Charting the path to new physics in the precision era

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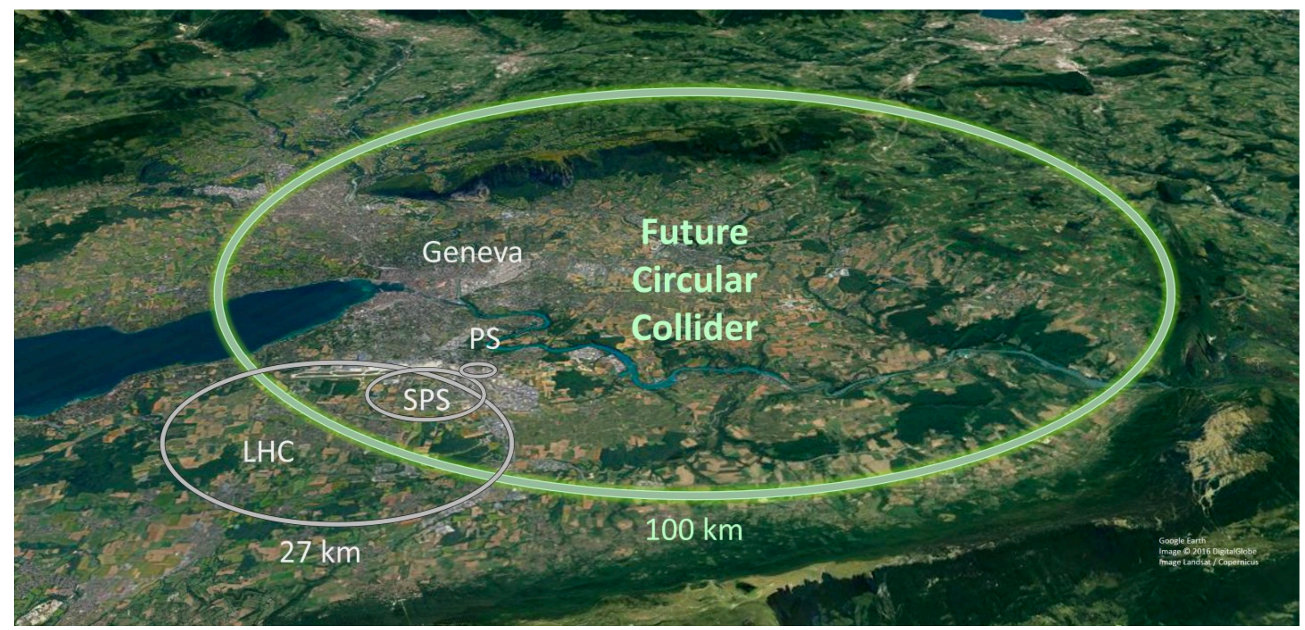

MITP: Charting EFT Structures to Characterize New Physics

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Generalitat Valenciana
Conselleria de Educación, Cultura, Universidades y Empleo

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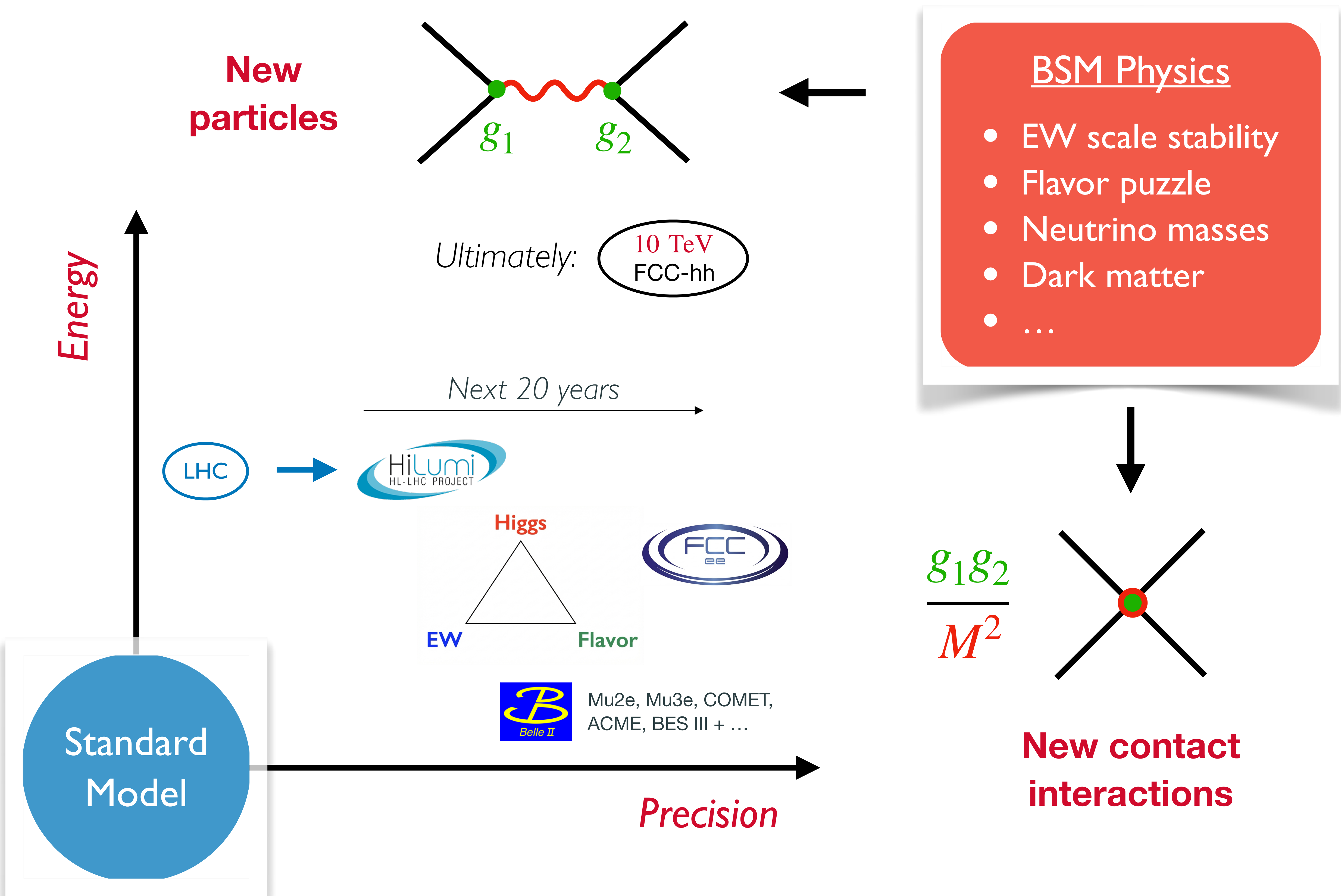
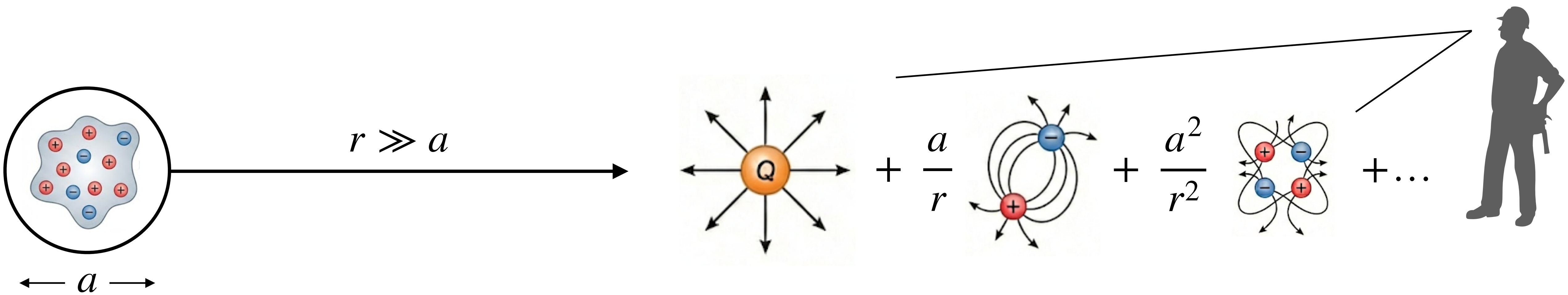
A global strategy for collider physics



Tools for the precision era: Separation of scales

- How does short-distance physics manifest at large distances (low energy)?

<u>Classic example of scale separation: Multipole expansion in electrostatics</u>



Organized as irreducible representations of the symmetry respected at long distance, $SO(3)$!

$$V(\mathbf{r}) = \frac{1}{r}\left[\boxed{Q} + \frac{\boxed{d_i}}{r}\hat{r}_i + \frac{\boxed{Q_{ij}}}{r^2}\hat{r}_i\hat{r}_j + \ldots \right]$$

Short-distance physics completely encoded into the moments! (constant coefficients)

The rest is "IR dynamics"! (how the potential changes as you move around)

Tools for the precision era: Effective field theory

- The SM effective field theory (SMEFT) is *based on exactly the same concepts*!

Constant coefficients containing info about the UV theory at $\Lambda_{\rm NP}$

Dynamics given by local operators built with SM fields and respecting IR symmetries

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda_{\rm NP}^2} \mathcal{O}_i(x) + \ldots$$

$$\boxed{\text{IR Effects} \sim \left(\frac{v, E}{\Lambda_{\rm NP}}\right)^2}$$

Heavy mass scale where new states should appear

✓ General unifying framework

✗ More parameters than independent observables

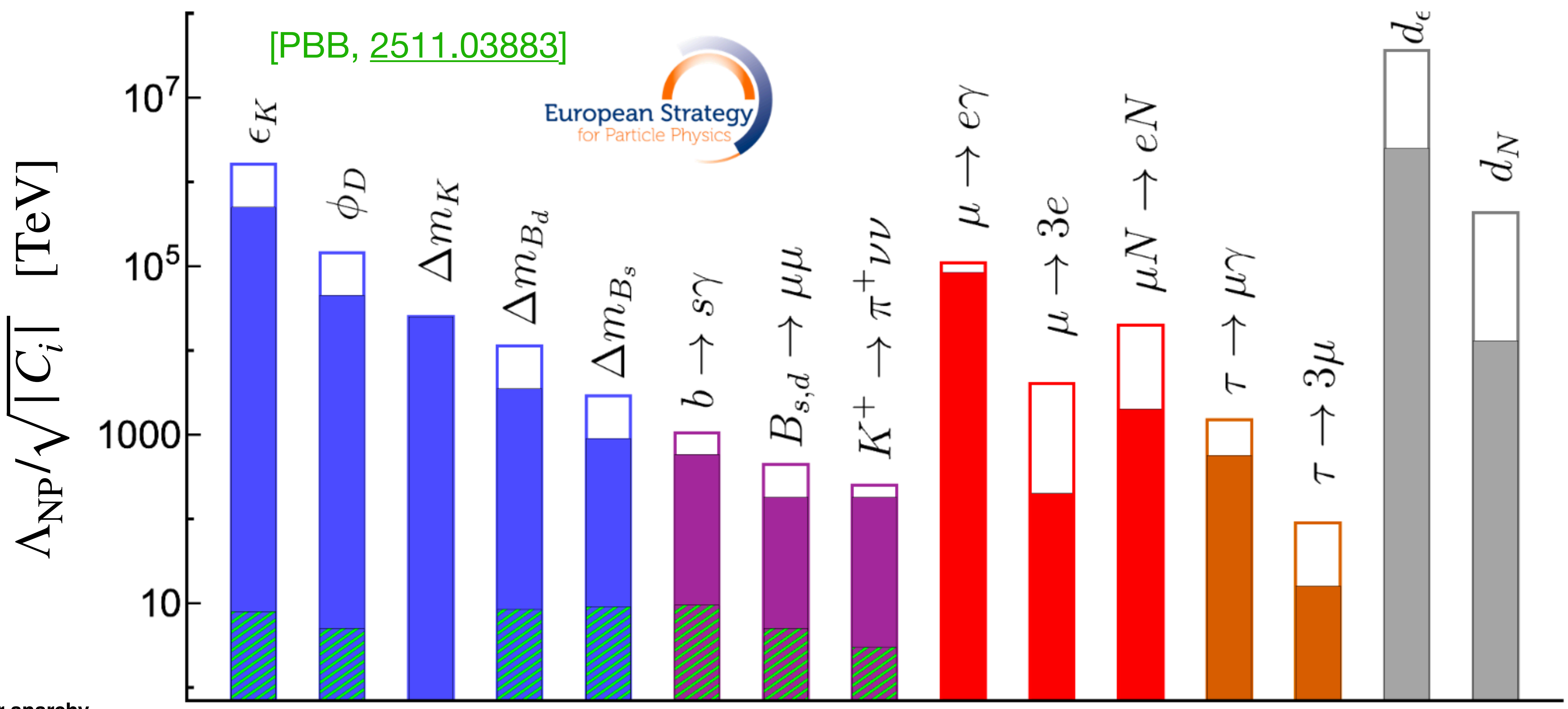
- Dimension-6 SMEFT: 59 unique operator structures, but 2499 parameters with 3 generations. Large # parameters ⇔ flavor multiplicity

$$\boxed{\text{Flavor symmetries in the IR that organize these parameters?}}$$

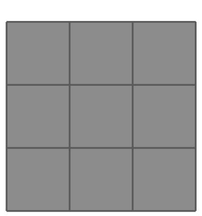
Flavor data and anarchy

- Vast majority of SMEFT operators are flavor-changing (>85%)

$$\mathscr{L}_{\rm SMEFT} \supset \sum_{i=1}^{2499} \frac{C_i}{\Lambda_{\rm NP}^2} \mathscr{O}_i$$



Flavor anarchy



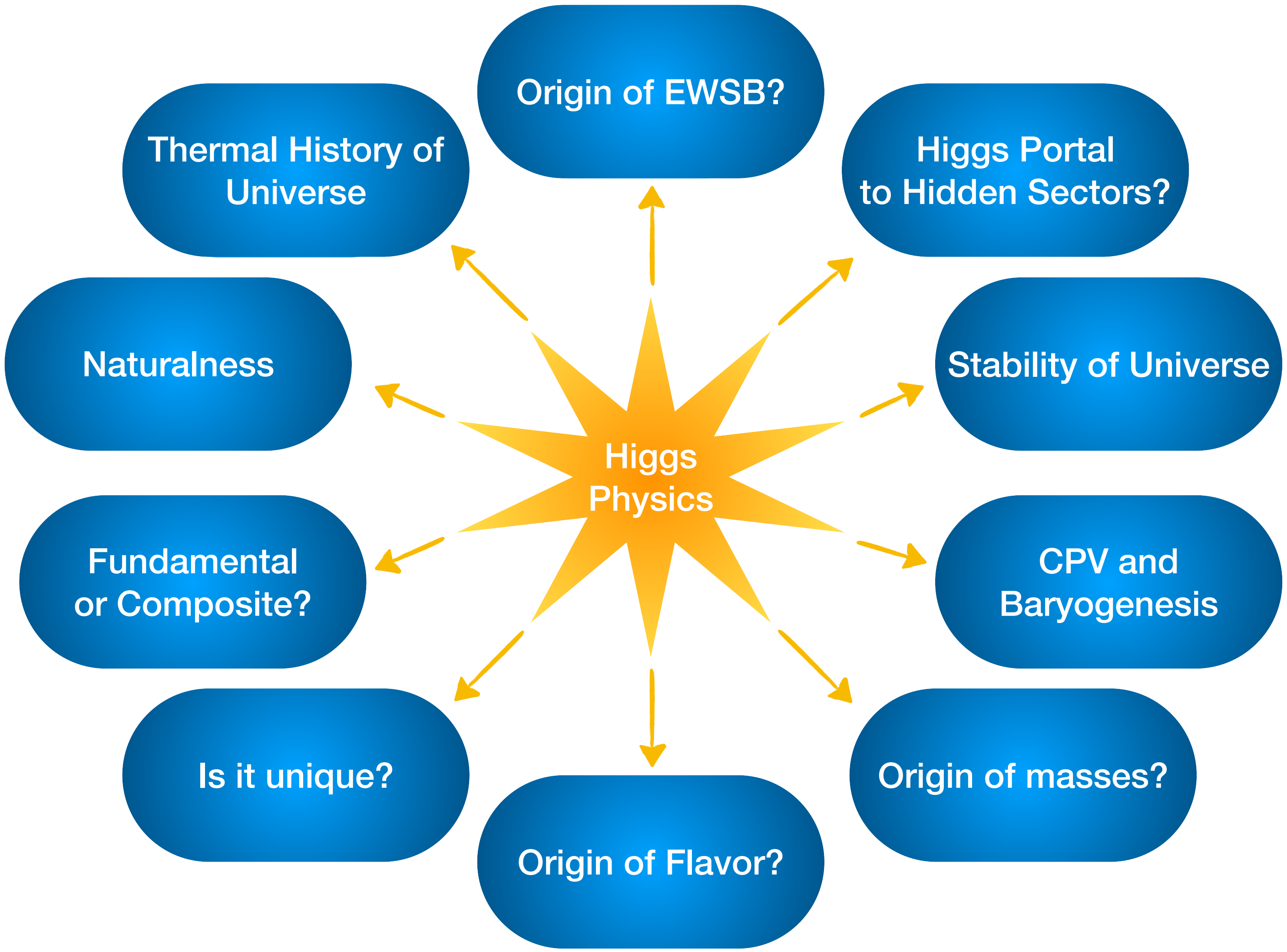
all $C_{ij} \sim \mathcal{O}(1)$

no symmetry

$C_i \sim O(1)$ does not look at all compatible with TeV-scale physics!

Why TeV-scale new physics?

Understanding: What is the microscopic theory of the Higgs?

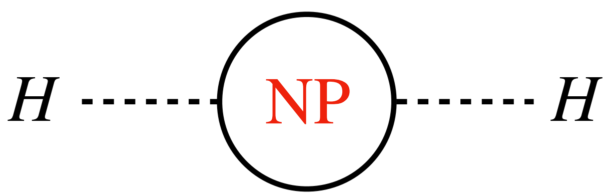


[Figure: Dawson, Meade, Ojalvoc, Vernieri, 2209.07510]

Why TeV-scale new physics?

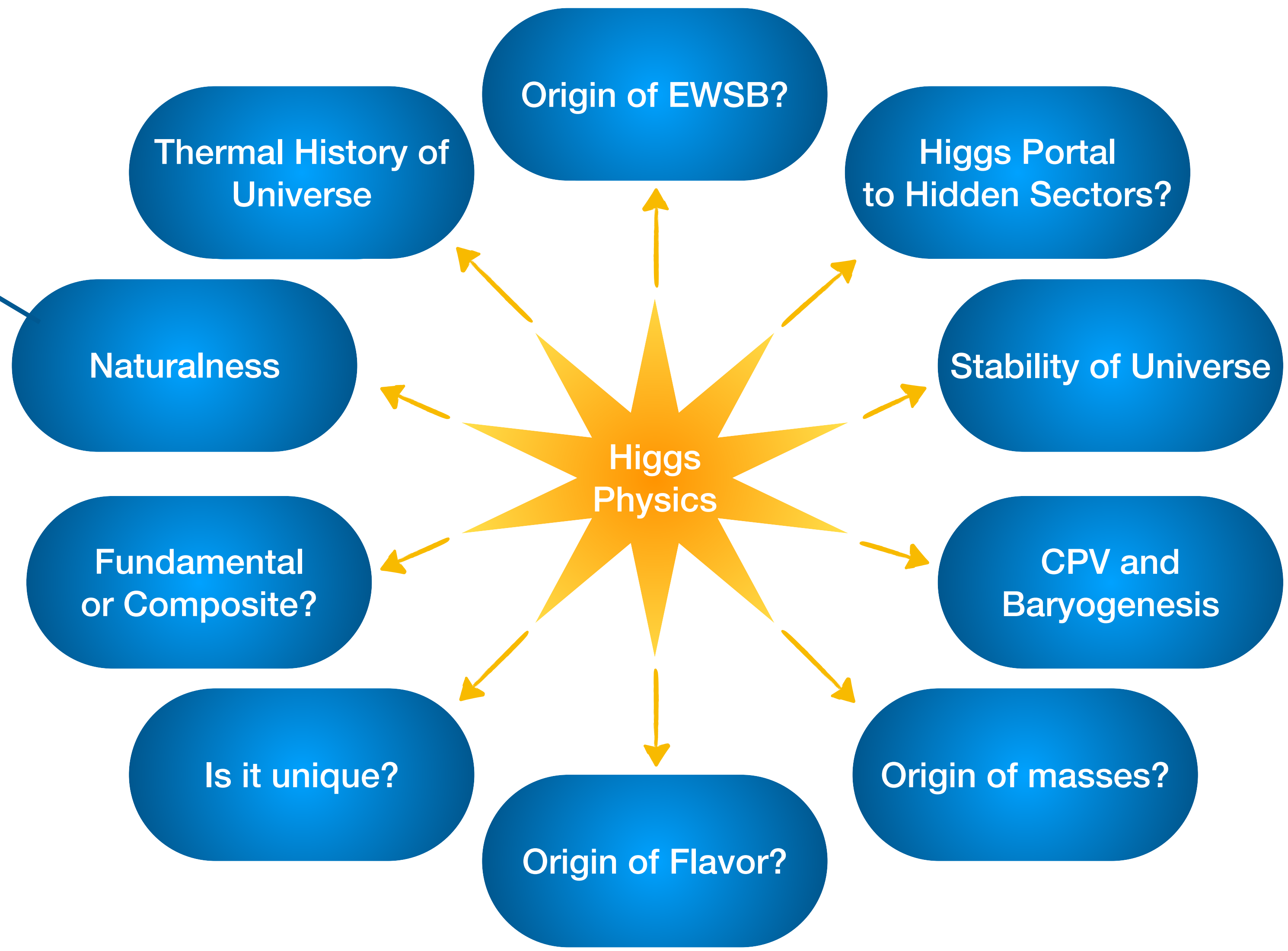
Understanding: What is the microscopic theory of the Higgs?

SM Higgs sector famously introduces an unstable scale



$$\delta m_H^2 \propto \Lambda_{\rm NP}^2$$

Puts a theoretical prior on TeV-scale physics!



