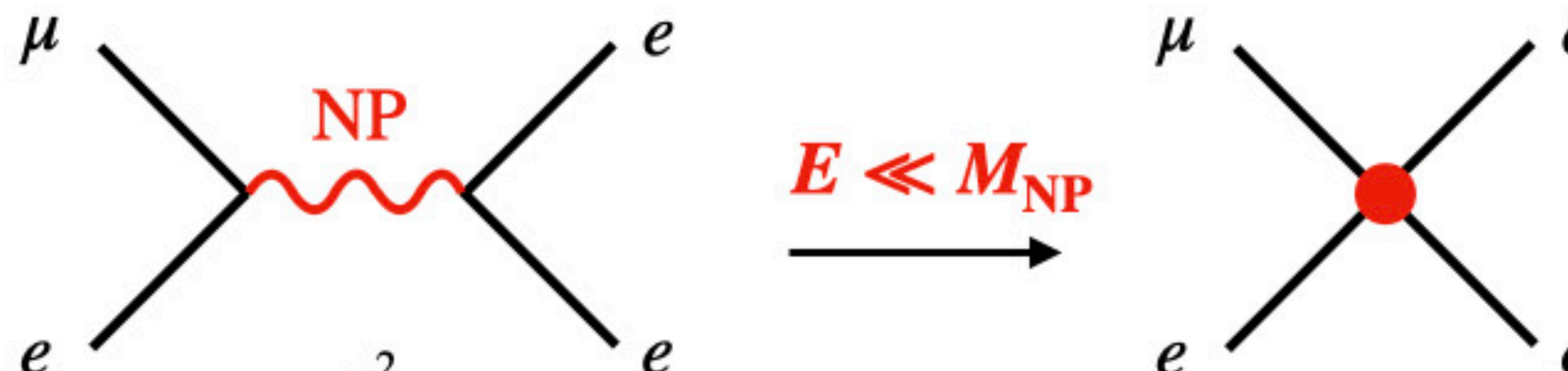


$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \frac{C_\nu}{\Lambda_\nu}(\bar{l}\tilde{H})(\tilde{H}^T l^c) + \sum_i \frac{C_i}{M_{\rm NP}^2}\mathcal{O}_i + \dots$$

The SM as an Effective Field Theory



- The same can be done for the SM! Indeed, the modern view of the SM is that it is yet another effective field theory.



$$\propto \frac{g_{\rm NP}^2}{p^2 - M_{\rm NP}^2} \qquad -g_{\rm NP}^2/M_{\rm NP}^2$$

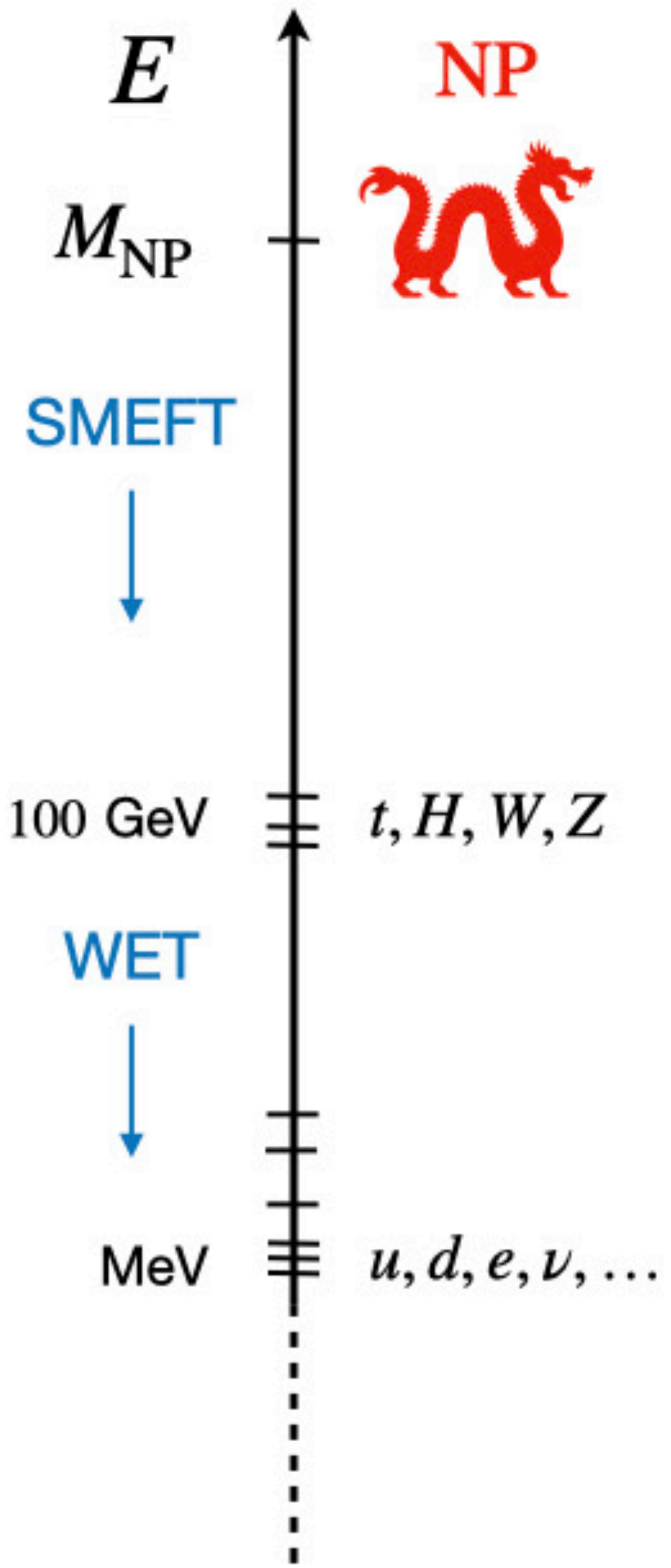
$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \frac{C_\nu}{\Lambda_\nu}(\bar{l}\tilde{H})(\tilde{H}^T l^c) + \sum_i \frac{C_i}{M_{\rm NP}^2}\mathcal{O}_i + \dots$$

Neutrino masses!

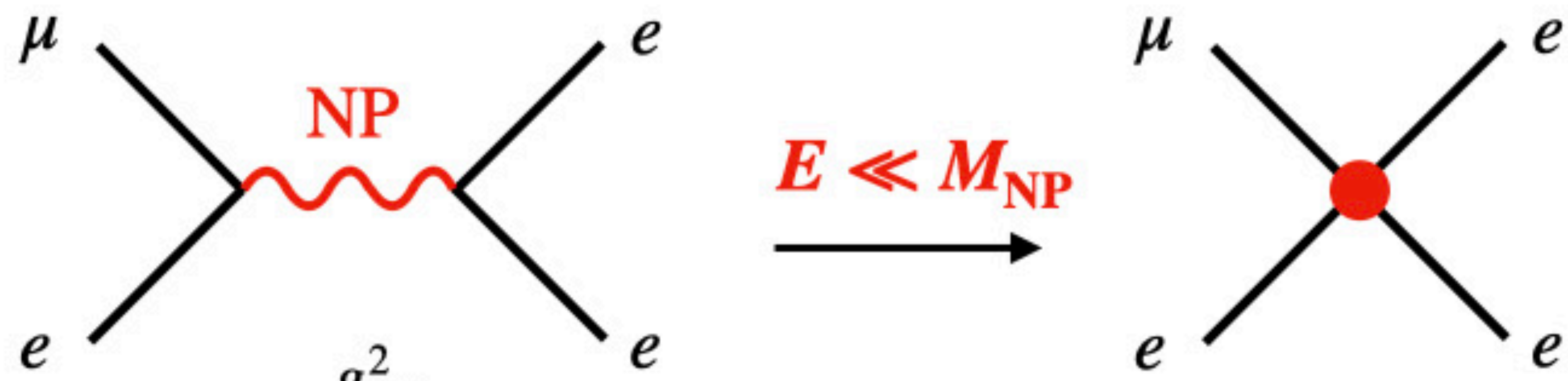
$(\Lambda_\nu \gg 100\ \text{GeV})$

[Weinberg, 1979]

The SM as an Effective Field Theory



- The same can be done for the SM! Indeed, the modern view of the SM is that it is yet another effective field theory.



$$\propto \frac{g_{\text{NP}}^2}{p^2 - M_{\text{NP}}^2} \qquad -g_{\text{NP}}^2/M_{\text{NP}}^2$$

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \frac{C_\nu}{\Lambda_\nu}(\bar{l}\tilde{H})(\tilde{H}^T l^c) + \sum_i \frac{C_i}{M_{\text{NP}}^2}\mathscr{O}_i + \ldots$$

Neutrino masses!

($\Lambda_\nu \gg 100$ GeV)

[Weinberg, 1979]

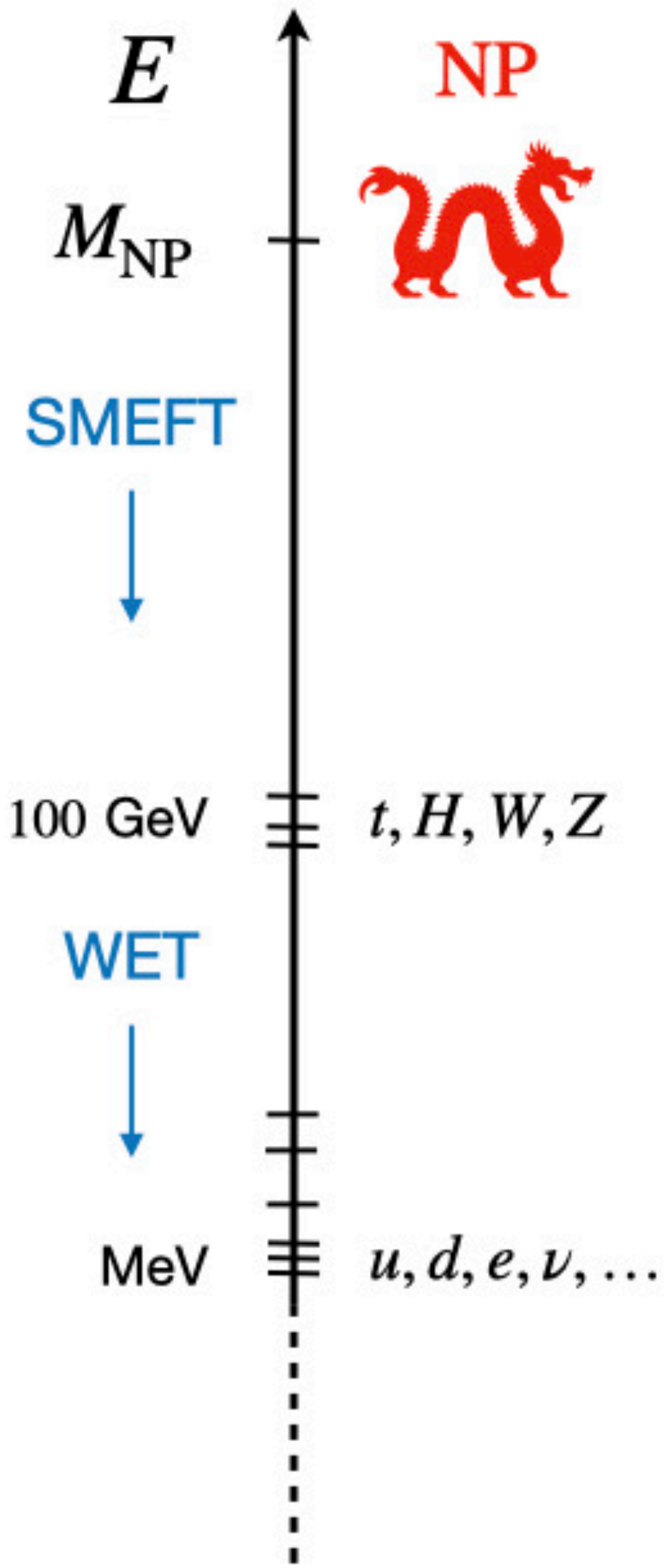
59 possible operators $\mathscr{O}_i$,

($\rightarrow$ 2499 including 3 flavors!)

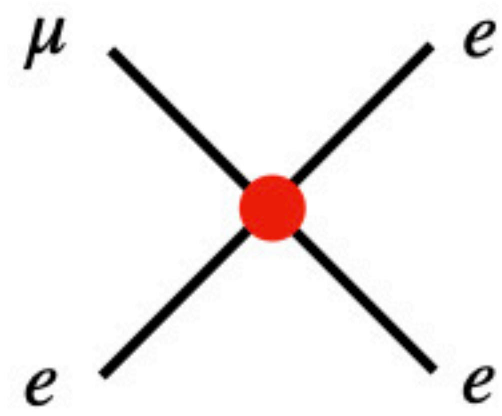
[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

The Flavor of the SMEFT

$\mathscr{L}_{\rm SMEFT} \supset C_{ll}^{ijkl}\,(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$



$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_i \frac{C_i}{M_{\rm NP}^2}\mathscr{O}_i + \ldots$$



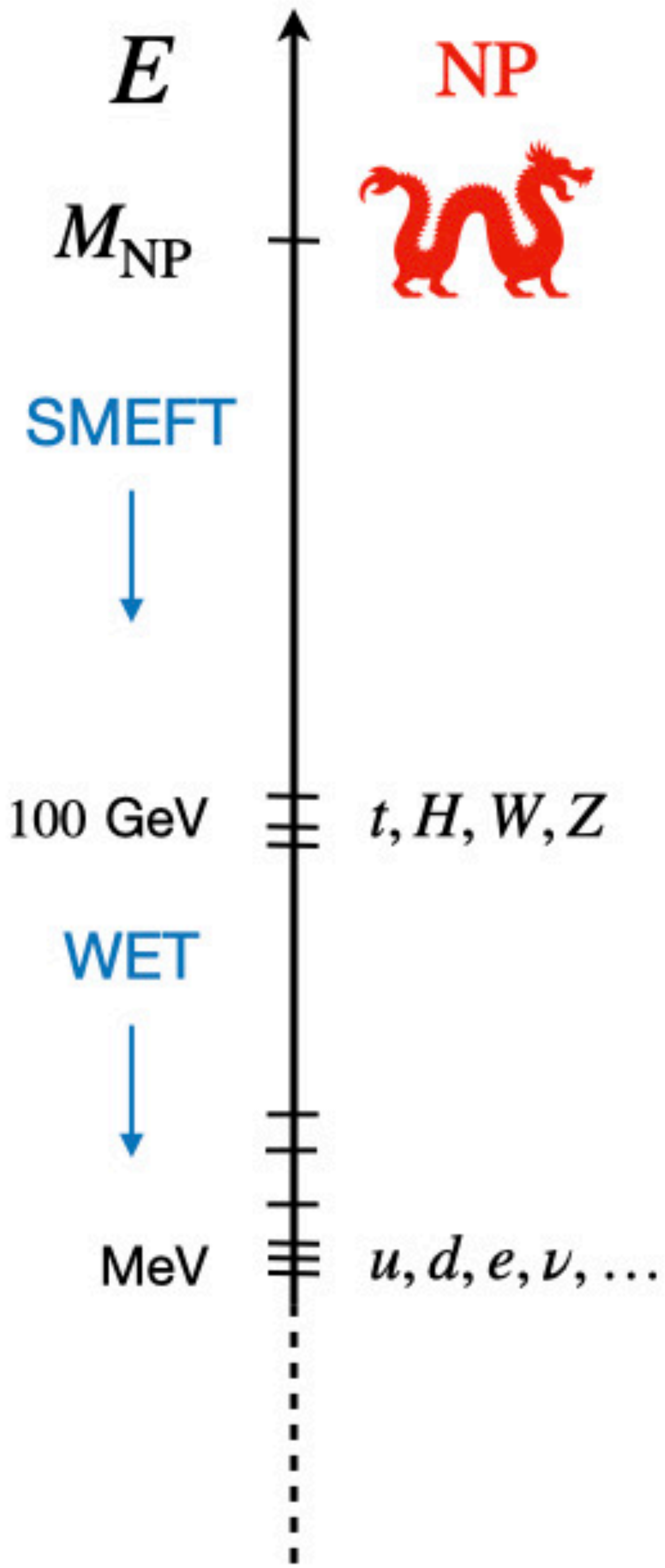
59 possible operators $\mathscr{O}_i$,
(→ 2499 including 3 flavors!)

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

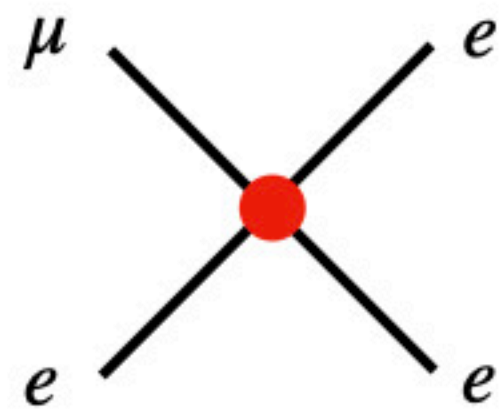
- Flavor of C_i is very important in the search for NP- if all flavors populated with O(1) couplings, processes like $\mu \to 3e$ require a very high NP scale $M_{\rm NP} \gtrsim 1000$ TeV.

The Flavor of the SMEFT

$\mathscr{L}_{\text{SMEFT}} \supset C_{ll}^{ijkl}\,(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$



$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{C_i}{M_{\text{NP}}^2}\mathscr{O}_i + \dots$$



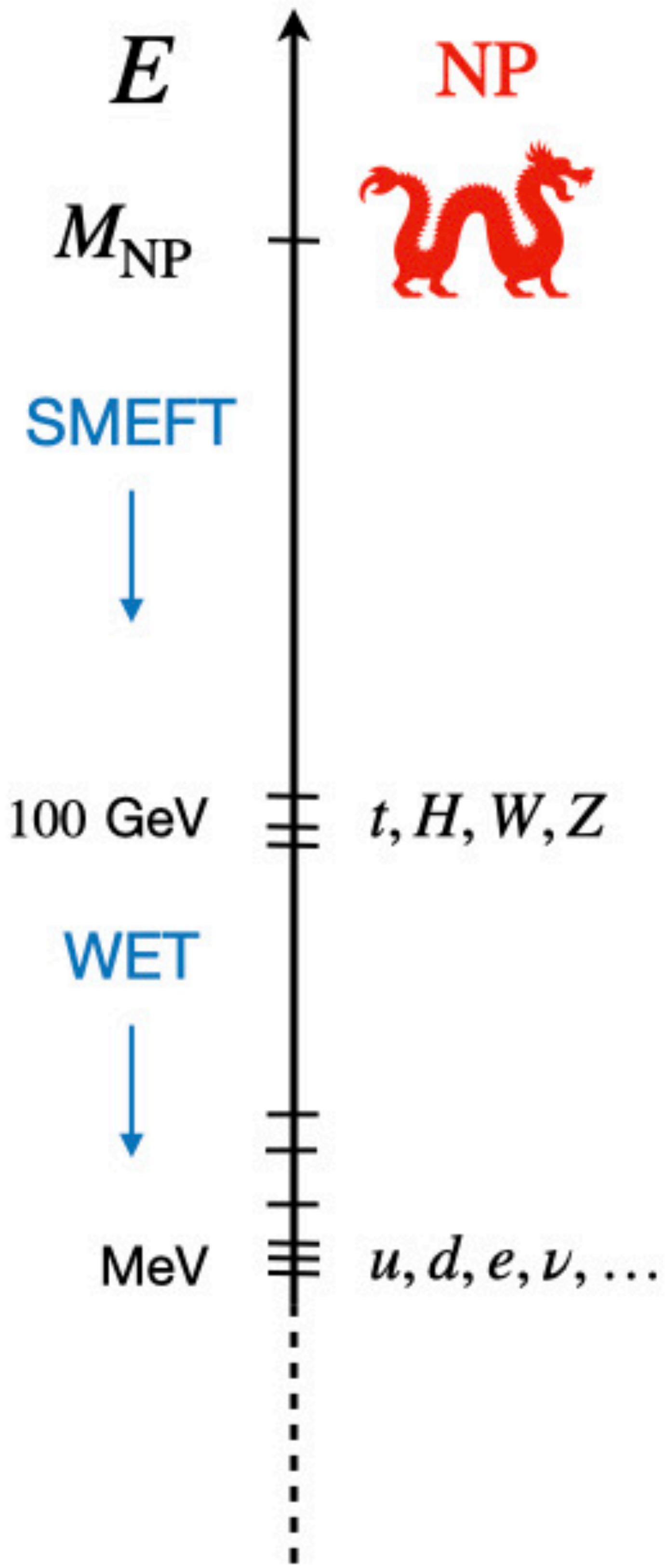
59 possible operators $\mathscr{O}_i$,
(→ 2499 including 3 flavors!)

