Status and future accelerator prospects of flavor physics

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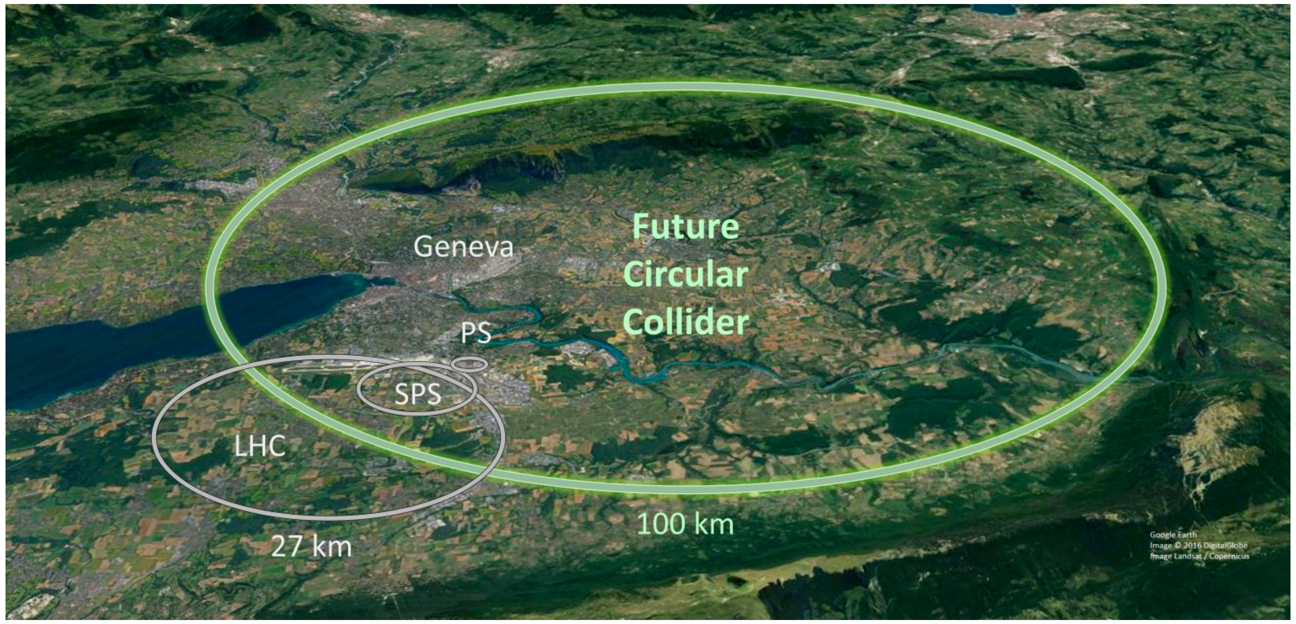
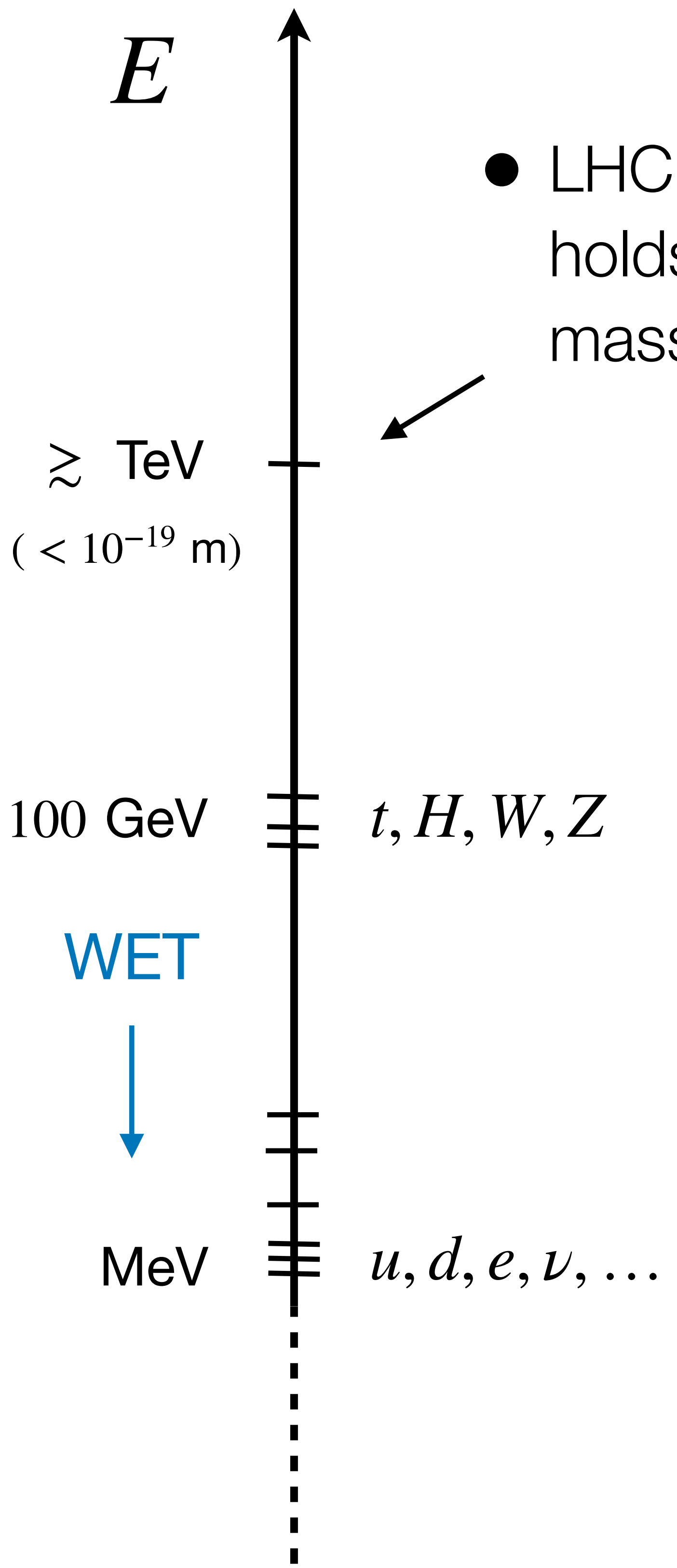


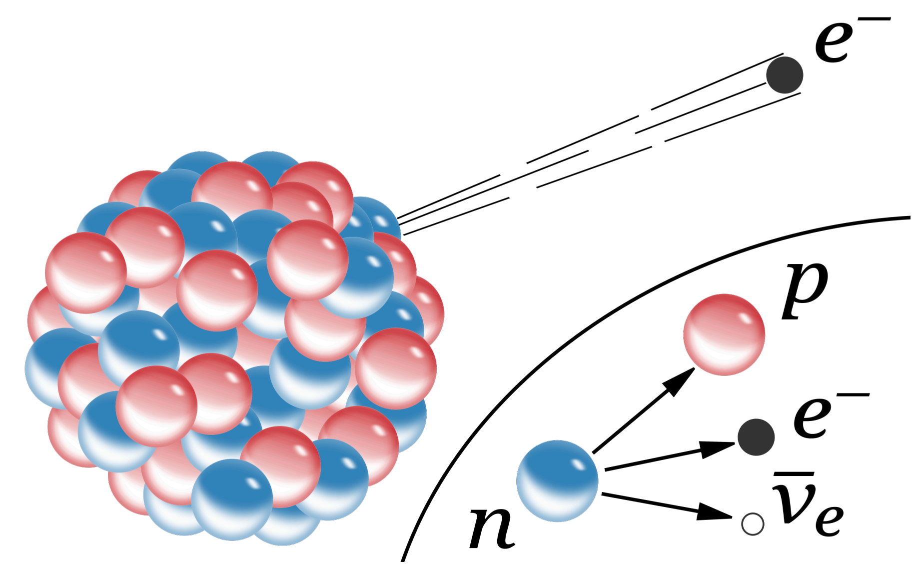
Corfu 2024
Future Accelerators
May 23rd, 2024

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

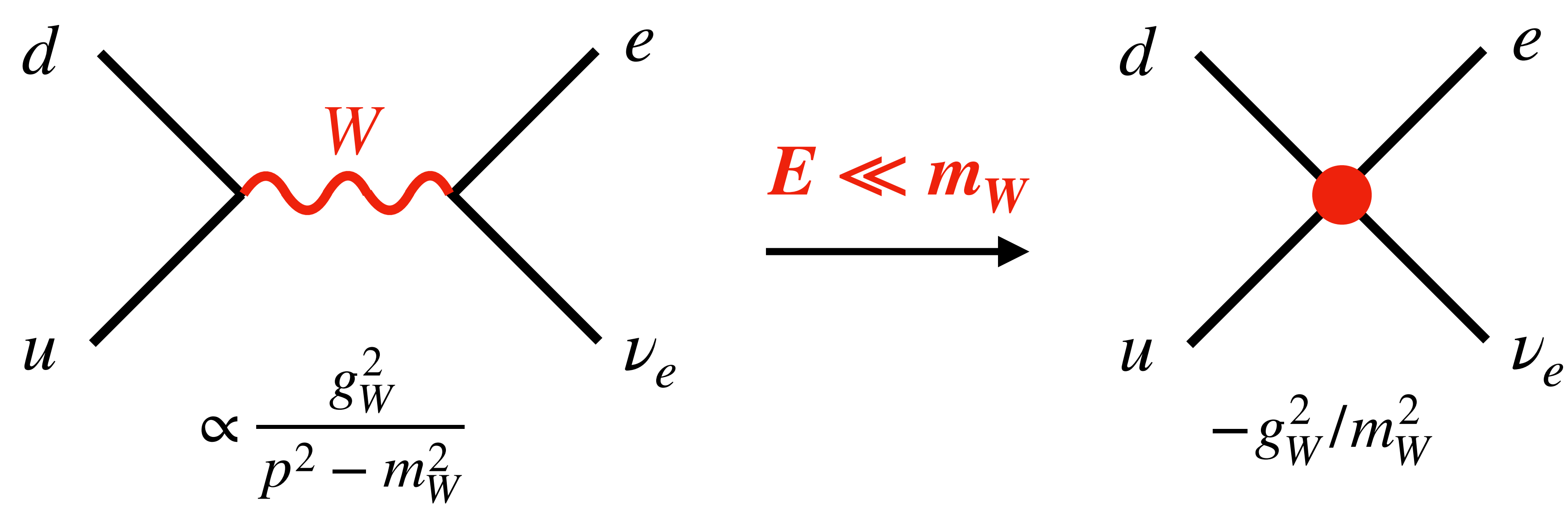
Searching for New Physics (NP) beyond the SM



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

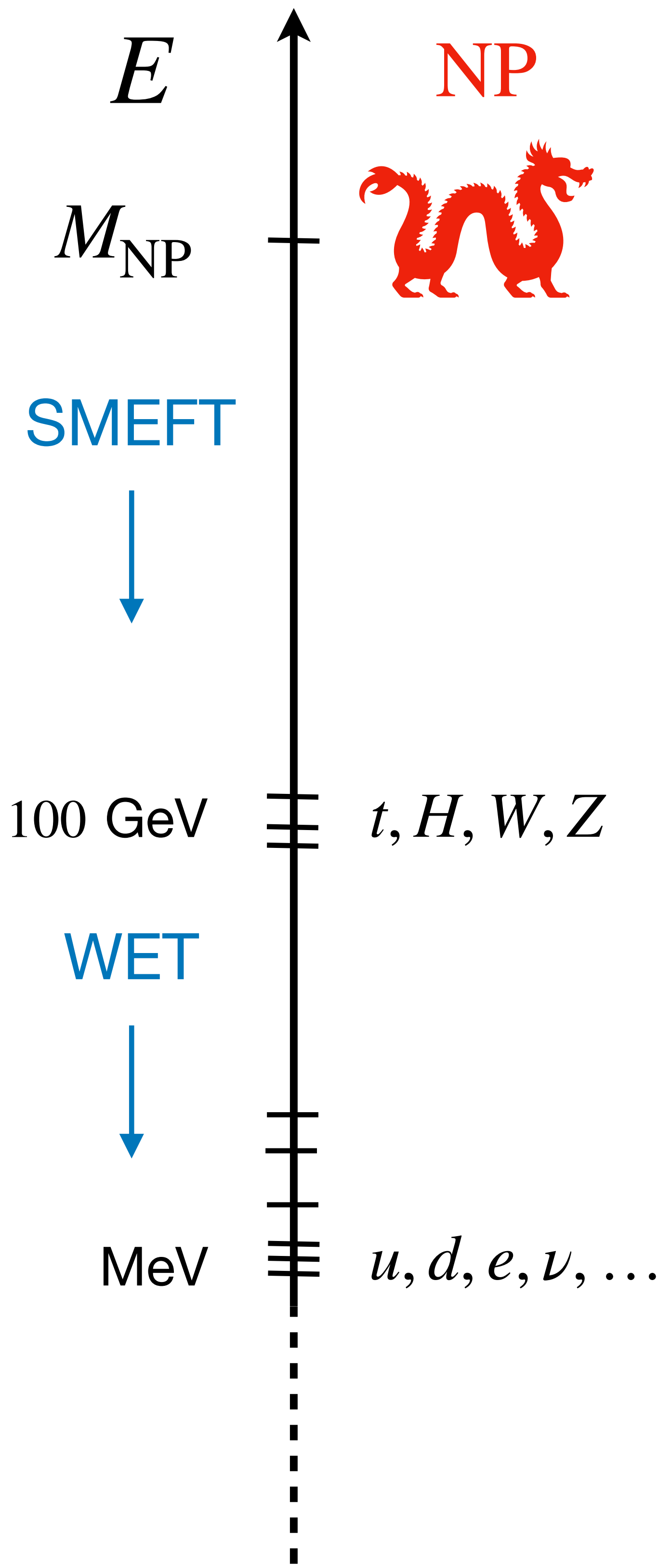


***Fermi Theory* [$E \ll m_W$]**

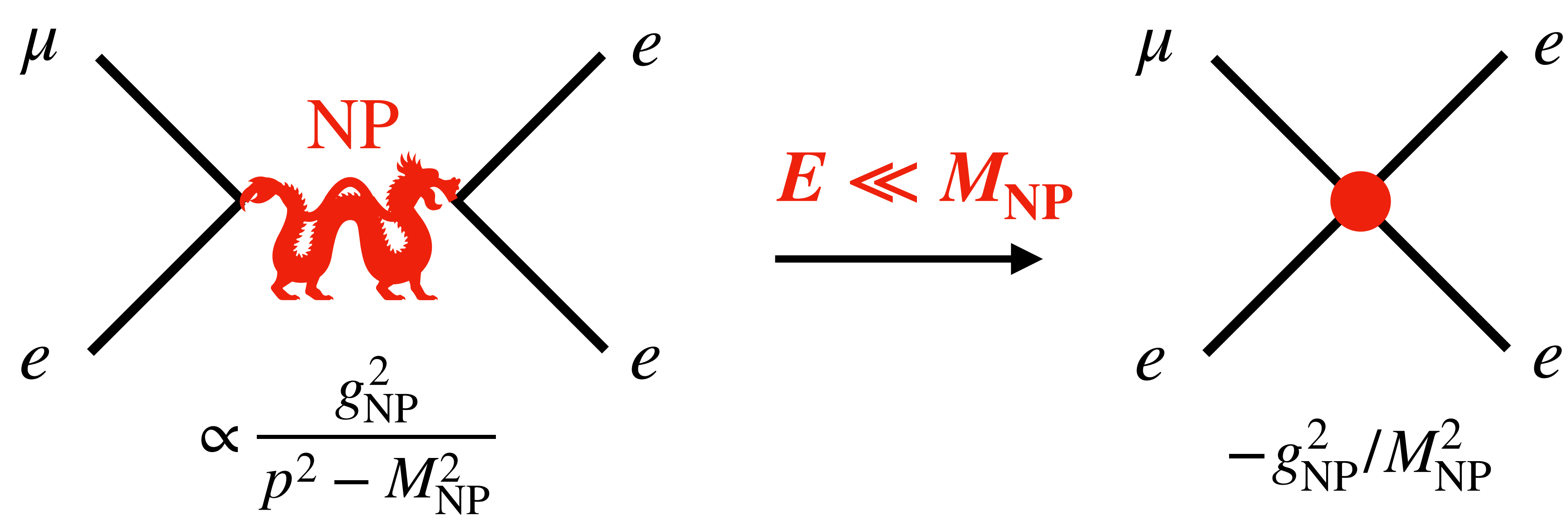


$$\mathscr{L}_{\text{WET}} = \mathscr{L}_{\text{QED}} + \mathscr{L}_{\text{QCD}} - \frac{g_W^2}{m_W^2}(\bar{u}_L \gamma_\mu d_L)(\bar{e}_L \gamma^\mu \nu_L) + \dots$$

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.



