Precision probes of BSM physics at FCC-ee

Ben Stefanek

IFIC Valencia

Particle Physics at Crossroads
Sapporo, Hokkaido
March 3rd, 2026

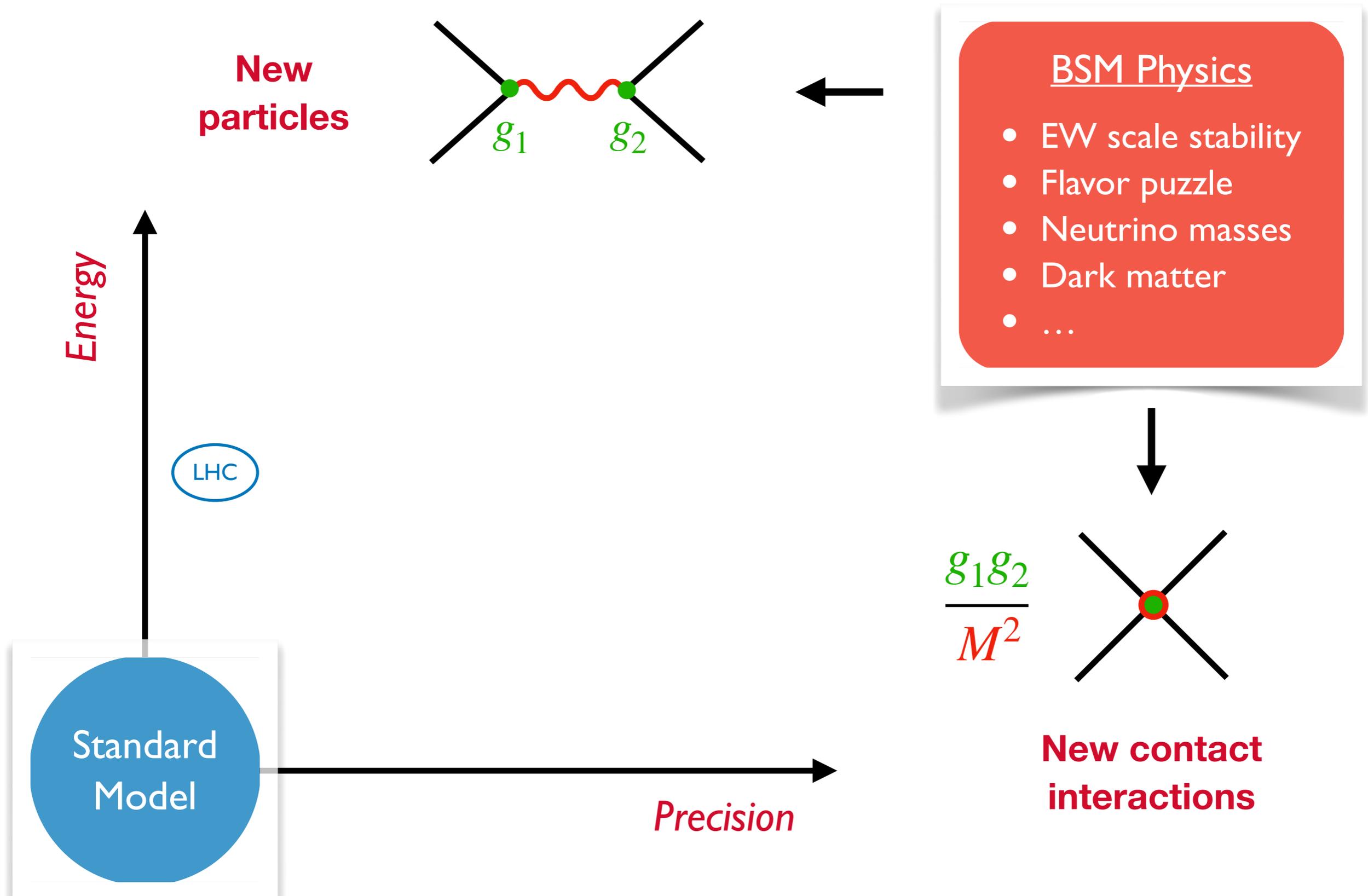# A global strategy for collider physics

New particles

g_1 g_2

Energy

LHC

BSM Physics

- EW scale stability
- Flavor puzzle
- Neutrino masses
- Dark matter
- ...

Standard Model

Precision

$$\frac{g_1 g_2}{M^2}$$

New contact interactions

A global strategy for collider physics

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Next 20 years

LHC

HiLumi
HL-LHC PROJECT

FCC
ee

B
Belle II

Mu2e, Mu3e, COMET, ACME, BES III + …

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Higgs

EW   Flavor

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Ultimately: 10 TeV $pp, \ell\ell, \gamma\gamma$

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$$\frac{g_1 g_2}{M^2}$$

New contact interactions

FCC is the flagship for BSM exploration

- FCC-ee is not only a Higgs factory!

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

EW   **Flavor**

Tera-Z program: $10^{12} \ Z's$
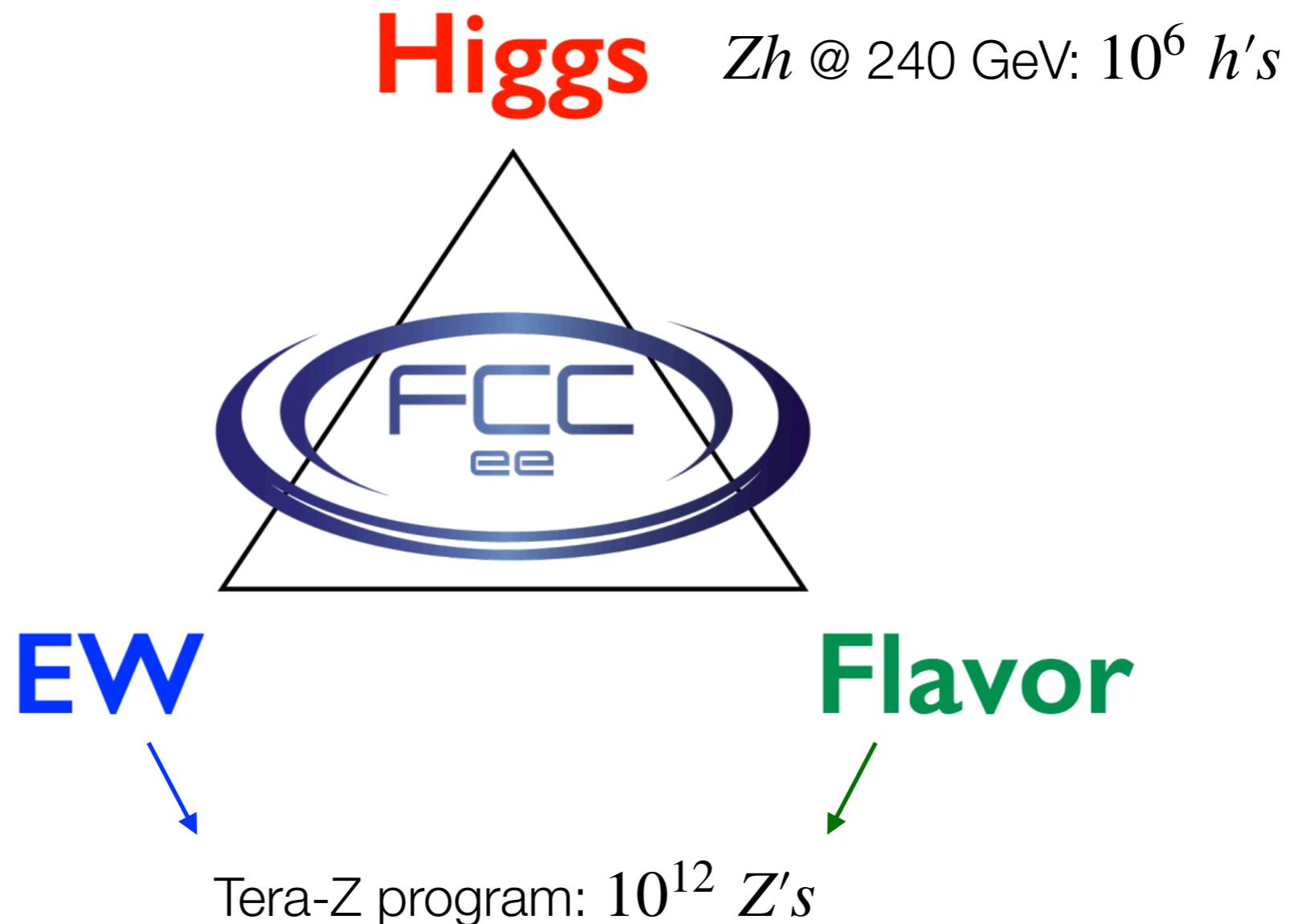
It is also an electroweak and flavor factory!

Higgs coupling measurements at FCC-ee

● With a million Higgses, hZZ, hWW, hbb couplings reach the per-mille level.
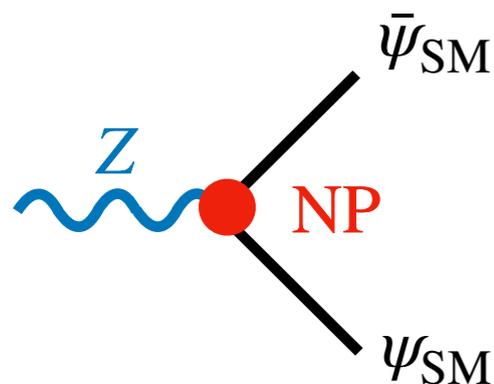
Estimating BSM sensitivity at FCC-ee

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

hZZ (0.1%)	hbb (0.36%)	htt (1%)	hhh (11%)
$\dfrac{1}{\Lambda^2}\partial_\mu|H|^2\partial^\mu|H|^2$	$\dfrac{y_b}{\Lambda^2}|H|^2\bar{q}_L^3 H b_R$	$\dfrac{y_t}{\Lambda^2}|H|^2\bar{q}_L^3\tilde{H}t_R$	$\dfrac{\lambda}{\Lambda^2}|H|^6$
$\Lambda \gtrsim 7.8$ 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$)$

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BSM "enhancement": $\qquad\quad (\Lambda \gtrsim 25\text{ TeV}) \qquad\qquad \text{——} \qquad\quad (\Lambda \gtrsim 2\text{ TeV})$

$\bar{\psi}_{\rm SM}$

Z

NP

$\psi_{\rm SM}$

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

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

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

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

Tera-Z factory brings novel precision challenges

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

	EWPO unfolding	SM theory	Exp sys.
	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
σ_{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_{FB}^e	126	25.7	25.2
A_{FB}^μ	125	21.1	20.6
A_{FB}^τ	126	23.3	22.8
A_{FB}^b	87.8	6.42	5.50
A_{FB}^c	89.1	10.2	9.62
A_{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]

Tera-Z at Tree Level (S1)