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

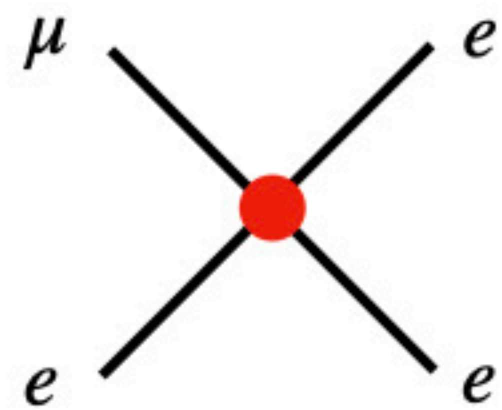
- Flavor of C_i is very important in the search for NP- if all flavors populated with O(1) couplings, processes like $\mu \to 3e$ require a very high NP scale $M_{\text{NP}} \gtrsim 1000$ TeV.
- Why? This process is zero in the SM- individual lepton number conservation is an accidental symmetry of the SM.

The Flavor of the SMEFT

$\mathscr{L}_{\text{SMEFT}} \supset C_{ll}^{ijkl}\, (\bar{l}_i \gamma_\mu l_j)(\bar{l}_k \gamma^\mu l_l)$



$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{C_i}{M_{\text{NP}}^2}\mathscr{O}_i + \ldots$$



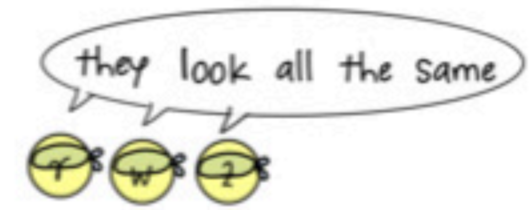
59 possible operators $\mathscr{O}_i$,
(→ 2499 including 3 flavors!)

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

- Flavor of C_i is very important in the search for NP- if all flavors populated with O(1) couplings, processes like $\mu \to 3e$ require a very high NP scale $M_{\text{NP}} \gtrsim 1000$ TeV.
- Why? This process is zero in the SM- individual lepton number conservation is an accidental symmetry of the SM.
- Any NP close by in energy cannot have an arbitrary flavor structure. Can we use the accidental symmetries of the SM as a guiding principle for flavor structure in the SMEFT?

Hints of NP structure: Flavor symmetries of the SM

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



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

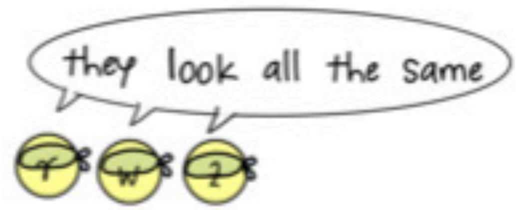
Turn on Yukawas

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

$$\mathscr{G}_F(\text{SM}) = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

Hints of NP structure: Flavor symmetries of the SM

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



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

Turn on Yukawas

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

$$\mathscr{G}_F(\text{SM}) = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

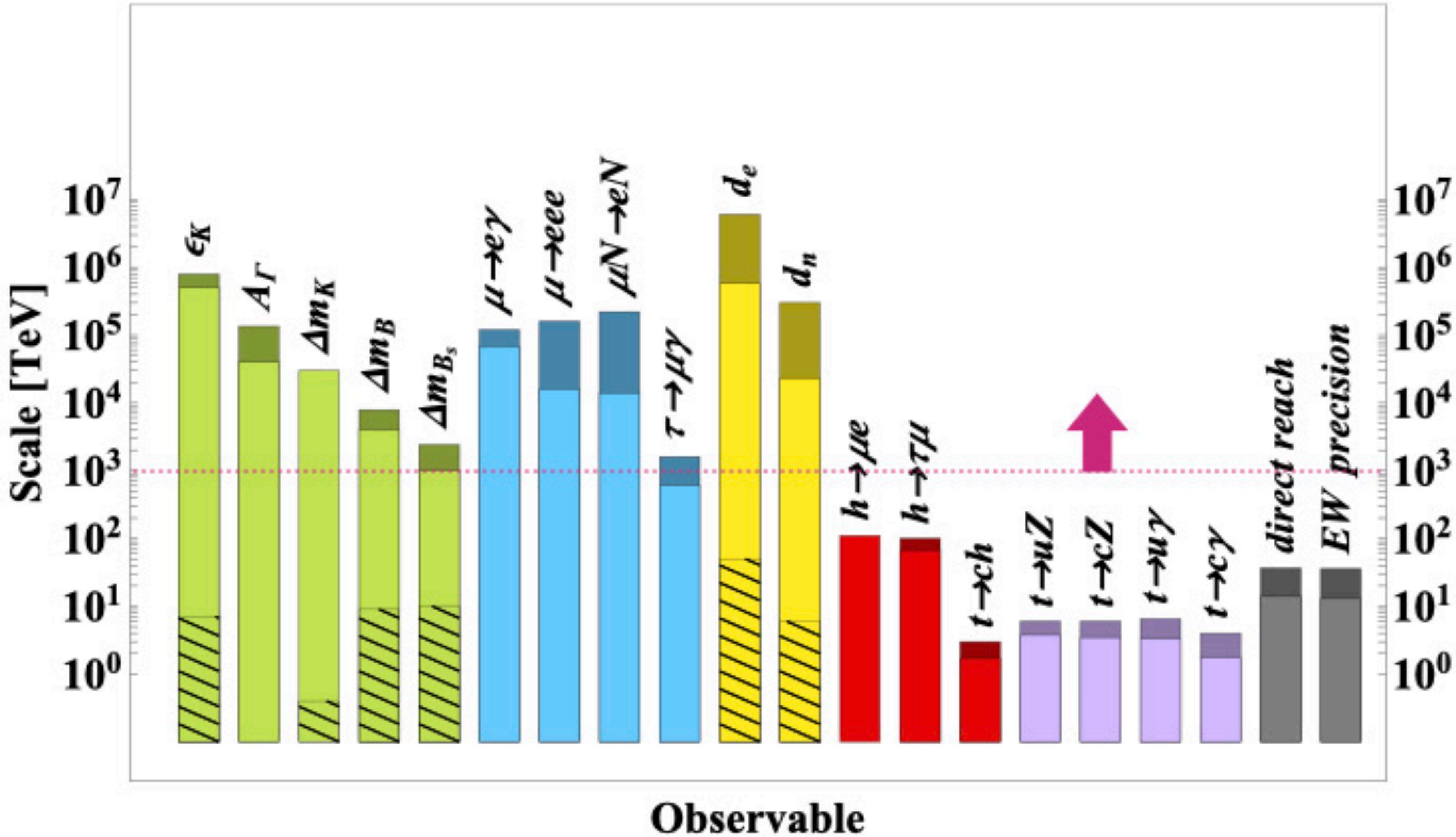
- But, since the light family Yukawa couplings are very small:

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

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

[Physics Briefing Book 2020, 1910.11775]

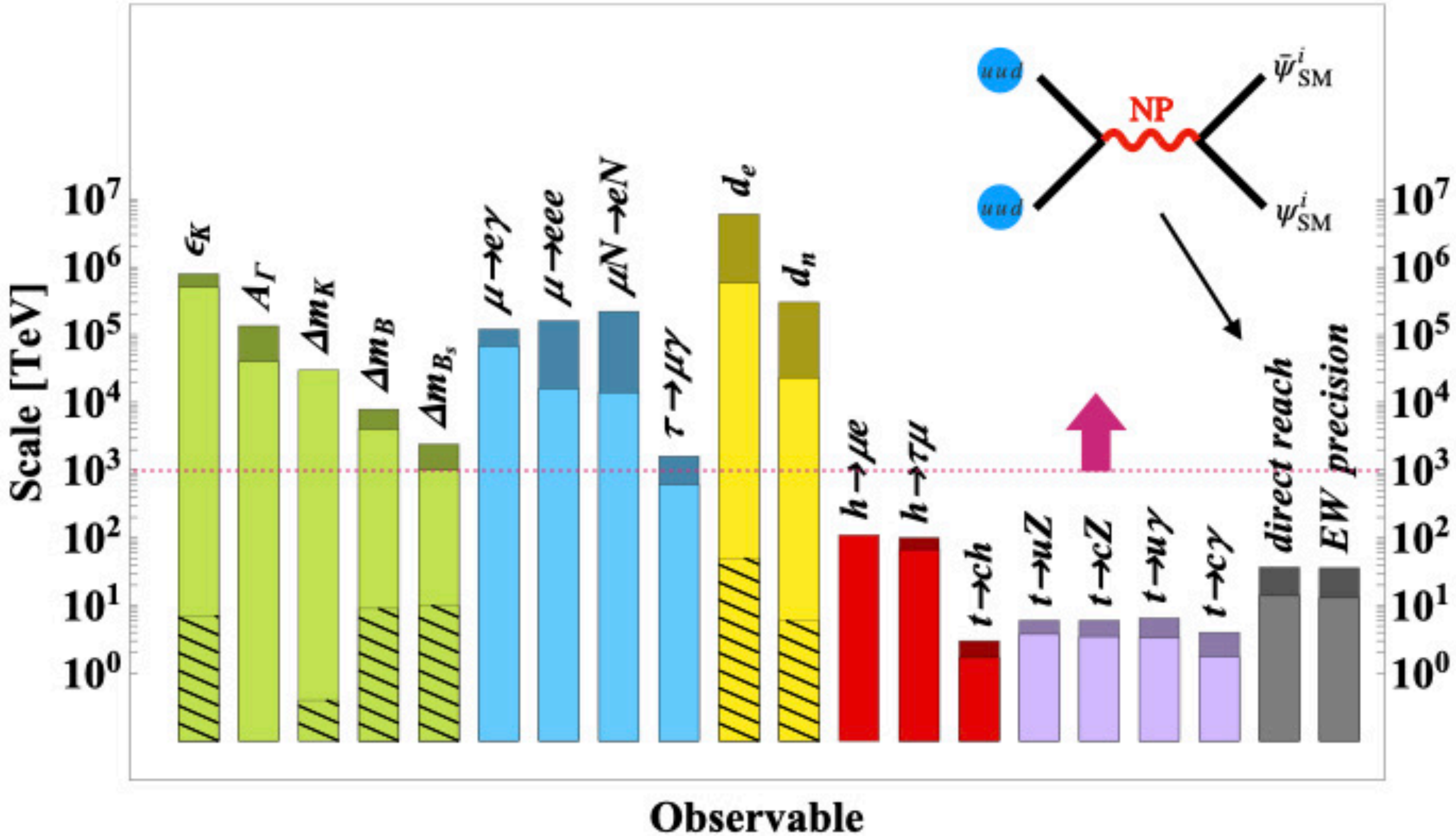
Hints of NP structure: Data



- No deviations in ***flavor data*** that test the accidental symmetries of the SM. Perhaps NP is very heavy, but there cannot be any large breaking of $U(2)^5$ at nearby energy scales.

[Physics Briefing Book 2020, 1910.11775]

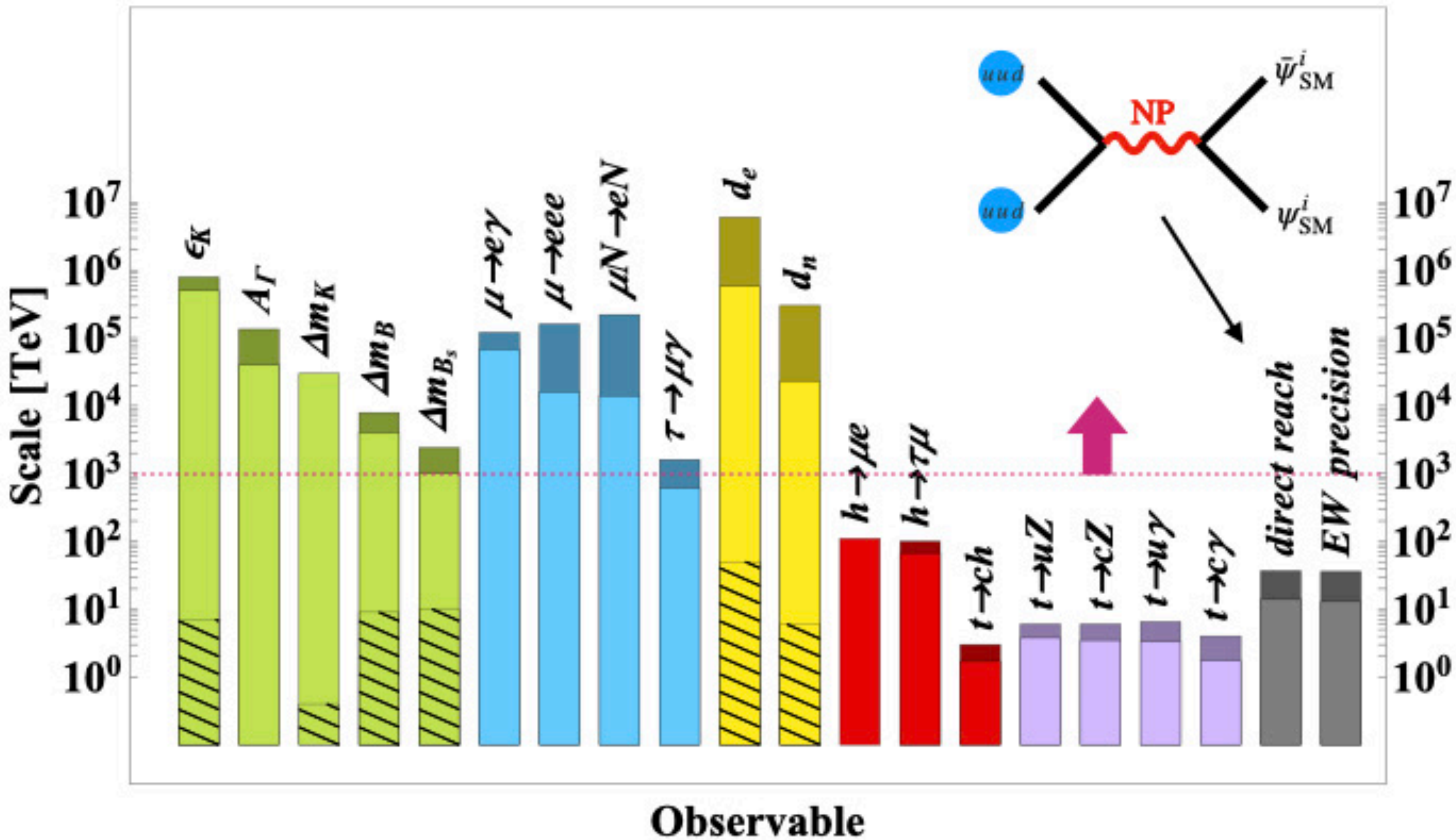
Hints of NP structure: Data



- No deviations in ***flavor data*** that test the accidental symmetries of the SM. Perhaps NP is very heavy, but there cannot be any large breaking of $U(2)^5$ at nearby energy scales.
- Similarly, ***direct searches at the LHC*** tell us that NP does not couple strongly to valence quarks at nearby energy scales.

