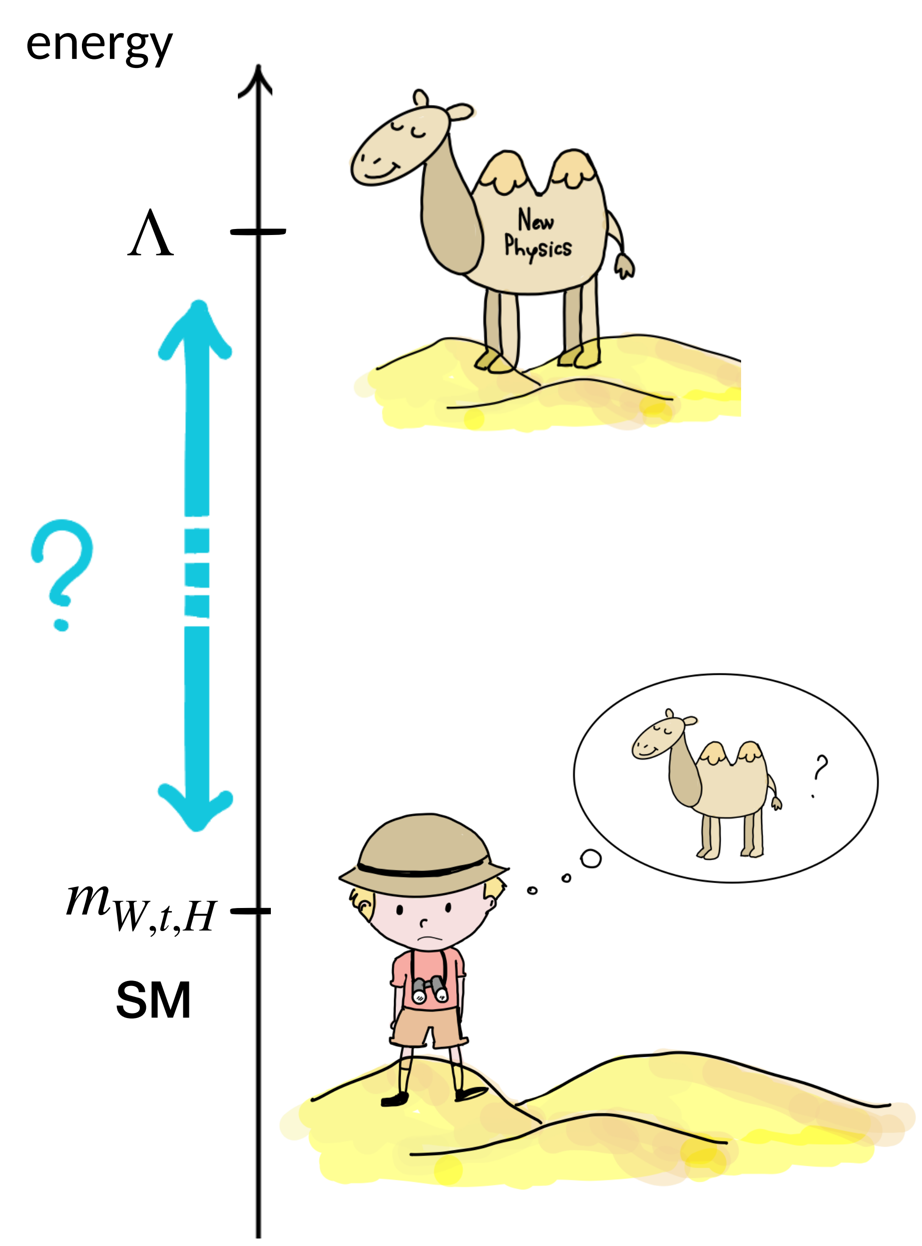
New Physics in the third generation: current status and future prospects

Claudia Cornella (JGU Mainz)

based on 2311.00020 with L. Allwicher, G. Isidori, and B. Stefanek

The scale of New Physics

We have many reasons to think that the SM must be extended at higher energies. But **how high**?

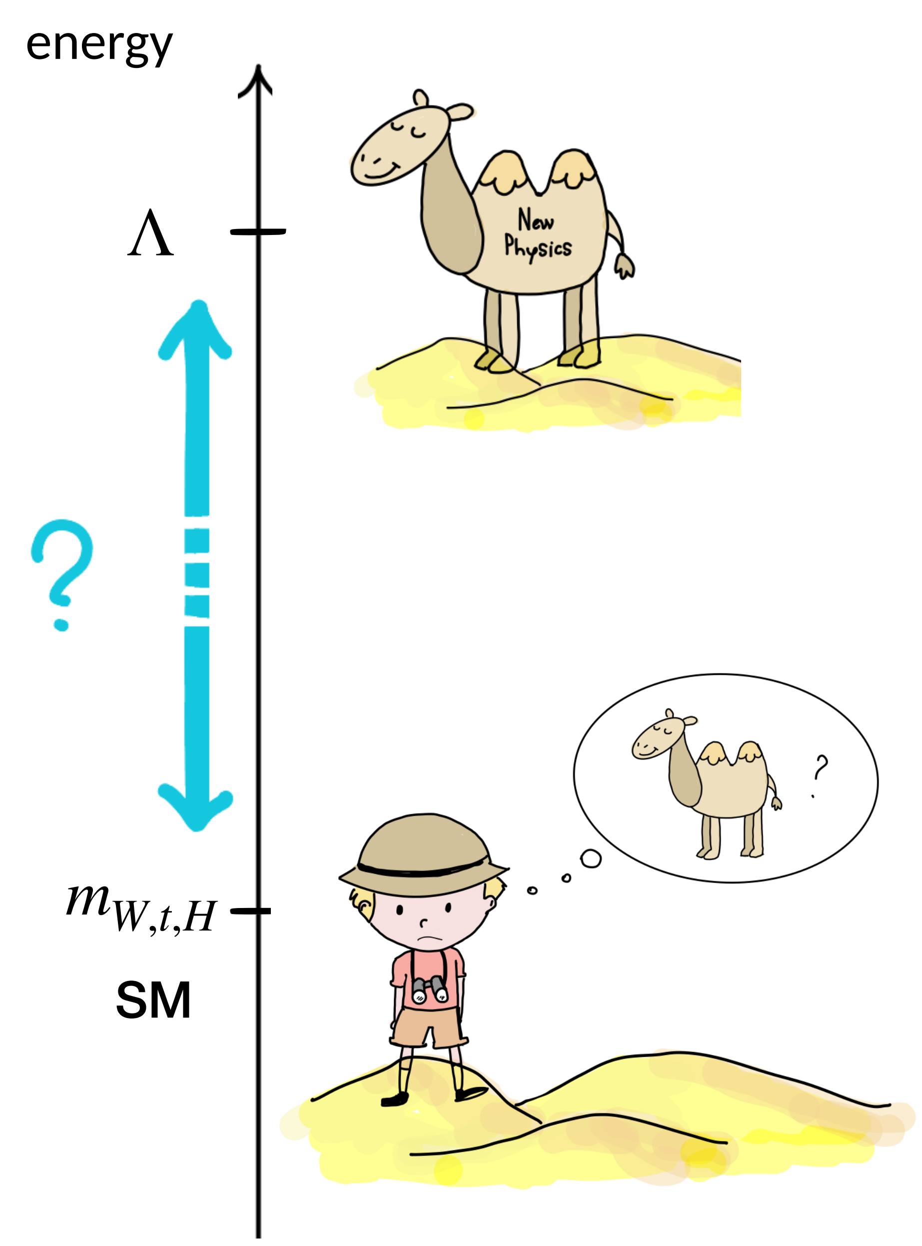


The scale of New Physics

We have many reasons to think that the SM must be extended at higher energies. But **how high**?

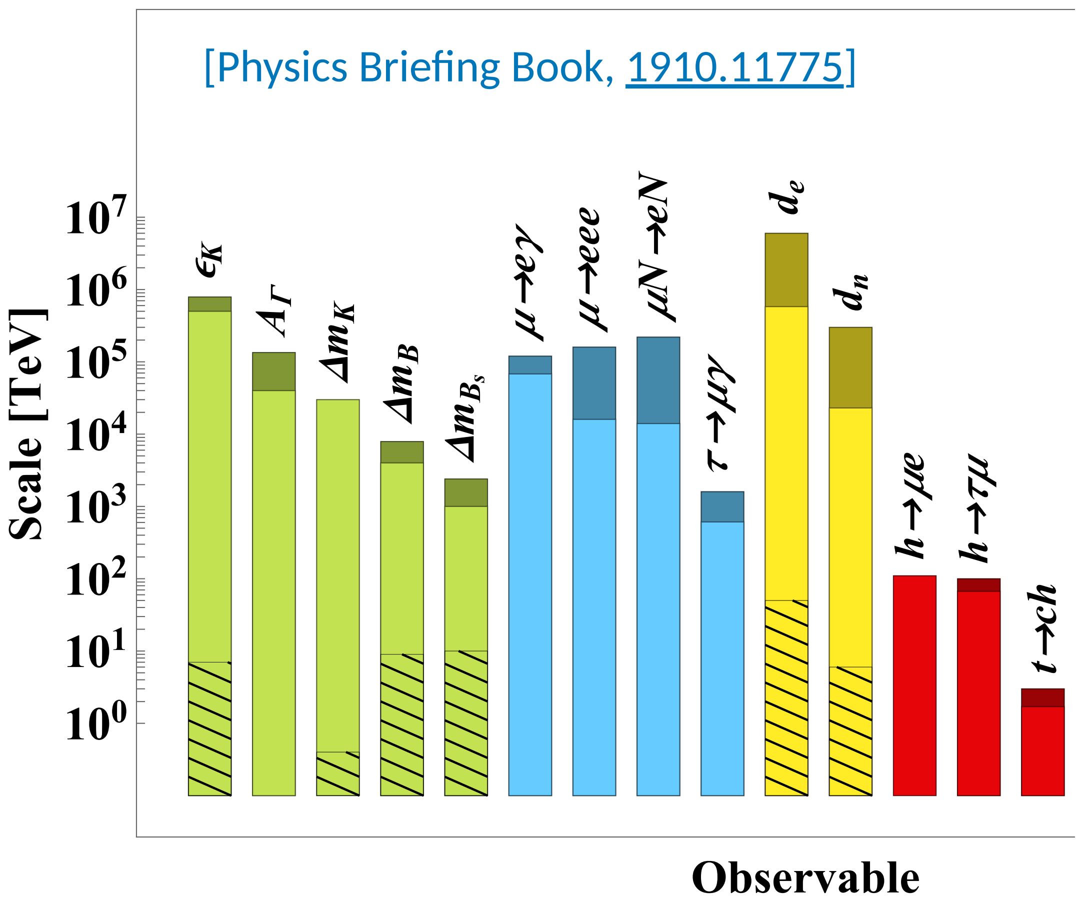
In absence of direct evidence, we rely on the **SMEFT**:

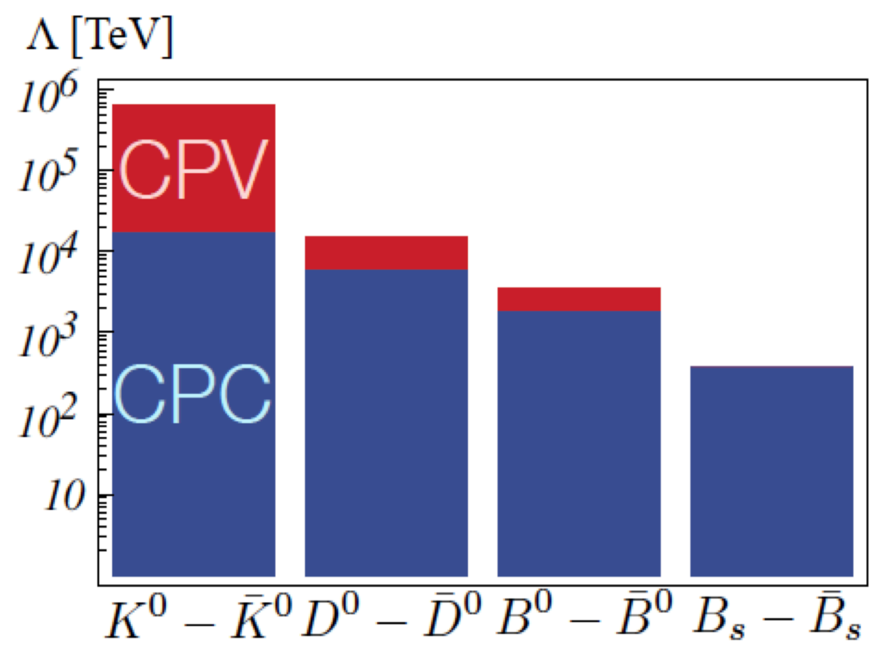
With data we place constraints on the coefficients of SMEFT operators, and interpret them as **constraints** on an (effective) **NP scale**.



The scale of New Physics

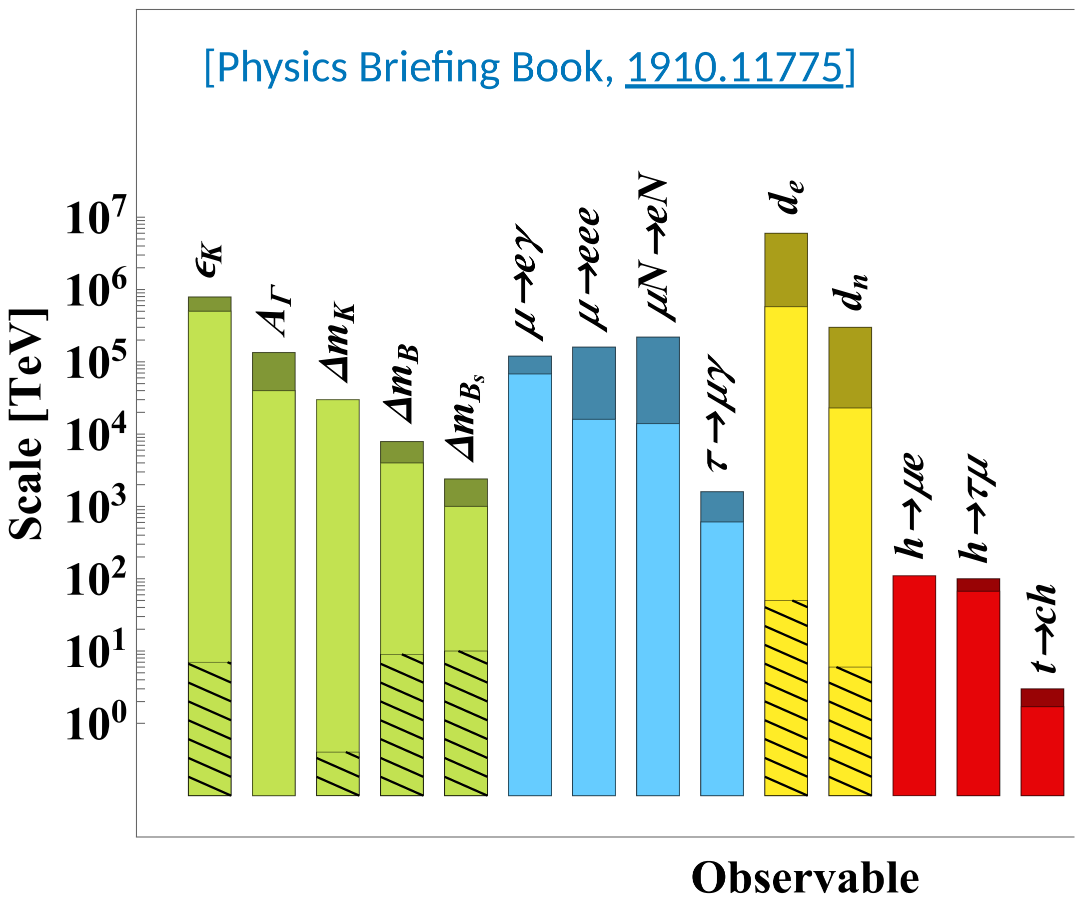
With O(1) NP couplings, bounds on **flavor-violating** operators point to **huge scales**:

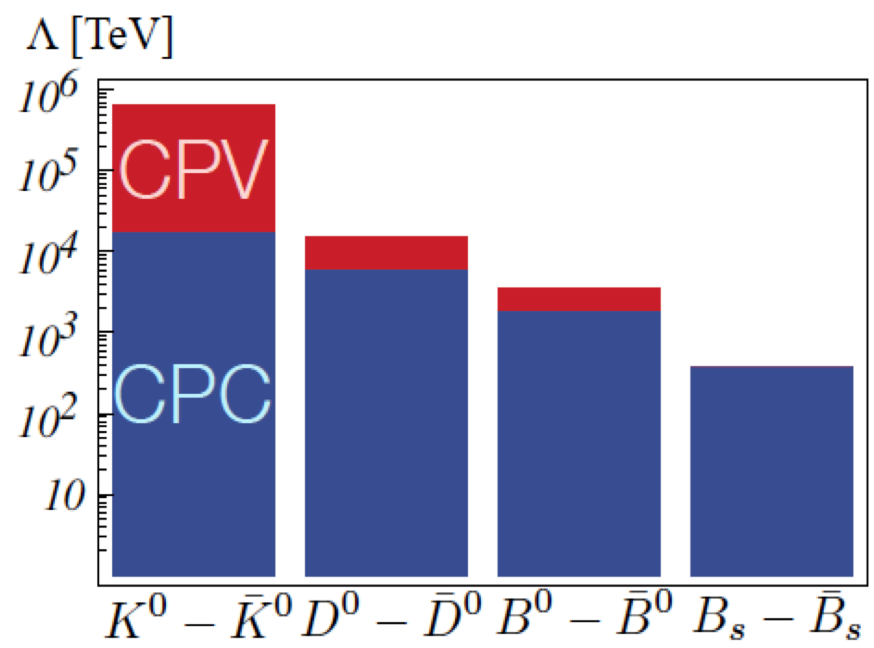




The scale of New Physics

With O(1) NP couplings, bounds on **flavor-violating** operators point to **huge scales**:

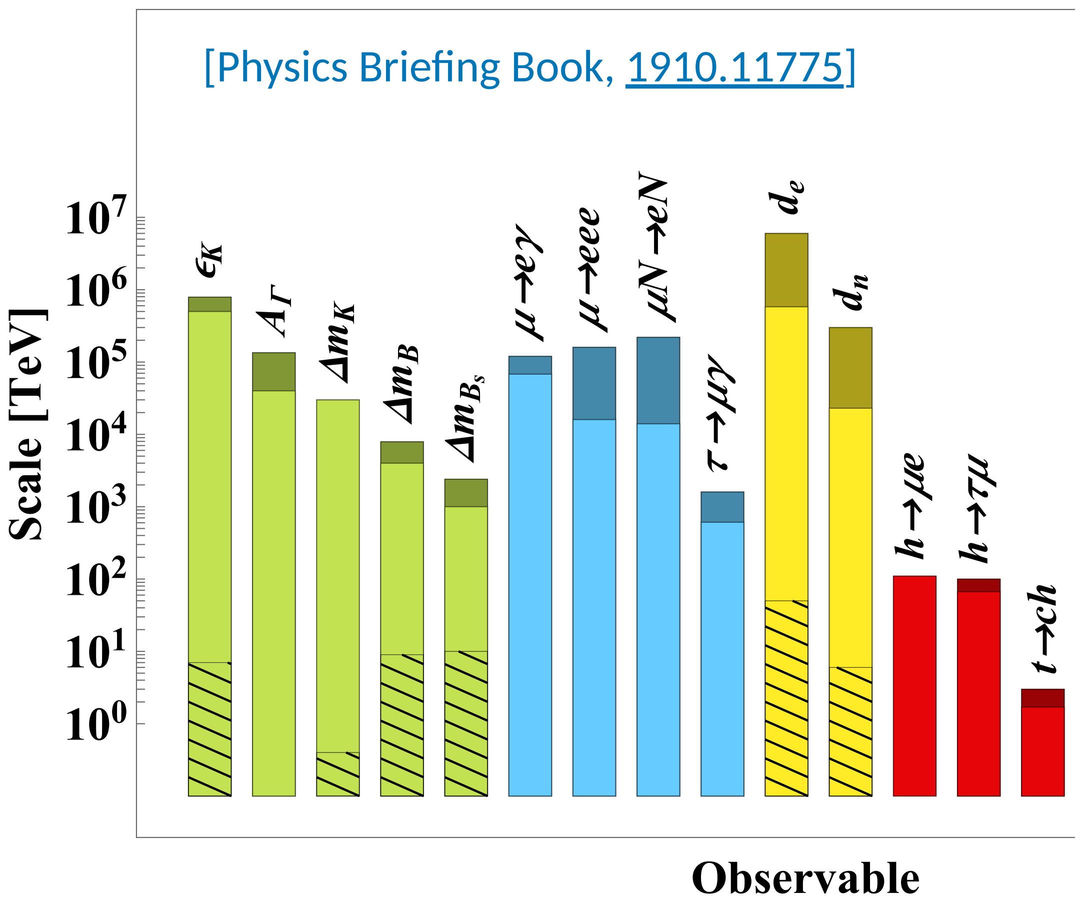


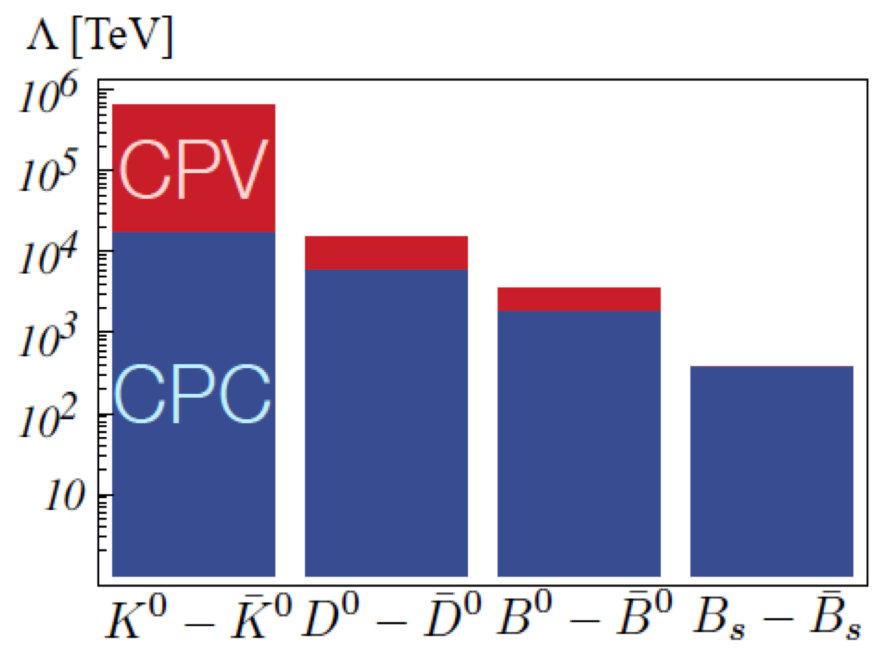


…but in realistic models these couplings can be suppressed, and give much looser constraints!

The scale of New Physics

With O(1) NP couplings, bounds on **flavor-violating** operators point to **huge scales**:





…but in realistic models these couplings can be suppressed, and give much looser constraints!

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

Goal

Here: focus on **models where NP predominantly couples to the third generation**.

1. **How low** can the energy **scale of new physics** be for these class of models, and which conditions make this possible?

2. **How will the bounds** on these models **change** in the **future**?
   (considering up-coming flavor and collider data, and, more long term, a future e+e- collider like the FCC-ee)

The SM flavor puzzle and the U(2) symmetry

Models where NP couples mostly to the **3rd family** are well-motivated: the 3rd generation plays a special role in the **hierarchy problem** and the **flavor puzzle**.

The SM flavor puzzle and the U(2) symmetry

Models where NP couples mostly to the **3rd family** are well-motivated: the 3rd generation plays a special role in the **hierarchy problem** and the **flavor puzzle**.

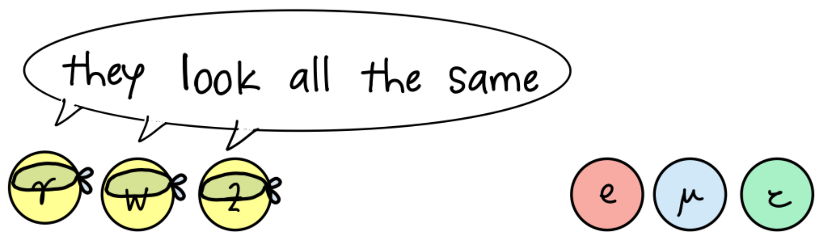
The **gauge** sector of the SM is **flavor blind**, and has a large accidental symmetry:

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

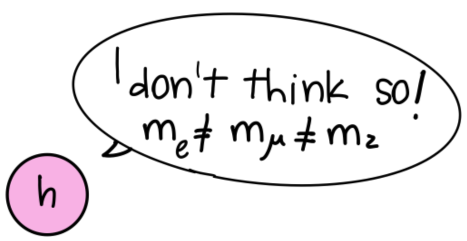
The SM flavor puzzle and the U(2) symmetry

Models where NP couples mostly to the **3rd family** are well-motivated: the 3rd generation plays a special role in the **hierarchy problem** and the **flavor puzzle**.

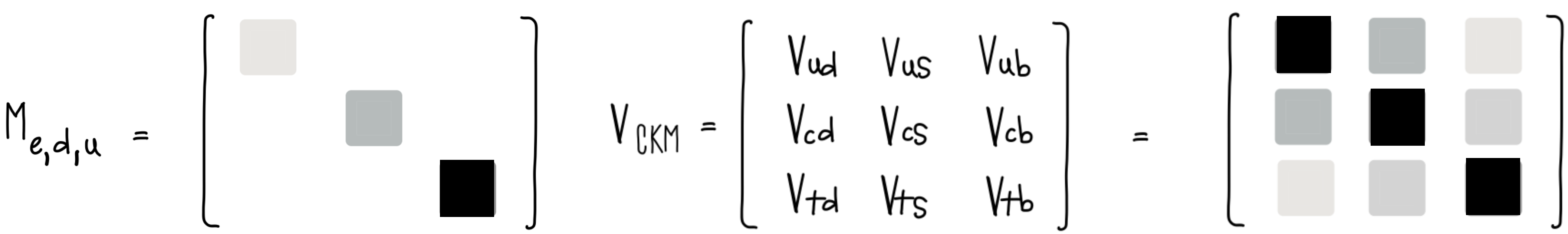
The **gauge** sector of the SM is **flavor blind**,
and has a large accidental symmetry:



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



Yukawa interactions **break** this symmetry in a specific way:



$$U^5(3) \to U(2)^5 \equiv U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e \qquad \psi = ((\psi_1\ \psi_2)\ \psi_3)$$

[Barbieri et al. 2022, Isidori,Straub 2012]

The New Physics flavor puzzle

The NP flavor puzzle:

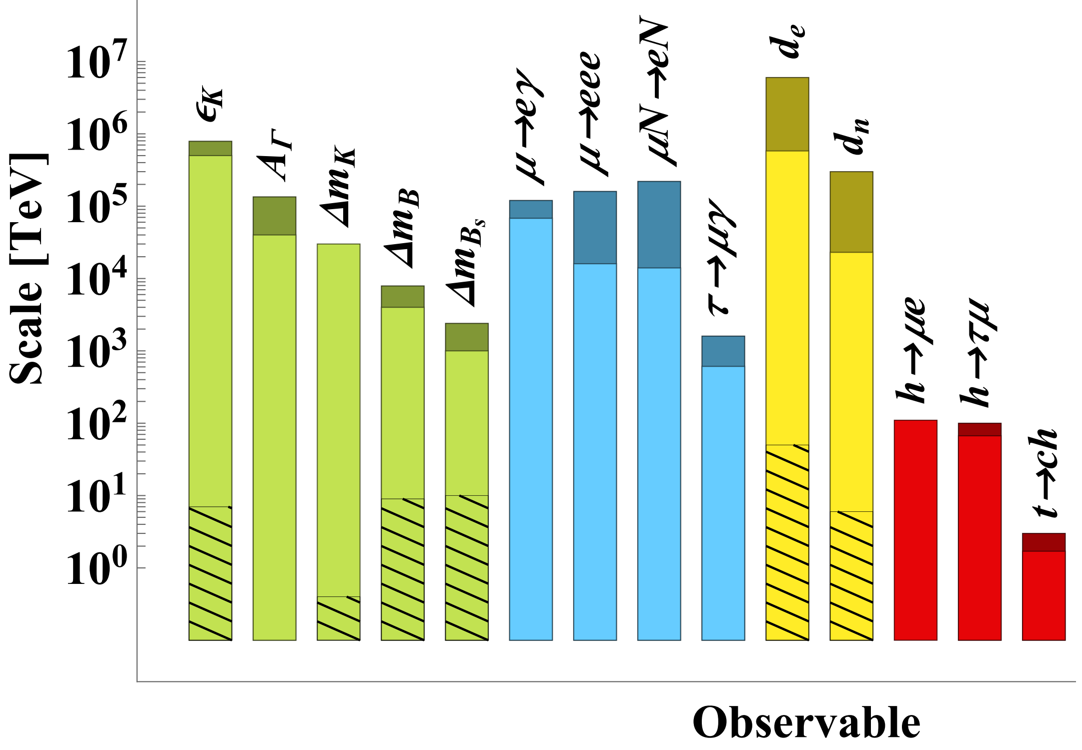
Flavor is just an accidental symmetry: nothing forbids it to be badly violated in the UV. Then why don't we observe sizeable non-standard flavor-violating effects?

Either because the scale of these interaction is astronomically high, or because the couplings of these operators are small.

In either case, the only **unambiguous** message of these bounds is that **there is no large breaking of U(2)^5 at nearby scales**.

U(2)^5 is a good symmetry also of the SMEFT!

[Physics Briefing Book 2020, 1910.11775]



$U(2)^5$ vs MFV

Previously, the way to allow for TeV NP while protecting it from flavor bounds was to assume **Minimal Flavor Violation**.

- Yukawas are the only sources of $G_f=U(3)^5$ breaking also beyond the SM.
- by construction, MFV gives little to no effect in flavor-changing processes.
- MFV describes (perturbations around) **flavor-universal NP** (1) = (2) = (3)

In particular, it does *not* suppress NP couplings to valence quarks….

And now LHC data push the scale of MFV NP to scales $\gtrsim$ 10 TeV!

$U(2)^5$ vs MFV

Previously, the way to allow for TeV NP while protecting it from flavor bounds was to assume **Minimal Flavor Violation**.

- Yukawas are the only sources of $G_f=U(3)^5$ breaking also beyond the SM.
- by construction, MFV gives little to no effect in flavor-changing processes.
- MFV describes (perturbations around) **flavor-universal NP**

In particular, it does *not* suppress NP couplings to valence quarks....

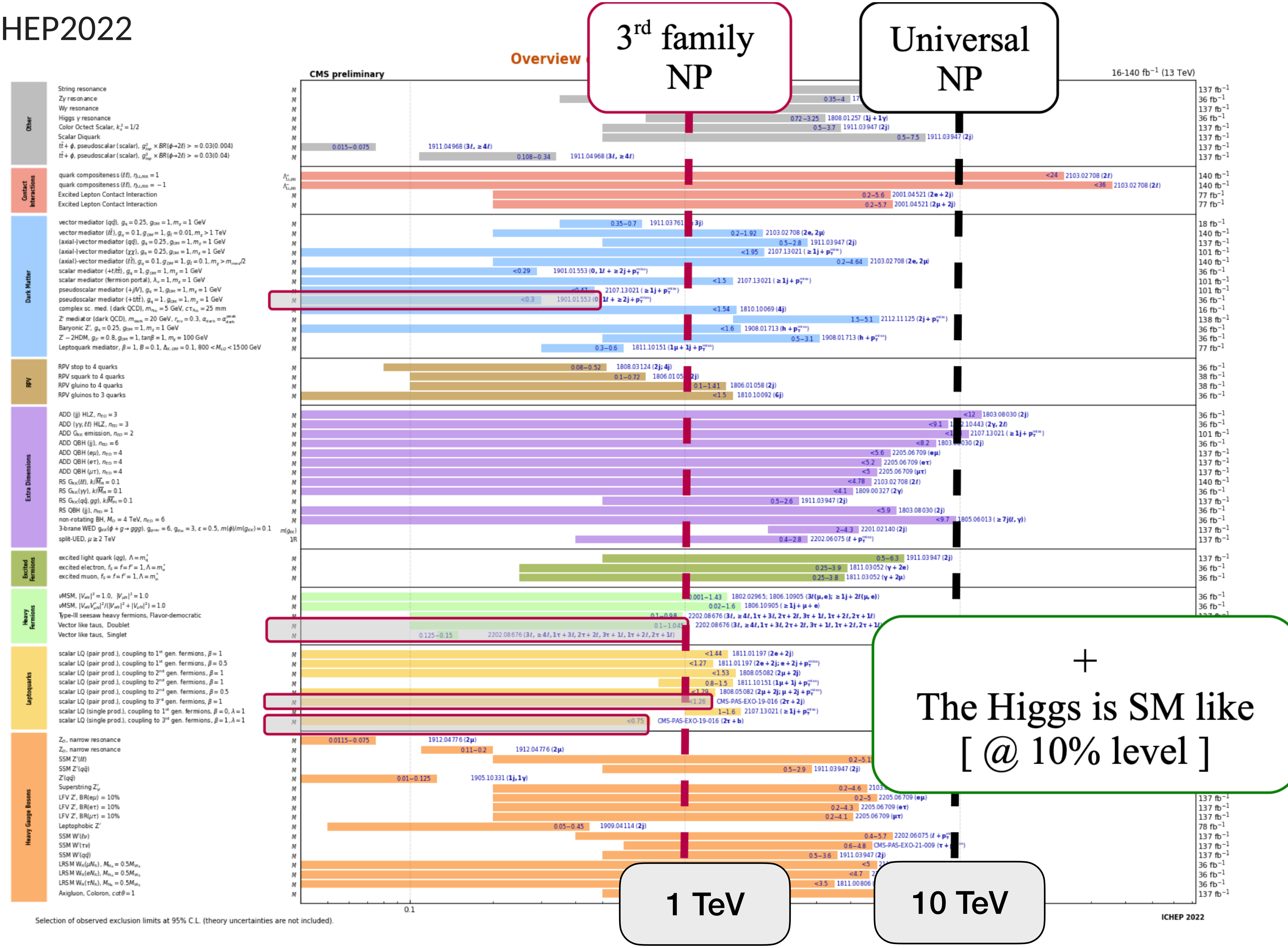
And now LHC data push the scale of MFV NP to scales $\gtrsim$ 10 TeV!

By contrast, **$U(2)^5$** describes **flavor non-universal NP**, placing a clear distinction between light and heavy generations.

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

Status of high-energy searches

@ICHEP2022



Flavor non-universal interactions

These considerations translate into model-building ideas!

For a while, attempts to extend the SM implicitly assumed:

- TeV-scale **flavor-universal** NP stabilising the Higgs
- flavor dynamics originates at some $\Lambda \gg$ TeV

Flavor non-universal interactions

These considerations translate into model-building ideas!