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

Neutrino masses!
($\Lambda_\nu \gg 100$ GeV)

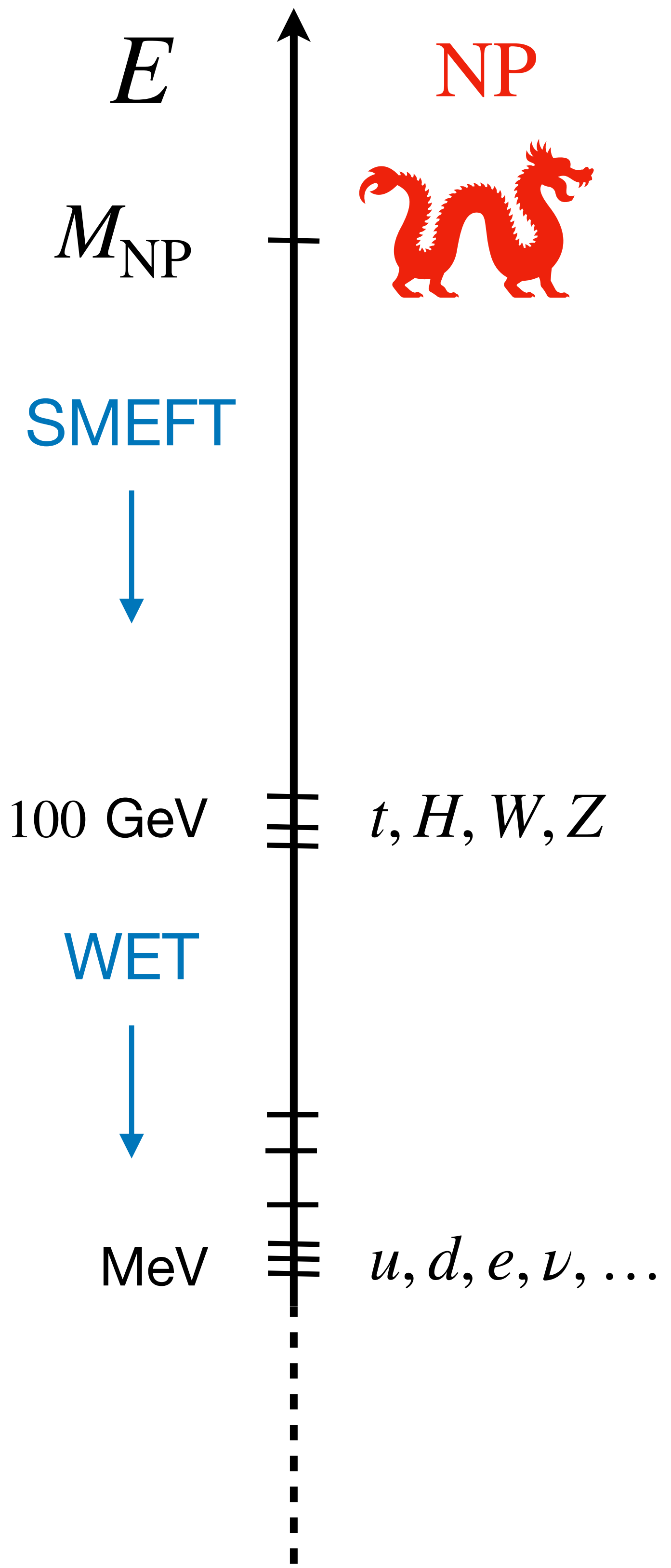
[Weinberg, 1979]

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

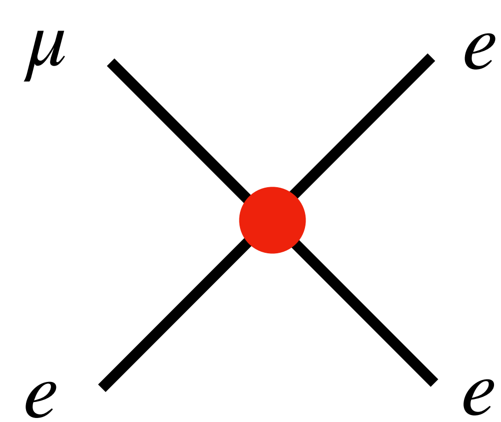
[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

The Flavor of the SMEFT

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



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



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

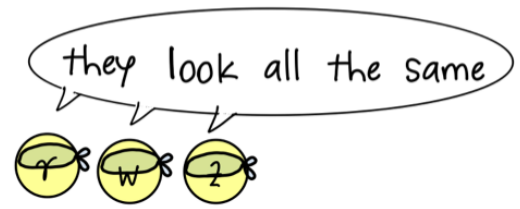
[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

- 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 $M_{\mathrm{NP}} \gtrsim 1000$ 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

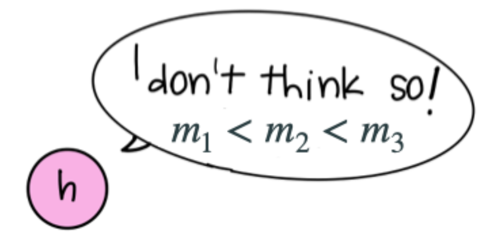
- Standard Model (SM) gauge sector is *flavor blind!*

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



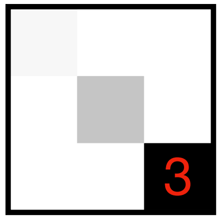
Turn on Yukawas

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



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

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

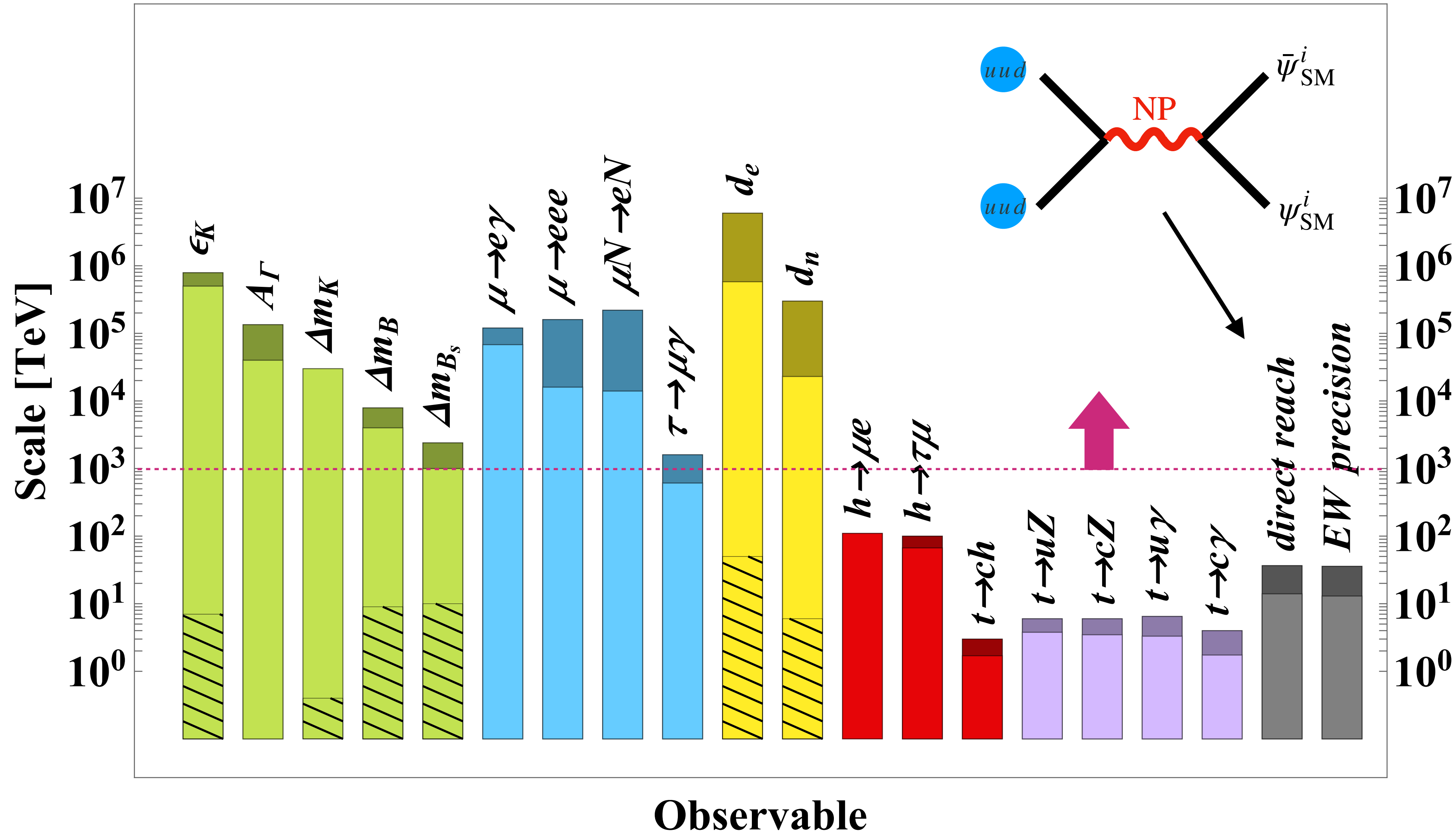


$$\mathcal{G}_F(\text{SM}) \approx U(2)^5 \equiv U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e$$

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

[Physics Briefing Book 2020, 1910.11775]

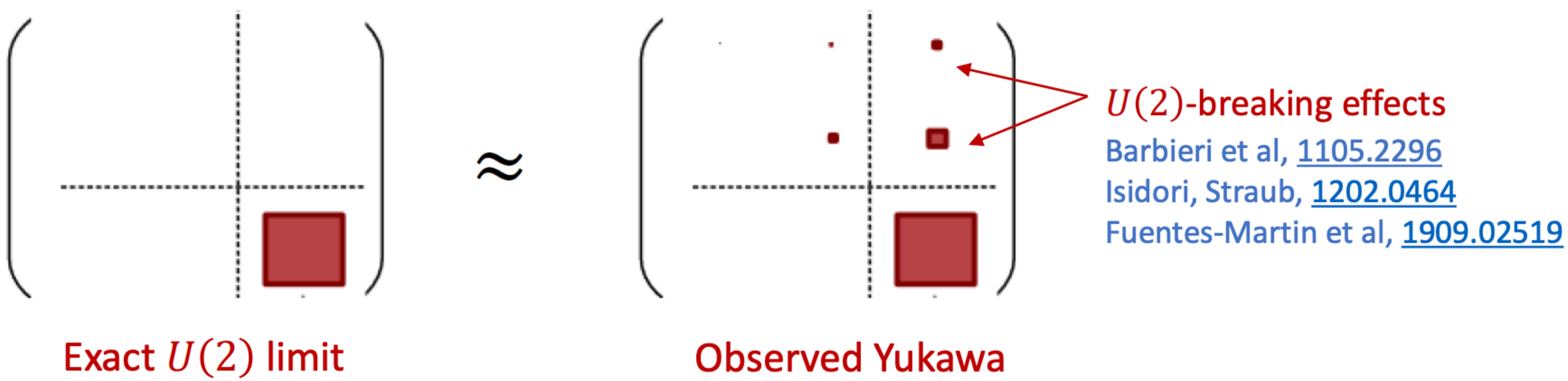
Hints of NP structure: Data



- 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.
- 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.
- 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.

