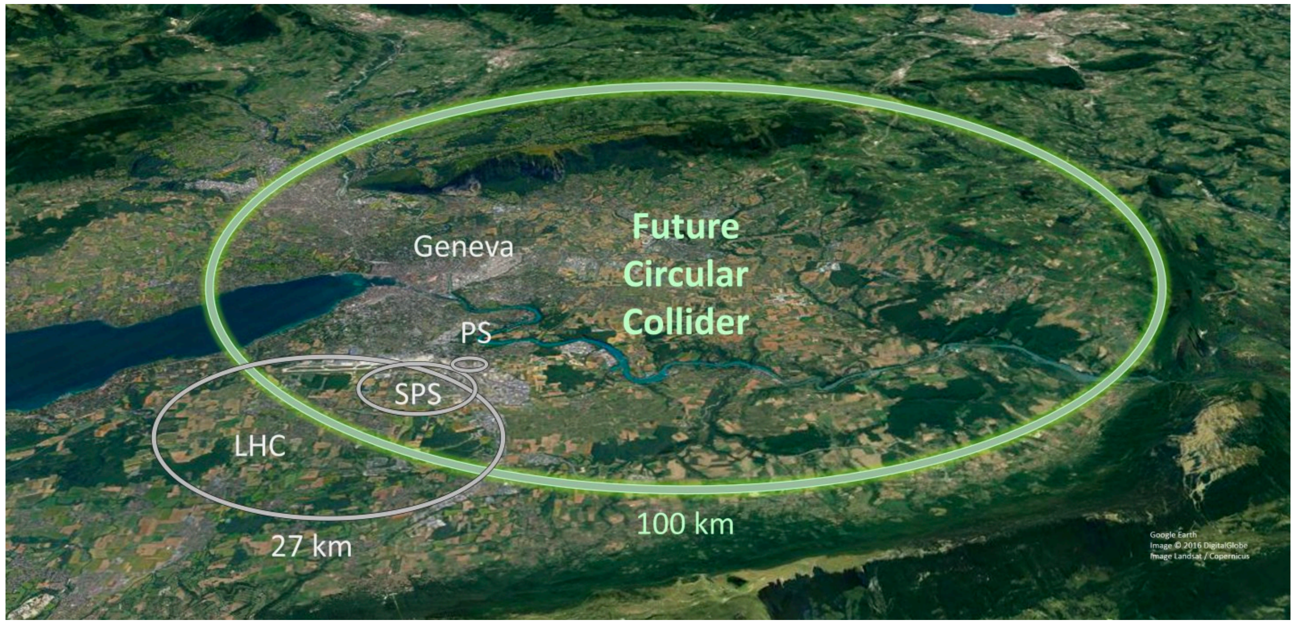
SMEFT analysis of composite Higgs models

Ben A. Stefanek
GENT Fellow, IFIC Valencia
Flavor and Origin of Matter Group

8th General Meeting of the
LHC EFT Working Group
December 3rd, 2024

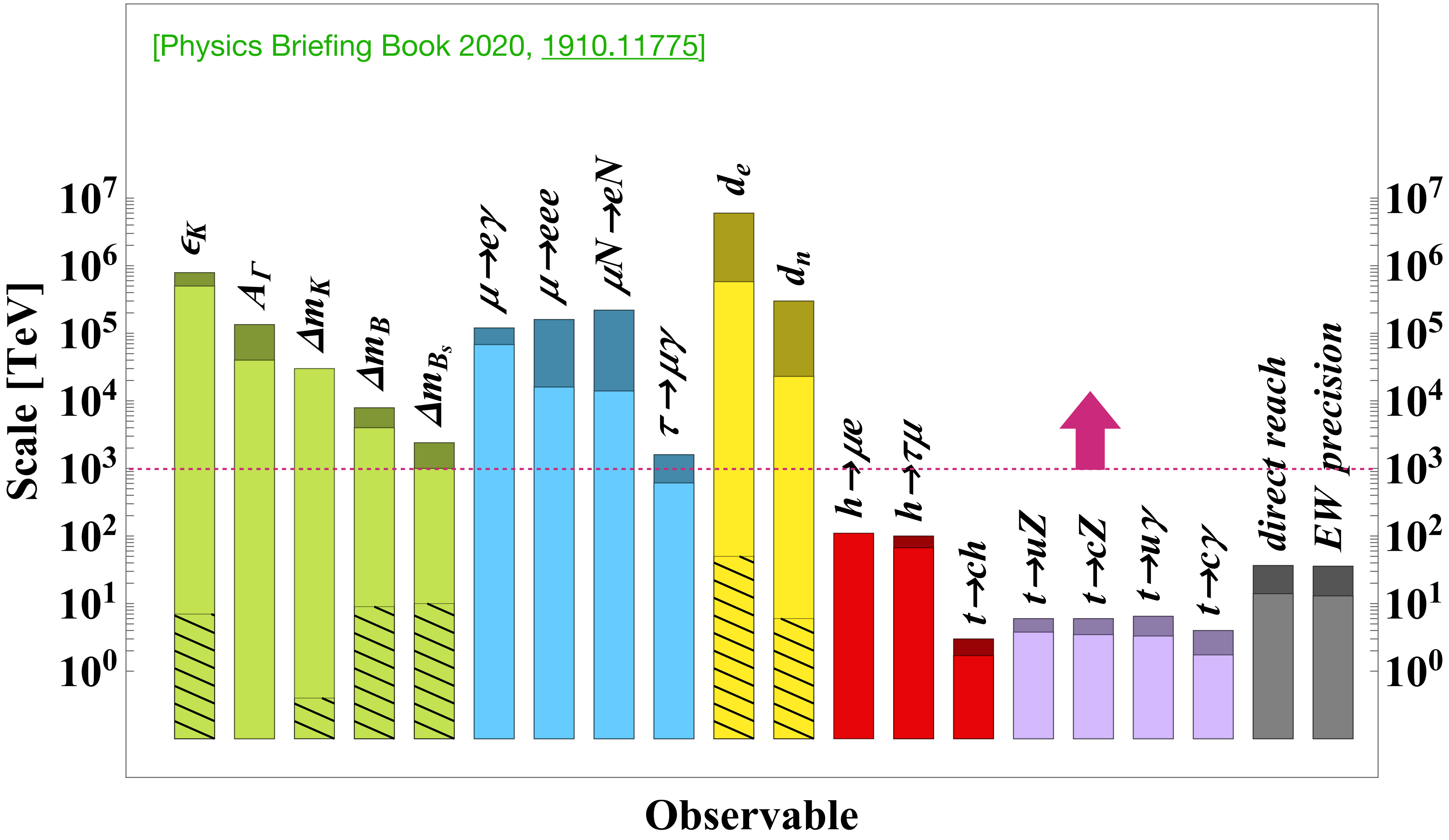


[Based on: BAS, 2407.09593]

GENERALITAT VALENCIANA
Conselleria de Educación, Cultura, Universidades y Empleo

CSIC
Consejo Superior de Investigaciones Científicas

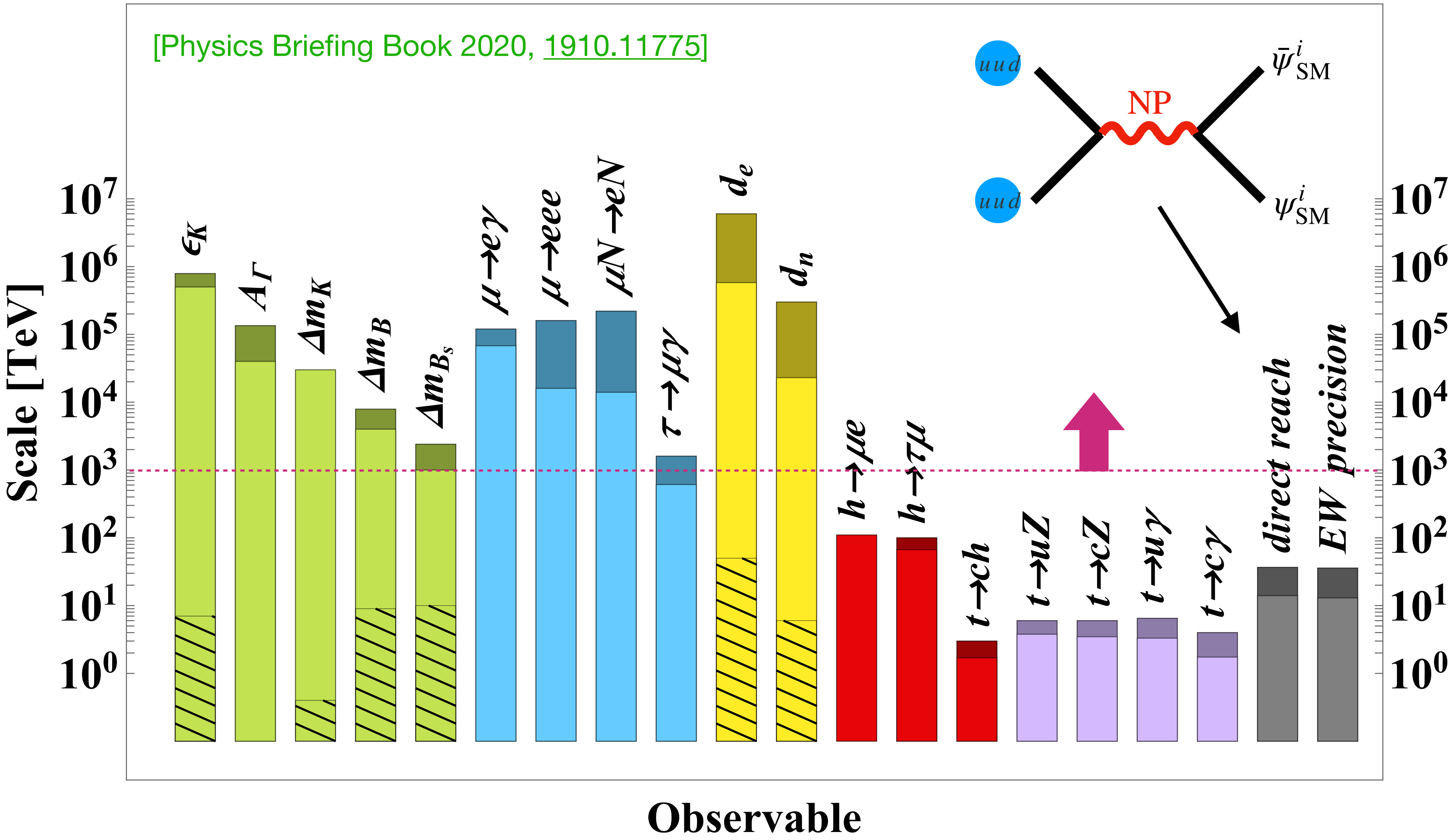
What do we know about the structure of new physics?


[Physics Briefing Book 2020, 1910.11775]

- No deviations in ***flavor data*** that test the accidental symmetries of the SM. What does this tell us about the flavor structure of NP? There are two limiting cases:

1. NP is very heavy, well above 1000 TeV. Then it's fine if the accidental symmetries of the SM are badly broken by NP.
2. NP is close to the TeV scale. The accidental symmetries of the SM must also be very good symmetries of the NP.