● Here are the Wilson coefficients entering the Z-pole at tree level in the $U(2)^5$ limit.
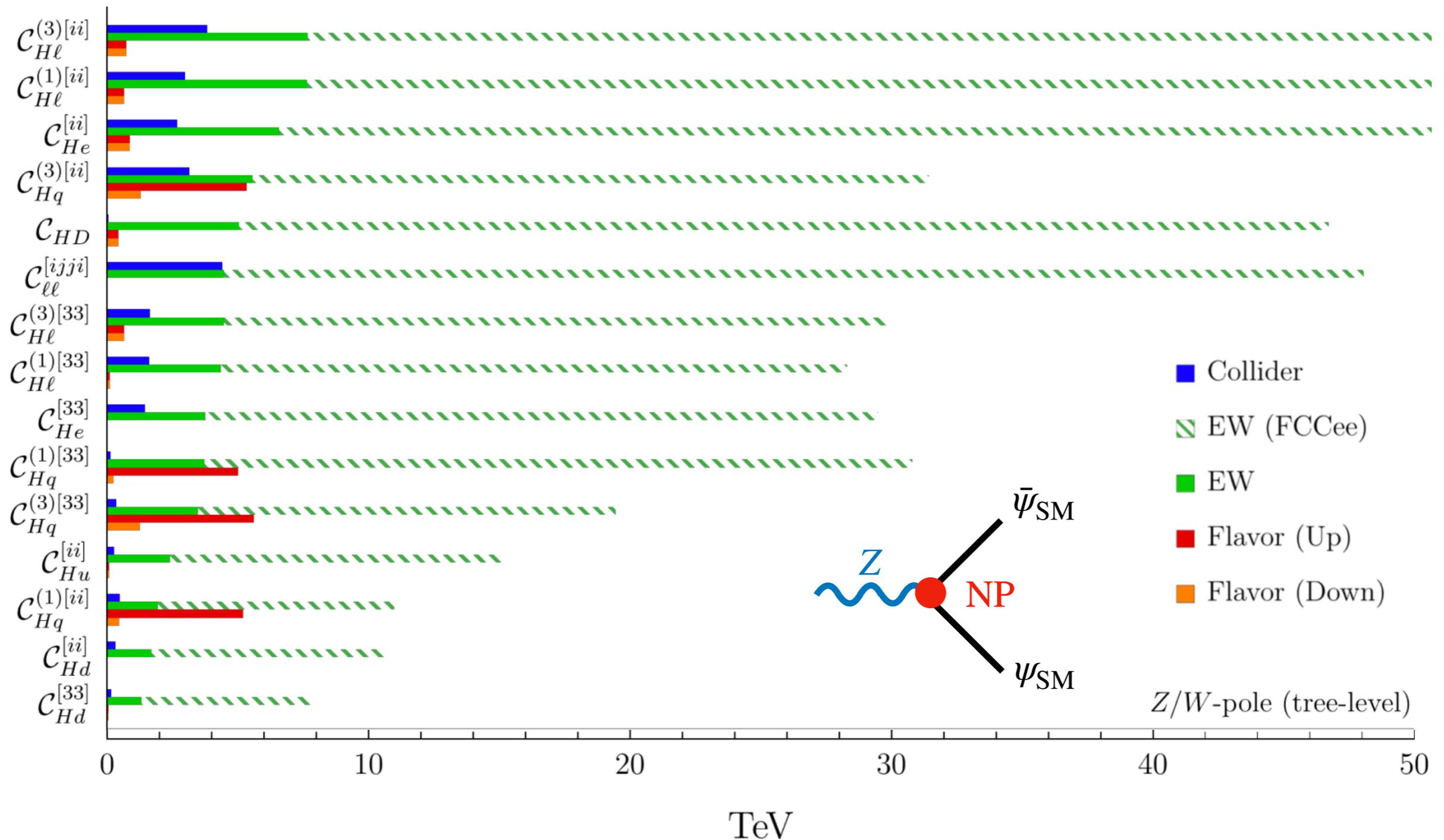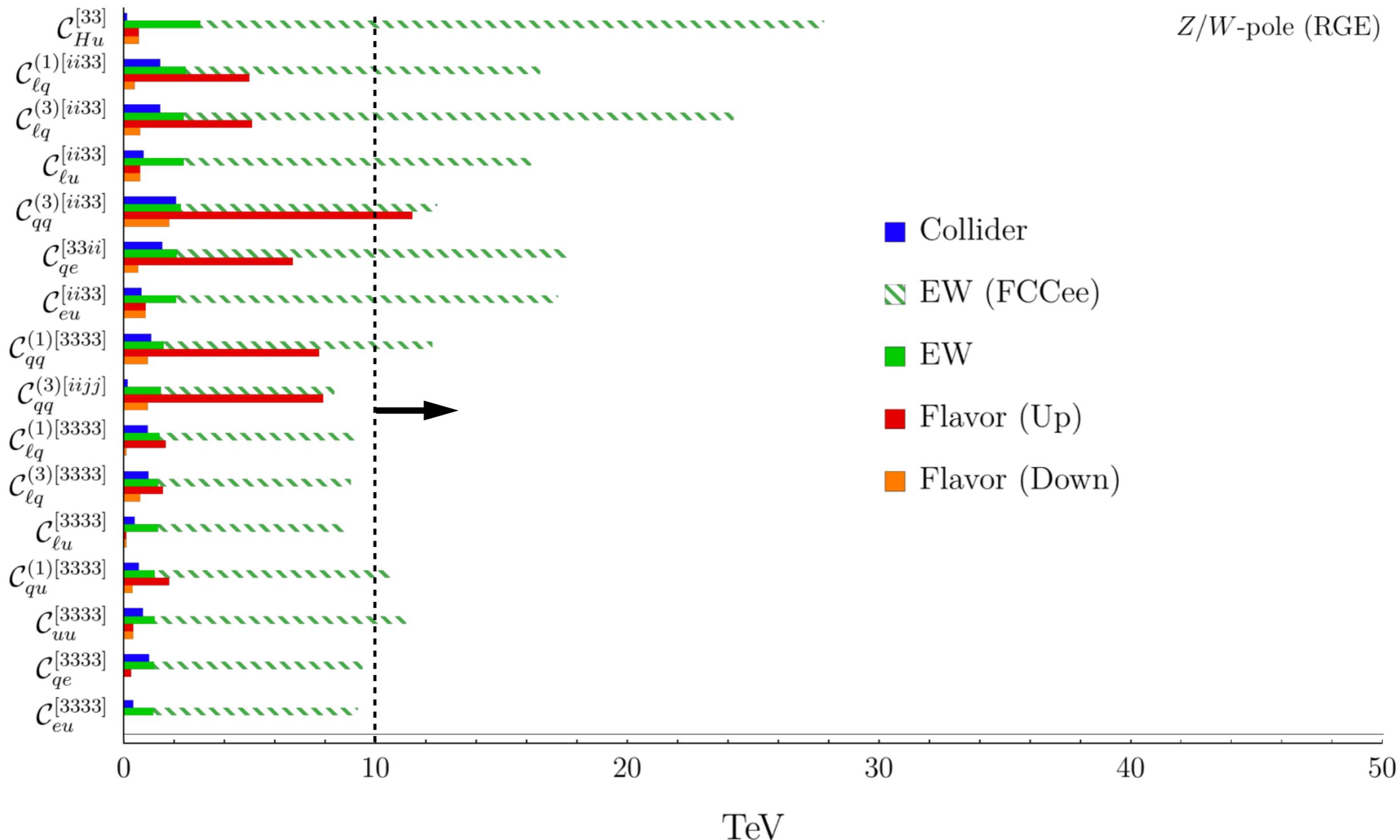
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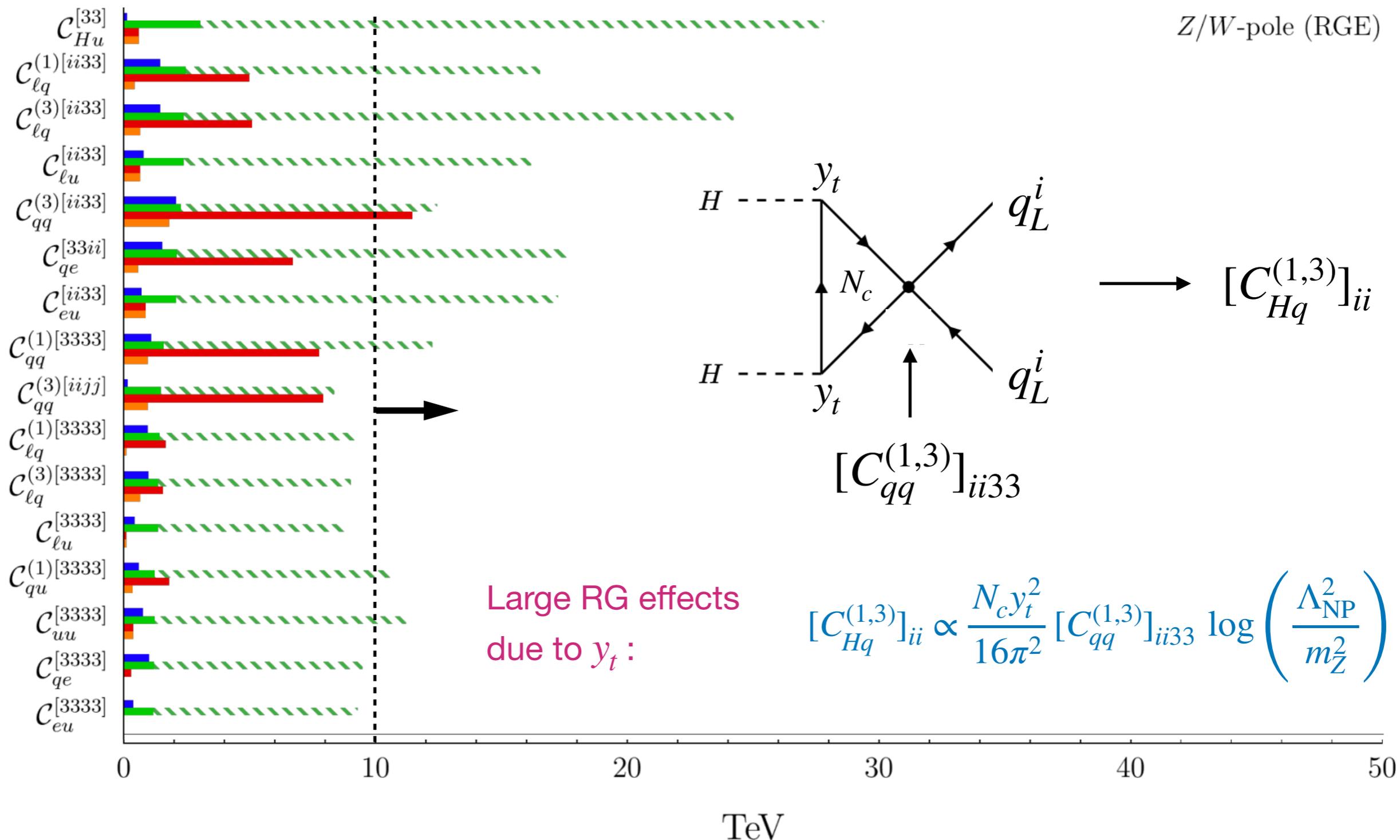
[Allwicher, Cornella, Isidori, BAS, 2311.00020]

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

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Z/W-pole (RGE)

$$\longrightarrow [C_{Hq}^{(1,3)}]_{ii}$$

$$[C_{qq}^{(1,3)}]_{ii33}$$

Large RG effects due to y_t :

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

Linear SM extensions at Tera-Z (S1)

- Heavy vector fields that can couple linearly to the SM ("Granada Dictionary")
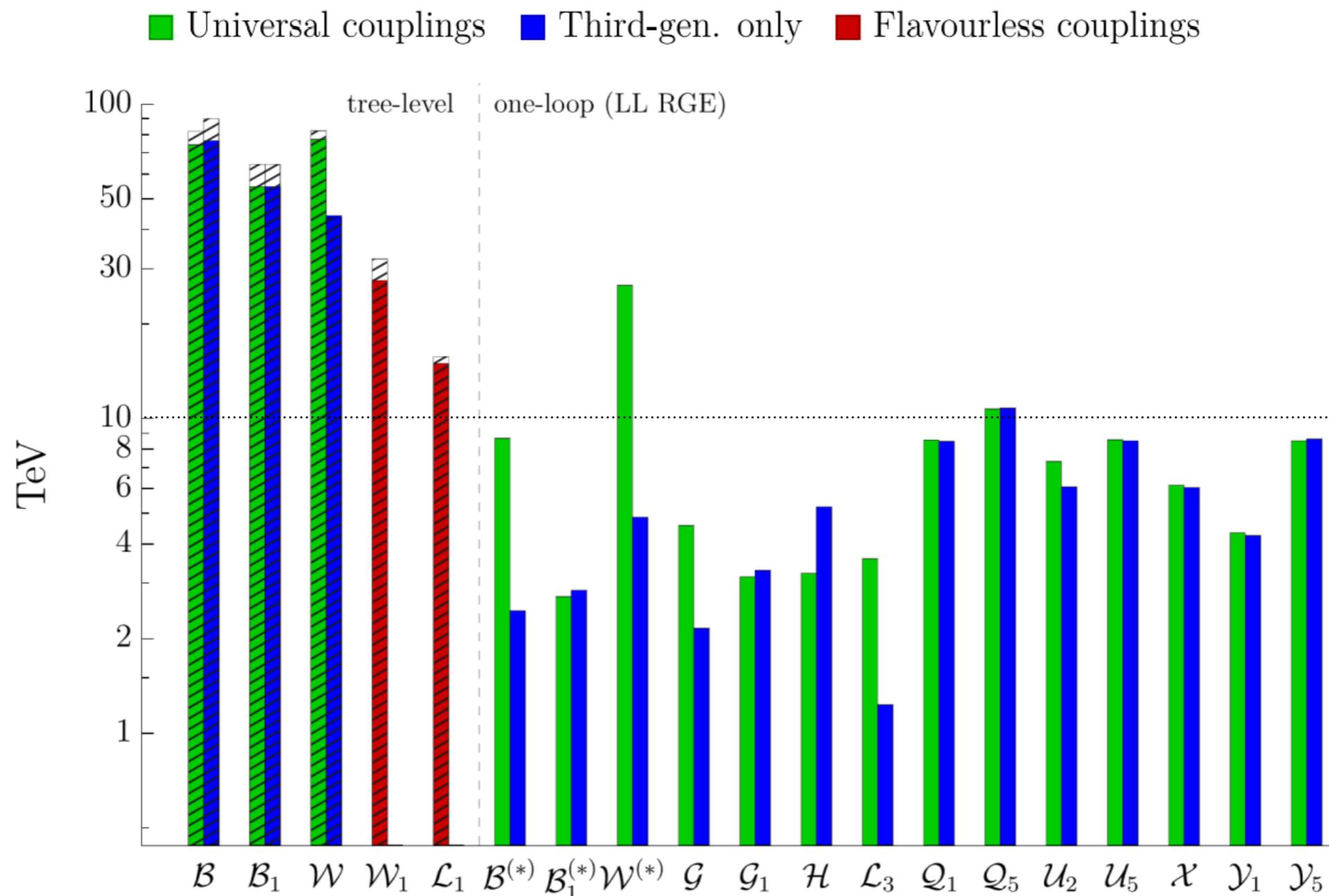
[Allwicher, McCullough, Renner, 2408.03992]   [de Blas, Criado, Pérez-Victoria, Santiago, 1711.10391]

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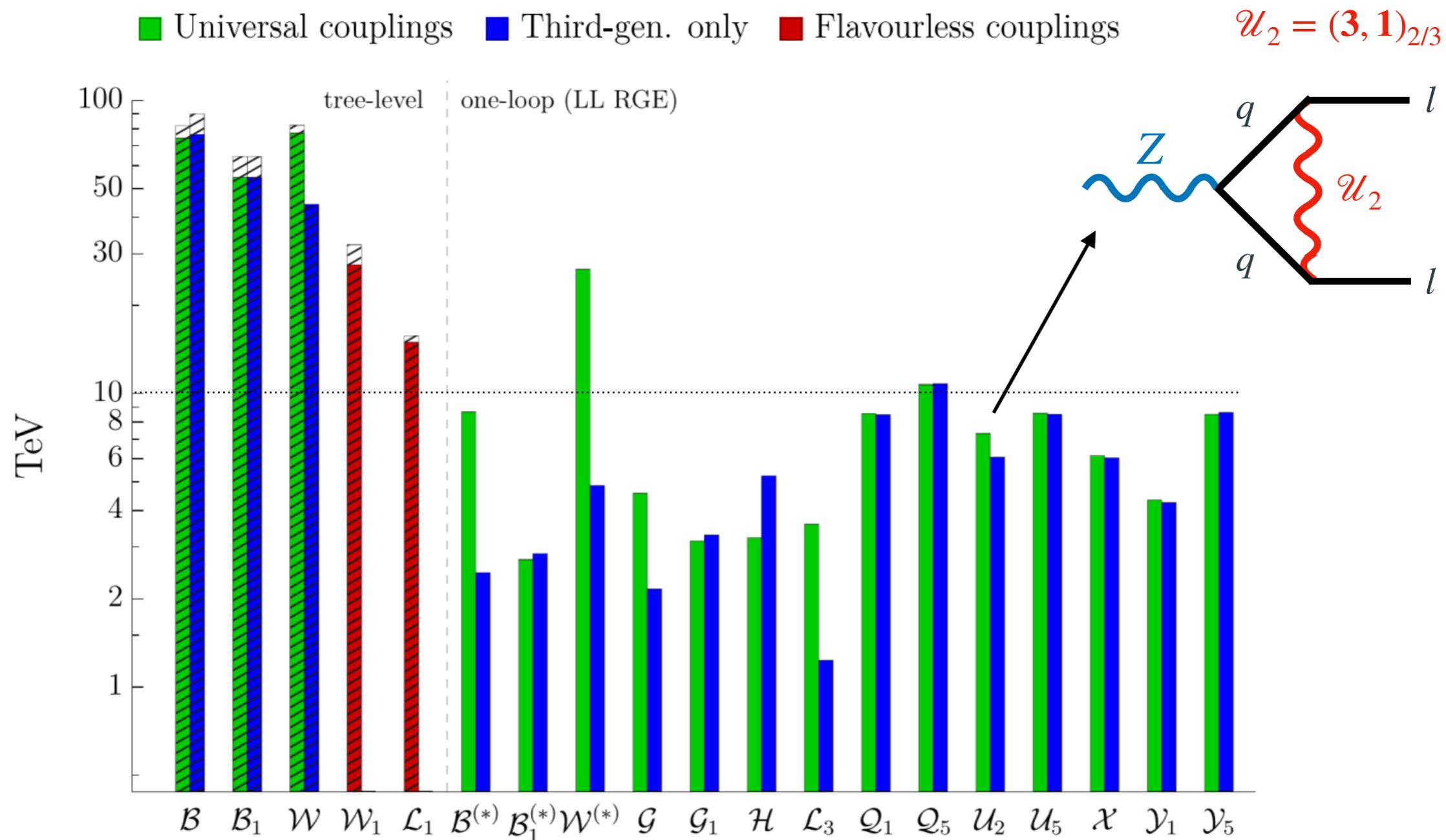
[Allwicher, McCullough, Renner, 2408.03992]   [de Blas, Criado, Pérez-Victoria, Santiago, 1711.10391]

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!

