Accuracy complements energy: EW precision at Tera-Z

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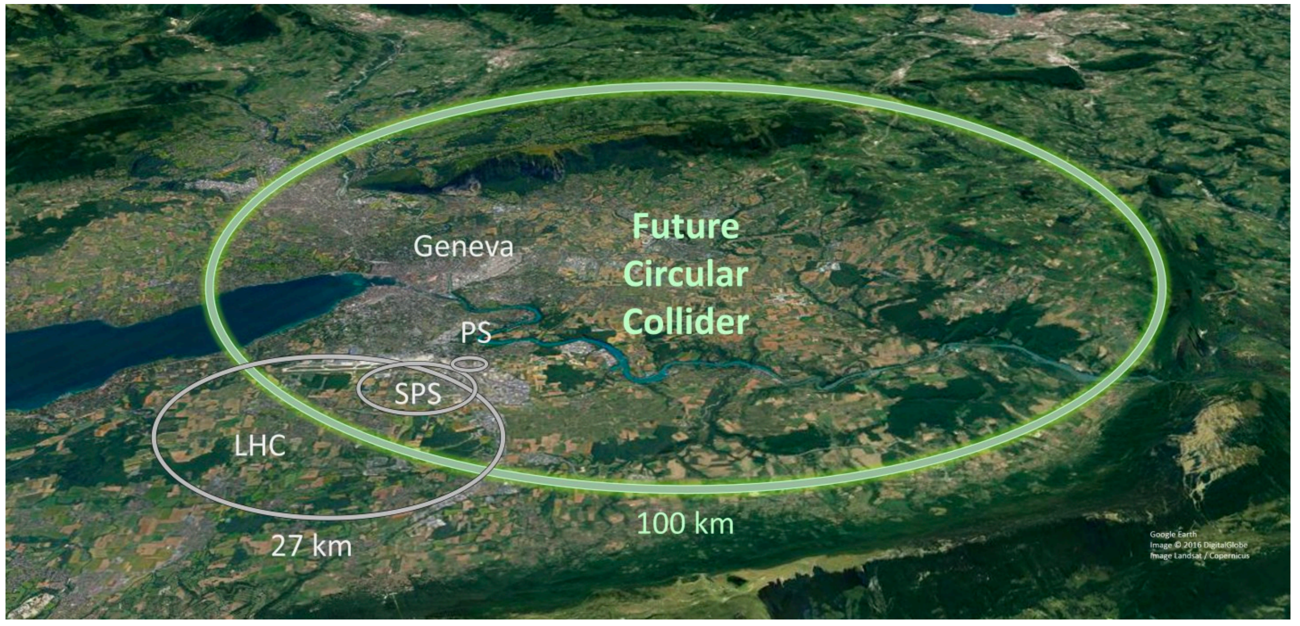

8th FCC Physics Workshop
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[Based on: 2412.14241, 2407.09593, 2311.00020]

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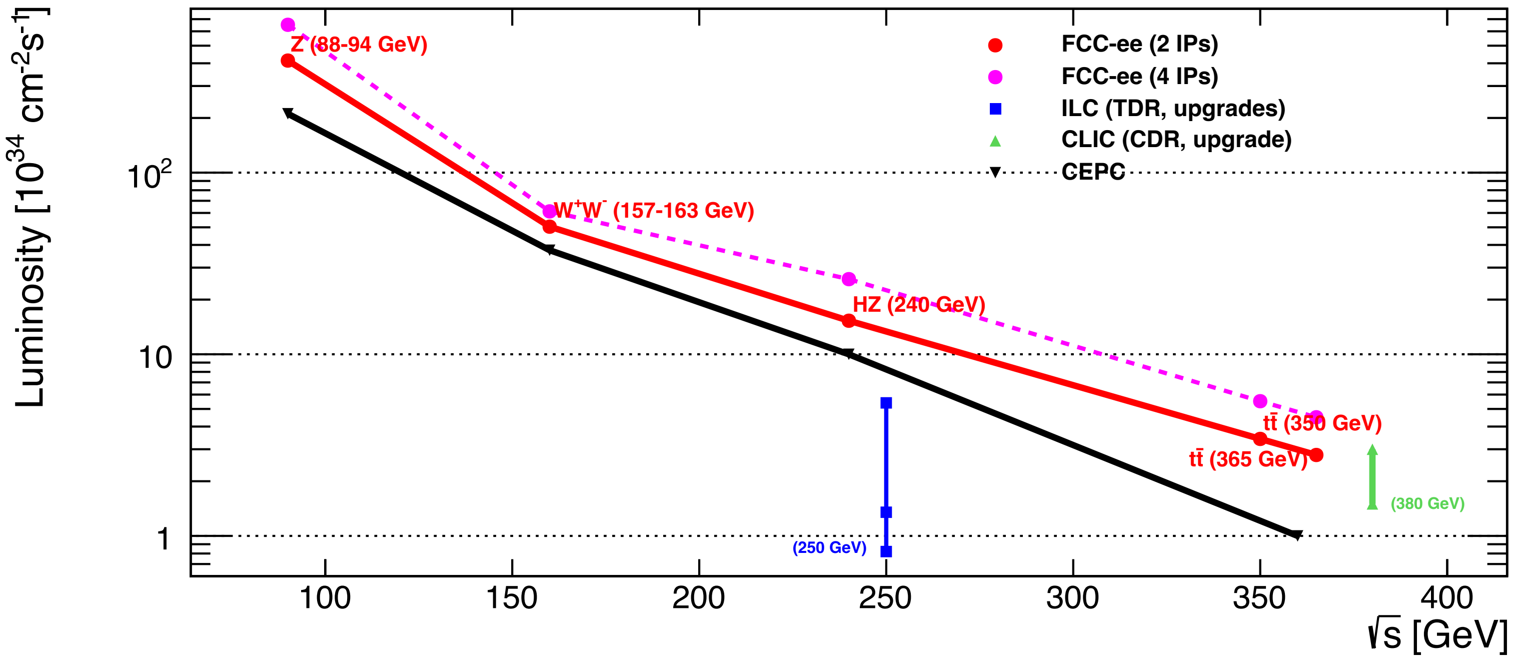
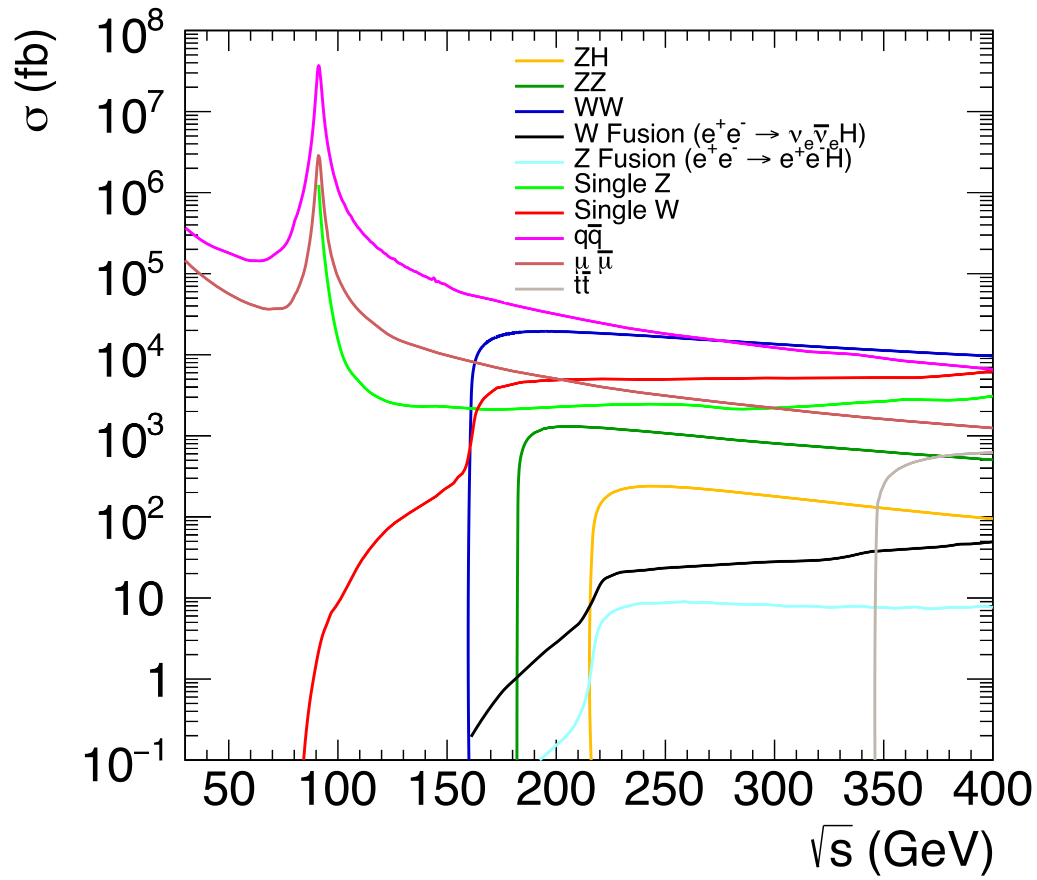
Run plan for FCC-ee





Energy →

Working point	Z years 1-2	Z, later	WW	HZ	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	115	230	28	8.5	0.95	1.55
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34
Physics goal (ab^{-1})	150		10	5	0.2	1.5
Run time (year)	2	2	2	3	1	4
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW → H	10^6 $t\bar{t}$ +200k HZ +50k WW → H	

← **Accuracy**

[FCC Snowmass 2021, 2203.06520]

Accuracy complements energy (ACE) at FCC-ee

- As a general principle, FCC-ee will have similar sensitivity to a given EFT operator both on and off the Z-pole in two main ways:

1. The same operator enters at *leading order off the Z-pole*, as well as at *next-to-leading order on the Z-pole* (similarly for NLO vs NNLO).

$$\Delta^{\rm NLO/LO}_{Z\,{\rm pole}/ZH} \sim \frac{1}{16\pi^2}\frac{\epsilon_Z}{\epsilon_{ZH}}\sqrt{\frac{N_Z}{N_{ZH}}} \sim O(1)\,, \qquad \begin{pmatrix} \epsilon_Z \sim 10^{-1}, & \epsilon_{ZH} \sim 1 \\ N_Z \sim 10^{12}, & N_{ZH} \sim 10^6 \end{pmatrix}$$

2. The same operator enters at *leading order both on and off the Z-pole*, but receives an *energy enhancement off the pole*. This wasn't the case at LEP!