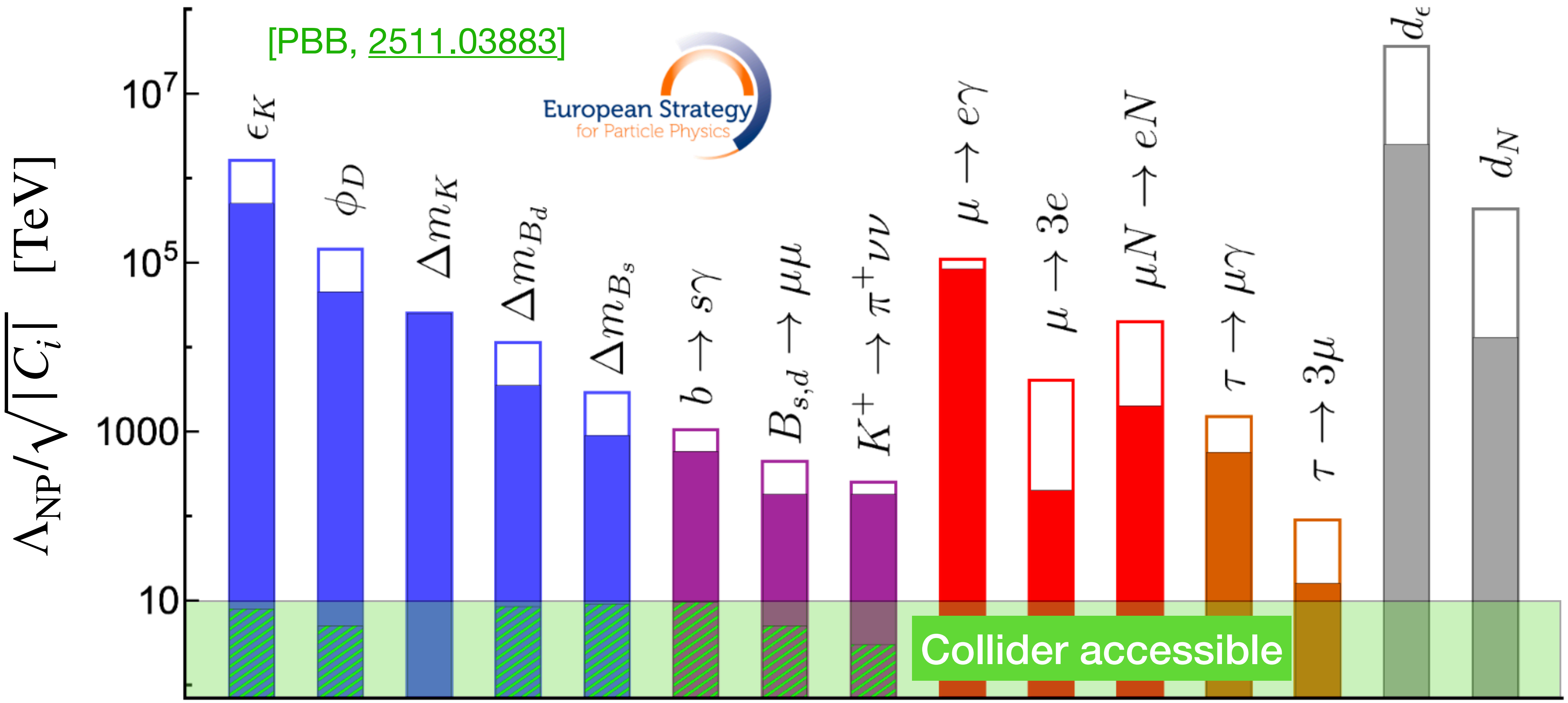
Exploration: It's the energy frontier of collider physics! LHC → FCC

1-10 TeV

[Figure: Dawson, Meade, Ojalvoc, Vernieri, 2209.07510]

The BSM flavor puzzle

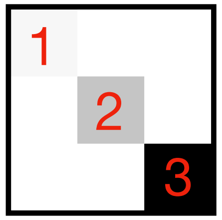
- How is a microscopic theory of the Higgs compatible with flavor data?



$\Longrightarrow$ TeV-scale new physics requires a *very specific structure* for C_i

Radiatively-stable structure ⇔ symmetries

- Hierarchical structure observed in the SM Yukawa couplings Y_f^{ij}



$\Longrightarrow$ Approximate flavor symmetries in the SM!

$\mathscr{L}_{\mathrm{SM}}$ without Yukawas: $U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$ Flavor universality

- Only large breaking is $y_t \sim 1$ $\longrightarrow$ $U(2)_q \times U(2)_u \times U(1)_t \times U(3)^3$
- Next breaking $y_{b,\tau} \sim 10^{-2}$ $\longrightarrow$ $U(2)^5 \times U(1)_{B_3} \times U(1)_{L_3}$
- Residual exact symmetry $\longrightarrow$ $U(1)_B \times U(1)^3$

Hierarchical Y_f^{ij} $\Longrightarrow$ Approximate symmetries of increasing quality

Radiatively-stable structure ⇔ symmetries

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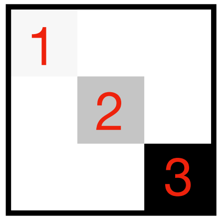

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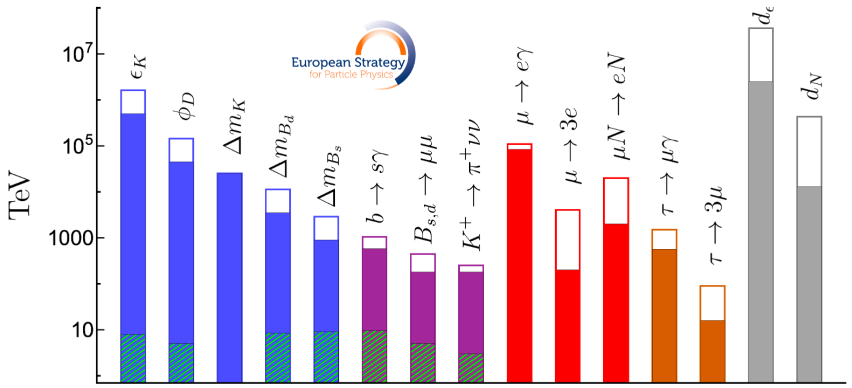


$\Longrightarrow$

New physics at collider-accessible energies must respect (a part) of the approximate symmetries of the SM.

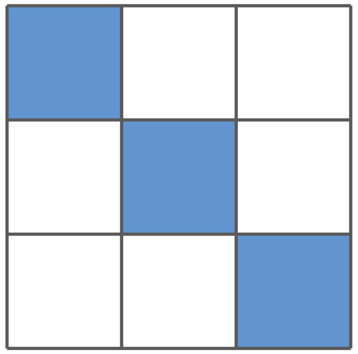
A brief history of flavor protection

Flavor terminology

- Just to clarify terminology so we're all on the same page. Consider the coupling matrix of a fermion bilinear, e.g.

$$C_{ij}(\bar{\psi}_i \gamma^\mu \psi_j)$$

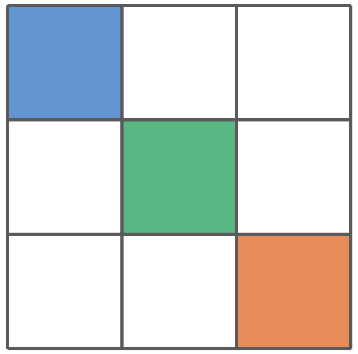
Flavor universality



$C = c\,\mathbf{1}$

$U(3)^5$
BSM blind to generation

Flavor non-universality



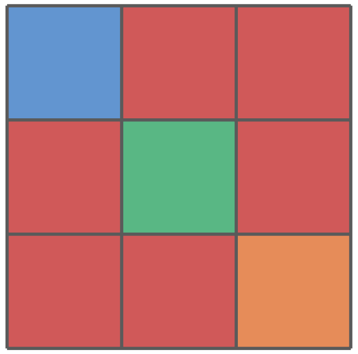
$C = \mathrm{diag}(c_1, c_2, c_3)$

$U(1)^{15}$ (Cartan)
$\Delta F = 0$, but generation-dependent interactions

rotate to mass basis

$U^\dagger\,\mathrm{diag}(c)\,U$
$\Rightarrow (c_i - c_j)\,\theta_{ij}$

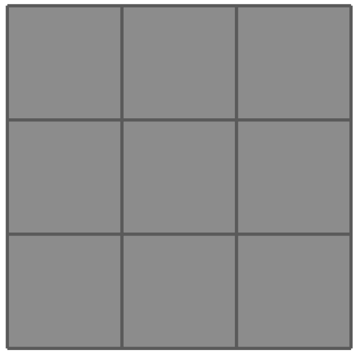
Flavor violation



$C_{ij} \neq 0,\ i \neq j$

$\Delta F \neq 0$: FCNC, cLFV
(mass basis)

Flavor anarchy



all $C_{ij} \sim \mathcal{O}(1)$

no symmetry

Minimal Flavor Violation

- Pioneering idea: The only sources of $U(3)^5$ and CP violation for BSM physics are the SM Yukawa couplings themselves.

Symmetry group: $U(3)^5 \equiv U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e$

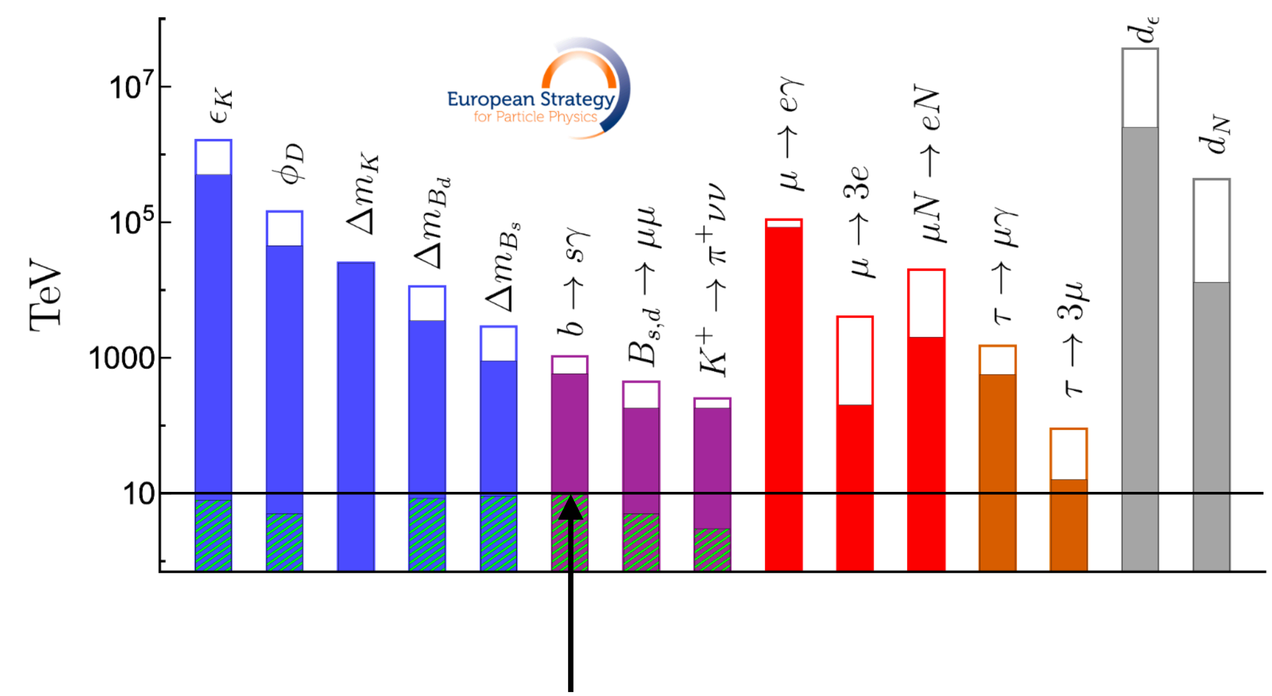
Symmetry-breaking spurions: $Y_u \sim (\mathbf{3}_q, \bar{\mathbf{3}}_u)$, $Y_d \sim (\mathbf{3}_q, \bar{\mathbf{3}}_d)$, $Y_e \sim (\mathbf{3}_\ell, \bar{\mathbf{3}}_e)$

SM fermions: $\mathbf{3}_f$ under $U(3)^5$

Wilson coefficients C_i built from positive powers of Y_f that form symmetry invariants:

$$\frac{1}{\Lambda_{\rm NP}^2}(\bar{q} Y_u Y_u^\dagger q)^2\,, \qquad [Y_u Y_u^\dagger]_{ij} \approx y_t^2 V_{3i}^* V_{3j}$$

BSM couplings C_i now inherit SM flavor selection rules!



<u>MFV</u> $\Lambda_{\rm NP} \lesssim 10$ TeV

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

Minimal Flavor Violation

- Shortcomings:

1. **Flavor-sterile "SM-like" TeV scale dynamics**
   Not an appropriate interpretation framework for EFT in the era of precision flavor physics experiments!
2. **No hint of a resolution to the SM flavor puzzle**
   Structure of Y_f^{ij} is simply assumed, but not explained.
3. **Naive power counting issues since $y_t \sim 1$***

MFV guarantees sufficient flavor protection, but it is ***not strictly necessary*** and is ***overly restrictive***. It excludes a broad class of potentially interesting flavor phenomena that could still be compatible with TeV-scale dynamics.

[*Kagan, Perez, Volansky, Zupan, 0903.1794]

Resummed MFV: $U(3)^5 \to U(2)^2 \times U(3)^3$

The next step: $U(2)^5$

- Key idea: Universality in the light families passes strongest flavor bounds, allow non-trivial third-family dynamics. [Barbieri, Isidori, Jones-Perez, Lodone, Straub, hep-ph/0207036]

Symmetry group: $U(2)^5 \equiv U(2)_q \times U(2)_u \times U(2)_d \times U(2)_\ell \times U(2)_e \qquad \mathbf{2}_f \oplus \mathbf{1}_f$

Symmetry-breaking spurions: $V_q \sim \mathbf{2}_q\,, \quad \Delta_u \sim (\mathbf{2}_q, \bar{\mathbf{2}}_u), \quad \Delta_d \sim (\mathbf{2}_q, \bar{\mathbf{2}}_d), \quad \Delta_e \sim (\mathbf{2}_\ell, \bar{\mathbf{2}}_e)$

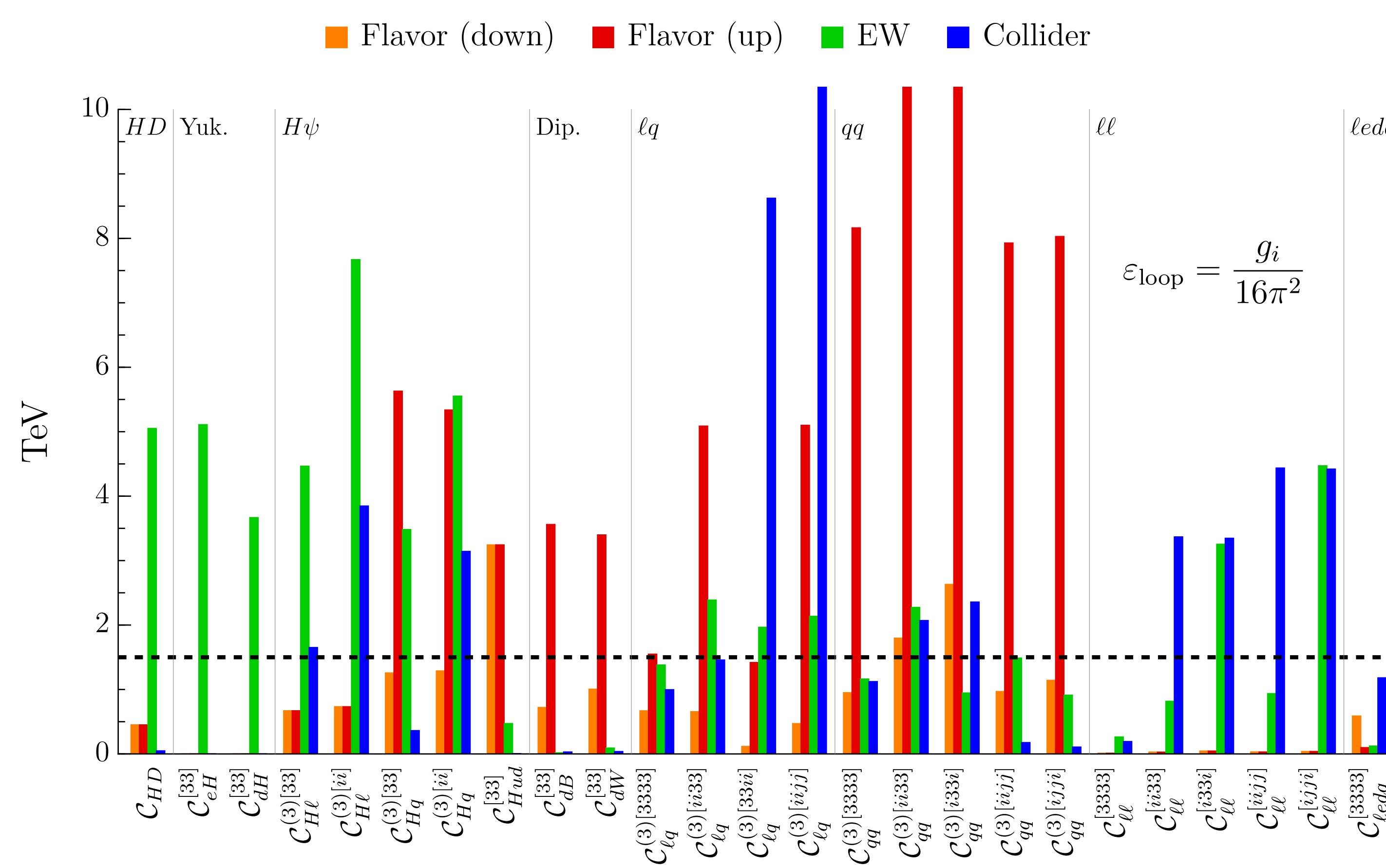
$$Y_{u,d} = \left(\begin{array}{c|c} \Delta_{u,d} & V_q \\ \hline 0 & y_{t,b} \end{array}\right)$$

EFT ops classified as $U(2)^5$ invariants:

$$\frac{1}{\Lambda_{\rm NP}^2}(\bar{q}_i V_q^i q_3)^2 \qquad B_{d,s} \text{ mixing}$$

- Allows $\Lambda_{\rm NP} \lesssim 10$ TeV, option to couple more to 3rd generation:

$$\bar{q}_p \gamma_\mu q_p \to \epsilon_Q (\bar{q}_i \gamma_\mu q_i) + (\bar{q}_3 \gamma_\mu q_3) \qquad (i = 1,2)$$



[Allwicher, Cornella, Isidori, BAS, 2311.00020]

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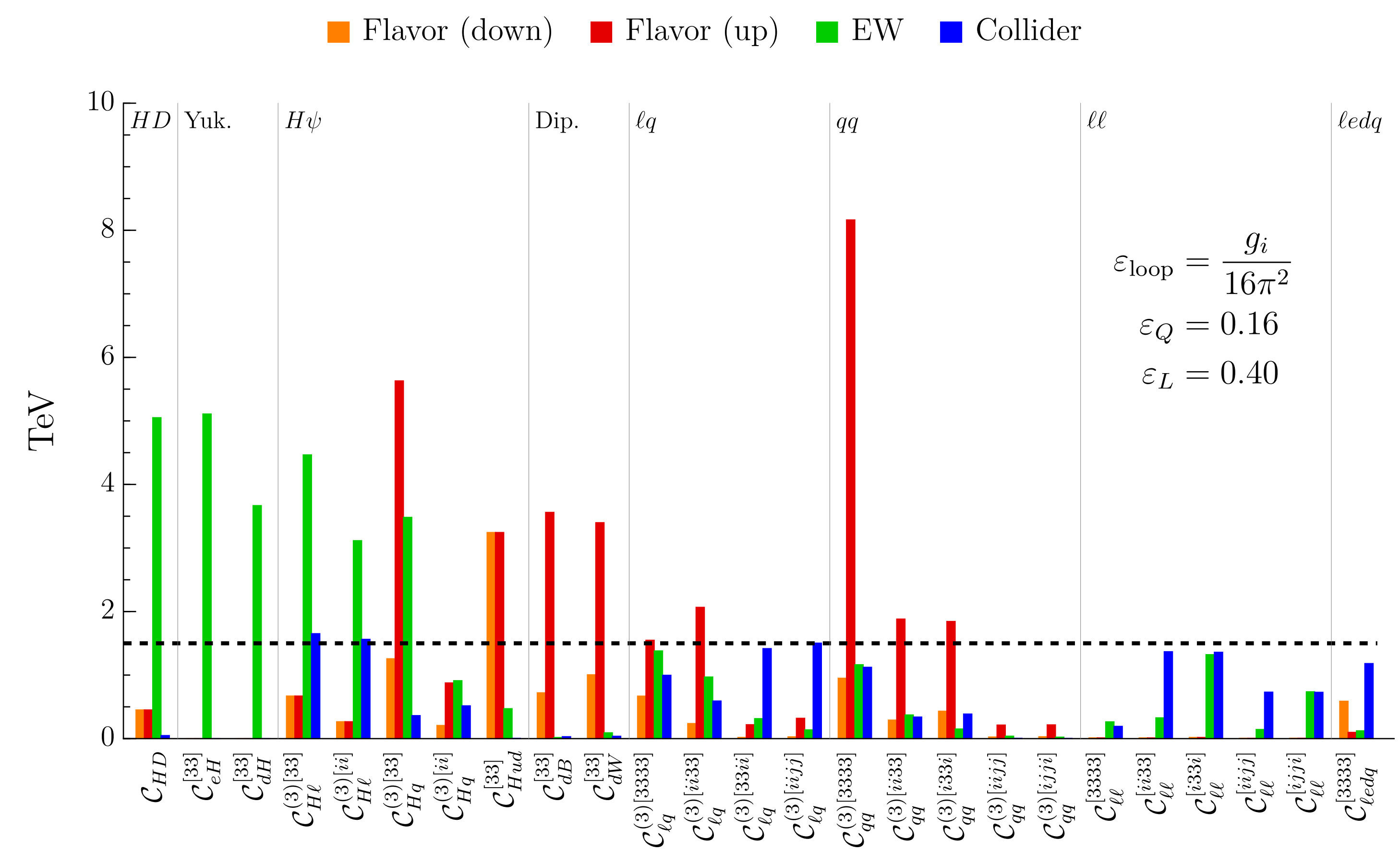


[Allwicher, Cornella, Isidori, BAS, 2311.00020]

The next step: $U(2)^5$

- Solves some MFV shortcomings:

1. **Non-trivial third-family TeV scale dynamics.**
   The leading interpretation framework in the past decade of *B* physics!
2. **Partial resolution to the SM flavor puzzle.**
   Separates the 3rd family from the light from the start.
   Hierarchical singular values of $\Delta_{u,d,e}$ unexplained!
3. **No issues with power counting**
   The largest breaking is $V_q \sim O(V_{ts}) \sim 10^{-2}$

And perhaps still too restrictive! What is the most general interpretation framework for TeV-scale BSM? And can we find a more complete explanation of the flavor puzzle?

Minimal Flavor Protection

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection

What is the maximum amount TeV-scale BSM can break $U(3)^5$ while respecting all bounds from FCNC and CP-violating observables?

- Least symmetry ⇔ largest allowed parameter space for TeV-scale new physics!