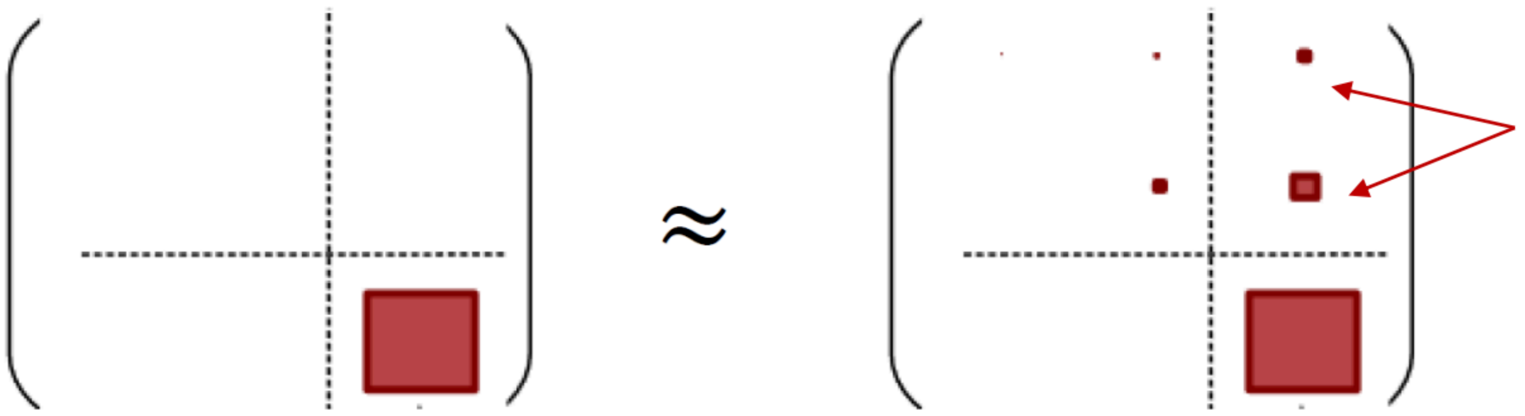
What do we know about the structure of new physics?



- 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 $U(2)^n$ 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 $U(2)^n$ flavor symmetry, just like the SM Yukawa couplings.



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

Exact $U(2)$ limit

Observed Yukawa

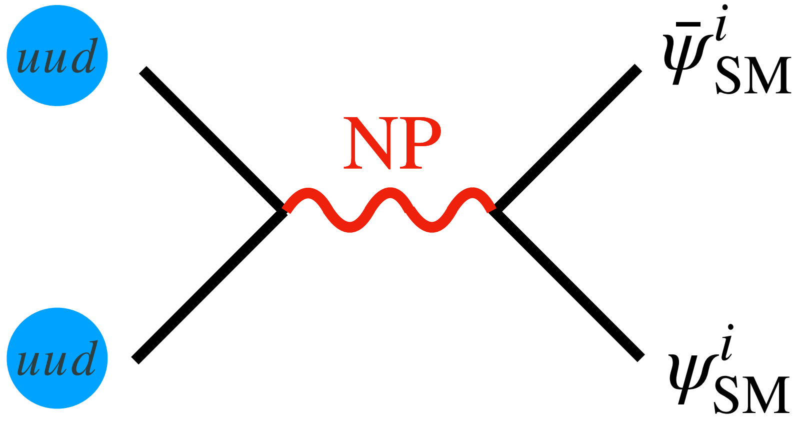
NP coupled only to 3rd family

Also small couplings to light families

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

Tera-Z: Flavor-blind probes of flavor

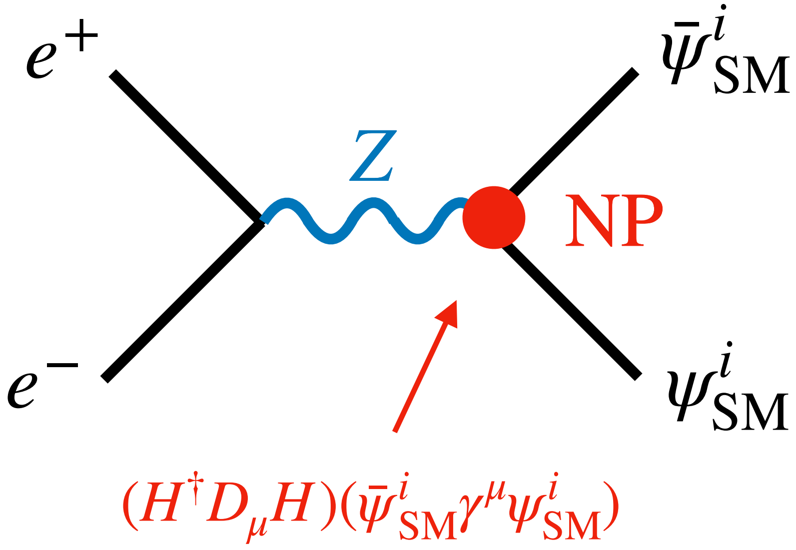
- Searches at the LHC have the benefit of potentially *directly* producing NP states, but also an inherent flavor asymmetry in the production:



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

10^{12} $Z's$

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

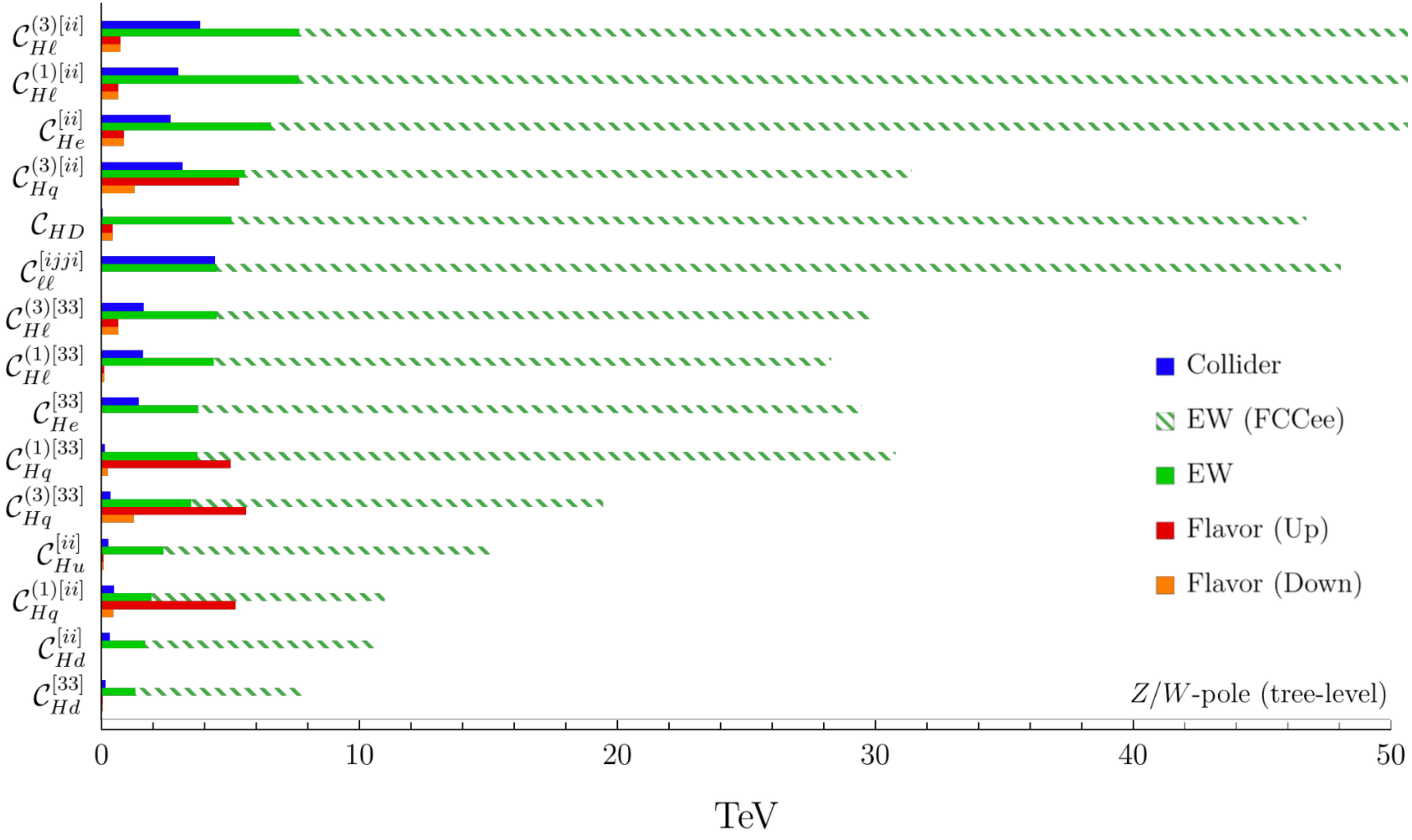


Tera-Z: Almost flavor democratic bounds. Non-universal NP scenarios such as 3rd family NP ($U(2)^n$) will be extremely well probed.

Tera-Z @ leading order

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

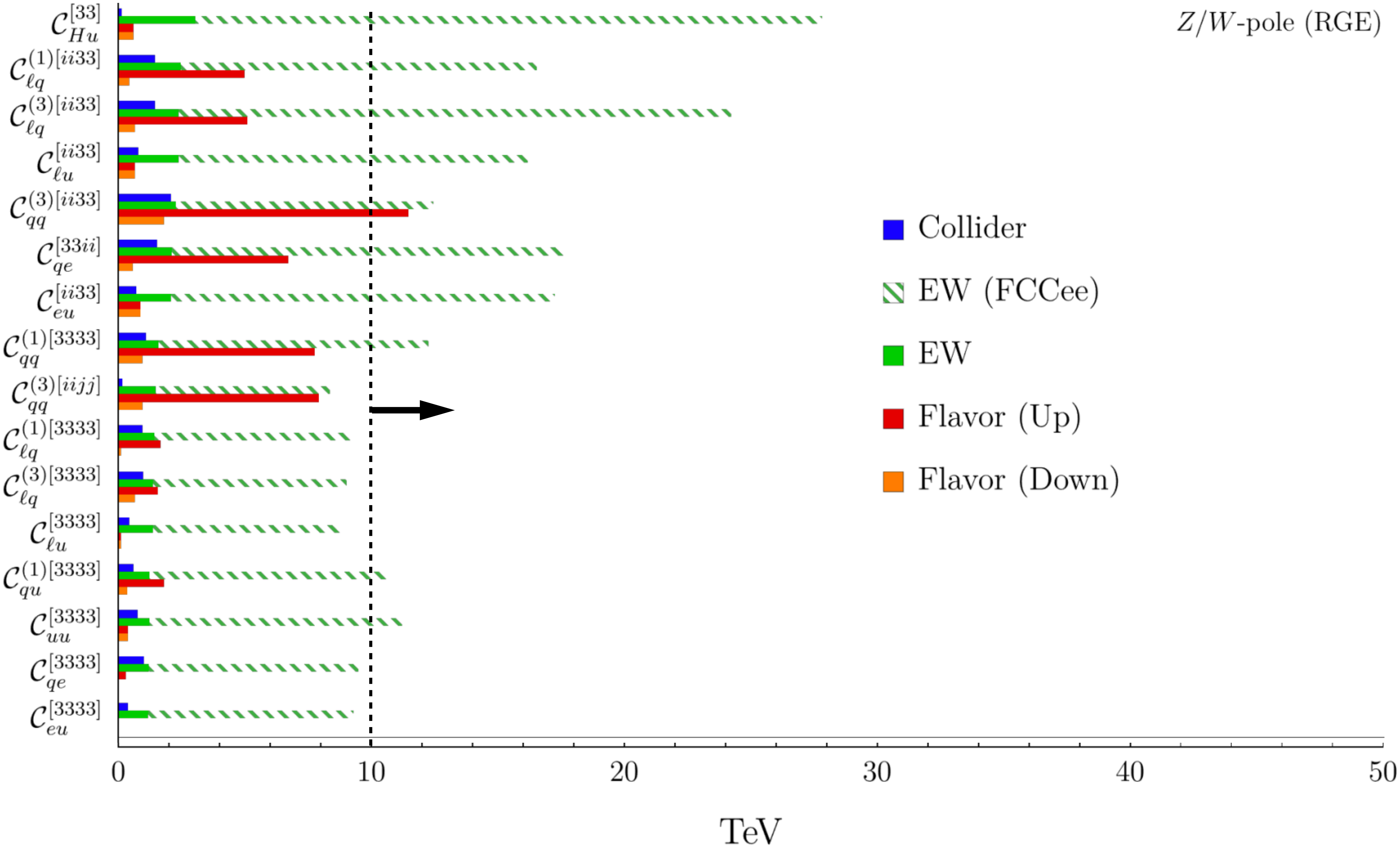
- Here are the Wilson coefficients entering the Z-pole at LO in the $U(2)^5$ limit.