For a while, attempts to extend the SM implicitly assumed:

- TeV-scale **flavor-universal** NP stabilising the Higgs
- flavor dynamics originates at some $\Lambda \gg$ TeV

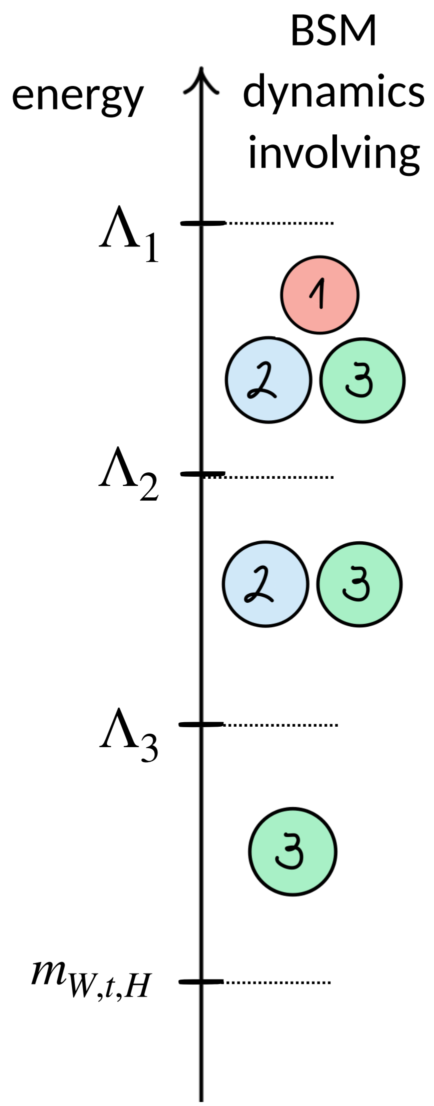
Now **flavor non-universal** interactions are gaining momentum.

[Dvali, Shiftman, '00, Panico, Pomarol 1603.06609;...Bordone, CC, Fuentes, Isidori 1712.01368; Barbieri, 2103.15635; Davighi, Isidori, 2303.01520; Davighi, Stefanek, 2305.16280]

- The 3 families are *not* identical up to very high energies.

  Multiscale picture: non-universal interactions acting on the i-th family switch on at $\Lambda_1 \gg \Lambda_2 \gg \Lambda_3 \gg m_W$

- interactions distinguishing light vs 3rd family emerge first @ Λ_3



Flavor non-universal interactions

These considerations translate into model-building ideas!

For a while, attempts to extend the SM implicitly assumed:

- TeV-scale **flavor-universal** NP stabilising the Higgs
- flavor dynamics originates at some Λ>> TeV

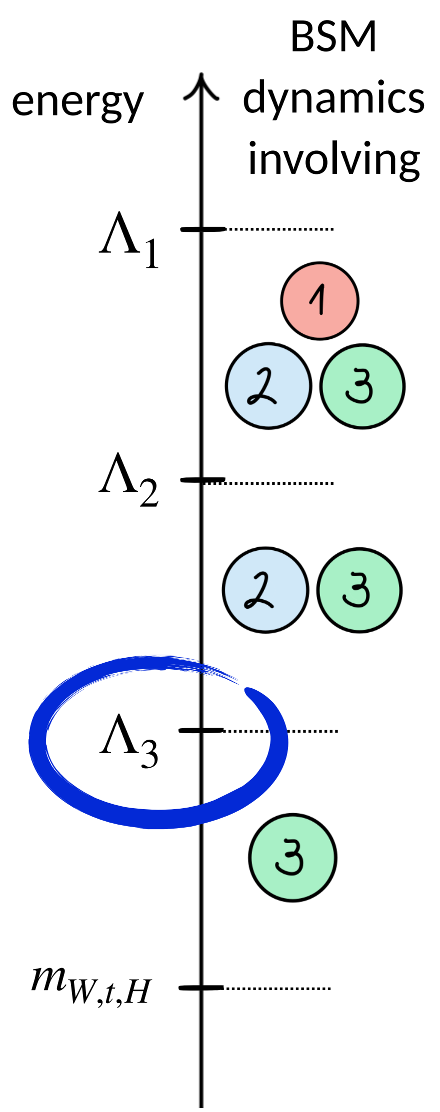
Now **flavor non-universal** interactions are gaining momentum.

[Dvali, Shiftman, '00, Panico, Pomarol 1603.06609;...Bordone, CC, Fuentes, Isidori 1712.01368; Barbieri, 2103.15635; Davighi, Isidori, 2303.01520; Davighi, Stefanek, 2305.16280]

- The 3 families are *not* identical up to very high energies.

  Multiscale picture: non-universal interactions acting on the i-th family switch on at $\Lambda_1 \gg \Lambda_2 \gg \Lambda_3 \gg m_W$

- interactions distinguishing light vs 3rd family emerge first @ Λ_3



The U(2) symmetric SMEFT

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

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

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]

The U(2) symmetric SMEFT

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

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

An example:

$$Q_{He}^{[ij]} = (H^\dagger i D_\mu H)(\bar{e}_i \gamma^\mu e_j)$$

SMEFT

6 independent structures

$U(2)^5$ - symmetric SMEFT

only 2 independent structures

$$Q_{He}^{[33]} = (H^\dagger i D_\mu H)(\bar{e}_3 \gamma^\mu e_3)\,,$$
$$Q_{He}^{[ii]} = (H^\dagger i D_\mu H)\sum_{i=1,2}(\bar{e}_i \gamma^\mu e_i)$$

The flavor rotation

What is the **third generation** in the SMEFT?

Non-trivial to define for the LH quark doublet because of the CKM misalignment!

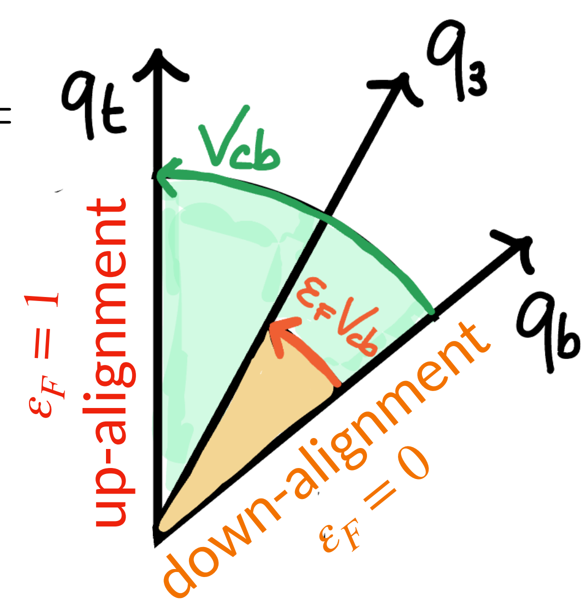
The flavor rotation

What is the **third generation** in the SMEFT?

Non-trivial to define for the LH quark doublet because of the CKM misalignment!

In the interaction basis where the dim-6 SMEFT operators are U(2)^5 symmetric, the 3rd generation quark doublet is somewhere **in-between** the down-aligned and the up-aligned case.

$$\begin{pmatrix} t_L \\ V_{td} d_L + V_{ts} s_L + V_{tb} b_L \end{pmatrix} = q_t$$



$$q_b = \begin{pmatrix} V_{ub}^* u_L + V_{cb}^* c_L + V_{tb}^* t_L \\ b_L \end{pmatrix}$$

We can describe this **misalignment** in terms of a single **angle** in the 2-3 sector, $\theta \sim V_{cb}\, \boldsymbol{\varepsilon_F}$.

Observables

EWPO

- W-pole observables [V. Bresó-Pla, A. Falkowski, M. González-Alonso, 2103.12074]
- Z-pole observables [L. Allwicher, G. Isidori, J. M. Lizana, N. Selimovic, B.Stefanek, 2302.11584]
- Higgs signal strengths + LFU tests in τ-decays

Observables

EWPO

- W-pole observables [V. Bresó-Pla, A. Falkowski, M. González-Alonso, 2103.12074]
- Z-pole observables [L. Allwicher, G. Isidori, J. M. Lizana, N. Selimovic, B.Stefanek, 2302.11584]
- Higgs signal strengths + LFU tests in τ-decays

Flavor

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

Observables

EWPO

- W-pole observables [V. Bresó-Pla, A. Falkowski, M. González-Alonso, 2103.12074]
- Z-pole observables [L. Allwicher, G. Isidori, J. M. Lizana, N. Selimovic, B.Stefanek, 2302.11584]
- Higgs signal strengths + LFU tests in τ-decays

Flavor

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

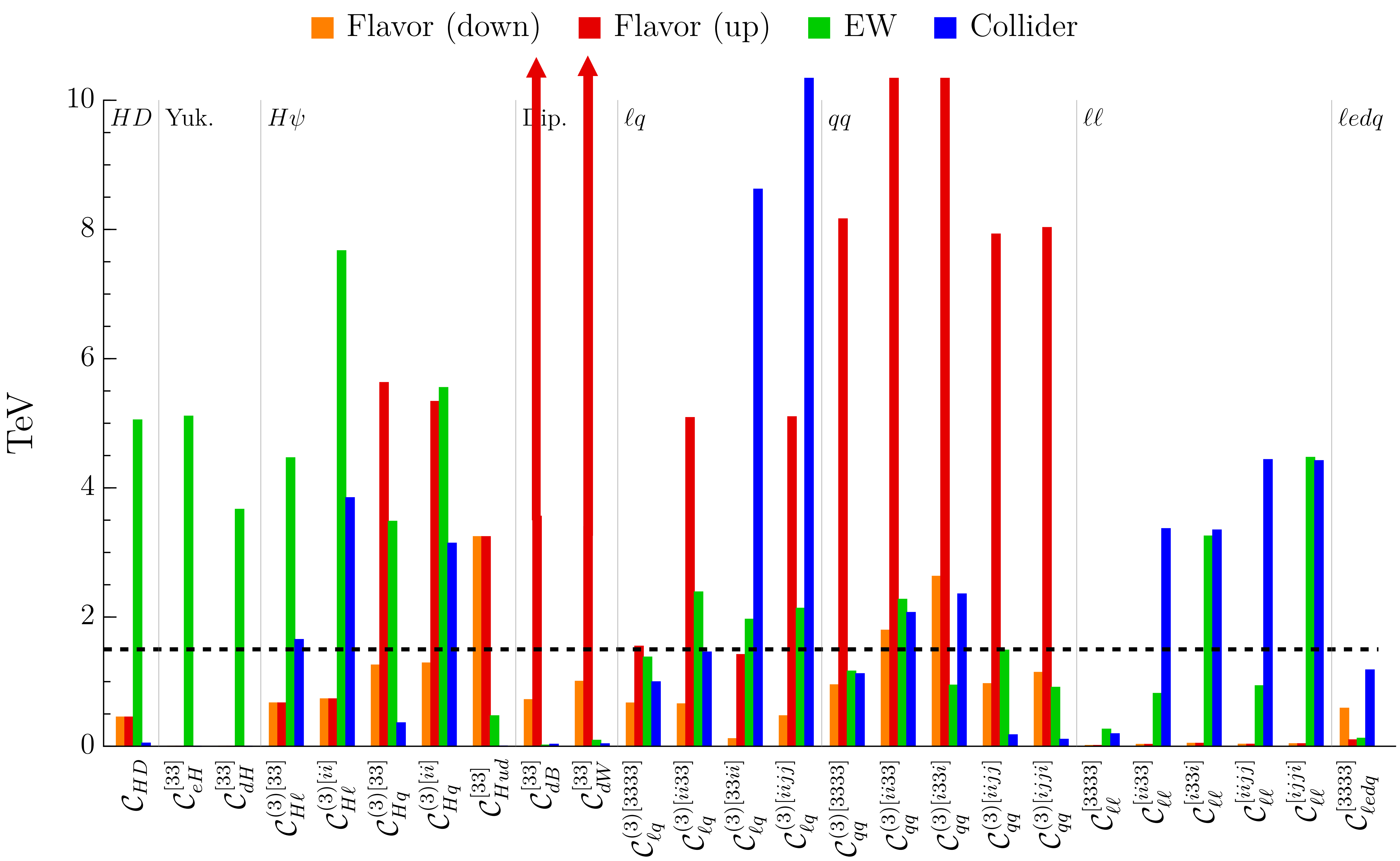
Collider

- LHC Drell-Yan $pp \to \ell\ell$ and mono-lepton $pp \to \ell\nu$ [L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, 2207.10756]
- LHC 4-quark observables
- LEP 4-lepton $ee \to \ell\ell$ [Ethier, Magni, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang, 2105.00006]

Analysis strategy

- Run all WCs to a reference scale Λ = 3 TeV.
- For LEFT running, LEFT-SMEFT matching and SMEFT running we use DSixTools, which allows us to work analytically in the WCs also beyond leading log.
- Once all observables have been expressed in terms of SMEFT WCs at the hight scale, we impose the $U(2)^5$ symmetry.
- We construct the combined likelihood from collider, EW, and flavour observables as a function of the 124 WCs of the $U(2)^5$-symmetric (and CP conserving) SMEFT, and switch them on one at a time to get lower bound on the NP scale.

Results



Flavor (down)
Flavor (up)
EW
Collider
TeV
0
2
4
6
8
10
HD
Yuk.
$H\psi$
Dip.
ℓq
qq
$\ell\ell$
ℓedq
$\mathcal{C}_{HD}$
$\mathcal{C}_{eH}^{[33]}$
$\mathcal{C}_{dH}^{[33]}$
$\mathcal{C}_{H\ell}^{(3)[33]}$
$\mathcal{C}_{H\ell}^{(3)[ii]}$
$\mathcal{C}_{Hq}^{(3)[33]}$
$\mathcal{C}_{Hq}^{(3)[ii]}$
$\mathcal{C}_{Hud}^{[33]}$
$\mathcal{C}_{dB}^{[33]}$
$\mathcal{C}_{dW}^{[33]}$
$\mathcal{C}_{\ell q}^{(3)[3333]}$
$\mathcal{C}_{\ell q}^{(3)[ii33]}$
$\mathcal{C}_{\ell q}^{(3)[33ii]}$
$\mathcal{C}_{\ell q}^{(3)[iijj]}$
$\mathcal{C}_{qq}^{(3)[3333]}$
$\mathcal{C}_{qq}^{(3)[ii33]}$
$\mathcal{C}_{qq}^{(3)[i33i]}$
$\mathcal{C}_{qq}^{(3)[iijj]}$
$\mathcal{C}_{qq}^{(3)[ijji]}$
$\mathcal{C}_{\ell\ell}^{[3333]}$
$\mathcal{C}_{\ell\ell}^{[ii33]}$
$\mathcal{C}_{\ell\ell}^{[i33i]}$
$\mathcal{C}_{\ell\ell}^{[iijj]}$
$\mathcal{C}_{\ell\ell}^{[ijji]}$
$\mathcal{C}_{\ell edq}^{[3333]}$

Results

Strong **complementarity** between 3 sectors.

Out of 124 bounds, 46 are dominated by **EWPO**, 42 by **collider**, 36 by **flavor**

Results

Strong **complementarity** between 3 sectors.

Out of 124 bounds, 46 are dominated by **EWPO**, 42 by **collider**, 36 by **flavor**

- the strongest bounds in the **EW sector** are 5 - 10 TeV for operators with one or more Higgs fields.

coeff.	$\Lambda_{\text{flav.}}^{\text{down}}$	$\Lambda_{\text{flav.}}^{\text{up}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$
$\mathcal{C}_{H\ell}^{(1)[33]}$	0.1	0.1	4.4	1.6
$\mathcal{C}_{H\ell}^{(1)[ii]}$	0.7	0.7	7.6	3.
$\mathcal{C}_{H\ell}^{(3)[33]}$	0.7	0.7	4.5	1.7
$\mathcal{C}_{H\ell}^{(3)[ii]}$	0.7	0.7	7.7	3.8
$\mathcal{C}_{He}^{[33]}$	-	-	3.8	1.5
$\mathcal{C}_{He}^{[ii]}$	0.9	0.9	6.6	2.7
$\mathcal{C}_{\ell q}^{(3)[3333]}$	0.7	1.5	1.4	1.
$\mathcal{C}_{\ell q}^{(3)[ii33]}$	0.7	5.1	2.4	1.5
$\mathcal{C}_{\ell q}^{(3)[33ii]}$	0.1	1.4	2.	8.6
$\mathcal{C}_{\ell q}^{(3)[iijj]}$	0.5	5.1	2.1	22.5

Results

Strong **complementarity** between 3 sectors.

Out of 124 bounds, 46 are dominated by **EWPO**, 42 by **collider**, 36 by **flavor**

- the strongest bounds in the **EW sector** are 5 - 10 TeV for operators with one or more Higgs fields.
- the strongest bounds from **collider data** are 5 - 20 TeV for 4-fermion operators with 1st-family quarks and leptons.

  Operators with 3rd-family fermions get milder bounds, ~ 1 TeV.

coeff.	$\Lambda^{\text{down}}_{\text{flav.}}$	$\Lambda^{\text{up}}_{\text{flav.}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$
$\mathcal{C}^{(1)[33]}_{H\ell}$	0.1	0.1	4.4	1.6
$\mathcal{C}^{(1)[ii]}_{H\ell}$	0.7	0.7	7.6	3.
$\mathcal{C}^{(3)[33]}_{H\ell}$	0.7	0.7	4.5	1.7
$\mathcal{C}^{(3)[ii]}_{H\ell}$	0.7	0.7	7.7	3.8
$\mathcal{C}^{[33]}_{He}$	-	-	3.8	1.5
$\mathcal{C}^{[ii]}_{He}$	0.9	0.9	6.6	2.7
$\mathcal{C}^{(3)[3333]}_{\ell q}$	0.7	1.5	1.4	1.
$\mathcal{C}^{(3)[ii33]}_{\ell q}$	0.7	5.1	2.4	1.5
$\mathcal{C}^{(3)[33ii]}_{\ell q}$	0.1	1.4	2.	8.6
$\mathcal{C}^{(3)[iijj]}_{\ell q}$	0.5	5.1	2.1	22.5

Results

Strong **complementarity** between 3 sectors.