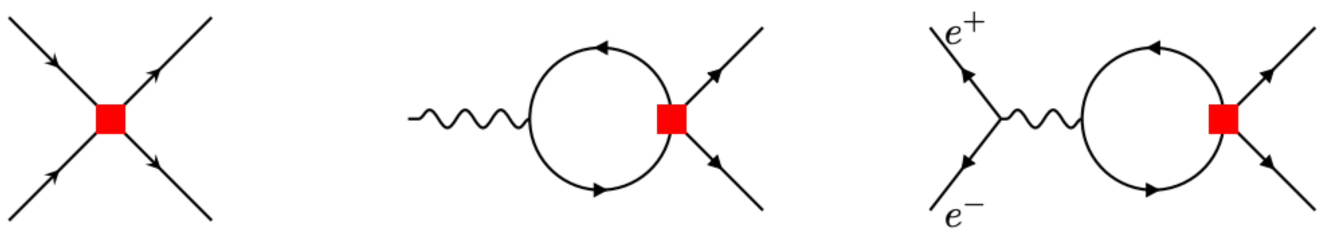
$$\Delta^{\rm LO/LO}_{Z\,{\rm pole}/WW} \sim \frac{m_Z^2}{E_{WW}^2}\frac{\epsilon_Z}{\epsilon_{WW}}\sqrt{\frac{N_Z}{N_{WW}}} \sim O(1)\,, \qquad \begin{pmatrix} E_{WW} \sim 200~\text{GeV} \\ N_Z \sim 10^{12}, \quad N_{WW} \sim 10^8 \end{pmatrix}$$

$$(N_Z/N_{WW})_{\rm LEP} \sim 10^2$$
$$(N_Z/N_{WW})_{\rm FCC} \sim 10^4$$

[Maura, BAS, You, 2412.14241]

Four fermion operators

- So far, this case has received the most attention in the literature. The general summary is that 4F operators with electrons are better off pole, while 4F operators with tops are better on pole. Otherwise, ACE holds + there is similar sensitivity.



(a) Four-fermion operator (b) Z-vertex correction (c) $e^+e^- \to \bar{f}f$

- We use the recent dedicated flavor tagging study for $e^+e^- \to f\bar{f}$ at FCC-ee. Don't miss the *talk by Alessandro Valenti this evening* for the details on this very nice analysis.

[Maura, BAS, You, 2412.14241]

Pure 3rd gen. 4F operators

$\Lambda^{[3333]}$ [TeV]	FCC-ee Z, W-pole+τ	FCC-ee above Z-pole
$\Lambda^{(1)}_{\ell q}$	15.7	1.1
$\Lambda^{(3)}_{\ell q}$	14.0	5.1
Λ_{eu}	16.2	1.6
Λ_{ed}	1.5	1.3
$\Lambda_{\ell u}$	15.4	1.5
$\Lambda_{\ell d}$	1.5	1.3
Λ_{qe}	16.7	1.1
$\Lambda_{\ell\ell}$	1.0	1.0
$\Lambda_{\ell e}$	2.1	1.5
Λ_{ee}	3.5	2.4
$\Lambda^{(1)}_{qq}$	13.1	2.4
$\Lambda^{(3)}_{qq}$	8.4	7.1
$\Lambda^{(1)}_{qu}$	9.4	1.4
$\Lambda^{(1)}_{qd}$	3.1	0.9
Λ_{uu}	12.1	1.9
Λ_{dd}	0.4	2.3
$\Lambda^{(1)}_{ud}$	2.8	1.9

[Greljo, Tiblom, Valenti 2411.02485]

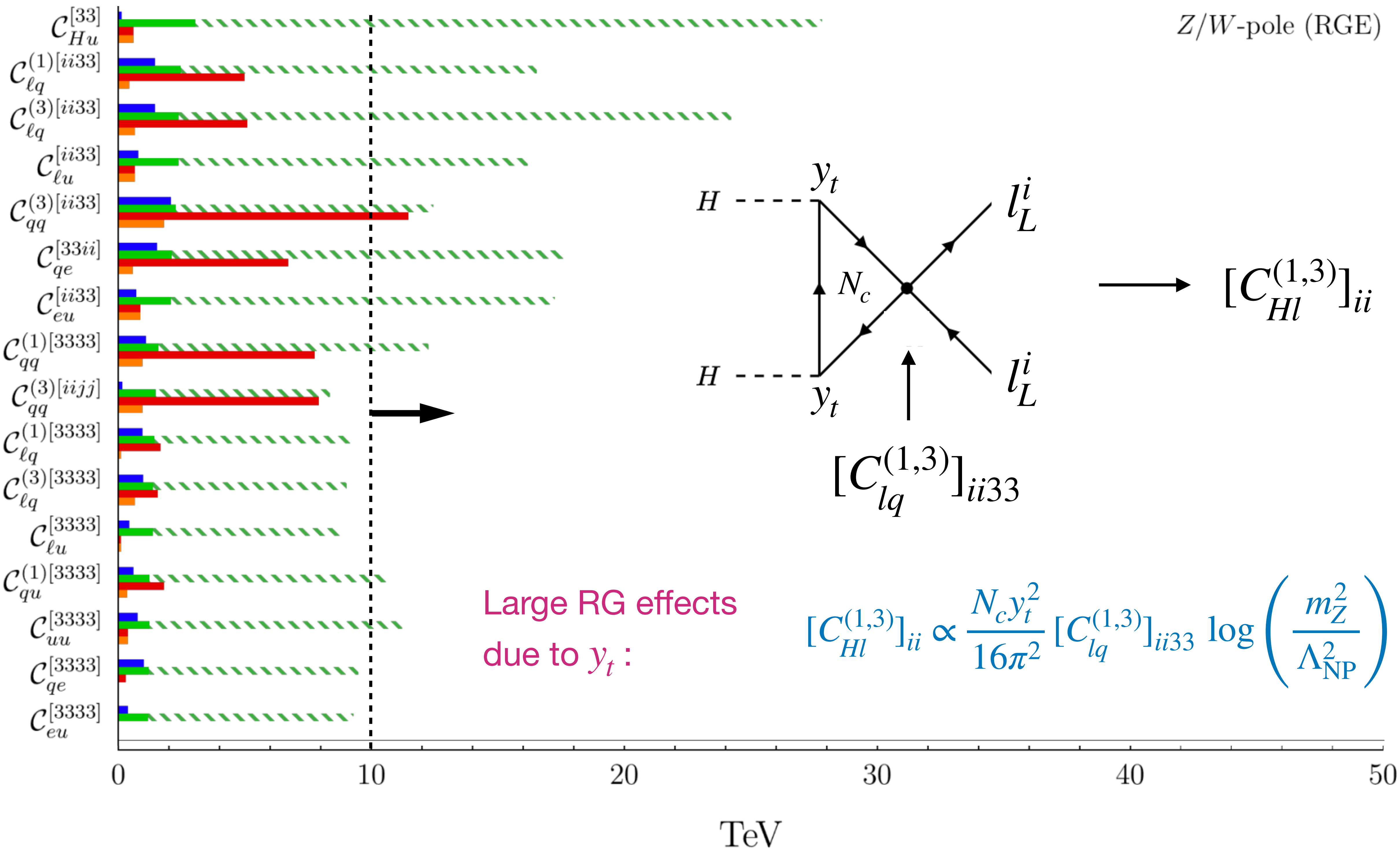
See Alessandro's talk for more!

Four fermion operators

[Allwicher, Cornella, Isidori, BAS, 2311.00020]

See also Lukas Allwicher's talk

- NLO contribution of top operators at the Z-pole (SMEFT perspective)



Large RG effects due to y_t :

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

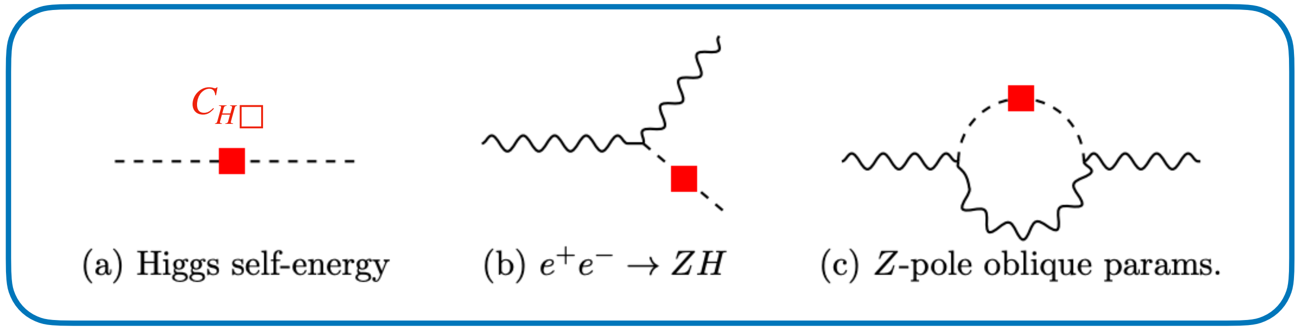
Higgs physics

See also Sally Dawson's talk

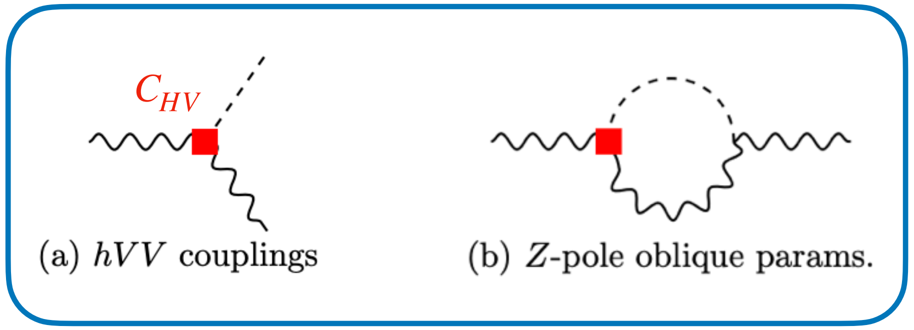
- The cross-section $\sigma(e^+e^- \to ZH)$ is sensitive to 3 (4) dimension-6 operators at LO (NLO) that can modify Higgs couplings:

$$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)\,, \qquad Q_H = (H^\dagger H)^3\,,$$
$$Q_{HW} = (H^\dagger H)W^I_{\mu\nu}W^{I\,\mu\nu}\,, \qquad Q_{HB} = (H^\dagger H)B_{\mu\nu}B^{\mu\nu}\,.$$

- All of these operators also enter the Z-pole at one higher loop order:



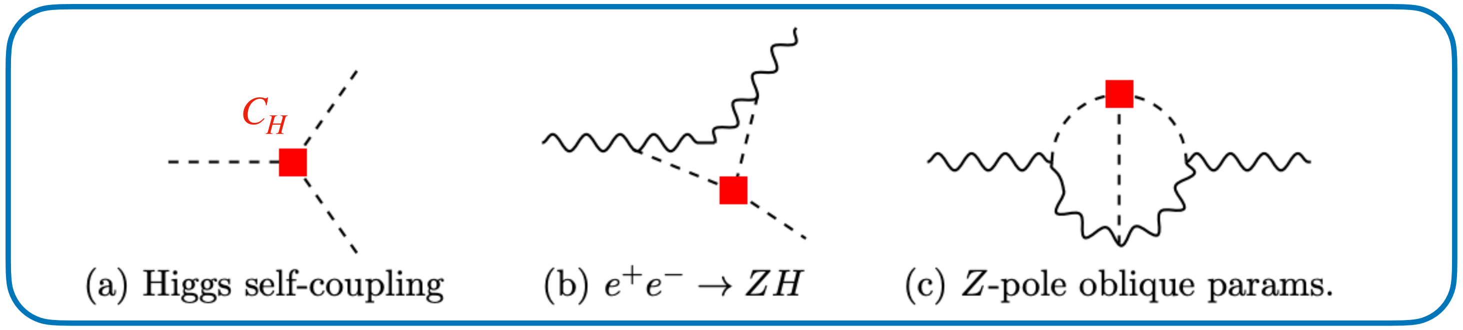
(a) Higgs self-energy (b) $e^+e^- \to ZH$ (c) Z-pole oblique params.