$$\implies y_t \simeq g_* \varepsilon_L \varepsilon_R$$
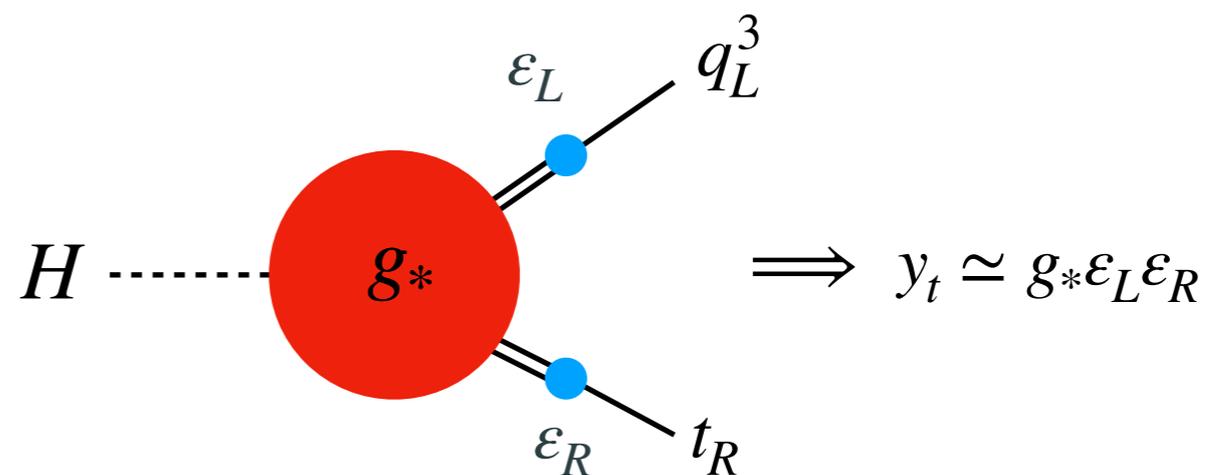
- Via these mixing parameters, the composite sector will unavoidably generate other large top+H operators, for example:
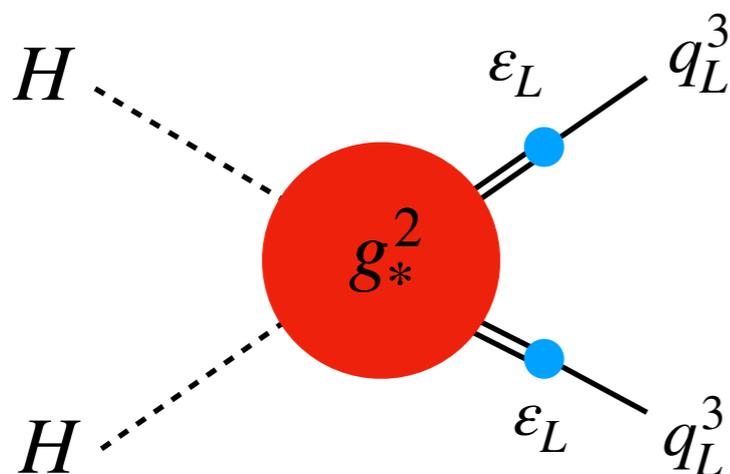
$$\mathcal{O}_{Hq}^{(1)} = (H^\dagger D_\mu H)(\bar{q}_L^3 \gamma^\mu q_L^3)$$
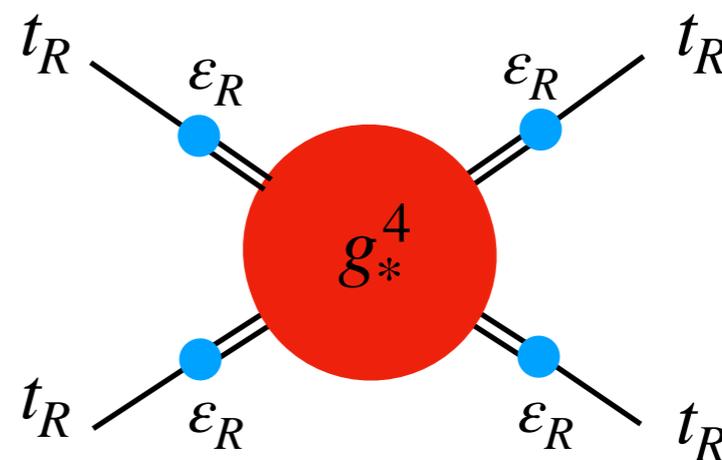
$$\mathcal{O}_{tt} = (\bar{t}_R \gamma_\mu t_R)(\bar{t}_R \gamma^\mu t_R)$$

Composite Higgs and custodial symmetry

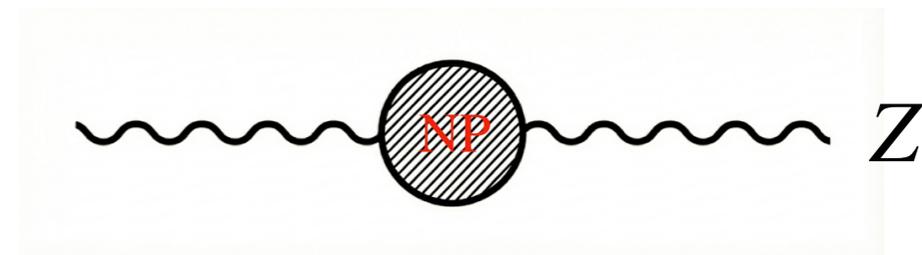- Composite Higgs models without custodial symmetry face severe constraints:

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

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

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

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

[Agashe, Contino, Da Rold, Pomarol, hep-ph/0605341]
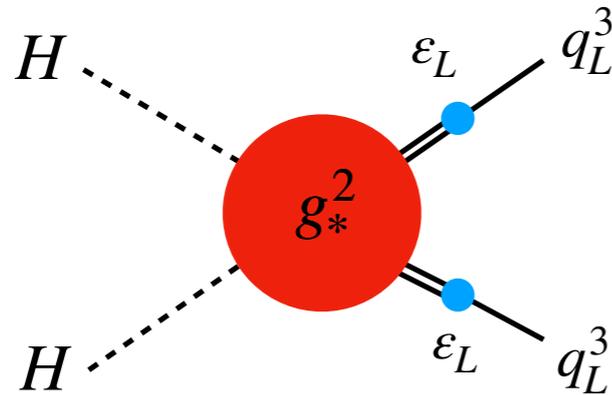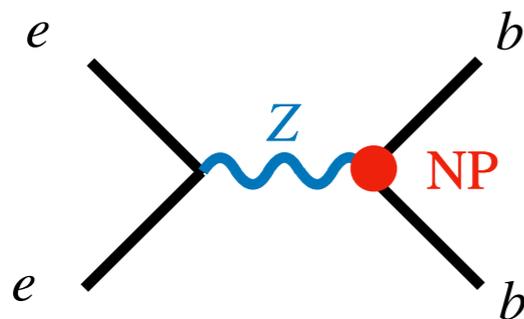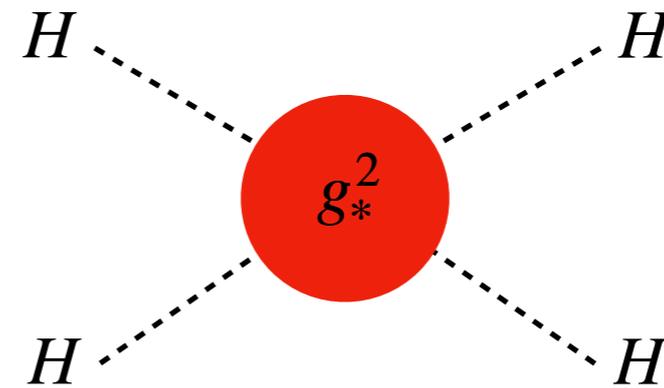
Top loops in composite Higgs models
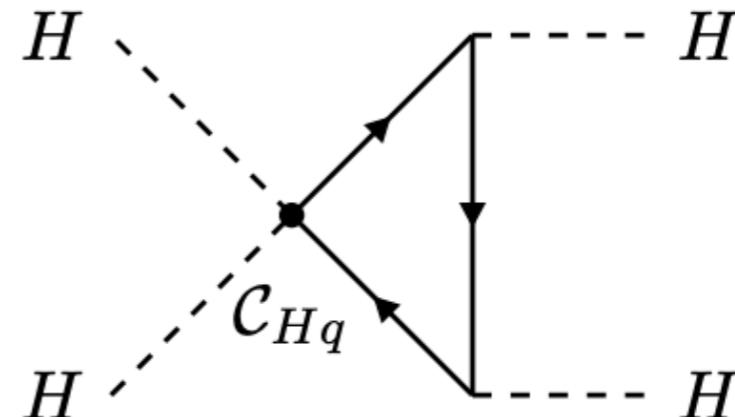
- SM does not respect custodial symmetry! Large breaking $y_t \sim O(1) \gg y_b$

Top quark loops give large effects $\propto N_c y_t^2 \log(m_Z^2/m_*^2)$
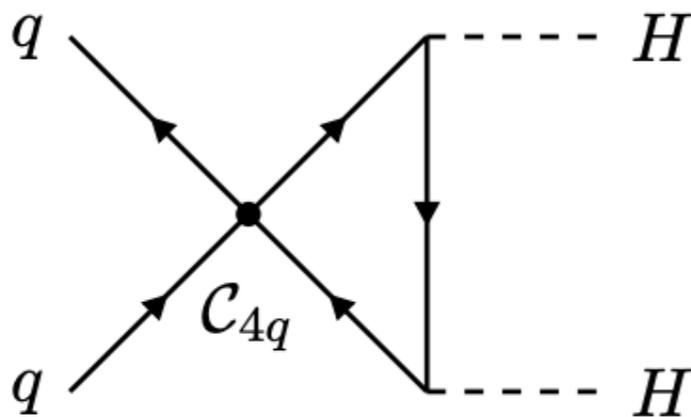
*4-top operators running
into Zbb vertex corrections.*

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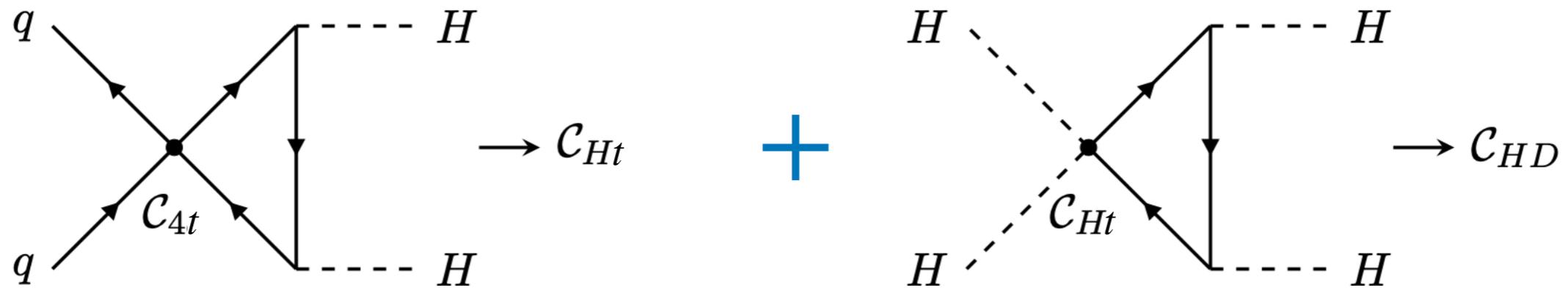

*Top vertex corrections running
into the T parameter.*

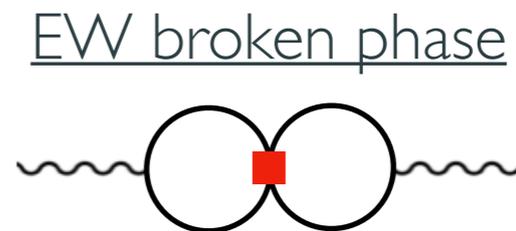$$\mathcal{O}_{Hq}^{(1)}, \mathcal{O}_{Ht} \rightarrow \mathcal{O}_{HD}$$

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!
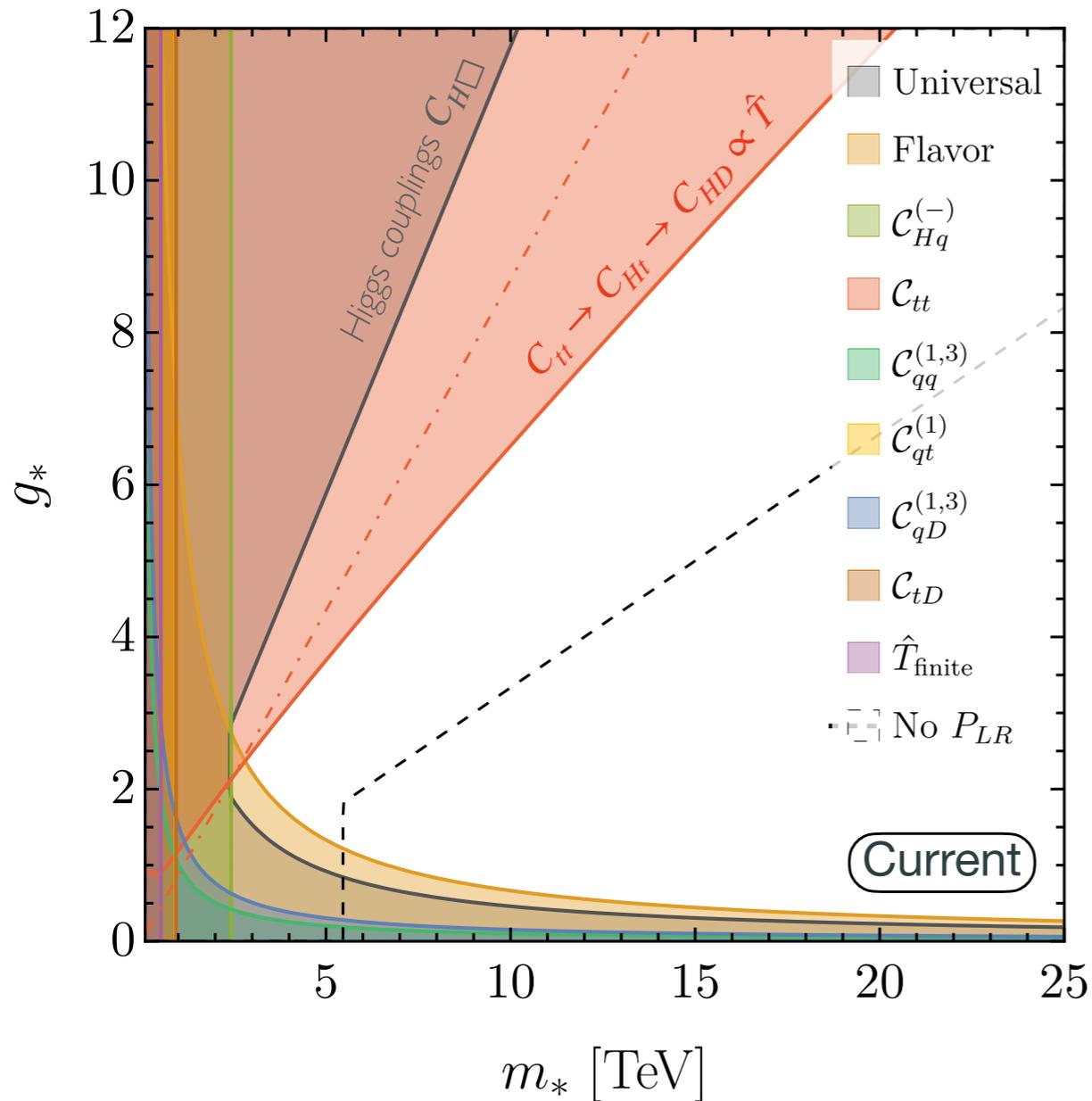
<u>EW broken phase</u>