Tera-Z beyond leading order

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

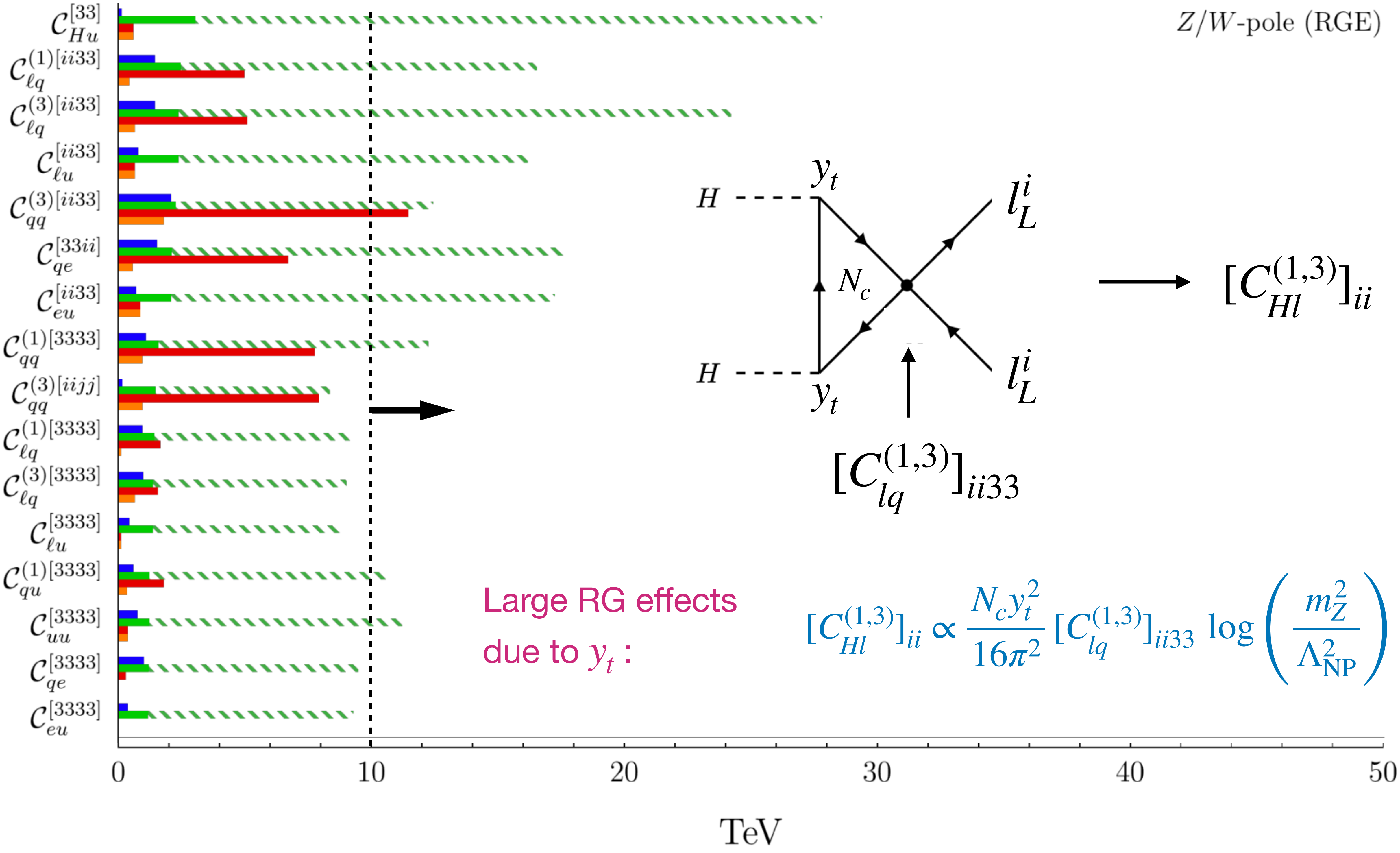
- At NLO, gain sensitivity to hundreds more operators, in some cases O(10 TeV):



Tera-Z beyond leading order

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

- At NLO, gain sensitivity to hundreds more operators, in some cases O(10 TeV):



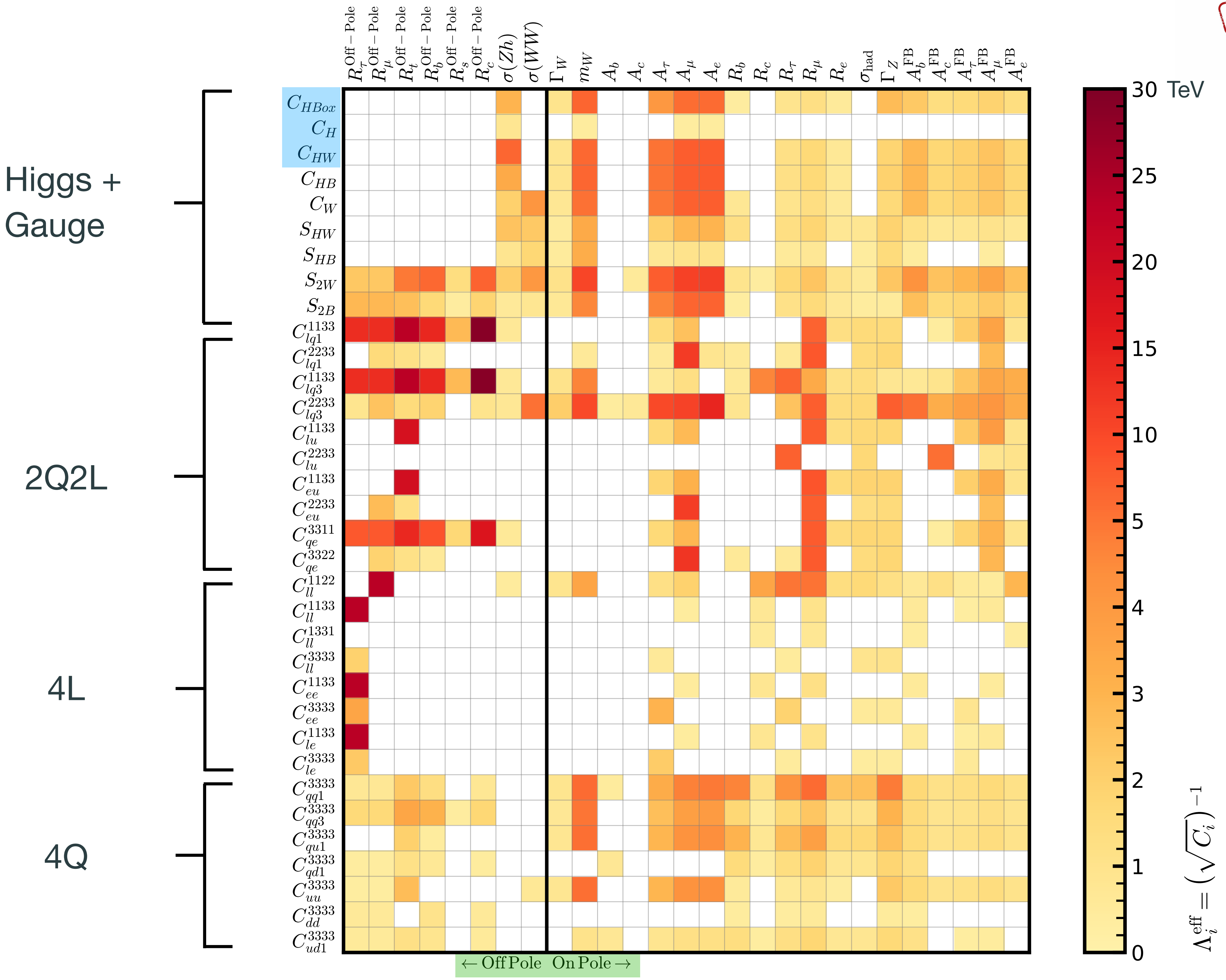
Large RG effects due to y_t :

$$[C_{Hl}^{(1,3)}]_{ii} \propto \frac{N_c y_t^2}{16\pi^2} [C_{lq}^{(1,3)}]_{ii33} \log\left(\frac{m_Z^2}{\Lambda_{\rm NP}^2}\right)$$

[Greljo, Tiblom, Valenti 2411.02485] [Maura, BAS, You 2412.XXXXX]

Accuracy at tera-Z complements energy

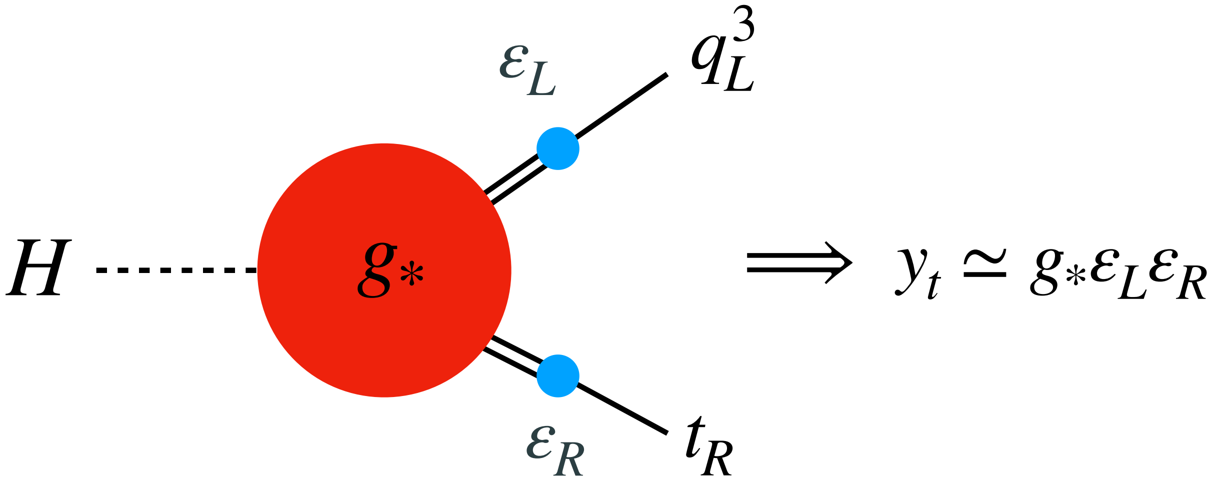
PRELIMINARY



Composite Higgs models

- Ok, so tera-Z is the ideal machine to indirectly search for NP at nearby energies protected by the accidental symmetries of the SM. But why do I care?
- Let's assume the EW hierarchy problem is solved because the Higgs arises as a composite state of some new strong dynamics described by one mass scale m_* and one coupling g_*.
- It is frequently claimed that such theories are good examples of "universal" theories, because the low-energy EFT simply features a strongly-interacting light Higgs (SILH).
- But that's not the full story, is it? We know the top Yukawa is O(1). This means that the left- or right-handed top (or both) must have a sizable degree of compositeness.