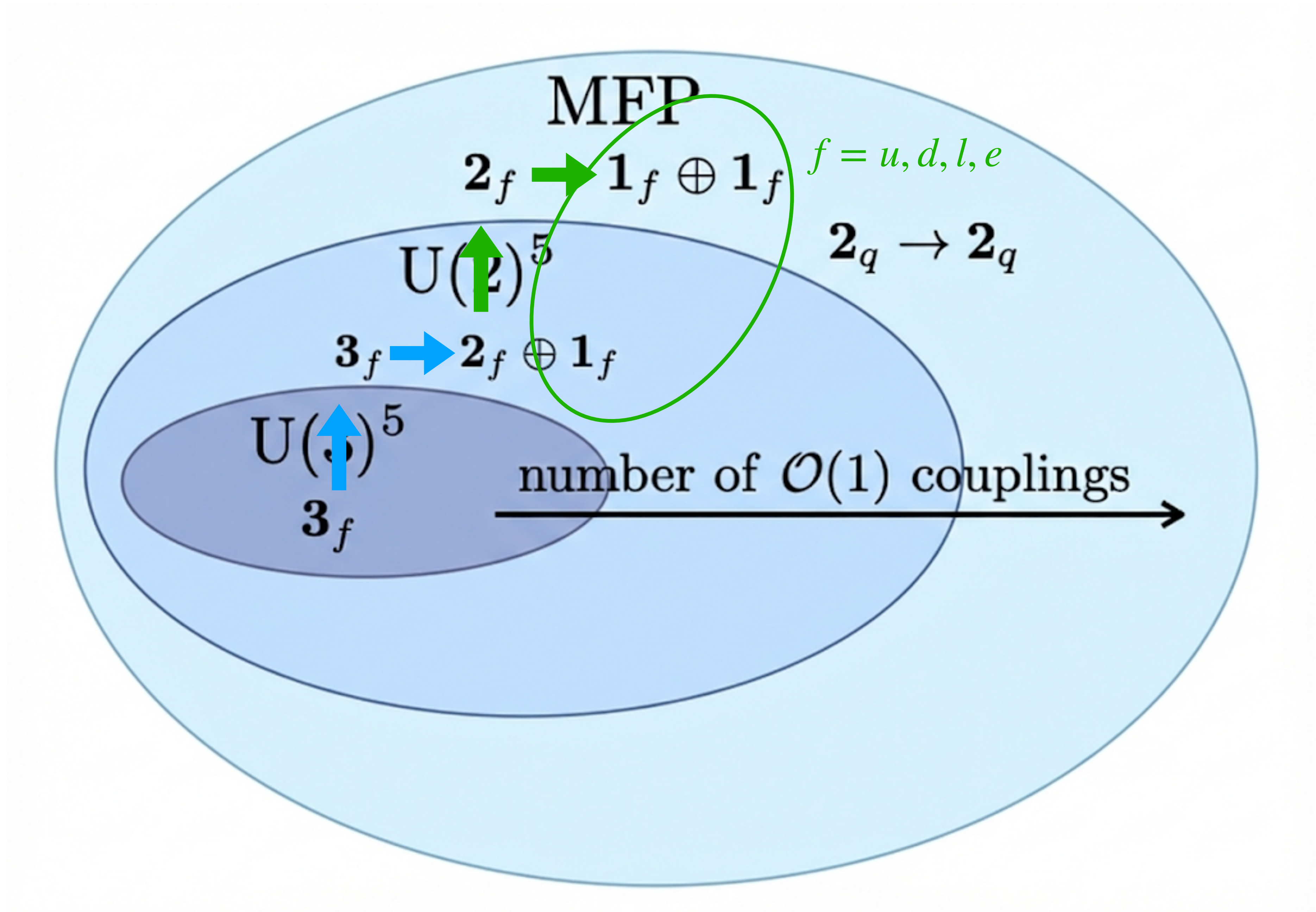
Find the minimal continuous subgroup $H_{\text{MFP}} \subset U(3)^5$ where:

1. All other directions in flavor space can be maximally violated, i.e., BSM can induce $\mathcal{O}(1)$ breaking of $U(3)^5 \to H_{\text{MFP}}$
2. Small spurions exist that reproduce all observed flavor parameters.
3. Structural protection against FCNC and CPV for the ***entire*** SMEFT.

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection

Symmetry: $SU(2)_q \times U(1)_X$



MFP: A novel symmetry-spurion framework for TeV-scale new physics

[Greljo, Palavrić, BAS, 2512.04159]

[Figure: 2601.07921]

The necessity of $SU(2)_q$

- Why not just a single $U(1)_X$ a la Froggatt-Nielsen? Let's try it- choose $X_{q_1} \neq X_{q_2} \neq X_{q_3}$ for no FV in interaction basis:

$$c\bar{q}\gamma_\mu M_{\rm int} q \qquad\qquad M_{\rm int} = {\rm diag}(a, b, 1)$$

- CKM guarantees that LH rotations ($L_u^\dagger L_d = V_{\rm CKM}$) generate FV which is of order

$$M_{\rm mass} = L M_{\rm int} L^\dagger \sim \begin{pmatrix} a & \lambda(b-a) & A\lambda^3[a-b+(1-a)z^*] \\ \lambda(b-a) & b & A\lambda^2(1-b) \\ A\lambda^3[a-b+(1-a)z] & A\lambda^2(1-b) & 1 \end{pmatrix}$$

K/D meson mixing

$$\frac{(a-b)^2\lambda^2}{\Lambda^2}(\bar{q}_1 q_2)^2 \lesssim \frac{1}{(2\times 10^4\ {\rm TeV})^2} \implies |a-b| \lesssim 10^{-3}\left(\frac{\Lambda}{10\ {\rm TeV}}\right)$$

**$SU(2)_q$ must be a very good symmetry below 10 TeV!

[Greljo, Palavrić, BAS, 2512.04159]

[Blum, Grossman, Nir, Perez, 0903.2118]

Minimal Flavor Protection: Symmetry group

- What about the rest? $U(1)_X \subset U(1)^{14} \subset U(3)^5$

$\boxed{\text{A single linear combination of the remaining Cartan generators is enough!}}$

(Perhaps the most surprising discovery… would have expected a larger group!)

- Our ansatz for the minimal continuous symmetry is therefore:

$$H_{\rm MFP} = SU(2)_q \times U(1)_X$$

$\Delta F = 2$, cLFV $\implies X_{f_1} \neq X_{f_2}$

$\cancel{(\bar{u}_1 u_2)^2, (\bar{d}_1 d_2)^2, (\bar{l}_1 l_2), (\bar{e}_1 e_2)}$

Forbidden in SMEFT interaction basis

Fermion fields

$$\mathbf{3}_{x_q} \to \mathbf{2}_{x_q} \oplus \mathbf{1}_{x_{q3}} \,,$$

$$\mathbf{3}_{x_f} \to \mathbf{1}_{x_{f_1}} \oplus \mathbf{1}_{x_{f_2}} \oplus \mathbf{1}_{x_{f_3}}$$

$$f \;=\; u,\, d,\, \ell,\, e$$

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection: Yukawa couplings

- As for $U(2)^5$, 4 spurions required: three $SU(2)_q$ doublets and one singlet.

$$\boldsymbol{V} \sim (\mathbf{2}, X_V) \quad \boldsymbol{W} \sim (\mathbf{2}, X_W), \quad \boldsymbol{U} \sim (\mathbf{2}, X_U), \quad \boldsymbol{z} \sim (\mathbf{1}, X_z)$$

SM fields	d_1, u_1	d_2	u_2	d_3	q_3, u_3	ℓ_i	e_i
$U(1)_X$ charge	$-X_V - 2X_z$	$X_V + X_z$	$-X_W$	$X_z - X_U$	$2X_z - X_U$	X_i	$X_i - (4-i)X_z$

Allowed Yukawa structure up to O(S^3): *All hierarchies produced for $V, W, U, z \sim O(10^{-2})$!*

$$Y_d = \begin{pmatrix} \boldsymbol{V} \boldsymbol{z}^2 & \widetilde{\boldsymbol{V}} \boldsymbol{z}^* & \boldsymbol{U} \boldsymbol{z}^* \\ 0 & 0 & \boldsymbol{z} \end{pmatrix} \qquad Y_e = \begin{pmatrix} \boldsymbol{z}^3 & 0 & 0 \\ 0 & \boldsymbol{z}^2 & 0 \\ 0 & 0 & \boldsymbol{z} \end{pmatrix}$$

$$Y_u = \begin{pmatrix} \boldsymbol{V} \boldsymbol{z}^2 & \boldsymbol{W} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\boldsymbol{z} = z, \;\; \boldsymbol{V} = v \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \;\; \boldsymbol{W} = w \begin{pmatrix} \sin\alpha \\ \cos\alpha \end{pmatrix}, \;\; \boldsymbol{U} = u \begin{pmatrix} \sin\beta \, e^{i\phi} \\ \cos\beta \end{pmatrix}$$

[Greljo, Palavrić, BAS, 2512.04159]

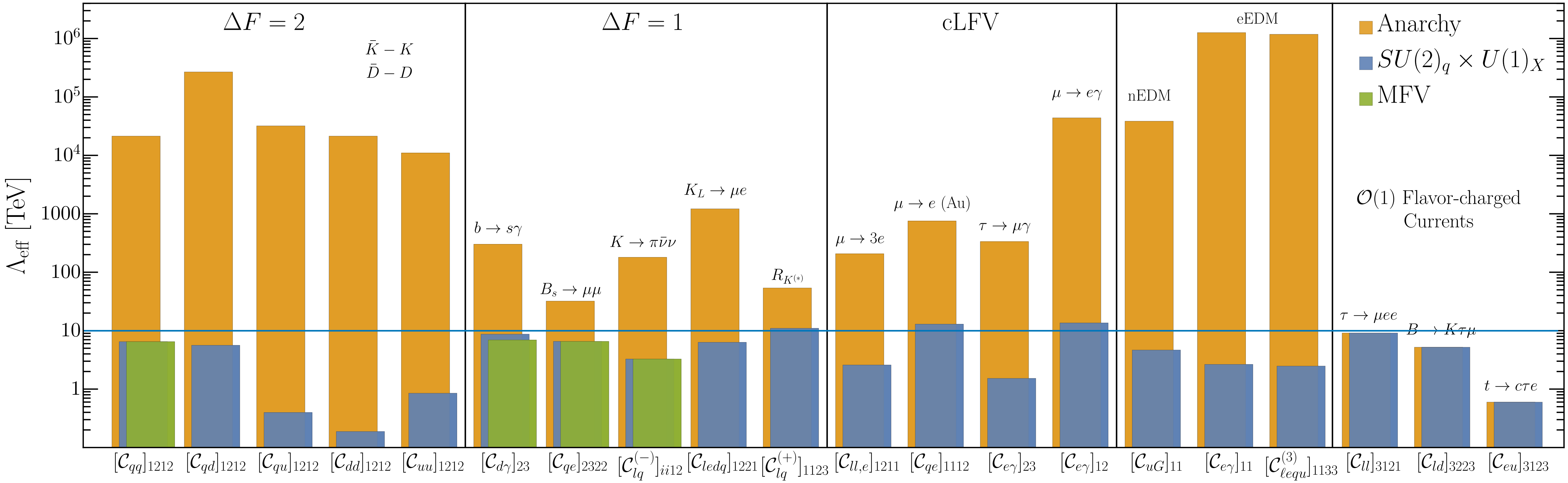
$\tan\alpha \approx V_{us}/V_{cs}$ $\qquad$ $\tan\beta e^{i\phi} \approx V_{td}^*/V_{ts}^*$

Flavor violation in MFP

$$\{X_V,\, X_W,\, X_U,\, X_z\} = \{1,\, \text{-}2,\, \text{-}3,\, 7\}\,,$$
$$\{X_1,\, X_2,\, X_3\} = \{\text{-}2,\, \text{-}3,\, \text{-}1\}\,.$$

- SMEFT now admits a series expansion in small spurions $S = V, W, U, z$ about the MFP-symmetric point:

$$\mathcal{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2} \sum_{H_{\text{MFP}}} \left[S^0\, \mathcal{O}_6^{[0]} + S^1\, \mathcal{O}_6^{[1]} + S^2\, \mathcal{O}_6^{[2]} + \cdots \right]$$



MFP allows for rich flavor dynamics: "TeV-scale flavor anarchy"!

[Greljo, Palavrić, BAS, 2512.04159]

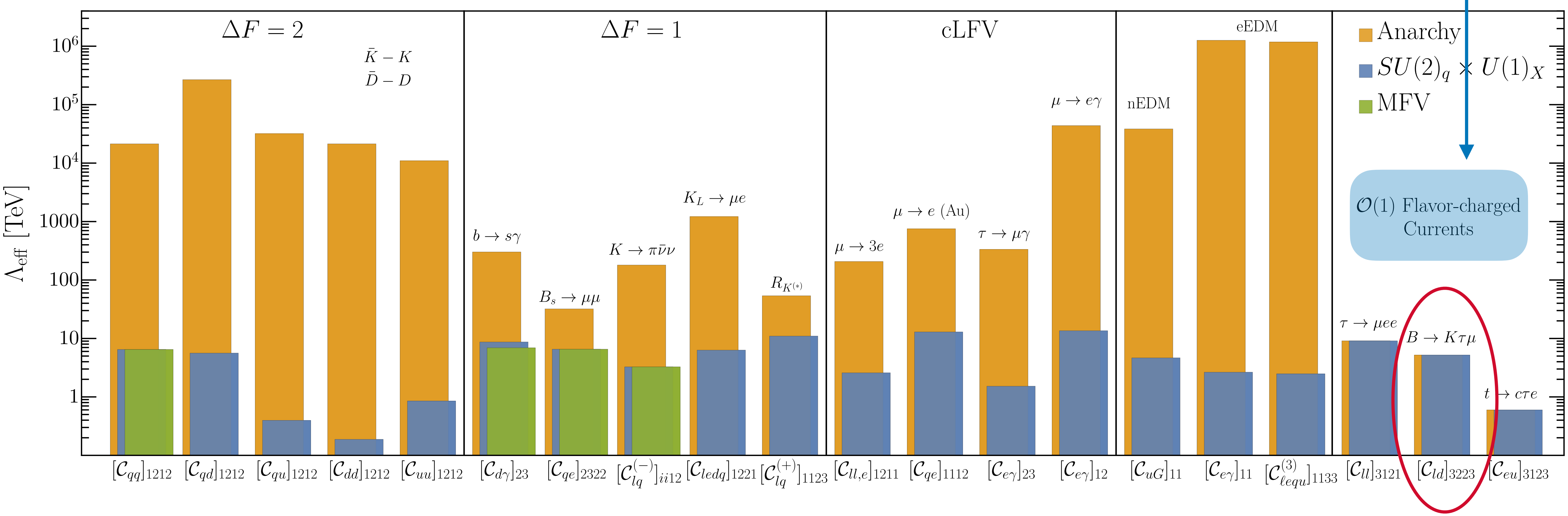
Flavor-charged currents

$$\{X_V,\, X_W,\, X_U,\, X_z\} = \{1,\, -2,\, -3,\, 7\}\,,$$
$$\{X_1,\, X_2,\, X_3\} = \{-2,\, -3,\, -1\}\,.$$

- SMEFT now admits a series expansion in small spurions about the MFP-symmetric point:

Flavor violation possible at $O(S^0)$, e.g: $\dfrac{1}{\Lambda_{\text{eff}}^2}(\bar{l}_3\gamma_\mu l_2)(\bar{d}_2\gamma^\mu d_3)$

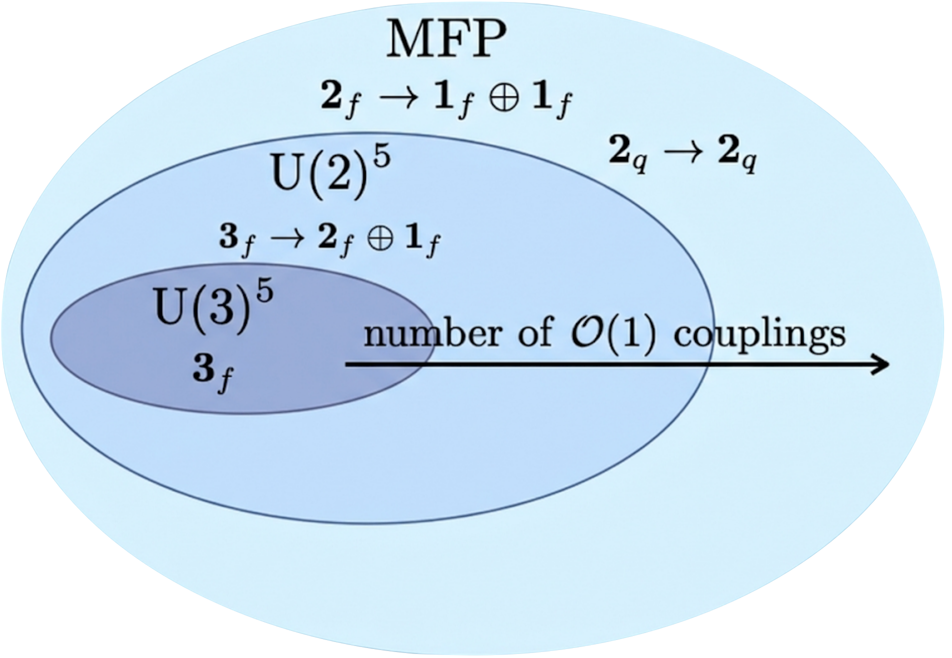
We call these flavor-charged currents!



MFP provides new targets for colliders and flavor factories!

[Greljo, Palavrić, BAS, 2512.04159]

Flavor-universality violation



Dimension-6 SMEFT $(\Delta B = 0)$

Operator basis w/ exact symmetry: $O(S^0)$

Operator class	$U(3)^5$		$U(2)^5$		$SU(2)_q \times U(1)_X$	
CP	even	odd	even	odd	even	odd
Bosonic	9	6	9	6	9	6
$\psi^2 H^3$	-	-	3	3	1	1
$\psi^2 X H$	-	-	8	8	3	3
$\psi^2 H^2 D$	7	-	15	1	20	1
$(\bar{L}L)(\bar{L}L)$	8	-	23	-	32	1
$(\bar{R}R)(\bar{R}R)$	9	-	29	-	61	1
$(\bar{L}L)(\bar{R}R)$	8	-	32	-	58	1
$(\bar{L}R)(\bar{R}L)$	-	-	1	1	1	1
$(\bar{L}R)(\bar{L}R)$	-	-	4	4	-	-
Total	41	6	124	23	185	15

Large reduction of O(1) parameters!

$$2499 \to \lesssim 200$$

MFP: More flavor-universality violation possible than in MFV and $U(2)^5$

[Greljo, Palavrić, BAS, 2512.04159]

Flavor-universality violation

- Start from the Cartan group, $U(1)^{15}$:

$$U(1)^{15} = U(1)^3_q \times U(1)^3_u \times U(1)^3_d \times U(1)^3_l \times U(1)^3_e$$

- Under this group, *fermion number cannot change, chirality cannot flip*. Counts self-conjugate operators.

Operator class	$U(1)^{15}$	
CP	even	odd
Bosonic	9	6
$\psi^2 H^3$	–	–
$\psi^2 X H$	–	–
$\psi^2 H^2 D$	21	–
$(\bar{L}L)(\bar{L}L)$	45	–
$(\bar{R}R)(\bar{R}R)$	60	–
$(\bar{L}L)(\bar{R}R)$	72	–
$(\bar{L}R)(\bar{R}L)$	–	–
$(\bar{L}R)(\bar{L}R)$	–	–
Total	**207**	**6**

207 CP even (8% of SMEFT)

H^6 and H^4D^2	
Q_H	$(H^\dagger H)^3$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\lvert H^\dagger D_\mu H\rvert^2$

$\psi^2 H^2 D$		X^2H^2 and X^3	
$Q_{H\ell}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu \ell)_{pp}$	Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\ell}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{\ell}\tau^I\gamma^\mu \ell)_{pp}$	Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)_{pp}$	Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)_{pp}$	Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)_{pp}$	Q_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)_{pp}$	Q_W	$\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)_{pp}$		

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)_{\substack{pprr\\prrp}}$	Q_{ee}	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)_{pprr}$	$Q_{\ell e}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{qq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)_{\substack{pprr\\prrp}}$	Q_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)_{\substack{pprr\\prrp}}$	$Q_{\ell u}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u)_{pprr}$
$Q_{qq}^{(3)}$	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)_{\substack{pprr\\prrp}}$	Q_{dd}	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)_{\substack{pprr\\prrp}}$	$Q_{\ell d}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)_{pprr}$
$Q_{\ell q}^{(1)}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma^\mu q)_{pprr}$	Q_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)_{pprr}$	Q_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{\ell q}^{(3)}$	$(\bar{\ell}\gamma_\mu \tau^I \ell)(\bar{q}\gamma^\mu \tau^I q)_{pprr}$	Q_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)_{pprr}$
		$Q_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)_{pprr}$
		$Q_{ud}^{(8)}$	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)_{pprr}$	$Q_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)_{pprr}$
				$Q_{qd}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)_{pprr}$

Flavor-universality violation

- For the symmetry to allow an O(1) top Yukawa, we should break

$$U(1)_{q_3} \times U(1)_{u_3} \to U(1)_{\rm diag} \equiv U(1)_{\rm top} \qquad \Longrightarrow \qquad U(1)^{15} \to U(1)^{14}$$

Operator class	$U(1)^{15}$		$U(1)^{14}$	
CP	even	odd	even	odd
Bosonic	9	6	9	6
$\psi^2 H^3$	–	–	1	1
$\psi^2 X H$	–	–	3	3
$\psi^2 H^2 D$	21	–	21	–
$(\bar{L}L)(\bar{L}L)$	45	–	45	–
$(\bar{R}R)(\bar{R}R)$	60	–	60	–
$(\bar{L}L)(\bar{R}R)$	72	–	72	–
$(\bar{L}R)(\bar{R}L)$	–	–	–	–
$(\bar{L}R)(\bar{L}R)$	–	–	–	–
Total	**207**	**6**	**211**	**10**

$\psi^2 H^3$ and $\psi^2 X H$	
Q_{uH}^{33}	$(H^\dagger H)(\bar{q}_3 u_3 \widetilde{H})$
Q_{uB}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} u_3 \widetilde{H}) B_{\mu\nu}$
Q_{uW}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} \tau^I u_3 \widetilde{H}) W_{\mu\nu}^I$
Q_{uG}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} T^A u_3 \widetilde{H}) G_{\mu\nu}^A$

- *Only 4 new operators- top dipoles and Yukawa modification. FUV.*
- *The leading irreducible chiral flipping + non-hermitian operators.*

Flavor-universality violation in MFP

- Now let's add $SU(2)_q$ to the picture: $q \equiv (q_1, q_2)^T$.

$SU(2)_q$ invariance requires: $U(1)_{q_1} \times U(1)_{q_2} \to U(1)_q \implies U(1)^{14} \to U(1)^{13}$

Operator class	$U(1)^{15}$		$U(1)^{14}$		$SU(2)_q \times U(1)^{13}$	
CP	even	odd	even	odd	even	odd
Bosonic	9	6	9	6	9	6
$\psi^2 H^3$	–	–	1	1	1	1
$\psi^2 XH$	–	–	3	3	3	3
$\psi^2 H^2 D$	21	–	21	–	19	–
$(\bar{L}L)(\bar{L}L)$	45	–	45	–	31	–
$(\bar{R}R)(\bar{R}R)$	60	–	60	–	60	–
$(\bar{L}L)(\bar{R}R)$	72	–	72	–	57	–
$(\bar{L}R)(\bar{R}L)$	–	–	–	–	–	–
$(\bar{L}R)(\bar{L}R)$	–	–	–	–	–	–
Total	**207**	**6**	**211**	**10**	**180**	**10**

- *$SU(2)_q$ correlates the WCs of operators w/ LH light quarks.*
- *Same operator classes, just less parameters.*
- *No change of phases.*

$$C_1(H^\dagger D_\mu H)(\bar{q}_1\gamma^\mu q_1) + C_2(H^\dagger D_\mu H)(\bar{q}_2\gamma^\mu q_2) + C_3(H^\dagger D_\mu H)(\bar{q}_3\gamma^\mu q_3) \to C_{12}(H^\dagger D_\mu H)(\bar{q}_i\gamma^\mu q_i) + C_3(H^\dagger D_\mu H)(\bar{q}_3\gamma^\mu q_3)$$

Flavor-universality violation in MFP

- The breaking $U(1)^{13} \to U(1)_X$ lands on MFP, thus $SU(2)_q \times U(1)^{13}$ *counts the charge-invariant MFP operators! They violate universality but not flavor*.
- The difference counts charge-dependent operators, which are necessarily non-Hermitian. Can violate both flavor and universality!