(a) hVV couplings (b) Z-pole oblique params.

Higgs self-coupling modifications starting at NLO (finite):

[1312.3322, 1702.07678, 1702.01737]

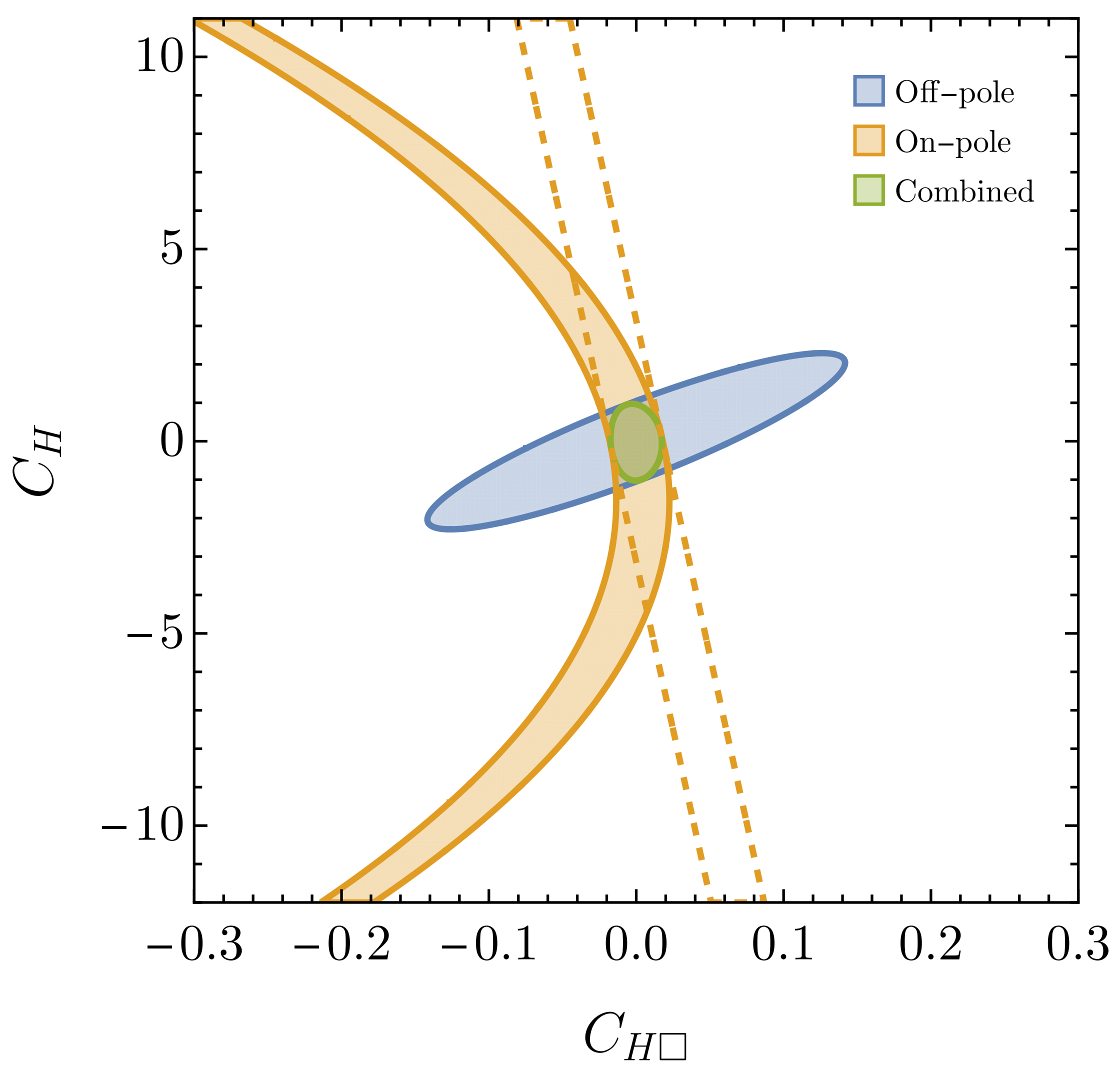


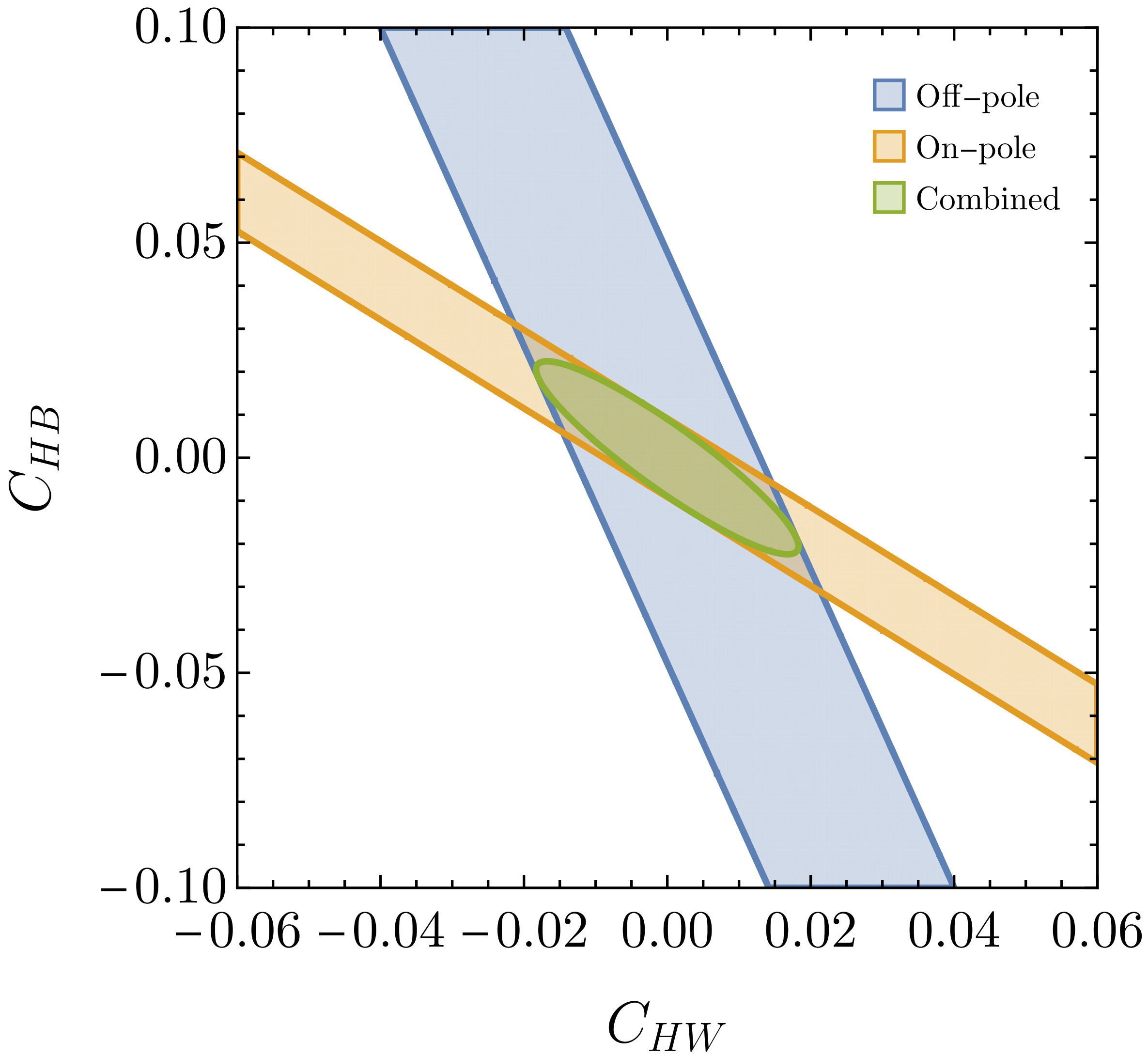
(a) Higgs self-coupling (b) $e^+e^- \to ZH$ (c) Z-pole oblique params.

[Maura, BAS, You, 2412.14241]

Accuracy complements energy for Higgs physics

- Since the Z-pole contributions have a relative one-loop suppression, we expect similar sensitivity via the first principle of accuracy complements energy:





NNLO Oblique Parameters:

$$10^6 \hat{S} = -0.71 C_H - 0.25 C_H^2 \,,$$
$$10^6 \hat{T} = 1.2 C_H + 0.36 C_H^2 \,.$$

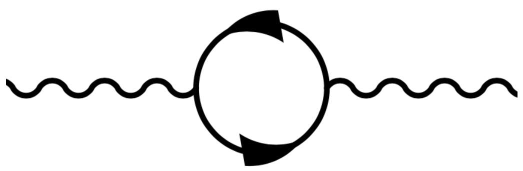
[1702.07678, 1702.01737]

*All Wilson coefficients are in units of TeV^{-2} and are renormalized at 1 TeV

[Maura, BAS, You, 2412.14241]

Gauge sector (2- and 3-point functions)

- We look at modifications of the EW gauge boson propagators (all runs) as well as modifications of gauge 3-point functions (aTGC).