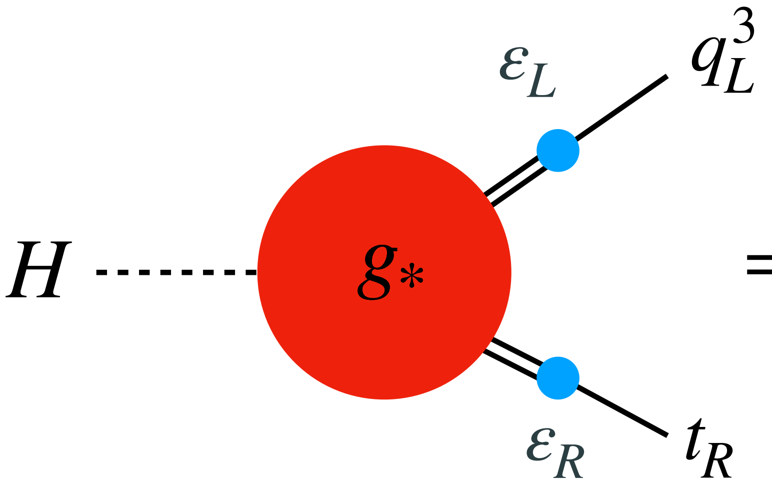
The top Yukawa is realized via partial compositeness



$$\Longrightarrow \quad y_t \simeq g_* \varepsilon_L \varepsilon_R$$

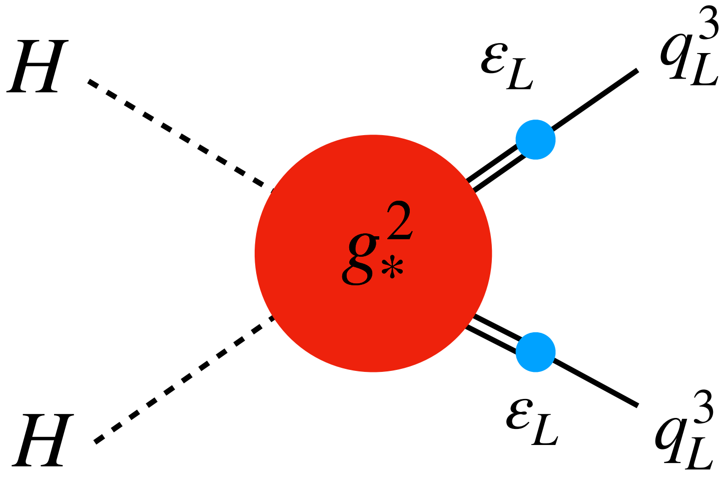
Non-universality of composite Higgs models

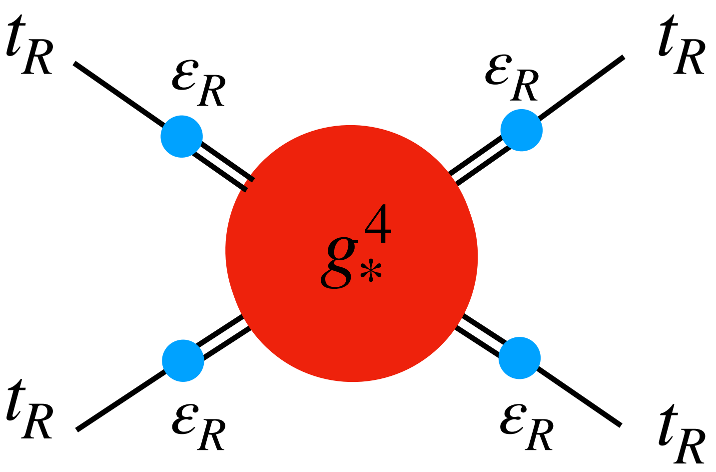
The top Yukawa is realized via partial compositeness



$$\Longrightarrow \; y_t \simeq g_* \varepsilon_L \varepsilon_R$$

- Via these mixing parameters, the composite sector will unavoidably generate other large top+H operators, for example:





$$\mathcal{O}_{Hq}^{(1)} = (H^\dagger D_\mu H)(\bar{q}_L^3 \gamma^\mu q_L^3)$$

$$\mathcal{O}_{tt} = (\bar{t}_R \gamma_\mu t_R)(\bar{t}_R \gamma^\mu t_R)$$

Non-universality of composite Higgs models

- The composite sector will unavoidably generate other large top+H operators at the high scale m_*

These operators are usually ignored via the following arguments:

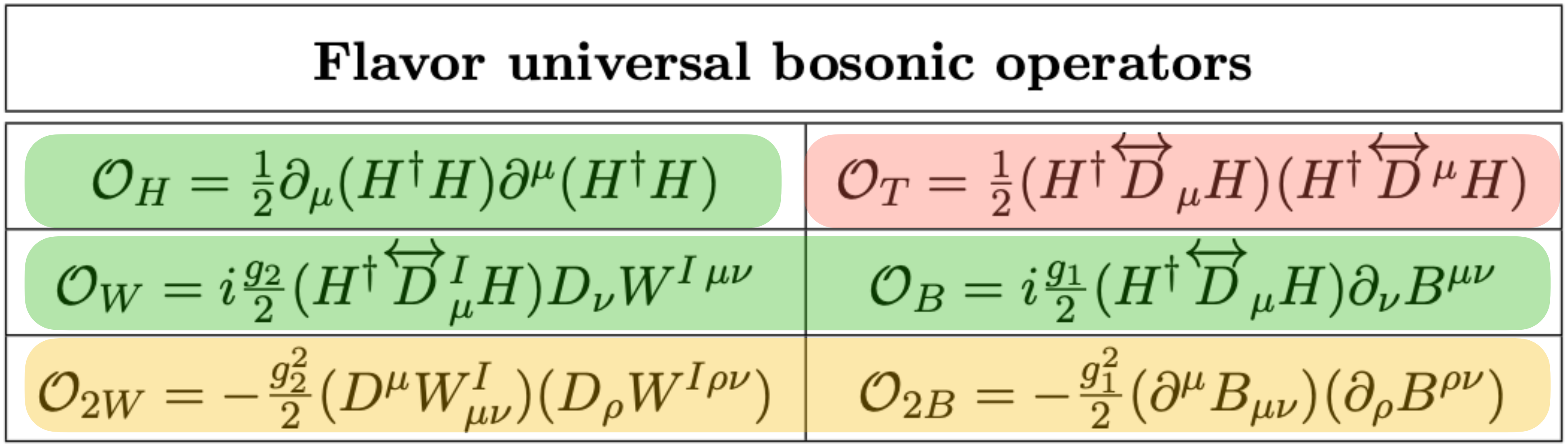
1. Some operators are phenomenologically irrelevant at LO.
2. Model building tricks exist to kill the LO contribution of the most dangerous operators, e.g. $Zbb \propto C_{Hq}^{(1)} + C_{Hq}^{(3)}$.
3. The rest are subdominant to universal constraints.

Flavor non-universal operators	
EW vertex corrections	
$\mathcal{O}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_L^3 \gamma^\mu q_L^3)$	$\mathcal{O}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_L^3 \gamma^\mu \tau^I q_L^3)$
$\mathcal{O}_{Ht} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R)$	$\mathcal{O}_{tD} = g_1 (\bar{t}_R \gamma^\mu t_R) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{qD}^{(1)} = g_1 (\bar{q}_L^3 \gamma^\mu q_L^3) \partial^\nu B_{\mu\nu}$	$\mathcal{O}_{qD}^{(3)} = g_2 (\bar{q}_L^3 \gamma^\mu \tau^I q_L^3) D^\nu W^I_{\mu\nu}$
4-fermion operators	
$\mathcal{O}_{qq}^{(1)} = (\bar{q}_L^3 \gamma^\mu q_L^3)(\bar{q}_L^3 \gamma_\mu q_L^3)$	$\mathcal{O}_{qq}^{(3)} = (\bar{q}_L^3 \gamma^\mu \tau^I q_L^3)(\bar{q}_L^3 \gamma_\mu \tau^I q_L^3)$
$\mathcal{O}_{qt}^{(1)} = (\bar{q}_L^3 \gamma^\mu q_L^3)(\bar{t}_R \gamma_\mu t_R)$	$\mathcal{O}_{qt}^{(8)} = (\bar{q}_L^3 \gamma^\mu T^A q_L^3)(\bar{t}_R \gamma_\mu T^A t_R)$
$\mathcal{O}_{tt} = (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)$	
Dipoles and Yukawas	
$\mathcal{O}_{tB} = g_1 (\bar{q}_L^3 \sigma^{\mu\nu} t_R) \widetilde{H} B_{\mu\nu}$	$\mathcal{O}_{tW} = g_2 (\bar{q}_L^3 \sigma^{\mu\nu} \tau^I t_R) \widetilde{H} W^I_{\mu\nu}$
$\mathcal{O}_{tG} = g_3 (\bar{q}_L^3 \sigma^{\mu\nu} T^A t_R) \widetilde{H} G^A_{\mu\nu}$	$\mathcal{O}_{tH} = (H^\dagger H)(\bar{q}_L^3 \widetilde{H} t_R)$

[BAS, 2407.09593]

Universal operators in composite Higgs models

- Now let's have a look at the operators we can write only involving the Higgs (and gauge fields of course). We work here in the SILH basis:



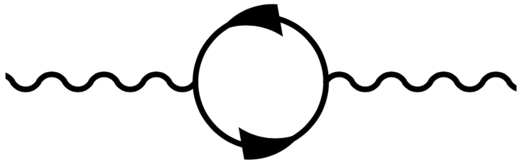
Flavor universal bosonic operators	
$\mathcal{O}_H = \frac{1}{2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$	$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D}^\mu H)$
$\mathcal{O}_W = i\frac{g_2}{2}(H^\dagger \overleftrightarrow{D}^I_\mu H)D_\nu W^{I\,\mu\nu}$	$\mathcal{O}_B = i\frac{g_1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu}$
$\mathcal{O}_{2W} = -\frac{g_2^2}{2}(D^\mu W^I_{\mu\nu})(D_\rho W^{I\rho\nu})$	$\mathcal{O}_{2B} = -\frac{g_1^2}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu})$

$\mathcal{O}_H$: Higgs coupling modifications

$\mathcal{O}_T$: Peskin-Takeuchi T parameter

$\mathcal{O}_{W+B}$: Peskin-Takeuchi S parameter

$\mathcal{O}_{2W,2B}$: $W+Y$ parameters

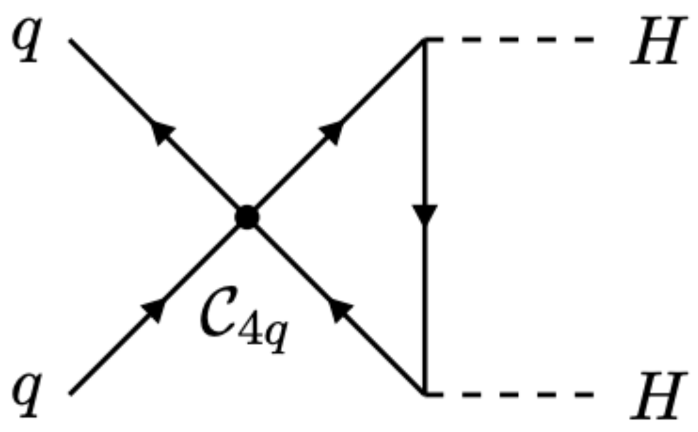


Recall: $$\Pi_{VV}(p^2) = \underset{\substack{\downarrow \\ T}}{\Pi_{VV}(0)} + \underset{\substack{\downarrow \\ S}}{p^2\Pi'_{VV}(0)} + \underset{\substack{\downarrow \\ W,\,Y}}{p^4\Pi''_{VV}(0)} + \ldots$$

[BAS, 2407.09593]

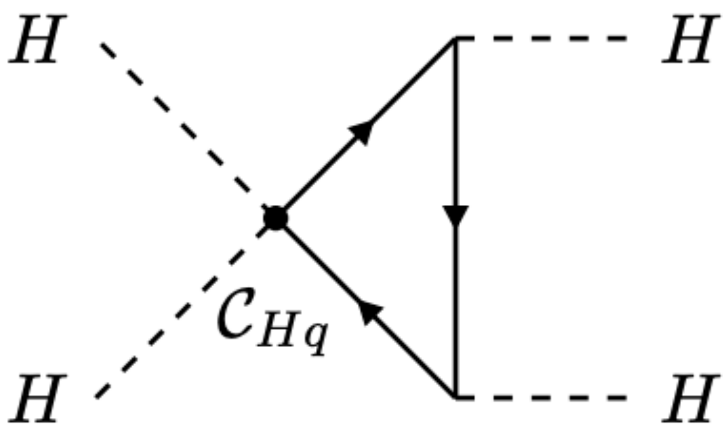
Intrinsic non-universality of composite Higgs models

- What's missing with this picture? Even if you play all of the model-building tricks, its true at LO only! The most dangerous operators are generated via RGE as we run from m_* to the EW scale.
- Phenomenologically, the most important effects are $\propto N_c y_t^2 \log(m_Z^2/m_*^2)$:



4-top operators running into EW vertex corrections.

$$\mathcal{O}_{qq}^{(1,3)}, \mathcal{O}_{qt}^{(1)}, \mathcal{O}_{tt} \to \mathcal{O}_{Hq}^{(1,3)}, \mathcal{O}_{Ht}$$



Top vertex corrections running into the T parameter.*

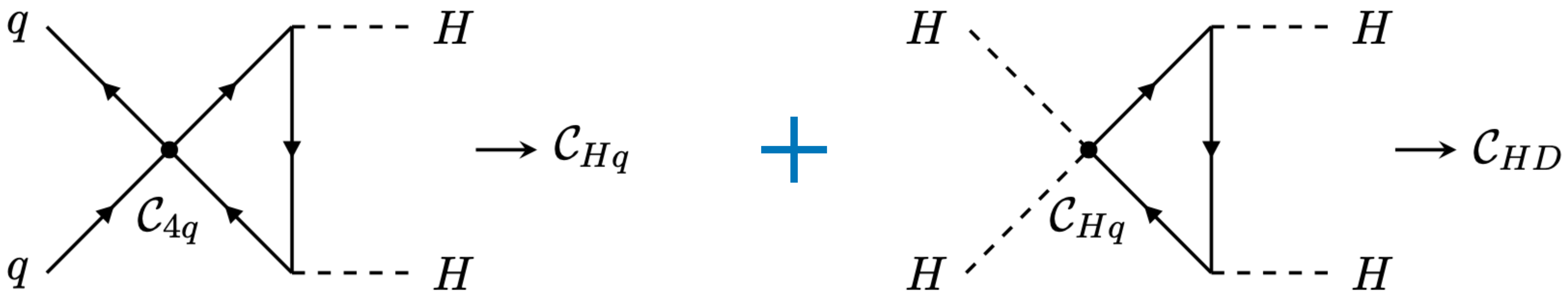
$$\mathcal{O}_{Hq}^{(1)}, \mathcal{O}_{Ht} \to \mathcal{O}_{HD}$$

[BAS, 2407.09593]

**Required custodial violation is coming from the SM!*

2-loop sensitivity to 4-top operators

- Some important effects occur only beyond the “first leading-log approximation”. They can be captured by integrating the full 1-loop RG equations, which resums higher loop effects of the form $(\alpha\log)^n$.