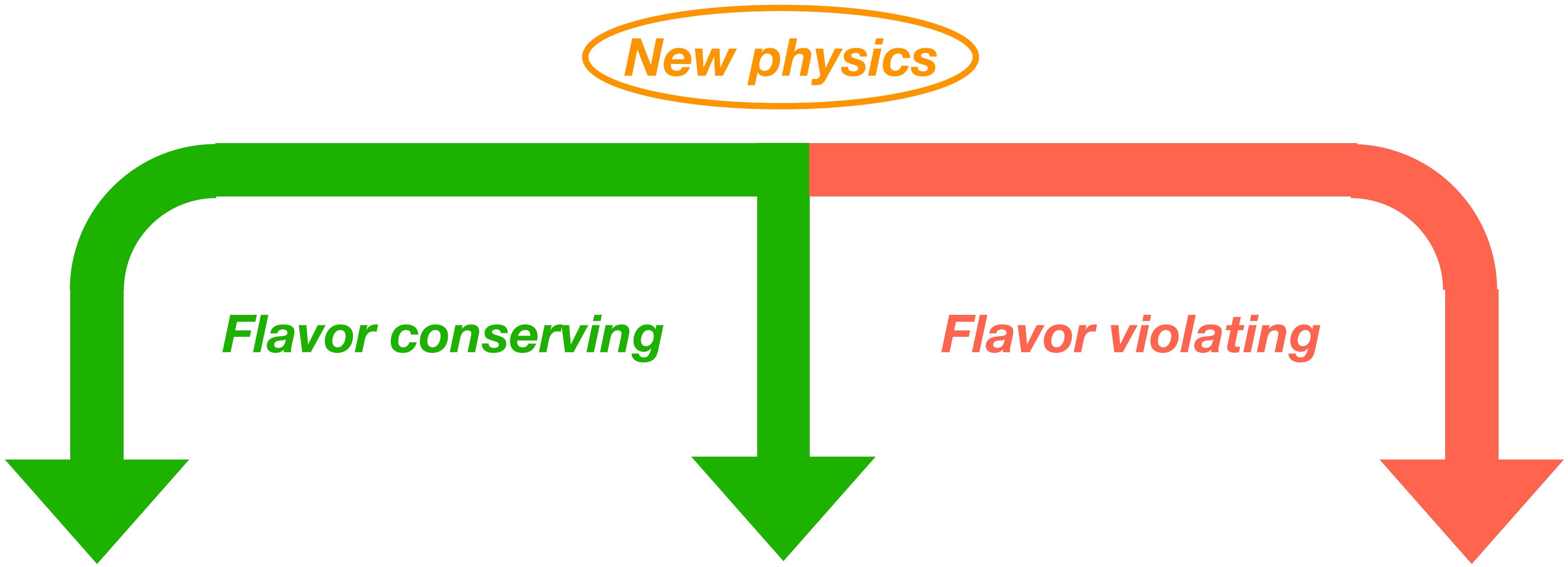


NP coupled only to 3rd family

Also small couplings to light families

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

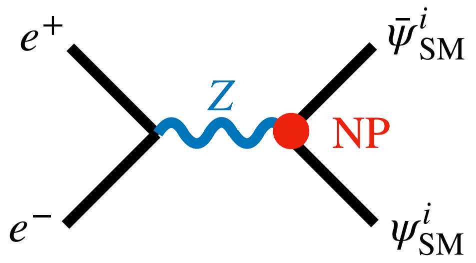
Combining data: NP must confront a triad of bounds



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

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

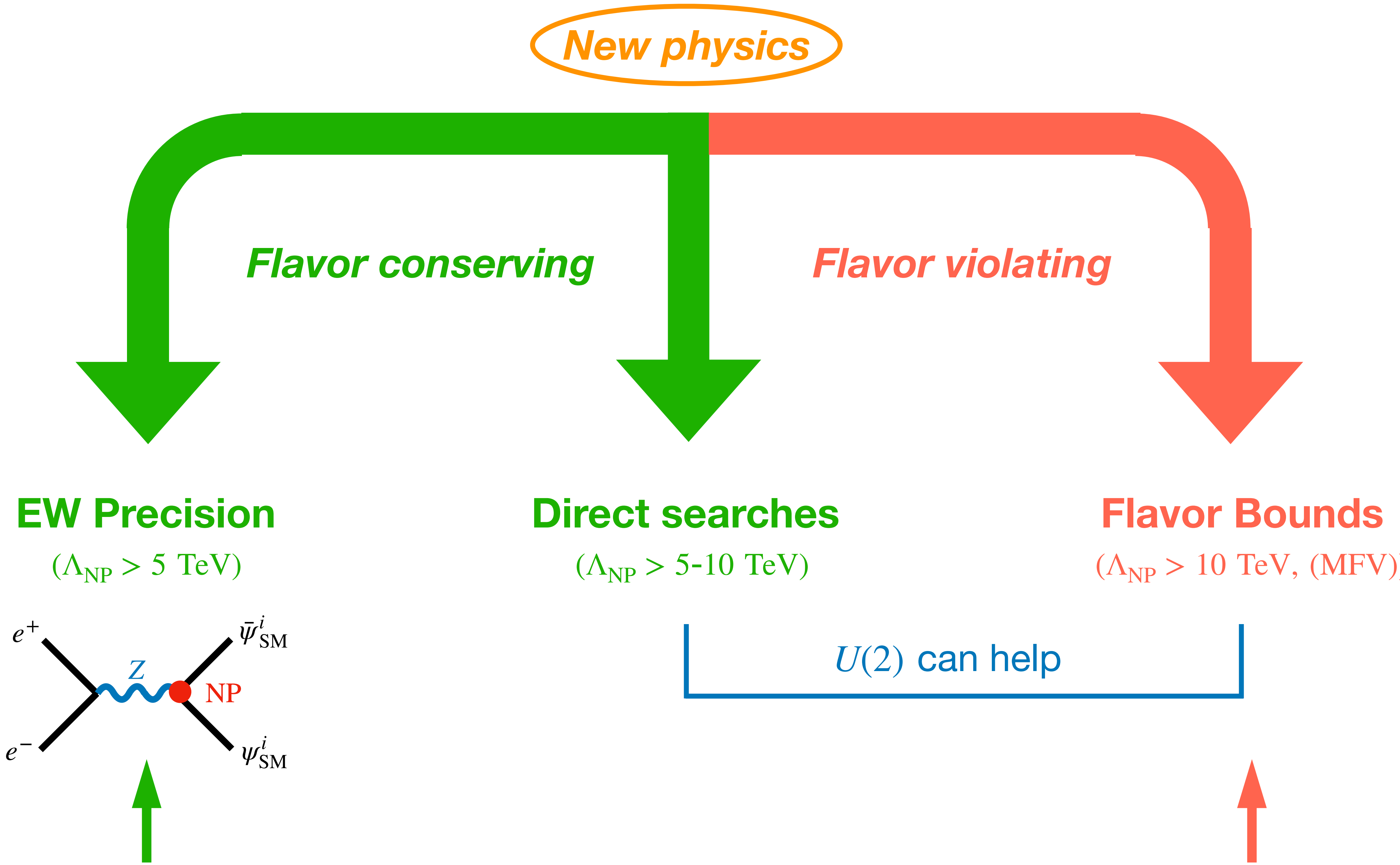
Flavor Bounds
($\Lambda_{\rm NP} > 10$ TeV, (MFV))



$U(2)$ can help

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

Combining data: NP must confront a triad of bounds

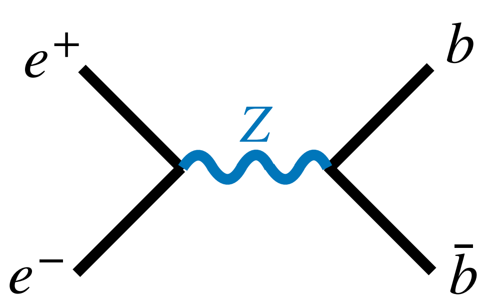


- These two directions are expected to dramatically improve with a tera-Z machine!

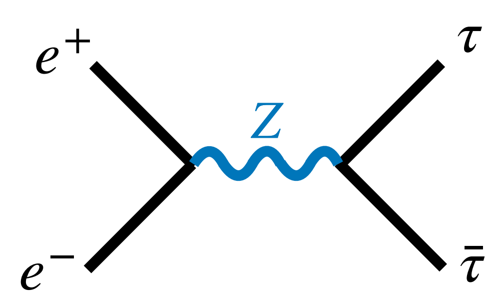
Heavy flavor physics at a tera-Z machine

Table 7: Expected production yields of heavy-flavored particles at Belle II (50 ab^{-1}) and FCC-ee (Z pole). The $X/\overline{X}$ represents the production of a B-hadron or its charge conjugated state. The Z branching fractions and hadronization rates are taken from [2].

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



$\approx 15.2\,\%$



$\approx 3.4\,\%$

- With 5×10^{12} Z-bosons, heavy flavors produced at the 1-100 billion level. In particular, the heavier $B_{s,c}$ and Λ_b will be accessible in large numbers.
- Unique opportunity to study a large number of B- and tau-decays in a clean e^+e^- environment. Expected benefit from large boost and excellent vertexing capability.

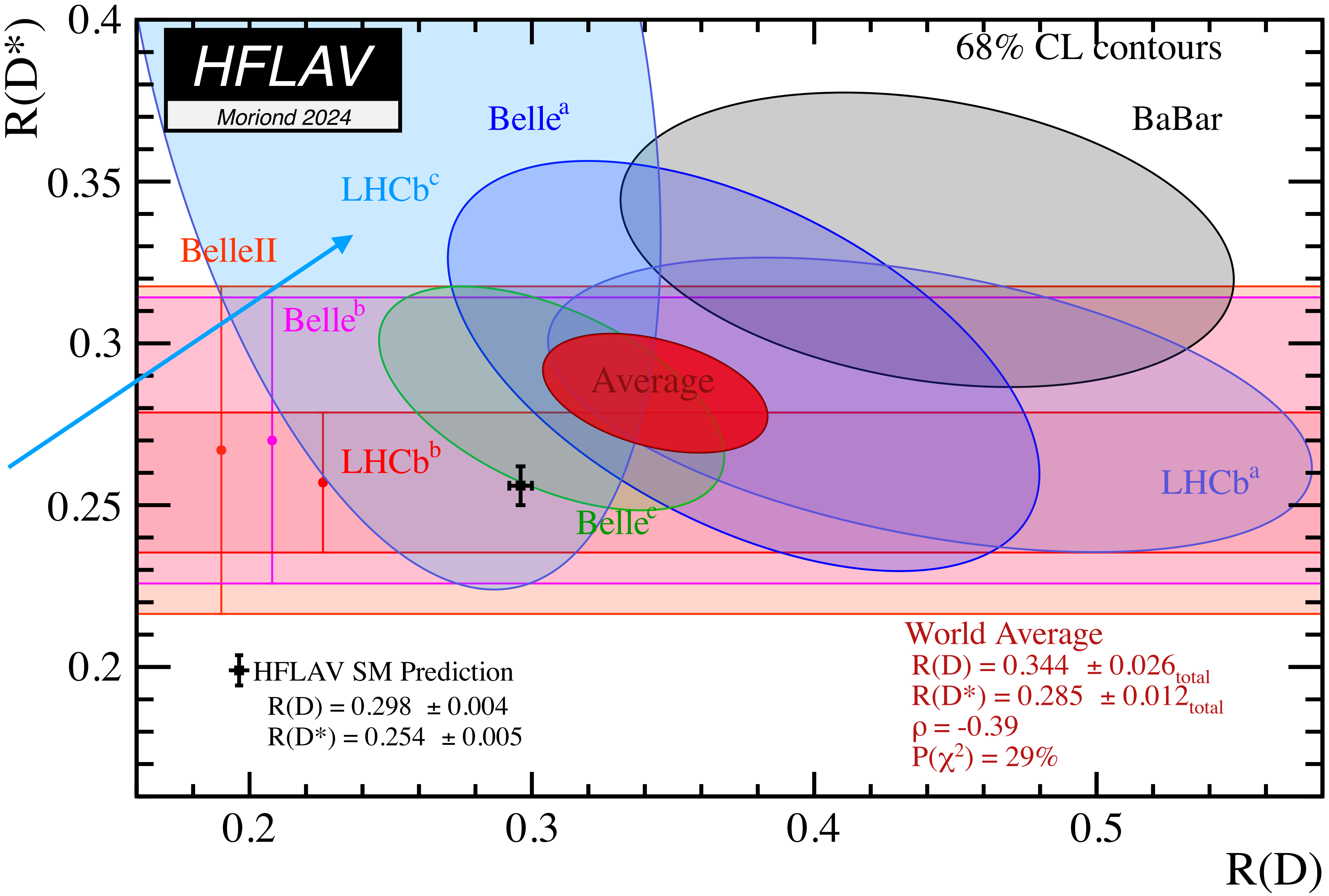
[FCC Snowmass Summary, 2203.06520]

Curiosities in $b \to c\tau\nu$ transitions: R_D and R_{D*}

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

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

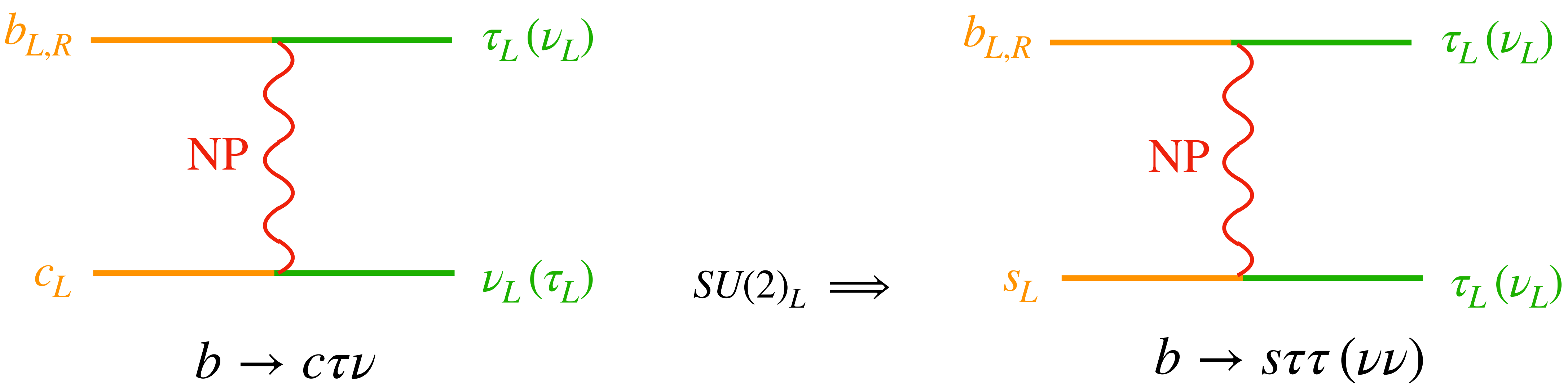
2024 LHCb $\tau \to \mu$:
First joint measurement of R_D & R_{D^*} using the D^+ state at LHCb.
[LHCb, Moriond '24]



- Theoretically clean. Measurements by Babar, Belle, LHCb in good agreement.
- Enhancement of $\sim 10\,\%$ over SM due to excess in tau mode: $B \to D^{(*)}\tau\bar{\nu}_\tau$. ✔
- Combined, ~$3.2\,\sigma$ **tension** w.r.t the SM prediction.