Hints of NP structure: Data

[Physics Briefing Book 2020, 1910.11775]



- No deviations in ***flavor data*** that test the accidental symmetries of the SM. Perhaps NP is very heavy, but there cannot be any large breaking of $U(2)^5$ at nearby energy scales.
- 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

- New physics is **NOT** flavor universal- there could be new flavor non-universal interactions as low as 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]

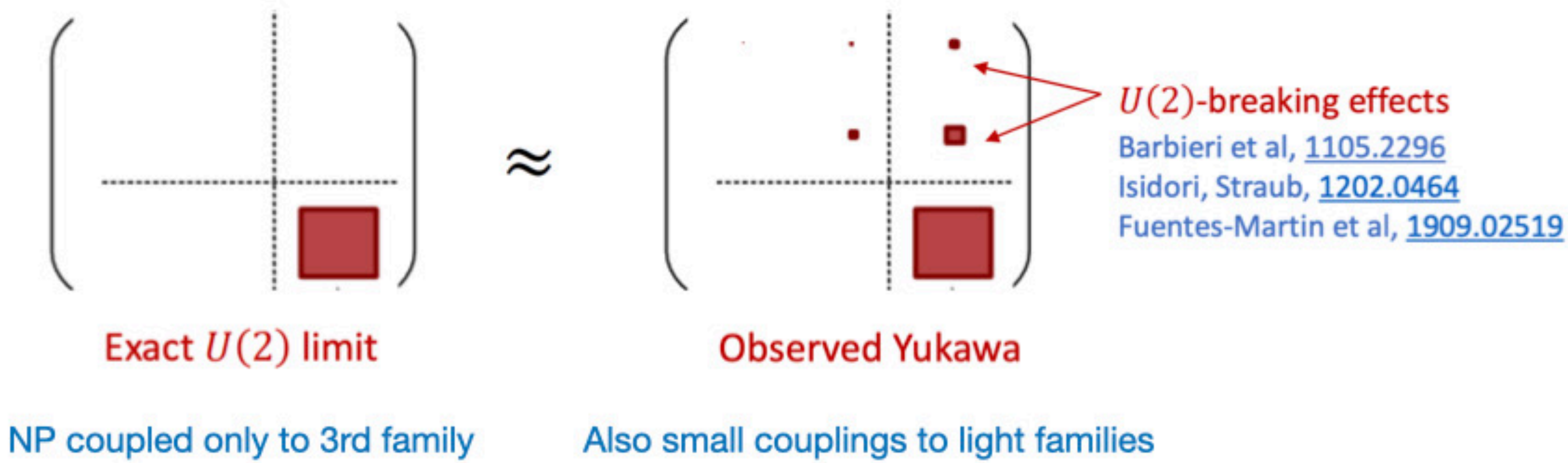
The hypothesis of (dominantly) third-family NP

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

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

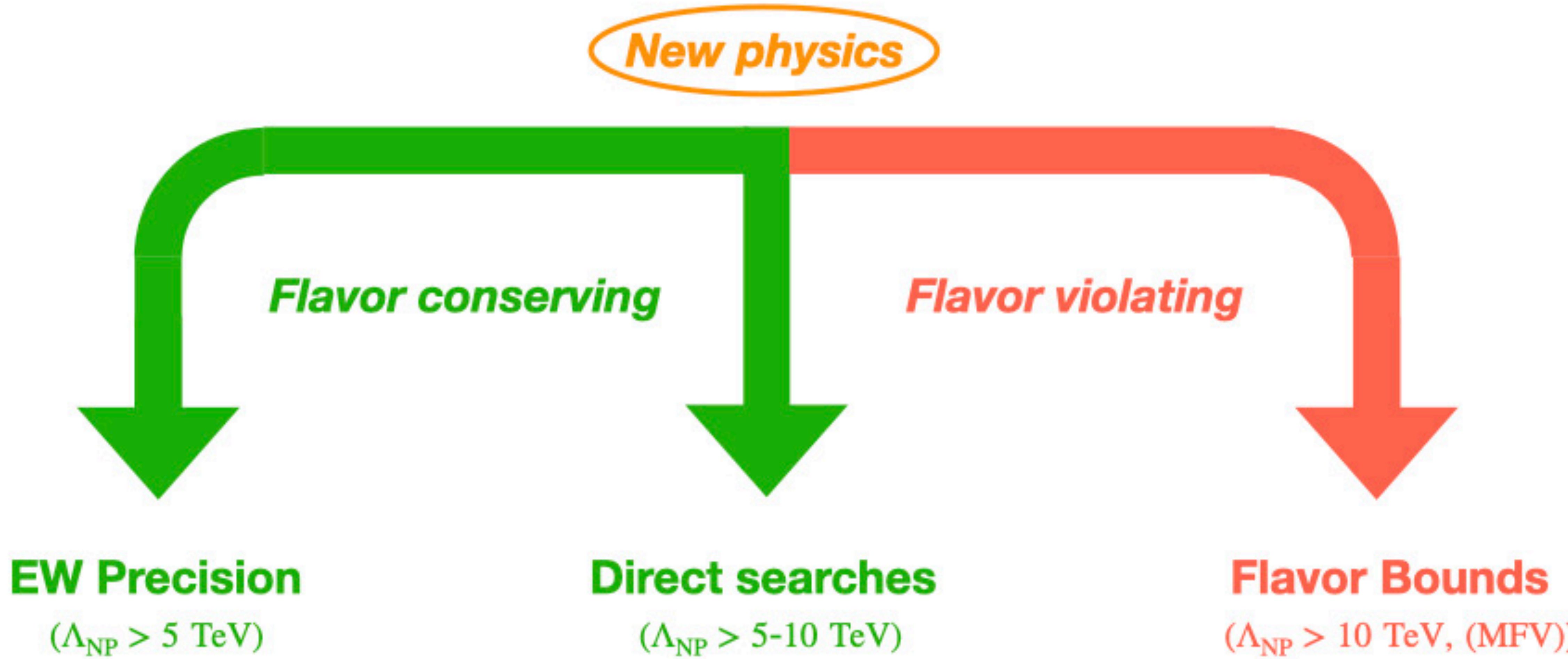
The hypothesis of (dominantly) third-family NP

- New physics is **NOT** flavor universal- there could be new flavor non-universal interactions as low as the TeV scale coupled dominantly to the third family. NP coupled to Higgs & top is what we need to address the EW hierarchy problem.
- 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 is described by an approximate $U(2)^5$ flavor symmetry, just like the SM Yukawa couplings.

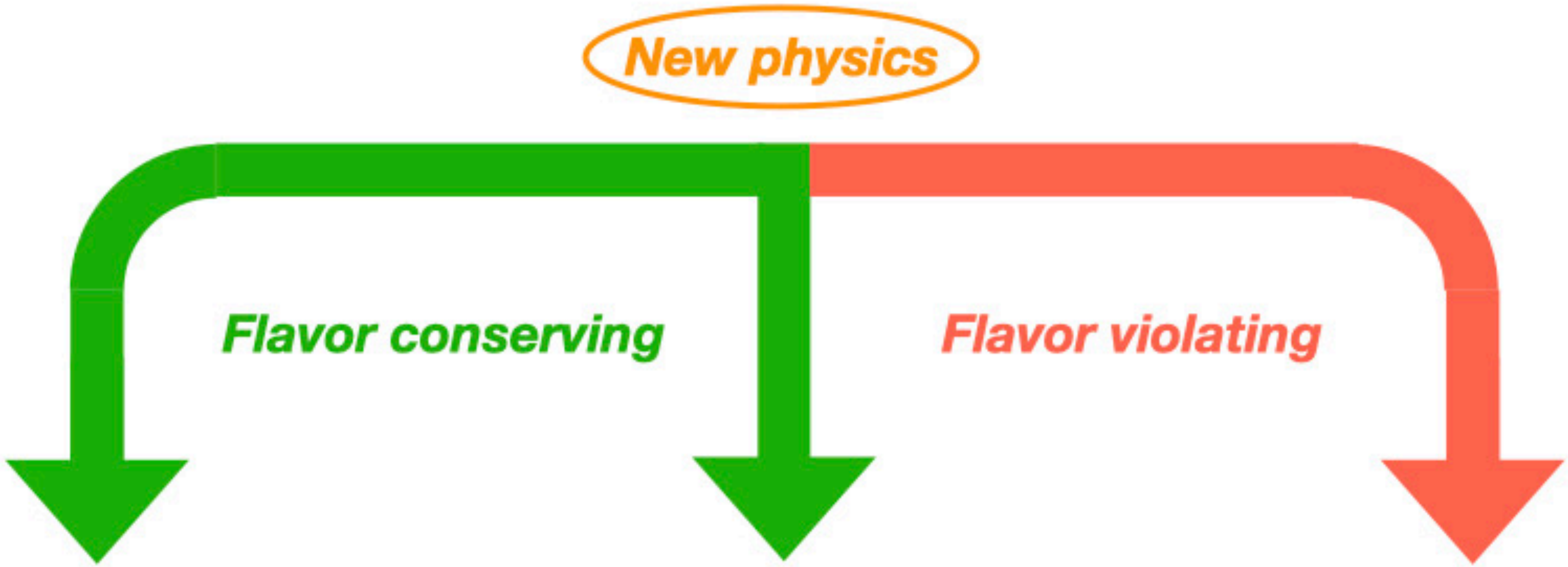


[R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone, D. Straub, 1105.2296]

Combining data: NP must confront a triad of bounds



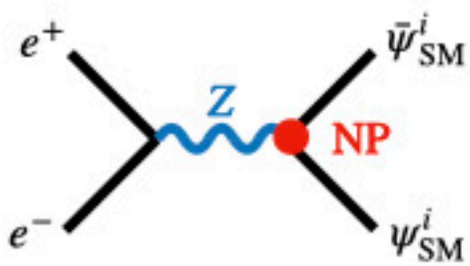
Combining data: NP must confront a triad of bounds



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

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

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

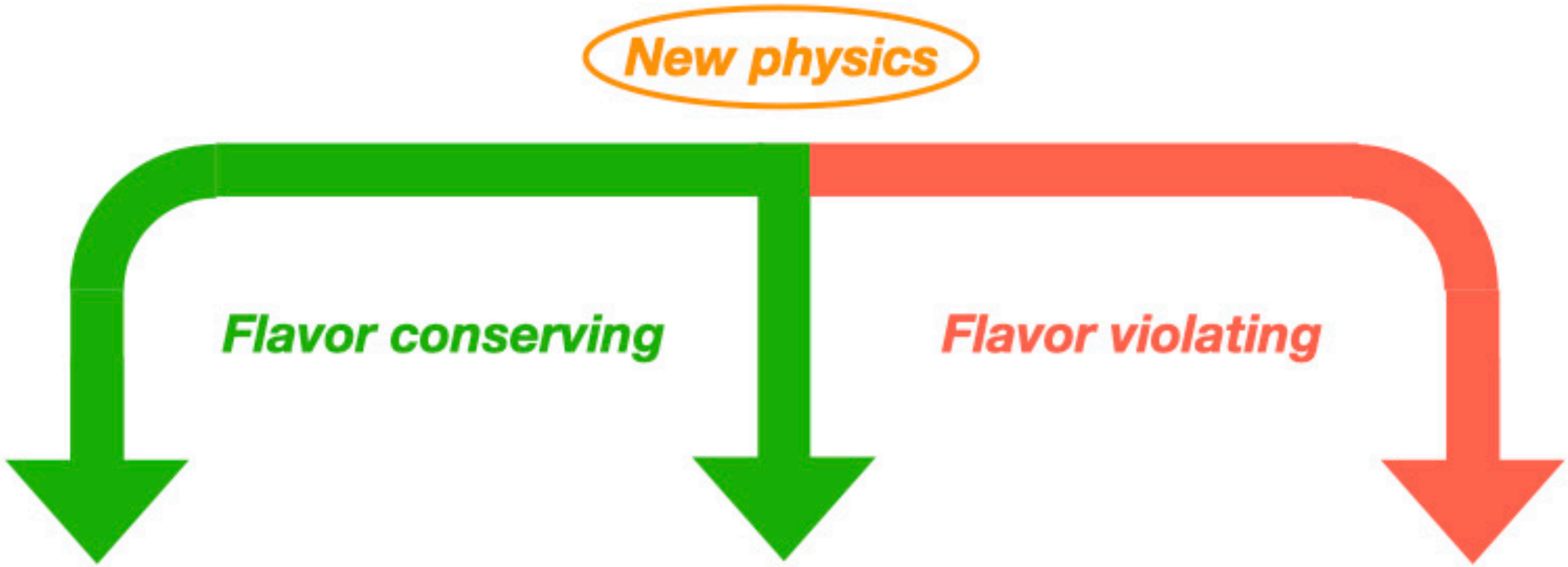


$U(2)$ can help

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

**For NP opportunities from flavor-violating Z decays, see the Thursday morning session.*

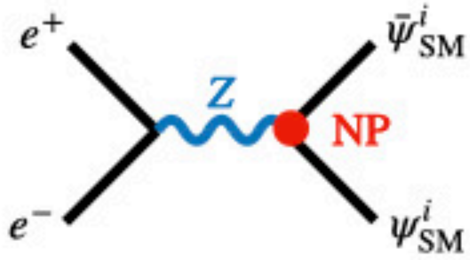
Combining data: NP must confront a triad of bounds



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

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

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



$U(2)$ can help

- 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	$U(2)^5$ [terms summed up to different orders] Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1V^1)$		$\mathcal{O}(V^3,\Delta^1V^1)$	
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]

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.

- 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]

Combined pheno analysis: Our procedure

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

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

```
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] -
 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] +...
```

Combined 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] -
 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] +...
```

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

Combined pheno analysis: Our procedure

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

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

```
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] -
 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] +...
```

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

- 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.

Combined pheno analysis: Our procedure

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

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