Operator class	$SU(2)_q \times U(1)^{13}$		$SU(2)_q \times U(1)_X$	
CP	**even**	**odd**	**even**	**odd**
Bosonic	9	6	9	6
$\psi^2 H^3$	1	1	1	1
$\psi^2 X H$	3	3	3	3
$\psi^2 H^2 D$	19	–	20	1
$(\bar{L}L)(\bar{L}L)$	31	–	32	1
$(\bar{R}R)(\bar{R}R)$	60	–	61	1
$(\bar{L}L)(\bar{R}R)$	57	–	58	1
$(\bar{L}R)(\bar{R}L)$	–	–	1	1
$(\bar{L}R)(\bar{L}R)$	–	–	–	–
Total	**180**	**10**	**185**	**15**

[Greljo, Palavrić, BAS, 2512.04159]

Flavor-universality violation in MFP

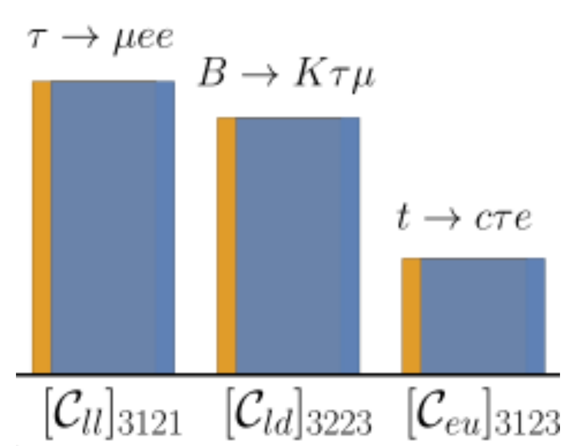
- The breaking $U(1)^{13} \to U(1)_X$ lands on MFP, thus $SU(2)_q \times U(1)^{13}$ *counts the charge-invariant MFP operators! They violate universality but not flavor*.
- The difference counts charge-dependent operators, which are necessarily non-Hermitian. Can violate both flavor and universality!

Operator class	$SU(2)_q \times U(1)^{13}$		$SU(2)_q \times U(1)_X$	
CP	even	odd	even	odd
Bosonic	9	6	9	6
$\psi^2 H^3$	1	1	1	1
$\psi^2 X H$	3	3	3	3
$\psi^2 H^2 D$	19	–	20	1
$(\bar{L}L)(\bar{L}L)$	31	–	32	1
$(\bar{R}R)(\bar{R}R)$	60	–	61	1
$(\bar{L}L)(\bar{R}R)$	57	–	58	1
$(\bar{L}R)(\bar{R}L)$	–	–	1	1
$(\bar{L}R)(\bar{L}R)$	–	–	–	–
Total	**180**	**10**	**185**	**15**

$[Q_{Hud}]_{11}$

$[Q_{\ell edq}]_{3333}$

3 flavor-charged currents



[Greljo, Palavrić, BAS, 2512.04159]

Applying MFP in SMEFT Likelihoods

Flavor-conserving observables (e.g. LHC + EWPO)

- Completely described by the charge-independent core of operators that are identified by imposing $SU(2)_q \times U(1)^{13}$ on the SMEFT.

Class	Operators	$SU(2)_q \times U(1)^{13}$ invariants	# / op.	# class
Bosonic	$\mathcal{Q}_H \quad \mathcal{Q}_{H\Box}$	—	1	9
	$\mathcal{Q}_{HD} \quad \mathcal{Q}_{HWB}$	—	1	
	$\mathcal{Q}_{HG} \quad \mathcal{Q}_{HW} \quad \mathcal{Q}_{HB}$	—	1	
	$\mathcal{Q}_G \quad \mathcal{Q}_W$	—	1	
$\psi^2 H^3,\ \psi^2 XH$	$\mathcal{Q}_{uH} \quad \mathcal{Q}_{uG} \quad \mathcal{Q}_{uW} \quad \mathcal{Q}_{uB}$	33	1	4
$\psi^2 H^2 D$	$\mathcal{Q}_{H\ell}^{(1)} \quad \mathcal{Q}_{H\ell}^{(3)} \quad \mathcal{Q}_{He} \quad \mathcal{Q}_{Hu} \quad \mathcal{Q}_{Hd}$	pp	3	19
	$\mathcal{Q}_{Hq}^{(1)} \quad \mathcal{Q}_{Hq}^{(3)}$	$ii,\ 33$	2	
$(\bar{L}L)(\bar{L}L)$	$\mathcal{Q}_{\ell\ell}$	$pprr\ (p \leq r),\ prrp\ (p < r)$	9	31
	$\mathcal{Q}_{qq}^{(1)} \quad \mathcal{Q}_{qq}^{(3)}$	$iijj,\ ijji,\ ii33,\ i33i,\ 3333$	5	
	$\mathcal{Q}_{\ell q}^{(1)} \quad \mathcal{Q}_{\ell q}^{(3)}$	$ppii,\ pp33$	6	
$(\bar{R}R)(\bar{R}R)$	$\mathcal{Q}_{ee}$	$pprr\ (p \leq r)$	6	60
	$\mathcal{Q}_{uu} \quad \mathcal{Q}_{dd}$	$pprr\ (p \leq r),\ prrp\ (p < r)$	9	
	$\mathcal{Q}_{ud}^{(1)} \quad \mathcal{Q}_{ud}^{(8)} \quad \mathcal{Q}_{eu} \quad \mathcal{Q}_{ed}$	$pprr$	9	
$(\bar{L}L)(\bar{R}R)$	$\mathcal{Q}_{\ell e} \quad \mathcal{Q}_{\ell u} \quad \mathcal{Q}_{\ell d}$	$pprr$	9	57
	$\mathcal{Q}_{qe} \quad \mathcal{Q}_{qu}^{(1)} \quad \mathcal{Q}_{qu}^{(8)} \quad \mathcal{Q}_{qd}^{(1)} \quad \mathcal{Q}_{qd}^{(8)}$	$iirr,\ 33rr$	6	
	Total CP-even, charge-independent MFP operators at $\mathcal{O}(S^0)$			**180**

Index conventions: $i, j \in \{1,2\}$ are $SU(2)_q$ doublet indices; 3 denotes the third-generation q_3; $p, r \in \{1,2,3\}$ label the generation of any $SU(2)_q$-singlet field (u, d, ℓ, e).

Flavor-violating observables

- Rotations are fully fixed in MFP and give charge-independent flavor violation. Start from SMEFT w/ $SU(2)_q \times U(1)^{13}$ and rotate to the mass basis after EWSB:

$$Y_d = \begin{pmatrix} \boldsymbol{V}\boldsymbol{z}^2 & \widetilde{\boldsymbol{V}}\boldsymbol{z}^* & \boldsymbol{U}\boldsymbol{z}^* \\ 0 & 0 & \boldsymbol{z} \end{pmatrix} \qquad Y_e = \begin{pmatrix} \boldsymbol{z}^3 & 0 & 0 \\ 0 & \boldsymbol{z}^2 & 0 \\ 0 & 0 & \boldsymbol{z} \end{pmatrix}$$

$$Y_u = \begin{pmatrix} \boldsymbol{V}\boldsymbol{z}^2 & \boldsymbol{W} & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \boldsymbol{z} = z, \ \boldsymbol{V} = v\begin{pmatrix} 1 \\ 0 \end{pmatrix}, \ \boldsymbol{W} = w\begin{pmatrix} \sin\alpha \\ \cos\alpha \end{pmatrix}, \ \boldsymbol{U} = u\begin{pmatrix} \sin\beta\, e^{i\phi} \\ \cos\beta \end{pmatrix}$$

$$V_{\rm CKM} = L_u^\dagger L_d = U_{12}^\dagger U_{23} U_{13}$$

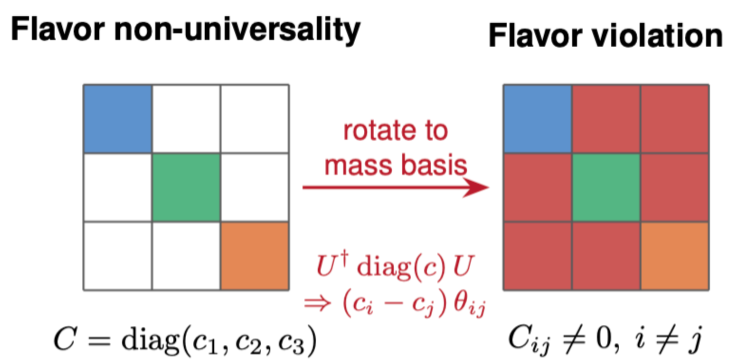
Yukawa texture forces rotations to factorize:

$$L_u = U_{12}, \qquad L_d = U_{23} U_{13}$$

Cabibbo rotation   Light-heavy mixing

Explicit rotation matrices for implementation

- Rotations are fully fixed in MFP and give charge-independent flavor violation. Start from SMEFT w/ $SU(2)_q \times U(1)^{13}$ and rotate to the mass basis after EWSB:



$$L_u = \boxed{U_{12}}, \qquad L_d = \boxed{U_{23} U_{13}}$$

Cabibbo rotation

Light-heavy mixing

What about right-handed rotations?

$$Y_{u,d} \sim \begin{pmatrix} \times & \times & \times \\ 0 & \times & \times \\ 0 & 0 & \times \end{pmatrix}$$

$$\Longrightarrow \theta_R^{ij} \approx \frac{m_i}{m_j} \theta_L^{ij} \quad (i < j)$$

	θ_{12}	θ_{13}	θ_{23}
u_L	λ	0	0
u_R	$\lambda \dfrac{m_u}{m_c} \approx 5 \times 10^{-4}$	0	0
d_L	$V_{td} V_{ts}^*$	V_{td}	V_{ts}
d_R	$\dfrac{m_d}{m_s} V_{td} V_{ts}^*$	$\dfrac{m_d}{m_b} V_{td}$	$\dfrac{m_s}{m_b} V_{ts}$
$e_L,\ e_R$	0	0	0

[Greljo, Palavrić, BAS, 2512.04159]

Probing the charge-independent core of MFP
(aka testing flavor non-universality)

Irreducible interactions for TeV-scale BSM

- 180 CP-even, charge-independent MFP operators are special because i) they can be O(1) at the TeV scale and ii) they cannot be set to zero by symmetry.

EWPOs

Higgs physics

Flavor (non-universality)

H^6 and H^4D^2	
Q_H	$(H^\dagger H)^3$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\lvert H^\dagger D_\mu H\rvert^2$

$\psi^2 H^3$ and $\psi^2 XH$	
Q_{uH}^{33}	$(H^\dagger H)(\bar{q}_3 u_3 \widetilde{H})$
Q_{uB}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} u_3 \widetilde{H}) B_{\mu\nu}$
Q_{uW}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} \tau^I u_3 \widetilde{H}) W^I_{\mu\nu}$
Q_{uG}^{33}	$(\bar{q}_3 \sigma^{\mu\nu} T^A u_3 \widetilde{H}) G^A_{\mu\nu}$

$\psi^2 H^2 D$		X^2H^2 and X^3	
$Q_{H\ell}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu \ell)_{pp}$	Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\ell}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{\ell}\tau^I\gamma^\mu \ell)_{pp}$	Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)_{pp}$	Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)_{pp}$	Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)_{pp}$	Q_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)_{pp}$	Q_W	$\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)_{pp}$		

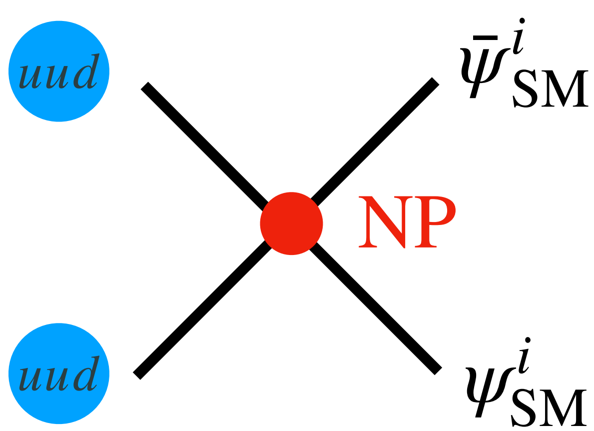
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)_{\substack{pprr\\prrp}}$	Q_{ee}	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)_{pprr}$	$Q_{\ell e}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{qq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)_{\substack{pprr\\prrp}}$	Q_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)_{\substack{pprr\\prrp}}$	$Q_{\ell u}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u)_{pprr}$
$Q_{qq}^{(3)}$	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)_{\substack{pprr\\prrp}}$	Q_{dd}	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)_{\substack{pprr\\prrp}}$	$Q_{\ell d}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)_{pprr}$
$Q_{\ell q}^{(1)}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma^\mu q)_{pprr}$	Q_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)_{pprr}$	Q_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{\ell q}^{(3)}$	$(\bar{\ell}\gamma_\mu \tau^I \ell)(\bar{q}\gamma^\mu \tau^I q)_{pprr}$	Q_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)_{pprr}$
		$Q_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)_{pprr}$
		$Q_{ud}^{(8)}$	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)_{pprr}$	$Q_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)_{pprr}$
				$Q_{qd}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)_{pprr}$

[Greljo, Palavrić, BAS, 2512.04159]

Why is this important for collider physics?

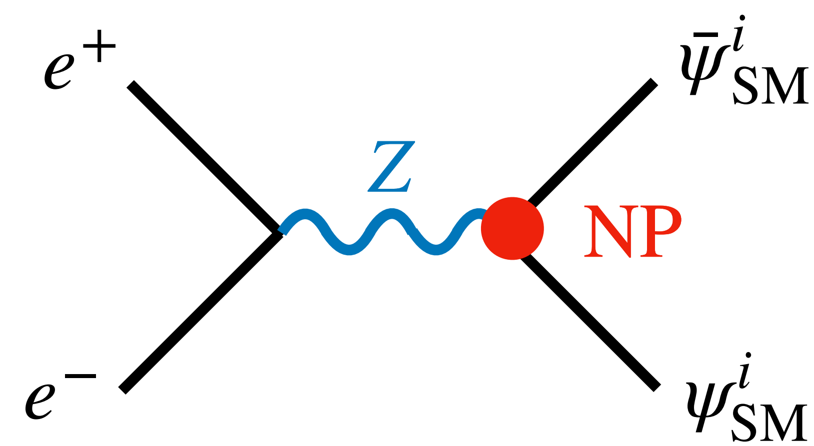
- These irreducible interactions are self-conjugate, just like tree-level neutral currents in the SM. They can interfere with SM neutral-current processes: Z-pole, DY, etc.

<u>Non-resonant LHC physics</u>



$$pp \to \bar{\psi}_{\rm SM}\psi_{\rm SM}$$

<u>Z-pole physics</u>



$$e^+e^- \to \bar{\psi}_{\rm SM}\psi_{\rm SM}$$

$$|\mathscr{A}|^2 = |\mathscr{A}_{\rm SM} + \mathscr{A}_{\rm NP}|^2 = |\mathscr{A}_{\rm SM}|^2 + 2{\rm Re}(\mathscr{A}_{\rm SM}\mathscr{A}^*_{\rm NP}) + |\mathscr{A}_{\rm NP}|^2$$

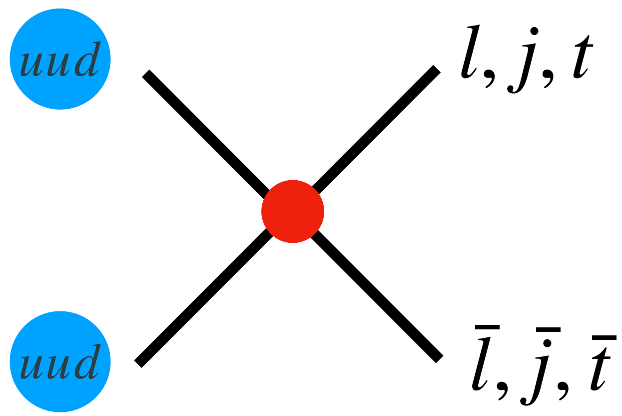
Self-conjugate SMEFT operators have the right chiral/analytic structure

[Haisch, BAS, 2608.10064]

Flavor non-universality at the LHC

[DY: Greljo, Marzocca, 1704.09015]

- A lot of progress can be made- no complete implementation in EFT likelihoods.



$$\sim \frac{E^2}{\Lambda^2}$$

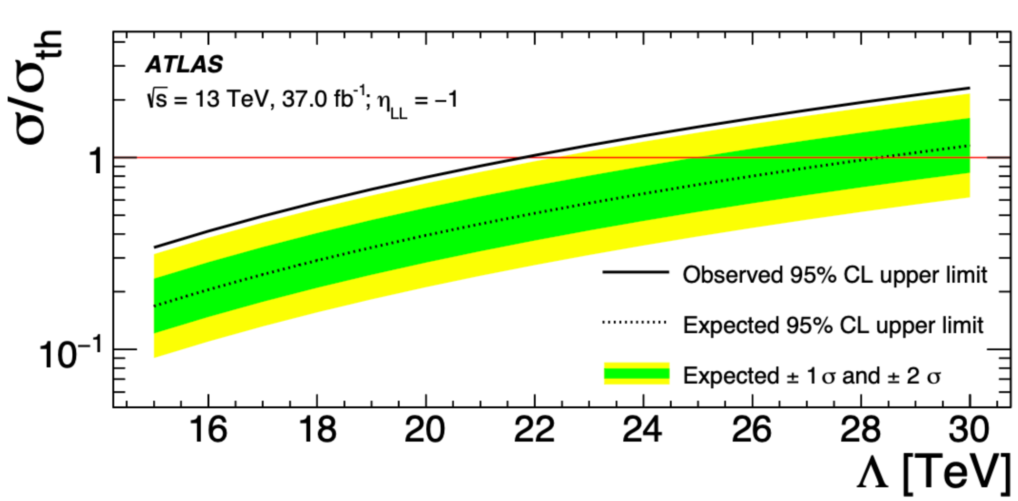
Non-resonant

Observables per flavor pair: m_{ff}, χ

Drell-Yan | Top + di-jets

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q_{\ell\ell}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)_{\substack{pprr\\prrp}}$	Q_{ee}	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)_{pprr}$	$Q_{\ell e}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{qq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)_{\substack{pprr\\prrp}}$	Q_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)_{\substack{pprr\\prrp}}$	$Q_{\ell u}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma^\mu u)_{pprr}$
$Q_{qq}^{(3)}$	$(\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)_{\substack{pprr\\prrp}}$	Q_{dd}	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)_{\substack{pprr\\prrp}}$	$Q_{\ell d}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma^\mu d)_{pprr}$
$Q_{\ell q}^{(1)}$	$(\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma^\mu q)_{pprr}$	Q_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)_{pprr}$	Q_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{\ell q}^{(3)}$	$(\bar{\ell}\gamma_\mu \tau^I \ell)(\bar{q}\gamma^\mu \tau^I q)_{pprr}$	Q_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)_{pprr}$
		$Q_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)_{pprr}$
		$Q_{ud}^{(8)}$	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)_{pprr}$	$Q_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)_{pprr}$
				$Q_{qd}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)_{pprr}$

For di-jets, only inclusive searches exist!



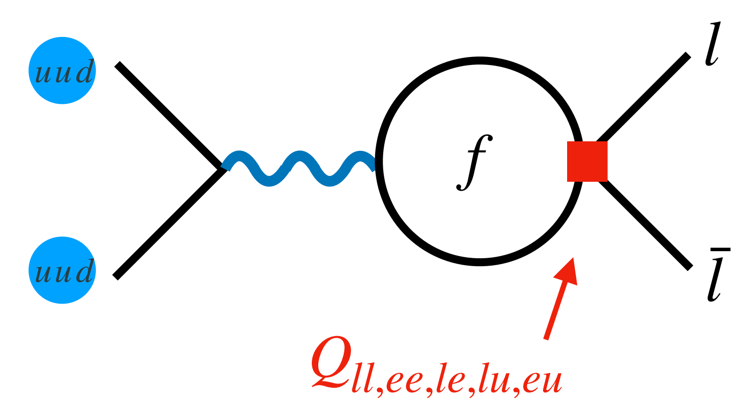
[ATLAS, 1703.09127
CMS, 1803.08030]

$$\mathscr{L} \supset \frac{2\pi}{\Lambda^2}\eta_{LL}(\bar{q}\gamma^\mu q)(\bar{q}\gamma_\mu q)$$

Rescaled limit:

$$\Lambda_{\text{eff}} \gtrsim 9 \text{ TeV}$$

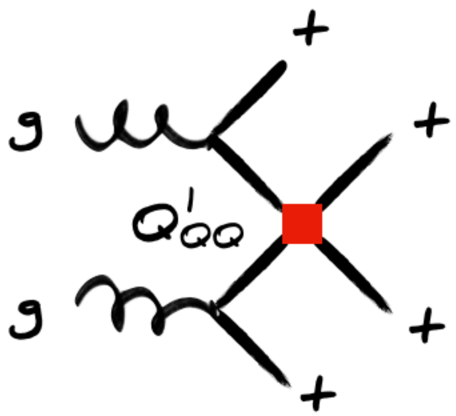
The rest: 1-loop Drell-Yan

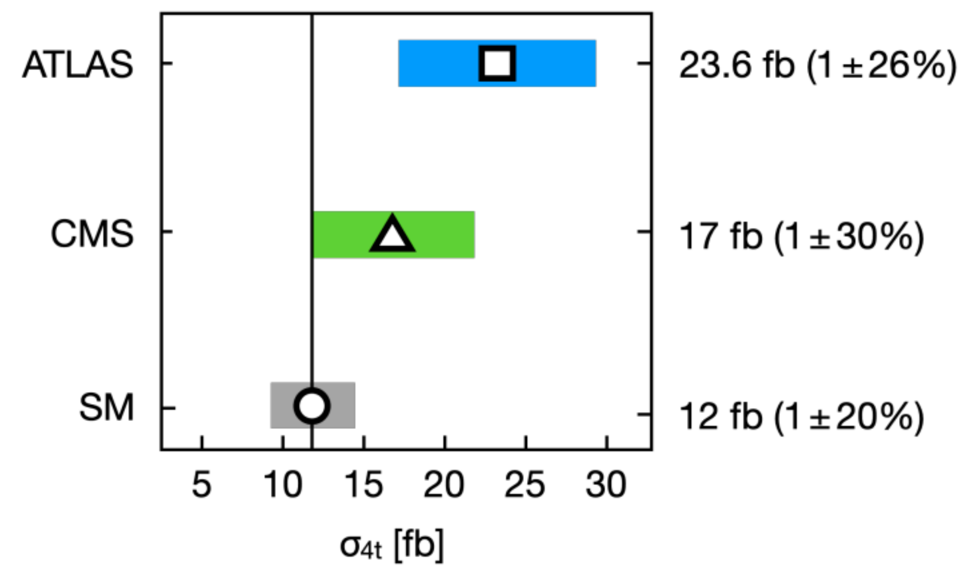


[Partial result in Dawson, Giardino, 2105.05852]

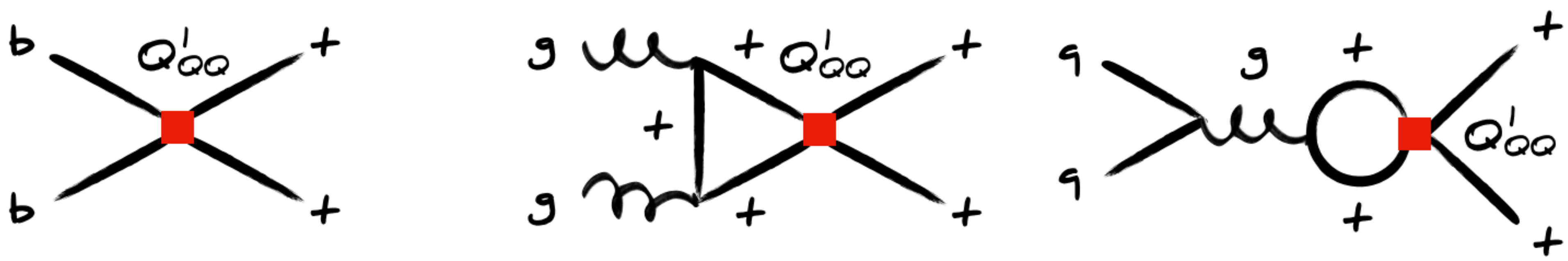
Example: 4 top operators

- 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.