Out of 124 bounds, 46 are dominated by **EWPO**, 42 by **collider**, 36 by **flavor**

For operators contributing to **flavor-violating** observables, U(2) is quite effective in reducing the associated scales.

coeff.	$\Lambda^{\text{down}}_{\text{flav.}}$	$\Lambda^{\text{up}}_{\text{flav.}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$
$\mathcal{C}_{qq}^{(1)[3333]}$	1.	7.8	1.6	1.1
$\mathcal{C}_{qq}^{(1)[ii33]}$	1.3	11.2	0.9	1.5
$\mathcal{C}_{qq}^{(1)[i33i]}$	2.5	11.3	0.7	1.6
$\mathcal{C}_{qq}^{(1)[iijj]}$	0.9	8.1	0.4	-
$\mathcal{C}_{qq}^{(1)[ijji]}$	1.1	8.1	0.5	-

Results

Strong **complementarity** between 3 sectors.

Out of 124 bounds, 46 are dominated by **EWPO**, 42 by **collider**, 36 by **flavor**

For operators contributing to **flavor-violating** observables, U(2) is quite effective in reducing the associated scales.

- Still, certain operators get bounds of 5 - 10 TeV**,** especially in the up-aligned scenario, similarly to MFV.

coeff.	$\Lambda^{\text{down}}_{\text{flav.}}$	$\Lambda^{\text{up}}_{\text{flav.}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$
$\mathcal{C}_{qq}^{(1)[3333]}$	1.	7.8	1.6	1.1
$\mathcal{C}_{qq}^{(1)[ii33]}$	1.3	11.2	0.9	1.5
$\mathcal{C}_{qq}^{(1)[i33i]}$	2.5	11.3	0.7	1.6
$\mathcal{C}_{qq}^{(1)[iijj]}$	0.9	8.1	0.4	-
$\mathcal{C}_{qq}^{(1)[ijji]}$	1.1	8.1	0.5	-

Results

Strong **complementarity** between 3 sectors.

Out of 124 bounds, 46 are dominated by **EWPO**, 42 by **collider**, 36 by **flavor**

For operators contributing to **flavor-violating** observables, U(2) is quite effective in reducing the associated scales.

- Still, certain operators get bounds of 5 - 10 TeV, especially in the up-aligned scenario, similarly to MFV.
- Down alignment can relax these bounds down to ~ few TeV.

coeff.	$\Lambda^{\text{down}}_{\text{flav.}}$	$\Lambda^{\text{up}}_{\text{flav.}}$	Λ_{EW}	$\Lambda_{\text{coll.}}$
$\mathcal{C}_{qq}^{(1)[3333]}$	1.	7.8	1.6	1.1
$\mathcal{C}_{qq}^{(1)[ii33]}$	1.3	11.2	0.9	1.5
$\mathcal{C}_{qq}^{(1)[i33i]}$	2.5	11.3	0.7	1.6
$\mathcal{C}_{qq}^{(1)[iijj]}$	0.9	8.1	0.4	-
$\mathcal{C}_{qq}^{(1)[ijji]}$	1.1	8.1	0.5	-

Results

- **Importance of RG effects in the EW sector**

  Without running, only 16 operators enter the EW fit.

  With running, 123 out of 124 operators enter the EW fit.

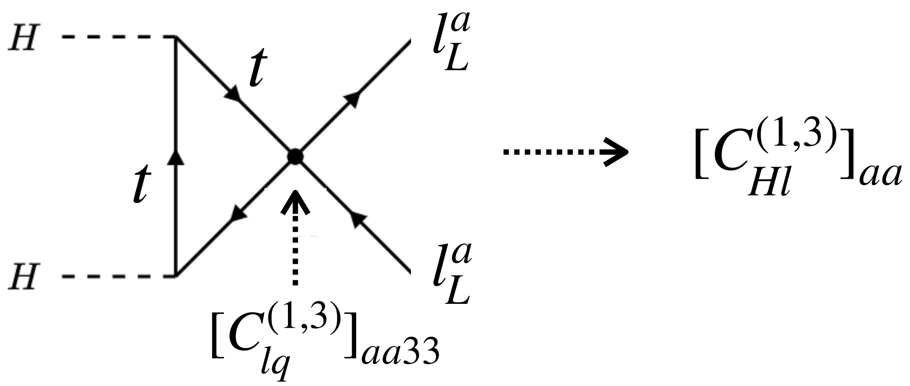
Results

- **Importance of RG effects in the EW sector**

  Without running, only 16 operators enter the EW fit.

  With running, 123 out of 124 operators enter the EW fit.

  44 get bounds stronger than 1 TeV!
  these are operators w/ 3rd-family quarks running with y_t into operators directly constrained by Z-pole obs.



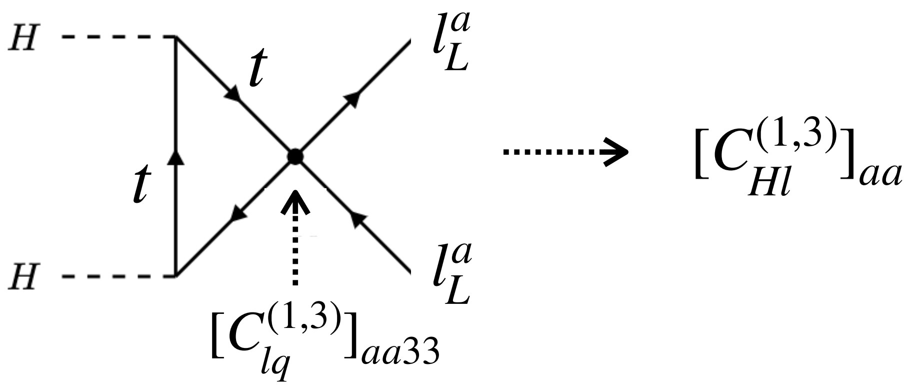
Results

- **Importance of RG effects in the EW sector**

  Without running, only 16 operators enter the EW fit.

  With running, 123 out of 124 operators enter the EW fit.

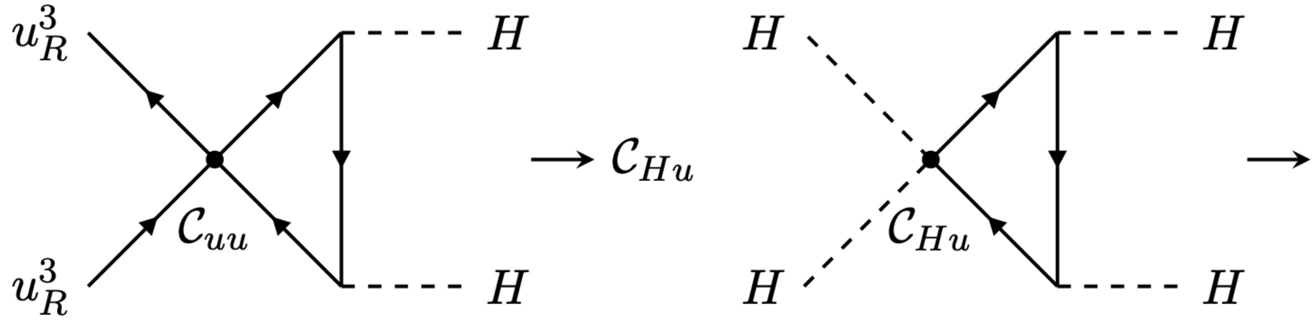
  44 get bounds stronger than 1 TeV!
  these are operators w/ 3rd-family quarks running with y_t into operators directly constrained by Z-pole obs.



- **Importance of going beyond LL when solving RGEs**

  NLL effects can change bounds by 30%

Example: $[O_{uu}]_{3333}$ enters the EW fit only at NLL by mixing with O_{HD}



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

The hypothesis of NP in the 3rd generation

Until now, we have used $U(2)^5$ without other assumptions.

$U(2)^5$ does not specify whether NP interacts more with light or 3rd-family fermions: it just distinguishes among them and protects against flavor violation in the light families.

The hypothesis of NP in the 3rd generation

Until now, we have used $U(2)^5$ without other assumptions.

$U(2)^5$ does not specify whether NP interacts more with light or 3rd-family fermions: it just distinguishes among them and protects against flavor violation in the light families.

Now focus on the well-motivated case where **NP couples mostly to the 3rd family**:

- WCs of operators w/light fields get a suppression ε_q, ε_l for each light quark & lepton:

$$C_{qe}^{[iijj]} = \frac{\varepsilon_q^2 \varepsilon_\ell^2}{\Lambda^2}$$

The hypothesis of NP in the 3rd generation

Until now, we have used U(2)^5 without other assumptions.

U(2)^5 does not specify whether NP interacts more with light or 3rd-family fermions: it just distinguishes among them and protects against flavor violation in the light families.

Now focus on the well-motivated case where **NP couples mostly to the 3rd family**:

- WCs of operators w/light fields get a suppression ε_q, ε_l for each light quark & lepton:

$$C_{qe}^{[iijj]} = \frac{\varepsilon_q^2 \varepsilon_\ell^2}{\Lambda^2}$$

Additional assumptions:

- WCs of operators with Higgs fields gets a suppression ε_H for each Higgs
- operators w/field strengths are loop generated ⇒ suppressed by $\epsilon_{\text{loop}} = \Pi_i \frac{g_i}{16\pi^2}$

The hypothesis of NP in the 3rd generation

Until now, we have used $U(2)^5$ without other assumptions.

$U(2)^5$ does not specify whether NP interacts more with light or 3rd-family fermions: it just distinguishes among them and protects against flavor violation in the light families.

Now focus on the well-motivated case where **NP couples mostly to the 3rd family**:

- WCs of operators w/light fields get a suppression ε_q, ε_l for each light quark & lepton:

$$C_{qe}^{[iijj]} = \frac{\varepsilon_q^2 \varepsilon_\ell^2}{\Lambda^2}$$

Additional assumptions:

- WCs of operators with Higgs fields gets a suppression ε_H for each Higgs
- operators w/field strengths are loop generated ⇒ suppressed by $\epsilon_{\text{loop}} = \Pi_i \frac{g_i}{16\pi^2}$

Only 4-fermion operators with 3rd family fields only are unsuppressed.
For them, $\Lambda \sim 1.5$ TeV.

The hypothesis of NP in the 3rd generation

Until now, we have used $U(2)^5$ without other assumptions.

$U(2)^5$ does not specify whether NP interacts more with light or 3rd-family fermions: it just distinguishes among them and protects against flavor violation in the light families.

Now focus on the well-motivated case where **NP couples mostly to the 3rd family**:

- WCs of operators w/light fields get a suppression ε_q, ε_l for each light quark & lepton:

$$C_{qe}^{[iijj]} = \frac{\varepsilon_q^2 \varepsilon_\ell^2}{\Lambda^2}$$

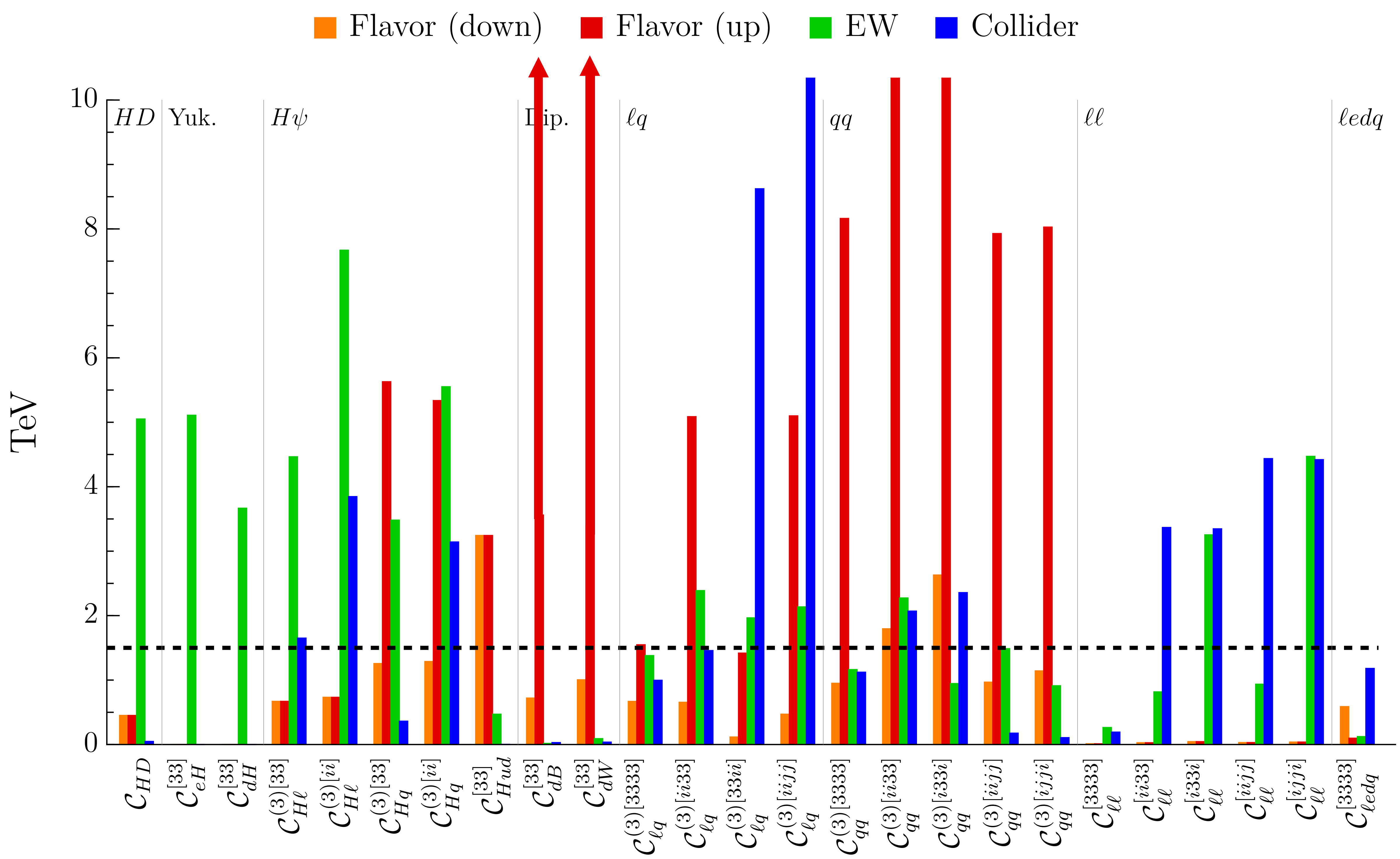
Additional assumptions:

- WCs of operators with Higgs fields gets a suppression ε_H for each Higgs
- operators w/field strengths are loop generated ⇒ suppressed by $\epsilon_{\text{loop}} = \Pi_i \frac{g_i}{16\pi^2}$

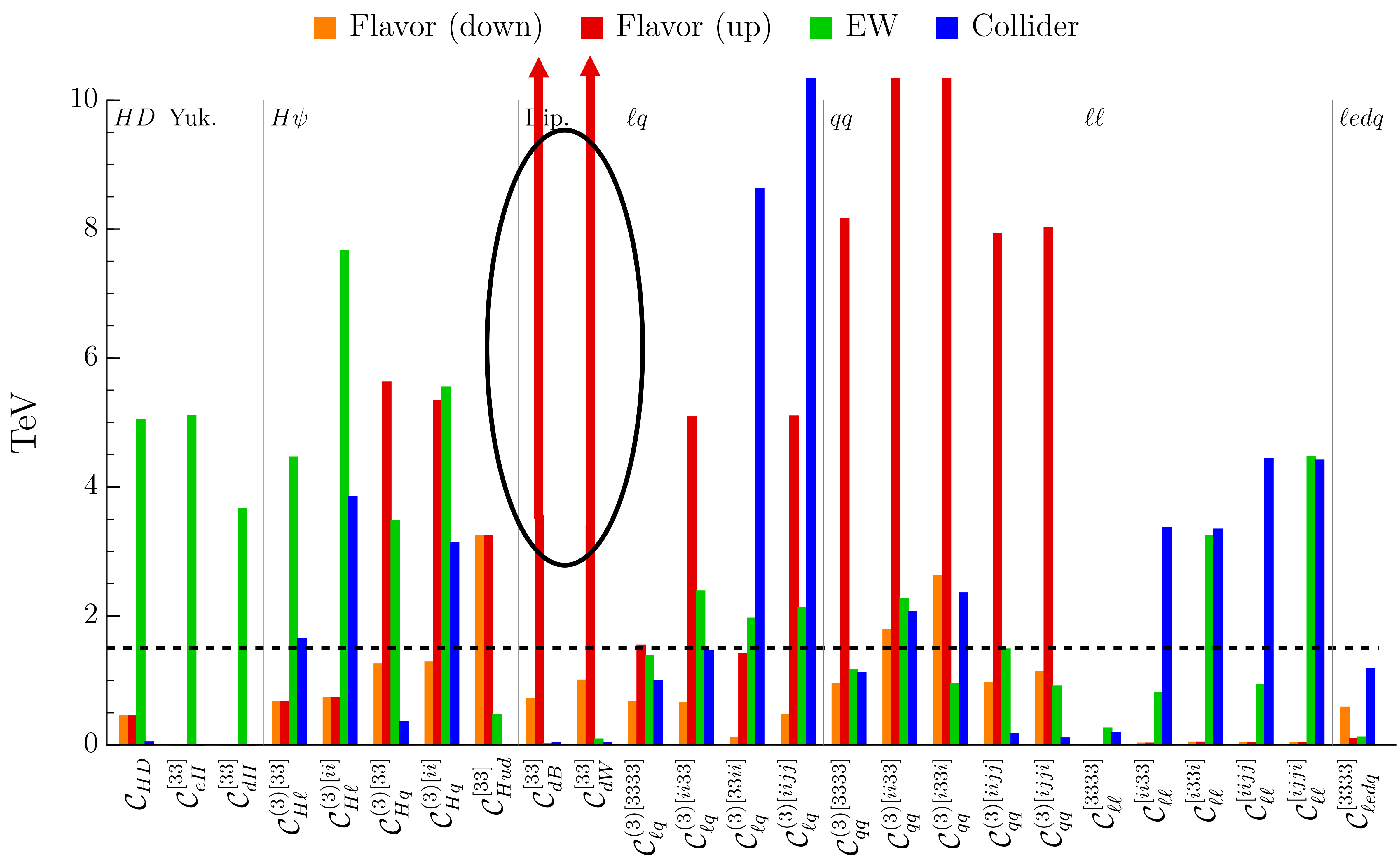
Only 4-fermion operators with 3rd family fields only are unsuppressed.
For them, $\Lambda \sim 1.5$ TeV.