```
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] +...
```

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

- 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.

Combined 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]

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 the Z-pole

- 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

Bounds from the Z-pole

- 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

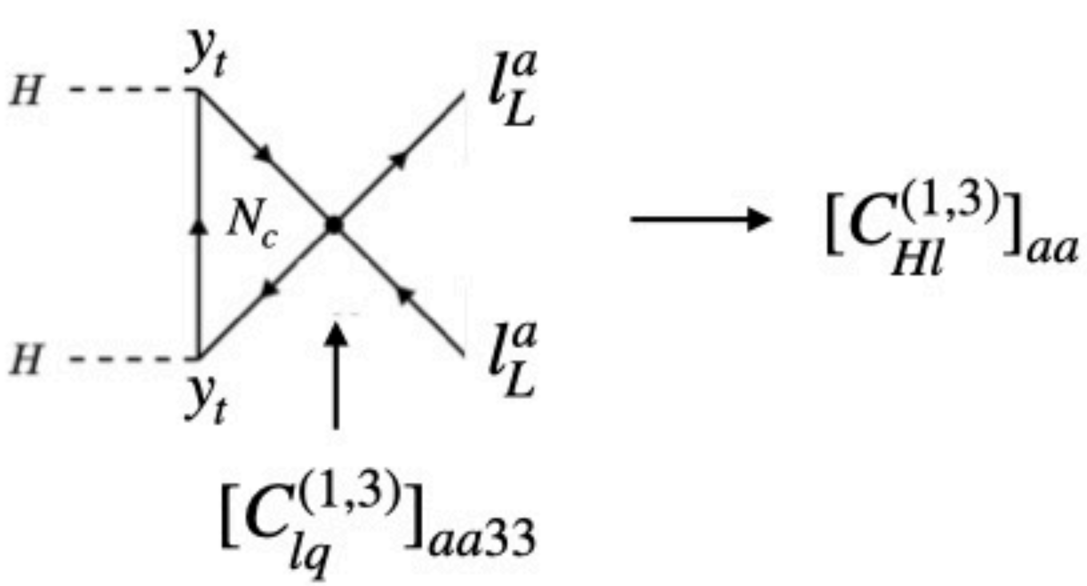
#	Wilson Coef.	$[\mathrm{Obs}]_{\mathrm{bound}}$	Λ_{bound} [TeV]
1	cHWB	A_b^{FB}	9.63
2	CHl1[l]	σ_{had}	8.07
3	CHl3[l]	A_b^{FB}	7.96
4	CHe[l]	σ_{had}	6.93
5	cHD	A_b^{FB}	5.74
6	CHq3[l]	R_τ	5.73
7	CHl1[h]	R_τ	4.57
8	CHl3[h]	R_τ	4.48
9	Cll[l, p, p, l]	A_b^{FB}	4.43
10	CHe[h]	R_τ	3.97
11	CHq3[h]	R_b	3.43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

#	Wilson Coef.	$[\mathrm{Obs}]_{\mathrm{bound}}$	Λ_{bound} [TeV]	Λ_{bound} [TeV] (LL)	$\Delta_{\mathrm{Full-LL}}$ (%)
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
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

Bounds from the Z-pole

- 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:

See also Sophie Renner's talk



#	Wilson Coef.	[Obs] bound	Λ_{bound} [TeV]	Λ_{bound} [TeV] (LL)	$\Delta_{Full-LL}$ (%)
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
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

Bounds from the Z-pole

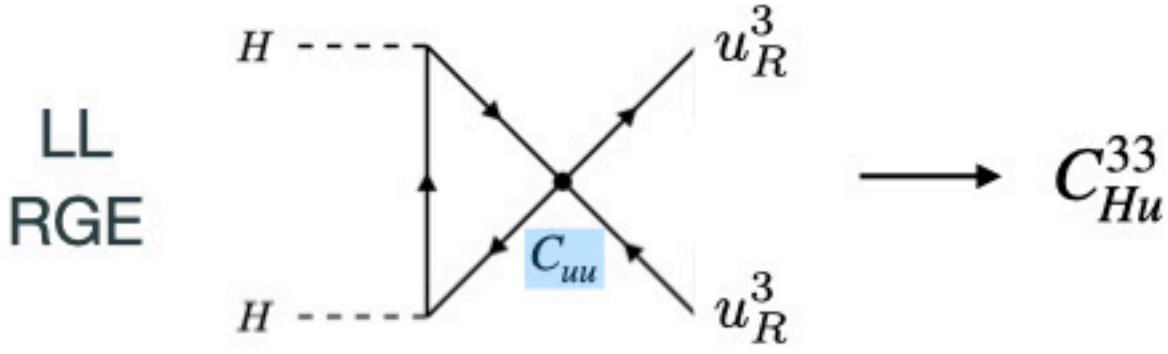
- Including RGE, we have 120 of 124, 38 with bounds $\gtrsim 1$ TeV.
- Resummation is important, even from $\Lambda_{\mathrm{NP}} = 3$ TeV.

[Allwicher, Cornella, Isidori, BAS, 2311.00020]
[Allwicher, Isidori, Lizana, Selimovic, BAS, 2302.11584]

#	Wilson Coef.	[Obs]$_{\mathrm{bound}}$	Λ_{bound} [TeV]	Λ_{bound} [TeV] (LL)	$\Delta_{\mathrm{Full-LL}}$ (%)
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
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

Bounds from the Z-pole

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



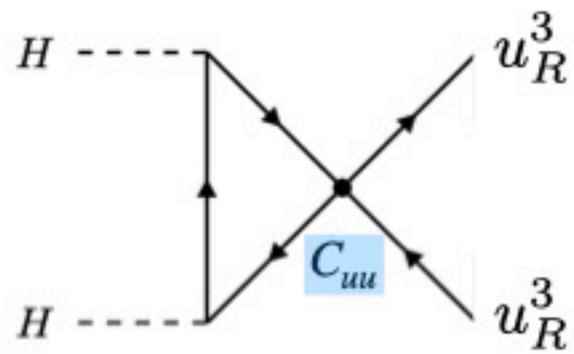
#	Wilson Coef.	[Obs] bound	Λ_{bound} [TeV]	Λ_{bound} [TeV] (LL)	$\Delta_{Full-LL}$ (%)
1	cHWB	A_b^{FB}	8.98	8.78	2.2
2	CHl3[l]	σ_{had}	7.75	7.64	1.4
3	CHl1[l]	σ_{had}	7.65	7.51	1.8
4	CHe[l]	σ_{had}	6.6	6.48	1.8
5	CHq3[l]	R_τ	5.56	5.48	1.4
6	cHD	A_b^{FB}	5.05	4.71	6.7
7	Cll[l, p, p, l]	A_b^{FB}	4.52	4.52	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
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

[Allwicher, Cornella, Isidori, BAS, 2311.00020]
[Allwicher, Isidori, Lizana, Selimovic, BAS, 2302.11584]

Bounds from the Z-pole

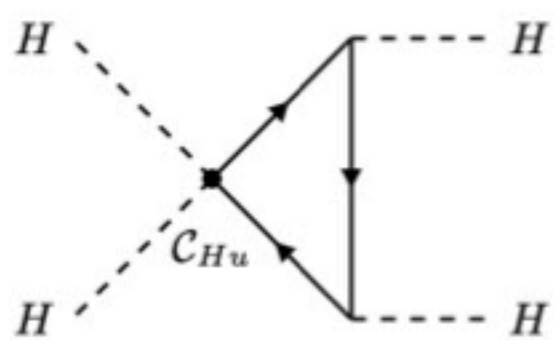
- Including RGE, we have 120 of 124, 38 with bounds $\gtrsim 1$ TeV.
- Resummation is important, even from $\Lambda_{\mathrm{NP}} = 3$ TeV.

LL RGE



$\longrightarrow C_{Hu}^{33}$

NLL RGE



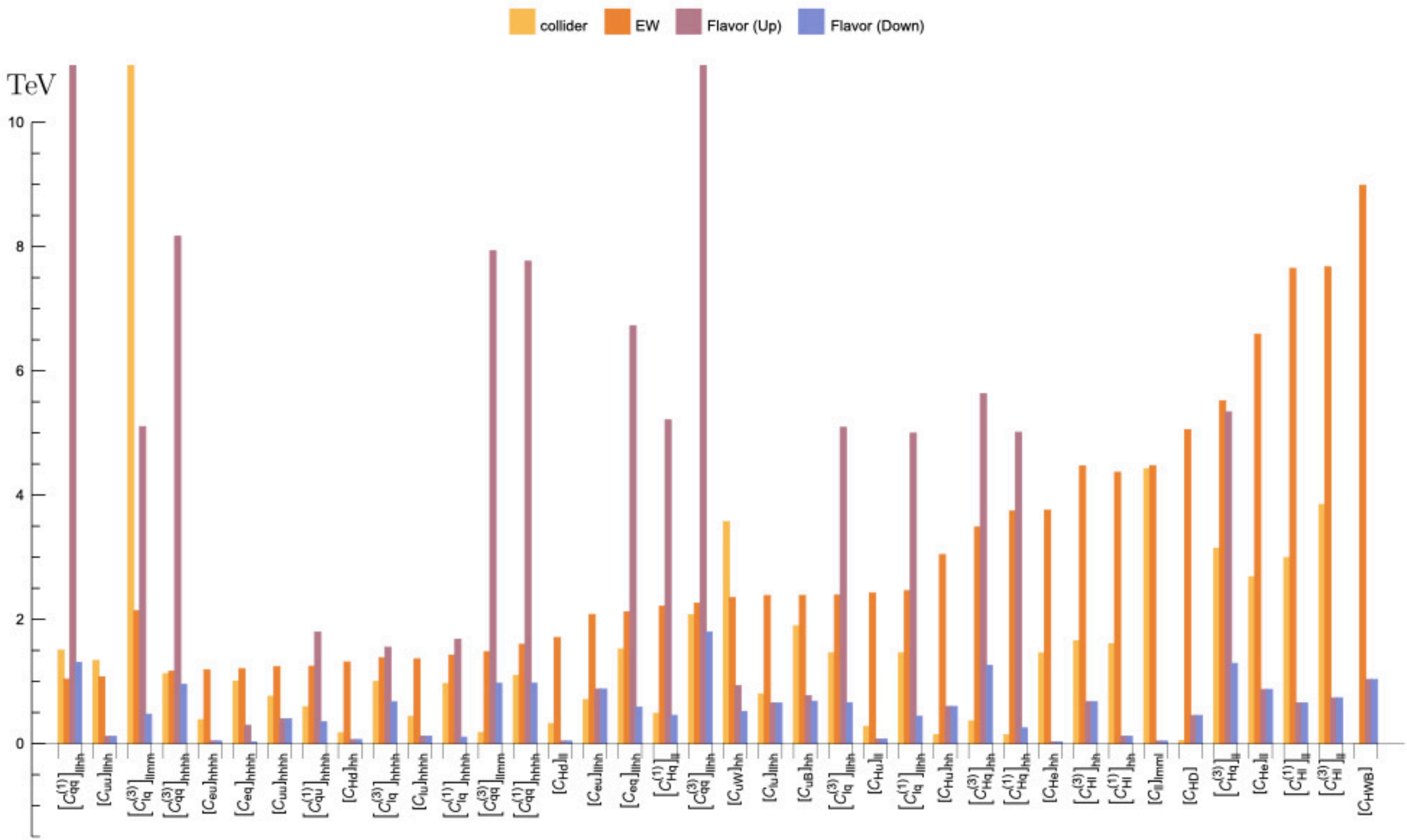
$\longrightarrow C_{HD}$

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

[Allwicher, Cornella, Isidori, BAS, 2311.00020]
[Allwicher, Isidori, Lizana, Selimovic, BAS, 2302.11584]

#	Wilson Coef.	[Obs] bound	Λ_{bound} [TeV]	Λ_{bound} [TeV] (LL)	$\Delta_{\mathrm{Full-LL}}$ (%)
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
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

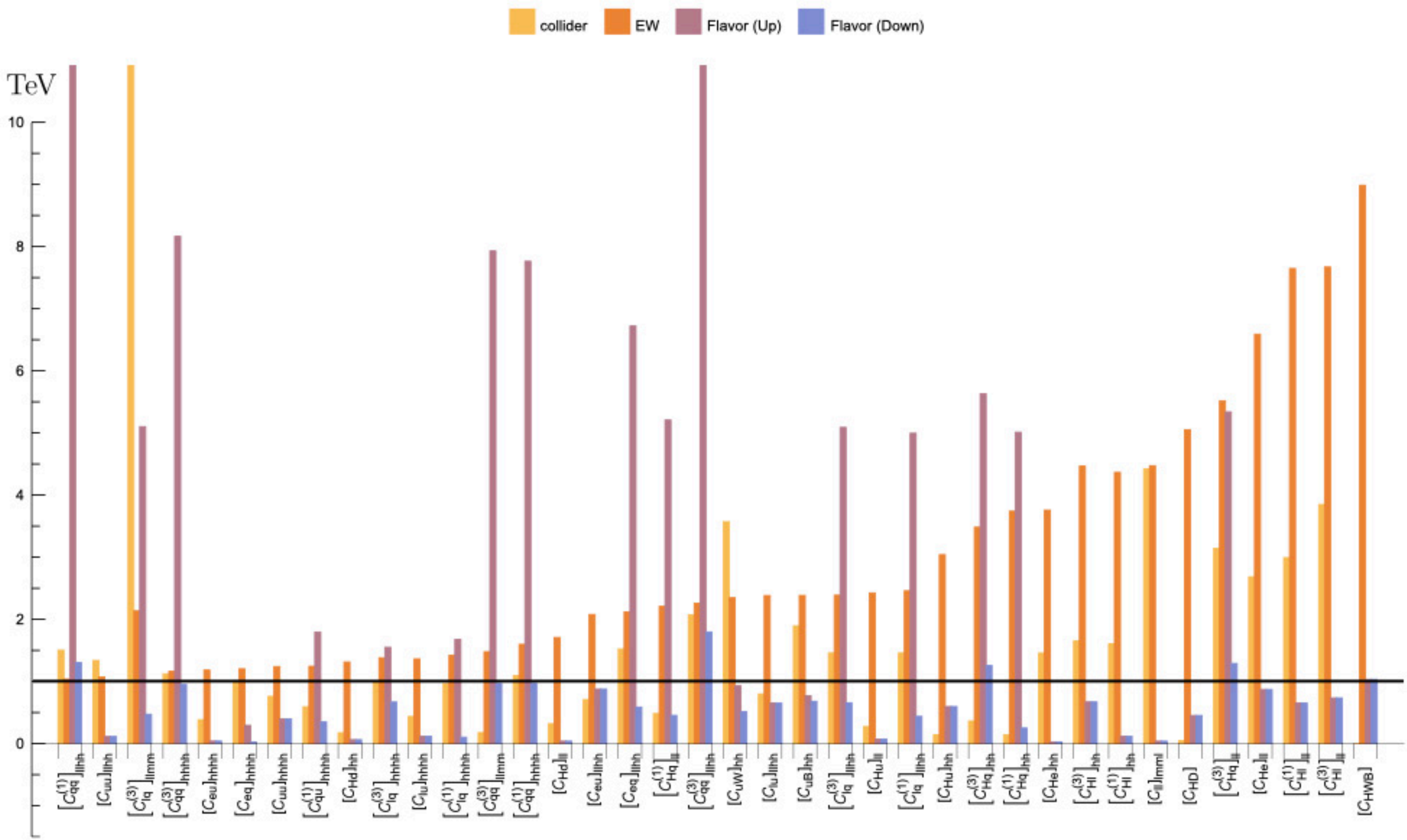
Current Bounds: Z-pole + Flavor + Direct Searches



[Allwicher, Cornella, Isidori, BAS, 2311.00020]

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

Current Bounds: Z-pole + Flavor + Direct Searches

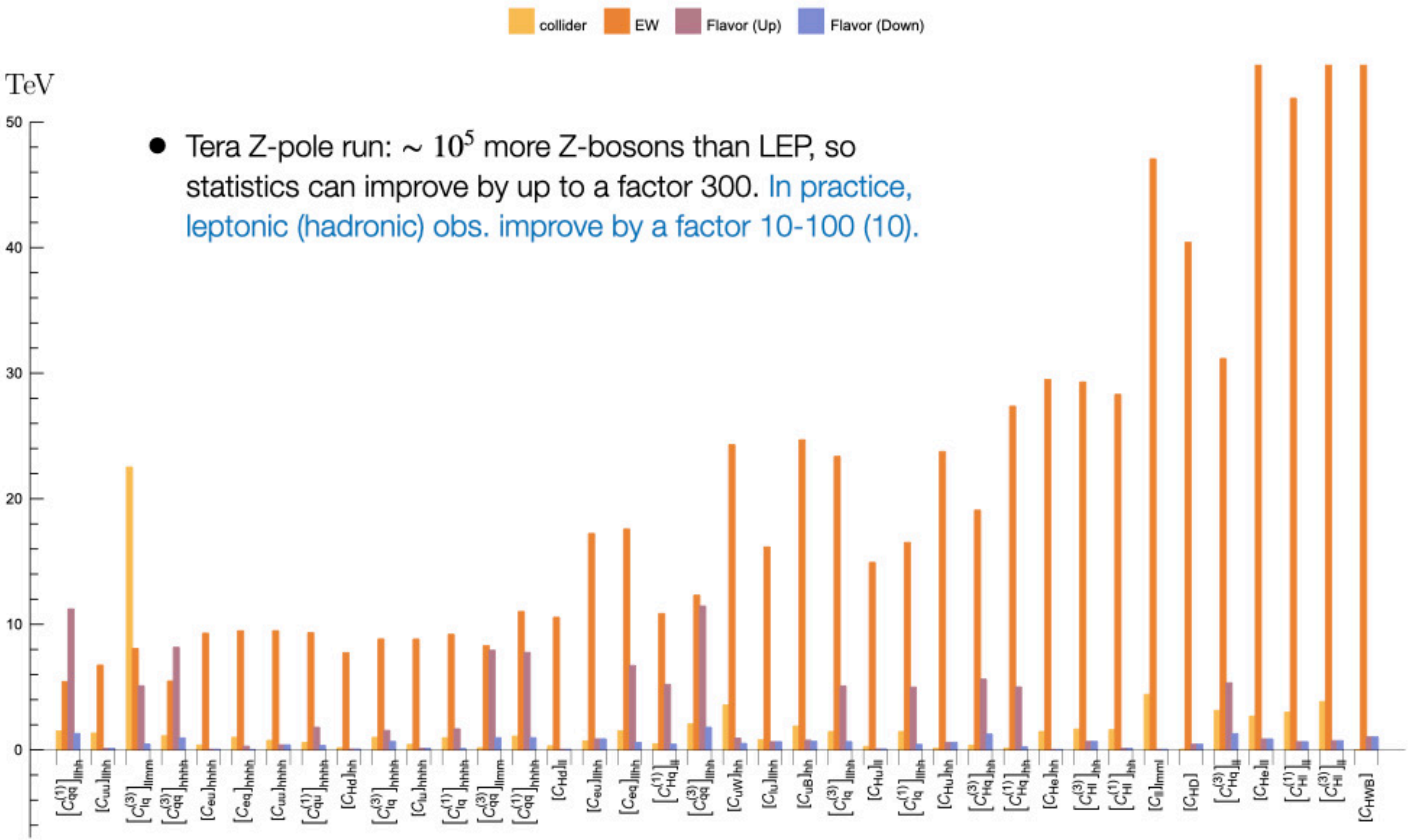


[Allwicher, Cornella, Isidori, BAS, 2311.00020]

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

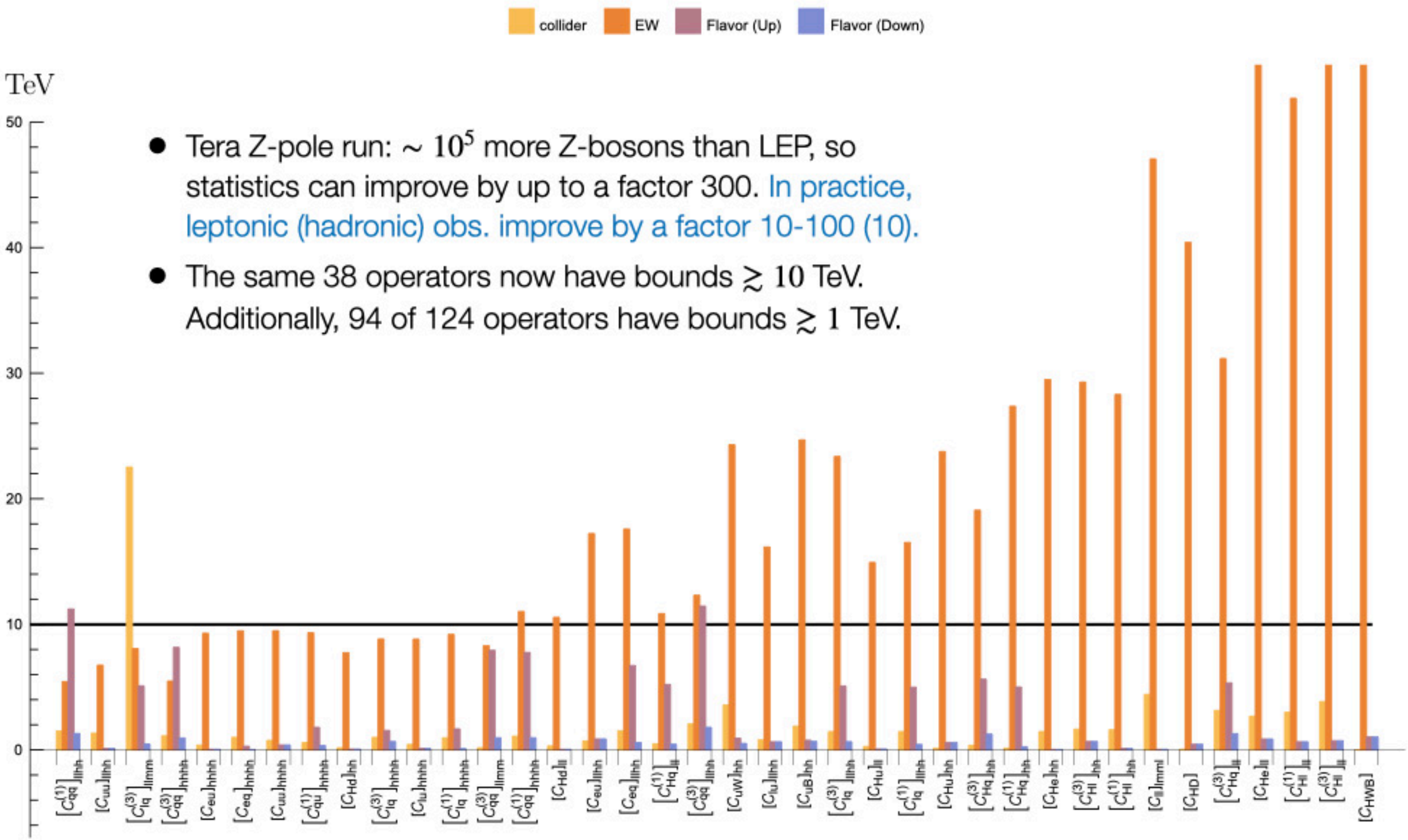
Projection: Tera-Z + Flavor + Direct Searches

- Tera Z-pole run: $\sim 10^5$ more Z-bosons than LEP, so statistics can improve by up to a factor 300. In practice, leptonic (hadronic) obs. improve by a factor 10-100 (10).



[Allwicher, Cornella, Isidori, BAS, 2311.00020]

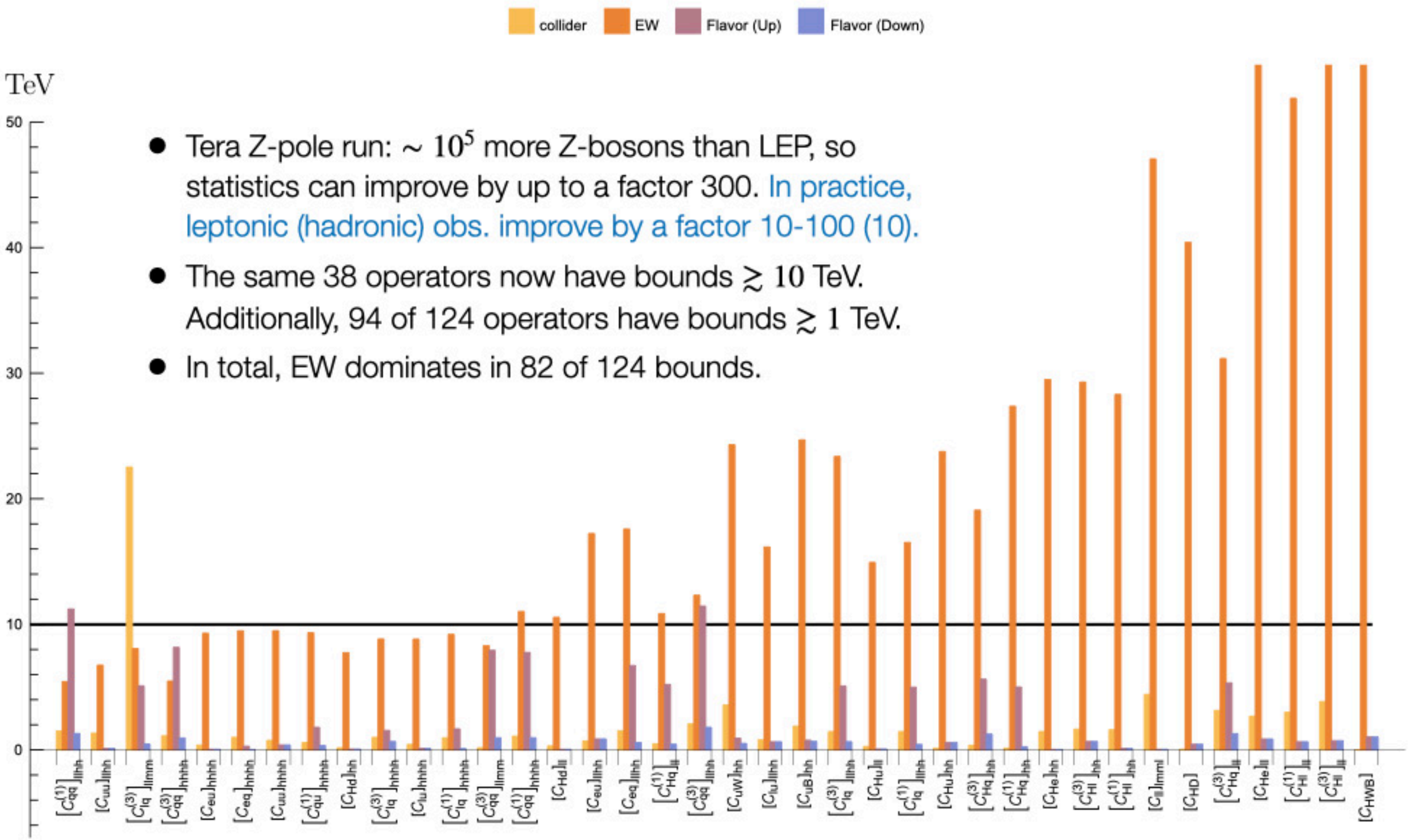
Projection: Tera-Z + Flavor + Direct Searches



- Tera Z-pole run: $\sim 10^5$ more Z-bosons than LEP, so statistics can improve by up to a factor 300. In practice, leptonic (hadronic) obs. improve by a factor 10-100 (10).
- The same 38 operators now have bounds $\gtrsim 10$ TeV. Additionally, 94 of 124 operators have bounds $\gtrsim 1$ TeV.