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

$\Pi_{VV}(0) \downarrow T$, $p^2\Pi'_{VV}(0) \downarrow S$, $p^4\Pi''_{VV}(0) \downarrow W, Y$

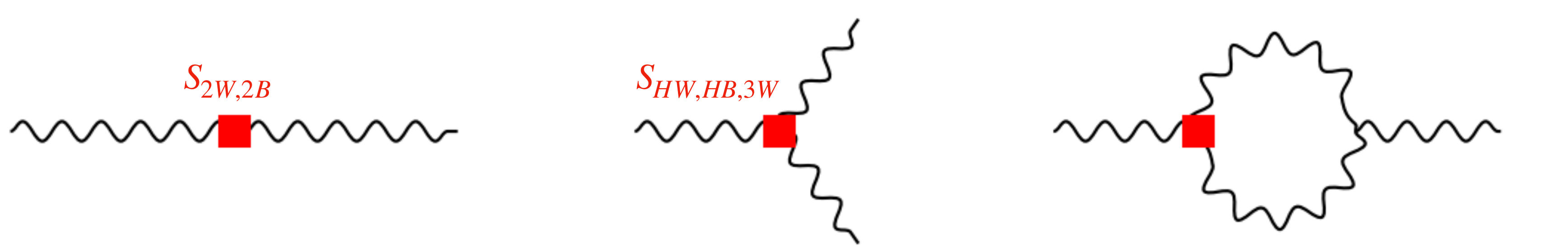
*S+T much better on-pole ← T

aTGC

$$\mathcal{O}_{HW} = i(D^\mu H)^\dagger \tau^I (D^\nu H) W^I_{\mu\nu}\,,$$
$$\mathcal{O}_{HB} = i(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}\,,$$
$$\mathcal{O}_{3W} = \varepsilon_{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}\,.$$

W+Y parameters

$$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu})\,,$$
$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^I_{\mu\nu})(D_\rho W^{I\rho\nu})\,,$$

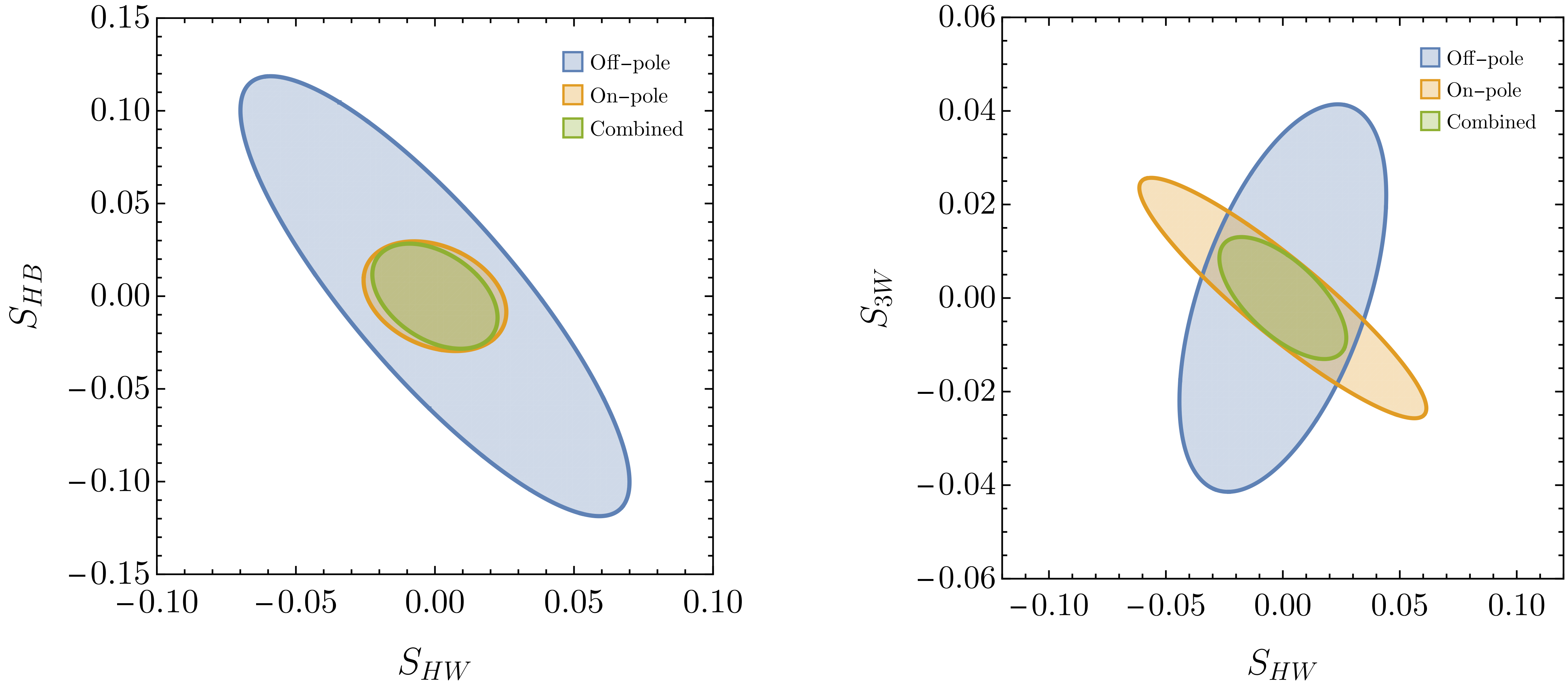


(a) W+Y parameters (b) aTGC (c) NLO Z-pole oblique params.

[Maura, BAS, You, 2412.14241]

Gauge sector: Anomalous triple gauge couplings

- Again, Z-pole contributions have a relative one-loop suppression. The Z-pole gives a better constraint on $\mathcal{O}_{HB}$, otherwise the sensitivity is similar.



$$\mathcal{O}_{HB} = \mathcal{O}_B - \frac{1}{2}\mathrm{y}_h g_1 Q_{HB} - \frac{1}{4}g_2 Q_{HWB}\,,$$

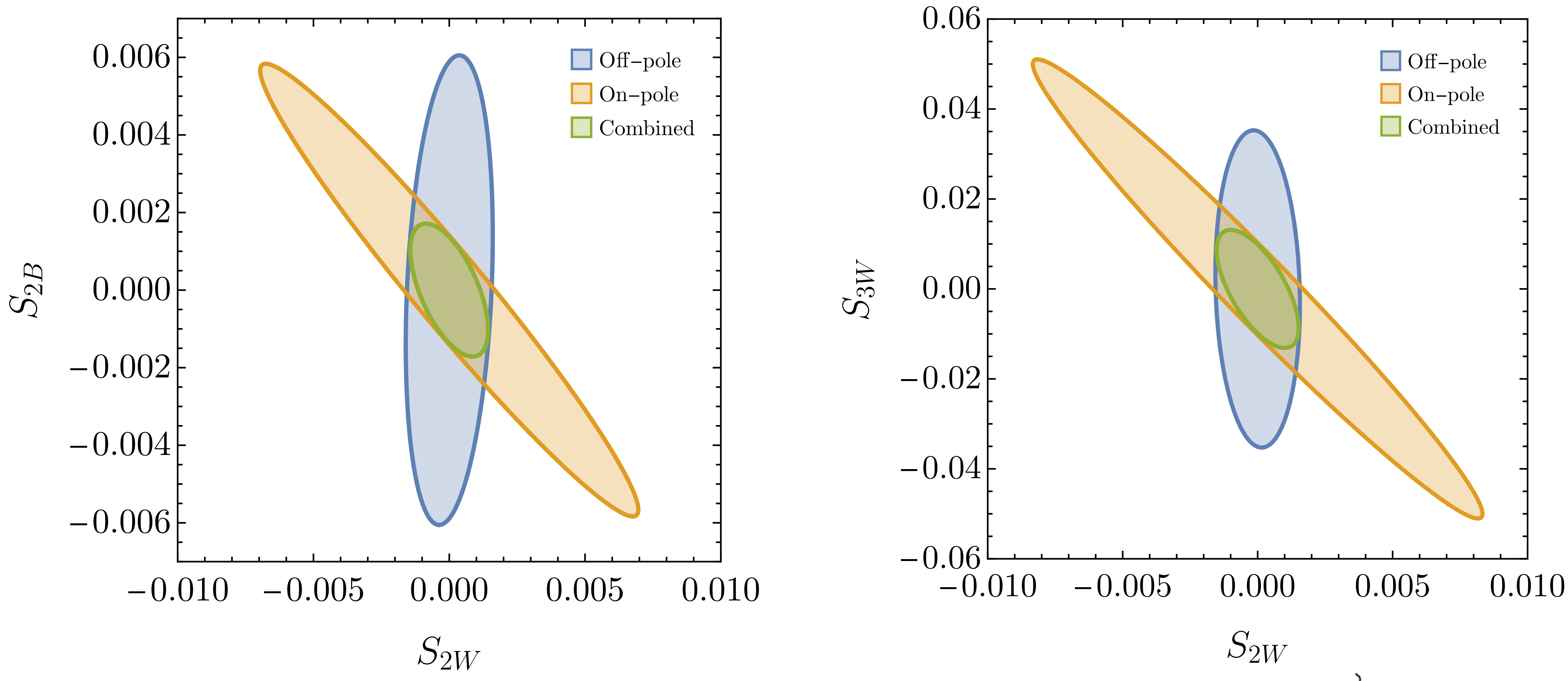
$$\mathcal{O}_{HW} = \mathcal{O}_W - \frac{1}{4}g_2 Q_{HW} - \frac{1}{2}\mathrm{y}_h g_1 Q_{HWB}\,,$$

*Otherwise flat direction for off-pole data is broken by $\sigma(ZH)$ sensitivity to $\mathcal{O}_{HW,HB}$.

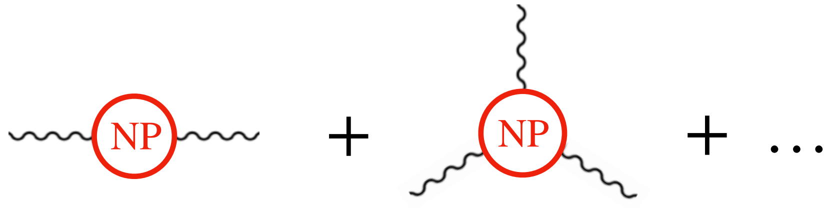
[Maura, BAS, You, 2412.14241]

Gauge sector: W+Y and correlation with aTGC

- The W+Y parameters contribute at LO both on and off the pole, but the off-pole energy enhancement is compensated by Z-pole statistics.



*In agreement with 2411.02485, both W+Y can be constrained at the 10^{-5} level, a factor of 10 better than current leading bounds from LHC.