Can we make the bounds on ALL other operators compatible with 1.5 TeV for reasonable values for the suppression factors ε_q, ε_l, and ε_H?

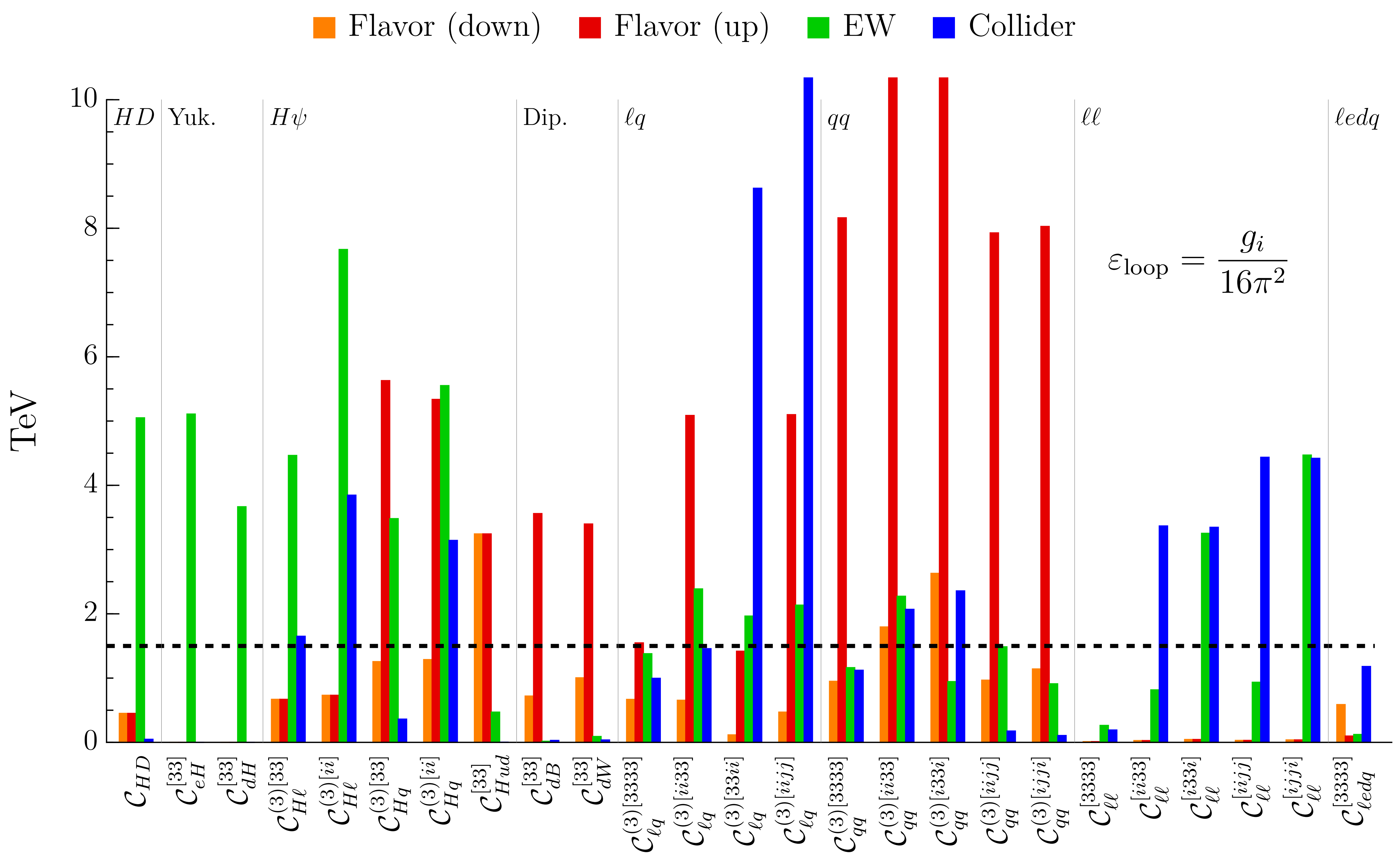
The hypothesis of NP in the 3rd generation



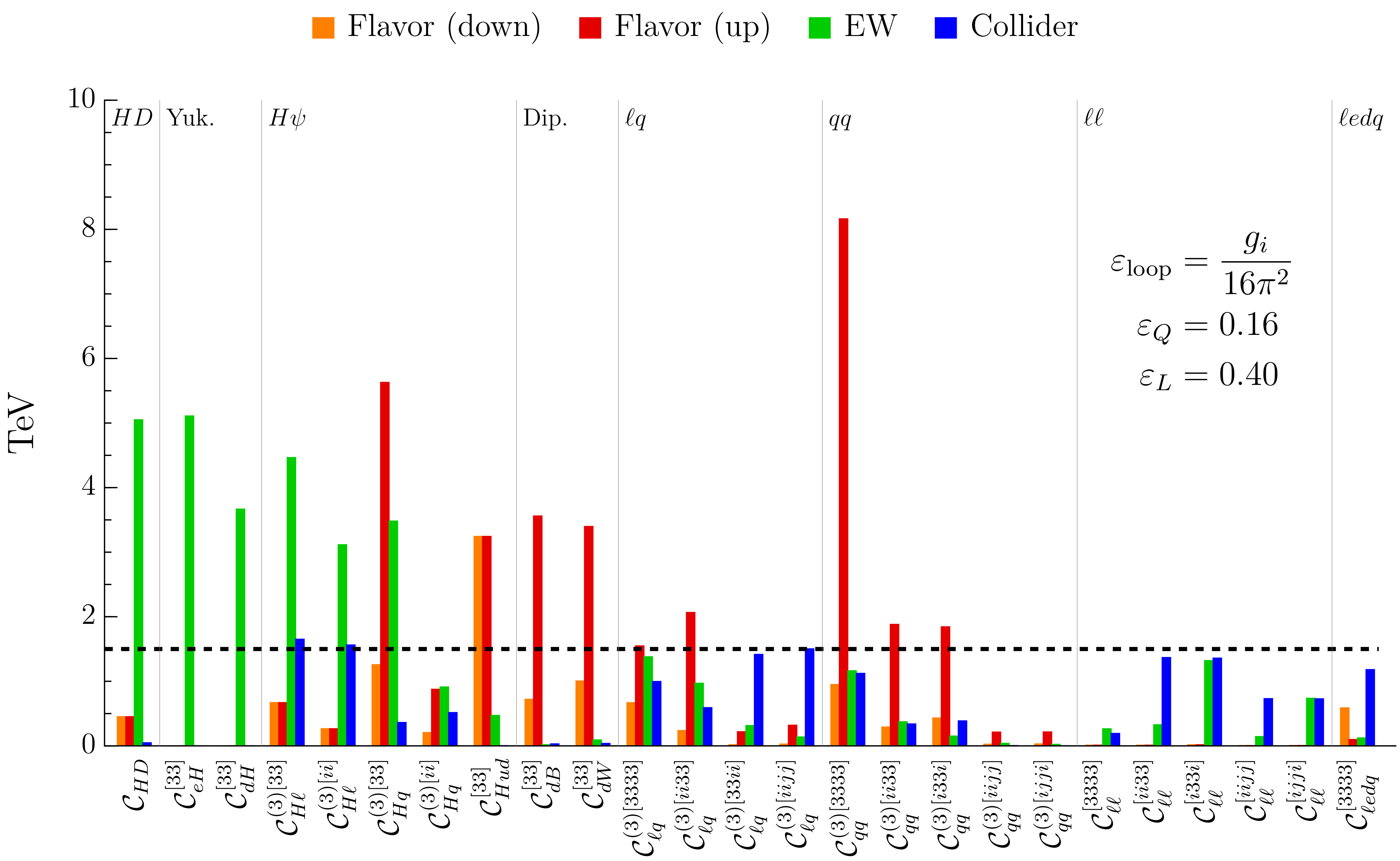
The hypothesis of NP in the 3rd generation



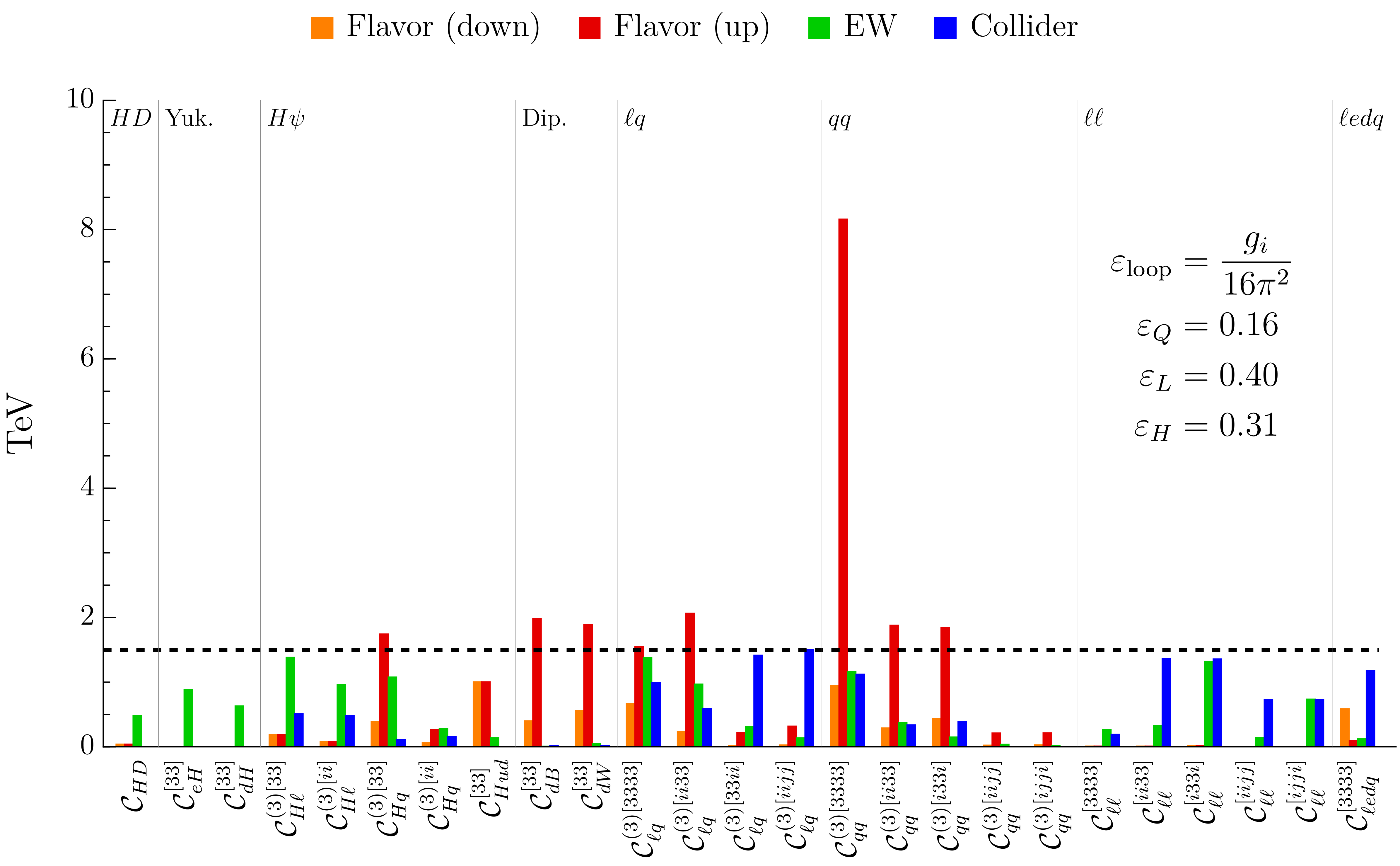
The hypothesis of NP in the 3rd generation



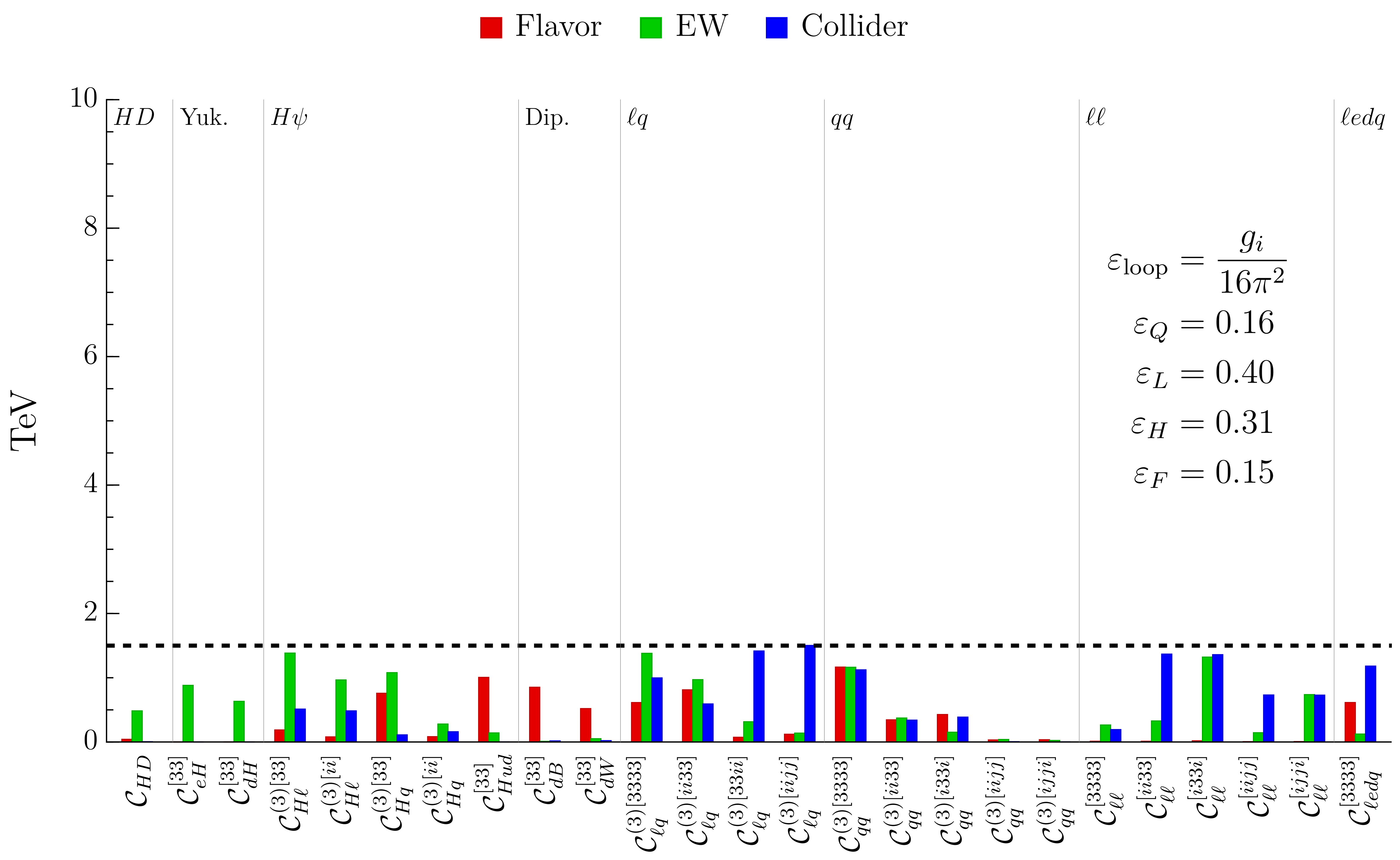
The hypothesis of NP in the 3rd generation



The hypothesis of NP in the 3rd generation



The hypothesis of NP in the 3rd generation



The hypothesis of NP in the 3rd generation

New Physics mainly coupled to the 3rd generation compatible with all current data can exist at scales as low as 1.5 TeV under these conditions:

$$\varepsilon_q \leq 0.16\,, \qquad \varepsilon_l \leq 0.40\,, \qquad \varepsilon_H \leq 0.31\,, \qquad \varepsilon_F \leq 0.15$$

The precise numbers are not “special”, but give a semi-quantitative **indication** of the general UV conditions NP models must meet to exist at nearby scales.