$$[\mathcal{C}_{HD}] = \frac{2N_c \, y_t^4}{(16\pi^2)^2} \left[(1 + 2N_c)\mathcal{C}_{qq}^{(1)} + 3\mathcal{C}_{qq}^{(3)} + 2(1 + N_c)\mathcal{C}_{tt} - 2N_c\mathcal{C}_{qt}^{(1)} \right] \log^2\left(\frac{\mu^2}{m_*^2}\right)$$
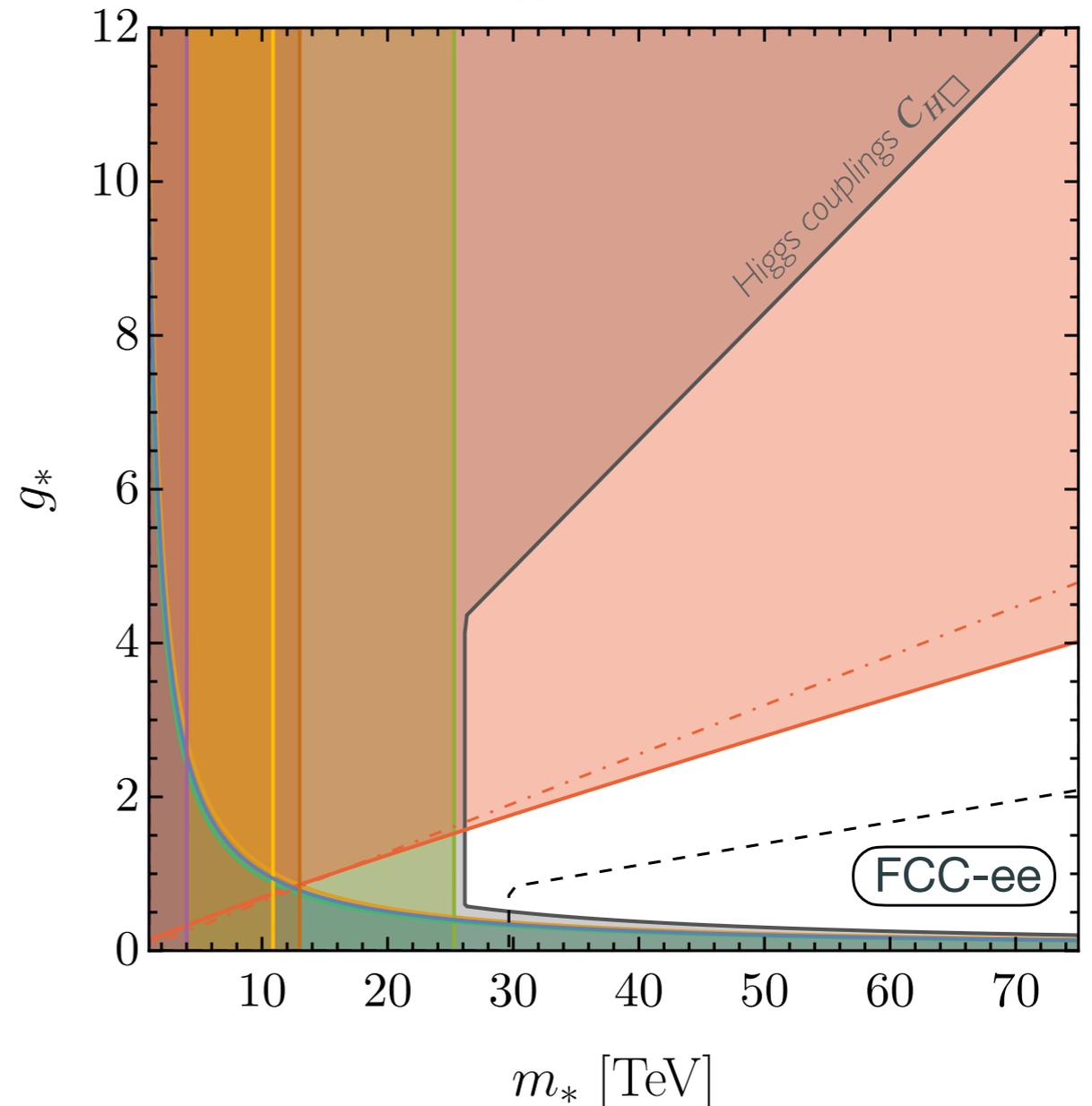
[BAS, 2407.09593]

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]

Future summary plots
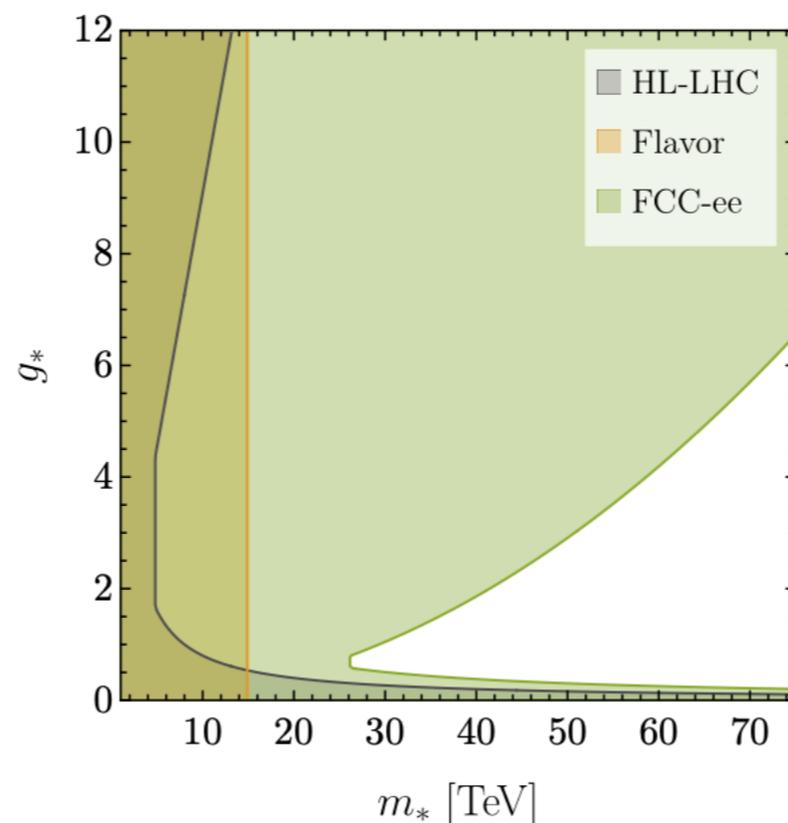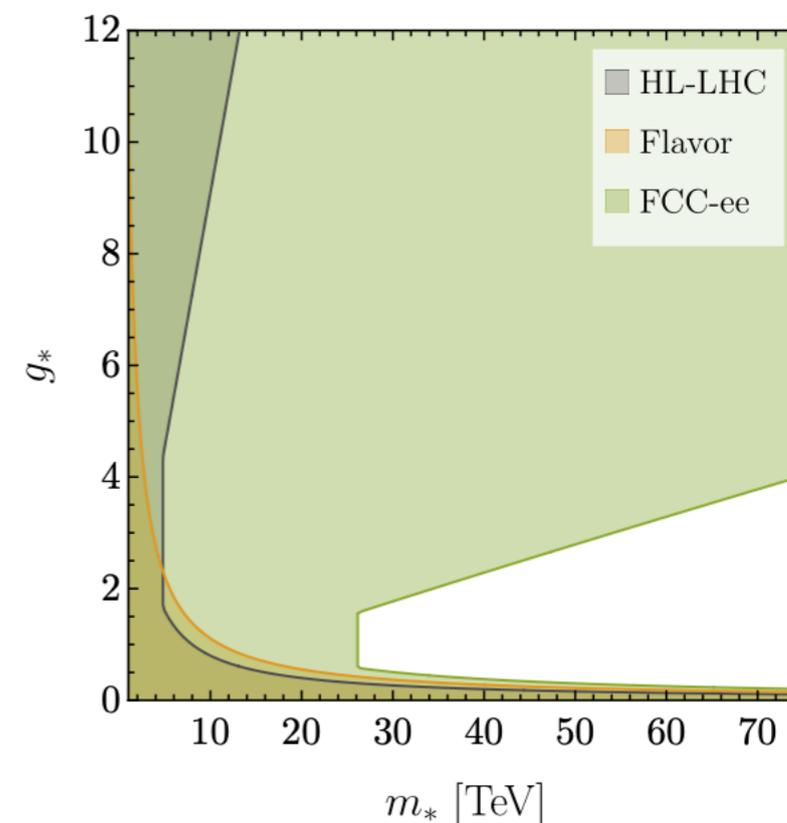
- RG effects from top operators provide the best bound in the most natural $g_* \gtrsim 1$ region (recall $\langle H \rangle \sim f = m_*/g_*$)
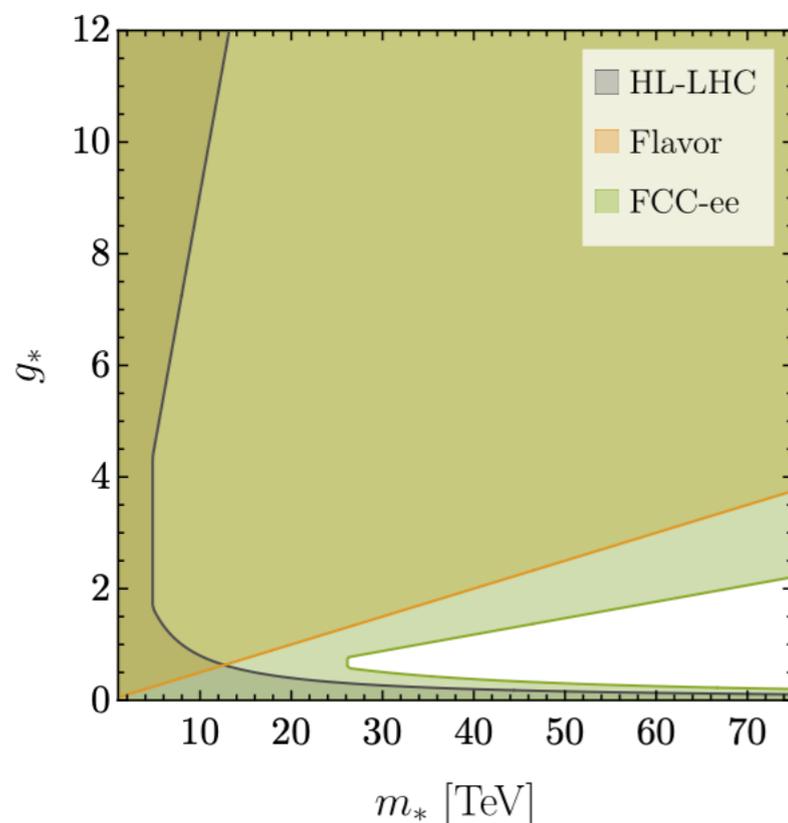
(a) Left compositeness (b) Mixed compositeness (c) Right compositeness

- FCC-ee can set a mixing independent bound of $m_* \gtrsim 25$ TeV. In the context of CHM, will test naturalness of the EW scale at the 10^{-4} level!

[BAS, 2407.09593]

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Conclusions

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- We looked at SMEFT, single mediator extensions, and composite Higgs models and found BSM sensitivity in the 10-100 TeV range.

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- The culmination of this program will be FCC-ee, a Higgs, electroweak, and flavor factory. The capability to produce trillions of Z bosons offers unprecedented BSM reach via precision EW measurements.

- We looked at SMEFT, single mediator extensions, and composite Higgs models and found BSM sensitivity in the 10-100 TeV range.

- I believe such a broad precision program is a very good way forward when we don't know where new physics will appear. Any deviations will provide clear targets for a 10 TeV pCM machine.

Backup

Run plan for FCC-ee
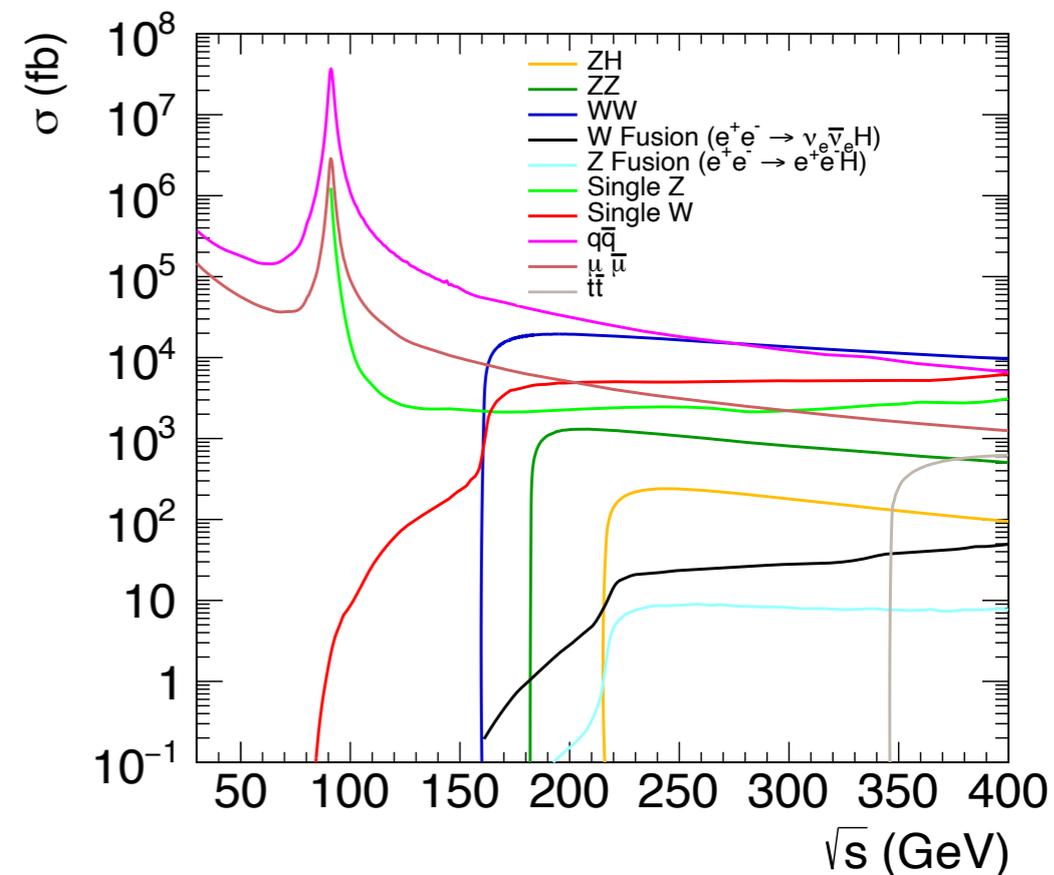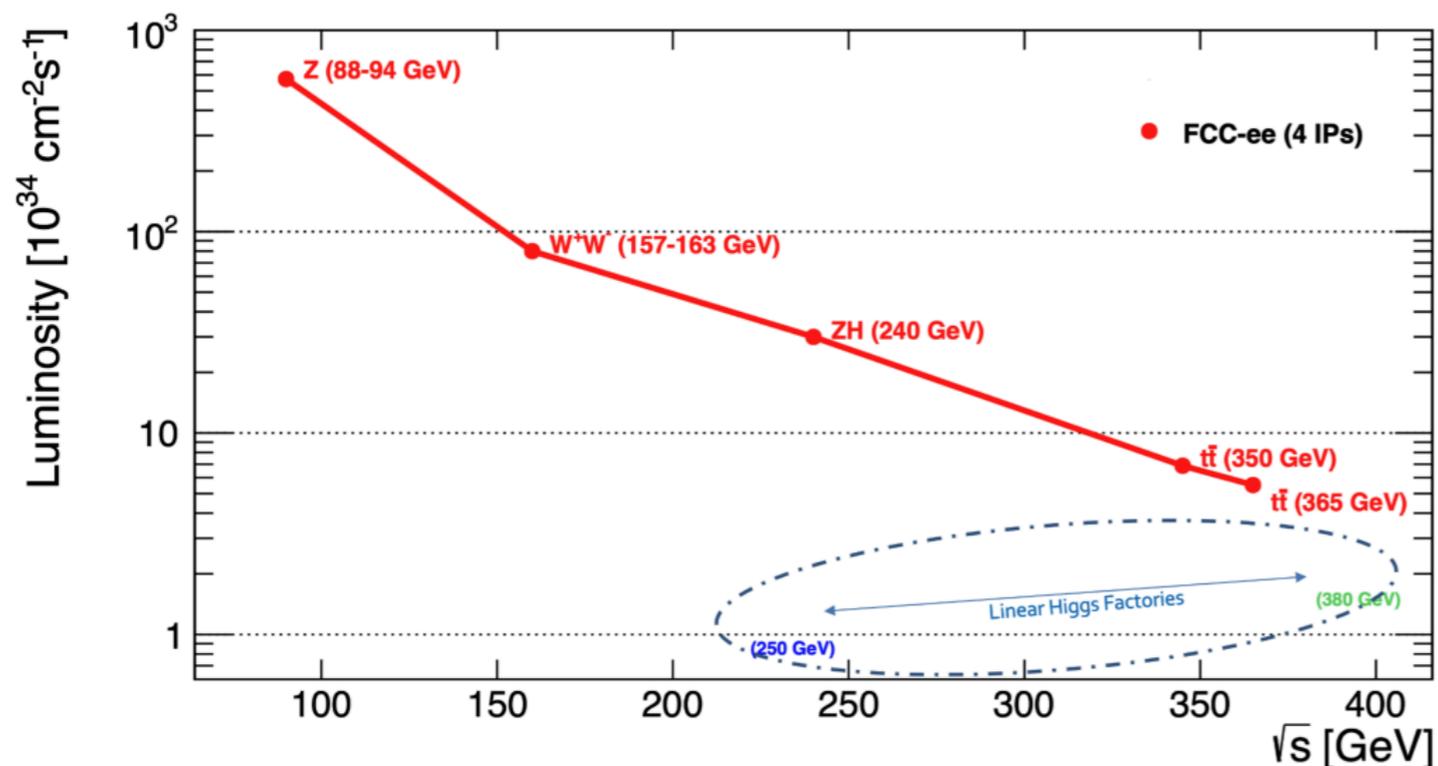
Energy →