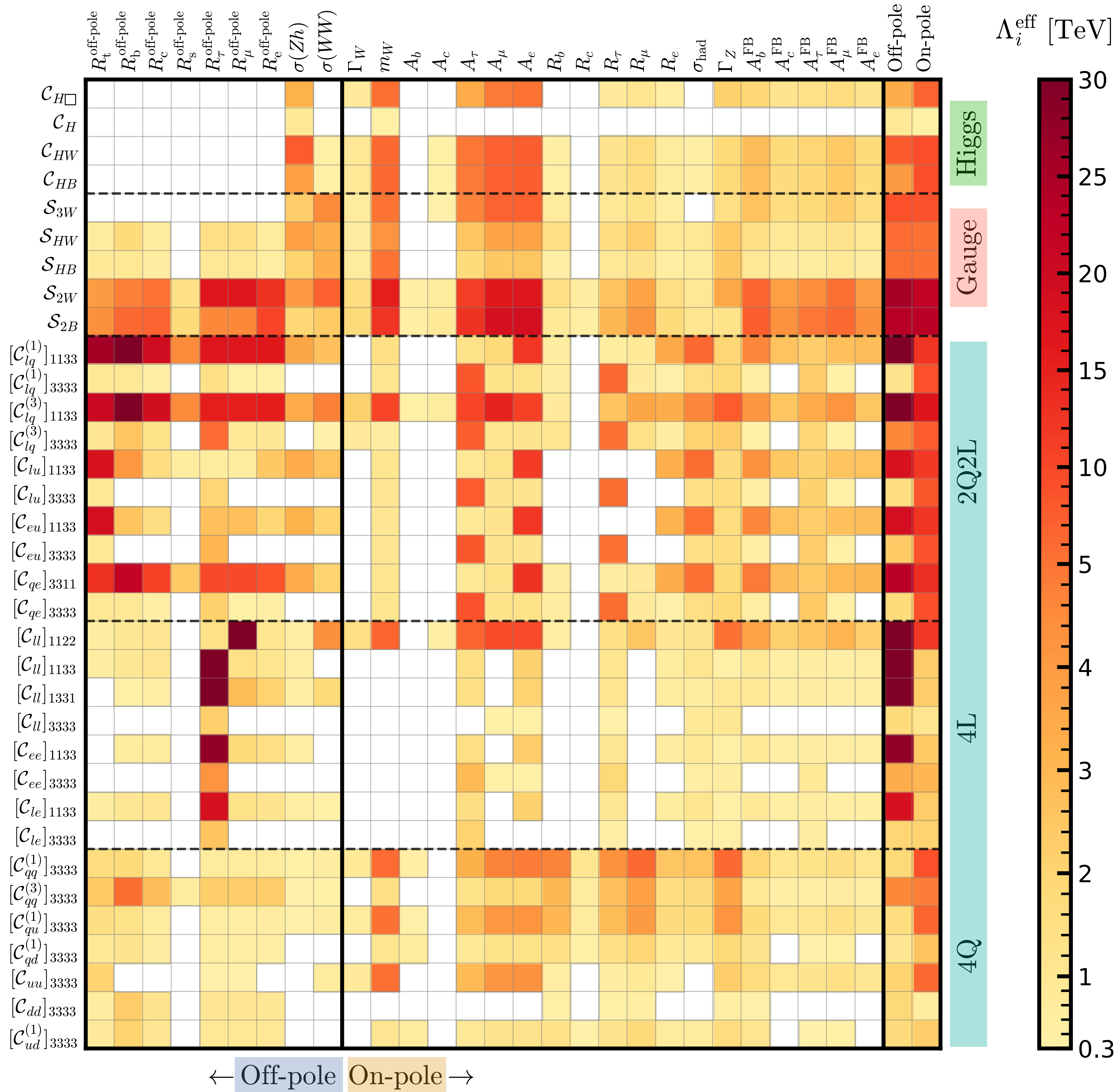
[Greljo, Tiblom, Valenti 2411.02485]

[Maura, BAS, You, 2412.14241]

Accuracy complements energy: EFT summary plot

Some comments

- All Z-pole contributions are NLO except W+Y.
- Still, the typical sensitivity is in the 10 TeV ballpark.
- Most important Z-pole observables: m_W, A_l
- Good complementarity on and off the pole for the Higgs and gauge sectors.
- Z-pole always wins or competes for 4F operators with tops.
- Off pole wins for operators with electrons, otherwise the two are complementary.



[Maura, BAS, You, 2412.14241]

Accuracy complements energy in specific UV models

Real singlet scalar model (with Z_2 symmetry)

- *Why do we care about it?* Simplest extension of the SM that allows for a first order EW phase transition and hardest "loryon" to probe experimentally.

$$\mathscr{L}_\phi = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{2}\kappa |H|^2 \phi^2 - \frac{1}{4!}\lambda_\phi \phi^4$$

- Integrating out ϕ at 1 loop generates finite contributions to only two operators, namely $Q_{H\Box}$ and Q_H. The matching conditions at the scale m_ϕ are

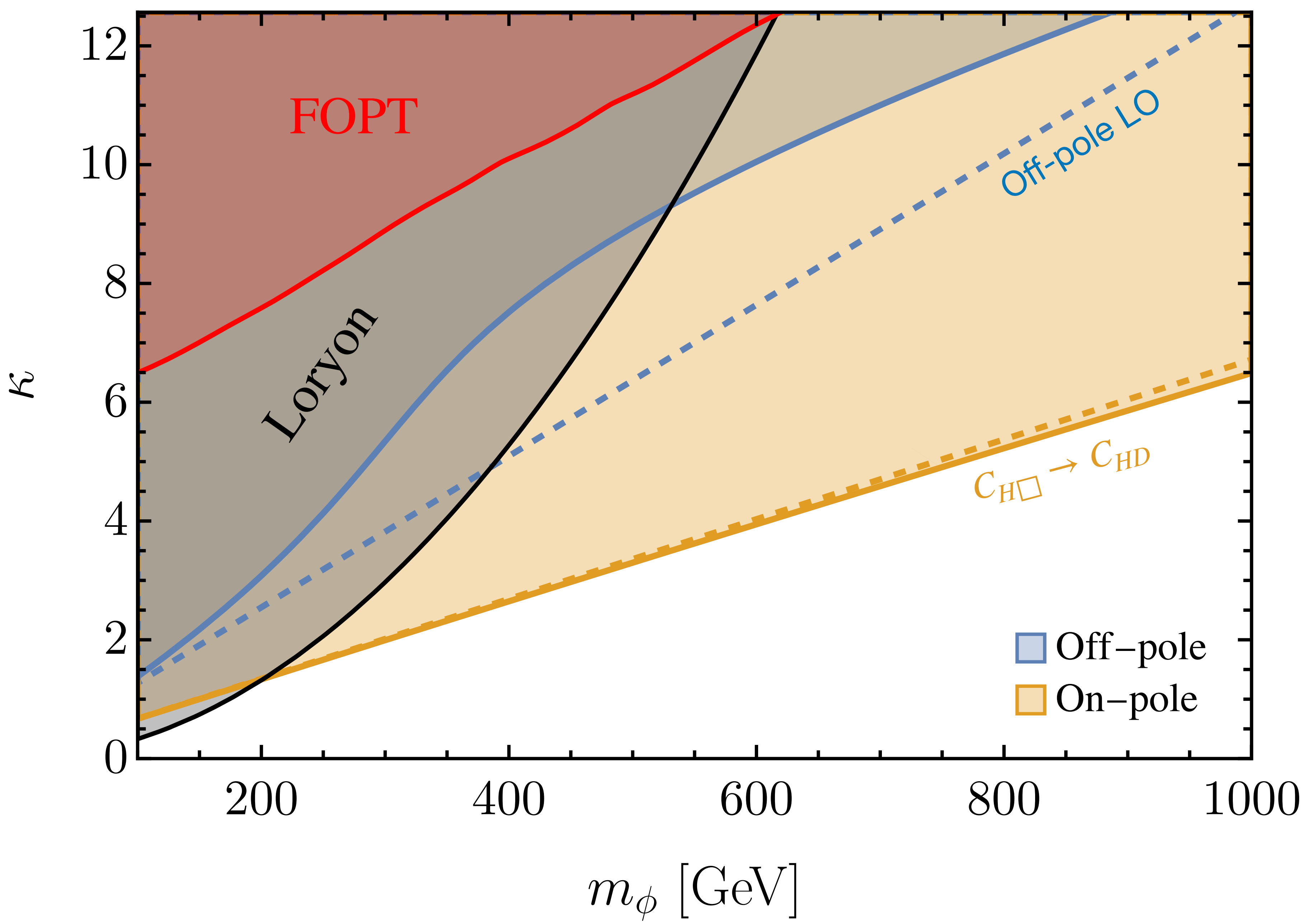
$$C_{H\Box} = -\frac{1}{16\pi^2}\frac{\kappa^2}{24 m_\phi^2}, \qquad C_H = -\frac{1}{16\pi^2}\frac{\kappa^3}{12 m_\phi^2}.$$

Off-pole:	LO (ZH)	NLO (ZH)
On-pole:	NLO	NNLO

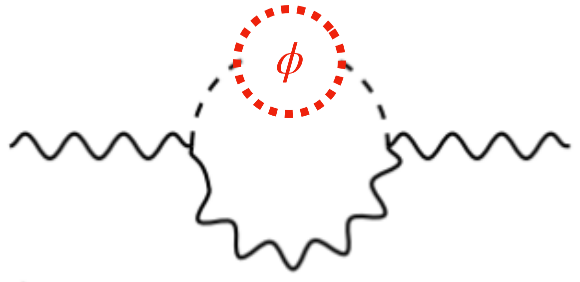
[Maura, BAS, You, 2412.14241]

Real singlet scalar model (with Z_2 symmetry)

- Full NLO result gives a weaker off-pole constraint due to a partial cancellation between the $Q_{H\Box}$ and Q_H contributions to $\sigma(ZH)$. Better constraint from Z-pole!



- Both Z-pole and ZH can exclude the region where a first order EWPT can occur.
- EFT breaks down for $m_\phi \lesssim v_{\rm EW}$, to know the correct result for low mass, need to compute S+T at 2-loops in the RSS model:



[Maura, BAS, You, WIP]

[Crawford, Sutherland, 2409.18177]

[Maura, BAS, You, 2412.14241]

Weakly interacting massive particles

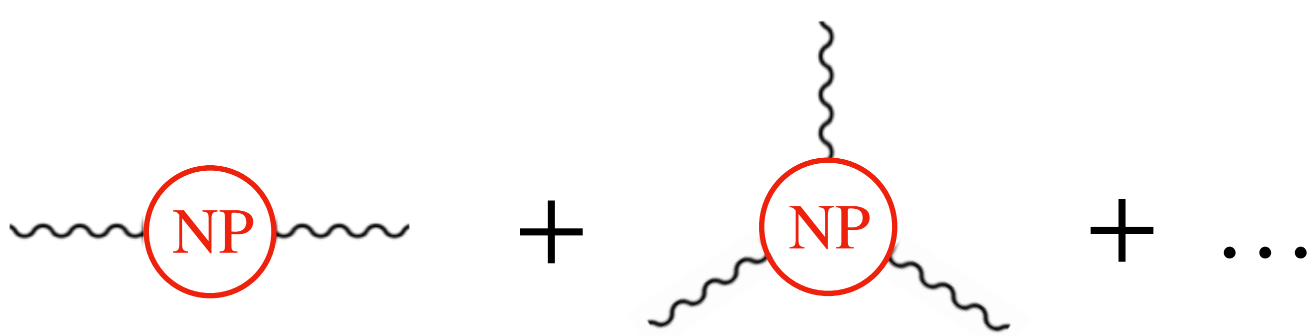
- *Why do we care about them?* Completely generic possibility that BSM states could carry EW charges, one of the simplest models for dark matter.