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

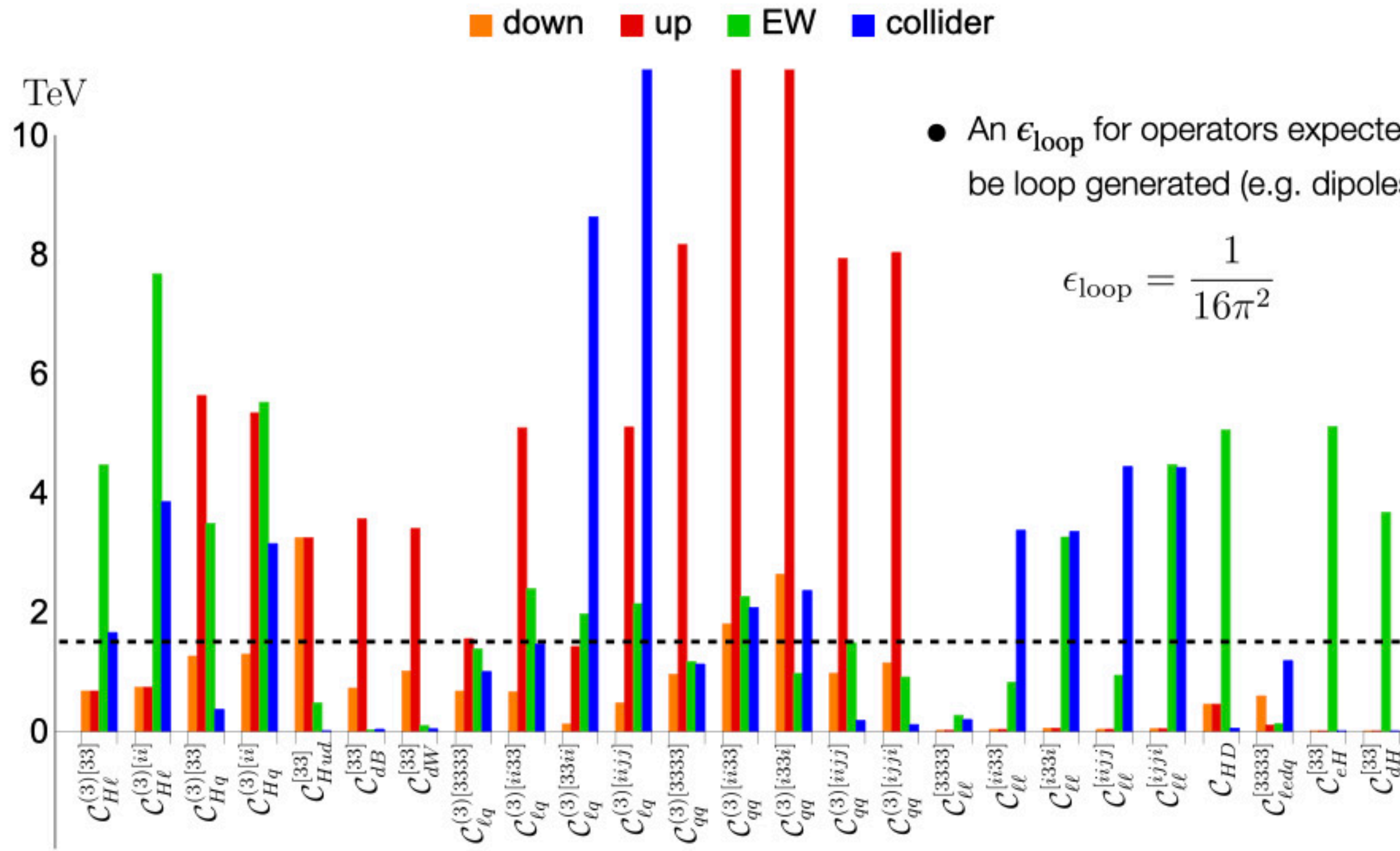
Projection: Tera-Z + Flavor + Direct Searches



- Tera Z-pole run: $\sim 10^5$ more Z-bosons than LEP, so statistics can improve by up to a factor 300. In practice, leptonic (hadronic) obs. improve by a factor 10-100 (10).
- The same 38 operators now have bounds $\gtrsim 10$ TeV. Additionally, 94 of 124 operators have bounds $\gtrsim 1$ TeV.
- In total, EW dominates in 82 of 124 bounds.

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Dynamical assumptions to allow for TeV-scale NP

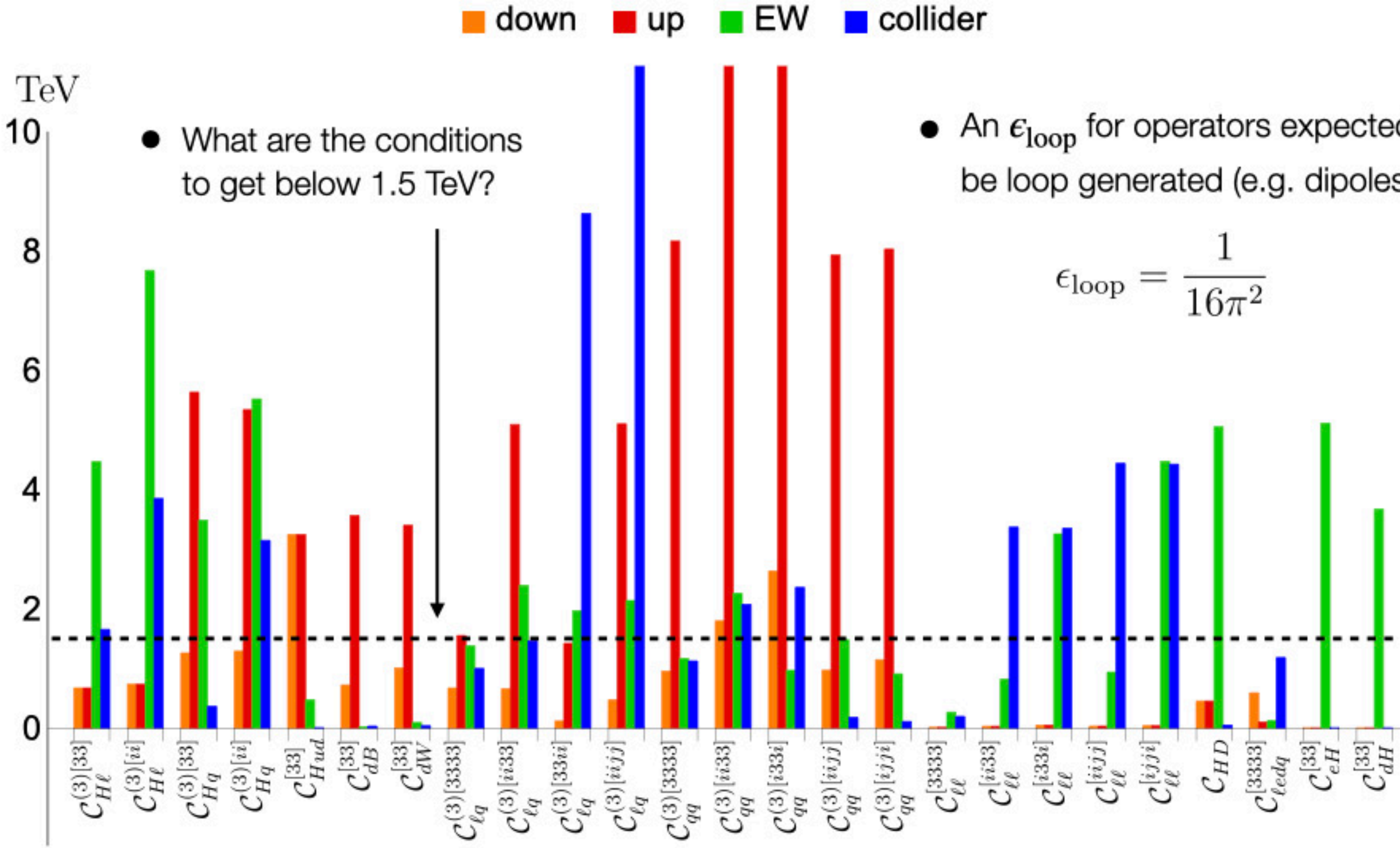


- An ϵ_{loop} for operators expected to be loop generated (e.g. dipoles).

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

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Dynamical assumptions to allow for TeV-scale NP



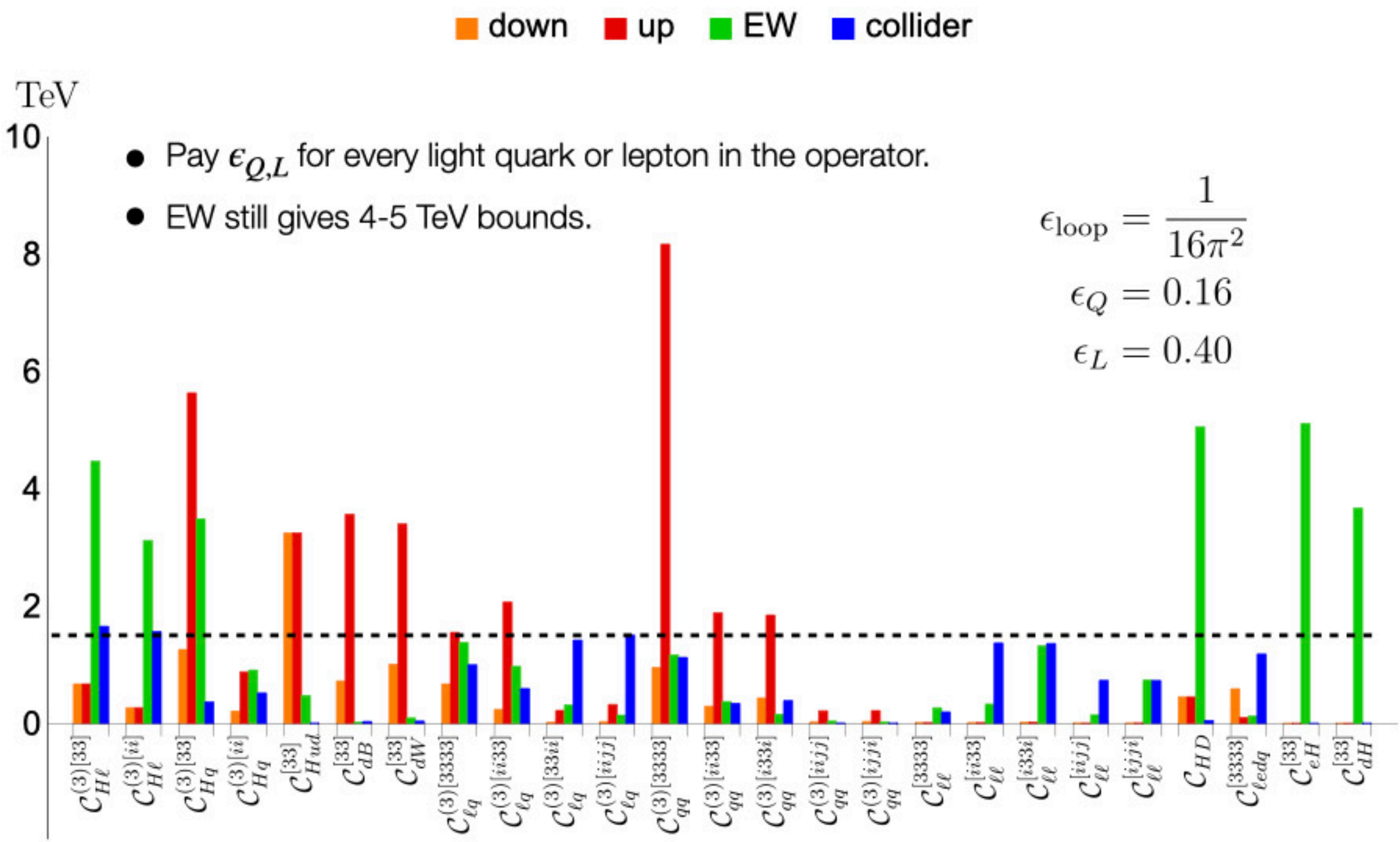
- What are the conditions to get below 1.5 TeV?

- An $\epsilon_{\rm loop}$ for operators expected to be loop generated (e.g. dipoles).

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

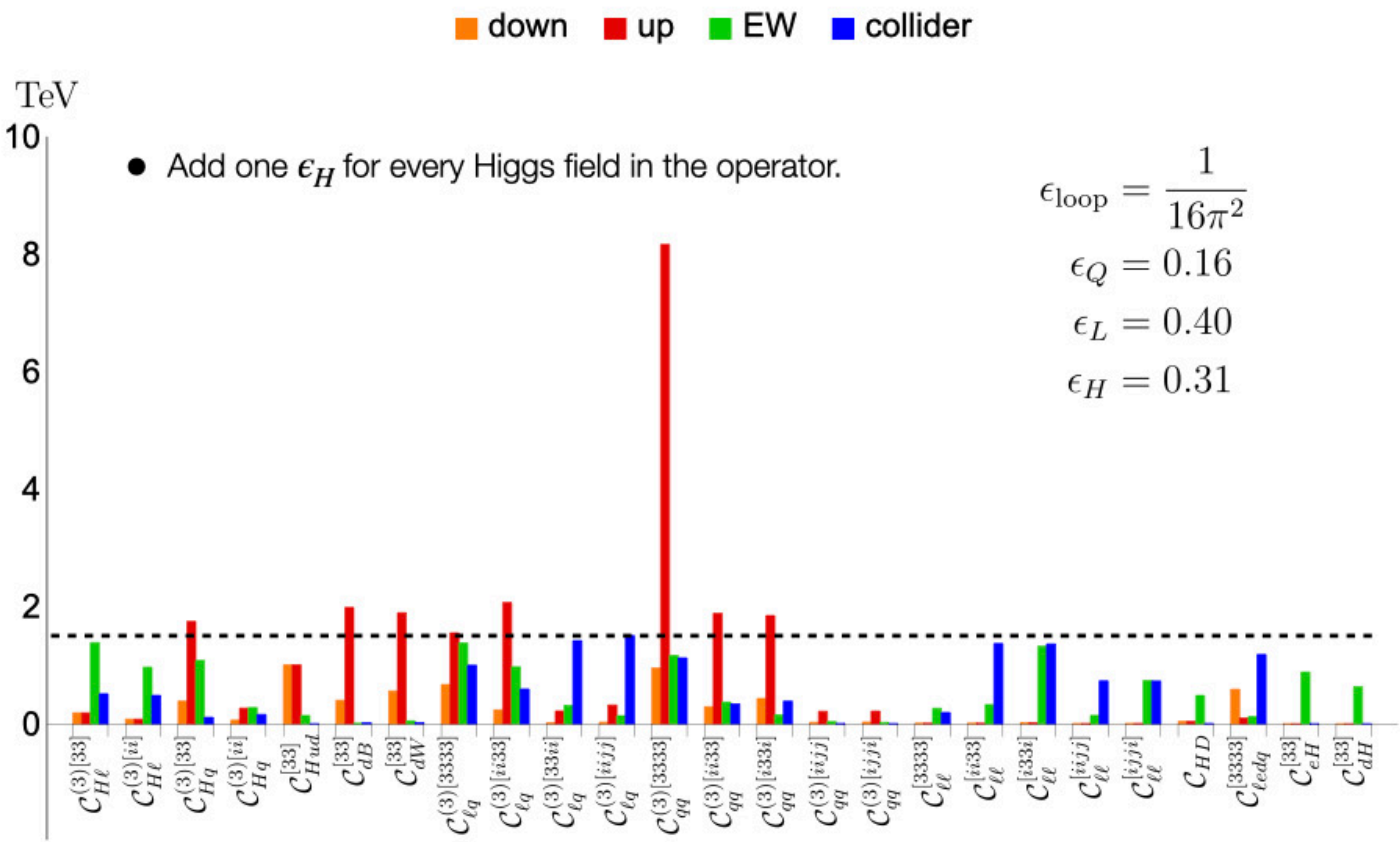
[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Hypothesis of dominantly third-family NP



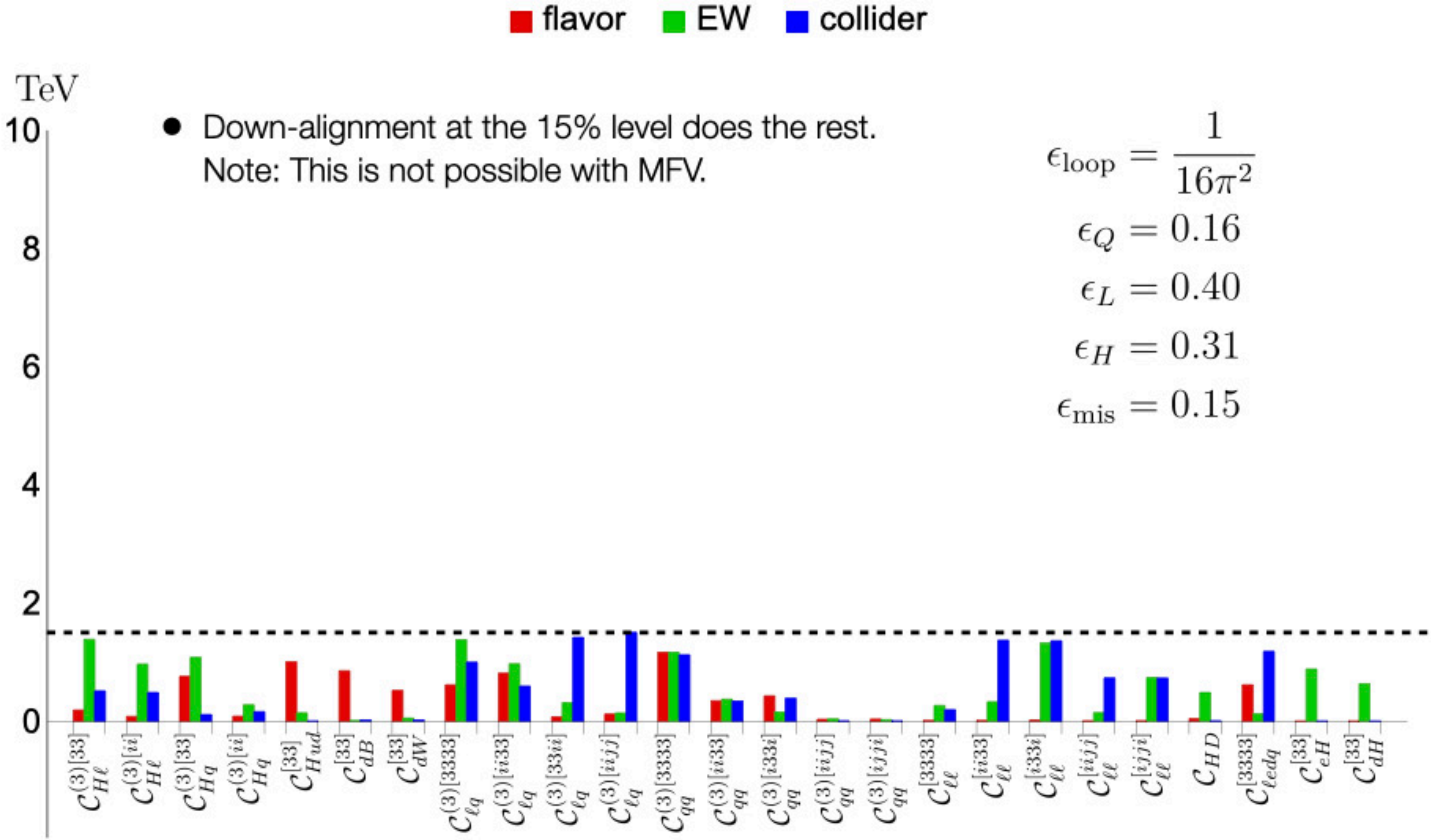
[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Third-family NP: Higgs couplings



[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Third-family NP: Flavor alignment



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

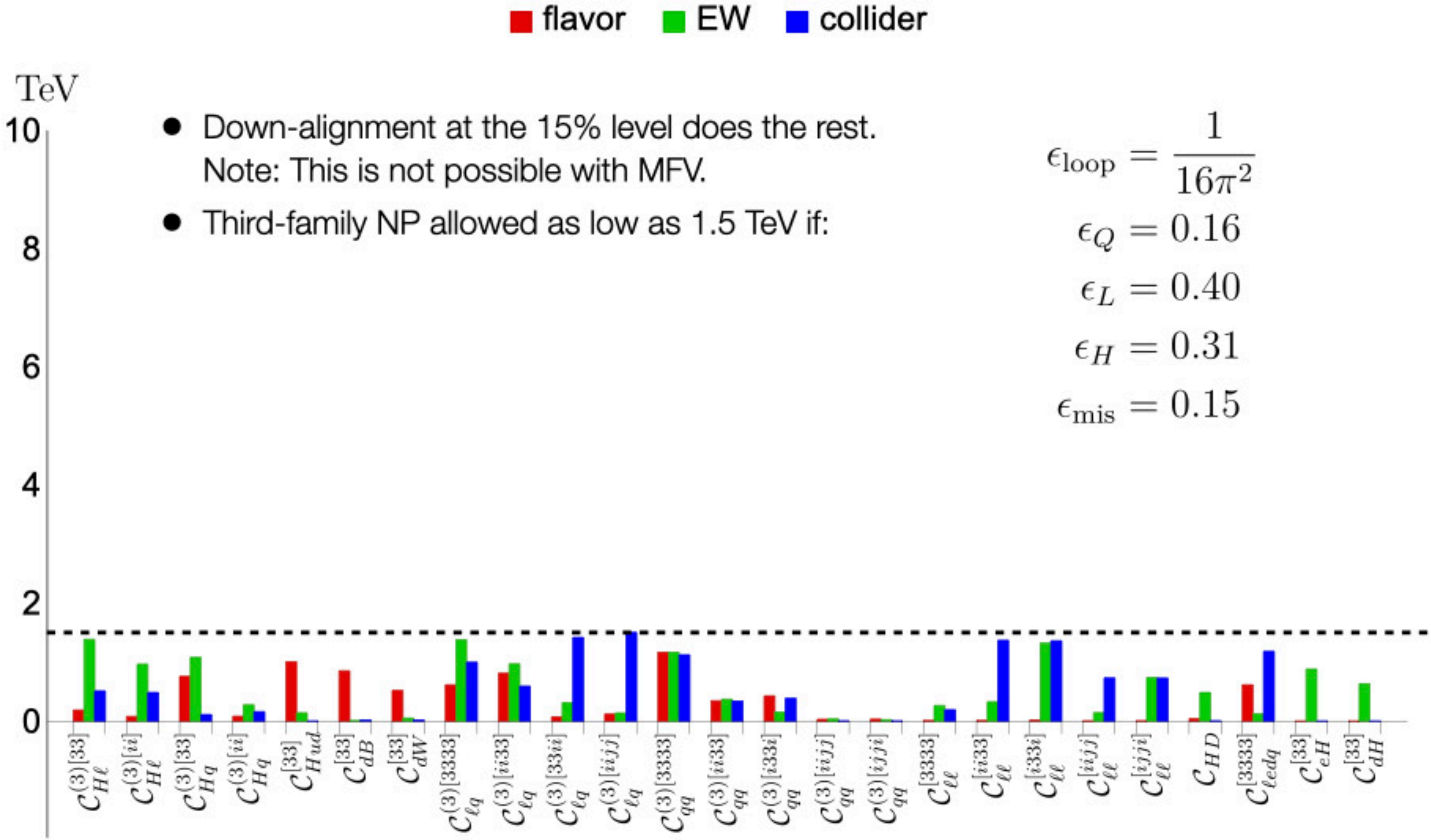
$$\epsilon_{\rm loop} = \frac{1}{16\pi^2}$$
$$\epsilon_Q = 0.16$$
$$\epsilon_L = 0.40$$
$$\epsilon_H = 0.31$$
$$\epsilon_{\rm mis} = 0.15$$

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Third-family NP: Flavor alignment

- Down-alignment at the 15% level does the rest. Note: This is not possible with MFV.
- Third-family NP allowed as low as 1.5 TeV if:

$$\epsilon_{\text{loop}} = \frac{1}{16\pi^2}$$
$$\epsilon_Q = 0.16$$
$$\epsilon_L = 0.40$$
$$\epsilon_H = 0.31$$
$$\epsilon_{\text{mis}} = 0.15$$

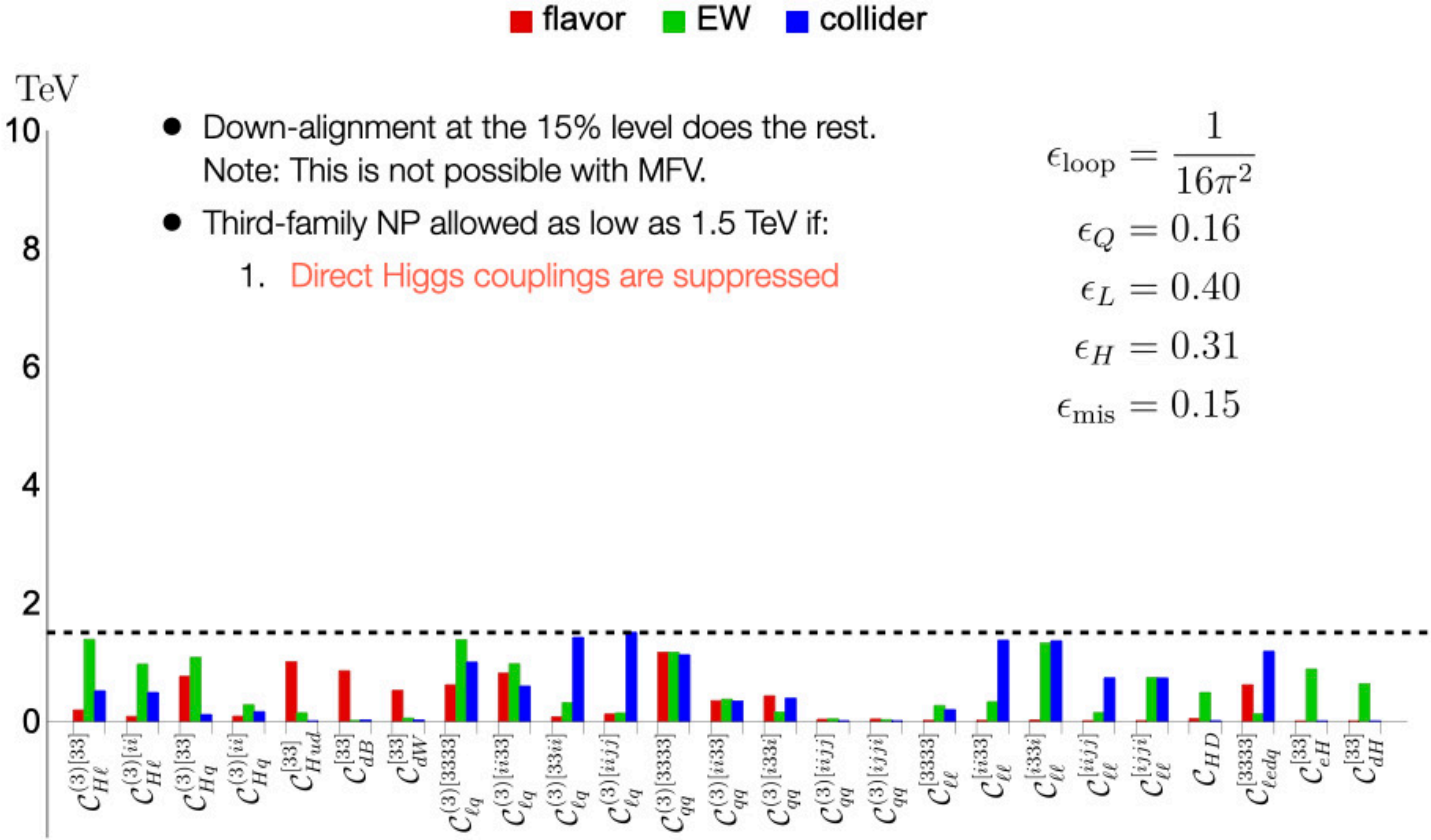


[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Third-family NP: Flavor alignment

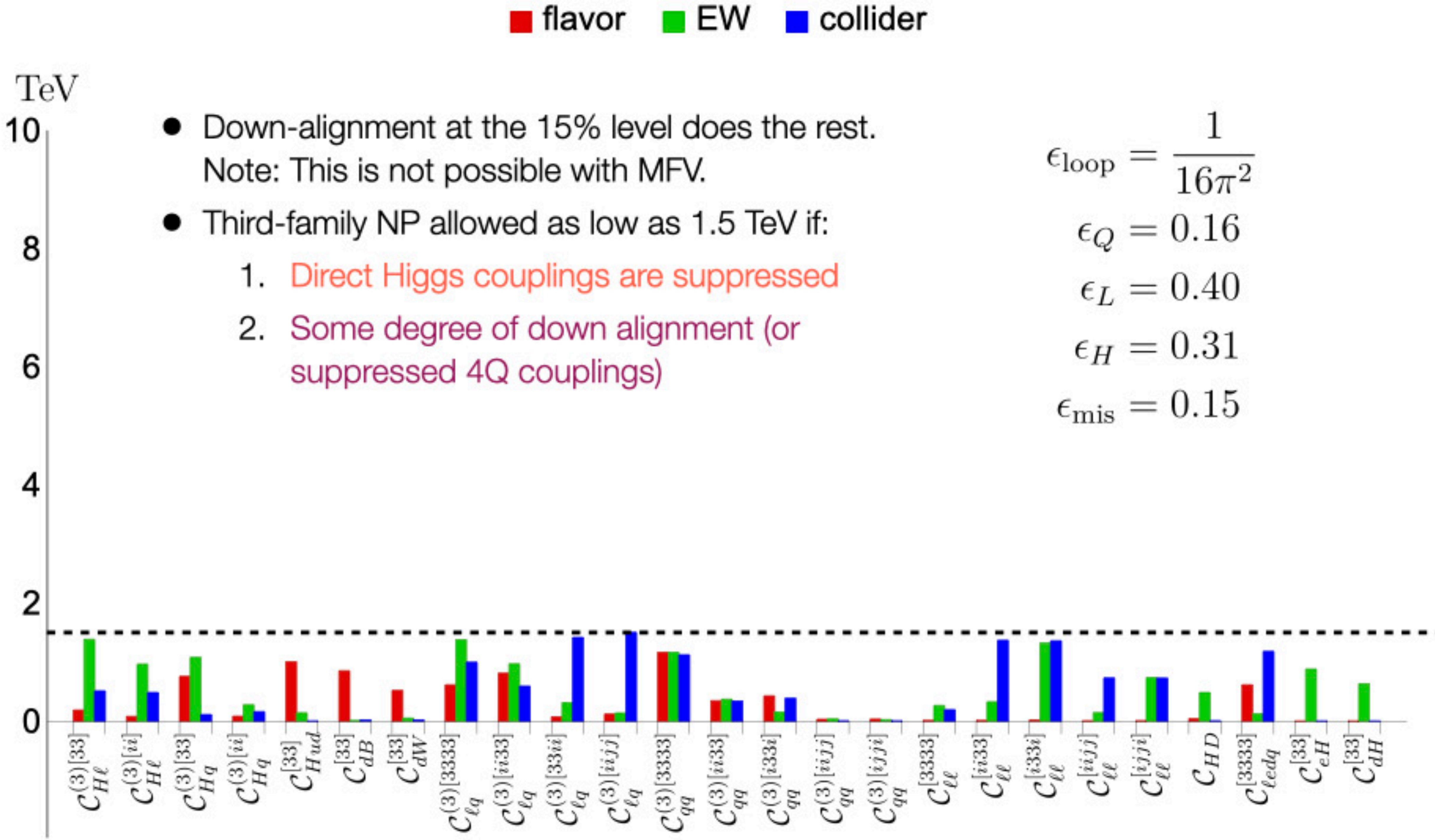
- Down-alignment at the 15% level does the rest.
  Note: This is not possible with MFV.
- Third-family NP allowed as low as 1.5 TeV if:
  1. Direct Higgs couplings are suppressed

$$\epsilon_{\text{loop}} = \frac{1}{16\pi^2}$$
$$\epsilon_Q = 0.16$$
$$\epsilon_L = 0.40$$
$$\epsilon_H = 0.31$$
$$\epsilon_{\text{mis}} = 0.15$$



[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Third-family NP: Flavor alignment

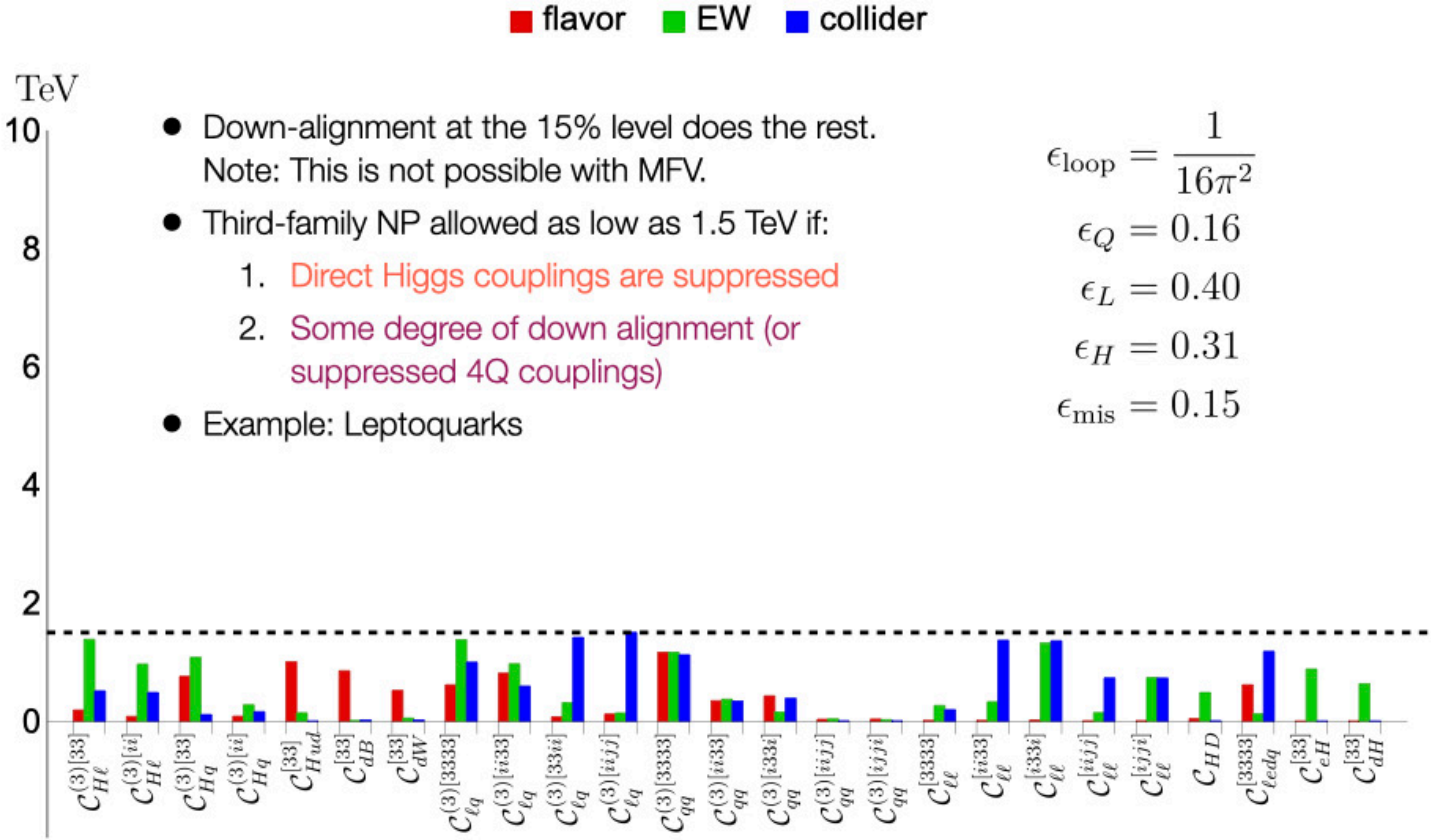


- Down-alignment at the 15% level does the rest. Note: This is not possible with MFV.
- Third-family NP allowed as low as 1.5 TeV if:
  1. Direct Higgs couplings are suppressed
  2. Some degree of down alignment (or suppressed 4Q couplings)

$$\epsilon_{\rm loop} = \frac{1}{16\pi^2}$$
$$\epsilon_Q = 0.16$$
$$\epsilon_L = 0.40$$
$$\epsilon_H = 0.31$$
$$\epsilon_{\rm mis} = 0.15$$

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Third-family NP: Flavor alignment

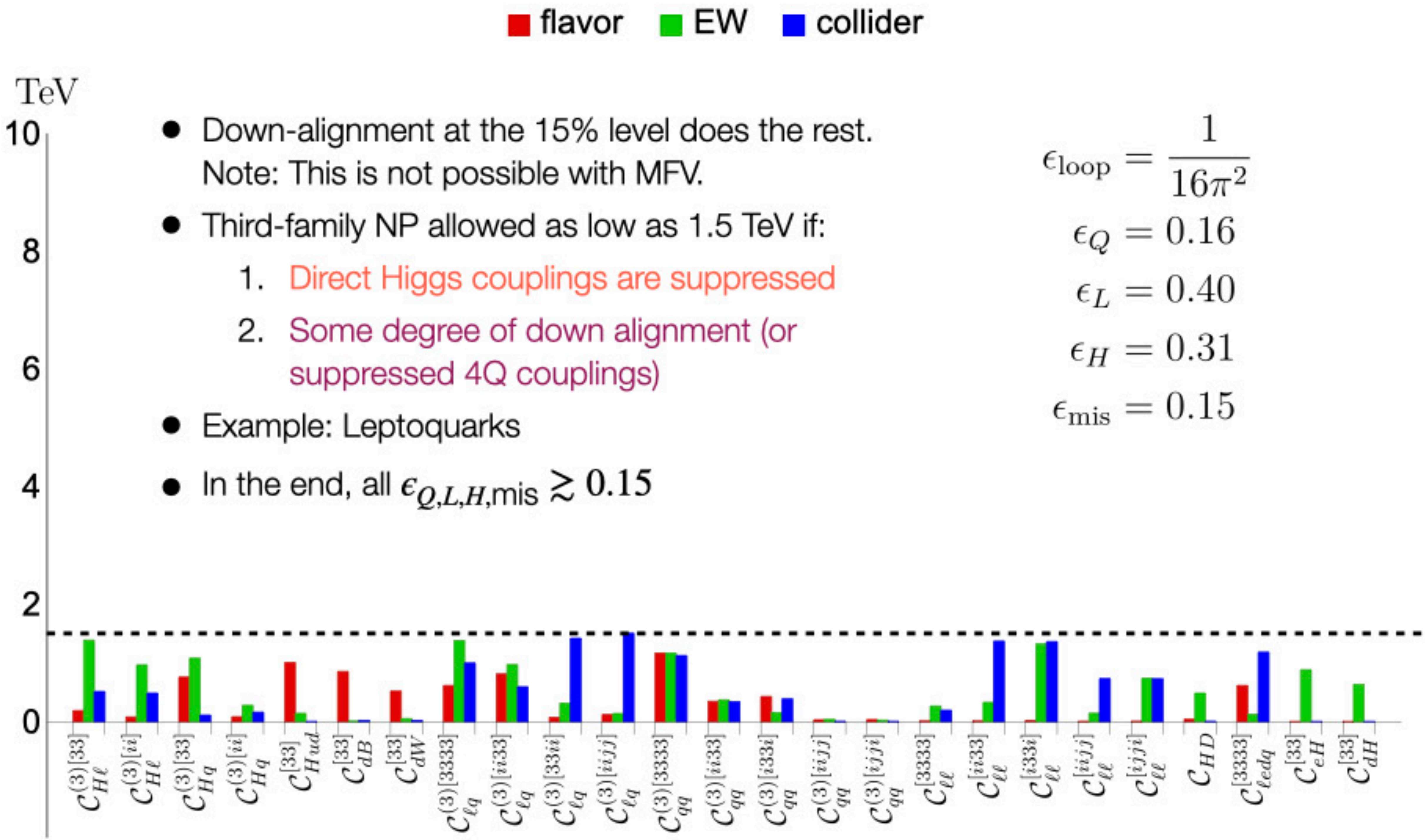


- Down-alignment at the 15% level does the rest. Note: This is not possible with MFV.
- Third-family NP allowed as low as 1.5 TeV if:
  1. Direct Higgs couplings are suppressed
  2. Some degree of down alignment (or suppressed 4Q couplings)
- Example: Leptoquarks

$$\epsilon_{\text{loop}} = \frac{1}{16\pi^2}$$
$$\epsilon_Q = 0.16$$
$$\epsilon_L = 0.40$$
$$\epsilon_H = 0.31$$
$$\epsilon_{\text{mis}} = 0.15$$

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Third-family NP: Flavor alignment

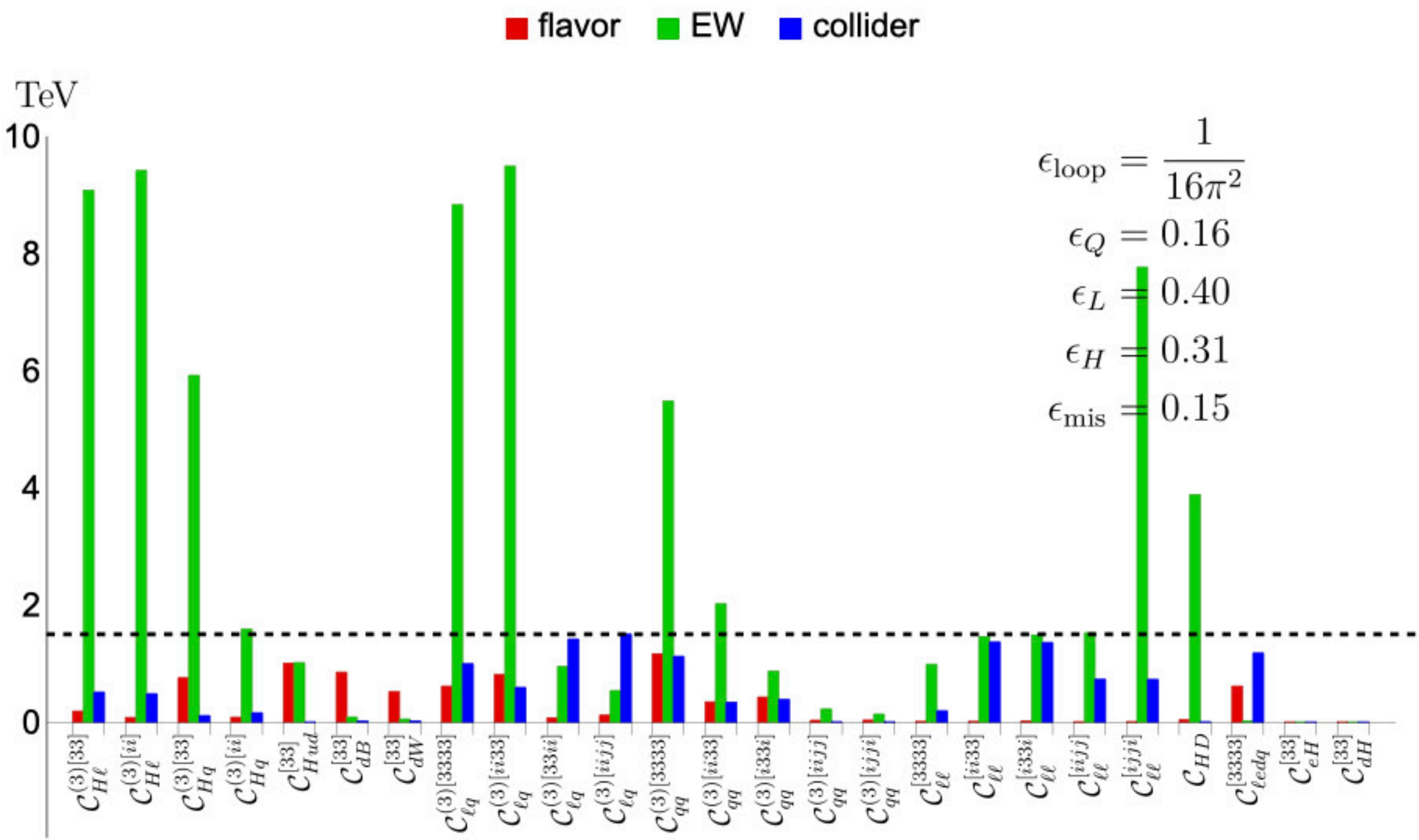


- Down-alignment at the 15% level does the rest. Note: This is not possible with MFV.
- Third-family NP allowed as low as 1.5 TeV if:
  1. Direct Higgs couplings are suppressed
  2. Some degree of down alignment (or suppressed 4Q couplings)
- Example: Leptoquarks
- In the end, all $\epsilon_{Q,L,H,\text{mis}} \gtrsim 0.15$

$$\epsilon_{\text{loop}} = \frac{1}{16\pi^2}$$
$$\epsilon_Q = 0.16$$
$$\epsilon_L = 0.40$$
$$\epsilon_H = 0.31$$
$$\epsilon_{\text{mis}} = 0.15$$

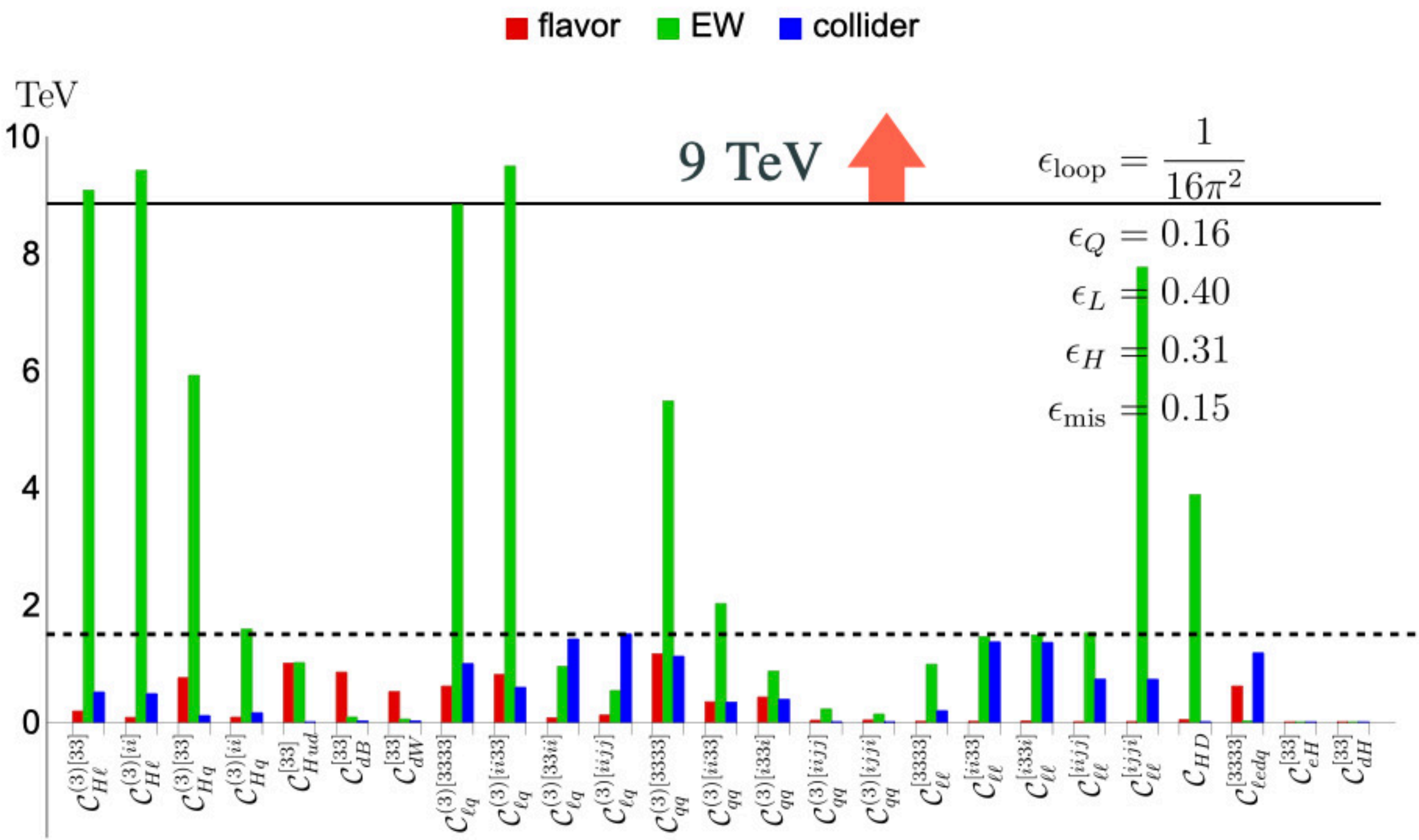
[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Tera-Z run will push even this scenario to O(10) TeV!