Connections between $b \to c\tau\nu$ and $b \to s\tau\tau\,(\nu\nu)$

- If NP, $R_{D^{(*)}}$ requires an O(10%) correction to a tree-level SM process



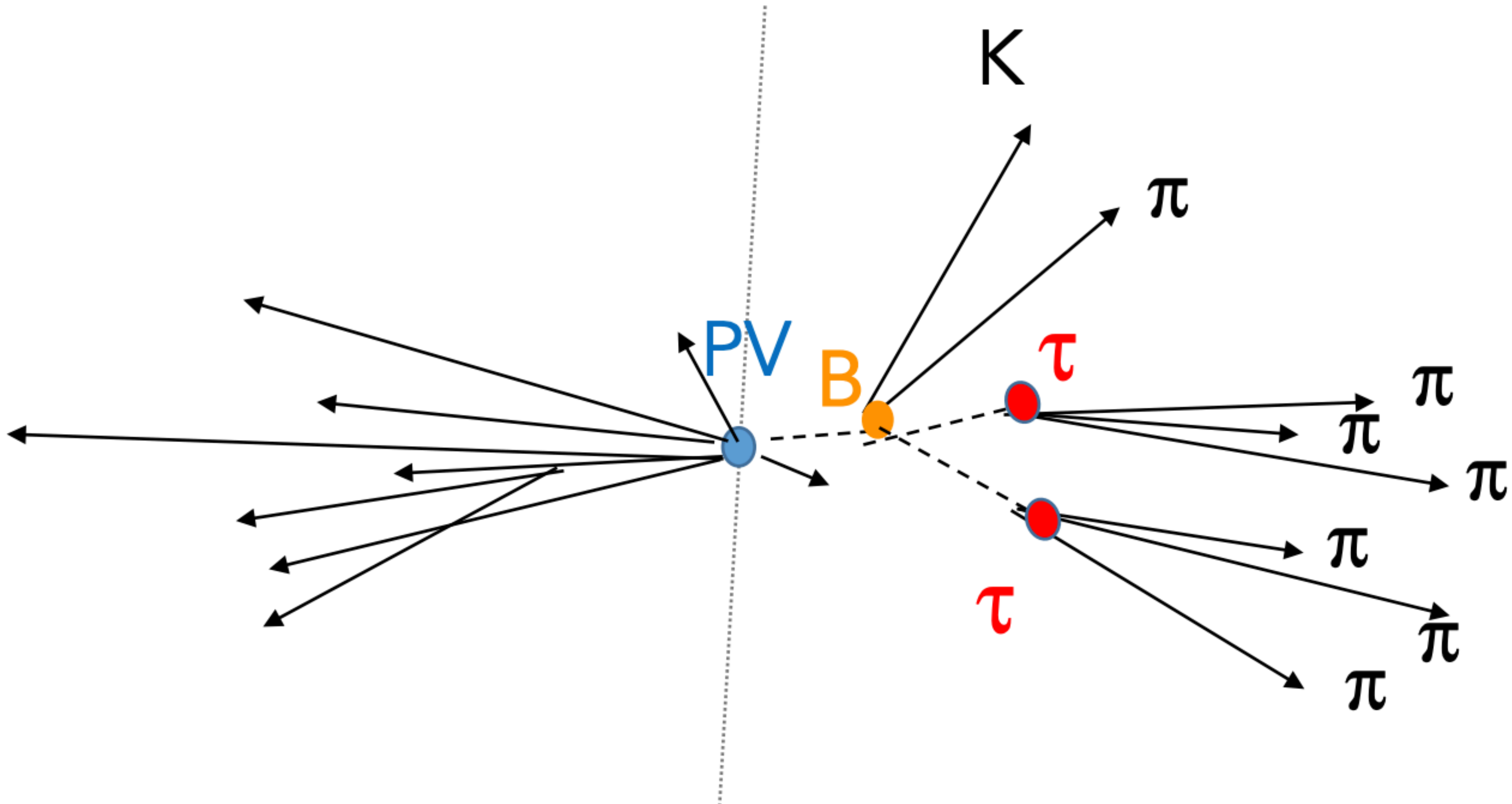
- For left-handed NP, $b \to s\tau\tau\,(\nu\nu)$ neutral currents are connected by $SU(2)_L$.

- Since $b \to s\tau\tau\,(\nu\nu)$ is a FCNC, it is a rare 1-loop process in the SM, but it is tree-level in the NP. We therefore expect a loop factor of NP enhancement!

- Allowed by current data, particularly in the poorly measured $b \to s\tau\tau$ transitions. Current bound is far from the SM rate- opportunity for large NP to hide!

Tera-Z searches for $b \to s\tau\tau$ transitions

- Tera-Z will be ideal for measuring rare $b \to s\tau\tau$ transitions! Examples are $B \to K^*\tau^+\tau^-$, $B_s \to \tau^+\tau^-$. A potential $B \to K^*\tau^+\tau^-$ event:

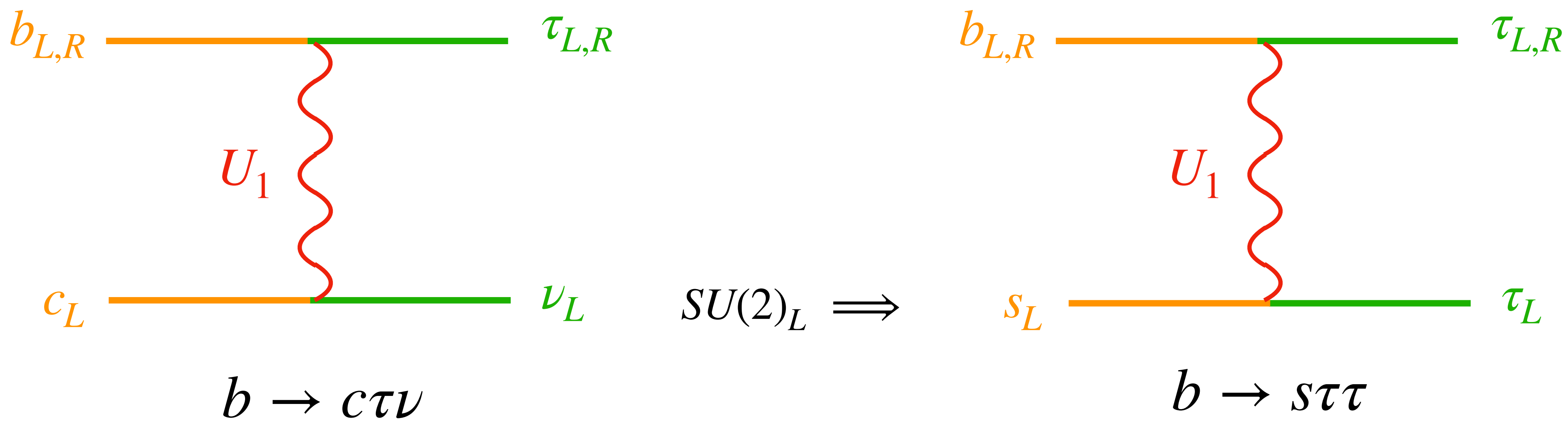


- Need to fix 6 dofs (two neutrinos). Possible since PV and B vertices give the B direction, tau vertices can be reconstructed, and tau mass (over) closes the system. About 1000 fully reconstructed events can be expected at FCC-ee!

[Figure: Marie-Hélène, FCCee Workshop Jan 2020] [Kamenik, Monteil, Semkiv, Vale Silva, 1705.11106]

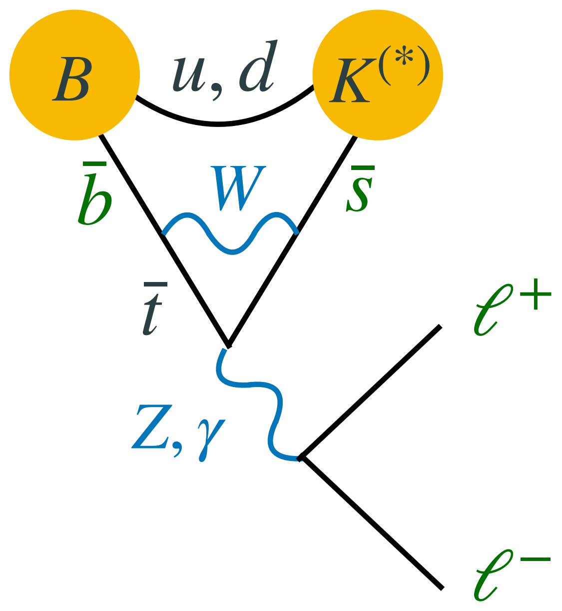
U_1 LQ connects $R_{D^{(*)}}$ to $b \to s\tau\tau$ observables

- We have tree-level effects in $b \to s\tau\tau$ connected to the size of $R_{D^{(*)}}$



- Since $b \to s\tau\tau$ is a FCNC, it is a 1-loop process in the SM. We therefore expect a huge NP enhancement in $b \to s\tau\tau$!

$$\frac{\mathscr{B}(B \to K^{(*)}\tau\tau)}{\mathscr{B}(B \to K^{(*)}\tau\tau)_{\rm SM}} \sim 16\pi^2 \frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\rm SM}}$$



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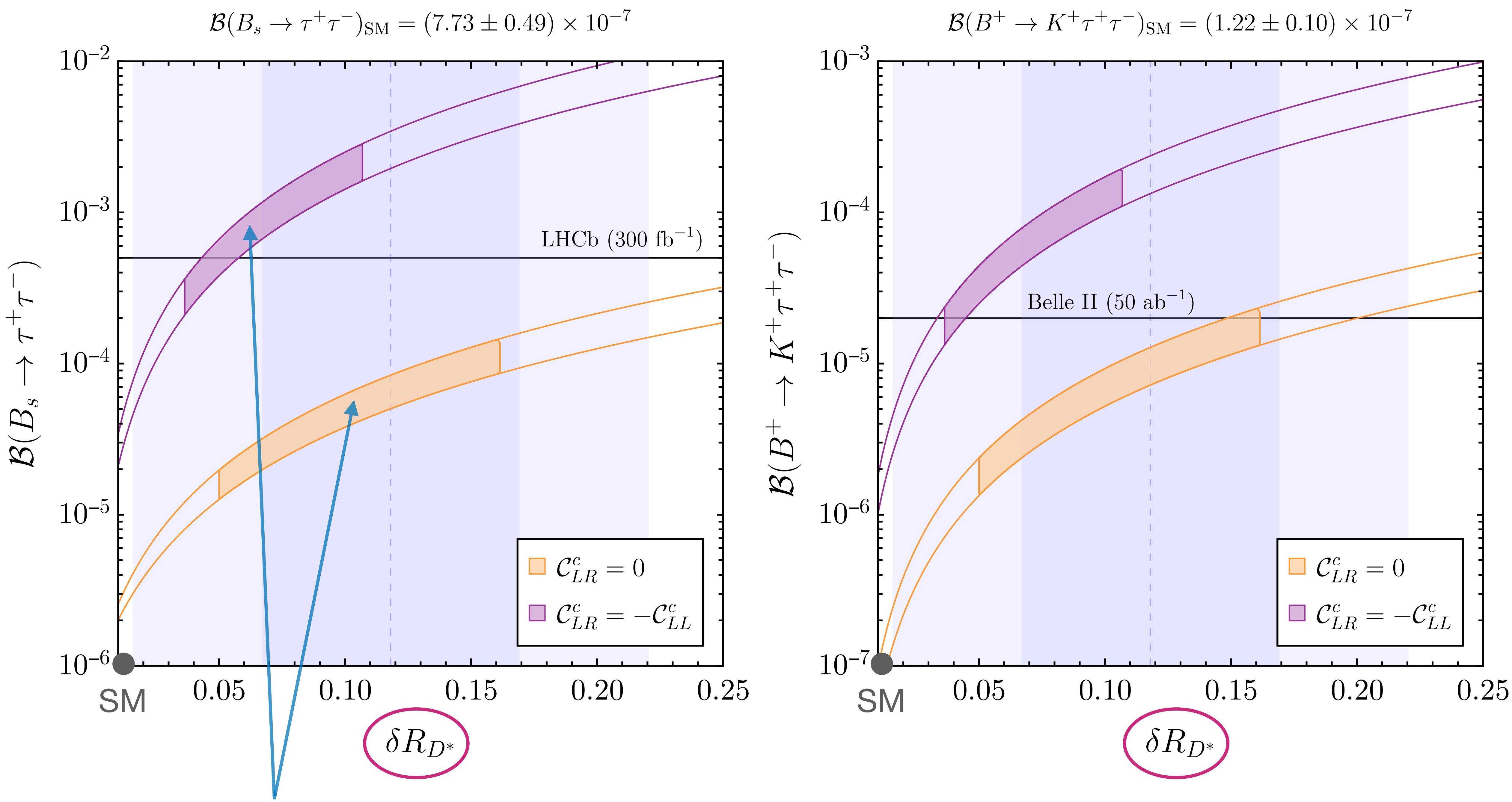

Updated 90% CL region preferred by low-energy $b \to c\tau\nu$ data 2210.13422

[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]

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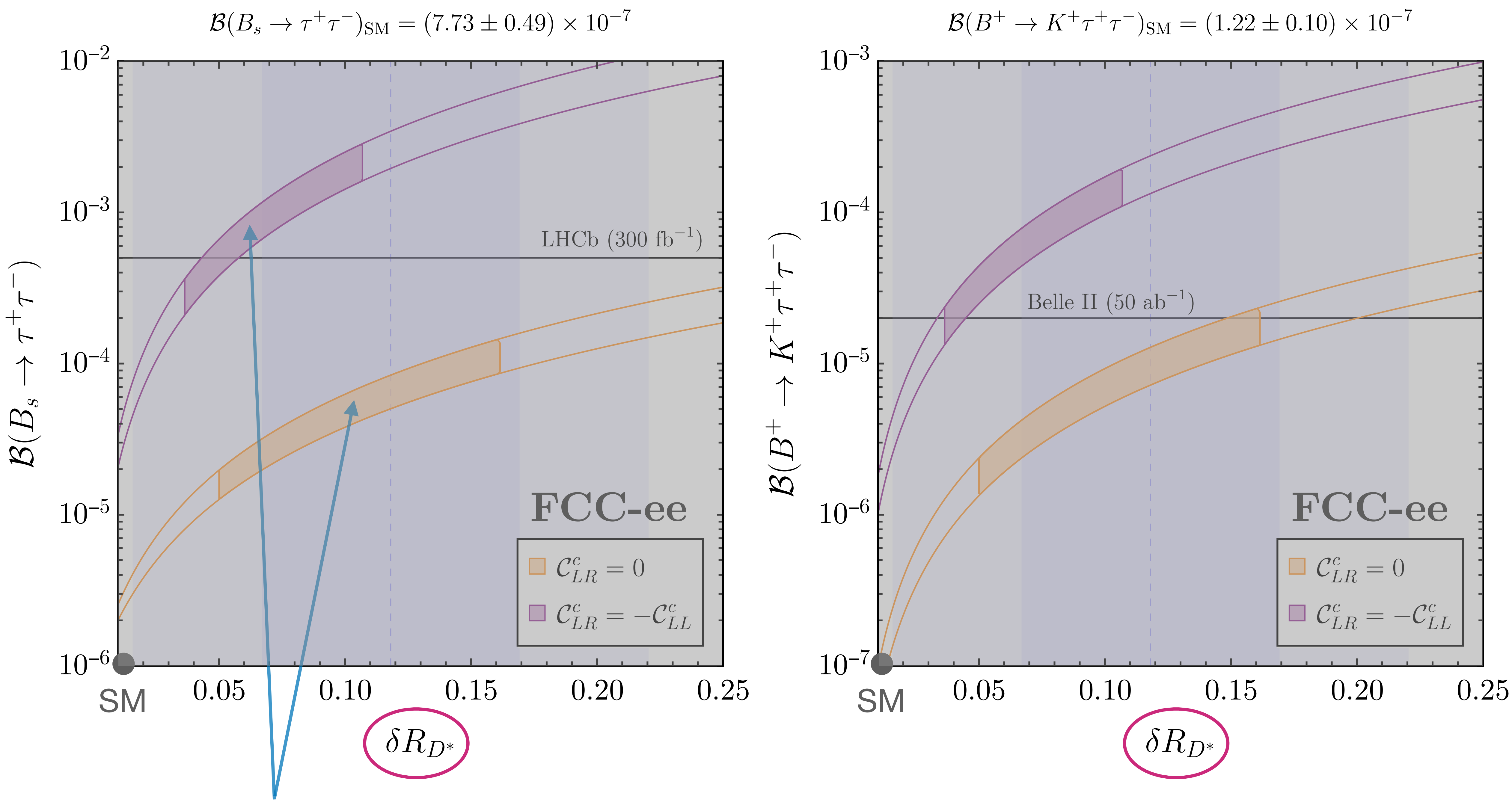