The hypothesis of NP in the 3rd generation

New Physics mainly coupled to the 3rd generation compatible with all current data can exist at scales as low as 1.5 TeV under these conditions:

$$\varepsilon_q \leq 0.16\,, \qquad \varepsilon_l \leq 0.40\,, \qquad \varepsilon_H \leq 0.31\,, \qquad \varepsilon_F \leq 0.15$$

The precise numbers are not "special", but give a semi-quantitative **indication** of the general UV conditions NP models must meet to exist at nearby scales.

Since these conditions are **simple** to realise & **radiatively stable**,
we can envision realistic SM extensions with NP predominantly coupled to the 3rd generation right at the TeV scale!

The hypothesis of NP in the 3rd generation

New Physics mainly coupled to the 3rd generation compatible with all current data can exist at scales as low as 1.5 TeV under these conditions:

$$\varepsilon_q \leq 0.16\,, \qquad \varepsilon_l \leq 0.40\,, \qquad \varepsilon_H \leq 0.31\,, \qquad \varepsilon_F \leq 0.15$$

The precise numbers are not "special", but give a semi-quantitative **indication** of the general UV conditions NP models must meet to exist at nearby scales.

Since these conditions are **simple** to realise & **radiatively stable**, **we can envision realistic SM extensions with NP predominantly coupled to the 3rd generation right at the TeV scale**!

…How would these bounds look like with a future tera Z machine, like FCC-ee?

Projections for FCC-ee

The expected improvements for Z- and W-pole observables, Higgs and tau decays are available from the literature.

[J. De Blas, G. Durieux, C.Grojean, J.Gu and A. Paul, 1907.04311, A. Blondel and P. Janot, 2106.13885, Snowmass 2203.06520]

Tera Z- pole run: **10^5 more Z bosons than LEP**, so statistics can improve by up to a factor 300.

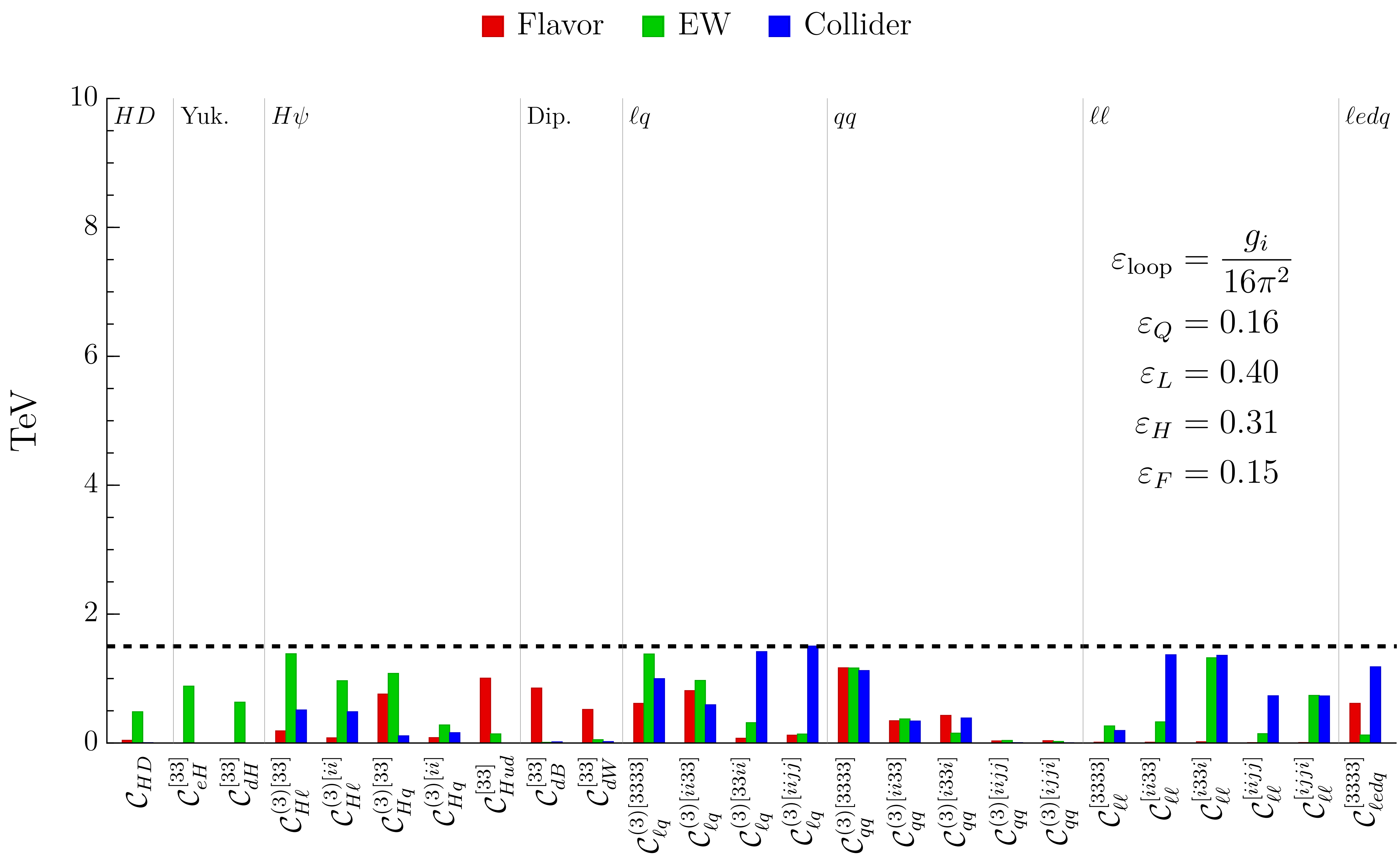
In practice, leptonic (hadronic) obs. improve by a factor 10-100 (10).

To build a projected EW likelihood for FCC-ee:

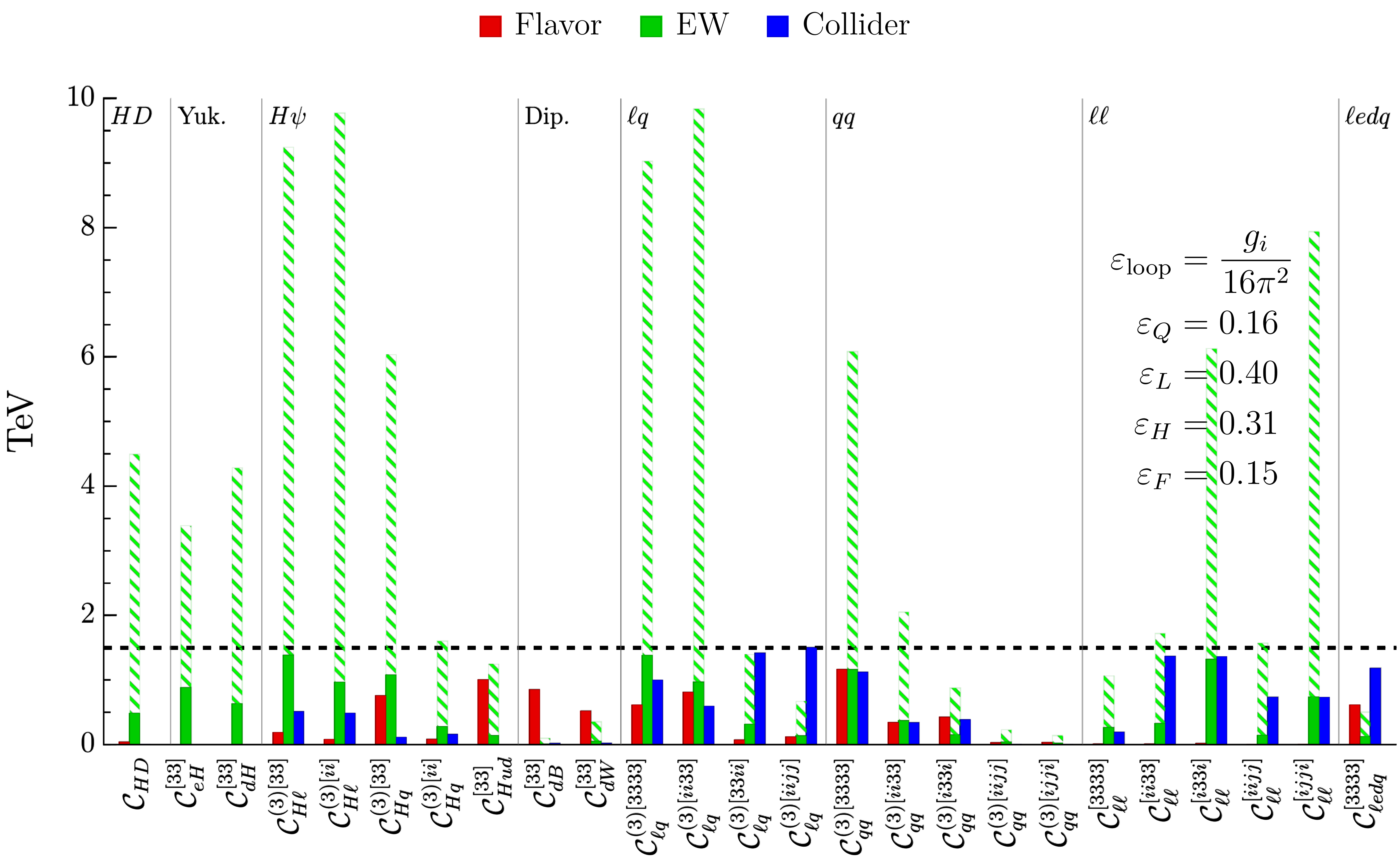
- Exp. values set to the SM
- error reduction as tabulated in the literature

Observable	Proj. Error Reduction
Γ_Z	23
$\sigma^0_{\rm had}$	7.4
R_b	10.2
R_c	11.6
$A^{0,b}_{\rm FB}$	15.5
$A^{0,c}_{\rm FB}$	15.4
A_b	7.13
A_c	5.05
R_e	8.03
R_μ	31.8
R_τ	21.7
$A^{0,e}_{\rm FB}$	30.8
$A^{0,\mu}_{\rm FB}$	26.7
$A^{0,\tau}_{\rm FB}$	21
A^{**}_e	130
A^{**}_μ	680
A^{**}_τ	340

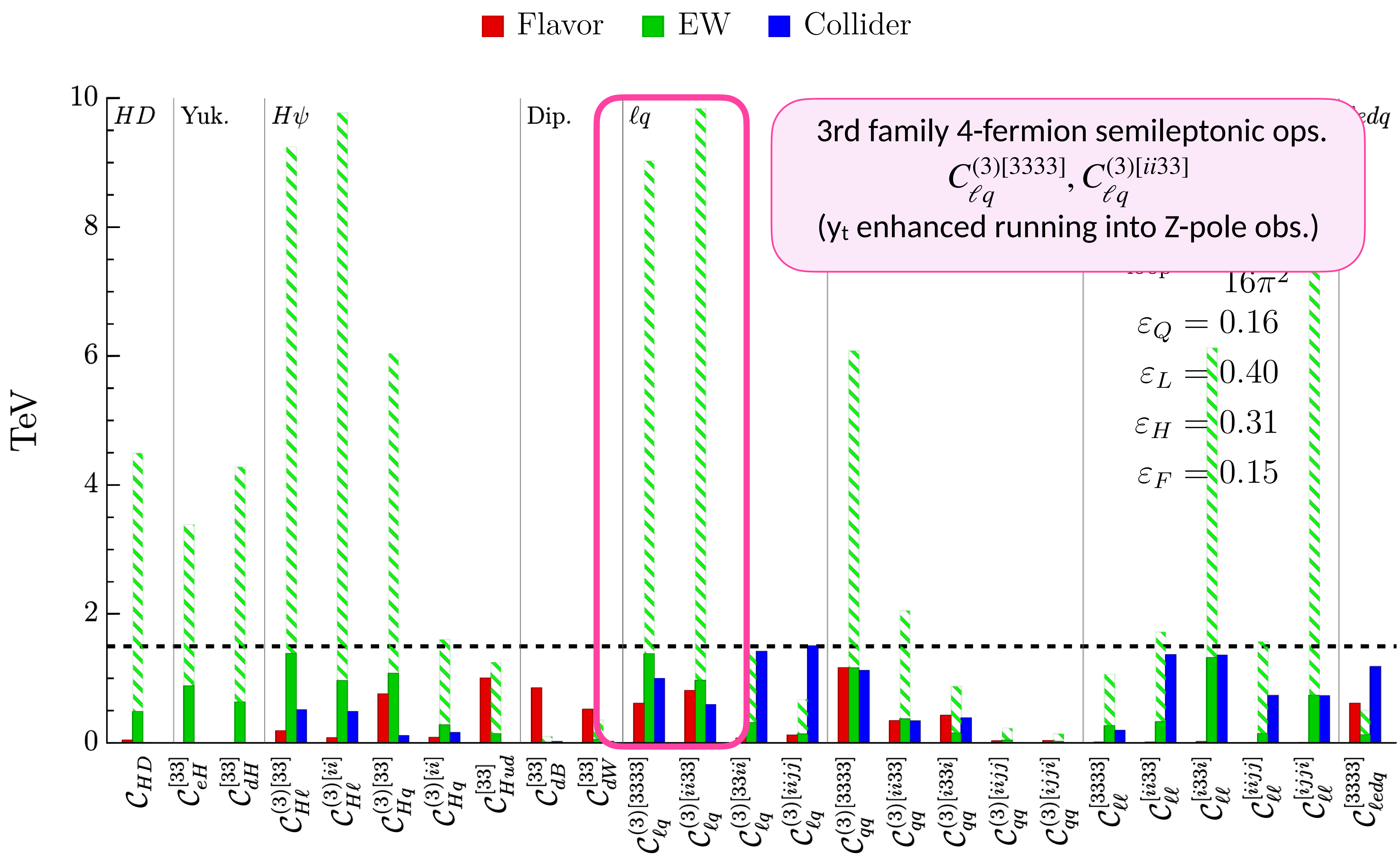
FCC and 3rd generation NP



FCC and 3rd generation NP



FCC and 3rd generation NP

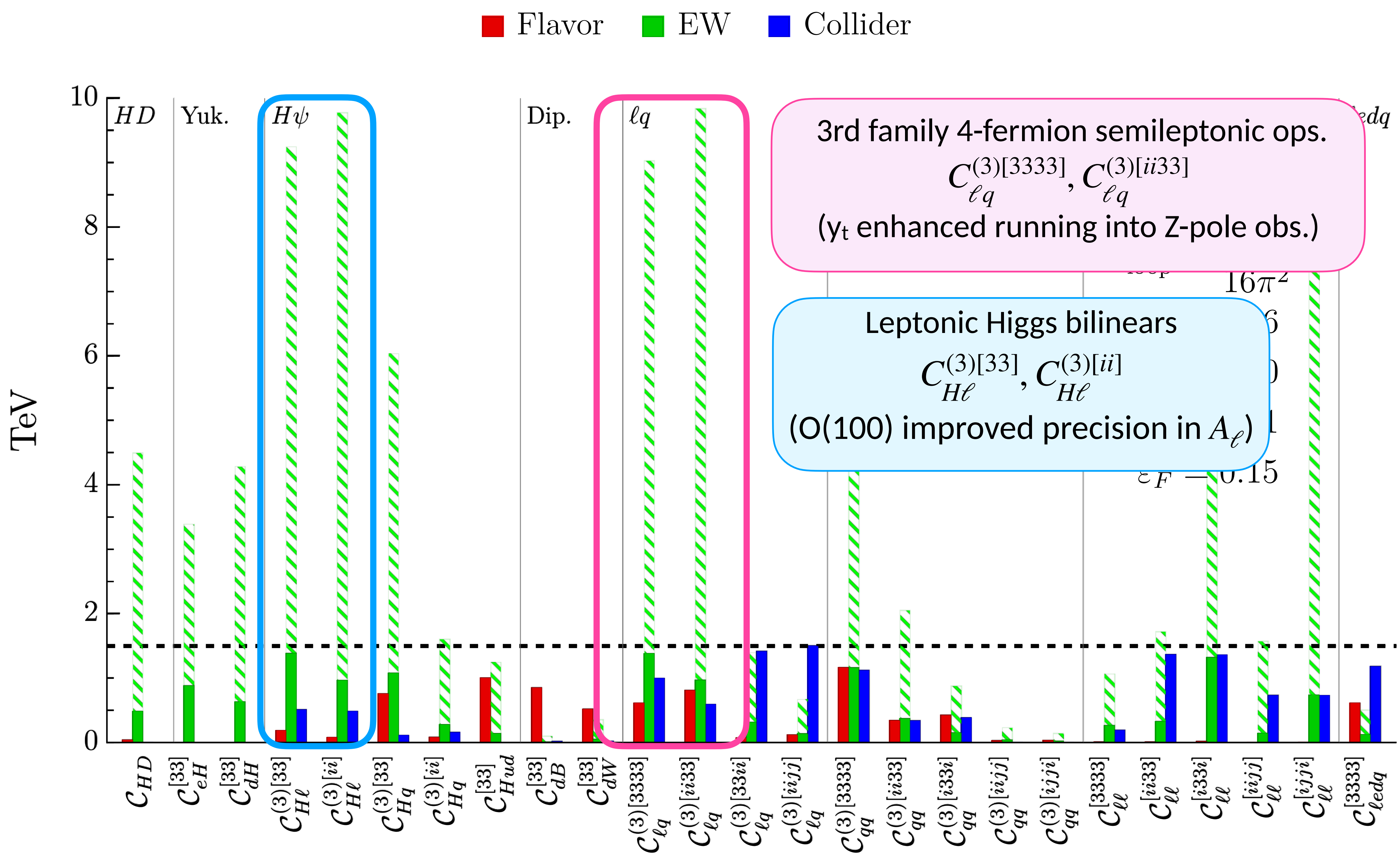


3rd family 4-fermion semileptonic ops.

$$C_{\ell q}^{(3)[3333]}, C_{\ell q}^{(3)[ii33]}$$

(y_t enhanced running into Z-pole obs.)