| Working point	Z pole	WW thresh.	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94	157, 163	240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	140	20	7.5	1.8	1.4
Lumi/year (ab^{-1})	68	9.6	3.6	0.83	0.66
Run time (year)	4	2	3	1	4
Integrated Lumi (ab^{-1})	205	19.2	10.8	0.42	2.70
Number of events	$6\,10^{12}$ Z	$2.4\,10^8$ WW	$2.2\,10^6$ HZ + 65k WW $\to$ H	$2\,10^6$ $t\bar{t}$ +370k HZ +92k WW $\to$ H	

← **Accuracy**

EW precision tests: Theoretical Uncertainties

- To match the precision of Tera-Z, work is needed on the SM theory side.

There are two different sources of theoretical errors- use R_b as an example:

1) Definition of pseudo observables (?)
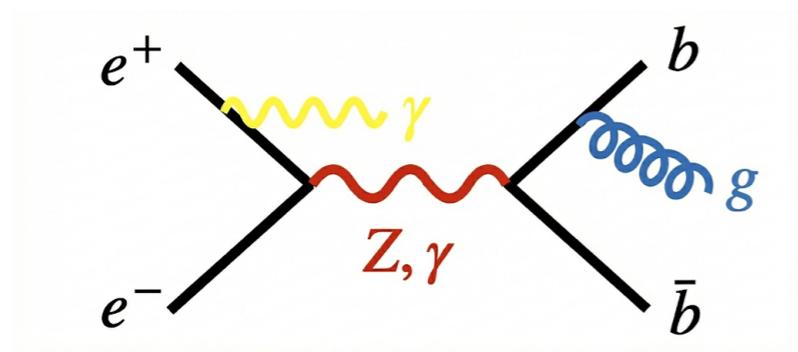
- *Z-pole "background"*: Subtraction of non-resonant contributions: Photon exchange and SM box graph contributions. Known at NLO. **BSM in these contributions?**

- *ISR/FSR QED/QCD*: Subtracted using MC, which currently includes NLO corrections with some resummation of leading soft and/or collinear contributions.

[PBB, 2511.03883]

2) SM predictions for pseudo observables

Complete NNLO corrections known + partial higher orders: $\alpha_t\alpha_s^2, \alpha_t\alpha_s^3, \alpha_t^2\alpha_s, \alpha_t^3$

	R_b	$\%\Delta$
Born	0.21733	—
$+\mathcal{O}(\alpha)$	0.21558	-0.81%
$+\mathcal{O}(\alpha\alpha_s)$	0.21593	+0.16%
$+\mathcal{O}(\alpha_t\alpha_s^2,\dots)$	0.21593	+0.00%
$+\mathcal{O}(N_f^2\alpha^2, N_f\alpha^2)$	0.21580	-0.06%
$+\mathcal{O}(\alpha_{\text{bos}}^2)$	0.21585	+0.02%

Since then: $N_f^3\alpha^3, N_f^2\alpha^2\alpha_s$ computed...O(0.001%)

Full $\mathrm{N^3LO}$ and at least partial $\mathrm{N^4LO}$ will be needed.

[Dubovyk, Freitas, Gluza, Riemann, Usovitsch, 1804.10236
Chen and Freitas, 2002.05845, 2012.08605]

Matching to composite Higgs model parameters

- The full UV Lagrangian can be written schematically as

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

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

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

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

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

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

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

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

Higgs couplings: Improvement vs. HL-LHC

- Improvement w.r.t. to HL-LHC is mainly concentrated in the hVV, hbb couplings.

Relative Improvement: HL-LHC vs FCC-ee and LCF
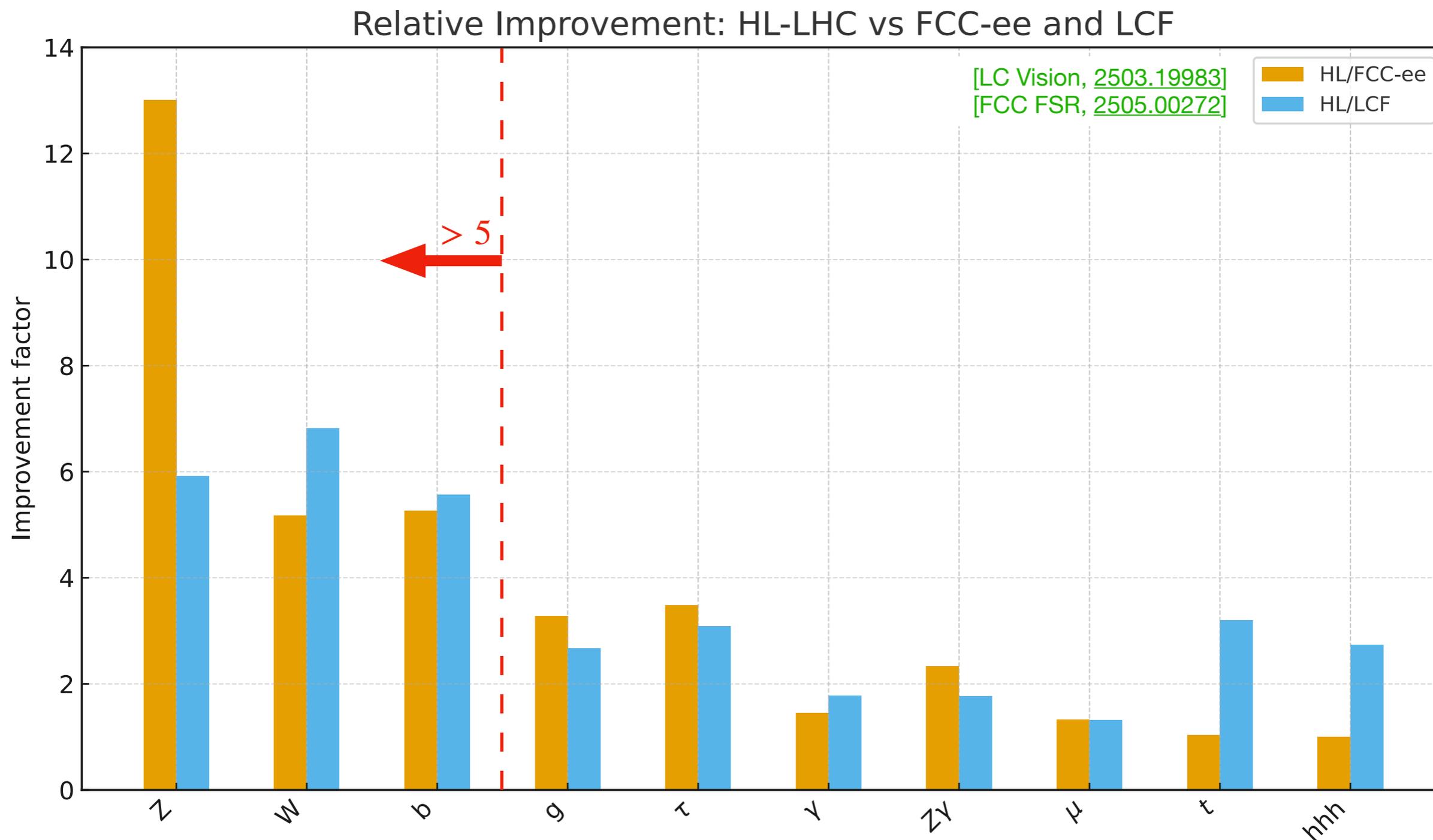
Heavy flavor physics at a Tera-Z machine

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

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

$\approx 15.2\,\%$

$\approx 3.4\,\%$
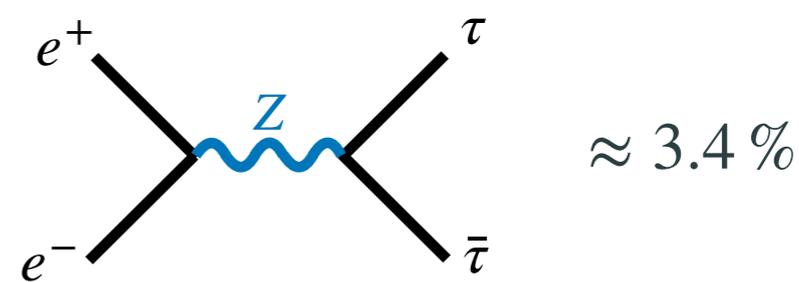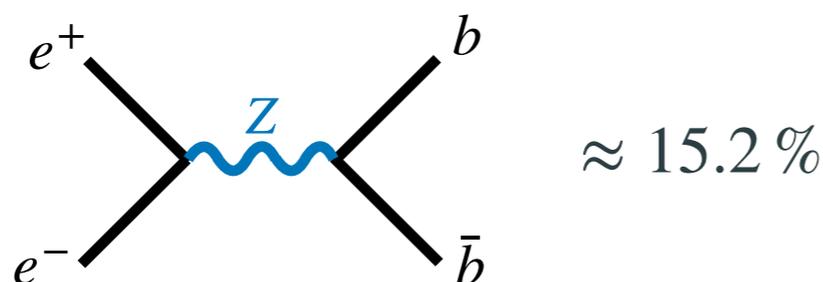
- With 5×10^{12} Z-bosons, heavy flavors produced at the 1-100 billion level. In particular, the heavier $B_{s,c}$ and Λ_b will be accessible in large numbers.

- Unique opportunity to study a large number of B- and tau-decays in a clean e^+e^- environment. Expected benefit from large boost and excellent vertexing capability.
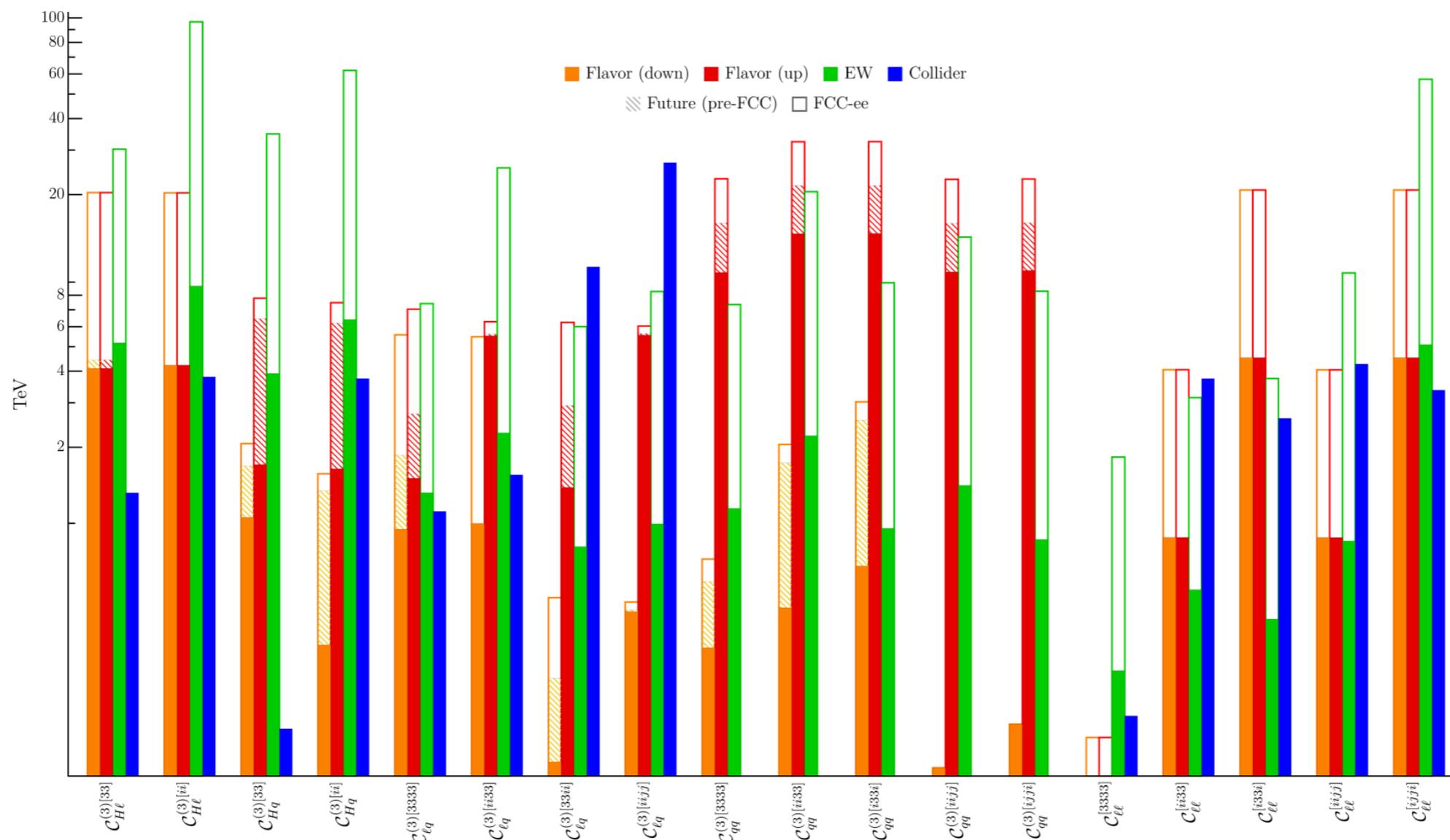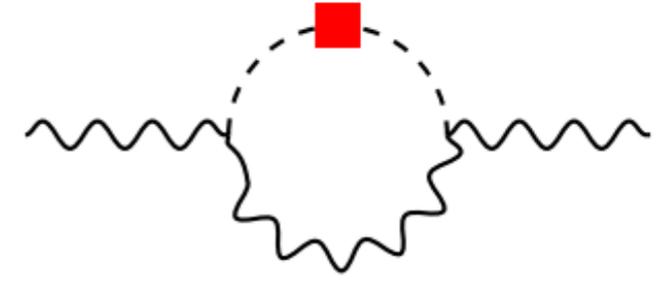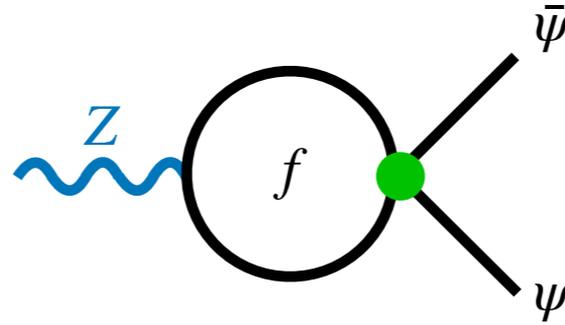
Heavy flavor physics at a Tera-Z machine