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[J. Aebischer, G. Isidori, M. Pesut, BAS, F. Wilsch, 2210.13422]

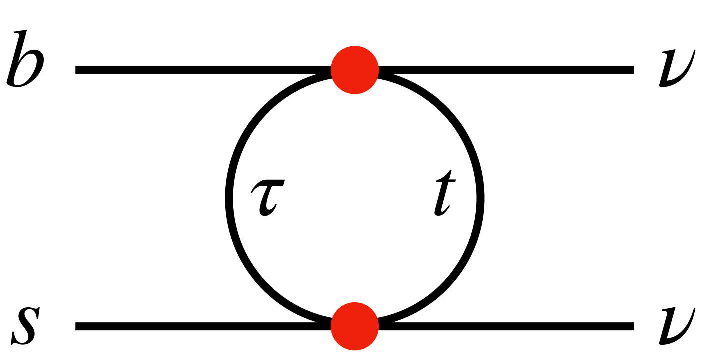
Tera-Z searches for $b \to s\nu\nu$ transitions

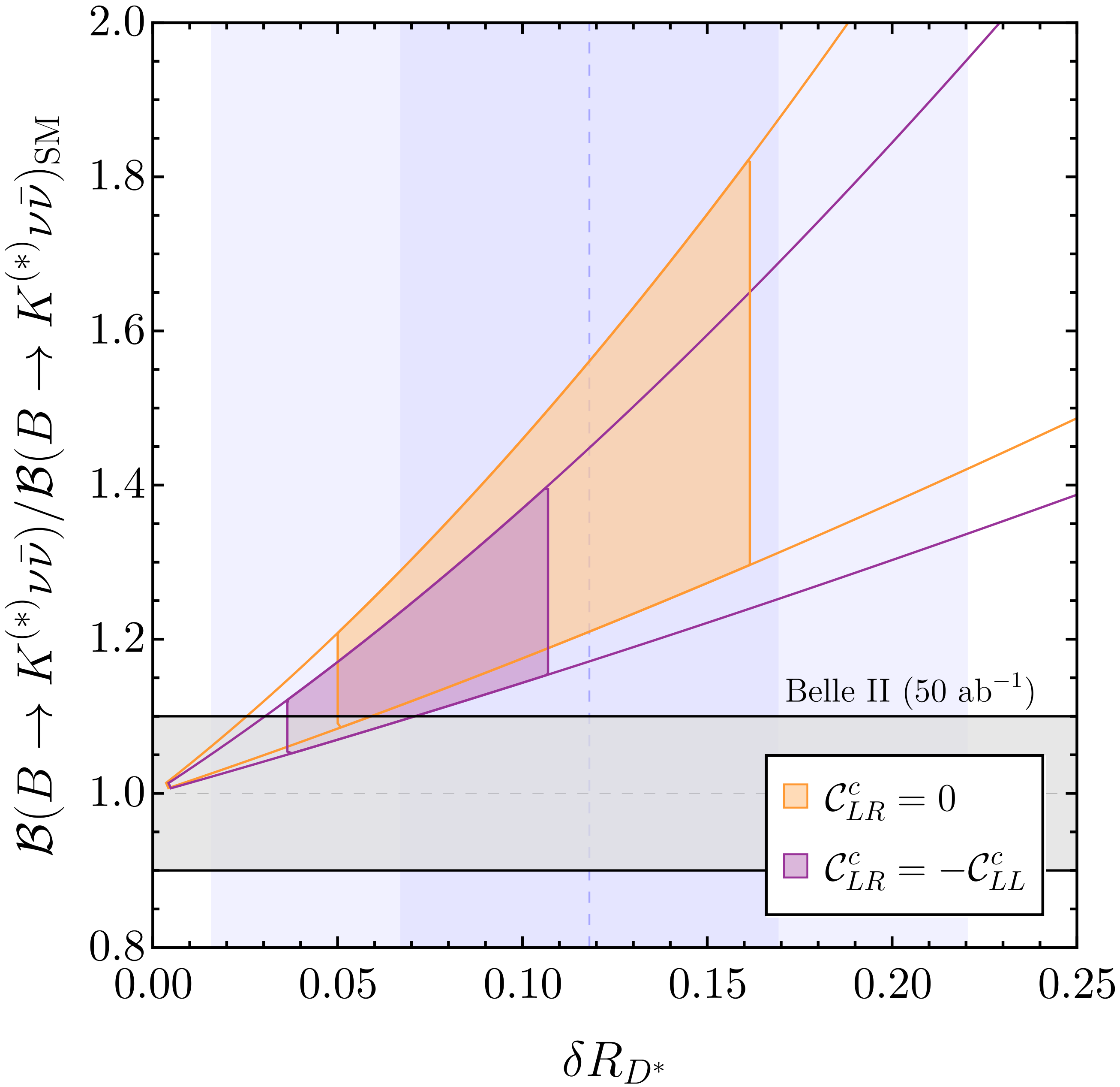
- The decay $B \to K^*\nu\bar{\nu}$ is theoretically clean (no long-distance charm loop), making it an excellent probe of NP. First observation recently by Belle II:

$$\frac{\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\overline{\text{exp}}}}{\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\text{SM}}} = 2.6 \pm 0.8$$

$\approx 2\sigma$

*Big effect- if NP, likely it should be tree-level. But Belle II (10%) and FCC-ee (1%) will test even loop models. The EFT of the U_1 gives:





[Belle II Collaboration, 2311.14647]

Tera-Z searches for $B_c \to \tau\nu$

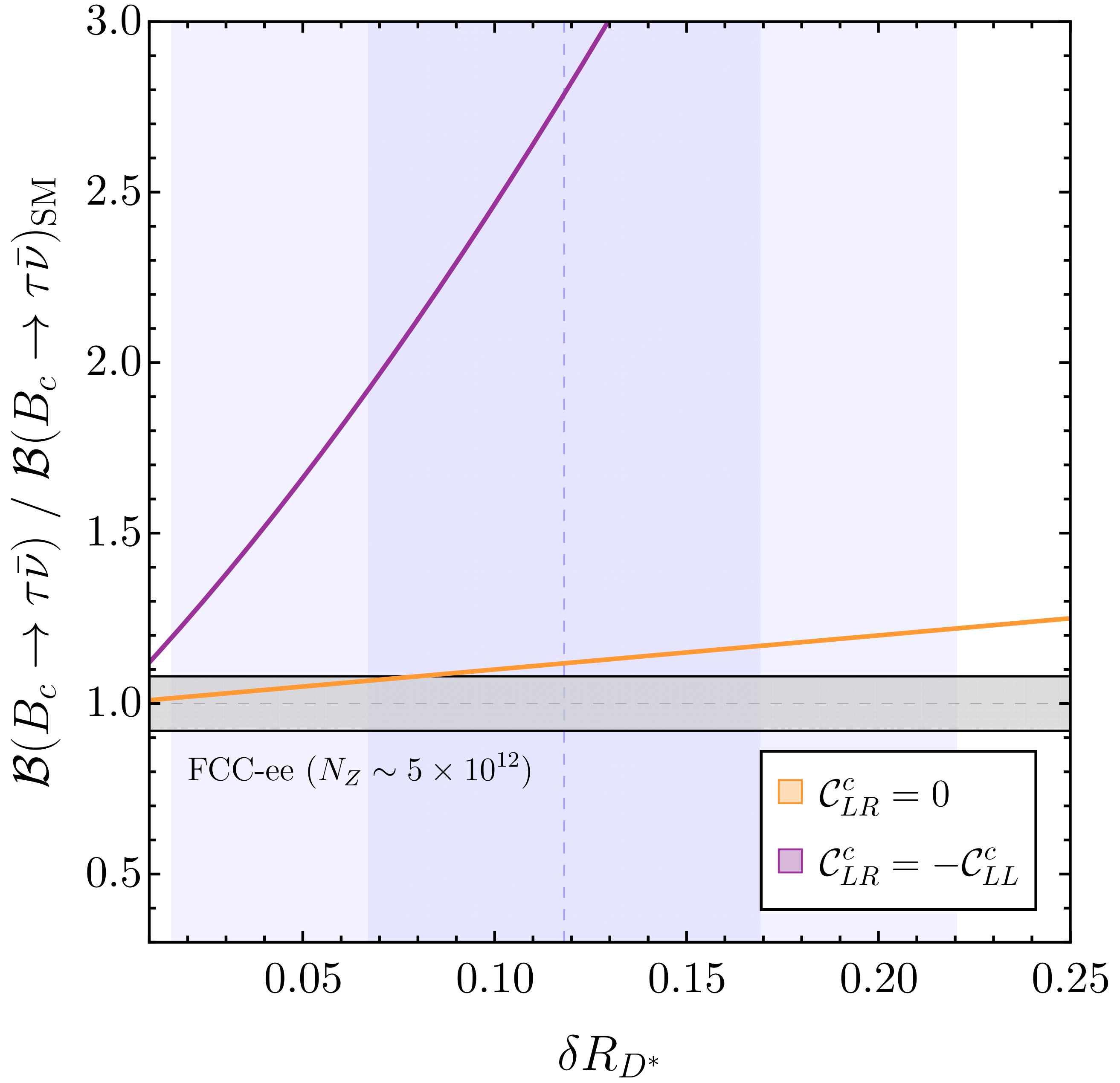
- Right now only an upper bound exists $B_c \to \tau\nu < 0.1\ (95\,\%\,\mathrm{CL})$

$N_Z (\times 10^{12})$	$N(B_c^+ \to \tau^+\nu_\tau)$	Relative σ (%)
0.5	430 ± 33	7.8
1	858 ± 46	5.5
2	1717 ± 64	3.8
3	2578 ± 83	3.2
4	3436 ± 93	2.7
5	4295 ± 103	2.4

$$\mathcal{B}(B_c^+ \to \tau^+\nu_\tau) = R_c \times \mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)^{\mathrm{SM}}$$

- Measurement of $\mathscr{B}(B_c \to \tau\nu)$ possible with $\lesssim 8\,\%$ precision.

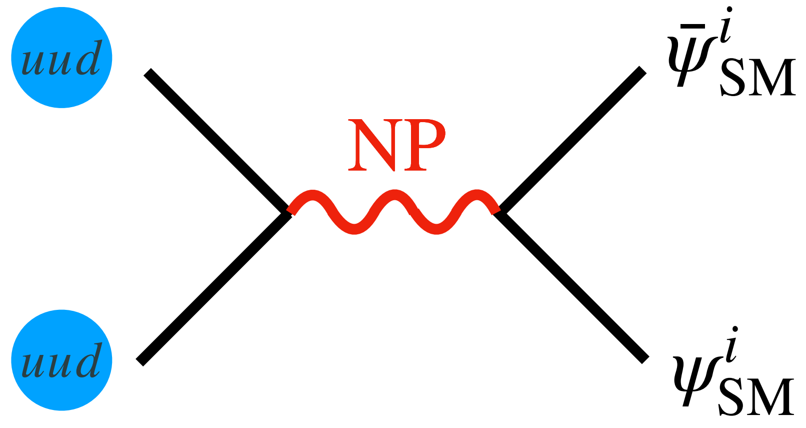
(*currently limited by knowledge of the normalization mode form factors)



[Ahmis, Hartmann, Helsens, Hill, Sumensari, 2105.13330]

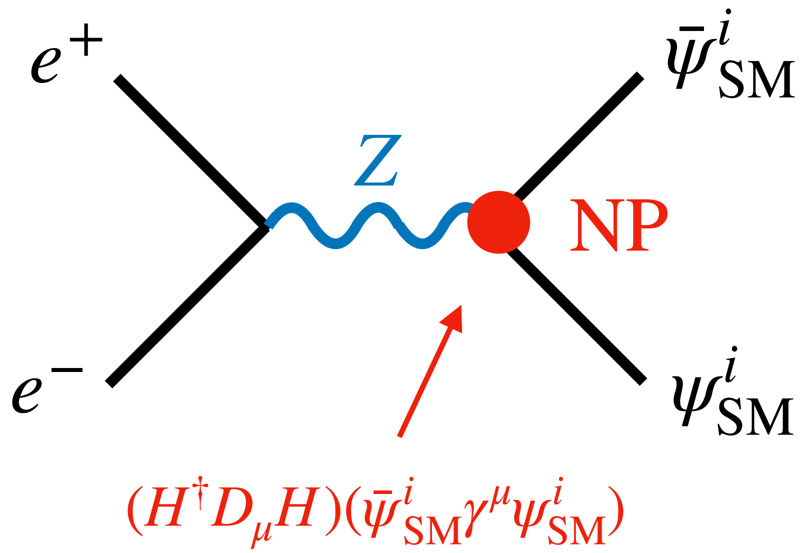
Tera-Z: Flavor blind probes of flavor

- Searches at the LHC have the benefit of potentially *directly* producing NP states, but also an inherent flavor asymmetry in the production:



LHC: Strong bounds on flavor universal NP O(10 TeV), but NP coupled to the third family is much less constrained O(1 TeV).

- At tera-Z, we can exploit the flavor blindness of the SM gauge interactions to *indirectly* probe NP coupled to any generation!



Tera-Z: Almost flavor democratic bounds. Non-universal NP scenarios such as 3rd family NP ($U(2)^5$) will be extremely well probed.

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.