- The full 2-loop computation is now also available: [Haisch, Schnell, 2410.13304]

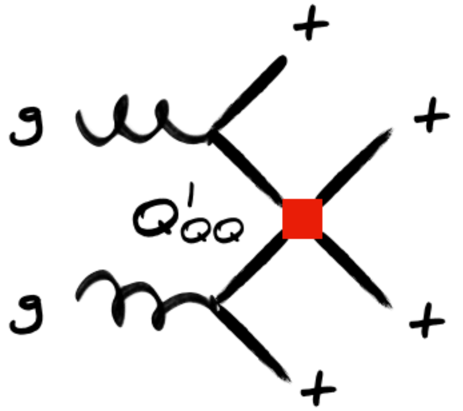
- This two-loop effect allows EWPD to gain sensitivity to 4-top operators. An analytic formula for this $\alpha_t^2\log^2$ contribution can be found if we neglect the running of the SM couplings:

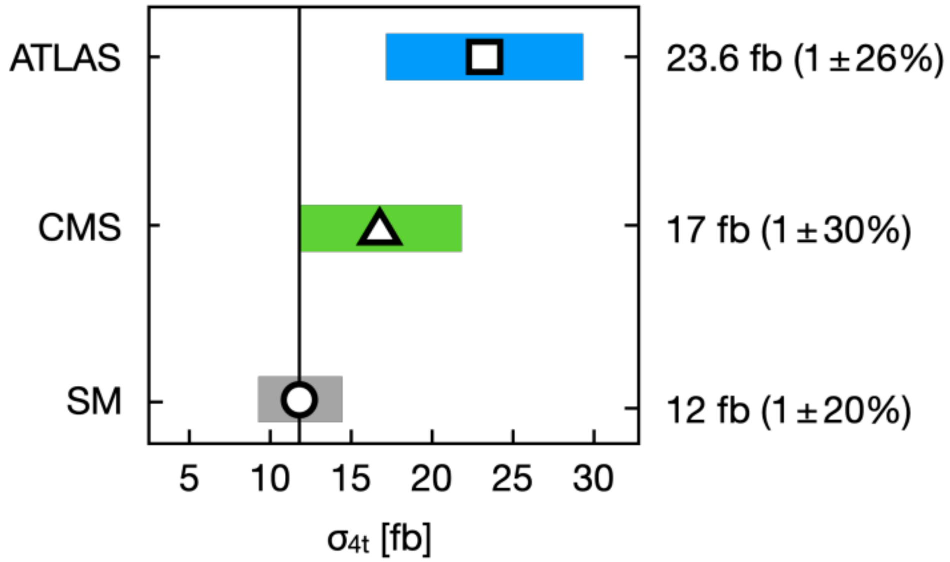
$$[\mathcal{C}_{HD}]_{\rm NLL} = \frac{2N_c\,y_t^4}{(16\pi^2)^2}\left[(1+2N_c)\mathcal{C}_{qq}^{(1)} + 3\mathcal{C}_{qq}^{(3)} + 2(1+N_c)\mathcal{C}_{tt} - 2N_c\mathcal{C}_{qt}^{(1)}\right]\log^2\left(\frac{\mu^2}{m_*^2}\right)$$

[BAS, 2407.09593] [Allwicher, Isidori, Lizana, Selimovic, BAS, 2302.11584]

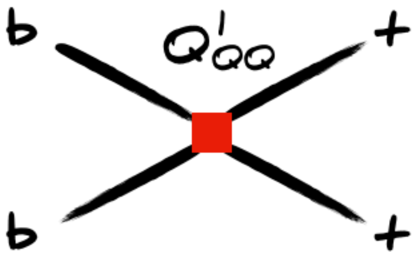
Constraints on 4-top operators from LHC data

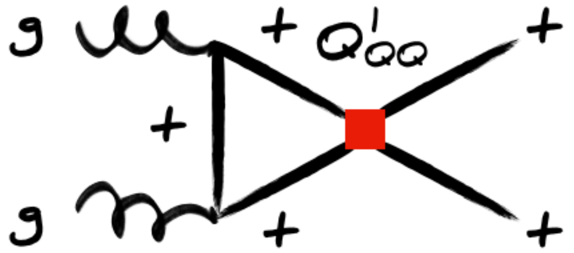
- At the LHC, 3rd generation four-quark operators can be probed at tree level only in 4t, 4b, 2b2t production. Present measurements all have large uncertainties.

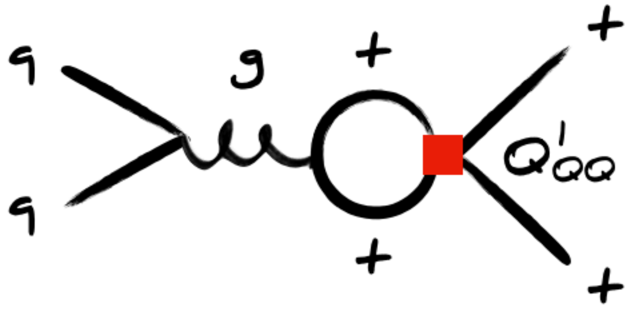




- Due to strong bottom PDF suppression, 3rd generation four-quark operators mainly contribute to 2-top production at 1-loop:







[Credit to Uli Haisch, HEFT 2024, Precision tests of 3rd-generation four-quark SMEFT operators]

Constraints on 4-top operators: EWPD vs. LHC data

- Limits come from fits by theorists and depend on whether the fit is linear or also includes quadratic terms.

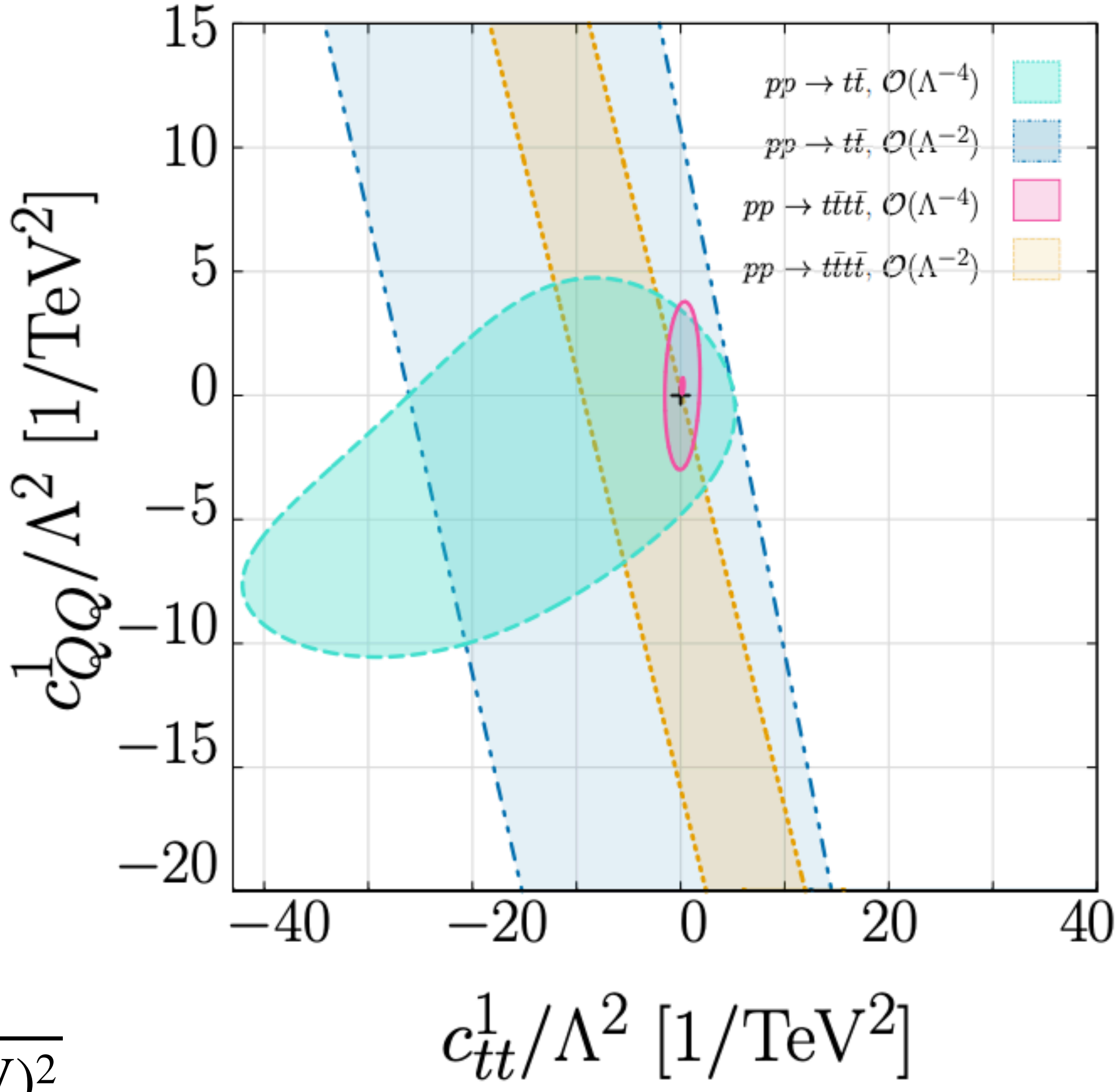
- Raises questions about stability of fit under d8 deformations & EFT applicability in general, since limits arise from configurations with momentum transfer of around 0.4 TeV (1.3 TeV) in 2t (4t) production.

- Depending on who you ask, bounds around 750–900 GeV for Ctt.