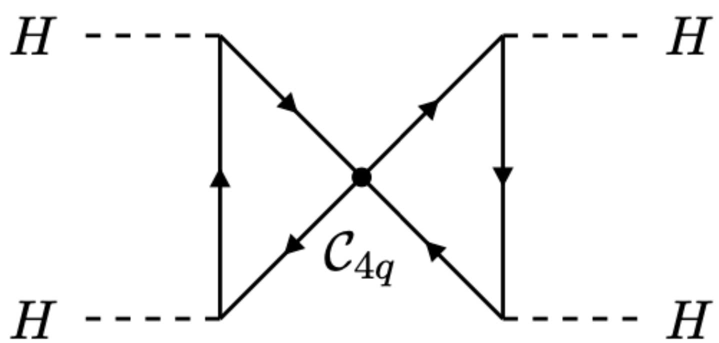


- Due to strong bottom PDF suppression, **3rd generation four-quark operators mainly contribute to 2-top production at 1-loop**:



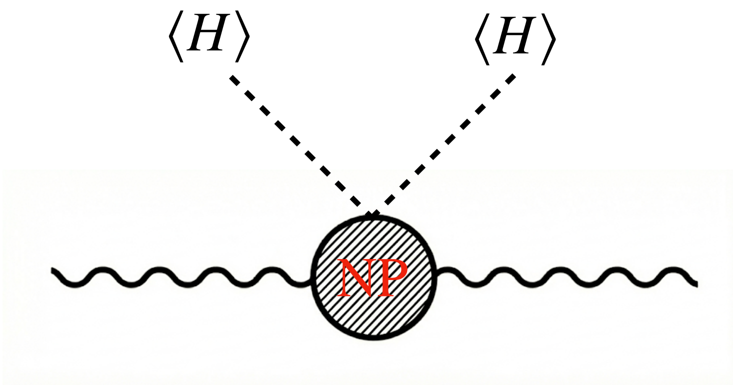
[Haisch, HEFT 2024, Precision tests of 3rd-generation four-quark SMEFT operators]

4-top operators and EW precision observables



$$Q_{HD} = |H^\dagger D_\mu H|^2$$

$\leftrightarrow$



T

- **In general the full 2-loop contribution to T takes the form of a second-order logarithmic polynomial**. E.g. for Ctt, we have:

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

[Haisch, Schnell, 2410.13304]

$c_1 = 1/2$ and $c_2 = 0\,*$

- Using the 1-loop EWPOs + 2 loop RGE, all μ-dependence drops at O($\alpha_t^2 L$):

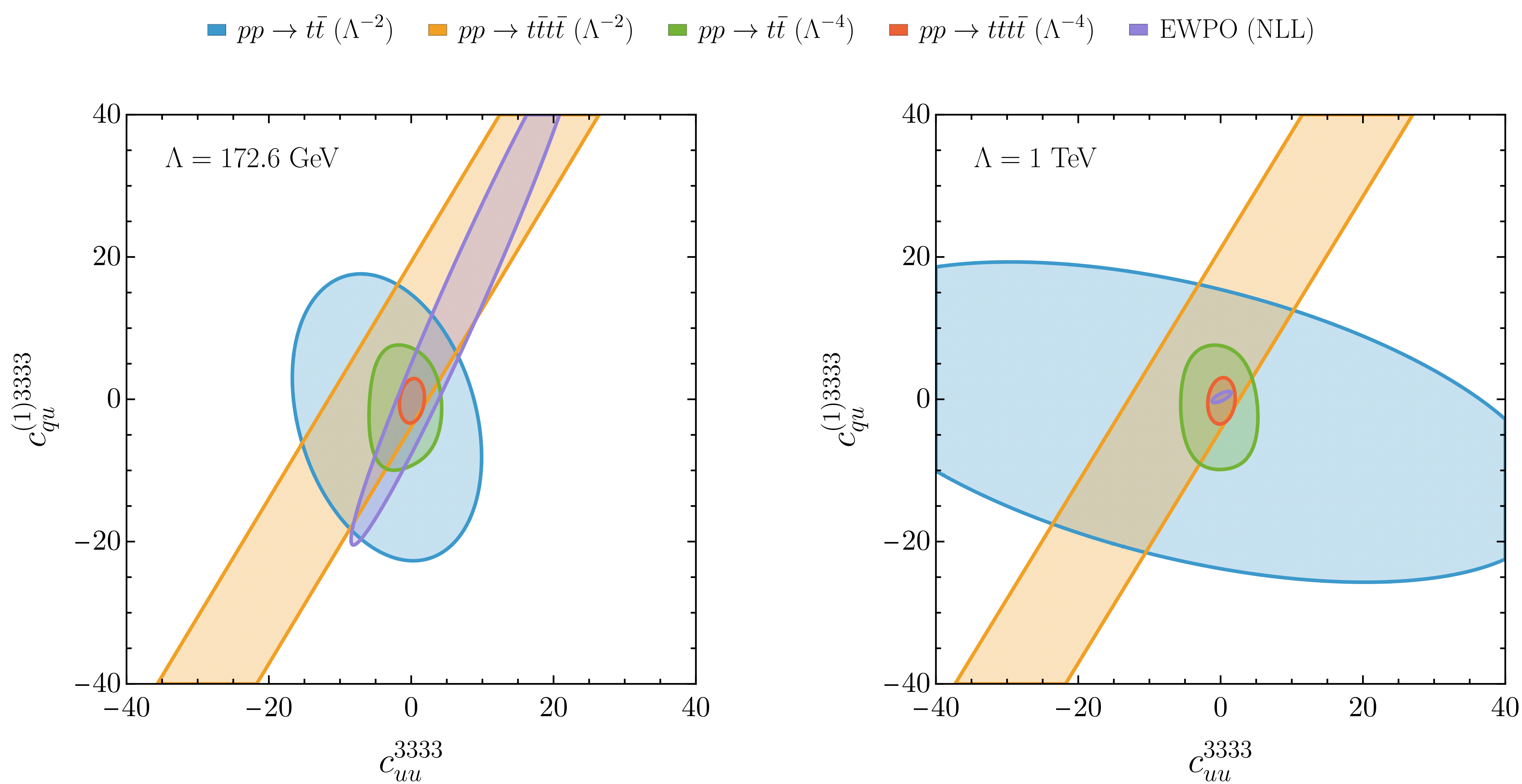
$$-\frac{2}{v^2}\hat{T} = C_{HD}(\Lambda) + \frac{3y_t^2}{4\pi^2}\log\left(\frac{\Lambda^2}{m_t^2}\right)C_{Ht}(\Lambda) + \frac{3y_t^4}{16\pi^4}\left[\log^2\left(\frac{\Lambda^2}{m_t^2}\right) - \frac{1}{2}\log\left(\frac{\Lambda^2}{m_t^2}\right)\right]C_{tt}(\Lambda)$$

[Haisch, BAS, 2608.10064]

[2-loop RGE: Born, Fuentes-Martin, Thomsen 2601.19974]

Example: 4 top operators

- Limits from top production depend strongly on the EFT truncation order, in contrast with EWPO. RGE very important for EWPOs due to the double log UV sensitivity.



[Haisch, BAS, 2608.10064]

FCC is the flagship for BSM exploration

- Wide agreement: *An e^+e^- Higgs factory is the highest priority future collider*.

Higgs Zh @ 240 GeV: 10^6 $h's$

Tera-Z program: 10^{12} $Z's$

- FCC-ee is not only a Higgs factory, but also an electroweak and flavor factory!

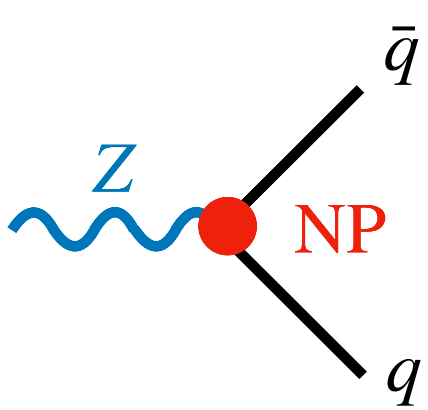
Sensitivity of the Tera-Z program

What can I do with 10^{12} Z bosons (Tera-Z)?

$$\frac{\delta g_Z}{g_Z} \sim 10^{-6} \approx \frac{v^2}{\Lambda^2} \implies \Lambda \sim 100 \text{ TeV} \quad (\text{Loops} : 10 \text{ TeV})$$

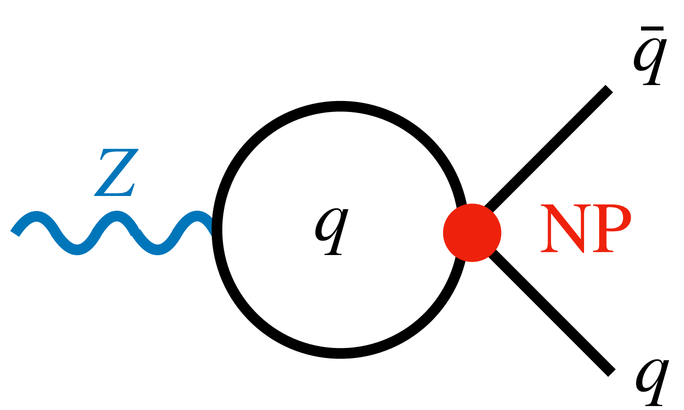
Loop contributions to Z-pole observables as sensitive as best tree-level Higgs measurements!

Tree level (LO)



$$O_{Hq}^{(1)} = (H^\dagger D_\mu H)(\bar{q}_i \gamma^\mu q_i)$$

One loop (NLO)



$$O_{qq}^{(1)} = (\bar{q}_i \gamma_\mu q_i)(\bar{q}_j \gamma^\mu q_j)$$

EW precision observables beyond 1-loop

- Can combine 1-loop fixed-order predictions with the 2-loop RGE to improve EWPOs to next-to-leading logarithmic accuracy. All ops $\gtrsim 1\ \mathrm{TeV}$ at Tera-Z.

Tree level

Leading-log effect

Next-to-leading log effect

H^6 and H^4D^2	
Q_H	$(H^\dagger H)^3$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\lvert H^\dagger D_\mu H\rvert^2$

ψ^2H^3 and ψ^2XH	
Q_{uH}^{33}	$(H^\dagger H)(\bar q_3 u_3 \widetilde H)$
Q_{uB}^{33}	$(\bar q_3\sigma^{\mu\nu}u_3\widetilde H)B_{\mu\nu}$
Q_{uW}^{33}	$(\bar q_3\sigma^{\mu\nu}\tau^I u_3\widetilde H)W^I_{\mu\nu}$
Q_{uG}^{33}	$(\bar q_3\sigma^{\mu\nu}T^A u_3\widetilde H)G^A_{\mu\nu}$

ψ^2H^2D		X^2H^2 and X^3	
$Q_{H\ell}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar\ell\gamma^\mu\ell)_{pp}$	Q_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$
$Q_{H\ell}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar\ell\tau^I\gamma^\mu\ell)_{pp}$	Q_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e\gamma^\mu e)_{pp}$	Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q\gamma^\mu q)_{pp}$	Q_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q\tau^I\gamma^\mu q)_{pp}$	Q_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u\gamma^\mu u)_{pp}$	Q_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d\gamma^\mu d)_{pp}$		

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
$Q_{\ell\ell}$	$(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell)_{\substack{pprr\\prrp}}$	Q_{ee}	$(\bar e\gamma_\mu e)(\bar e\gamma^\mu e)_{pprr}$	$Q_{\ell e}$	$(\bar\ell\gamma_\mu\ell)(\bar e\gamma^\mu e)_{pprr}$
$Q_{qq}^{(1)}$	$(\bar q\gamma_\mu q)(\bar q\gamma^\mu q)_{\substack{pprr\\prrp}}$	Q_{uu}	$(\bar u\gamma_\mu u)(\bar u\gamma^\mu u)_{\substack{pprr\\prrp}}$	$Q_{\ell u}$	$(\bar\ell\gamma_\mu\ell)(\bar u\gamma^\mu u)_{pprr}$
$Q_{qq}^{(3)}$	$(\bar q\gamma_\mu\tau^I q)(\bar q\gamma^\mu\tau^I q)_{\substack{pprr\\prrp}}$	Q_{dd}	$(\bar d\gamma_\mu d)(\bar d\gamma^\mu d)_{\substack{pprr\\prrp}}$	$Q_{\ell d}$	$(\bar\ell\gamma_\mu\ell)(\bar d\gamma^\mu d)_{pprr}$
$Q_{\ell q}^{(1)}$	$(\bar\ell\gamma_\mu\ell)(\bar q\gamma^\mu q)_{pprr}$	Q_{eu}	$(\bar e\gamma_\mu e)(\bar u\gamma^\mu u)_{pprr}$	Q_{qe}	$(\bar q\gamma_\mu q)(\bar e\gamma^\mu e)_{pprr}$
$Q_{\ell q}^{(3)}$	$(\bar\ell\gamma_\mu\tau^I\ell)(\bar q\gamma^\mu\tau^I q)_{pprr}$	Q_{ed}	$(\bar e\gamma_\mu e)(\bar d\gamma^\mu d)_{pprr}$	$Q_{qu}^{(1)}$	$(\bar q\gamma_\mu q)(\bar u\gamma^\mu u)_{pprr}$
		$Q_{ud}^{(1)}$	$(\bar u\gamma_\mu u)(\bar d\gamma^\mu d)_{pprr}$	$Q_{qu}^{(8)}$	$(\bar q\gamma_\mu T^A q)(\bar u\gamma^\mu T^A u)_{pprr}$
		$Q_{ud}^{(8)}$	$(\bar u\gamma_\mu T^A u)(\bar d\gamma^\mu T^A d)_{pprr}$	$Q_{qd}^{(1)}$	$(\bar q\gamma_\mu q)(\bar d\gamma^\mu d)_{pprr}$
				$Q_{qd}^{(8)}$	$(\bar q\gamma_\mu T^A q)(\bar d\gamma^\mu T^A d)_{pprr}$

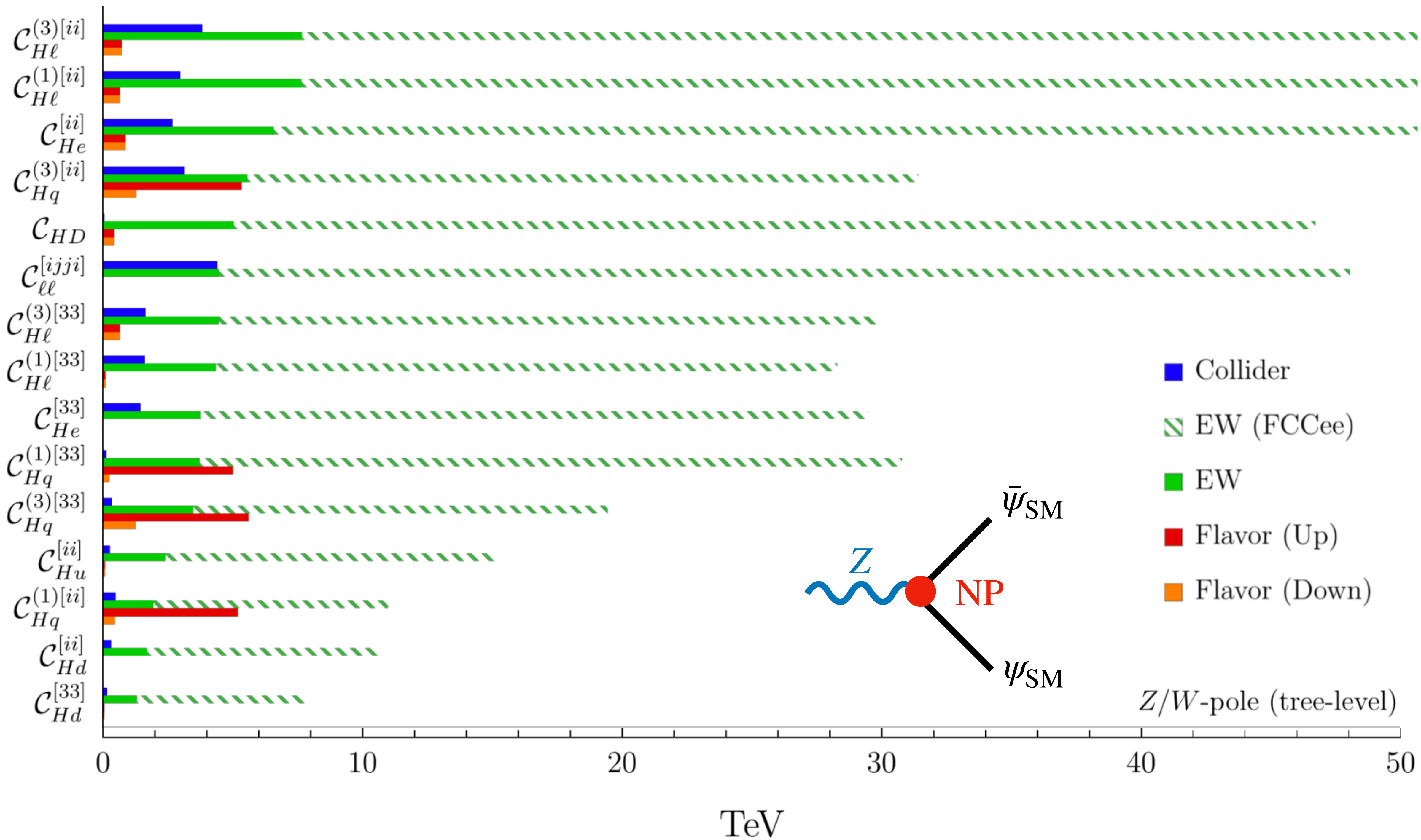
[Haisch, BAS, 2608.10064]

[Born, Fuentes-Martin, Thomsen 2601.19974, Biekötter, Pecjak 2503.07724, Bellafronte, Dawson, Giardino 2304.00029]

Tera-Z at Tree Level (S1)

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

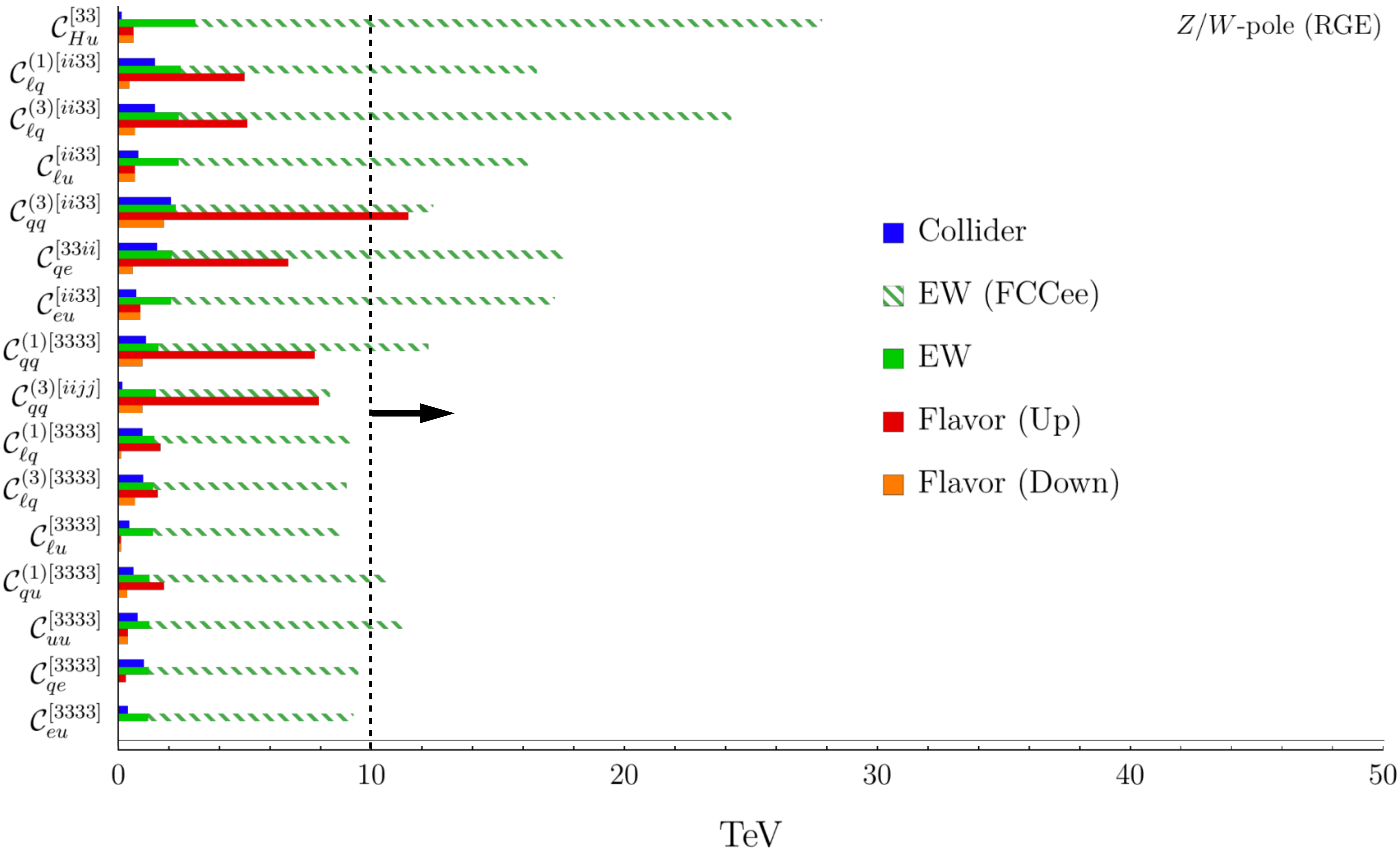
- Here are the Wilson coefficients entering the Z-pole at tree level in the $U(2)^5$ limit.