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

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

- 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 $\Lambda_{\rm NP} = 3\ {\rm TeV}$. 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] +...
```

- 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]

HighPT

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

Flavor Bounds

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

Bounds from 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

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1	cHWB	A_b^{FB}	8.98	8.78	2.2
2	CHl3[l]	σ_{had}	7.75	7.64	1.4
3	CHl1[l]	σ_{had}	7.65	7.51	1.8
4	CHe[l]	σ_{had}	6.6	6.48	1.8
5	CHq3[l]	R_τ	5.56	5.48	1.4
6	cHD	A_b^{FB}	5.05	4.71	6.7
7	Cll[l, p, p, l]	A_b^{FB}	4.52	4.52	0.
8	CHl1[h]	R_τ	4.37	4.3	1.6
9	CHl3[h]	R_τ	4.36	4.3	1.4
10	CHe[h]	R_τ	3.76	3.68	2.1
11	CHq1[h]	Γ_Z	3.74	4.34	-16.
12	CHq3[h]	R_b	3.48	3.53	-1.4
13	CHu[h]	A_b^{FB}	3.04	3.99	-31.3
14	Clq1[l, l, h, h]	σ_{had}	2.46	2.87	-16.7
15	CHu[l]	R_τ	2.43	2.39	1.6
16	Clq3[l, l, h, h]	A_b^{FB}	2.41	2.72	-12.9
17	Clu[l, l, h, h]	σ_{had}	2.39	2.81	-17.6
18	CuB[h]	A_b^{FB}	2.38	2.79	-17.2
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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
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33	Cqe[h, h, h, h]	R_τ	1.2	1.41	-17.5
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35	Cqq3[h, h, h, h]	m_W	1.16	0.77	33.6
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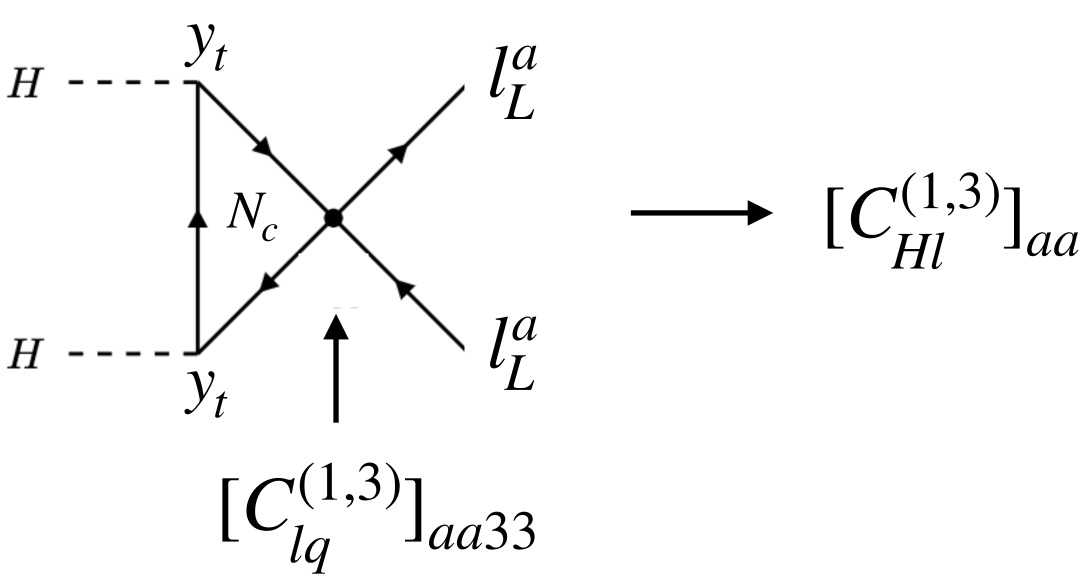
Bounds from the Z-pole

- 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:



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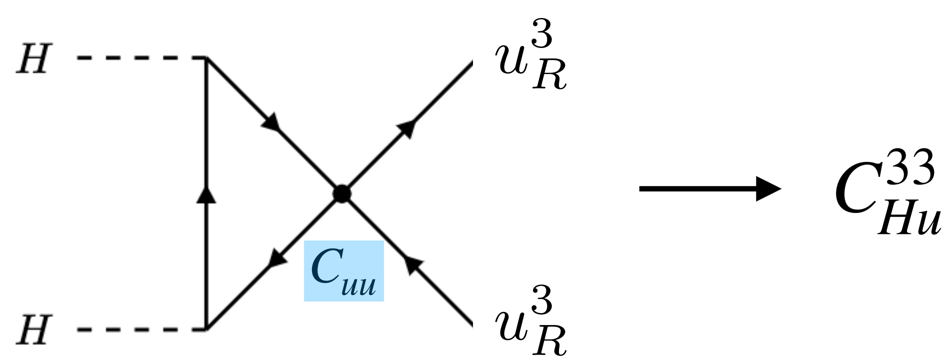
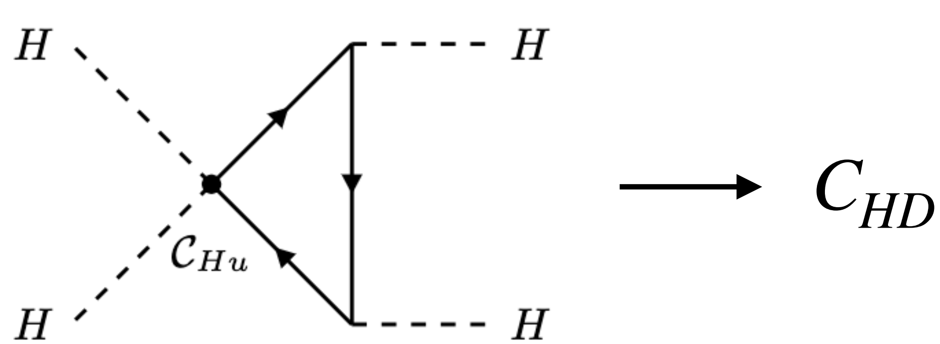
- Including RGE, we have 120 of 124, 38 with bounds $\gtrsim 1$ TeV.
- Resummation is important, even from $\Lambda_{\rm NP} = 3$ TeV.

LL RGE



NLL RGE



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

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

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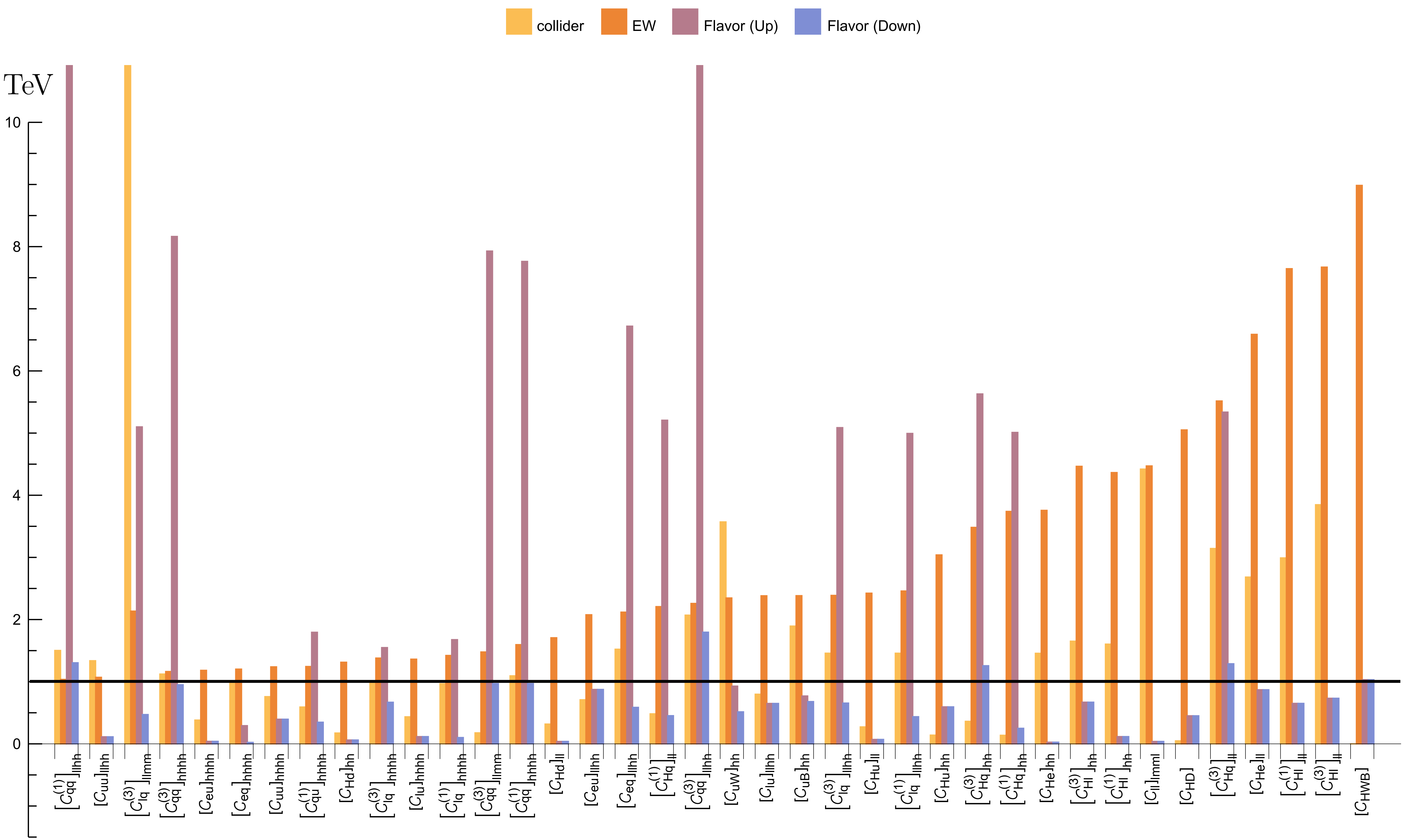
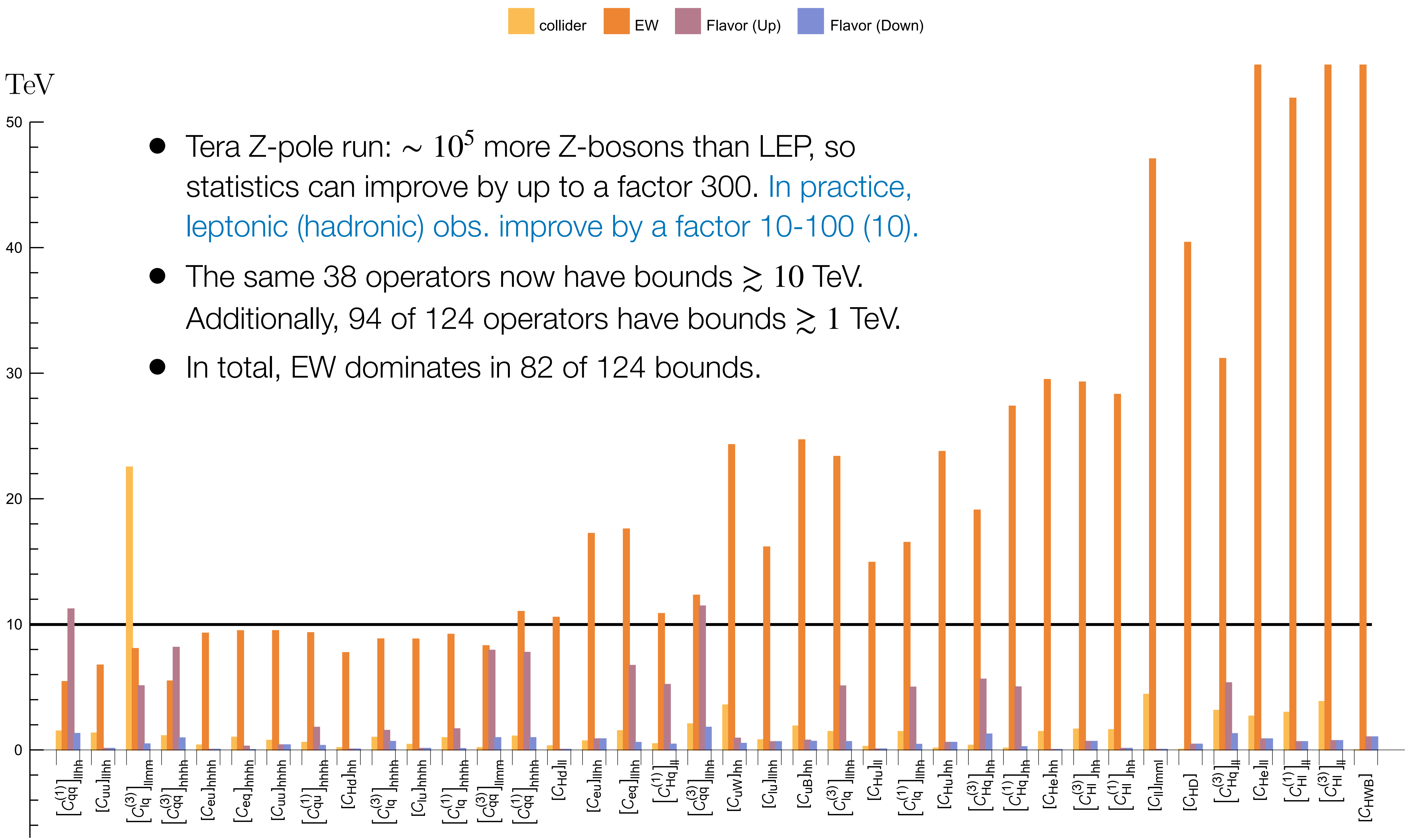
Current Bounds: Z-pole + Flavor + Direct Searches



[Allwicher, Cornella, Isidori, BAS, 2311.00020]

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

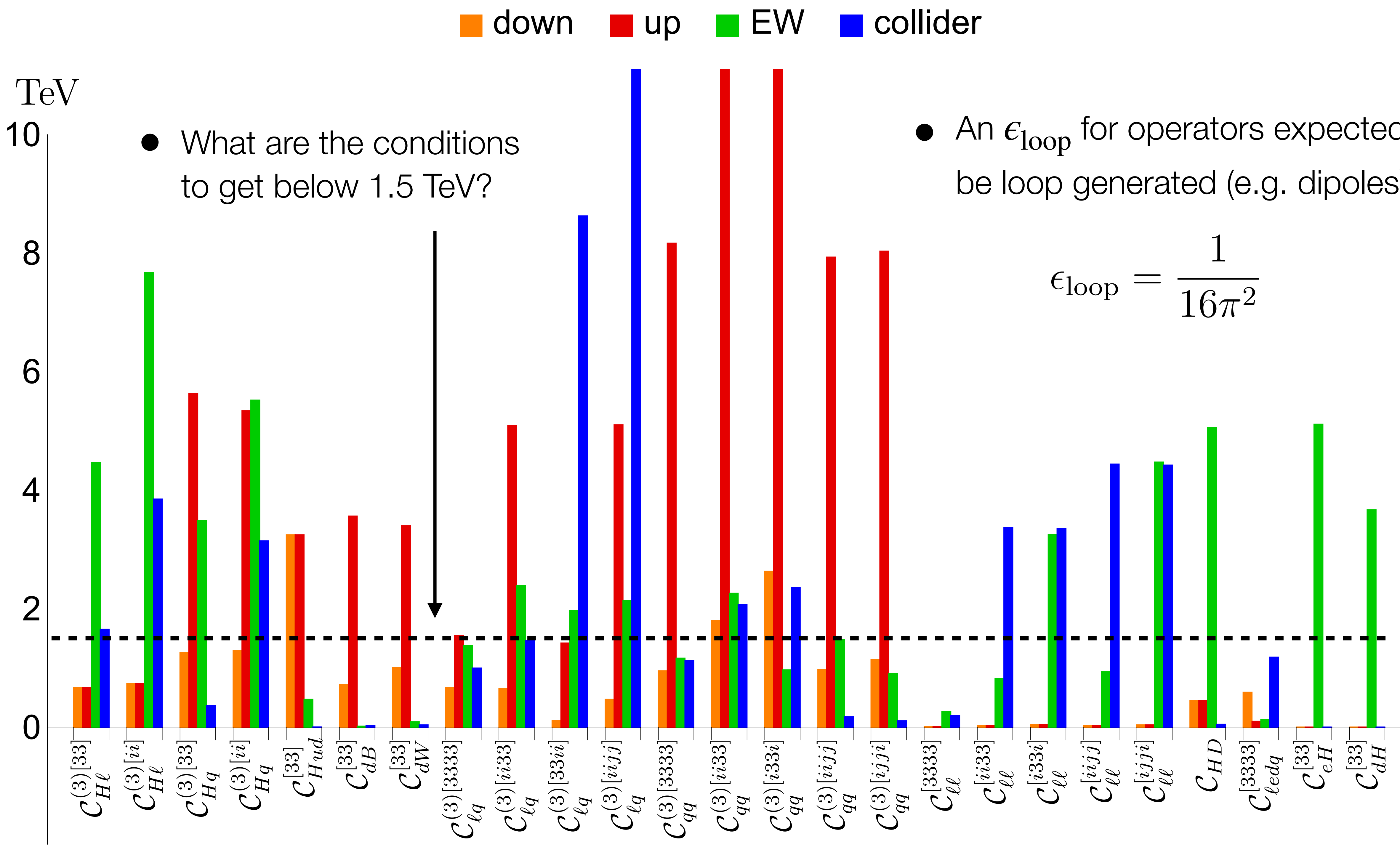
Projection: Tera-Z + Flavor + Direct Searches



- 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).
- 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



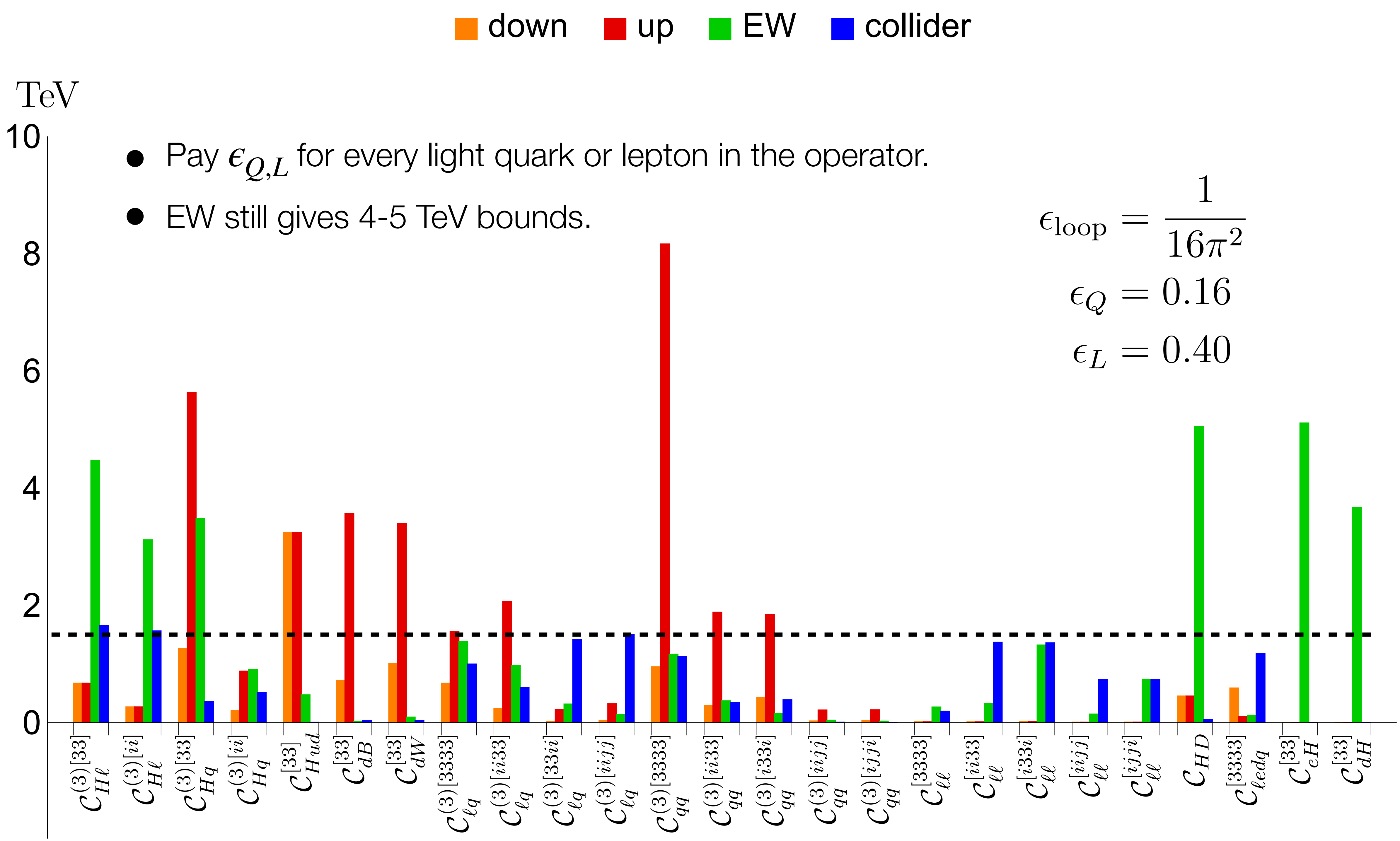
- What are the conditions to get below 1.5 TeV?

- 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]

Hypothesis of dominantly third-family NP

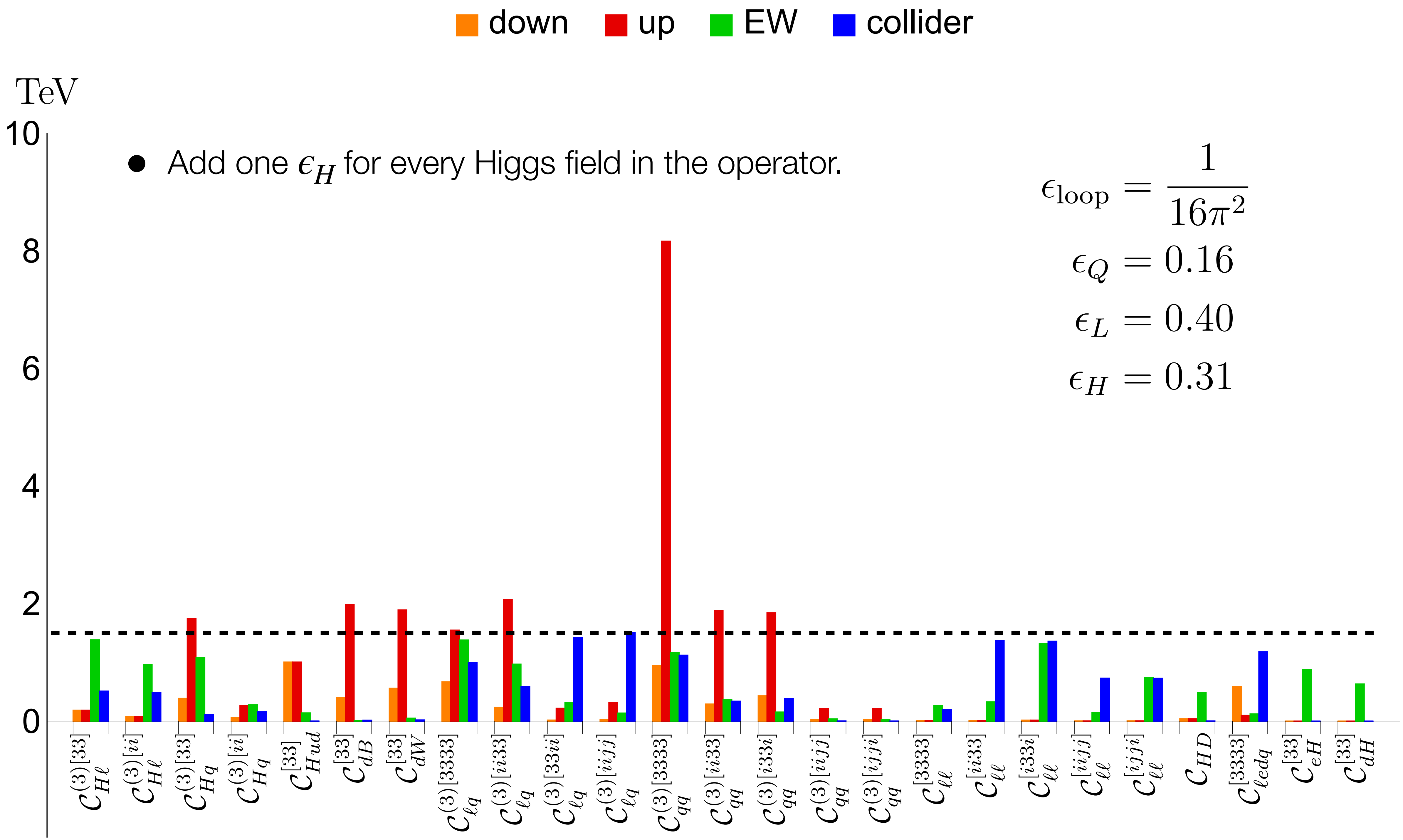