- On the other hand, EWPD gives a robust 2-loop bound from *T*

$$\hat{T} = -\frac{v^2}{2} C_{HD} < 10^{-3} \implies C_{tt} \leq \frac{1}{(1.2\ \text{TeV})^2}$$

[Degrande et al., 2402.06528]



[Credit to Uli Haisch, HEFT 2024, Precision tests of 3rd-generation four-quark SMEFT operators]

Partial compositeness: A few more details

- To say something more quantitative about composite Higgs in particular, we need to provide a bit more detail on the fermionic mixing

$$\mathcal{L}_{\rm mix} = \underbrace{\lambda_L \bar{q}_L^3 \mathcal{O}_L + \lambda_R \bar{t}_R \mathcal{O}_R}_{\text{Generates } y_t} + \overbrace{\lambda_q^i \bar{q}_L^i \mathcal{O}_q}^{\text{Generates } V_{ts},\, V_{td}} + \mathcal{L}_{\rm light}$$

Light family masses+mixings

- This theory respects a $U(2)_q \times U(2)_u \times U(3)_d \times U(3)_l \times U(3)_e$ flavor symmetry without the coupling λ_q^i. This coupling breaks $U(2)_q$ and will control flavor violation in the theory. For example, B-meson mixing behaves as: $(\bar{q}_L^i \lambda_q^i \gamma_\mu q_L^3)^2$

[BAS, 2407.09593]

Matching to composite Higgs model parameters

- The full UV Lagrangian can be written schematically as

$$\mathcal{L}_{\mathrm{UV}} = \mathcal{L}_{\mathrm{SM}'} + \mathcal{L}_{\mathrm{strong}} + g A_\mu^{\mathrm{SM}} J^\mu_{\mathrm{strong}} + \mathcal{L}_{\mathrm{mix}}(\psi, \mathcal{O}_\psi)$$

- After integrating out all heavy composite states, the low energy theory has the form

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}'} + \frac{m_*^4}{g_*^2} \widehat{\mathcal{L}}_{\mathrm{EFT}} \left(\frac{g_* H}{m_*}, \frac{D_\mu}{m_*}, \frac{g F_{\mu\nu}}{m_*^2}, \frac{\lambda_L \bar{q}_L^3}{m_*^{3/2}}, \frac{\lambda_R \bar{t}_R}{m_*^{3/2}}, \frac{\lambda_q^i \bar{q}_L^i}{m_*^{3/2}}, \frac{g_*^2}{16\pi^2}, \frac{g}{16\pi^2} \right)$$

- Let us write the WCs in terms of composite Higgs model parameters :

$$C_W g (H^\dagger D^I_\mu H) D_\nu W^{I\mu\nu} \implies C_W \sim \frac{m_*^4}{g_*^2} \frac{g_*^2}{m_*^4} \frac{1}{m_*^2} = \frac{1}{m_*^2}$$

(S-parameter)

$$C_{tt} (\bar{t}_R \gamma_\mu t_R)(\bar{t}_R \gamma_\mu t_R) \implies C_{tt} \sim \frac{m_*^4}{g_*^2} \frac{\lambda_R^4}{m_*^6} = \frac{\lambda_R^4}{g_*^2 m_*^2} = \frac{g_*^2}{m_*^2} \epsilon_R^4$$

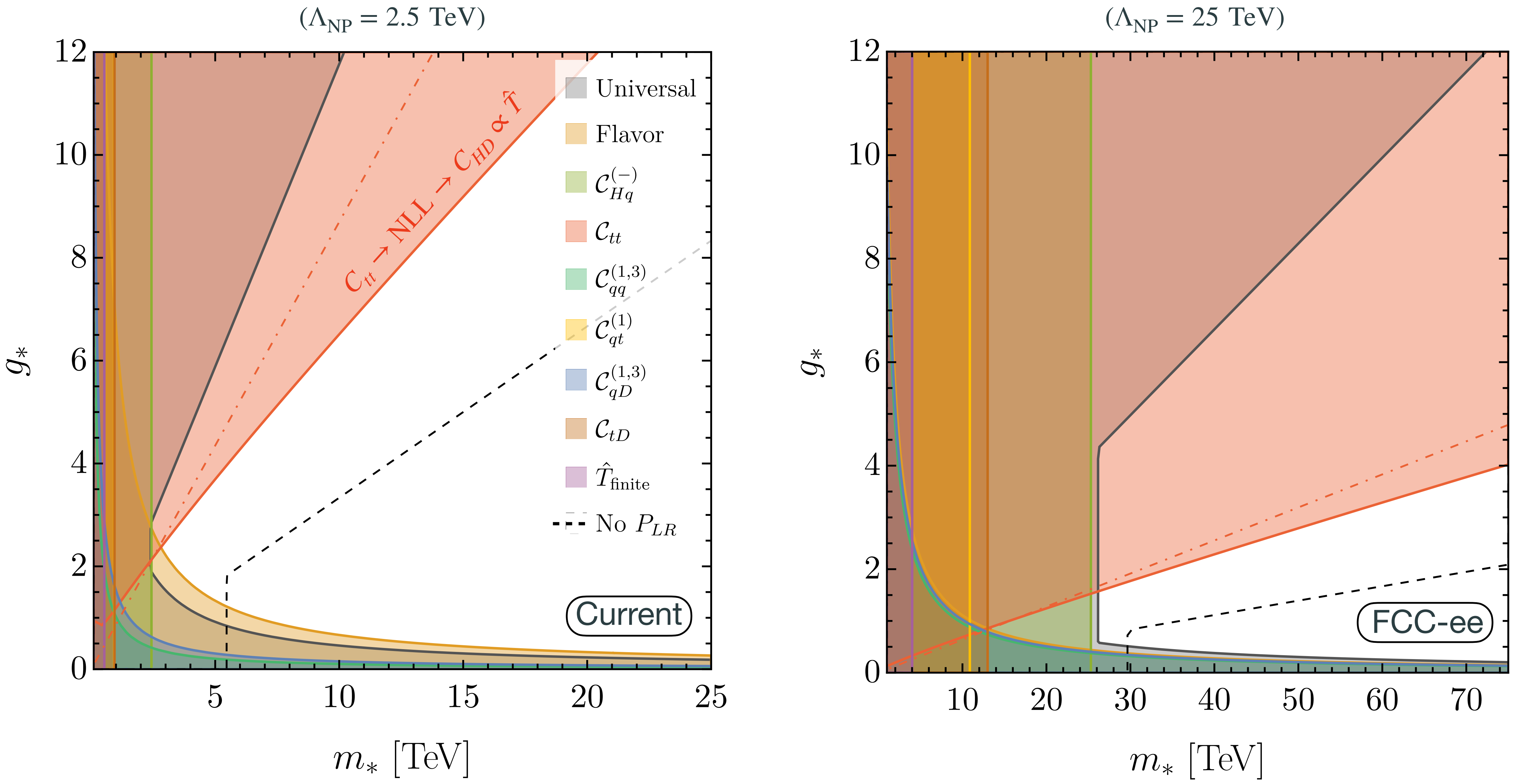
($4t_R$ operator)

$(\lambda_{L,R} = g_* \, \epsilon_{L,R})$

[G. F. Giudice, C. Grojean, A. Pomarol, R. Rattazzi, hep-ph/0703164]

Results: Right compositeness

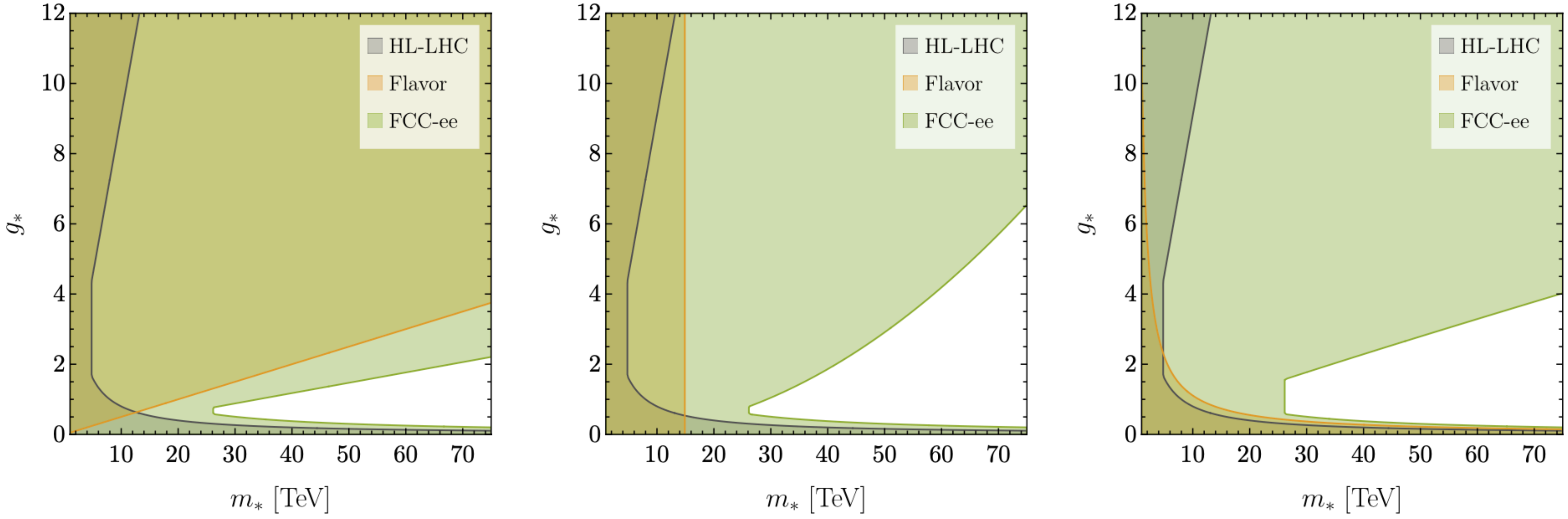
- Right compositeness has $\epsilon_L = y_t/g_*\,,\ \epsilon_R = 1.$ Flavor constraints: $C_{B_s} \propto \dfrac{g_*^2}{m_*^2}\epsilon_L^4$



[BAS, 2407.09593] [Universal constraints: Glioti, Rattazzi, Ricci, Vecchi, 2402.09503]

Future summary plots

- Flavor non-universal RG effects give the best bound for $g_* \gtrsim 1$, while universal effects are only better for $g_* < 1$. Interestingly: $\langle H \rangle \sim f = m_*/g_*$



(a) Left compositeness (b) Mixed compositeness (c) Right compositeness

- In all cases, FCC-ee dominates over other sectors, setting a mixing-independent bound of $m_* \gtrsim 25$ TeV. Adds the most new info in the mixed + right comp. cases.

[BAS, 2407.09593]