[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Tera-Z run will push even this scenario to O(10) TeV!



[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Conclusions

- If we do not want to completely give up hope on the Higgs mass being fundamentally calculable and not fine-tuned beyond the first few digits, then we must still hope for NP lying close by at the few TeV scale.

Conclusions

- If we do not want to completely give up hope on the Higgs mass being fundamentally calculable and not fine-tuned beyond the first few digits, then we must still hope for NP lying close by at the few TeV scale.
- We cannot have TeV-scale NP without some kind of flavor protection. Given the current direct search bounds from the LHC, flavor universal NP no longer seems very natural with bounds O(10) TeV.

Conclusions

- If we do not want to completely give up hope on the Higgs mass being fundamentally calculable and not fine-tuned beyond the first few digits, then we must still hope for NP lying close by at the few TeV scale.
- We cannot have TeV-scale NP without some kind of flavor protection. Given the current direct search bounds from the LHC, flavor universal NP no longer seems very natural with bounds O(10) TeV.
- Instead, $U(2)$ flavor symmetries are very well-motivated since 1) NP can couple more to the third and less to the light families and 2) we expect NP solving the hierarchy problem (and/or flavor puzzle) to be mostly coupled to the Higgs and 3rd family. We have shown that room currently remains for 3rd family new physics.

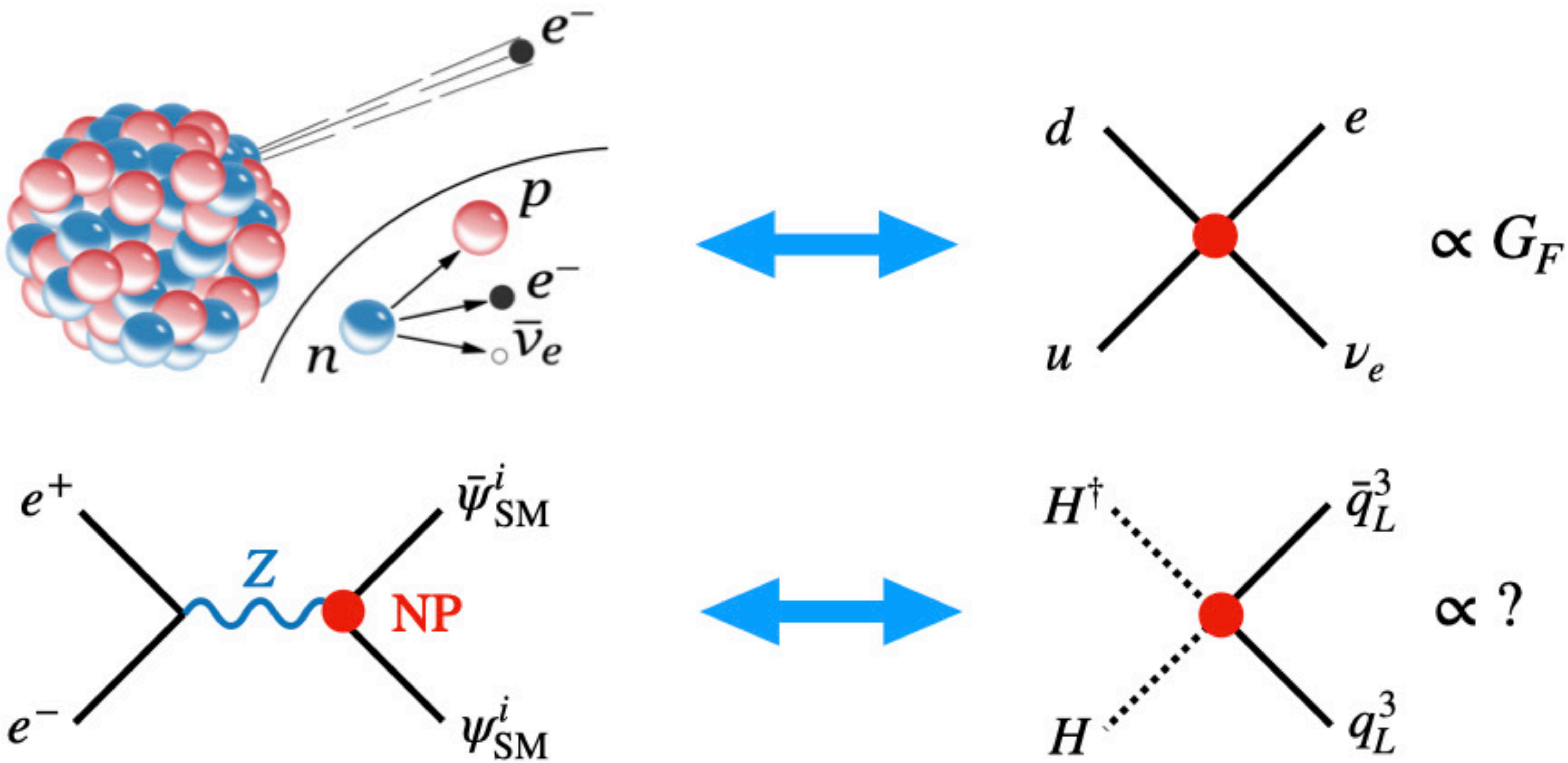
Conclusions

- If we do not want to completely give up hope on the Higgs mass being fundamentally calculable and not fine-tuned beyond the first few digits, then we must still hope for NP lying close by at the few TeV scale.
- We cannot have TeV-scale NP without some kind of flavor protection. Given the current direct search bounds from the LHC, flavor universal NP no longer seems very natural with bounds O(10) TeV.
- Instead, $U(2)$ flavor symmetries are very well-motivated since 1) NP can couple more to the third and less to the light families and 2) we expect NP solving the hierarchy problem (and/or flavor puzzle) to be mostly coupled to the Higgs and 3rd family. We have shown that room currently remains for 3rd family new physics.
- In all models solving the hierarchy problem and/or flavor puzzle, there is NP coupled to the Higgs, making EWPT a powerful probe. But even without direct Higgs couplings, EWPTs unavoidably give strong bounds on a large class of operators via RG evolution.

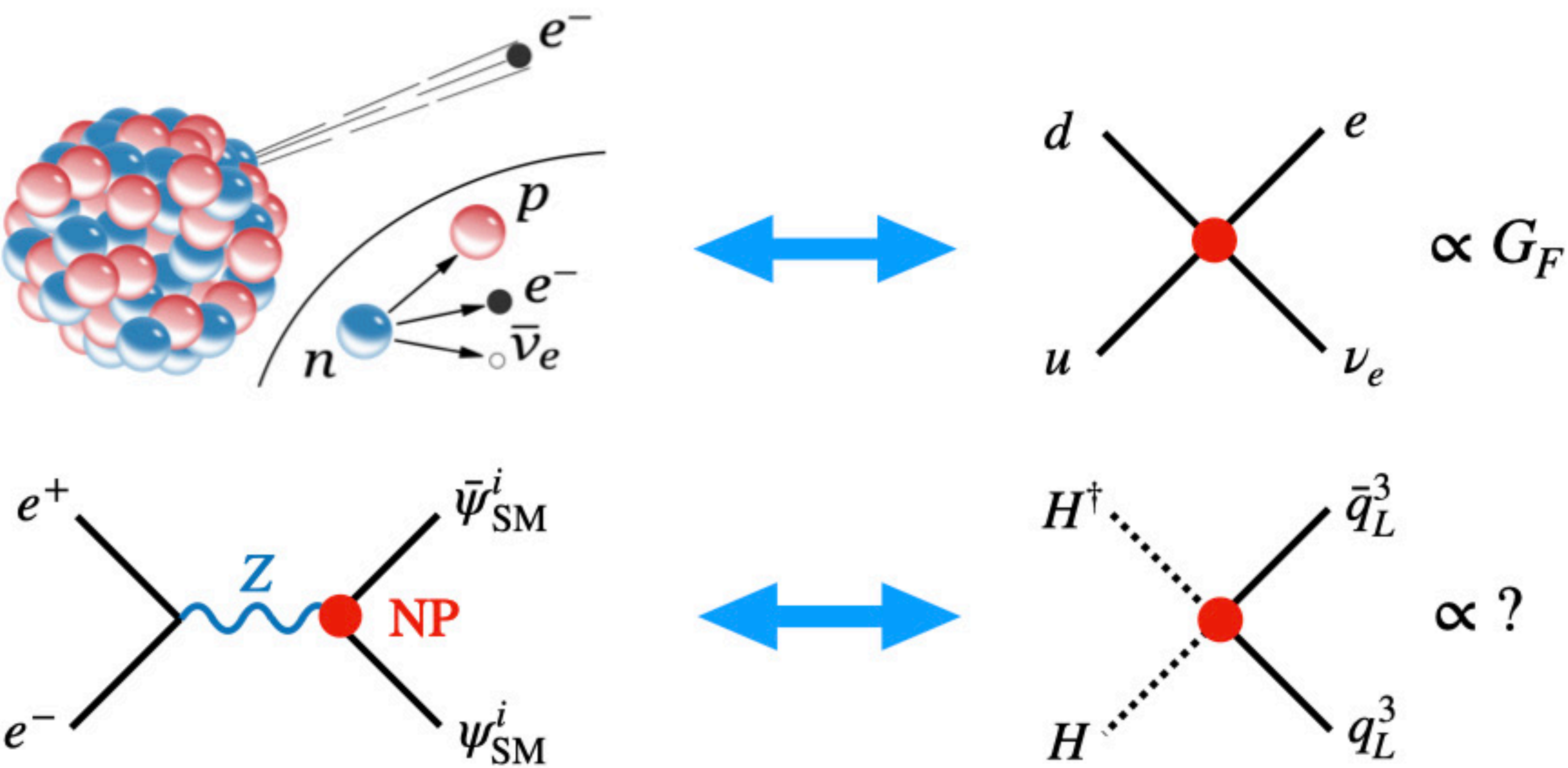
Conclusions

- If we do not want to completely give up hope on the Higgs mass being fundamentally calculable and not fine-tuned beyond the first few digits, then we must still hope for NP lying close by at the few TeV scale.
- We cannot have TeV-scale NP without some kind of flavor protection. Given the current direct search bounds from the LHC, flavor universal NP no longer seems very natural with bounds O(10) TeV.
- Instead, $U(2)$ flavor symmetries are very well-motivated since 1) NP can couple more to the third and less to the light families and 2) we expect NP solving the hierarchy problem (and/or flavor puzzle) to be mostly coupled to the Higgs and 3rd family. We have shown that room currently remains for 3rd family new physics.
- In all models solving the hierarchy problem and/or flavor puzzle, there is NP coupled to the Higgs, making EWPT a powerful probe. But even without direct Higgs couplings, EWPTs unavoidably give strong bounds on a large class of operators via RG evolution.
- Because EWPT are much more flavor democratic, not even third family NP can hide. A future tera-Z machine will probe NP protected by the accidental symmetries of the SM in the 10-50 TeV range. In this sense, it seems clear that FCC-ee is the best way forward.

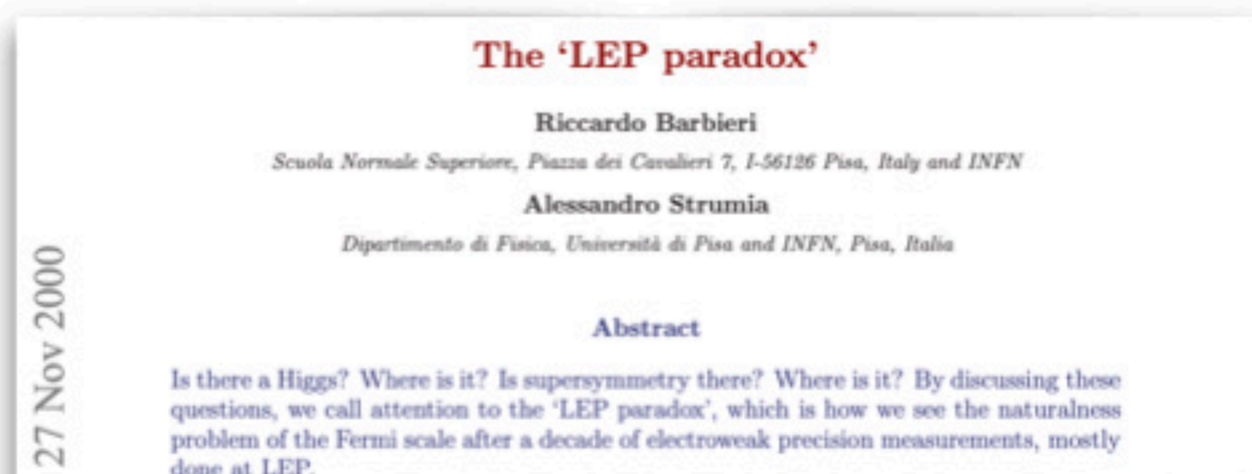
A final comment…



A final comment…



- *In any case, FCC-ee will set the expectations for FCC-hh, just as LEP did for the LHC.*



The 'LEP paradox'

Riccardo Barbieri

Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy and INFN

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.

Backup Slides

EWPT are (still) a powerful probe of NP

The 'LEP paradox'