Figure 9: Bounds on a selection of $U(2)^5$-symmetric SMEFT operators from flavor, electroweak, and collider observables. The expected future sensitivities before the start of FCC are shown as hatched bars, while the empty bars represent the expected reach at FCC-ee. For all operators RG running from a reference scale of 1 TeV is taken into account, and all bounds are shown at 2σ.

[Allwicher, Isidori, Pesut, 2503.17019]

Importance of loops at the Z-pole

- RG effects mix four-fermion operators into Z-vertex corrections at 1 loop. Higgs physics also shows up in the S+T parameters.

$$\delta g_Z^{\psi\psi} \sim \frac{N_c g^2}{16\pi^2}\left(1 + \frac{m_f^2}{m_Z^2}\right) C_{4f} \log \frac{\Lambda_{\rm NP}^2}{m_Z^2}$$

$$T \sim \frac{20}{3}\frac{g_Y^2}{16\pi^2} C_{H\square} \log \frac{\Lambda_{\rm NP}^2}{m_Z^2}$$

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

$\psi^2 H^2 D$		X^2H^2 and X^3		$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q_{H\ell}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu\ell)_{pp}$	Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{\ell\ell}$	$(\bar{\ell}\gamma_\mu\ell)(\bar{\ell}\gamma^\mu\ell)_{pprr\atop prrp}$	Q_{ee}	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)_{pprr}$	$Q_{\ell e}$	$(\bar{\ell}\gamma_\mu\ell)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{H\ell}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{\ell}\tau^I\gamma^\mu\ell)_{pp}$	Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{qq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)_{pprr\atop prrp}$	Q_{uu}	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)_{pprr\atop prrp}$	$Q_{\ell u}$	$(\bar{\ell}\gamma_\mu\ell)(\bar{u}\gamma^\mu u)_{pprr}$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)_{pp}$	Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	$Q_{qq}^{(3)}$	$(\bar{q}\gamma_\mu\tau^I q)(\bar{q}\gamma^\mu\tau^I q)_{pprr\atop prrp}$	Q_{dd}	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)_{pprr\atop prrp}$	$Q_{\ell d}$	$(\bar{\ell}\gamma_\mu\ell)(\bar{d}\gamma^\mu d)_{pprr}$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)_{pp}$	Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	$Q_{\ell q}^{(1)}$	$(\bar{\ell}\gamma_\mu\ell)(\bar{q}\gamma^\mu q)_{pprr}$	Q_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)_{pprr}$	Q_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)_{pprr}$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)_{pp}$	Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\ell q}^{(3)}$	$(\bar{\ell}\gamma_\mu\tau^I\ell)(\bar{q}\gamma^\mu\tau^I q)_{pprr}$	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_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)_{pp}$	Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$			$Q_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)_{pprr}$	$Q_{qu}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)_{pprr}$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)_{pp}$					$Q_{ud}^{(8)}$	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)_{pprr}$	$Q_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)_{pprr}$
								$Q_{qd}^{(8)}$	$(\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)_{pprr}$

[Maura, BAS, You, 2412.14241]

Searching for SUSY at FCC-ee: Stops

- **First, look at stops**: most important couplings are (w/ MFV: $\mathbf{X}_u = X_t \mathbf{Y}_u^{\mathrm{SM}}$)

$$\mathcal{L}_{\mathrm{stop}} \supset \tilde{u}_R^\dagger \mathbf{X}_u H_u \tilde{Q}_L - (\mathbf{y_u y_u^\dagger})(H_u \tilde{Q}_L)^\dagger (H_u \tilde{Q}_L) + \mathrm{h.c.}$$
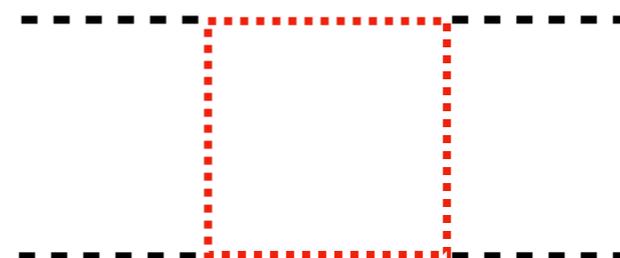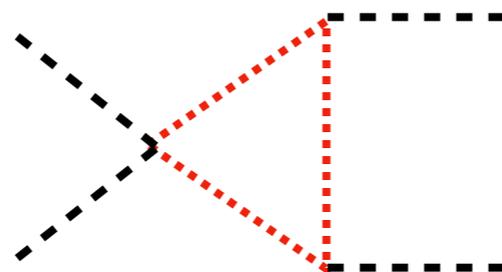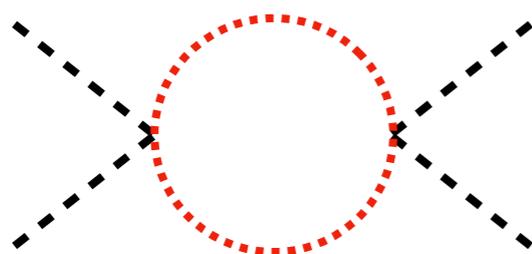
$$C_{HD} \propto \qquad \frac{y_t^4}{16\pi^2 M_{\tilde{t}}^2} \qquad\qquad \frac{y_t^4}{16\pi^2 M_{\tilde{t}}^2}\frac{X_t^2}{M_{\tilde{t}}^2} \qquad\qquad \frac{y_t^4}{16\pi^2 M_{\tilde{t}}^2}\frac{X_t^4}{M_{\tilde{t}}^4}$$

- **Zero-momentum part of these graphs contributes to the Higgs quartic**. We assume large trilinears- required to get a heavy enough Higgs in the MSSM.

[Greljo, BAS, Valenti, 2507.03073]

Searching for SUSY at FCC-ee: Stops (S1 scenario)

- Since trilinears are large, we resum them by working in the EW broken phase.

$$\sin 2\theta_{\tilde{t}} = \frac{2m_t X_t}{M_{\tilde{t}_2}^2 - M_{\tilde{t}_1}^2}, \qquad X_t^2 = 6M_{\tilde{t}_1}M_{\tilde{t}_2} \quad \text{(to maximize Higgs mass)}$$

Lightest stop mostly LH

Lightest stop mostly RH

[Greljo, BAS, Valenti, 2507.03073]

Searching for SUSY at FCC-ee: Stops (S3 scenario)

- R_b also important in the S3 case (weak Higgsino mass dependence for $\mu < M_{\tilde{t}}$). Huge potential on the SM theory side!

$$H \cdots \tilde{Q} \cdots q_L \quad \tilde{H} \quad q_L \quad \propto \frac{y_t^4 X_t^2}{16\pi^2 M_{\tilde{t}}^4}$$
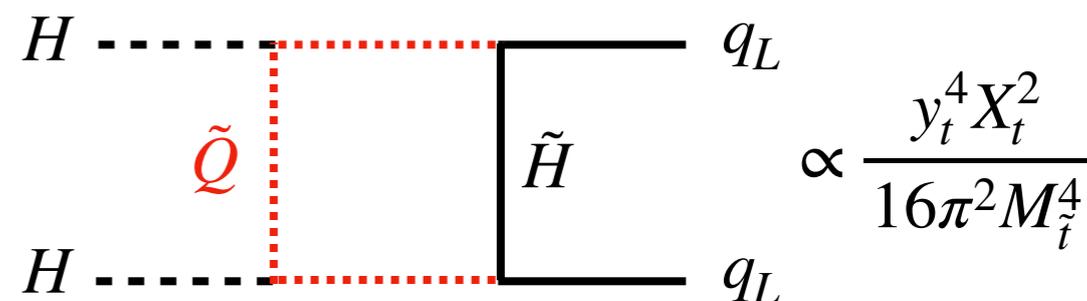
Lightest stop mostly LH

■ $S+T$ ■ $Zh\,(h \to gg, \gamma\gamma)$ ■ $Zb\bar{b}$
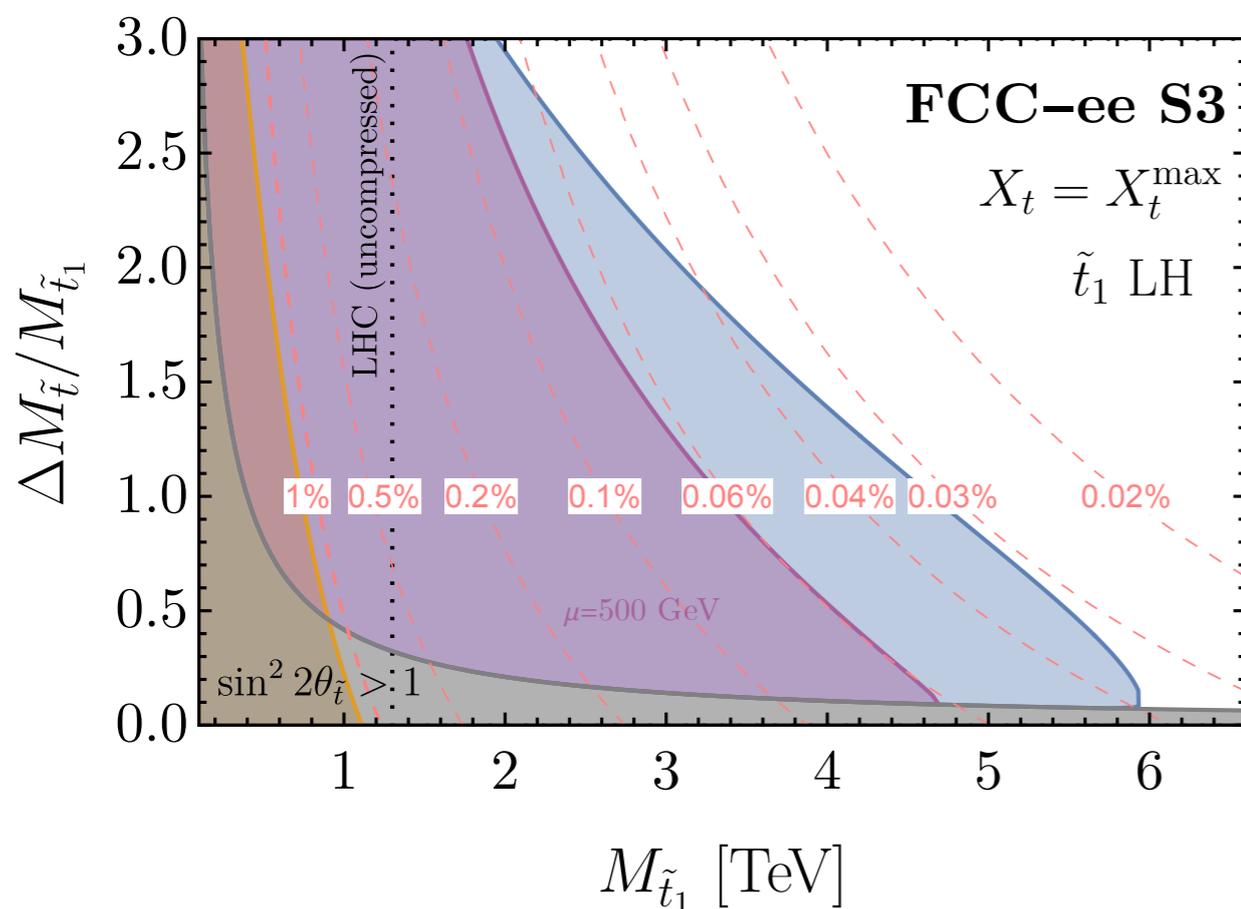
Lightest stop mostly RH

■ $S+T$ ■ $Zh\,(h \to gg, \gamma\gamma)$ ■ $Zb\bar{b}$

[Greljo, BAS, Valenti, 2507.03073]

Searching for SUSY at FCC-ee: Heavy Higgs

- **SUSY is also a (Type II) 2HDM: Let's look at the heavy Higgs ($\beta - \alpha = \pi/2$):**

$$\mathcal{L}_\Phi \supset -\bar{q}_L \widetilde{\Phi}(\cot\beta\, Y_u^{\mathrm{SM}})u_R + \bar{q}_L \Phi(\tan\beta\, Y_d^{\mathrm{SM}})d_R + \bar{\ell}_L \Phi(\tan\beta\, Y_e^{\mathrm{SM}})e_R - \frac{g_Z^2}{8}\sin 4\beta |H|^2 \Phi^\dagger H + \mathrm{h.c.}$$

$$C_{dH}, C_{eH} \propto \frac{g_Z Y_{d,e}}{M_A^2}\sin 4\beta \tan\beta$$

[Greljo, BAS, Valenti, 2507.03073]