Loops at Tera-Z (S1)

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

- Top loops bring 10 TeV+ sensitivity, due to large RGE effects with top Yukawa



Loops at Tera-Z (S1)

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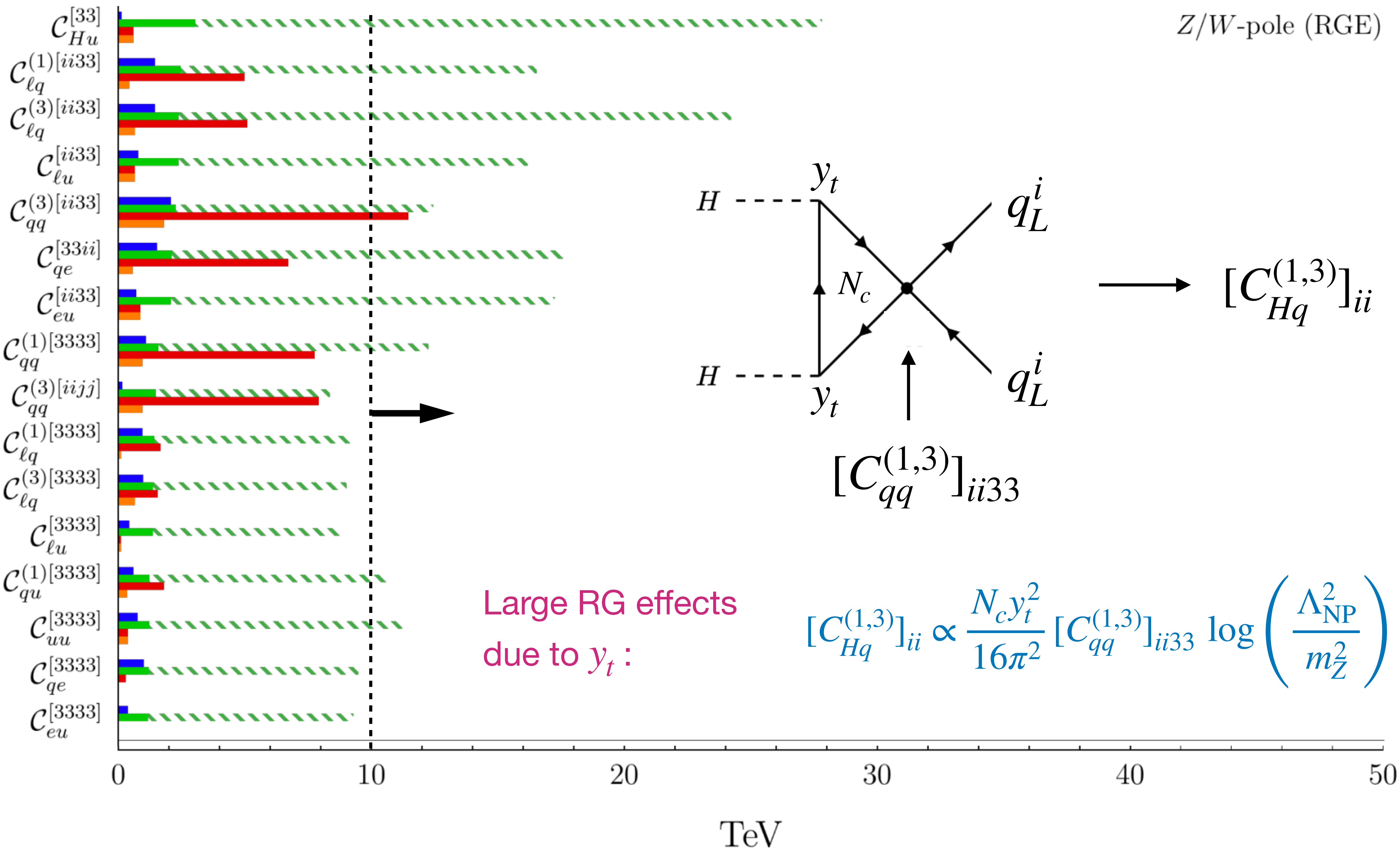


Large RG effects due to y_t :

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

Conclusions

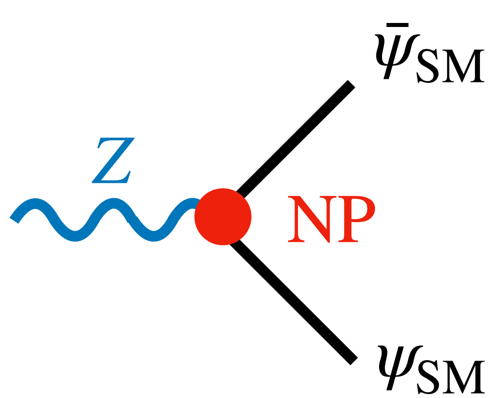
- We are still searching for a microscopic theory of the Higgs! The next 20 years will see a broad precision program with HL-LHC → FCC.
- Flavor data tells us that NP at the TeV scale has to be organized according to approximate global symmetries in the IR.
- Minimal flavor protection (MFP) identifies a core 180 CP-even operators that TeV scale BSM can populate with O(1) Wilson coefficients.
- These operators have the right structure to run into EW precision observables- almost all are probed at NLL precision.
- FCC-ee sensitivity in the 1-10+ TeV range. I think such a broad precision program is the best way forward as we don't know where NP is.

Backup

Estimating BSM sensitivity at FCC-ee

- What is the BSM reach of Higgs coupling measurements? $(\delta\kappa \sim v^2 C/g_{\mathrm{SM}})$

hZZ (0.1%)	hbb (0.36%)	htt (1%)	hhh (11%)
$\frac{1}{\Lambda^2}\partial_\mu \lvert H\rvert^2 \partial^\mu \lvert H\rvert^2$	$\frac{y_b}{\Lambda^2}\lvert H\rvert^2 \bar{q}_L^3 H b_R$	$\frac{y_t}{\Lambda^2}\lvert H\rvert^2 \bar{q}_L^3 \tilde{H} t_R$	$\frac{\lambda}{\Lambda^2}\lvert H\rvert^6$
$\Lambda \gtrsim 7.8$ TeV	$\Lambda \gtrsim 4.1$ TeV	$\Lambda \gtrsim 2.5$ TeV	$\Lambda \gtrsim 750$ GeV
BSM "enhancement":	$(\Lambda \gtrsim 25$ TeV$)$	——	$(\Lambda \gtrsim 2$ TeV$)$



$$\frac{1}{\Lambda^2}(H^\dagger D_\mu H)(\bar{\psi}\gamma^\mu\psi)$$

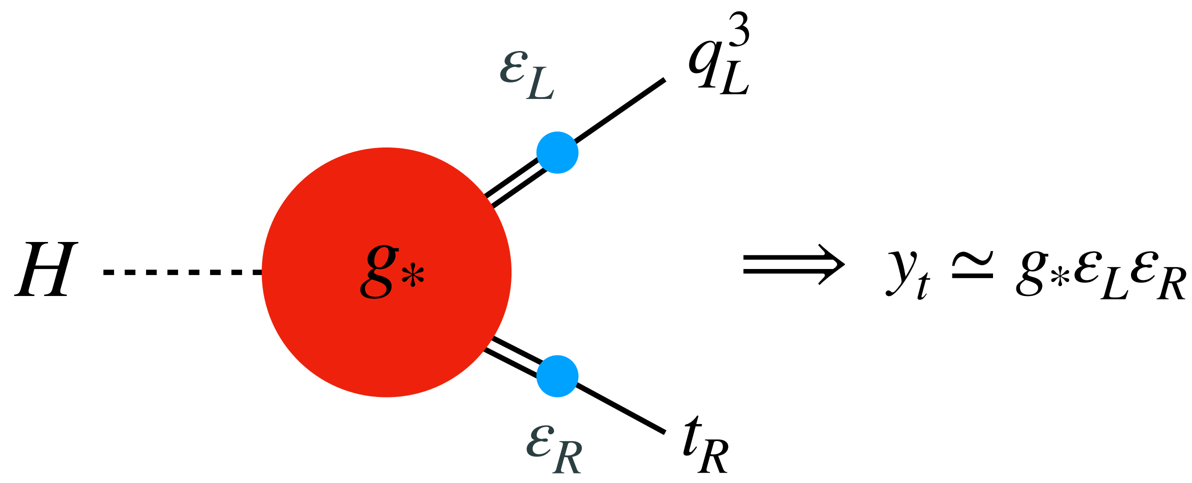
But what can I do with 10^{12} Z bosons (Tera-Z)?

$$\frac{\delta g_Z}{g_Z} \sim 10^{-6} \approx \frac{v^2}{\Lambda^2} \implies \Lambda \sim 100\ \mathrm{TeV} \quad (\mathrm{Loops}:\ 10\ \mathrm{TeV})$$

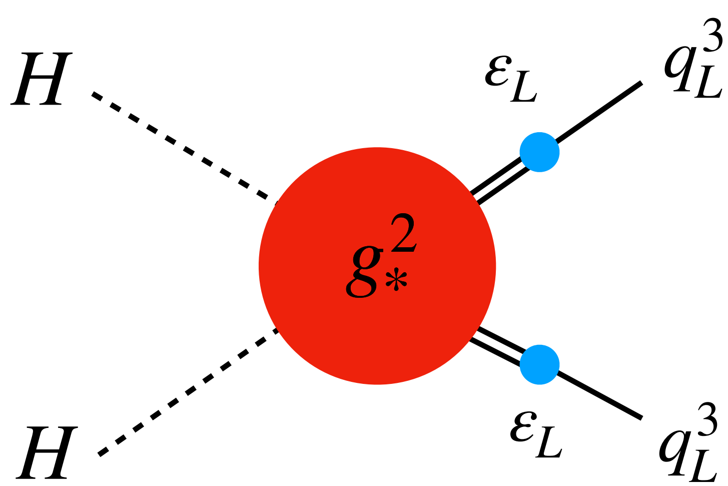
Loop contributions to Z-pole observables as sensitive as tree-level Higgs measurements!

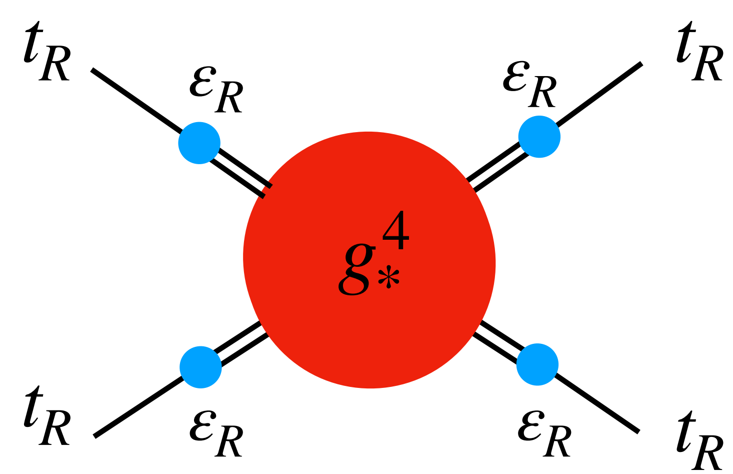
Example: 4 top operators in CHM

- The Higgs is a pNGB of a composite sector described by coupling g_* and mass scale m_*. The top must have sizable mixing!



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



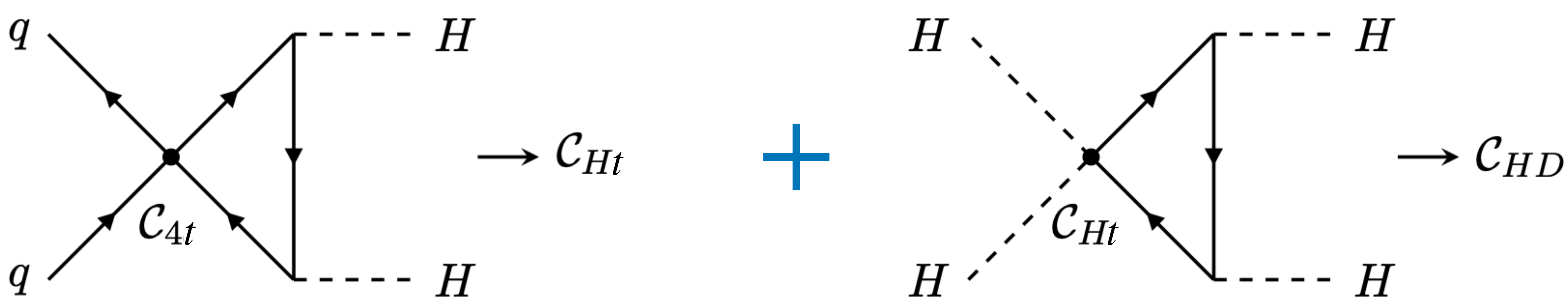


$$\mathcal{O}_{Hq}^{(1)} = (H^\dagger D_\mu H)(\bar{q}_L^3\gamma^\mu q_L^3)$$

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

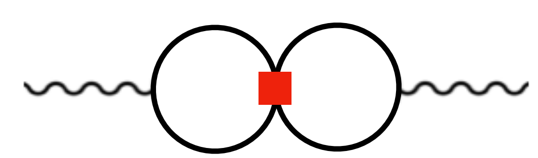
Example: 4 top operators

- These 4 top operators also contribute to EWPO at loop level. In the case of the 4-t_R operator, the leading contribution is a 2-loop effect. Resummed RGE: $(\alpha \log)^n$



This $\alpha_t^2 \log^2$ effect allows EWPO to gain sensitivity to 4-t_R operators!

EW broken phase



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

[BAS, 2407.09593]

Example: 4 top operators

- EWPO already gives a stronger (and more robust) limit on 4 top operators:

#	Wilson Coef.	Obs EWPO (NLL)	Λ_{bound} [TeV]	Obs Top (LHC)	Λ_{bound} [TeV]	Obs Higgs (LHC)	Λ_{bound} [TeV]	Best Dataset	Best Obs	Λ_{best} [TeV]
1	CHG	R_τ	0.17	$d\sigma_{tt}/d\cos\theta_*$ (CMS)	0.372	μ^{ZZ}_{ggF} (ATLAS)	20.872	Higgs (LHC)	μ^{ZZ}_{ggF} (ATLAS)	20.872
2	CuG[3, 3]	m_W	1.307	$d\sigma_{tt}/d\cos\theta_*$ (CMS)	1.721	μ^{ZZ}_{ggF} (ATLAS)	4.364	Higgs (LHC)	μ^{ZZ}_{ggF} (ATLAS)	4.364
3	CG	R_τ	0.243	$d\sigma_{tt}/dm_{tt}$ (CMS)	2.603	μ^{ZZ}_{ggF} (ATLAS)	1.209	Top (LHC)	$d\sigma_{tt}/dm_{tt}$ (CMS)	2.603
4	Cqq1[3, 3, 3, 3]	R_μ	1.609	$\sigma_{t\bar{t}t\bar{t}}$ (ATLAS)	0.722	μ^{WW}_{VBF} (ATLAS)	0.148	EWPO (NLL)	R_μ	1.609
5	CHbox	m_W	0.962	σ^{incl}_{tt} (CMS)	0.006	$\mu^{\gamma\gamma}_{ggF}$ (ATLAS)	1.219	Higgs (LHC)	$\mu^{\gamma\gamma}_{ggF}$ (ATLAS)	1.219
6	Cqu1[3, 3, 3, 3]	m_W	1.201	$\sigma_{t\bar{t}t\bar{t}}$ (CMS)	0.554	μ^{WW}_{ggF} (ATLAS)	0.305	EWPO (NLL)	m_W	1.201
7	Cqq3[3, 3, 3, 3]	R_μ	1.107	$\sigma_{t\bar{t}t\bar{t}}$ (ATLAS)	0.854	μ^{WW}_{WH} (ATLAS)	0.082	EWPO (NLL)	R_μ	1.107
8	Cuu[3, 3, 3, 3]	m_W	1.009	$\sigma_{t\bar{t}t\bar{t}}$ (CMS)	0.724	μ^{WW}_{VBF} (ATLAS)	0.159	EWPO (NLL)	m_W	1.009
9	CuH[3, 3]	m_W	0.328	--	0	μ^{WW}_{ggF} (ATLAS)	0.954	Higgs (LHC)	μ^{WW}_{ggF} (ATLAS)	0.954
10	Cqu8[3, 3, 3, 3]	m_W	0.176	$\sigma_{t\bar{t}t\bar{t}}$ (ATLAS)	0.417	μ^{WW}_{ggF} (ATLAS)	0.29	Top (LHC)	$\sigma_{t\bar{t}t\bar{t}}$ (ATLAS)	0.417

FCC-ee Projection (S1)

#	Wilson Coef.	Obs FCCee (S1)	Λ_{bound} [TeV]	Obs Top (HL-LHC)	Λ_{bound} [TeV]	Obs Higgs (HL-LHC)	Λ_{bound} [TeV]	Best Dataset	Best Obs	Λ_{best} [TeV]
1	CHG	R_μ	1.835	$d\sigma_{tt}/dm_{tt}$ (CMS)	0.474	$\mu^{\gamma\gamma}_{ggF}$ (ATLAS HL-LHC)	34.09	Higgs (HL-LHC)	$\mu^{\gamma\gamma}_{ggF}$ (ATLAS HL-LHC)	34.09
2	Cqq1[3, 3, 3, 3]	Γ_Z	14.721	$\sigma_{t\bar{t}t\bar{t}}$ (CMS)	0.982	μ^{WW}_{VBF} (ATLAS HL-LHC)	0.331	FCCee (S1)	Γ_Z	14.721
3	Cqu1[3, 3, 3, 3]	Γ_Z	10.244	$\sigma_{t\bar{t}t\bar{t}}$ (CMS)	0.765	μ^{WW}_{ggF} (CMS HL-LHC)	0.498	FCCee (S1)	Γ_Z	10.244
4	Cqq3[3, 3, 3, 3]	Γ_Z	10.22	$\sigma_{t\bar{t}t\bar{t}}$ (CMS)	1.017	μ^{ZZ}_{ggF} (ATLAS HL-LHC)	0.197	FCCee (S1)	Γ_Z	10.22
5	CuG[3, 3]	m_W	7.877	$d\sigma_{tt}/dm_{tt}$ (CMS)	2.194	$\mu^{\gamma\gamma}_{ggF}$ (ATLAS HL-LHC)	7.624	FCCee (S1)	m_W	7.877
6	Cuu[3, 3, 3, 3]	m_W	5.968	$\sigma_{t\bar{t}t\bar{t}}$ (CMS)	0.995	μ^{WW}_{VBF} (ATLAS HL-LHC)	0.349	FCCee (S1)	m_W	5.968
7	CHbox	m_W	5.805	σ^{incl}_{tt}	0.006	$\mu^{\gamma\gamma}_{ggF}$ (ATLAS HL-LHC)	2.142	FCCee (S1)	m_W	5.805
8	CG	R_μ	2.617	$d\sigma_{tt}/dm_{tt}$ (CMS)	2.478	$\mu^{\gamma\gamma}_{ggF}$ (ATLAS HL-LHC)	2.286	FCCee (S1)	R_μ	2.617
9	CuH[3, 3]	m_W	1.953	--	0	μ^{ZZ}_{ggF} (ATLAS HL-LHC)	1.786	FCCee (S1)	m_W	1.953
10	Cqu8[3, 3, 3, 3]	m_W	1.005	$\sigma_{t\bar{t}t\bar{t}}$ (CMS)	0.551	μ^{ZZ}_{ggF} (ATLAS HL-LHC)	0.539	FCCee (S1)	m_W	1.005

Tera-Z factory brings novel precision challenges

Stat precision: $\frac{\delta O}{O} \sim 10^{-6} \approx \frac{v^2}{\Lambda^2} \implies \Lambda \sim 100\ \text{TeV} \quad (\text{Loops}: 10\ \text{TeV})$

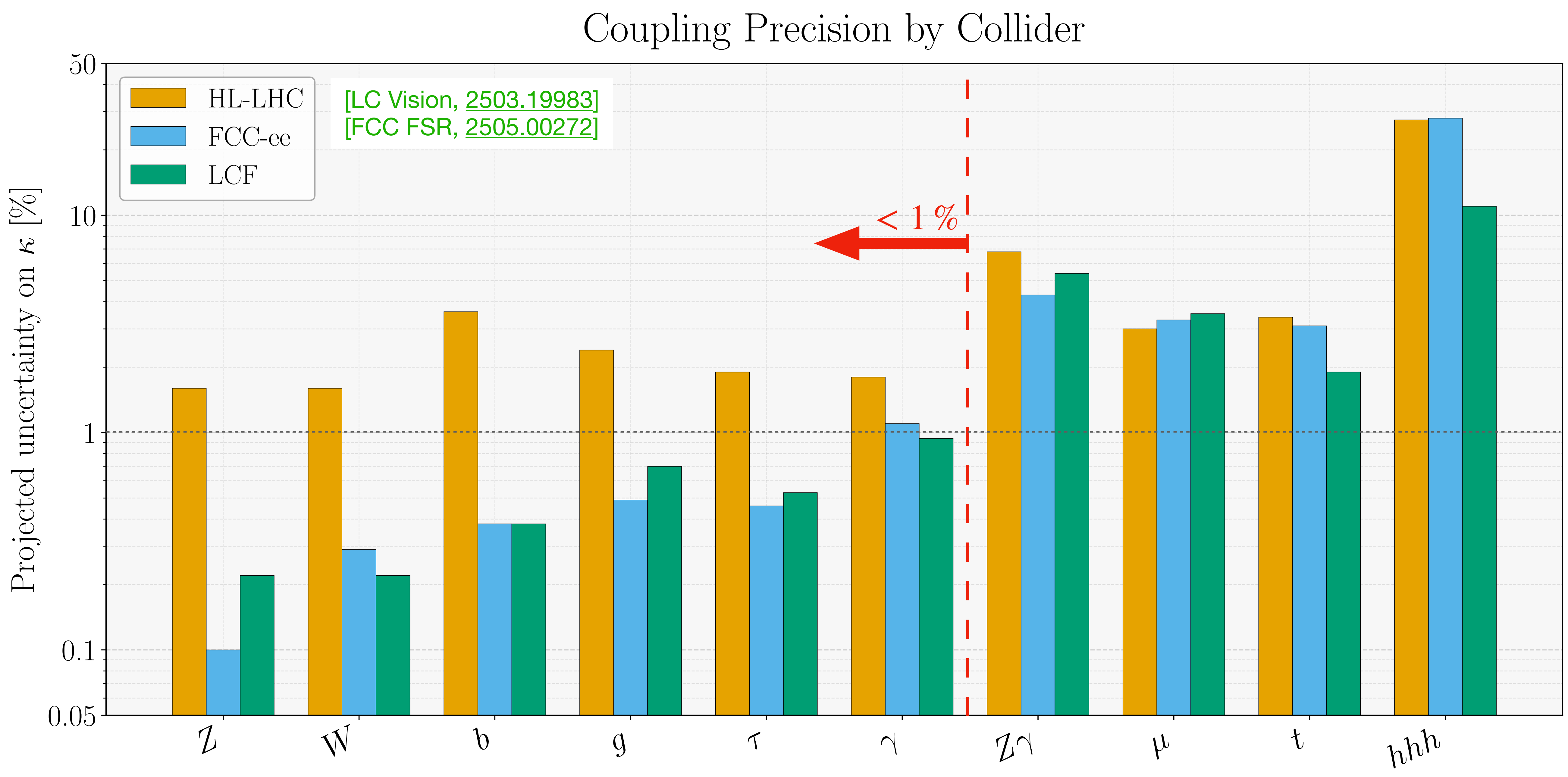
$\delta O/O \sim$	10^{-4}	10^{-5}	10^{-6}
	Scenario S1	**Scenario S2**	**Scenario S3**
Observable	**TH PO+TH agg.+EXP** (10^{-5})	**TH agg.+EXP** (10^{-5})	**EXP Only** (10^{-5})
Γ_Z	1.55	0.820	0.510
$\sigma_{\rm had}$	4.33	2.06	1.93
R_e	2.21	1.05	0.410
R_μ	2.20	1.02	0.330
R_τ	2.20	1.03	0.350
R_b	20.1	1.63	0.180
R_c	100	1.19	0.260
$A_{\rm FB}^e$	126	25.7	25.2
$A_{\rm FB}^\mu$	125	21.1	20.6
$A_{\rm FB}^\tau$	126	23.3	22.8
$A_{\rm FB}^b$	87.8	6.42	5.50
$A_{\rm FB}^c$	89.1	10.2	9.62
$A_{\rm FB}^s$	88.2	10.7	10.2
$\sin^2\theta_W$	6.87	0.780	0.730
A_e	87.9	9.78	9.20
A_μ	90.1	22.1	21.8
A_τ	90.5	23.4	23.2
A_b	11.7	10.5	10.5
A_c	16.9	9.00	8.99
A_s	14.2	13.2	13.2
M_W	0.490	0.320	0.300
Γ_W	16.1	16.1	16.1

More conservative ⟷ More aggressive

[Greljo, BAS, Valenti, 2507.03073] [FCC-ee FSR, 2505.00272] [EW PPG EWPO TH Discussion]