Riccardo Barbieri

Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy and INFN

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.

EWPT are (still) a powerful probe of NP

The 'LEP paradox'

Riccardo Barbieri

Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy and INFN

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.

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 $m_h \approx (100 \div 200)\,\mathrm{GeV}$ 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.

EWPT are (still) a powerful probe of NP

The 'LEP paradox'

Riccardo Barbieri

Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy and INFN

Alessandro Strumia

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

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.

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.

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.

How does the Higgs fit into the story?

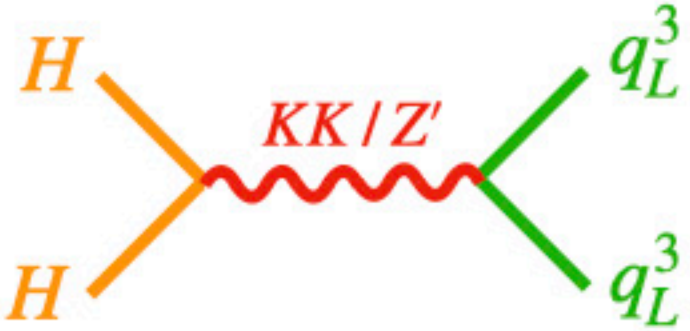
- To address the EW hierarchy problem, there should be new states coupled to the Higgs and/or top, e.g. SUSY, composite Higgs, etc.
- The same is true in models that aim to address the SM fermion mass hierarchies, e.g. new flavor non-universal EW gauge symmetries.

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.
- The same is true in models that aim to address the SM fermion mass hierarchies, e.g. new flavor non-universal EW gauge symmetries.
- These well-motivated classes of models generically lead to sizable corrections to EW precision observables (at least in third-family quarks).

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.
- The same is true in models that aim to address the SM fermion mass hierarchies, e.g. new flavor non-universal EW gauge symmetries.
- These well-motivated classes of models generically lead to sizable corrections to EW precision observables (at least in third-family quarks).

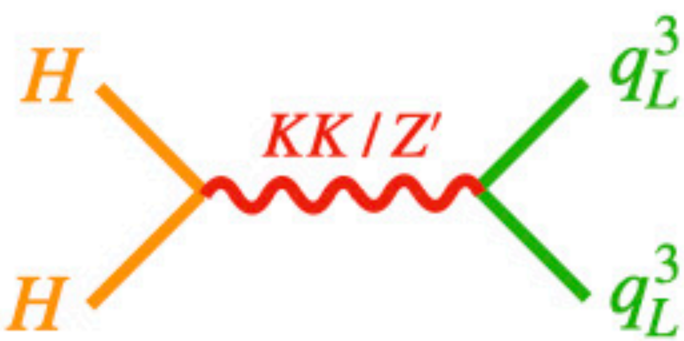


$$C_{Hq}^{(1)[33]}(H^\dagger D_\mu H)(\bar{q}_L^3 \gamma^\mu q_L^3)$$

EWPT: $C_{Hq}^{(1)[33]} \lesssim (4\text{ TeV})^{-2}$

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.
- The same is true in models that aim to address the SM fermion mass hierarchies, e.g. new flavor non-universal EW gauge symmetries.
- These well-motivated classes of models generically lead to sizable corrections to EW precision observables (at least in third-family quarks).



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

EWPT: $C_{Hq}^{(1)[33]} \lesssim (4\text{ TeV})^{-2}$

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

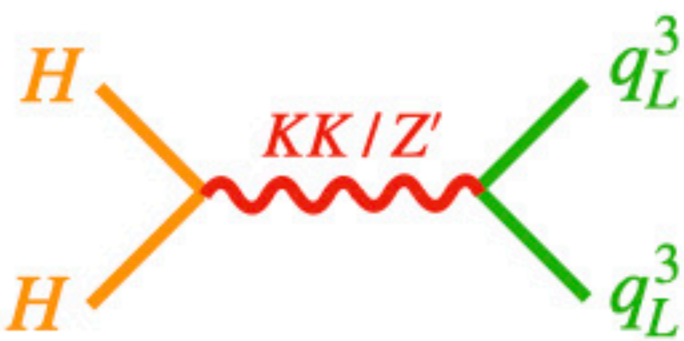
EWPT: $C_{HD} \lesssim (5\text{ TeV})^{-2}$

How does the Higgs fit into the story?

- 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!



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

EWPT: $C_{Hq}^{(1)[33]} \lesssim (4\ \text{TeV})^{-2}$

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

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

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.	$\Lambda^{\text{down}}_{\text{flav.}}$	$\Lambda^{\text{up}}_{\text{flav.}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$	$\Lambda^{\text{down}}_{\text{all}}$	Obs.	$\Lambda^{\text{up}}_{\text{all}}$	Obs.
$\mathcal{C}_{H\ell}^{(1)[33]}$	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.	$\Lambda^{\rm down}_{\rm flav.}$	$\Lambda^{\rm up}_{\rm flav.}$	$\Lambda_{\rm EW}$	$\Lambda_{\rm coll.}$	$\Lambda^{\rm down}_{\rm all}$	Obs.	$\Lambda^{\rm up}_{\rm all}$	Obs.
$\mathcal{C}_{eH}^{[33]}$	-	-	5.1	-	5.1	$H \to \tau\tau$	5.1	$H \to \tau\tau$
$\mathcal{C}_{uH}^{[33]}$	-	-	0.2	-	0.2	$H \to \tau\tau$	0.2	$H \to \tau\tau$
$\mathcal{C}_{dH}^{[33]}$	-	-	3.7	-	3.7	$H \to bb$	3.7	$H \to bb$
$\mathcal{C}_{Hud}^{[33]}$	3.2	3.2	0.5	-	3.2	$B \to X_s\gamma$	3.2	$B \to X_s\gamma$
$\mathcal{C}_{eB}^{[33]}$	-	-	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	$A_b^{\rm FB}$	2.7	$A_b^{\rm FB}$
$\mathcal{C}_{dB}^{[33]}$	15.2	74.8	0.4	0.7	15.2	$B \to X_s\gamma$	74.8	$B \to X_s\gamma$
$\mathcal{C}_{eW}^{[33]}$	-	-	1.	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	QuarkDipoles	3.8	QuarkDipoles
$\mathcal{C}_{dW}^{[33]}$	15.7	53.	1.4	0.6	15.7	$B \to X_s\gamma$	53.	$B \to X_s\gamma$
$\mathcal{C}_{uG}^{[33]}$	0.1	0.3	0.5	2.7	2.7	QuarkDipoles	2.7	QuarkDipoles