Searching for SUSY at FCC-ee: Heavy Higgs

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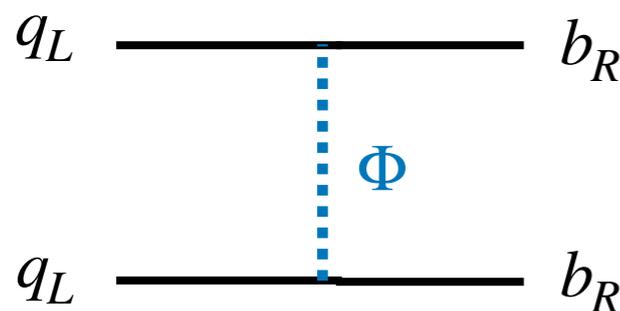
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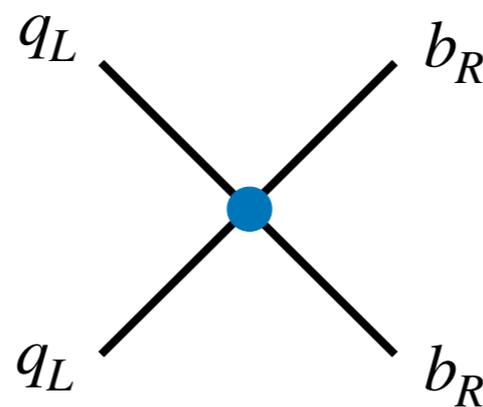

$$C_{dH}, C_{eH} \propto \frac{g_Z Y_{d,e}}{M_A^2}\sin 4\beta \tan\beta \qquad [C_{Hq}^{(1)}]_{33} \propto \frac{y_t^4 \cot\beta^2}{16\pi^2 M_A^2}\log\frac{m_Z^2}{M_A^2} \qquad [C_{Hd}]_{33} \propto \frac{y_t^2 y_b^2 \tan\beta^2}{16\pi^2 M_A^2}\log\frac{m_Z^2}{M_A^2}$$
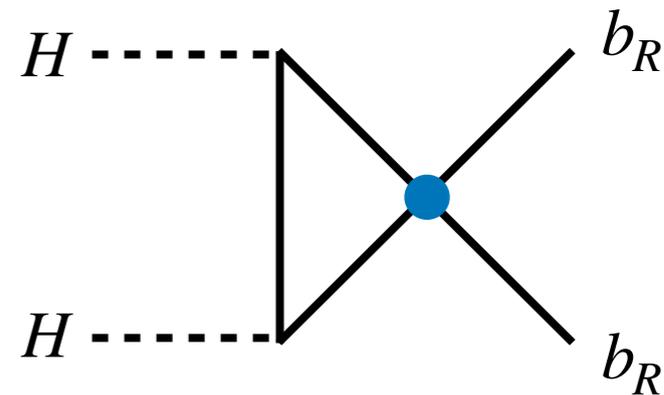
- Box graphs have a log that can be understood from RG mixing in the SMEFT.
  Not typical for SUSY w/ R-parity since sparticles come in pairs- heavy
  Higgs is the only one that couples linearly to the SM (tree-level matching).

[Greljo, BAS, Valenti, 2507.03073]

Searching for SUSY at FCC-ee: Heavy Higgs

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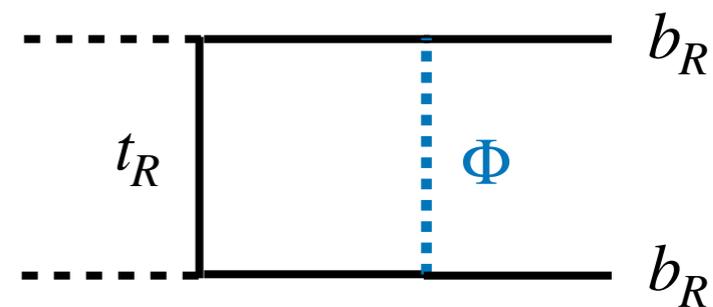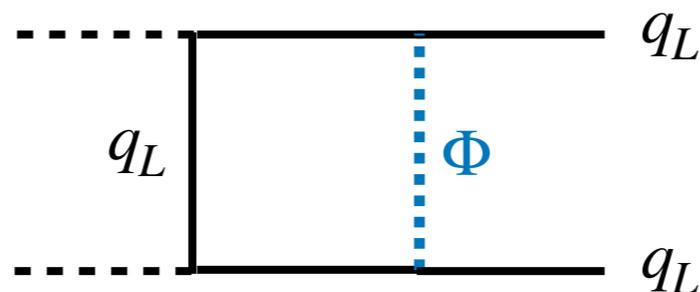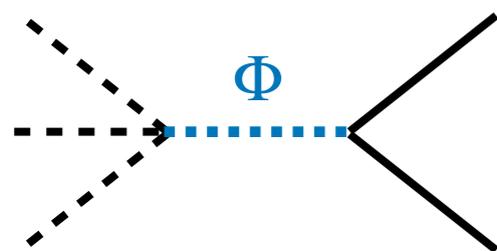
$$C_{dH}, C_{eH} \propto \frac{g_Z Y_{d,e}}{M_A^2}\sin 4\beta \tan \beta$$

$$[C_{Hq}^{(1)}]_{33} \propto \frac{y_t^4 \cot \beta^2}{16\pi^2 M_A^2}\log \frac{m_Z^2}{M_A^2}$$

$$[C_{Hd}]_{33} \propto \frac{y_t^2 y_b^2 \tan \beta^2}{16\pi^2 M_A^2}\log \frac{m_Z^2}{M_A^2}$$

Match

RGE

[Greljo, BAS, Valenti, 2507.03073]

$\mu = M_A$

$\mu = M_Z$

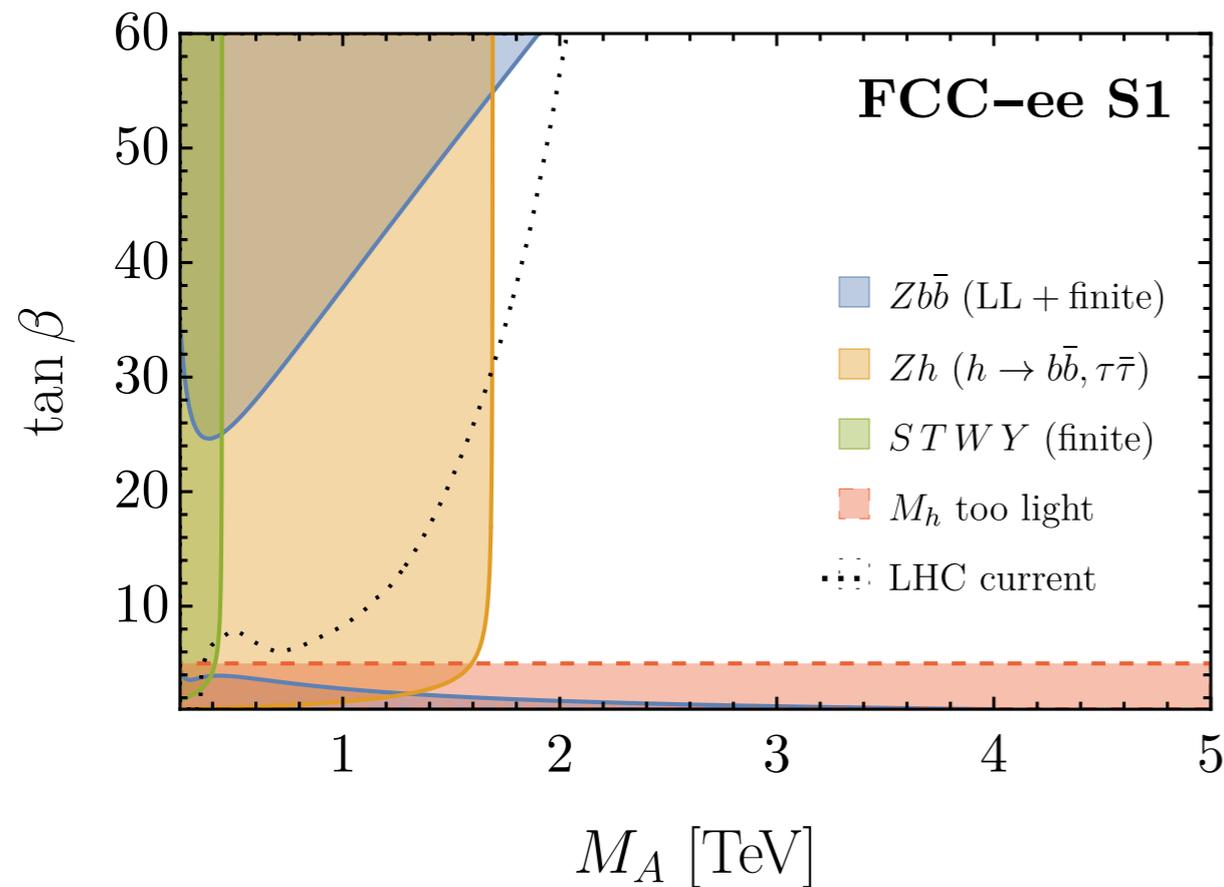# Searching for SUSY at FCC-ee: Heavy Higgs

Higgs couplings

$$g_Z Y_{d,e} \sin 4\beta \tan \beta \rightarrow -4 g_Z Y_{d,e}$$
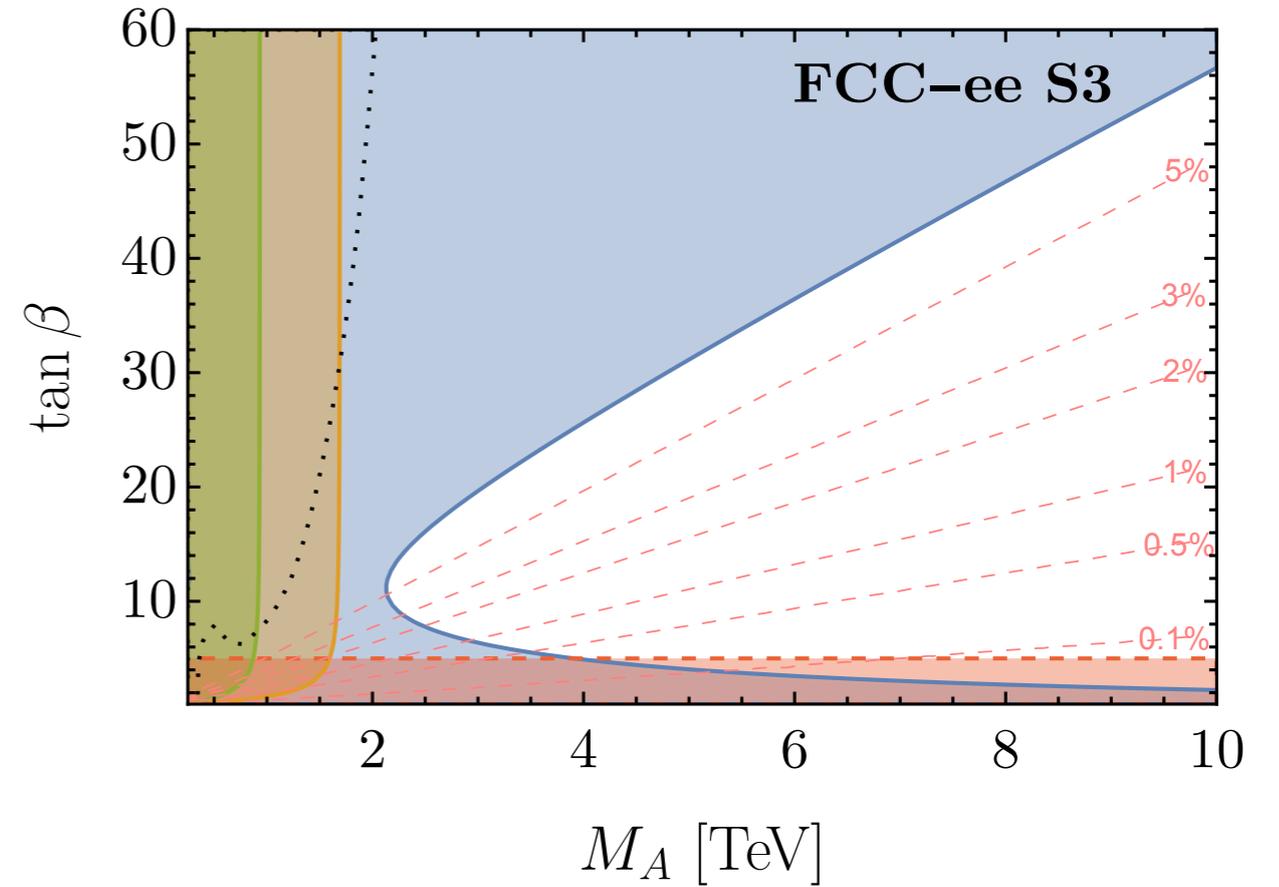
Zbb vertex corrections

$$y_t^2 y_b^2 \tan \beta^2 = y_t^4 \cot^2 \beta \implies \tan \beta = \sqrt{\frac{m_t}{m_b}} \approx 10$$
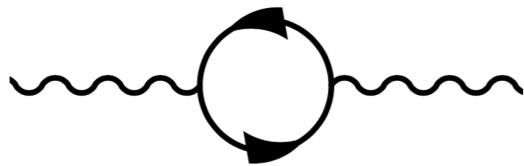
Theory Limited (S1)

Exp. Errors Only (S3)

- Z-pole improvement driven by R_b. Again, huge potential on the SM theory side!
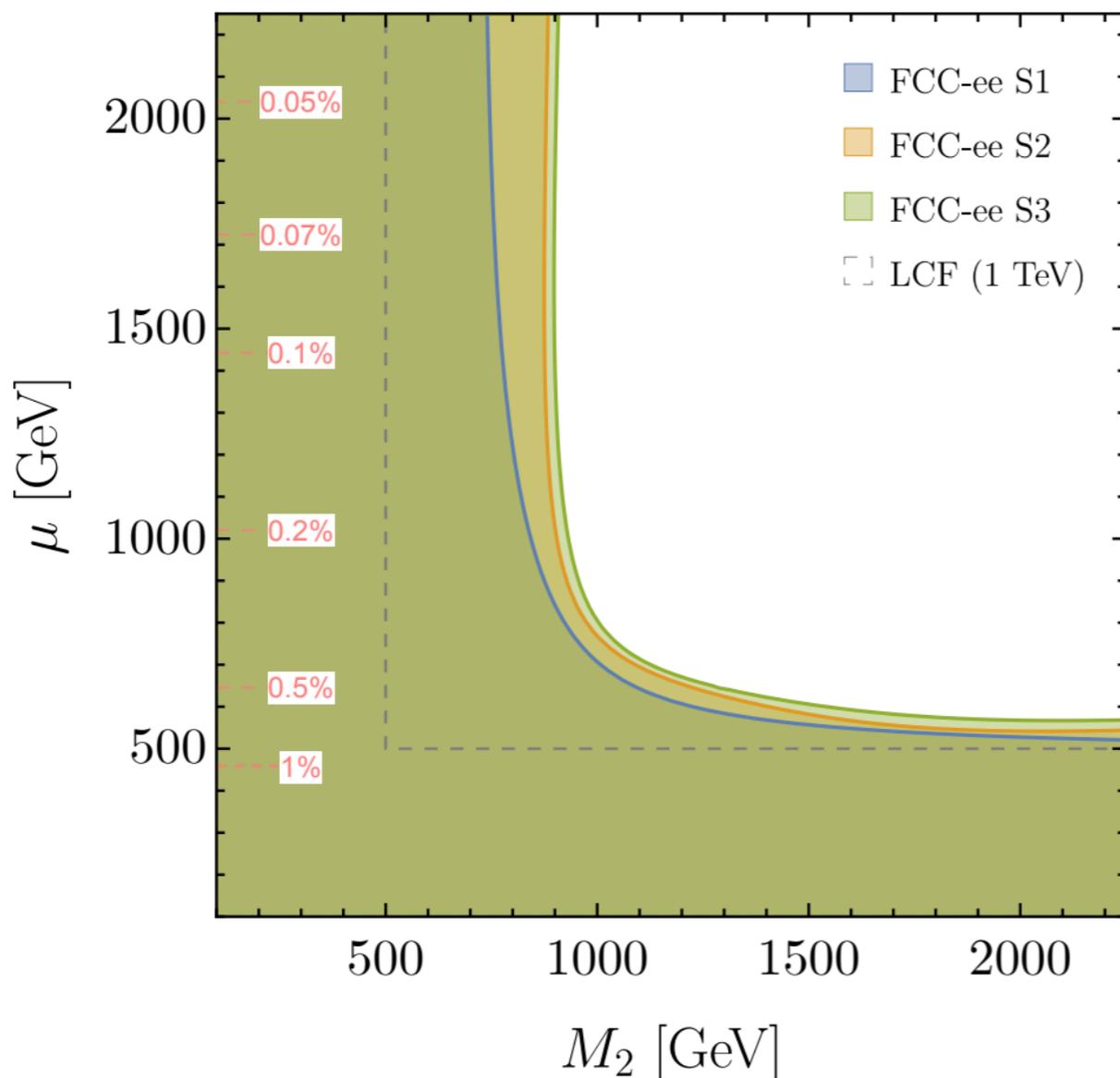
[Greljo, BAS, Valenti, 2507.03073]

Searching for SUSY at FCC-ee: Winos and Higgsinos

● **We also did an STWY fit for Winos and Higgsinos**. Dominated by W-parameter, to which the contributions from all sparticles are additive. Lowest allowed masses!