Conclusions

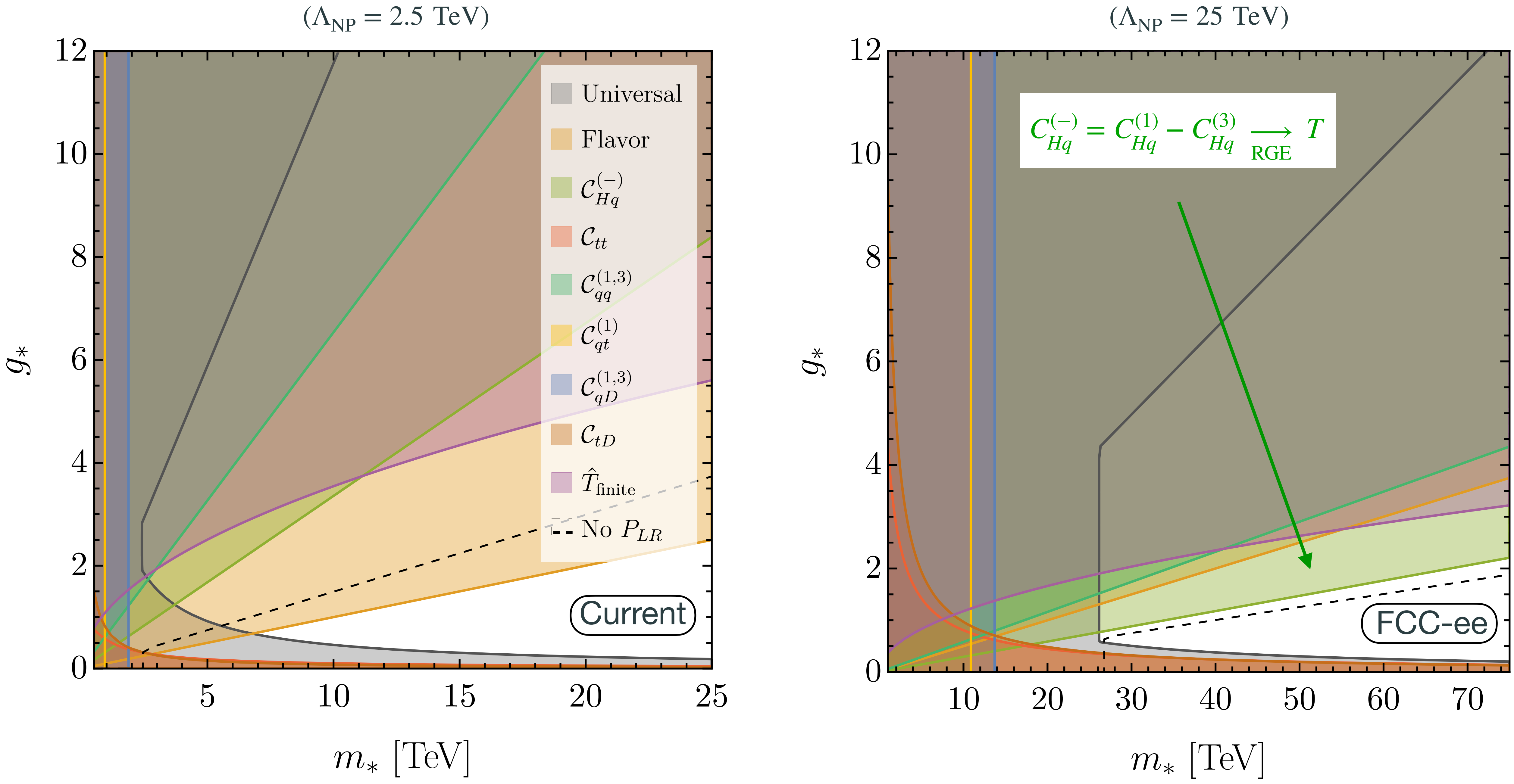
- If we are interested in connecting with experiment, we should ask for an EFT with the right features to describe NP at nearby (experimentally accessible) energy scales. Given the current direct search limits from the LHC, flavor universality no longer seems very natural with bounds O(10) TeV.
- Instead, $U(2)$ 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. These features are exhibited in classic scenarios such as composite Higgs models.
- Remarkably, the Z-pole at NLO has sensitivity to almost all $U(2)$-symmetric operators! Top operators in particular run strongly into Z-pole observables, but in general the loop suppression can be compensated for due to precision. A future machine with a tera-Z run plan such as FCC-ee is the best way to probe NP protected by the accidental symmetries of the SM in the 1-100 TeV range.
- In some cases, the Z-pole even has sensitivity to 2-loop BSM effects. We described such an effect here: there is sensitivity to 4-top operators via their two-loop contribution to the T parameter. This allows current EW precision data to set the best bound on these operators and provides an important and previously overlooked probe of composite Higgs models.

Backup

Left compositeness

- Left compositeness has $\epsilon_L = 1,\ \epsilon_R = y_t/g_*$.

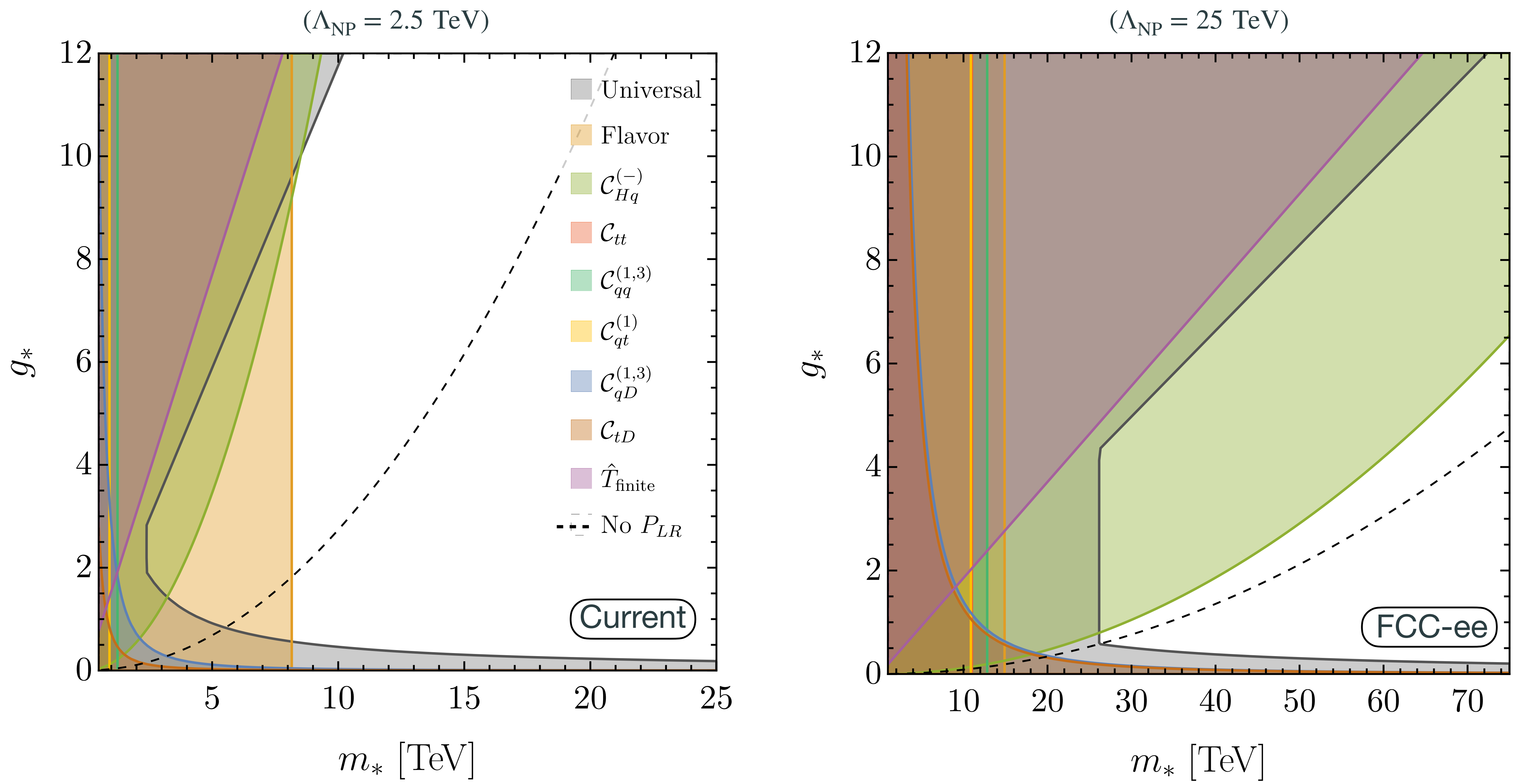
Flavor constraints: $C_{B_s} \propto \dfrac{g_*^2}{m_*^2}\epsilon_L^4$



[BAS, 2407.09593]

Mixed compositeness

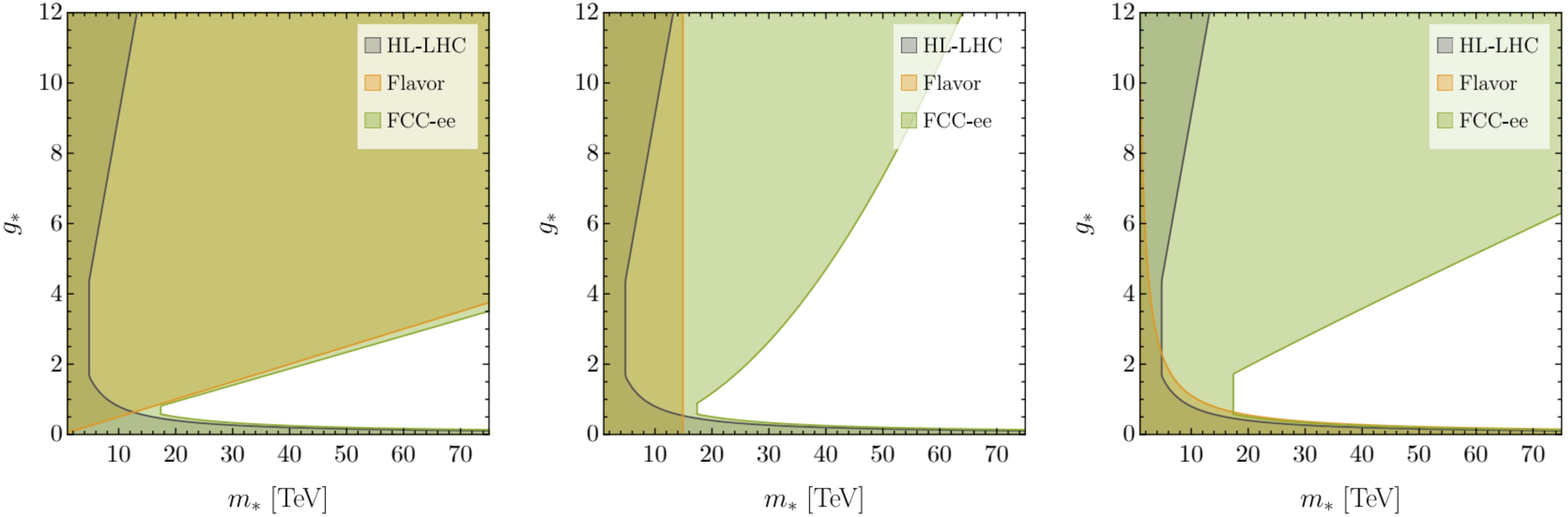
- Mixed compositeness has $\epsilon_L = \epsilon_R = \sqrt{y_t/g_*}$. Flavor constraints: $C_{B_s} \propto \frac{g_*^2}{m_*^2}\epsilon_L^4$



[BAS, 2407.09593]

Future summary plots (with theory uncertainty)

- Flavor non-universal RG effects give the best bound for $g_* \gtrsim 1$, while universal effects are only better for $g_* < 1$. Interestingly: $\langle H \rangle \sim f = m_*/g_*$



(a) Left compositeness (b) Mixed compositeness (c) Right compositeness

Assuming:

$$[\Delta m_W]_{\rm Th} \simeq 1 \text{ MeV}\,,$$
$$[\Delta A_\ell]_{\rm Th} \simeq 5 \times 10^{-5}$$

These absolute theoretical uncertainties are about a factor of 3 (2) larger than the projected absolute experimental error in the case of mW (Ae).

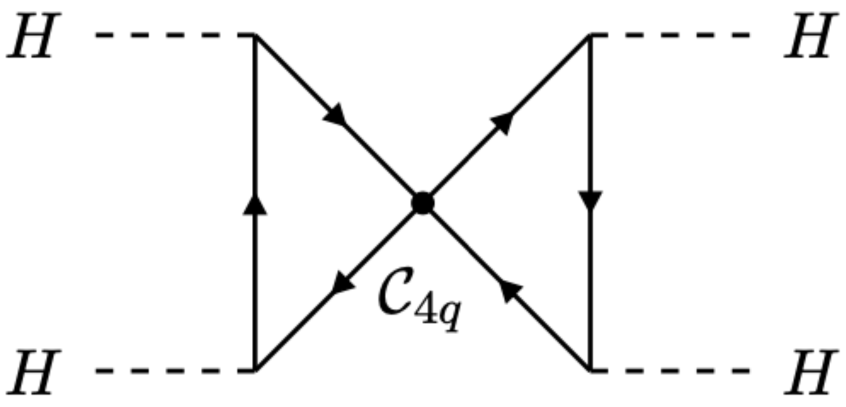
[BAS, 2407.09593]

The full 2-loop contribution to the T parameter

- While the double-log contribution is expected to dominate, in general the full 2-loop contribution of 4-top operators to the T parameter takes the form of a second-order logarithmic polynomial. E.g. for Ctt, we have:

$$[\mathcal{C}_{HD}]_{\text{2-loop}} = \frac{N_c(N_c+1)}{4\pi^2}\alpha_t^2\Big[\underbrace{\log^2(\mu^2/m_*^2)}_{\text{1-loop RGE}} + \underbrace{c_1\log(\mu^2/m_*^2)}_{\text{2-loop RGE}} + \underbrace{c_2}_{\text{finite}}\Big]\mathcal{C}_{tt}\,.$$

- The O(1) constants c1+c2 cannot be obtained from the 1-loop RG equations. In particular, c1 corresponds to the 2-loop anomalous dimension. To get all contributions, we need to do a 2-loop computation:



$\Longrightarrow$

U. Haisch and L. Schnell, Precision tests of third-generation four-quark operators: matching SMEFT to LEFT, to appear soon