$\mathcal{C}_{dG}^{[33]}$	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.	$\Lambda^{\text{down}}_{\text{flav.}}$	$\Lambda^{\text{up}}_{\text{flav.}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$	$\Lambda^{\text{down}}_{\text{all}}$	Obs.	$\Lambda^{\text{up}}_{\text{all}}$	Obs.
$\mathcal{C}^{[3333]}_{\ell edq}$	0.6	-	0.1	1.2	1.1	$pp \to \tau\tau$	1.2	$pp \to \tau\tau$
$\mathcal{C}^{(1)[3333]}_{quqd}$	1.8	5.5	1.7	0.4	2.2	$B \to X_s\gamma$	5.5	$B \to X_s\gamma$
$\mathcal{C}^{(8)[3333]}_{quqd}$	1.	5.1	0.7	0.2	1.	$B \to X_s\gamma$	5.1	$B \to X_s\gamma$
$\mathcal{C}^{(1)[3333]}_{\ell equ}$	-	-	2.1	-	2.1	$H \to \tau\tau$	2.1	$H \to \tau\tau$
$\mathcal{C}^{(3)[3333]}_{\ell equ}$	-	-	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.	$\Lambda^{\text{down}}_{\text{flav.}}$	$\Lambda^{\text{up}}_{\text{flav.}}$	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	3.4	3.3	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$	3.3	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$\mathcal{C}_{\ell\ell}^{[i33i]}$	-	-	3.3	3.3	4.2	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$	4.2	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$\mathcal{C}_{\ell\ell}^{[iijj]}$	-	-	0.9	4.4	4.4	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$	4.4	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$\mathcal{C}_{\ell\ell}^{[ijji]}$	-	-	4.5	4.4	4.9	A_b^{FB}	4.9	A_b^{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	$\text{Im}(C_D)$	8.1	$\lvert C_{Bs}\rvert$
$\mathcal{C}_{qq}^{(1)[ijji]}$	1.1	8.1	0.5	-	1.	$\text{Im}(C_D)$	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	σ_{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^{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 $(\bar{L}L)(\bar{L}L)$ terms

RRRR 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.
$C_{ee}^{[3333]}$	-	-	0.3	0.2	0.3	R_τ	0.3	R_τ
$C_{ee}^{[ii33]}$	-	-	0.7	3.2	3.2	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$	3.2	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$C_{ee}^{[iijj]}$	-	-	0.8	4.2	4.2	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$	4.2	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$C_{uu}^{[3333]}$	0.4	0.4	1.2	0.8	1.3	A_b^{FB}	1.3	A_b^{FB}
$C_{uu}^{[ii33]}$	0.1	0.1	1.1	1.3	1.4	FourQuarksTop	1.4	FourQuarksTop
$C_{uu}^{[i33i]}$	-	-	0.5	1.3	1.4	FourQuarksTop	1.4	FourQuarksTop
$C_{uu}^{[iijj]}$	-	-	0.3	-	0.3	R_τ	0.3	R_τ
$C_{uu}^{[ijji]}$	-	-	0.3	-	0.3	R_τ	0.3	R_τ
$C_{dd}^{[3333]}$	-	-	-	-	-	R_b	-	R_b
$C_{dd}^{[ii33]}$	-	-	0.1	-	0.1	R_τ	0.1	R_τ
$C_{dd}^{[i33i]}$	-	-	-	-	-	Γ_Z	-	Γ_Z
$C_{dd}^{[iijj]}$	-	-	0.2	-	0.2	R_τ	0.2	R_τ
$C_{dd}^{[ijji]}$	-	-	0.1	-	0.1	R_τ	0.1	R_τ
$C_{eu}^{[3333]}$	-	-	1.2	0.4	1.2	R_τ	1.2	R_τ
$C_{eu}^{[ii33]}$	0.9	0.9	2.1	0.7	2.2	σ_{had}	2.2	σ_{had}
$C_{eu}^{[33ii]}$	-	-	0.3	2.8	2.8	$pp \to \tau\tau$	2.8	$pp \to \tau\tau$
$C_{eu}^{[iijj]}$	-	-	0.6	7.4	7.4	$pp \to ee$	7.4	$pp \to ee$
$C_{ed}^{[3333]}$	-	-	0.2	1.	1.	$pp \to \tau\tau$	1.	$pp \to \tau\tau$
$C_{ed}^{[ii33]}$	-	-	0.3	1.5	1.5	$pp \to \mu\mu$	1.5	$pp \to \mu\mu$
$C_{ed}^{[33ii]}$	-	-	0.2	2.8	2.8	$pp \to \tau\tau$	2.8	$pp \to \tau\tau$
$C_{ed}^{[iijj]}$	-	-	0.4	4.4	4.4	$pp \to \mu\mu$	4.4	$pp \to \mu\mu$
$C_{ud}^{(1)[3333]}$	0.1	0.1	0.4	0.3	0.4	R_b	0.4	R_b
$C_{ud}^{(1)[ii33]}$	-	-	0.1	-	0.1	R_τ	0.1	R_τ
$C_{ud}^{(1)[33ii]}$	-	-	0.5	1.2	1.2	FourQuarksTop	1.2	FourQuarksTop
$C_{ud}^{(1)[iijj]}$	-	-	0.2	-	0.2	R_τ	0.2	R_τ
$C_{ud}^{(8)[3333]}$	0.1	0.1	-	0.2	0.2	FourQuarksBottom	0.2	FourQuarksBottom
$C_{ud}^{(8)[ii33]}$	-	-	-	-	-	-	-	-
$C_{ud}^{(8)[33ii]}$	-	-	0.1	0.7	0.7	FourQuarksTop	0.7	FourQuarksTop
$C_{ud}^{(8)[iijj]}$	-	-	-	-	-	-	-	-

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.	$\Lambda^{\rm down}_{\rm flav.}$	$\Lambda^{\rm up}_{\rm flav.}$	$\Lambda_{\rm EW}$	$\Lambda_{\rm coll.}$	$\Lambda^{\rm down}_{\rm all}$	Obs.	$\Lambda^{\rm up}_{\rm all}$	Obs.
$\mathcal{C}_H$	-	-	-	-	-	-	-	-
$\mathcal{C}_{H\Box}$	0.2	0.2	0.6	0.1	0.6	$A_b^{\rm FB}$	0.6	$A_b^{\rm FB}$
$\mathcal{C}_{HD}$	0.5	0.5	5.1	-	5.	$A_b^{\rm FB}$	5.	$A_b^{\rm FB}$
$\mathcal{C}_{HG}$	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	$A_b^{\rm FB}$	0.9	$A_b^{\rm FB}$
$\mathcal{C}_{HW}$	0.7	0.7	0.9	-	1.	$A_b^{\rm FB}$	1.	$A_b^{\rm FB}$
$\mathcal{C}_{HWB}$	1.	1.	9.	-	9.	$A_b^{\rm FB}$	9.	$A_b^{\rm FB}$
$\mathcal{C}_G$	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	$A_b^{\rm FB}$	0.9	$A_b^{\rm FB}$

Table 8. CP-conserving bosonic operators