- Assuming an n-tuplet of $SU(2)_L$ with hypercharge Y that interacts with the SM only via EW gauge interactions, the full d6 EFT Lagrangian reads

$$\mathscr{L}_{\rm EFT}^{d=6} = -\frac{S_{2B}}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu}) - \frac{S_{2W}}{2}(D^\mu W^I_{\mu\nu})(D_\rho W^{I\rho\nu}) + S_{3W}\, \epsilon_{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$$

with the following matching conditions at the scale $M_{\rm WIMP}$:

$$S_{2B} = \frac{g_1^2}{16\pi^2}\frac{nY^2}{30M^2_{\rm WIMP}}N_2, \qquad S_{2W} = \frac{g_2^2}{16\pi^2}\frac{n(n^2-1)}{360M^2_{\rm WIMP}}N_2, \qquad S_{3W} = \frac{g_2^3}{16\pi^2}\frac{n(n^2-1)}{2160M^2_{\rm WIMP}}N_3\,,$$

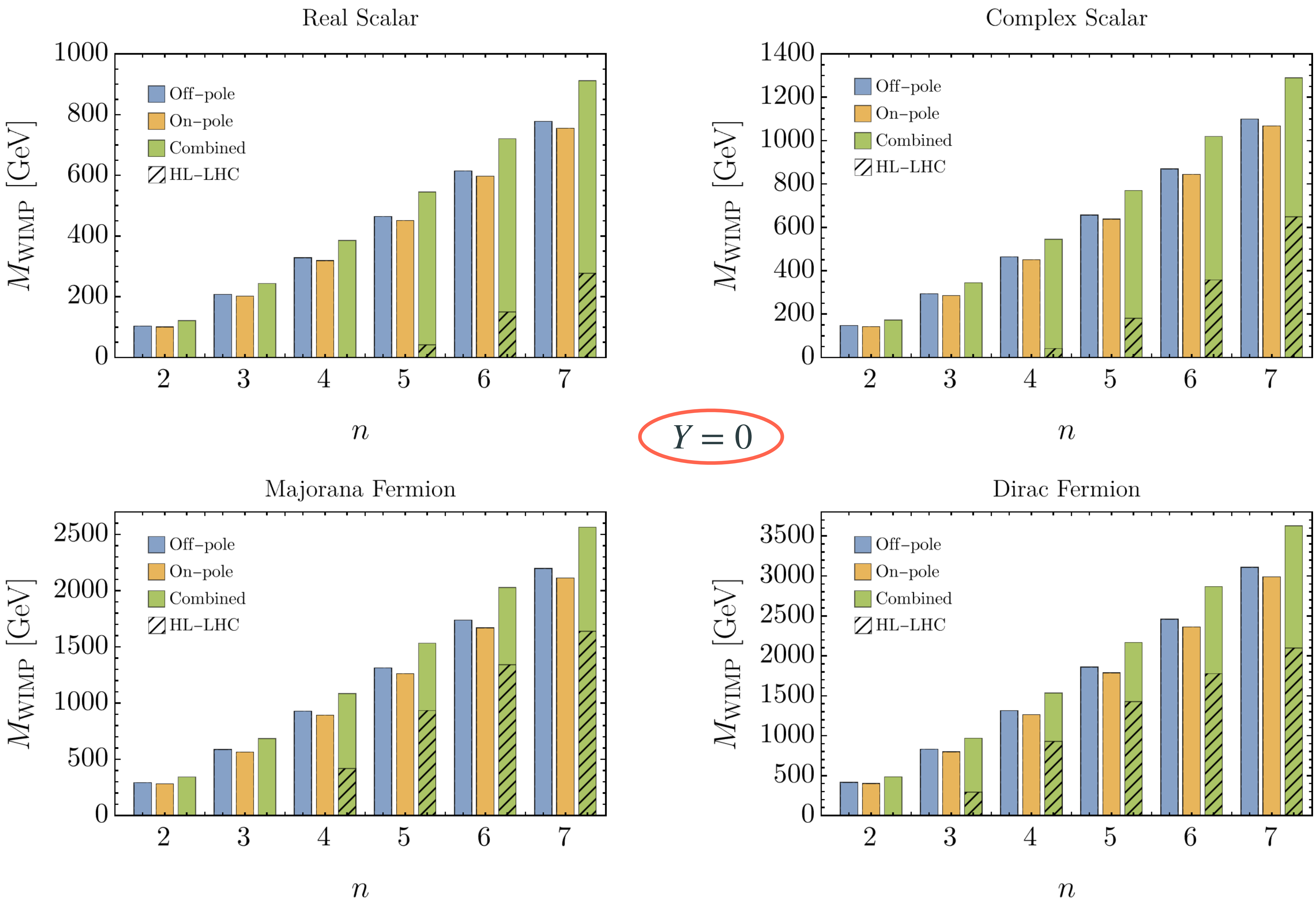


	RS, CS, MF, DF
$N_2 =$	$1/2, 1, 4, 8$
$N_3 =$	$1/2, 1, -1, -2$

[Maura, BAS, You, 2412.14241]

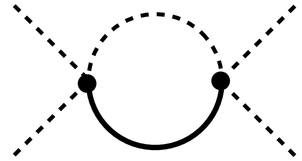
Weakly interacting massive particles

[Maura, BAS, You, 2412.14241]
[Di Luzio, Gröber, Panico, 1810.10993]



Custodial quadruplet model

4 Higgs operators at 1-loop:



- *Why do we care about it?* At tree level, the model generates only the $|H|^6$ operator. Interesting example for Higgs factories as it allows for sizable Higgs self-coupling deviations, with effects in other operators relegated to the 1-loop level.

New states: $\Theta_1 \sim \mathbf{4}_{1/2}\,, \quad \Theta_3 \sim \mathbf{4}_{3/2} \longrightarrow \boldsymbol{\Theta} \sim (\mathbf{4},\mathbf{4}) \quad \text{of} \quad SU(2)_L \times SU(2)_R$

$$\mathscr{L}_{\rm CQ} \supset -M_4^2\left(|\Theta_1|^2 + |\Theta_3|^2\right) - \lambda_4\left(H^*H^*(\varepsilon H)\Theta_1 + \frac{1}{\sqrt{3}}H^*H^*H^*\Theta_3\right) + \mathrm{h.c.}$$

-The full 1-loop matching at dimension-6 can be written in two lines:

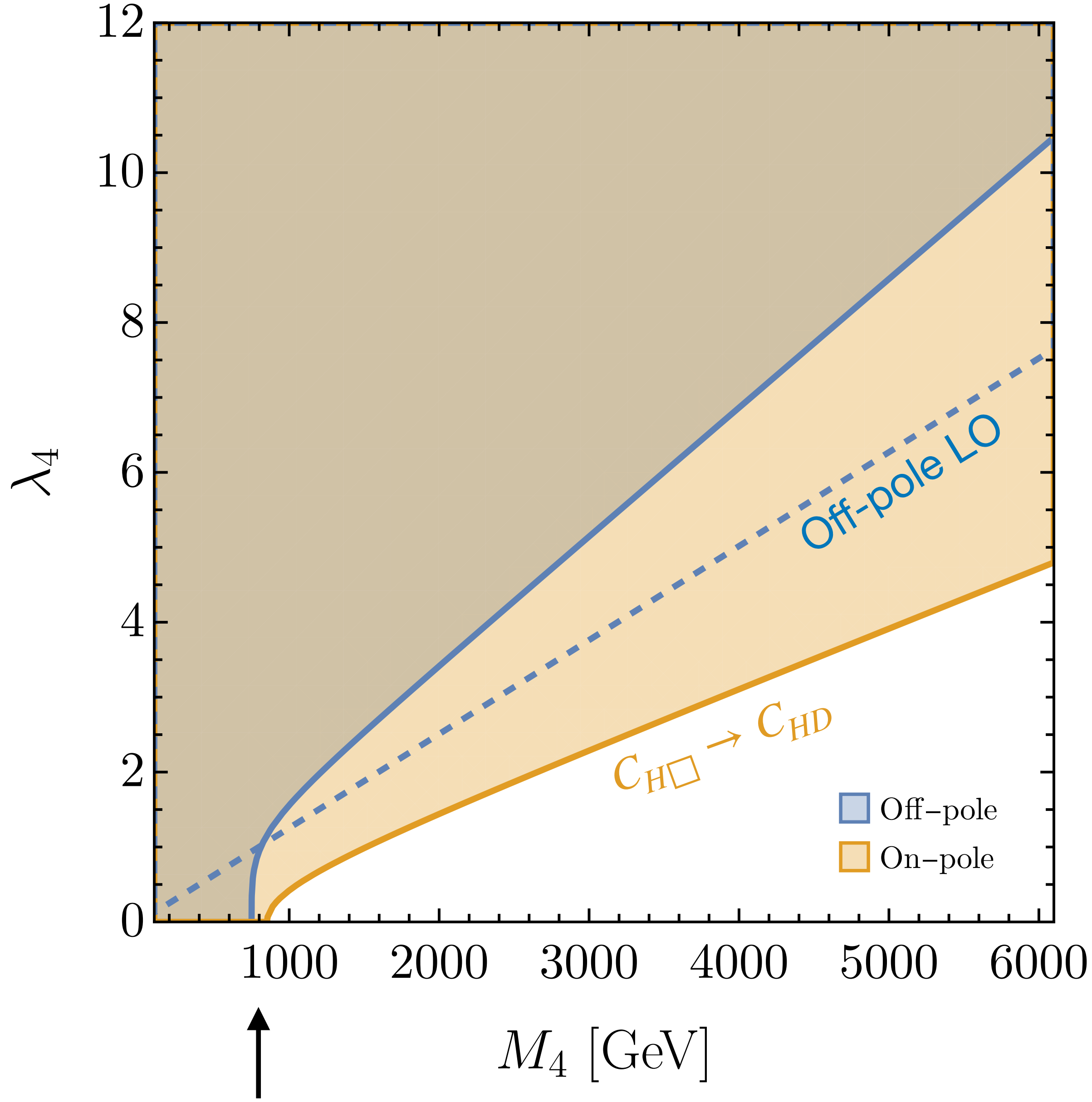
$$\mathscr{L}_{\rm CQ}^{\rm d=6} = \frac{2}{3}\frac{\lambda_4^2}{M_4^2}\left(1 + \frac{21\lambda_{\rm SM}}{16\pi^2}\right)|H|^6 + \frac{\lambda_4^2}{4\pi^2 M_4^2}|H|^2\Box|H|^2 - \frac{\lambda_4^2}{3\pi^2 M_4^2}|H|^2(H^\dagger D^2 H + \mathrm{h.c.})$$
$$+\frac{1}{48\pi^2 M_4^2}\left[\frac{g_2^3}{3!}\epsilon_{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu} - \frac{g_1^2}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu}) - \frac{g_2^2}{2}(D^\mu W^I_{\mu\nu})(D_\rho W^{I\rho\nu})\right]$$