FCC and 3rd generation NP



3rd family 4-fermion semileptonic ops.

$C_{\ell q}^{(3)[3333]}, C_{\ell q}^{(3)[ii33]}$

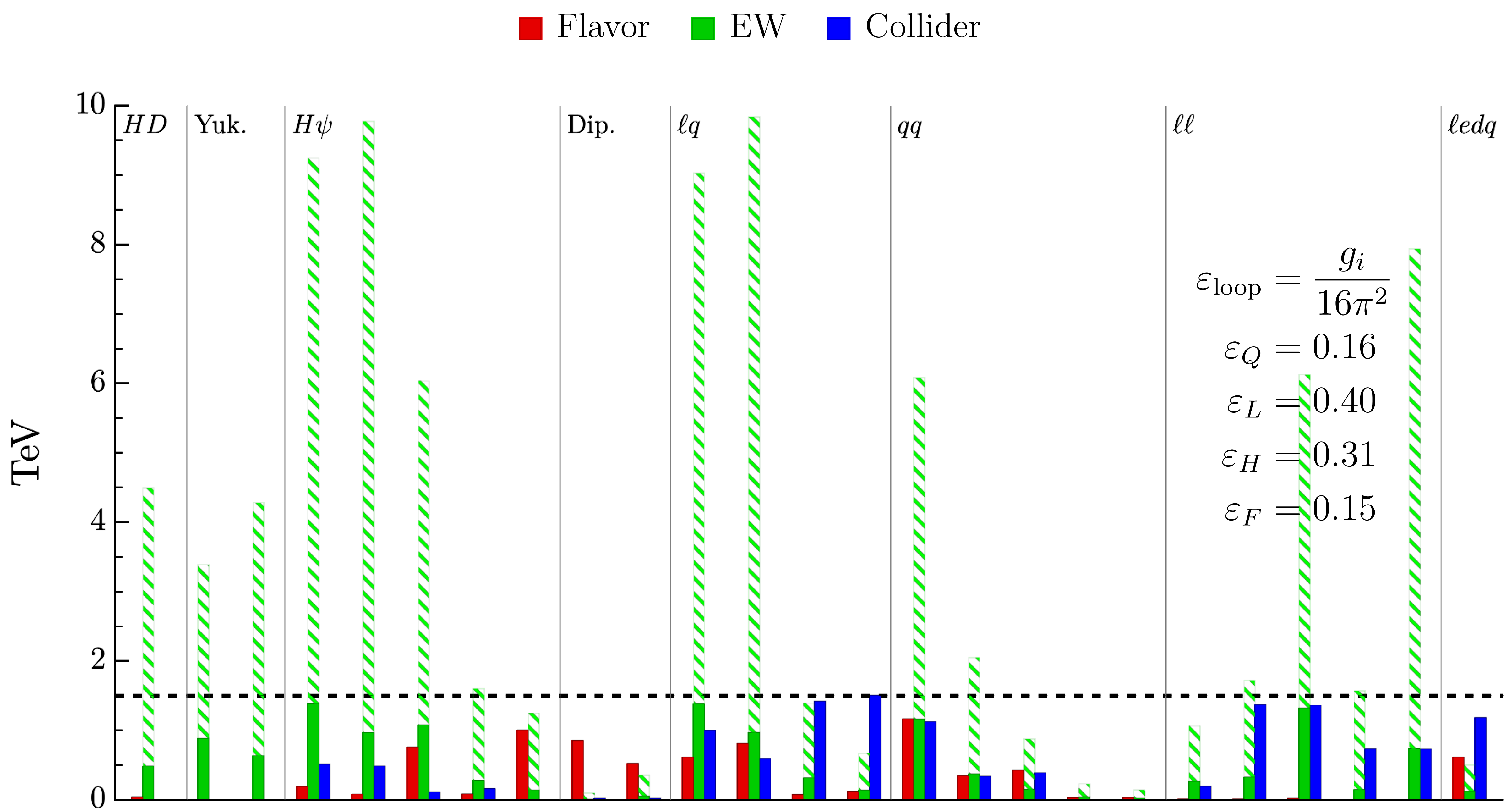
(y_t enhanced running into Z-pole obs.)

Leptonic Higgs bilinears

$C_{H\ell}^{(3)[33]}, C_{H\ell}^{(3)[ii]}$

(O(100) improved precision in A_ℓ)

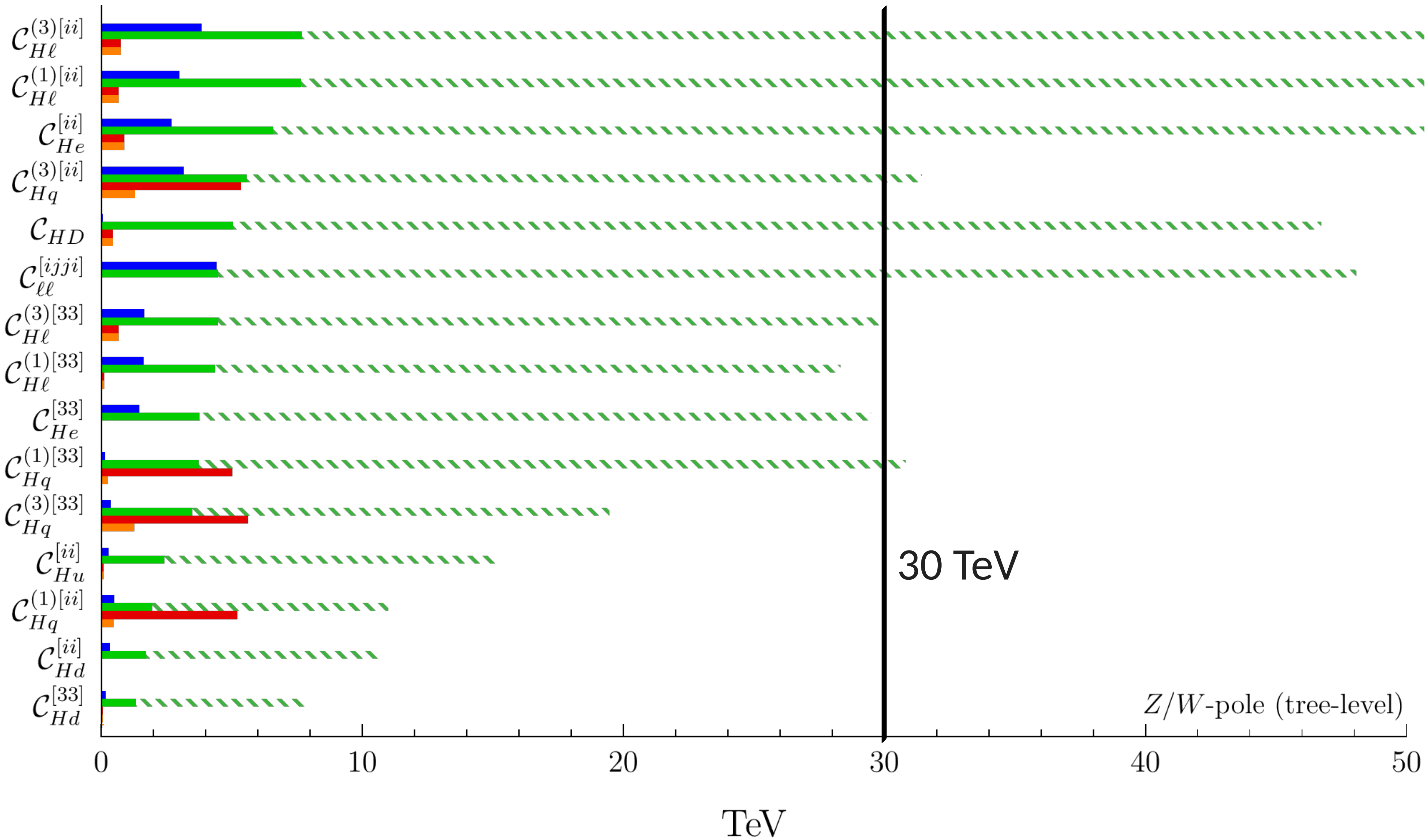
FCC and 3rd generation NP



FCC-ee could probe third-generation New Physics up to ~ 10 TeV!

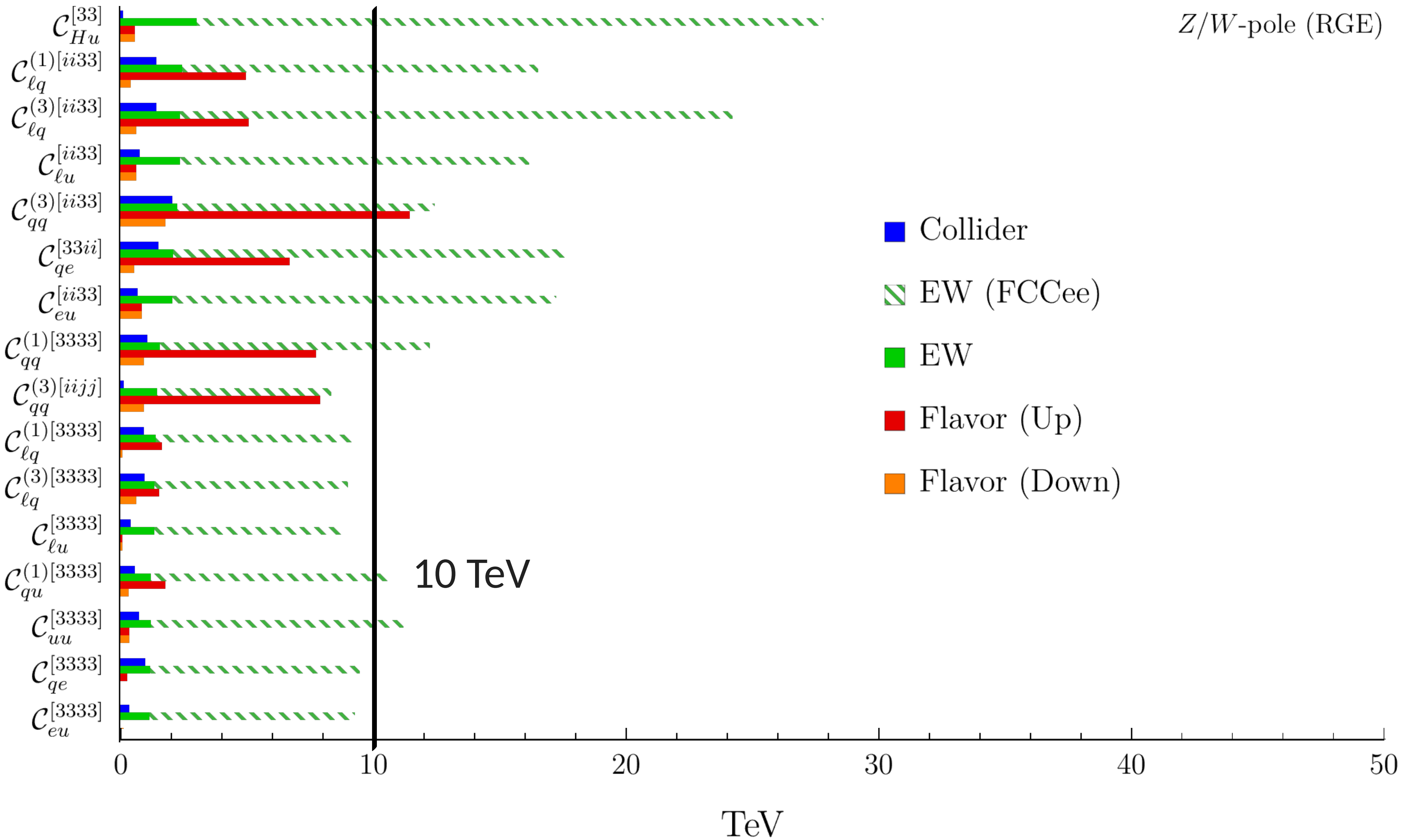
FCC-ee for "generic" U(2) NP (no suppression factors)

- Operators entering Z-pole observables at tree-level get bounds of 30-50 TeV



FCC-ee for "generic" U(2) NP (no suppression factors)

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



FCC-ee for “generic” U(2) NP (no suppression factors)

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

Two comments:

- A future EW precision machine such as FCC-ee is a great way to probe NP with sizeable couplings to the Higgs
- NP that does not couple directly to the Higgs but does couple to the 3rd generation can be probed up to effective scales of about 10 TeV

FCC-ee for "generic" U(2) NP (no suppression factors)

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

Two comments:

- A future EW precision machine such as FCC-ee is a great way to probe NP with sizeable couplings to the Higgs

- NP that does not couple directly to the Higgs but does couple to the 3rd generation can be probed up to effective scales of about 10 TeV

FCC-ee can push most of the existing bounds on NP from the EW sector by one order of magnitude!

Conclusions

We investigated NP scenarios characterized by a $U(2)^5$ symmetry acting on the light families. We included EW, flavor, and collider data, and accounted for RG effects.

Our main focus was **NP coupled mostly to the 3rd generation**, because of its strong theoretical motivation.

1. **How low** can the energy **scale of new physics** be for these class of models, and which conditions make this possible?
2. **How will the bounds** on these models **change** in the **future**?

Conclusions

We investigated NP scenarios characterized by a $U(2)^5$ symmetry acting on the light families. We included EW, flavor, and collider data, and accounted for RG effects.

Our main focus was **NP coupled mostly to the 3rd generation**, because of its strong theoretical motivation.

1. **How low** can the energy **scale of new physics** be for these class of models, and which conditions make this possible?
2. **How will the bounds** on these models **change** in the **future**?

1. **NP in the 3rd family is compatible with a scale as low as 1.5 TeV** under simple, non-tuned assumptions. Well-motivated NP models can be nearby!

Conclusions

We investigated NP scenarios characterized by a $U(2)^5$ symmetry acting on the light families. We included EW, flavor, and collider data, and accounted for RG effects.

Our main focus was **NP coupled mostly to the 3rd generation**, because of its strong theoretical motivation.

1. **How low** can the energy **scale of new physics** be for these class of models, and which conditions make this possible?
2. **How will the bounds** on these models **change** in the **future**?

1. **NP in the 3rd family is compatible with a scale as low as 1.5 TeV** under simple, non-tuned assumptions. Well-motivated NP models can be nearby!
2. A future tera-Z machine like **FCC-ee** can probe these scenarios up to **10 TeV**. **Precision flavor measurement** can provide complementary information, e.g. $B \to K\nu\bar{\nu}$ and $K \to \pi\nu\bar{\nu}$ can help determine the flavor alignment.

Back-up slides

Rare decays and 3rd generation NP

More short-term, improvements in flavor and collider observables can help us probe this scenario. Consider the **rare decays** $B \to K\nu\bar{\nu}$ and $K \to \pi\nu\bar{\nu}$.

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp}}{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM}} = 2.8 \pm 0.8\,,$$

[Exp: combination from Belle II @EPS 2023]

~3σ tension with the SM

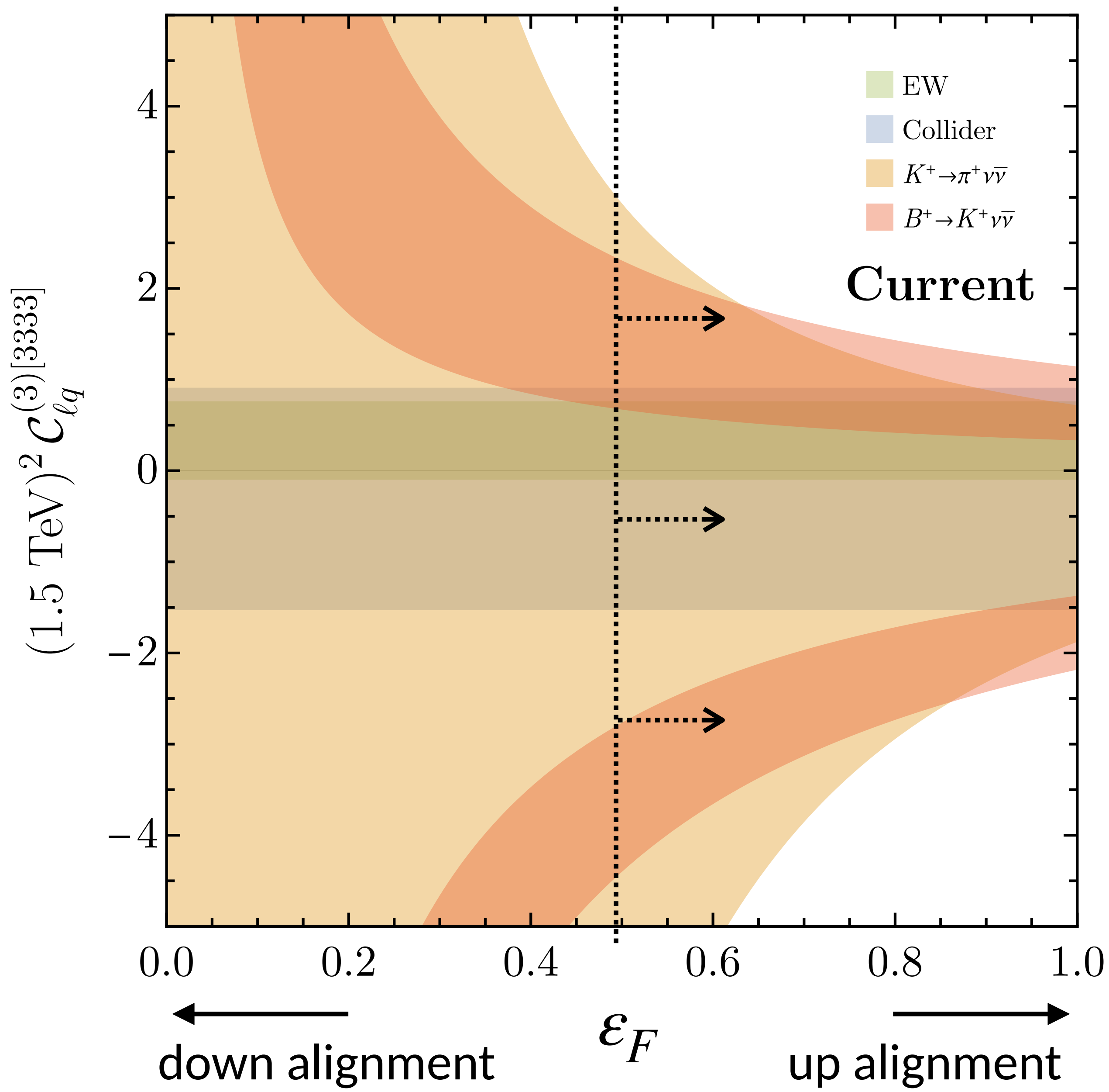
$$\frac{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\rm exp}}{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\rm SM}} = 1.23 \pm 0.39$$