Recall: $\Pi_{VV}(p^2) = \Pi_{VV}(0) + p^2\Pi'_{VV}(0) + p^4\Pi''_{VV}(0) + \dots$

$$T \qquad\qquad S \qquad\qquad W, Y$$

Wino/Higgsino W+Y Parameters
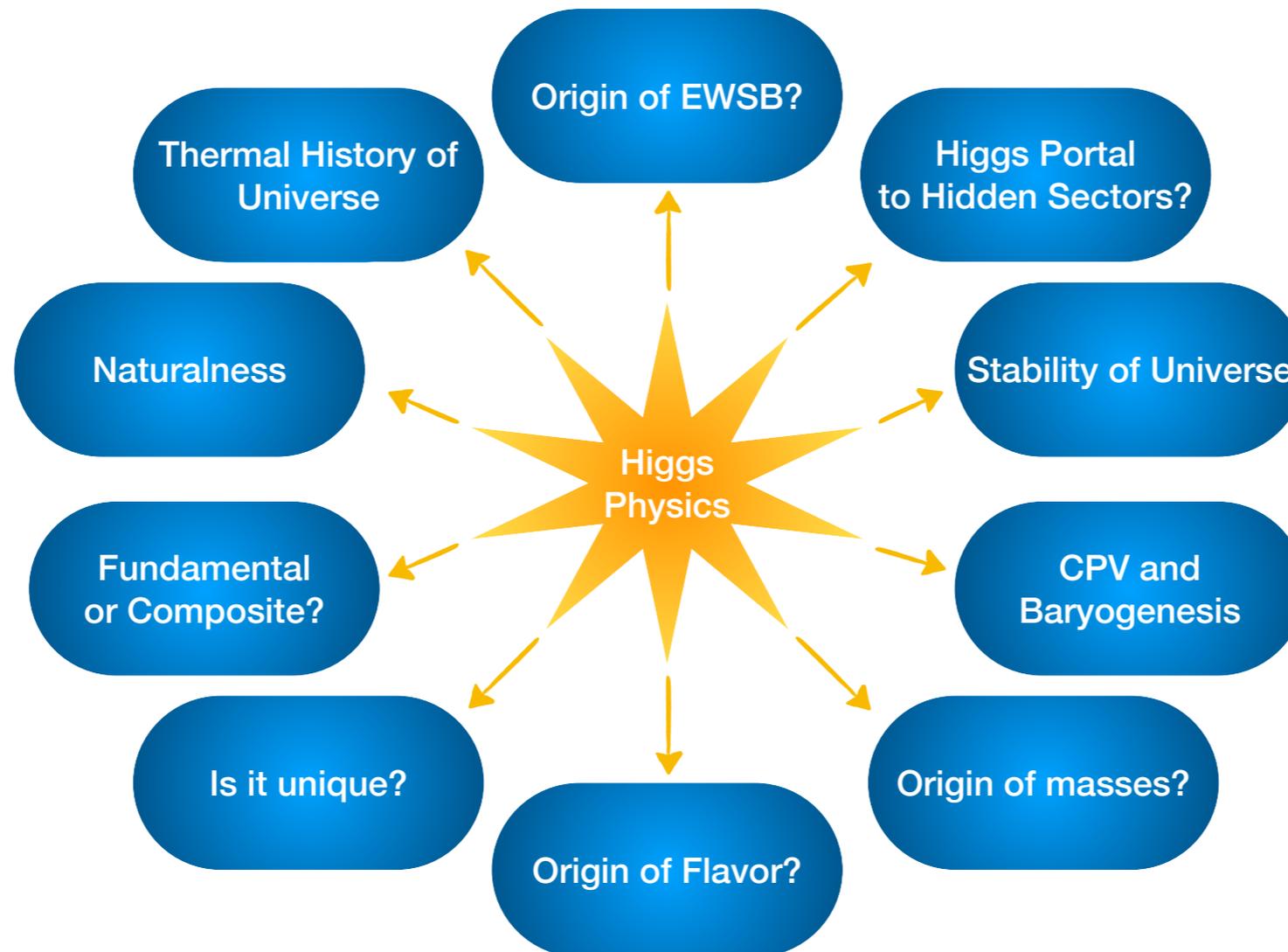
$$\hat{Y} = \frac{\alpha_1}{30\pi}\frac{M_W^2}{\mu^2}$$

$$\hat{W} = \frac{\alpha_2}{30\pi}\left[\frac{M_W^2}{\mu^2} + \frac{2M_W^2}{M_2^2}\right]$$

[Greljo, BAS, Valenti, 2507.03073]

Why TeV-scale new physics?

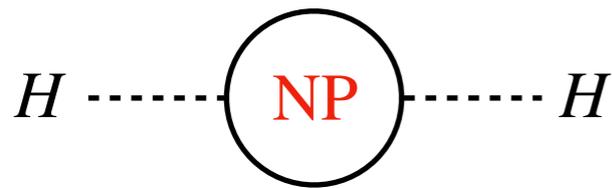***Understanding:*** What is the microscopic theory of the Higgs?

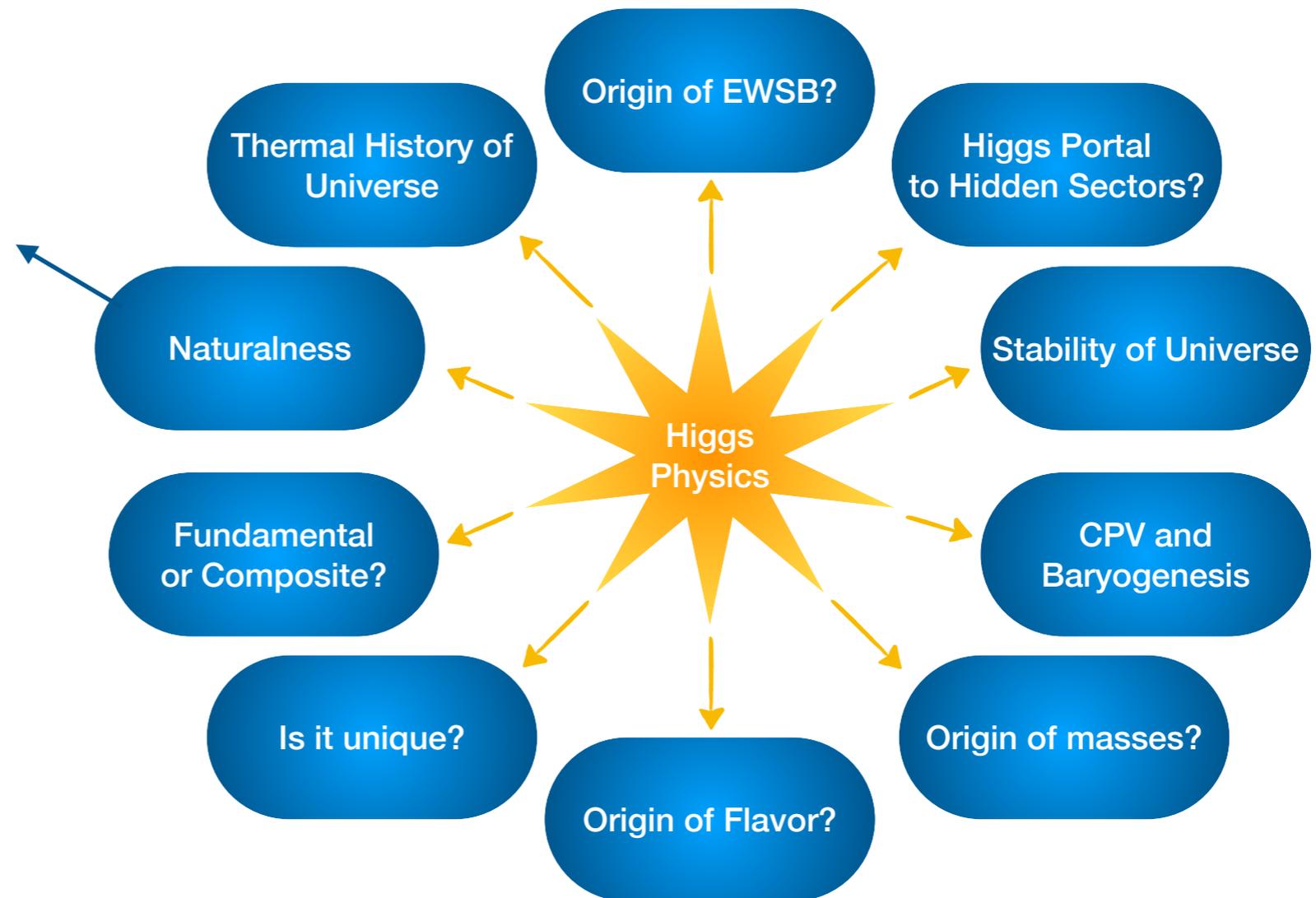[Figure: Dawson, Meade, Ojalvoc, Vernieri, 2209.07510]

Why TeV-scale new physics?

Understanding: What is the microscopic theory of the Higgs?

SM Higgs sector famously
introduces an unstable scale

$$H \cdots \bigcirc\!\!\text{NP} \cdots H$$

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

Puts a theoretical prior
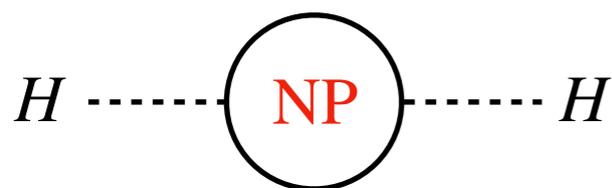on TeV-scale physics!

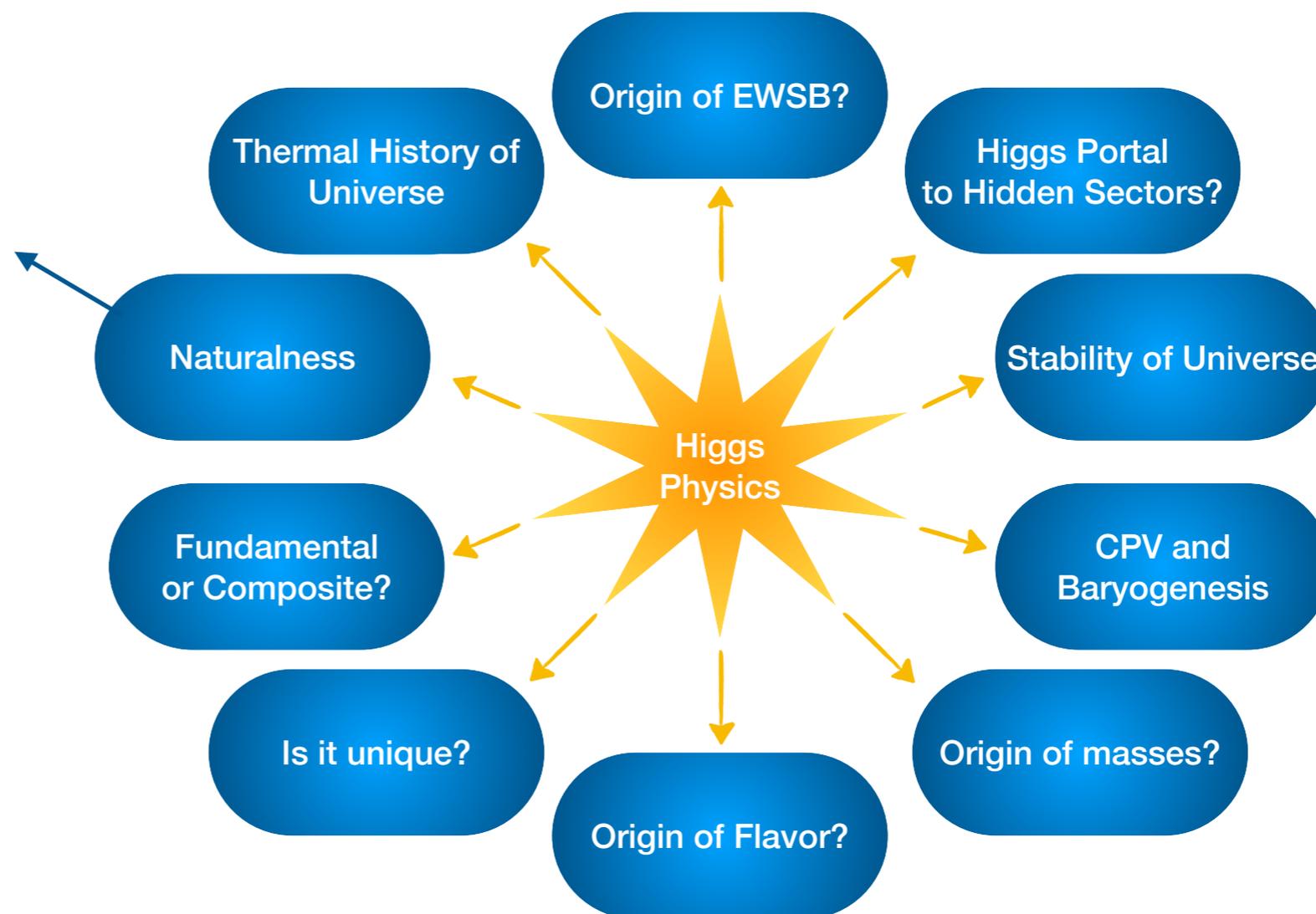[Figure: Dawson, Meade, Ojalvoc, Vernieri, 2209.07510]

Why TeV-scale new physics?

Understanding: What is the microscopic theory of the Higgs?

SM Higgs sector famously introduces an unstable scale

$$H \dashv\!\!\!-\!\!\!\vdash \overset{\bigcirc}{NP} \dashv\!\!\!-\!\!\!\vdash H$$

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

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]