[Durieux, McCullough, Salvioni 2209.00666]

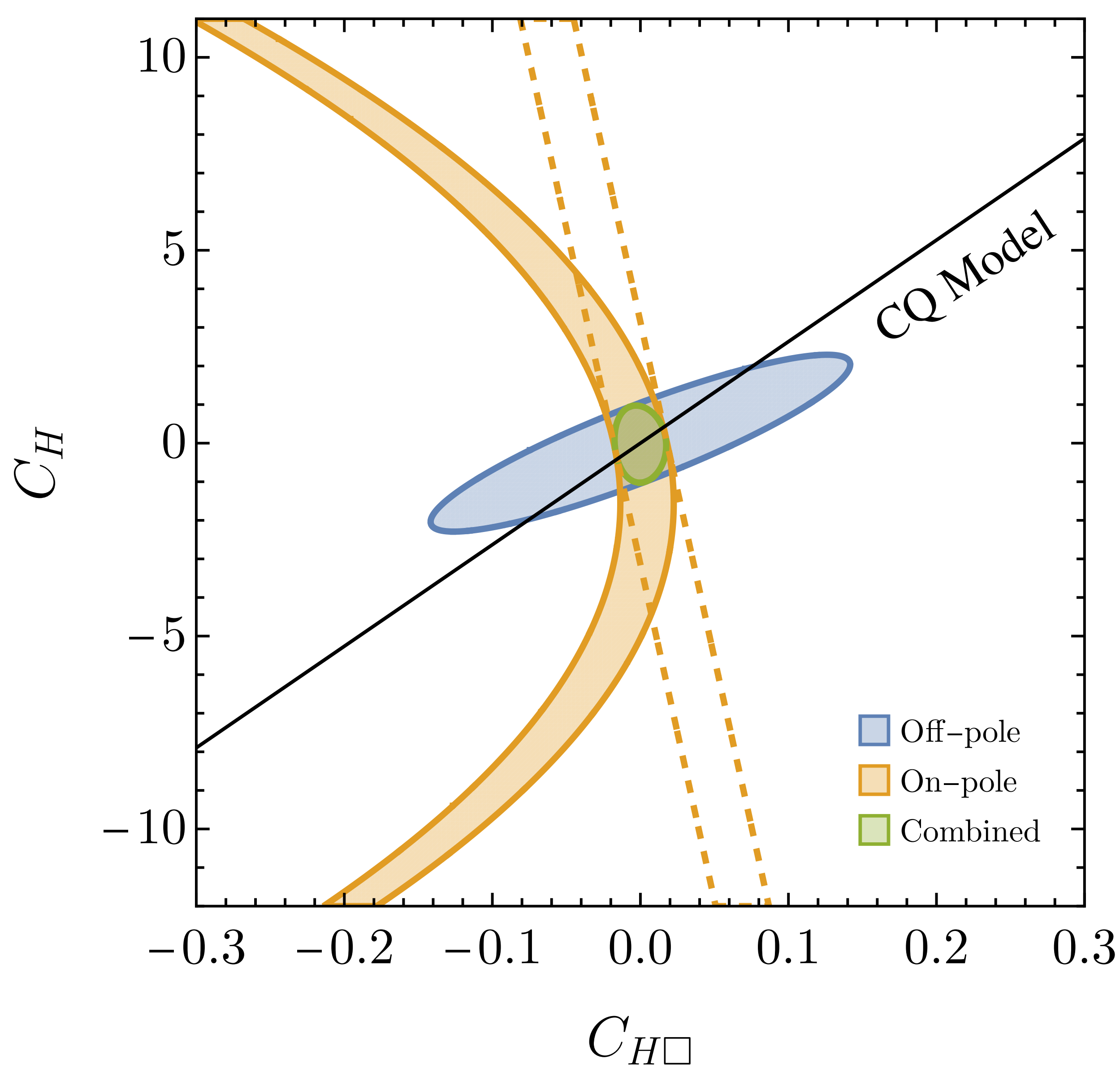
[Maura, BAS, You, 2412.14241]

Custodial quadruplet model

- While $C_{H\Box}$ is 1-loop and C_H is tree, the reverse is true in how they affect $\sigma(ZH)$, so they contribute similarly, but with the opposite sign. Again, partial cancellation!



*Lower λ_4-independent bound on the mass comes from W+Y parameters.



*Off-pole direction not fully flat because we include $\sigma(ZH)$ at 240+365 GeV.

Conclusions

- The Tera-Z run has access at NLO (or even NNLO) to many Wilson coefficients that are typically thought to be better constrained at LO off the pole. It is a simple counting argument to see that, in general, a similar sensitivity to these Wilson coefficients is expected at Tera-Z.

- The same is true for operators that enter both on and off pole at LO, but are energy enhanced off the pole. The prototypical example here is the electroweak W+Y parameters, which can be constrained at the 10^{-5} level in both cases.

- A Tera-Z program will thus anticipate much of the BSM physics at higher energy runs. Accuracy will complement energy since on- and off-pole data can be combined to break flat directions and increase the overall FCC-ee sensitivity to new physics.

- The dominant Tera-Z probes are higher loop contributions to the oblique S+T parameters (seen as shifts in m_W and A_l). Because many operators contribute to these beyond LO, making our analysis fully rigorous via a global SMEFT fit seems very difficult (especially at 2 loops).

- However, one can disentangle the various contributions and make concrete statements in the context of specific UV models. To illustrate this point, we gave several well-motivated examples where the model sensitivity does indeed benefit from combining on- and off-pole data.

Backup

Non-universality of composite Higgs models

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

These operators are usually ignored via the following arguments:

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

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

[BAS, 2407.09593]

Universal operators in composite Higgs models

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

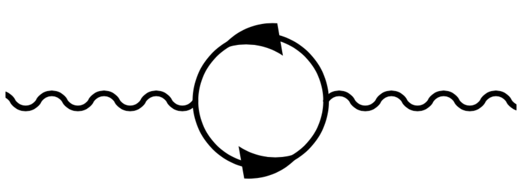
Flavor universal bosonic operators	
$\mathcal{O}_H = \frac{1}{2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$	$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \overleftrightarrow{D}^\mu H)$
$\mathcal{O}_W = i\frac{g_2}{2}(H^\dagger \overleftrightarrow{D}^I_\mu H)D_\nu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

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

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

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

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



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

$\Pi_{VV}(0) \rightarrow T$, $\quad p^2\Pi'_{VV}(0) \rightarrow S$, $\quad p^4\Pi''_{VV}(0) \rightarrow W, Y$

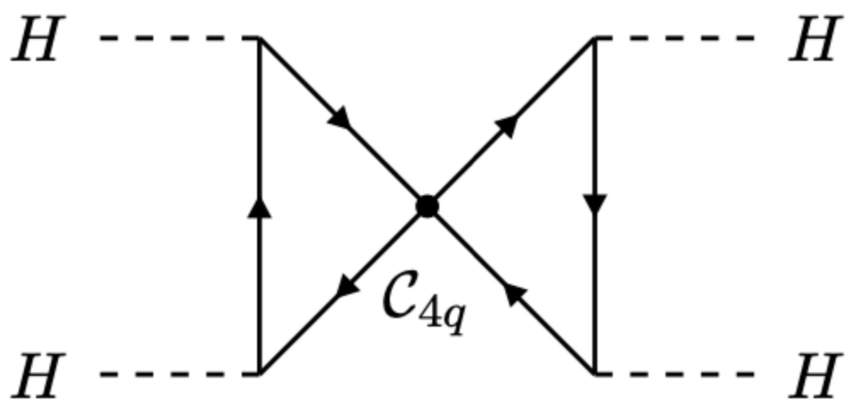
[BAS, 2407.09593]

The full 2-loop contribution to the T parameter

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

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

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



$\Longrightarrow$

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

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

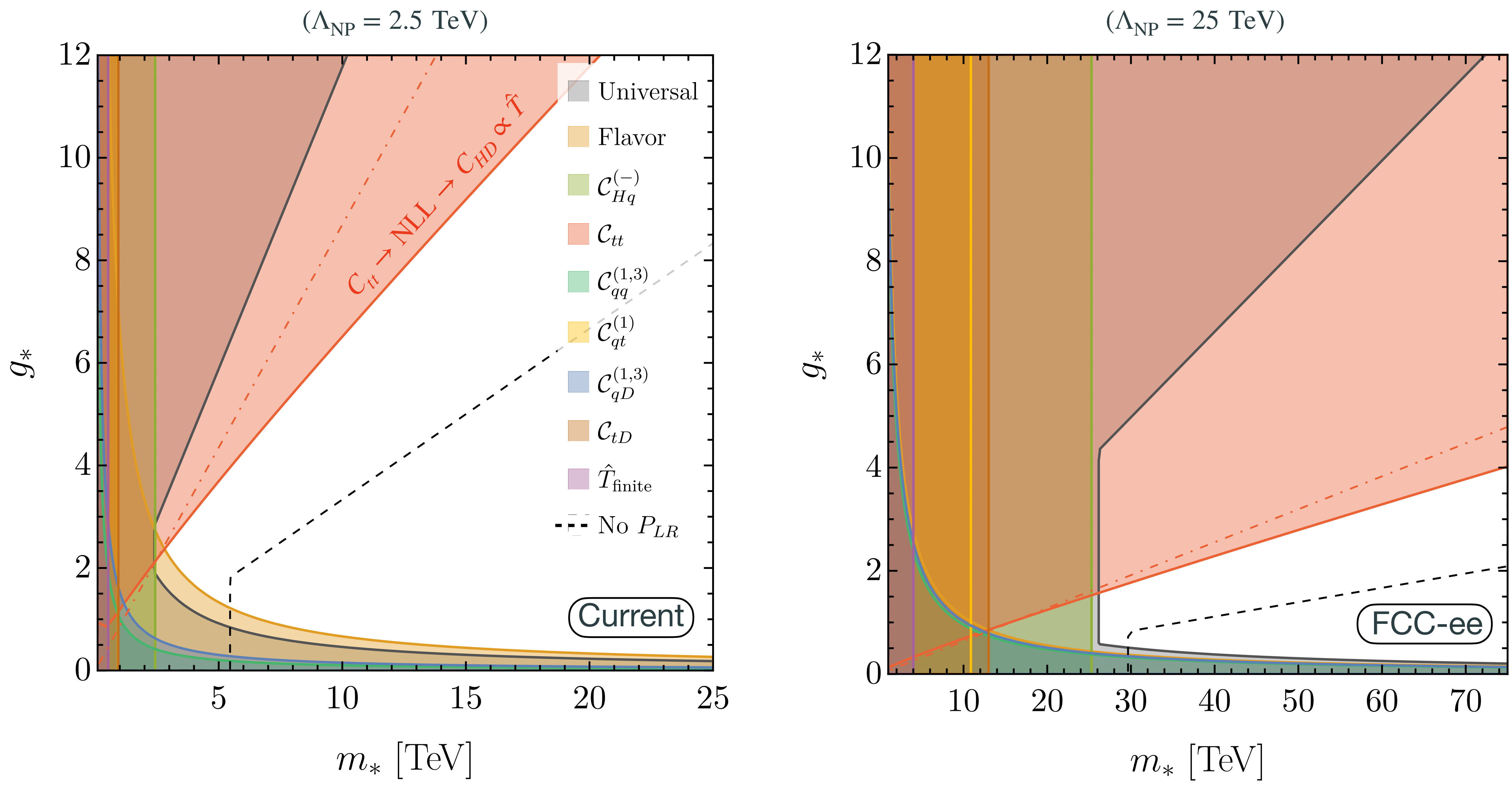
[BAS, 2407.09593]