- Pay $\epsilon_{Q,L}$ for every light quark or lepton in the operator.
- EW still gives 4-5 TeV bounds.

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

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

Third-family NP: Higgs couplings



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

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

$$\epsilon_Q = 0.16$$

$$\epsilon_L = 0.40$$

$$\epsilon_H = 0.31$$

[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 $\epsilon_{Q,L,H,\text{mis}} \gtrsim 0.15$

$$\epsilon_{\text{loop}} = \frac{1}{16\pi^2}$$
$$\epsilon_Q = 0.16$$
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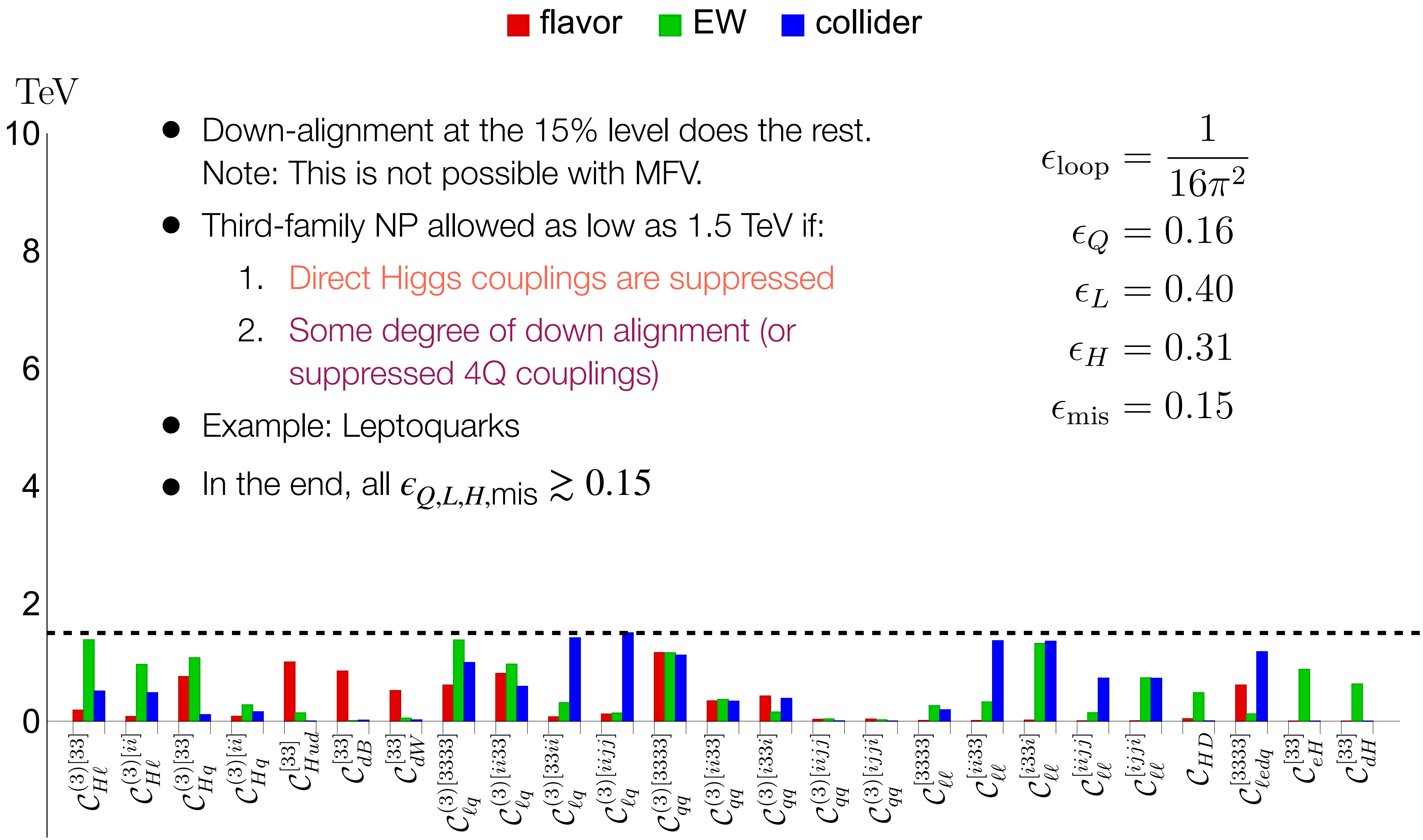
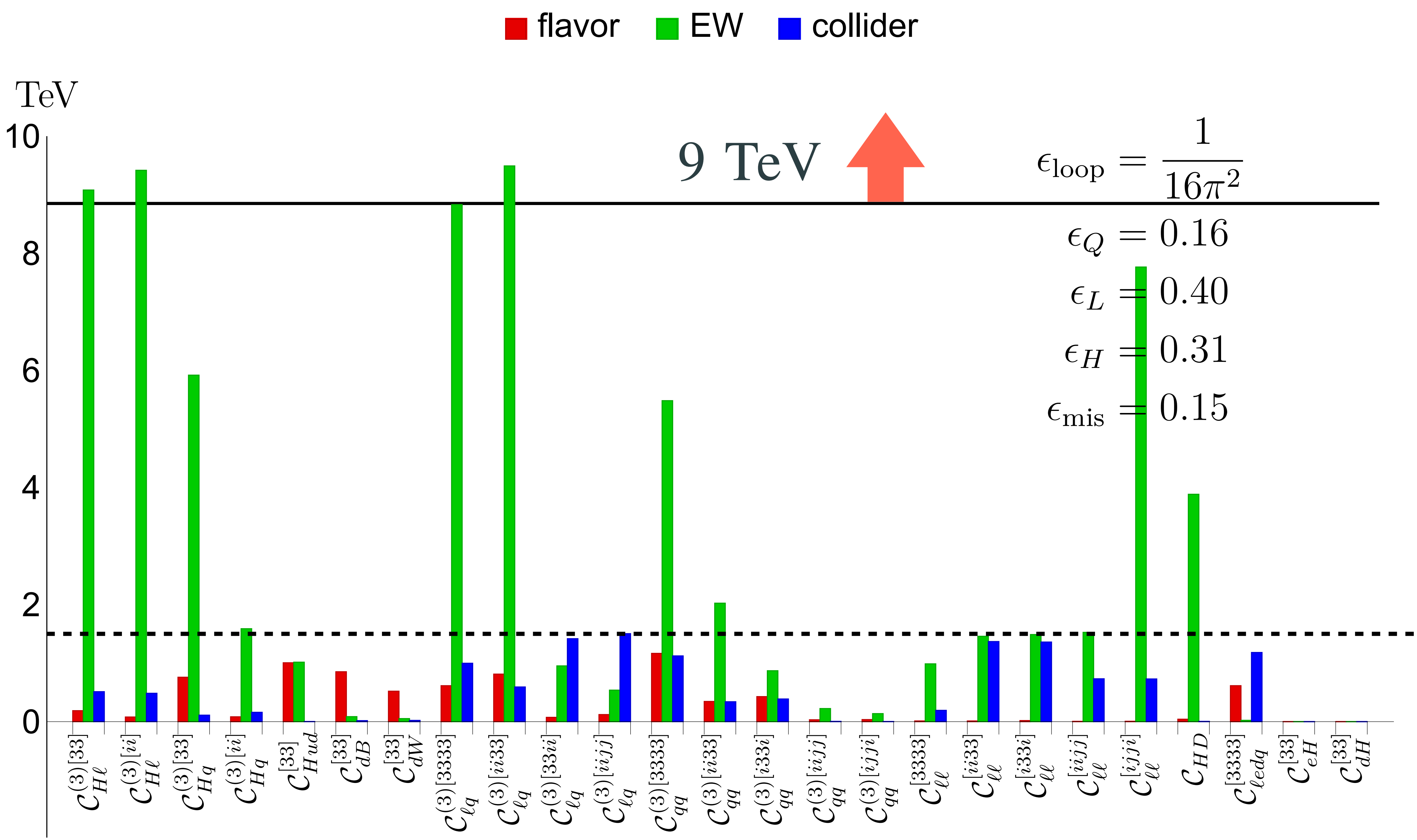


[Allwicher, Cornella, Isidori, BAS, 2311.00020]

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



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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.

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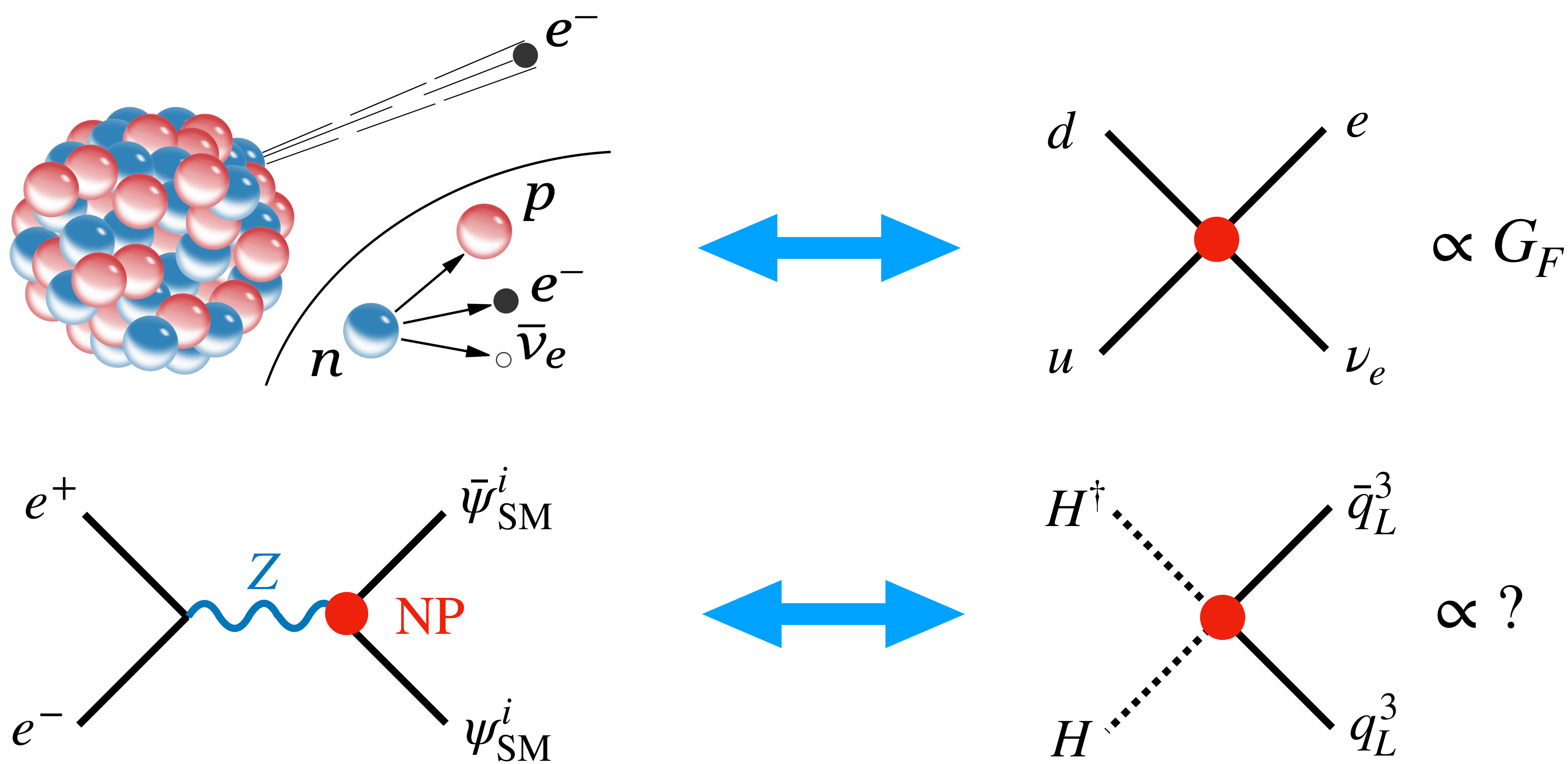
- Future machines featuring a tera-Z run plan allow for an exquisite heavy flavor program, in particular B and tau physics. Combining the two gives us an opportunity to probe never before measured rare B decays with final state taus (good place for NP).

- Because EWPT are much more flavor democratic, not even third family NP can hide. A future tera-Z machine will indirectly probe NP protected by the accidental symmetries of the SM in the 10-100 TeV range.

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'

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Alessandro Strumia

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

27 Nov 2000

Abstract

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Backup Slides

EWPT are (still) a powerful probe of NP

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

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

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

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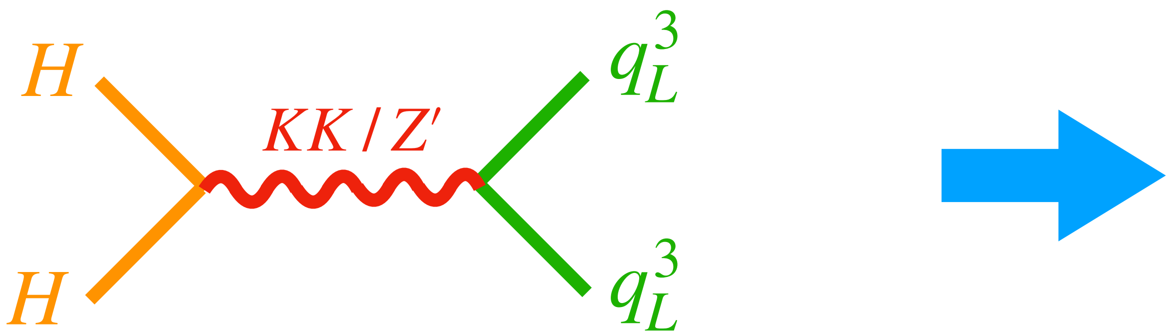
- These well-motivated classes of models generically lead to sizable corrections to EW precision observables (at least in third-family quarks).



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

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

How does the Higgs fit into the story?

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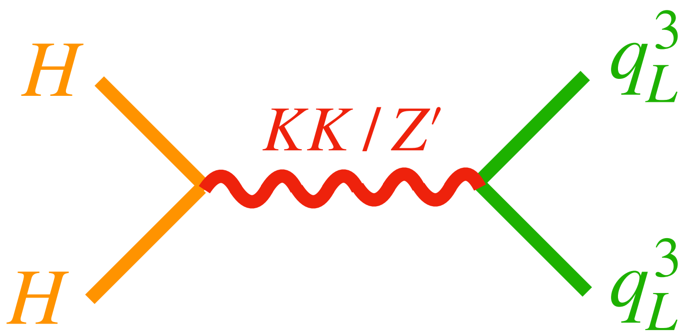

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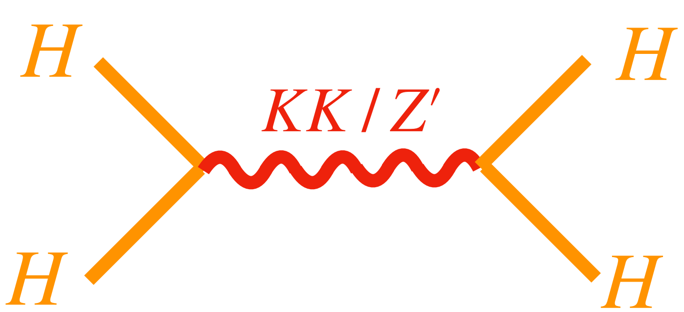


$$C_{HD}\,|H^\dagger D_\mu H|^2$$

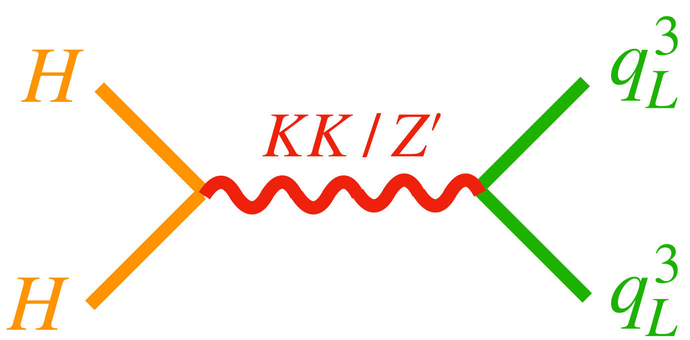
EWPT: $C_{HD} \lesssim (5\text{ TeV})^{-2}$

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).

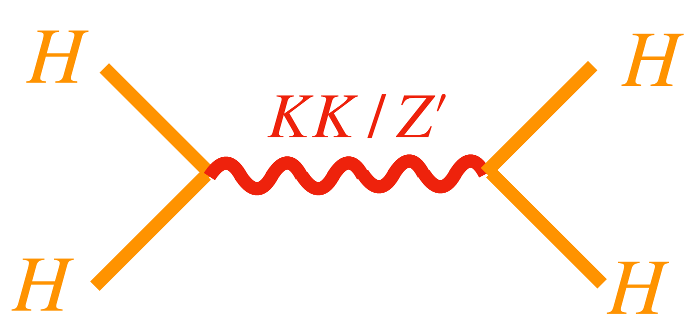