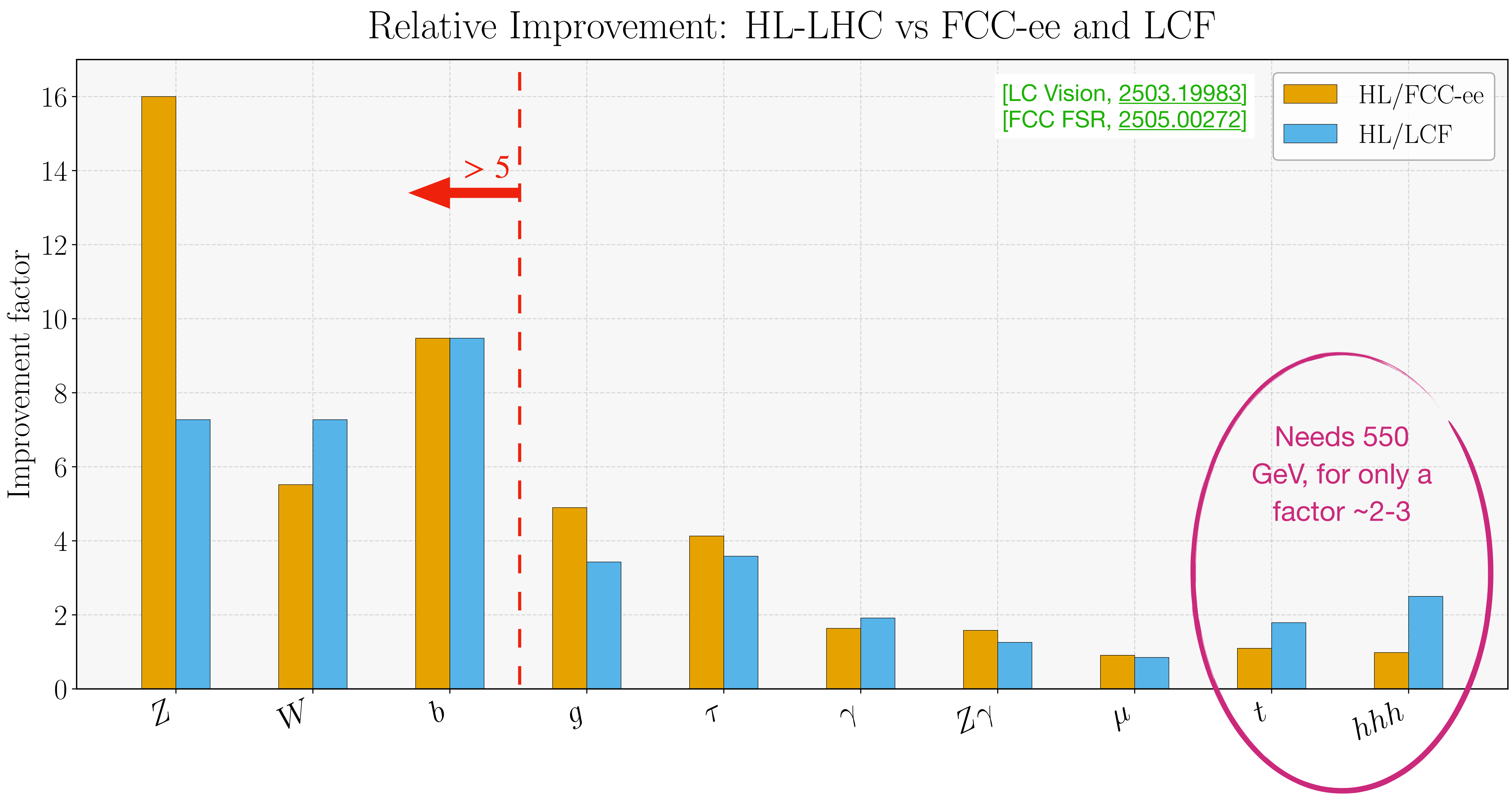
Higgs couplings at Future Colliders

- With a million Higgses, hZZ, hWW, hbb couplings reach the per-mille level.



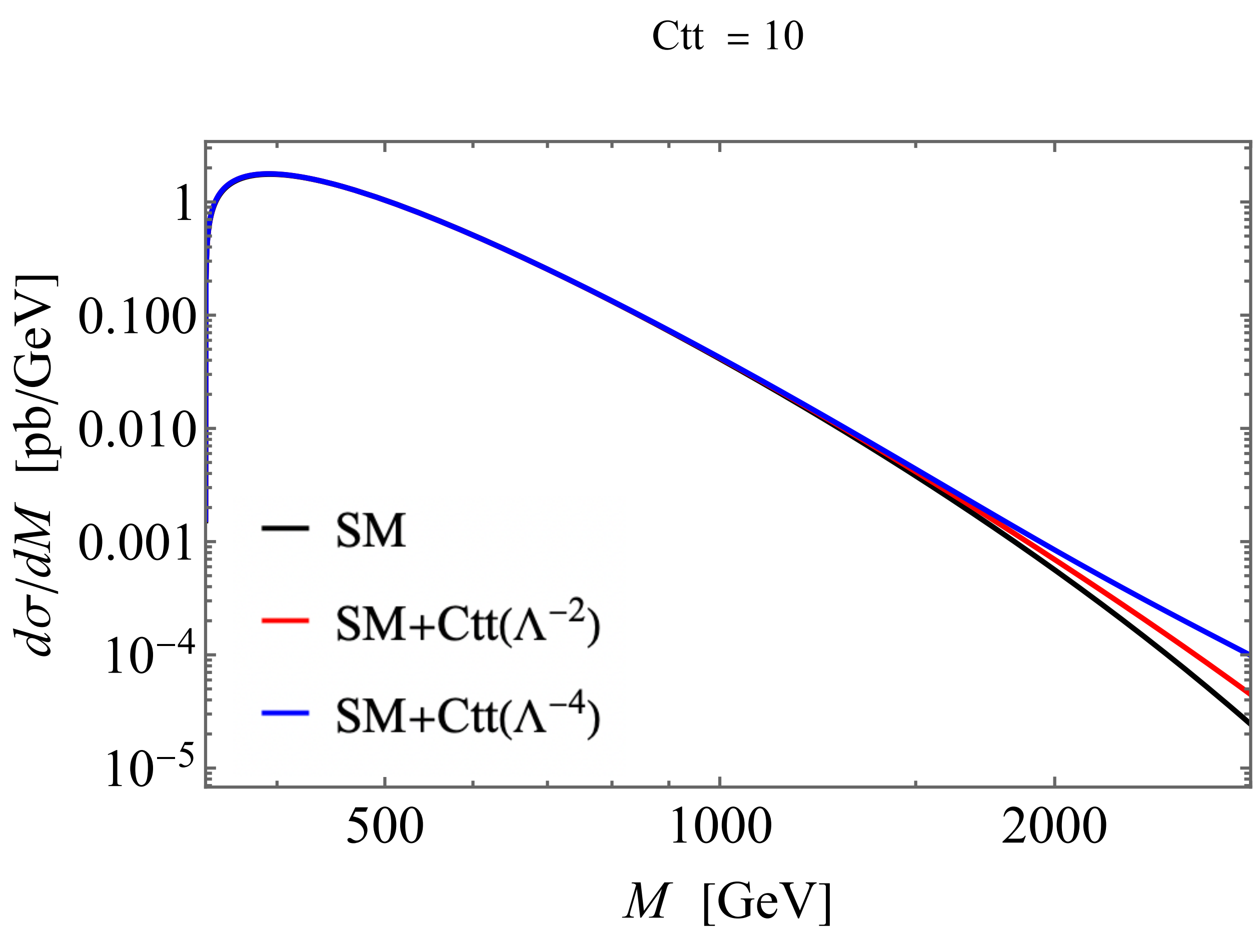
Higgs couplings: Improvement vs. HL-LHC

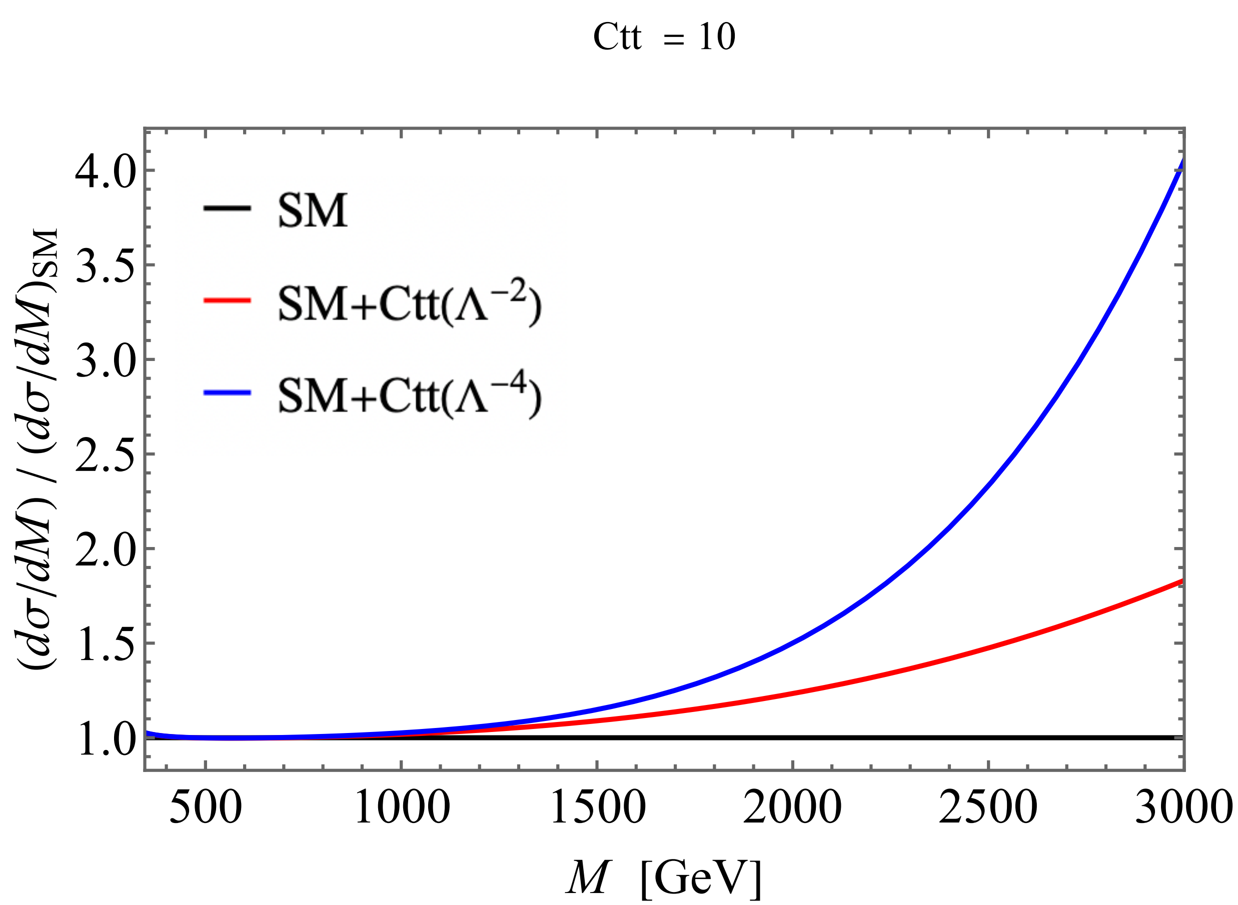
- Improvement with respect to HL-LHC is mainly concentrated in the hVV, hbb couplings. Both machines measure these well at 240 GeV!



Example: 4 top operators

- Limits on SMEFT operators from top pair production come from very high energy bins where the inclusion of quadratics has a sizable impact.

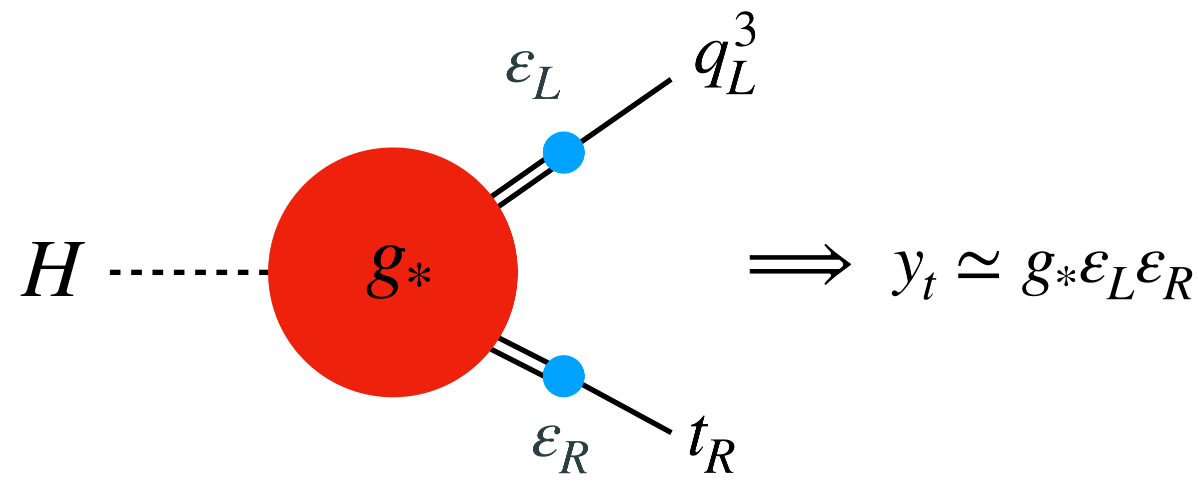




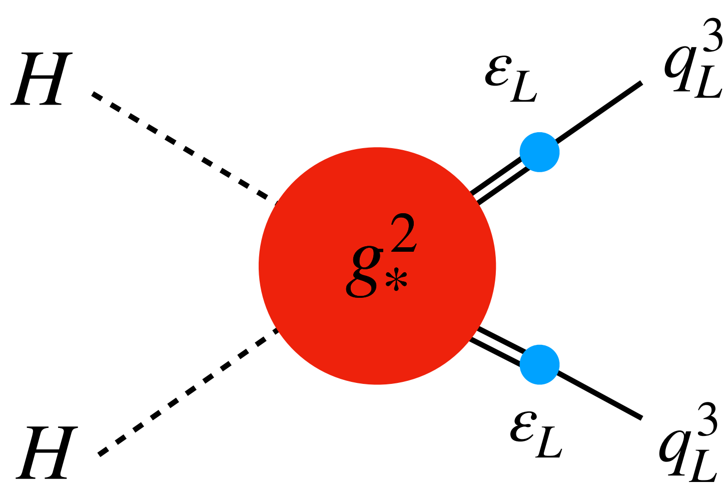
[Haisch, BAS, to appear]

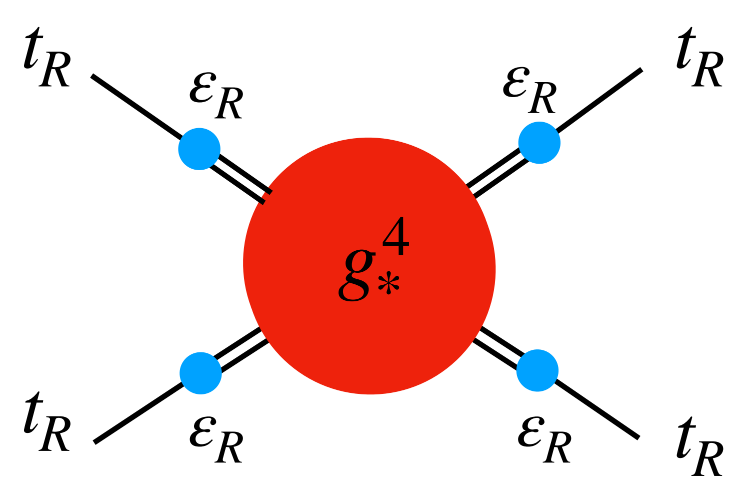
Composite Higgs models

- The Higgs is a pNGB of a composite sector described by coupling g_* and mass scale m_*. The top must have sizable mixing!



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





$$\mathcal{O}_{Hq}^{(1)} = (H^\dagger D_\mu H)(\bar{q}_L^3 \gamma^\mu q_L^3) \qquad \mathcal{O}_{tt} = (\bar{t}_R \gamma_\mu t_R)(\bar{t}_R \gamma^\mu t_R)$$

Matching to composite Higgs model parameters

- The full UV Lagrangian can be written schematically as

$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM'} + \mathcal{L}_{\rm strong} + g A_\mu^{\rm SM} J^\mu_{\rm strong} + \lambda_L \bar{q}_L^3 \mathcal{O}_L + \lambda_R \bar{t}_R \mathcal{O}_R$$

- **Integrating out all heavy composite states, the low energy theory has the form**

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

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

$$C_W g (H^\dagger D_\mu^I H) D_\nu W^{I\,\mu\nu} \implies C_W \sim \frac{m_*^4}{g_*^2}\frac{g_*^2}{m_*^4}\frac{1}{m_*^2} = \frac{1}{m_*^2} \qquad \text{(S-parameter)}$$

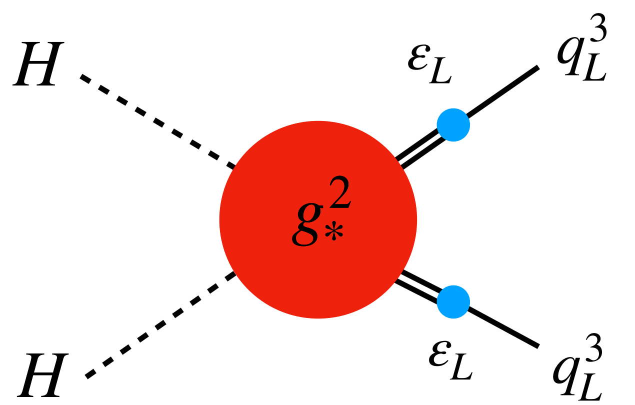
$$C_{tt}(\bar{t}_R\gamma_\mu t_R)(\bar{t}_R\gamma_\mu t_R) \implies C_{tt} \sim \frac{m_*^4}{g_*^2}\frac{\lambda_R^4}{m_*^6} = \frac{\lambda_R^4}{g_*^2 m_*^2} = \frac{g_*^2}{m_*^2}\epsilon_R^4 \qquad \text{(}4t_R\text{ operator)}$$

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

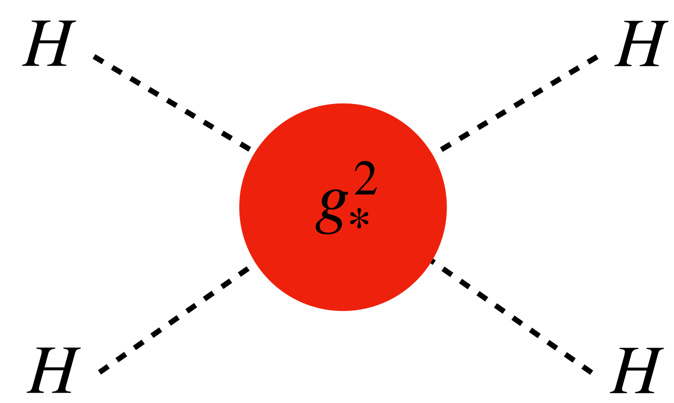
[G. F. Giudice, C. Grojean, A. Pomarol, R. Rattazzi, hep-ph/0703164]

Composite Higgs model building

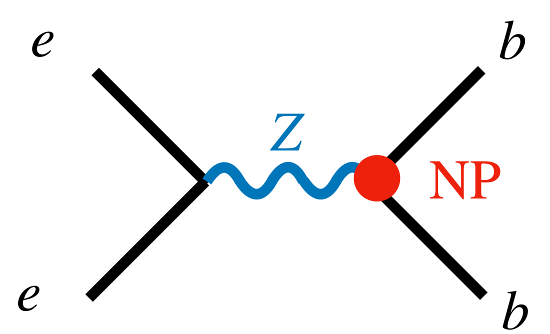
- Composite Higgs models without custodial symmetry face severe constraints:



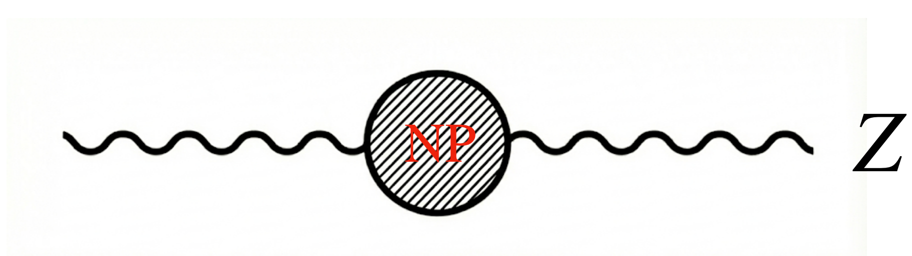
$$\frac{g_*^2 \epsilon_L^2}{m_*^2}(H^\dagger D_\mu H)(\bar{q}_L^3 \gamma^\mu q_L^3)$$



$$\frac{g_*^2}{m_*^2}|H^\dagger D_\mu H|^2$$



$$\delta g_Z^{b_L b_L} \propto C_{Hq}^{(1)} + C_{Hq}^{(3)}$$

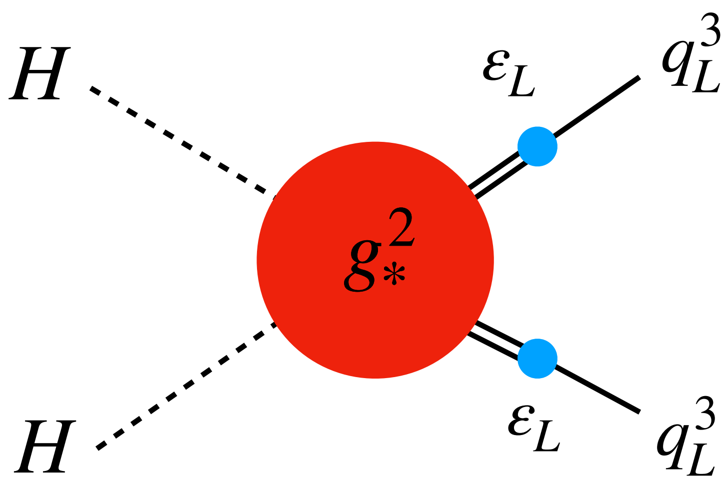


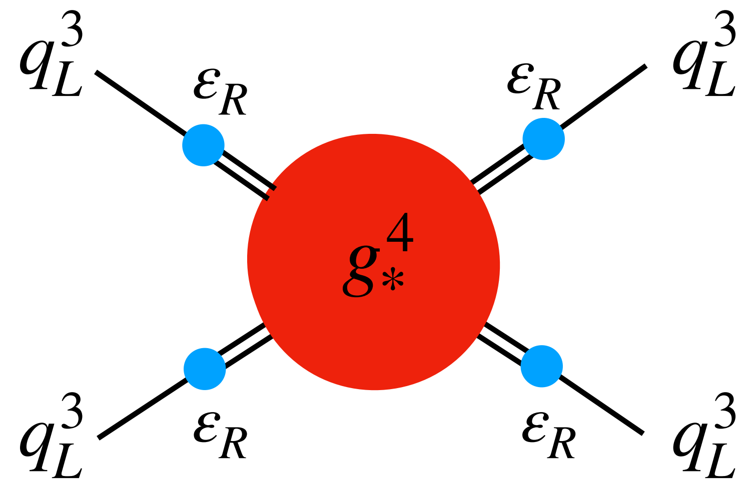
$$T = -\frac{v^2}{2} C_{HD}$$

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

Composite Higgs model building

- But, custodial symmetry does not forbid large top operators:

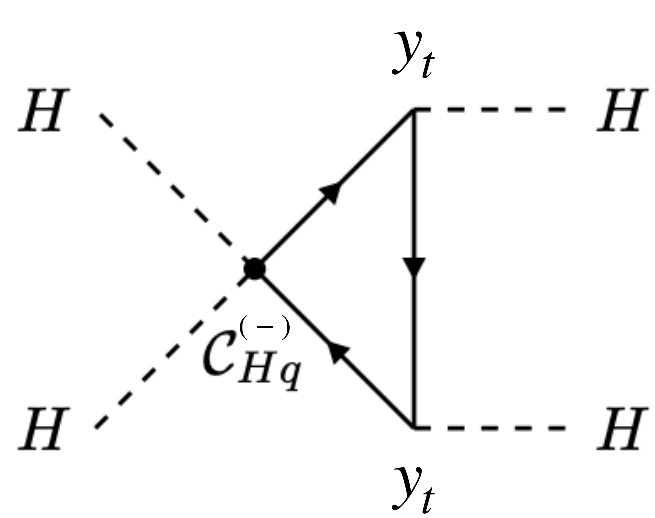




$$\delta g_Z^{t_L t_L} \propto C_{Hq}^{(1)} - C_{Hq}^{(3)} \propto \frac{g_*^2 \epsilon_L^2}{m_*^2}$$

$$C_{qq}, C_{tt} \propto \frac{g_*^2 \epsilon_L^4}{m_*^2}, \frac{g_*^2 \epsilon_R^4}{m_*^2}$$

- SM loops unavoidably break custodial symmetry: $y_t \sim O(1) \gg y_b$.