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

Results: Right compositeness

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

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

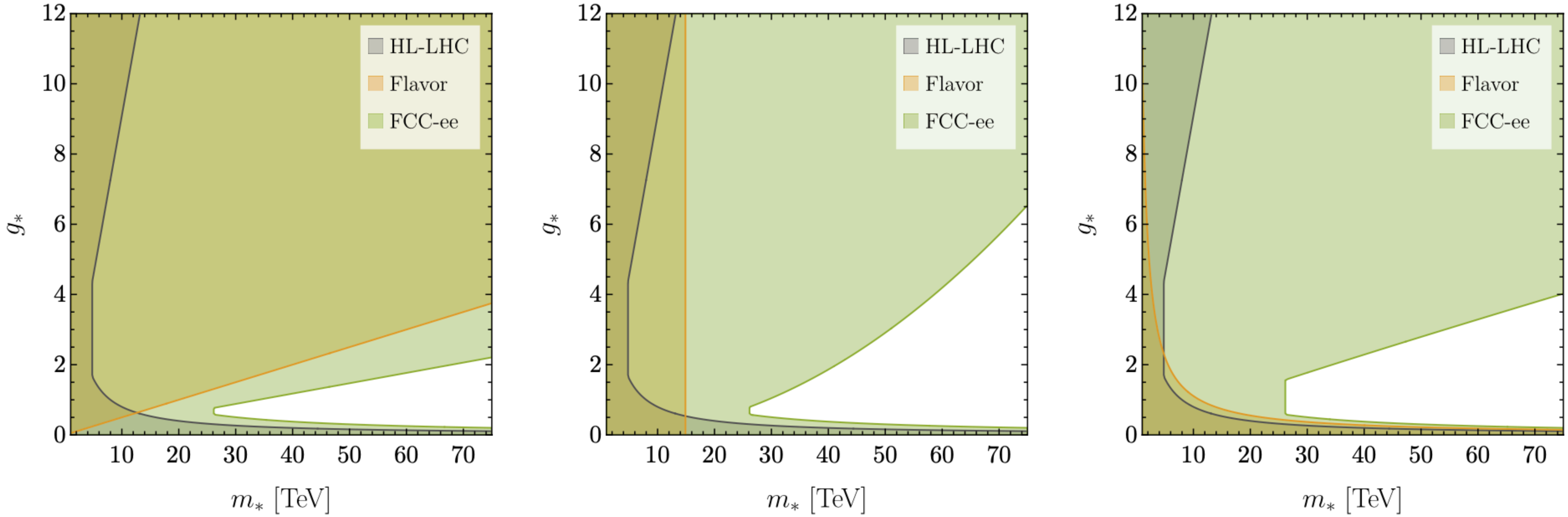


[BAS, 2407.09593]

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

Future summary plots

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



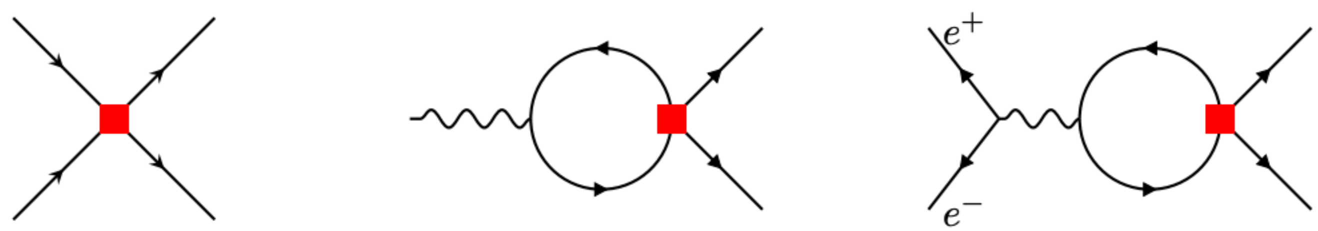
(a) Left compositeness (b) Mixed compositeness (c) Right compositeness

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

[BAS, 2407.09593]

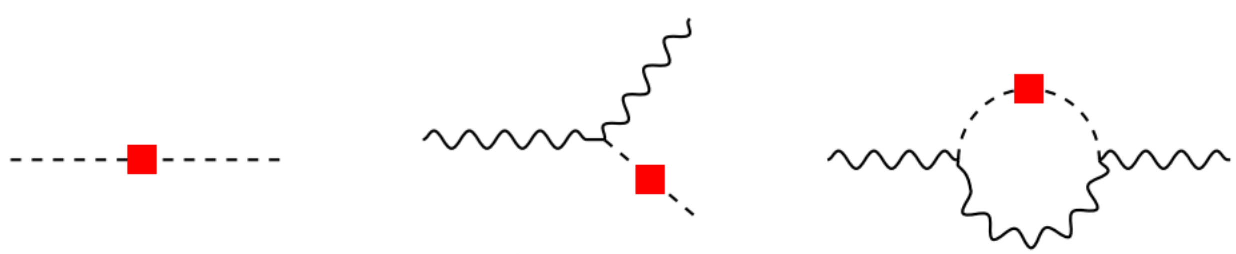
Suspects for complementary probes via AcE

1. *Four fermion operators* (receive energy enhancement off-pole)



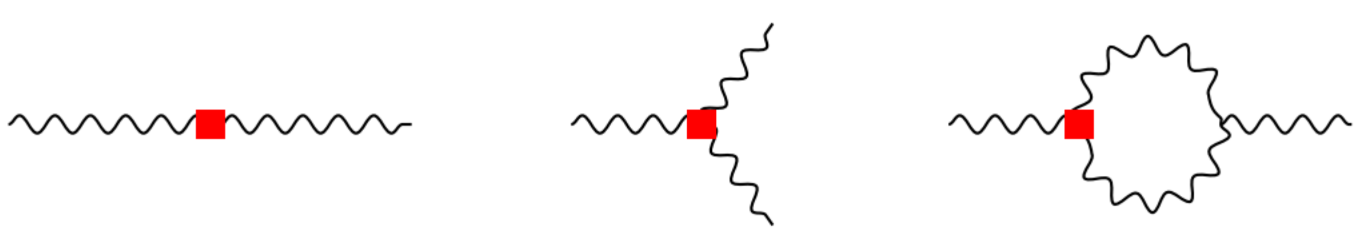
(a) Four-fermion operator (b) Z-vertex correction (c) $e^+e^- \to \bar{f}f$

2. *Higgs physics* (enter Z-pole obs. at one higher loop order)

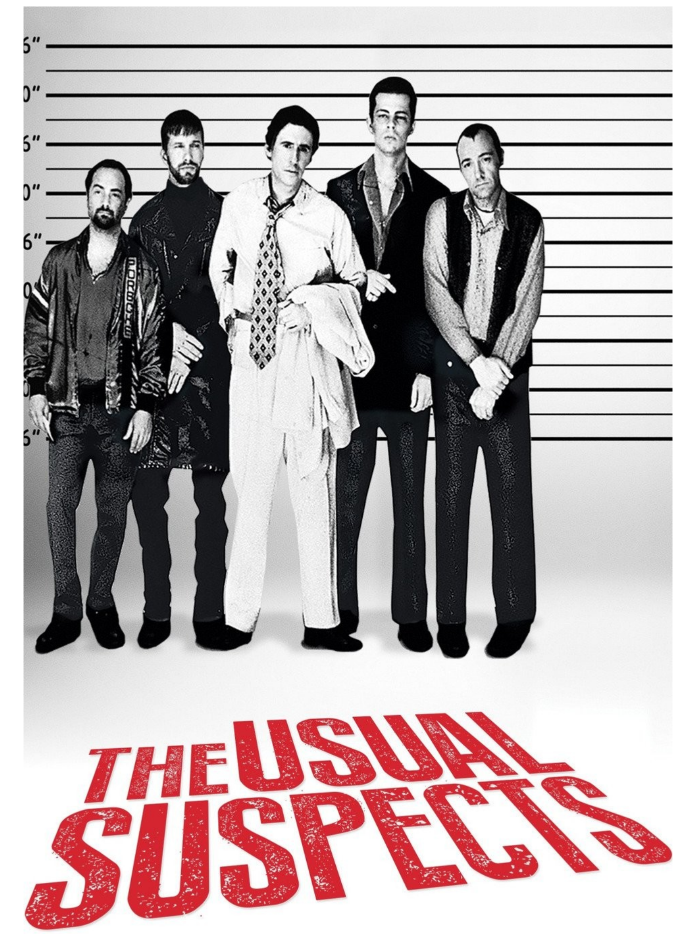


(a) Higgs self-energy (b) $e^+e^- \to ZH$ (c) Z-pole oblique params.

3. *Gauge two- and three-point functions* (both effects at play)



(a) LO Z-pole oblique params. (b) aTGC (c) NLO Z-pole oblique params.



[Maura, BAS, You, 2412.14241]