Both operators are $U(2)^5$ preserving!

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
	$c_{Qq}^{1,8}$	✓	✓			✓	✓	✓	✓	
	$c_{Qq}^{1,1}$	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	$c_{Qq}^{3,8}$	✓	✓	(✓)	(✓)	✓	✓	✓	✓	
	$c_{Qq}^{3,1}$	(✓)	(✓)	✓	✓	✓	(✓)	(✓)	(✓)	
	c_{tq}^{8}	✓	✓			✓	✓	✓	✓	
	c_{tq}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
2-heavy-2-light	c_{tu}^{8}	✓	✓			✓	✓	✓	✓	
	c_{tu}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{Qu}^{8}	✓	✓			✓	✓	✓	✓	
	c_{Qu}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{td}^{8}	✓	✓			✓	✓	✓	✓	
	c_{td}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{Qd}^{8}	✓	✓			✓	✓	✓	✓	
	c_{Qd}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{QQ}^{1}					✓				
	c_{QQ}^{8}					✓				
4-heavy	c_{Qt}^{1}					✓				
	c_{Qt}^{8}					✓				
	c_{tt}^{1}					✓				
4-lepton	c_{ll}			✓	✓		✓	✓	✓	✓
	$c_{t\varphi}$						✓	✓	✓	
	c_{tG}	✓	✓			✓	✓	✓	✓	
	$c_{b\varphi}$						✓	✓	✓(b)	
	$c_{c\varphi}$						✓	✓		
	$c_{\tau\varphi}$						✓	✓		
	c_{tW}	✓		✓	✓		✓	✓		
	c_{tZ}		✓		✓		✓	✓		
	$c_{\varphi Q}^{(3)}$		✓(b)	✓	✓		✓(b)	✓(b)	✓(b)	
2-fermion +bosonic	$c_{\varphi Q}^{(-)}$		✓		✓		✓	✓	✓(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.	$\Lambda_{\rm flav.}^{\rm down}$	$\Lambda_{\rm flav.}^{\rm up}$	$\Lambda_{\rm EW}$	$\Lambda_{\rm coll.}$	$\Lambda_{\rm all}^{\rm down}$	Obs.	$\Lambda_{\rm all}^{\rm up}$	Obs.
$\mathcal{C}_{H\ell}^{(1)[33]}$	0.1	0.1	4.4	1.6	4.3	R_τ	4.3	R_τ
$\mathcal{C}_{H\ell}^{(1)[ii]}$	0.7	0.7	7.6	3.	7.8	$\sigma_{\rm had}$	7.8	$\sigma_{\rm had}$
$\mathcal{C}_{H\ell}^{(3)[33]}$	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	$\sigma_{\rm had}$	7.7	$\sigma_{\rm had}$
$\mathcal{C}_{He}^{[33]}$	-	-	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	$\sigma_{\rm had}$	6.7	$\sigma_{\rm had}$
$\mathcal{C}_{Hq}^{(1)[33]}$	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	$A_b^{\rm FB}$	3.1	$A_b^{\rm FB}$
$\mathcal{C}_{Hu}^{[ii]}$	-	-	2.4	0.3	2.4	R_τ	2.4	R_τ

Table 2. Hermitian ψ^2 operators

Non-hermitian bi-fermion operators

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

Table 3. Non-hermitian ψ^2 operators

Scalar and Tensor operators

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

Table 4. Non-hermitian ψ^4 operators

LLLL vector operators

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

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

RRRR vector operators

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

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

LLRR vector operators

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

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

Bosonic operators

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

Table 8. CP-conserving bosonic operators