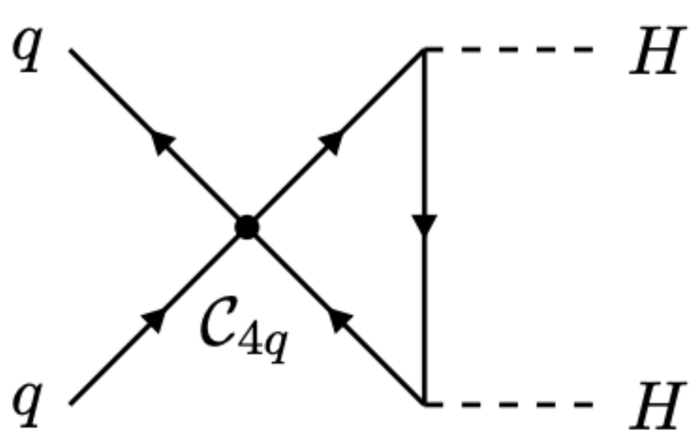
$\rightarrow T$

[BAS, 2407.09593]

Top loops in composite Higgs models

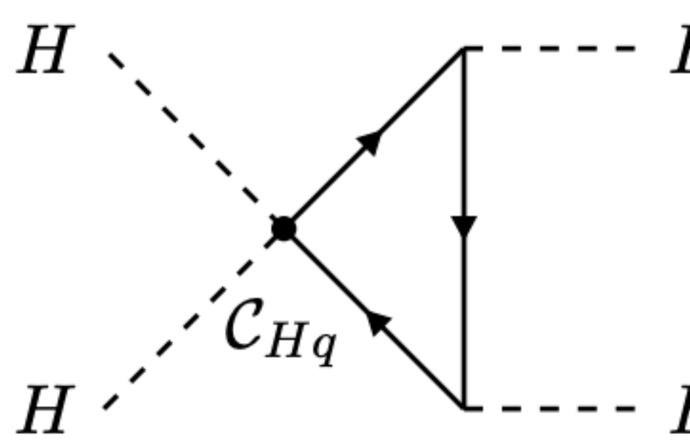
- The most dangerous operators are re-generated via RGE as we run from m_* down to the EW scale!

Top Yukawa loops give large effects $\propto N_c y_t^2 \log(m_Z^2/m_*^2)$



4-top operators running into Zbb 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.

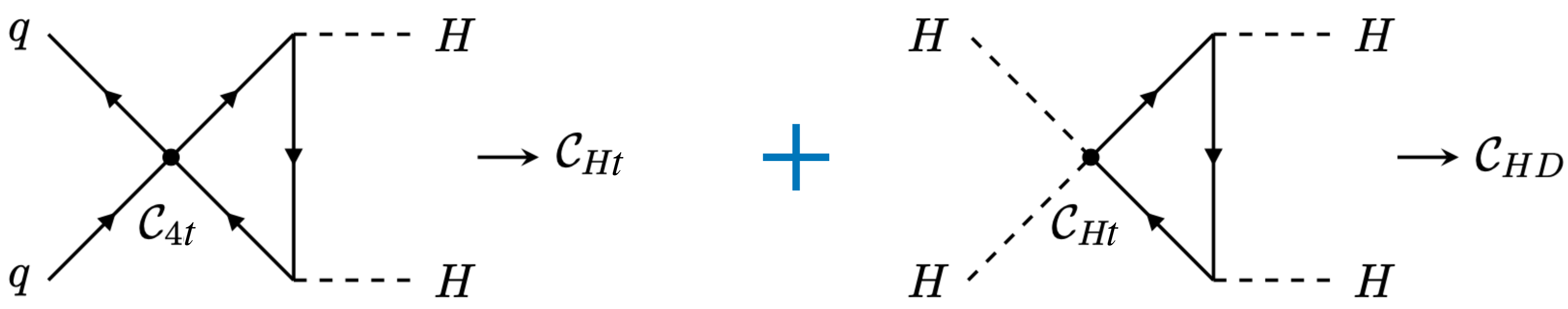
$$\mathcal{O}_{Hq}^{(1)}, \mathcal{O}_{Ht} \to \mathcal{O}_{HD}$$

Irreducible RG effects! Cannot be avoided with clever model building!

[BAS, 2407.09593]

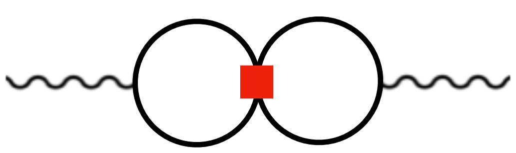
2-loop sensitivity to 4-top operators

- Some important effects occur only beyond the first leading-log approx. Integrating the 1-loop RG equations resums higher loop effects of the form $(\alpha \log)^n$:



This $\alpha_t^2 \log^2$ effect allows EWPO to gain sensitivity to 4-t_R operators!

EW broken phase

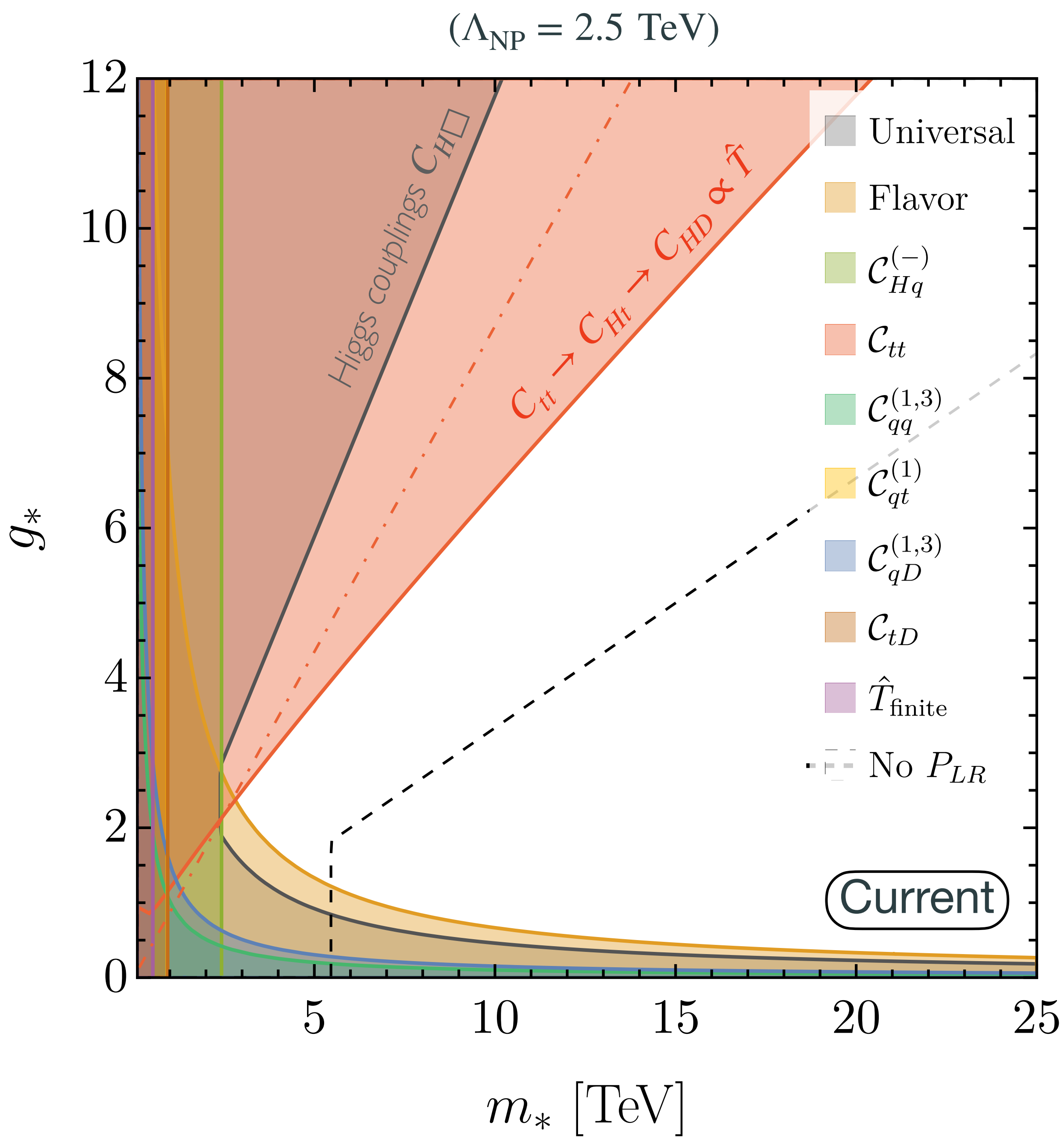


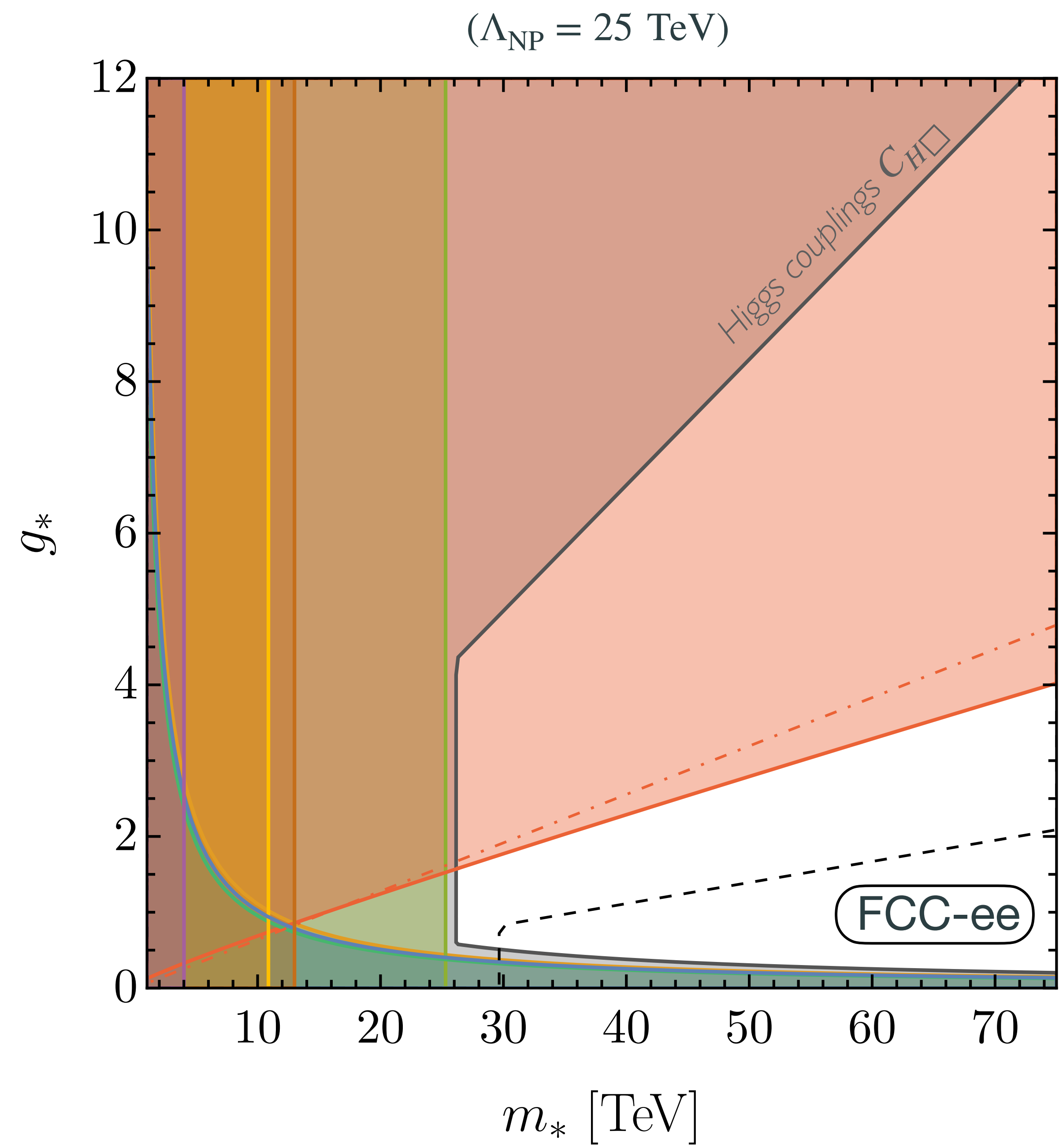
$$[\mathcal{C}_{HD}] = \frac{2N_c\, y_t^4}{(16\pi^2)^2}\left[(1+2N_c)\mathcal{C}_{qq}^{(1)} + 3\mathcal{C}_{qq}^{(3)} + 2(1+N_c)\mathcal{C}_{tt} - 2N_c\mathcal{C}_{qt}^{(1)}\right]\log^2\left(\frac{\mu^2}{m_*^2}\right)$$

[BAS, 2407.09593]

Results: Right compositeness (lowest NP scale)

- 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]

A novel probe of composite Higgs models!

Right-handed rotations

- Ok so we need $SU(2)_q$. But what about $U(2)_u \times U(2)_d$? In general, RH rotations are not fixed, but they cannot be smaller than chirally-suppressed LH ones:

$$Y_{u,d} \sim \begin{pmatrix} \times & \times & \times \\ 0 & \times & \times \\ 0 & 0 & \times \end{pmatrix} \qquad \Longrightarrow \quad \theta_R^{ij} \approx \frac{m_i}{m_j}\theta_L^{ij} \quad (i < j)$$

Light mass ratios: $\quad m_d/m_s \approx 5 \times 10^{-2} \qquad m_u/m_c \approx 2 \times 10^{-3}$

$$\bar{K} - K: \quad \frac{(a-b)^2\lambda^2}{\Lambda^2}\frac{m_d^2}{m_s^2}(\bar{d}_1 d_2)^2 \lesssim \frac{1}{(2 \times 10^4\ \text{TeV})^2} \quad \Longrightarrow \; |a-b| \lesssim 0.05\left(\frac{\Lambda}{10\ \text{TeV}}\right)$$

$$\bar{D} - D: \quad \frac{(a-b)^2\lambda^2}{\Lambda^2}\frac{m_u^2}{m_c^2}(\bar{u}_1 u_2)^2 \lesssim \frac{1}{(2 \times 10^4\ \text{TeV})^2} \quad \Longrightarrow \; |a-b| \lesssim O(1)\left(\frac{\Lambda}{10\ \text{TeV}}\right)$$

**$U(2)_{u,d}$ could be broken at 10 TeV if the Cabibbo angle comes mostly from L_u.

(Limits are weaker by a factor ~20 if the rotation is real)

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection: Lepton Yukawas

- Start with lepton Yukawas, which require just a single spurion:

$$z \sim (\mathbf{1}, X_z) \qquad [l_i] = X_i\,, \qquad [e_i] = X_i - (4-i)X_z$$

- For $z \approx 2 \times 10^{-2}$, we get a Froggatt-Nielsen like solution for lepton Yukawas

$$Y_e = \begin{pmatrix} y_1^e z^3 & 0 & 0 \\ 0 & y_2^e z^2 & 0 \\ 0 & 0 & y_3^e z \end{pmatrix}$$

Off-diagonals and cLFV forbidden if:

$$(X_i - X_j) \bmod X_z \neq 0 \quad \forall\, i \neq j$$

- What about neutrinos? In general, we would also imprint hierarchies there

$$\mathscr{L}_{d=5} = C_{ij} \frac{z^{N_{ij}}}{\Lambda} \bar{l}_i^c l_j HH$$

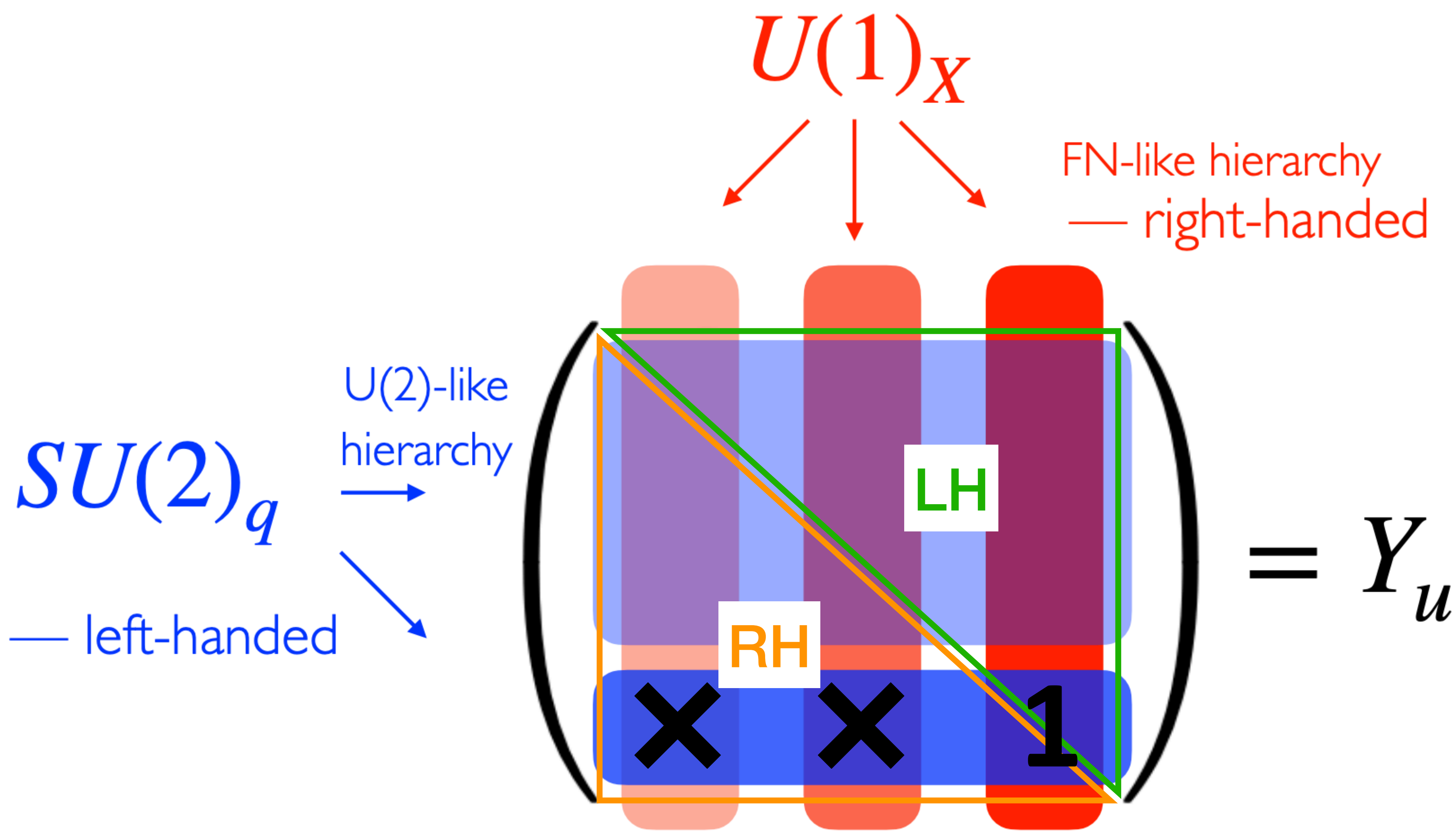
Weinberg operator forbidden if:

$$(X_i + X_j) \bmod X_z \neq 0 \quad \forall\, i, j$$

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection: Quark Yukawas

- Quark Yukawas arise essentially as hybrid between $U(2)$ and Froggatt-Nielson:



✕ *Cannot be populated if $Y_{u,d}$ arise from $SU(2)_q$-doublet spurions*

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection: Quark Yukawas

- The quark Yukawas require a minimum of three $SU(2)_q$-doublet spurions:

$SU(2)_q$ spurions: $\boldsymbol{V} \sim (\mathbf{2}, X_V) \quad \boldsymbol{W} \sim (\mathbf{2}, X_W), \quad \boldsymbol{U} \sim (\mathbf{2}, X_U)$

Quarks	$d_1,\ u_1$	d_2	u_2	d_3	$q_3,\ u_3$
$U(1)_X$ charge	$-X_V - 2X_z$	$X_V + X_z$	$-X_W$	$X_z - X_U$	$2X_z - X_U$

- With these charges, the up and down Yukawas have the following texture:

$$Y_u = \begin{pmatrix} \boldsymbol{V} \boldsymbol{z}^2 & \boldsymbol{W} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad Y_d = \begin{pmatrix} \boldsymbol{V} \boldsymbol{z}^2 & \widetilde{\boldsymbol{V}} \boldsymbol{z}^* & \boldsymbol{U} \boldsymbol{z}^* \\ 0 & 0 & \boldsymbol{z} \end{pmatrix}$$

$$\widetilde{\boldsymbol{V}} = i\sigma_2 \boldsymbol{V}^*$$

[Greljo, Palavrić, BAS, 2512.04159]

Minimal Flavor Protection: Quark Yukawas

$$Y_u = \begin{pmatrix} \boldsymbol{V} \boldsymbol{z}^2 & \boldsymbol{W} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad Y_d = \begin{pmatrix} \boldsymbol{V} \boldsymbol{z}^2 & \widetilde{\boldsymbol{V}} \boldsymbol{z}^* & \boldsymbol{U} \boldsymbol{z}^* \\ 0 & 0 & \boldsymbol{z} \end{pmatrix}.$$

- Without loss of generality, we can choose a basis where:

$$\boldsymbol{z} = z, \quad \boldsymbol{V} = v \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \boldsymbol{W} = w \begin{pmatrix} \sin\alpha \\ \cos\alpha \end{pmatrix}, \quad \boldsymbol{U} = u \begin{pmatrix} \sin\beta \, e^{i\phi} \\ \cos\beta \end{pmatrix}$$

12 down alignment

$\tan\alpha \approx V_{us}/V_{cs}$

$\tan\beta e^{i\phi} \approx V_{td}^*/V_{ts}^*$

All mass hierarchies explained for $v, w, u, z \sim \mathcal{O}(10^{-2})$ ✔

11 hierarchical SM parameters traded for 4 of the same order!
Towards a solution to the SM flavor puzzle…

[Greljo, Palavrić, BAS, 2512.04159]