$c_1 = -1/2$ and $c_2 = 0$ *

[BAS, 2407.09593]

---

*$\overline{\text{MS}}$ for WCs, OSS for SM params

Single operator bounds including (resummed) RGE

Model-building tricks

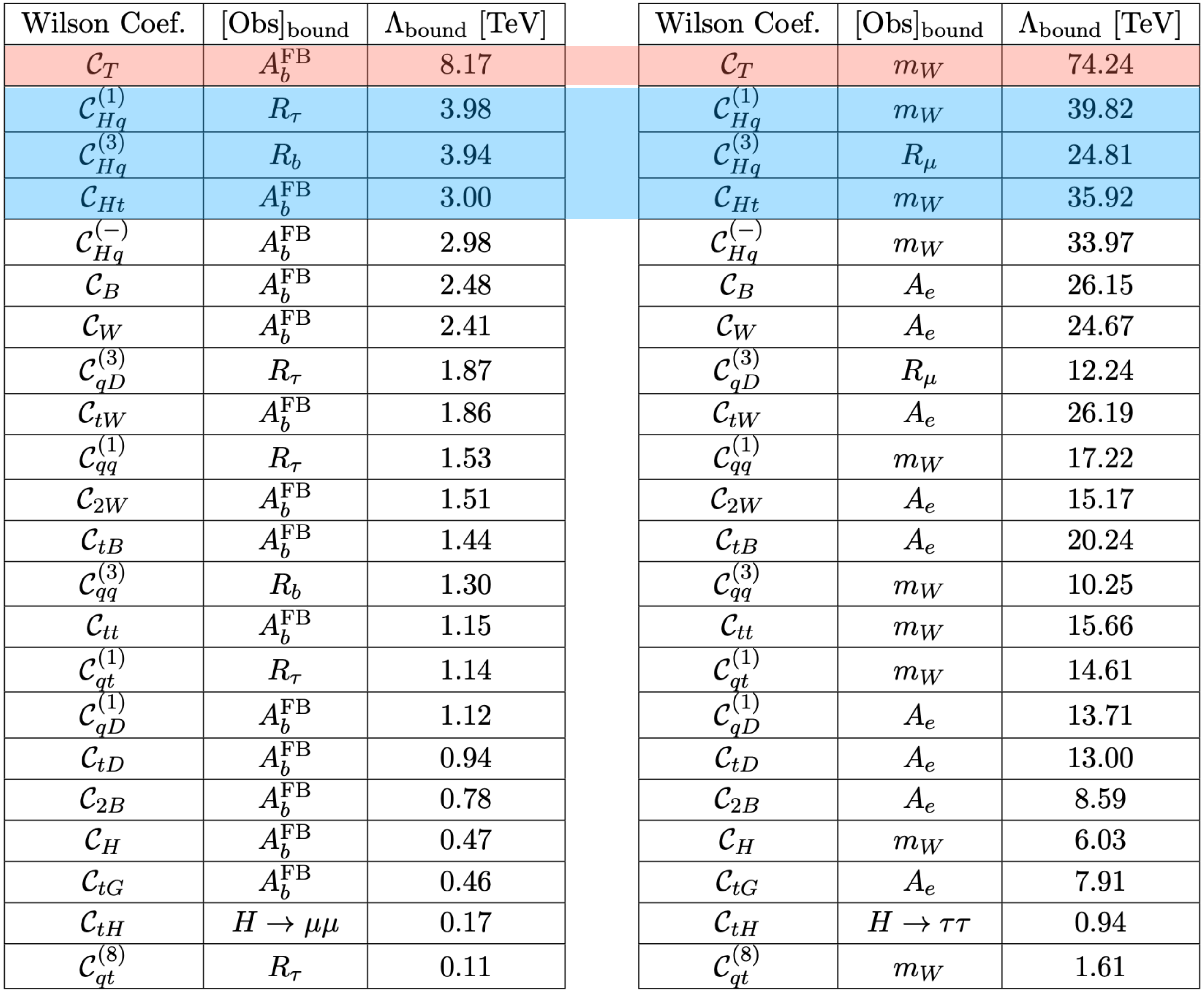
Custodial symmetry in the strong sector

$C_T = 0$ (LO)

A custodial symmetry for Zbb

$$C_{Hq}^{(1)} + C_{Hq}^{(3)} = 0$$

$$C_{Ht} = 0 \text{ (LO)}$$



Wilson Coef.	$[\mathrm{Obs}]_{\mathrm{bound}}$	Λ_{bound} [TeV]
$\mathcal{C}_T$	A_b^{FB}	8.17
$\mathcal{C}_{Hq}^{(1)}$	R_τ	3.98
$\mathcal{C}_{Hq}^{(3)}$	R_b	3.94
$\mathcal{C}_{Ht}$	A_b^{FB}	3.00
$\mathcal{C}_{Hq}^{(-)}$	A_b^{FB}	2.98
$\mathcal{C}_B$	A_b^{FB}	2.48
$\mathcal{C}_W$	A_b^{FB}	2.41
$\mathcal{C}_{qD}^{(3)}$	R_τ	1.87
$\mathcal{C}_{tW}$	A_b^{FB}	1.86
$\mathcal{C}_{qq}^{(1)}$	R_τ	1.53
$\mathcal{C}_{2W}$	A_b^{FB}	1.51
$\mathcal{C}_{tB}$	A_b^{FB}	1.44
$\mathcal{C}_{qq}^{(3)}$	R_b	1.30
$\mathcal{C}_{tt}$	A_b^{FB}	1.15
$\mathcal{C}_{qt}^{(1)}$	R_τ	1.14
$\mathcal{C}_{qD}^{(1)}$	A_b^{FB}	1.12
$\mathcal{C}_{tD}$	A_b^{FB}	0.94
$\mathcal{C}_{2B}$	A_b^{FB}	0.78
$\mathcal{C}_H$	A_b^{FB}	0.47
$\mathcal{C}_{tG}$	A_b^{FB}	0.46
$\mathcal{C}_{tH}$	$H \to \mu\mu$	0.17
$\mathcal{C}_{qt}^{(8)}$	R_τ	0.11

(a) Current bounds ($\Lambda_{\mathrm{NP}} = 2.5$ TeV)

Wilson Coef.	$[\mathrm{Obs}]_{\mathrm{bound}}$	Λ_{bound} [TeV]
$\mathcal{C}_T$	m_W	74.24
$\mathcal{C}_{Hq}^{(1)}$	m_W	39.82
$\mathcal{C}_{Hq}^{(3)}$	R_μ	24.81
$\mathcal{C}_{Ht}$	m_W	35.92
$\mathcal{C}_{Hq}^{(-)}$	m_W	33.97
$\mathcal{C}_B$	A_e	26.15
$\mathcal{C}_W$	A_e	24.67
$\mathcal{C}_{qD}^{(3)}$	R_μ	12.24
$\mathcal{C}_{tW}$	A_e	26.19
$\mathcal{C}_{qq}^{(1)}$	m_W	17.22
$\mathcal{C}_{2W}$	A_e	15.17
$\mathcal{C}_{tB}$	A_e	20.24
$\mathcal{C}_{qq}^{(3)}$	m_W	10.25
$\mathcal{C}_{tt}$	m_W	15.66
$\mathcal{C}_{qt}^{(1)}$	m_W	14.61
$\mathcal{C}_{qD}^{(1)}$	A_e	13.71
$\mathcal{C}_{tD}$	A_e	13.00
$\mathcal{C}_{2B}$	A_e	8.59
$\mathcal{C}_H$	m_W	6.03
$\mathcal{C}_{tG}$	A_e	7.91
$\mathcal{C}_{tH}$	$H \to \tau\tau$	0.94
$\mathcal{C}_{qt}^{(8)}$	m_W	1.61

(b) FCC-ee projection ($\Lambda_{\mathrm{NP}} = 25$ TeV)

[Agashe, Contino, Da Rold, Pomarol, hep-ph/0605341]

Single operator bounds including (resummed) RGE

Symmetry protected

S parameter

NLO/RG non-universal effects

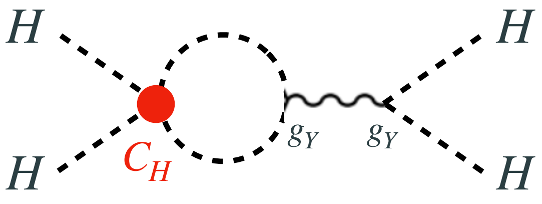
NLO/RG universal effects

Wilson Coef.	$[\mathrm{Obs}]_{\rm bound}$	$\Lambda_{\rm bound}$ [TeV]
$\mathcal{C}_T$	$A_b^{\rm FB}$	8.17
$\mathcal{C}_{Hq}^{(1)}$	R_τ	3.98
$\mathcal{C}_{Hq}^{(3)}$	R_b	3.94
$\mathcal{C}_{Ht}$	$A_b^{\rm FB}$	3.00
$\mathcal{C}_{Hq}^{(-)}$	$A_b^{\rm FB}$	2.98
$\mathcal{C}_B$	$A_b^{\rm FB}$	2.48
$\mathcal{C}_W$	$A_b^{\rm FB}$	2.41
$\mathcal{C}_{qD}^{(3)}$	R_τ	1.87
$\mathcal{C}_{tW}$	$A_b^{\rm FB}$	1.86
$\mathcal{C}_{qq}^{(1)}$	R_τ	1.53
$\mathcal{C}_{2W}$	$A_b^{\rm FB}$	1.51
$\mathcal{C}_{tB}$	$A_b^{\rm FB}$	1.44
$\mathcal{C}_{qq}^{(3)}$	R_b	1.30
$\mathcal{C}_{tt}$	$A_b^{\rm FB}$	1.15
$\mathcal{C}_{qt}^{(1)}$	R_τ	1.14
$\mathcal{C}_{qD}^{(1)}$	$A_b^{\rm FB}$	1.12
$\mathcal{C}_{tD}$	$A_b^{\rm FB}$	0.94
$\mathcal{C}_{2B}$	$A_b^{\rm FB}$	0.78
$\mathcal{C}_H$	$A_b^{\rm FB}$	0.47
$\mathcal{C}_{tG}$	$A_b^{\rm FB}$	0.46
$\mathcal{C}_{tH}$	$H \to \mu\mu$	0.17
$\mathcal{C}_{qt}^{(8)}$	R_τ	0.11

(a) Current bounds ($\Lambda_{\rm NP} = 2.5$ TeV)

Wilson Coef.	$[\mathrm{Obs}]_{\rm bound}$	$\Lambda_{\rm bound}$ [TeV]
$\mathcal{C}_T$	m_W	74.24
$\mathcal{C}_{Hq}^{(1)}$	m_W	39.82
$\mathcal{C}_{Hq}^{(3)}$	R_μ	24.81
$\mathcal{C}_{Ht}$	m_W	35.92
$\mathcal{C}_{Hq}^{(-)}$	m_W	33.97
$\mathcal{C}_B$	A_e	26.15
$\mathcal{C}_W$	A_e	24.67
$\mathcal{C}_{qD}^{(3)}$	R_μ	12.24
$\mathcal{C}_{tW}$	A_e	26.19
$\mathcal{C}_{qq}^{(1)}$	m_W	17.22
$\mathcal{C}_{2W}$	A_e	15.17
$\mathcal{C}_{tB}$	A_e	20.24
$\mathcal{C}_{qq}^{(3)}$	m_W	10.25
$\mathcal{C}_{tt}$	m_W	15.66
$\mathcal{C}_{qt}^{(1)}$	m_W	14.61
$\mathcal{C}_{qD}^{(1)}$	A_e	13.71
$\mathcal{C}_{tD}$	A_e	13.00
$\mathcal{C}_{2B}$	A_e	8.59
$\mathcal{C}_H$	m_W	6.03
$\mathcal{C}_{tG}$	A_e	7.91
$\mathcal{C}_{tH}$	$H \to \tau\tau$	0.94
$\mathcal{C}_{qt}^{(8)}$	m_W	1.61

(b) FCC-ee projection ($\Lambda_{\rm NP} = 25$ TeV)



[BAS, 2407.09593]