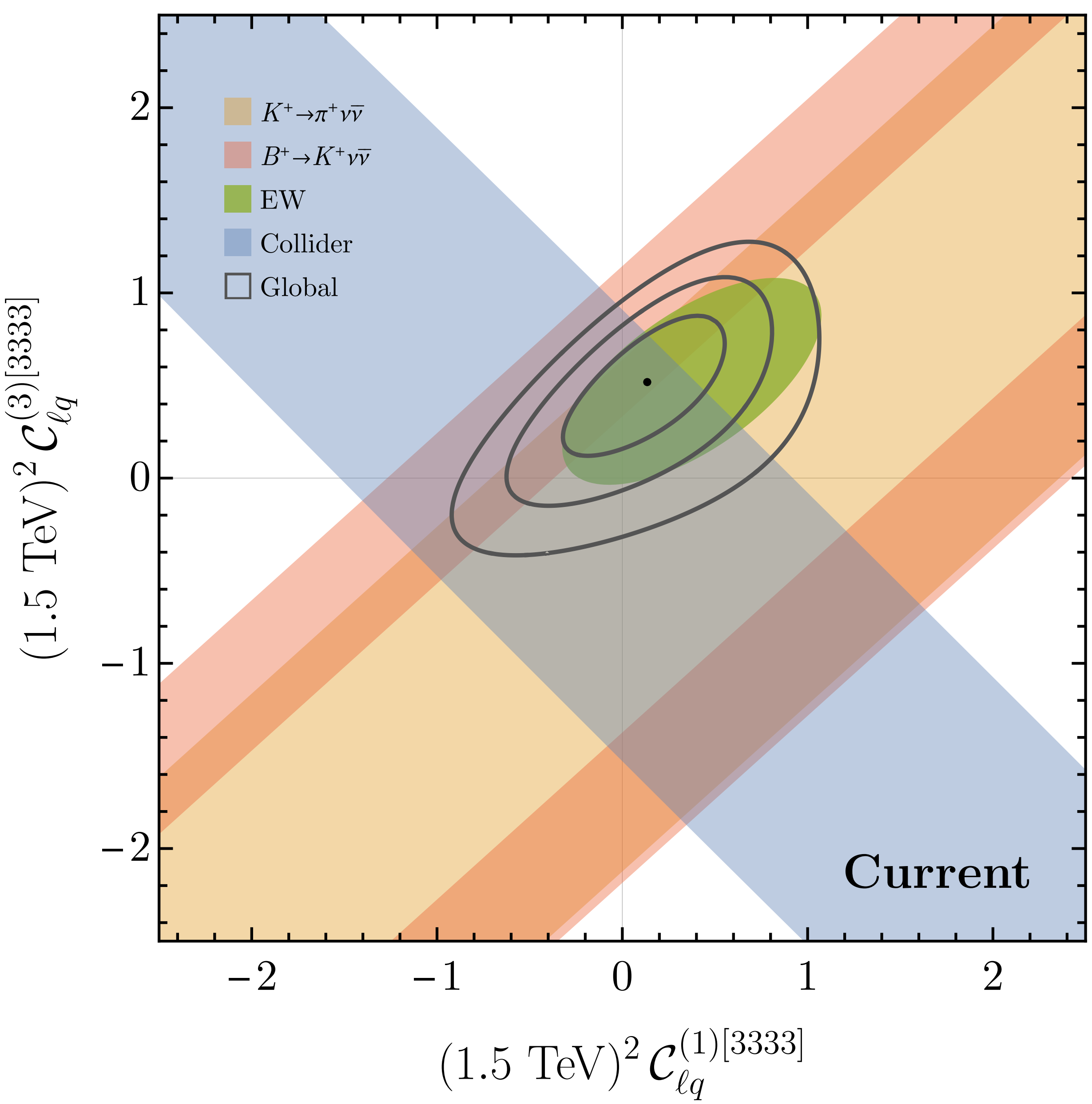
[Exp: NA62 2021; SM: Buras et al. 2015]

Compatible with the SM at 1σ

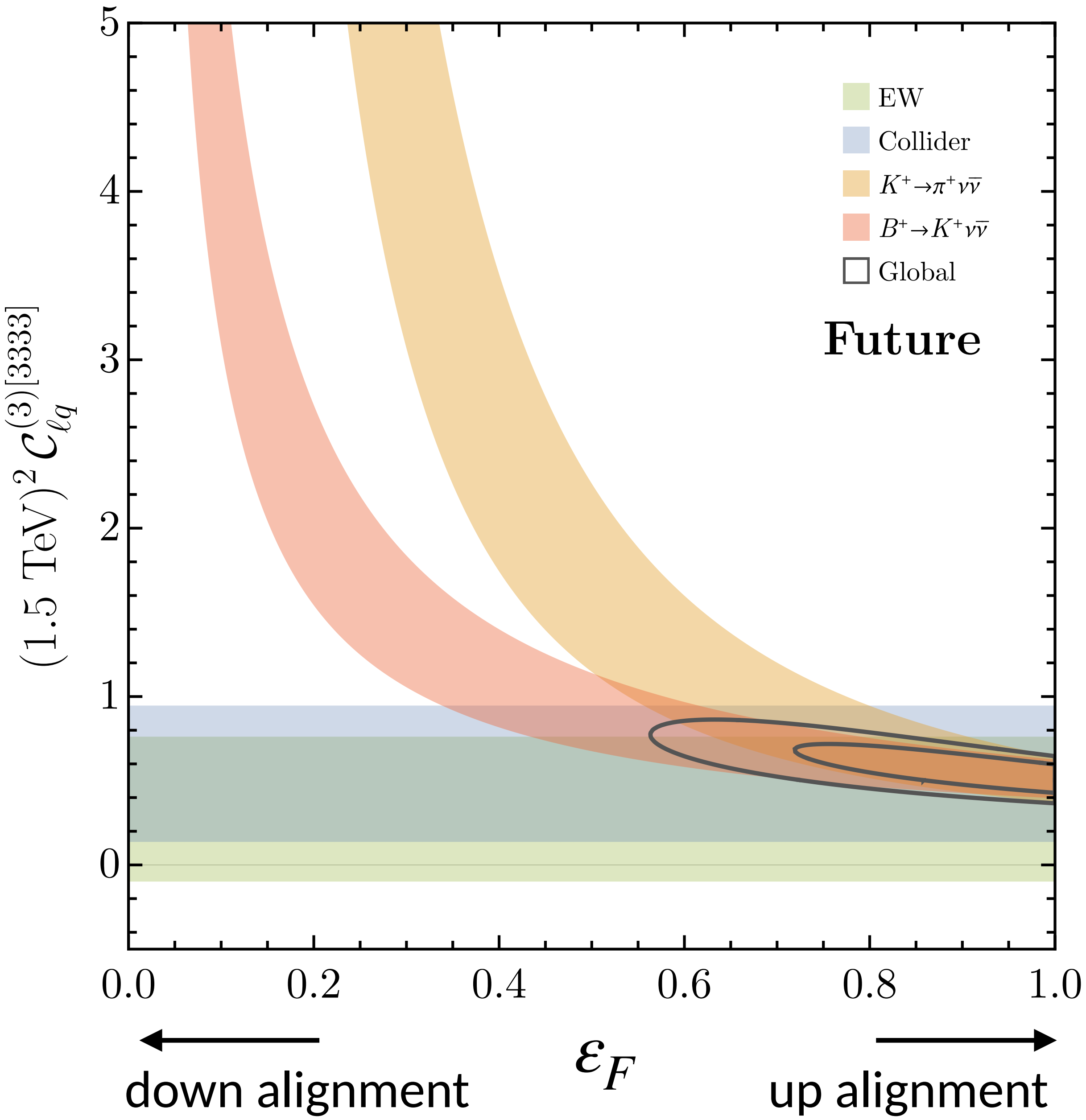
- theoretically clean
- significant improvements expected in the next years:
  Belle II will measure $B \to K\nu\bar{\nu}$ @ 10%, and NA62(HIKE) $K \to \pi\nu\bar{\nu}$ @ 15%(5%)
- sensitive to a limited number of EFT operators: $C_{\ell q}^{(3)[3333]}$, $C_{\ell q}^{(1)[3333]}$
- scale differently with the alignment parameter ε_F

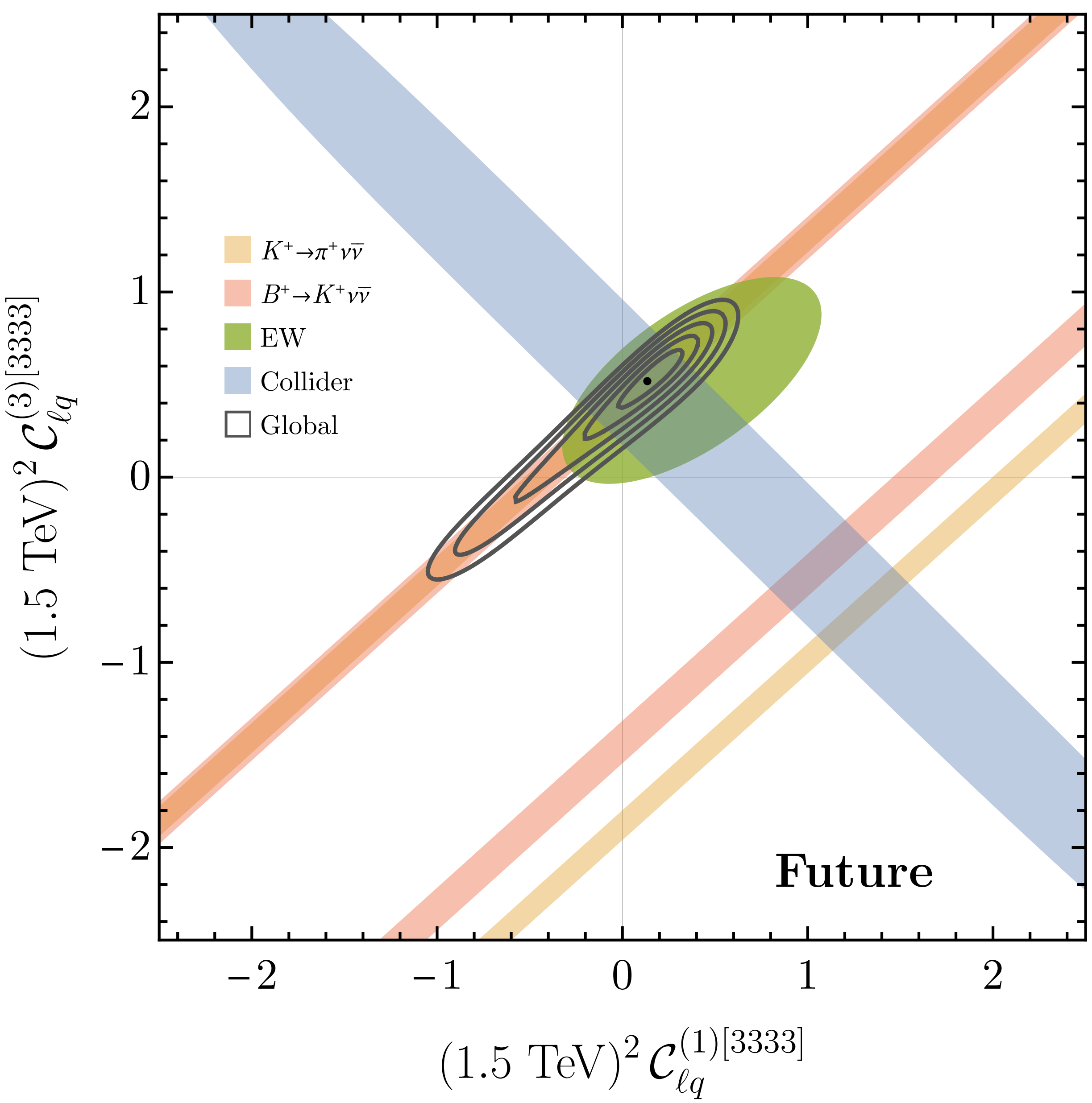
Rare decays and 3rd generation NP: current data





Rare decays and 3rd generation NP: projections





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}
$\mathcal{C}^{(3)[33]}_{H\ell}$	0.7	0.7	4.5	1.7	4.4	R_τ	4.4	R_τ
$\mathcal{C}^{(3)[ii]}_{H\ell}$	0.7	0.7	7.7	3.8	7.7	σ_{had}	7.7	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}
$\mathcal{C}^{(1)[33]}_{Hq}$	0.3	5.	3.7	0.1	3.7	Γ_Z	5.1	$B_s \to \mu\mu$
$\mathcal{C}^{(1)[ii]}_{Hq}$	0.5	5.2	1.9	0.5	2.	R_c	5.4	$B_s \to \mu\mu$
$\mathcal{C}^{(3)[33]}_{Hq}$	1.3	5.6	3.5	0.4	3.4	R_b	5.5	$B_s \to \mu\mu$
$\mathcal{C}^{(3)[ii]}_{Hq}$	1.3	5.3	5.6	3.1	5.7	R_τ	7.7	Γ_Z
$\mathcal{C}^{[33]}_{Hd}$	-	-	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

3H and dipole operators

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

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	$H \to \tau\tau$

LLLL vector operators

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

RRRR vector operators

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

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	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$\mathcal{C}_{\ell e}^{[33ii]}$	-	-	0.3	1.9	2.	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$	2.	$(e^+e^- \to \mu^+\mu^-)_{\text{FB}}$
$\mathcal{C}_{\ell e}^{[iijj]}$	-	-	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}
$\mathcal{C}_{\ell u}^{[33ii]}$	-							
$\mathcal{C}_{\ell u}^{[iijj]}$	-							
$\mathcal{C}_{\ell d}^{[3333]}$	-							
$\mathcal{C}_{\ell d}^{[ii33]}$	-							
$\mathcal{C}_{\ell d}^{[33ii]}$	-							
$\mathcal{C}_{\ell d}^{[iijj]}$	-							
$\mathcal{C}_{qe}^{[3333]}$	-	0						
$\mathcal{C}_{qe}^{[33ii]}$	0.6	6						
$\mathcal{C}_{qe}^{[ii33]}$	-	0						
$\mathcal{C}_{qe}^{[iijj]}$	-							
$\mathcal{C}_{qu}^{(1)[3333]}$	0.3	1						
$\mathcal{C}_{qu}^{(1)[ii33]}$	0.3	1						
$\mathcal{C}_{qu}^{(1)[33ii]}$	-	0						
$\mathcal{C}_{qu}^{(1)[iijj]}$	-	0						
$\mathcal{C}_{qu}^{(8)[3333]}$	0.2	0						
$\mathcal{C}_{qu}^{(8)[ii33]}$	0.3	0						
$\mathcal{C}_{qu}^{(8)[33ii]}$	-	0						
$\mathcal{C}_{qu}^{(8)[iijj]}$	-	0						
$\mathcal{C}_{qd}^{(1)[3333]}$	0.2	0						
$\mathcal{C}_{qd}^{(1)[ii33]}$	-	0						
$\mathcal{C}_{qd}^{(1)[33ii]}$	-	0						
$\mathcal{C}_{qd}^{(1)[iijj]}$	-	0						
$\mathcal{C}_{qd}^{(8)[3333]}$	-							
$\mathcal{C}_{qd}^{(8)[ii33]}$	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	-	$\lvert C_{Bs}\rvert$

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

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}
$\mathcal{C}_{HD}$	0.5	0.5	5.1	-	5.	A_b^{FB}	5.	A_b^{FB}
$\mathcal{C}_{HG}$	0.8	0.8	0.4	-	0.9	$B \to X_s\gamma$	0.9	$B \to X_s\gamma$
$\mathcal{C}_{HB}$	0.5	0.5	0.9	-	0.9	A_b^{FB}	0.9	A_b^{FB}
$\mathcal{C}_{HW}$	0.7	0.7	0.9	-	1.	A_b^{FB}	1.	A_b^{FB}
$\mathcal{C}_{HWB}$	1.	1.	9.	-	9.	A_b^{FB}	9.	A_b^{FB}
$\mathcal{C}_G$	1.1	1.1	0.1	-	1.1	$B \to X_s\gamma$	1.1	$B \to X_s\gamma$
$\mathcal{C}_W$	0.3	0.3	0.9	-	0.9	A_b^{FB}	0.9	A_b^{FB}