Model-Independent Higgs and Top Precision

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To appear soon, with Junghwan Lee, Martin Perello, Junping Tian, Marcel Vos

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Why do we want Higgs precision program?

- We cannot score
  if we don't have a ball.

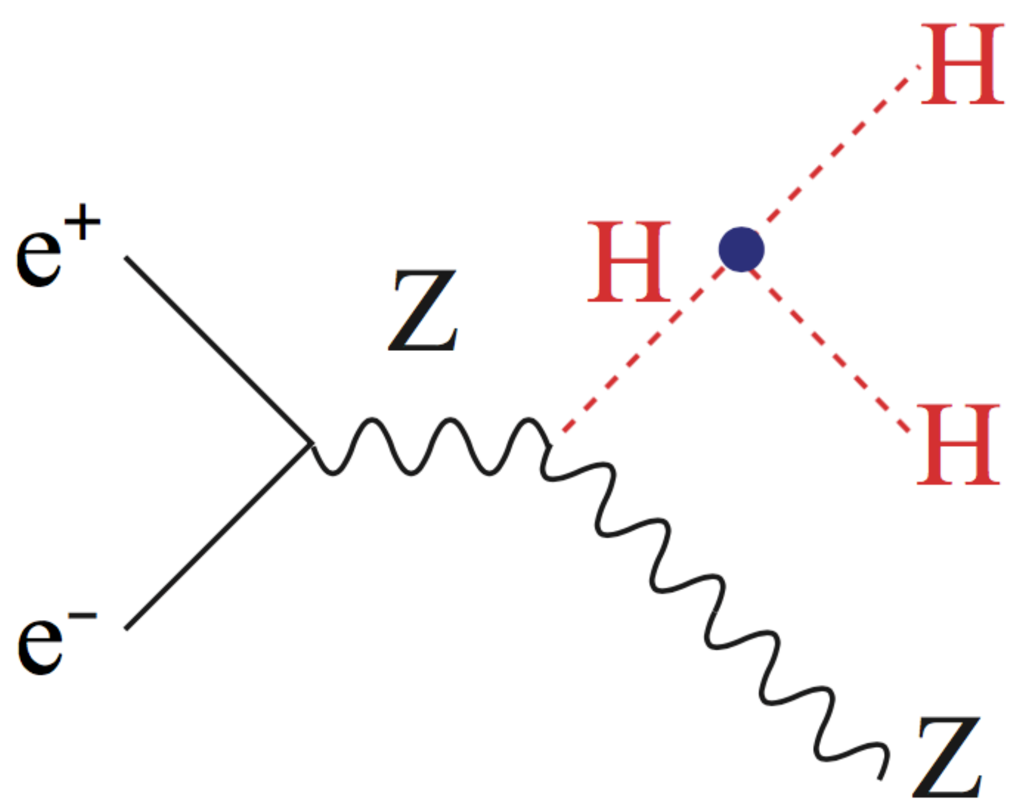
- We have a ball today
  — the Higgs boson.

taken from C.Grojean's slide

How do we measure Higgs precisely?

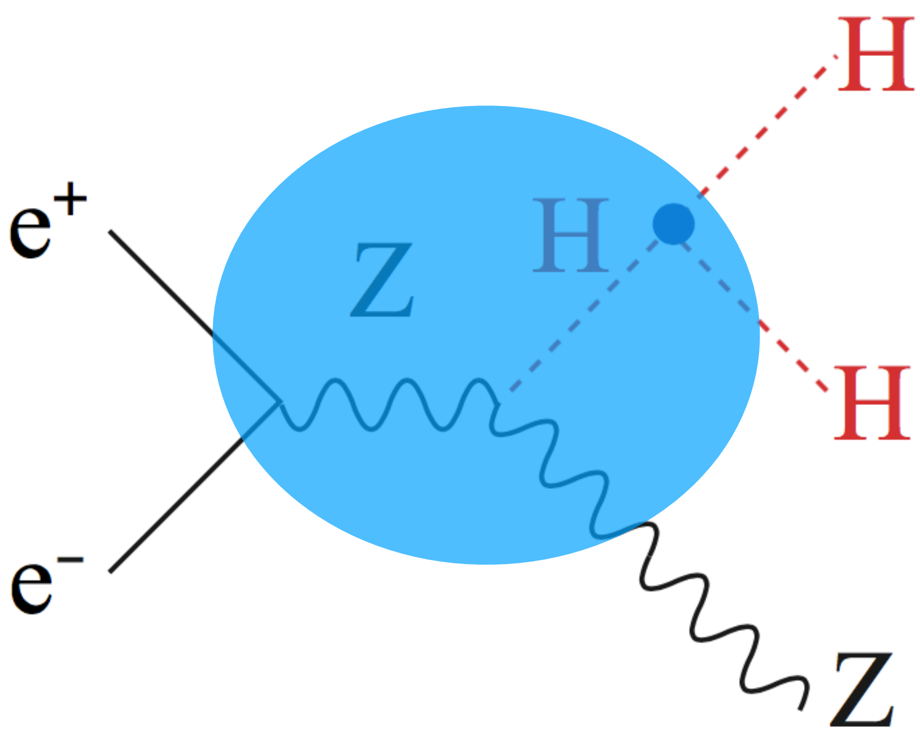
By measuring cross sections precisely.

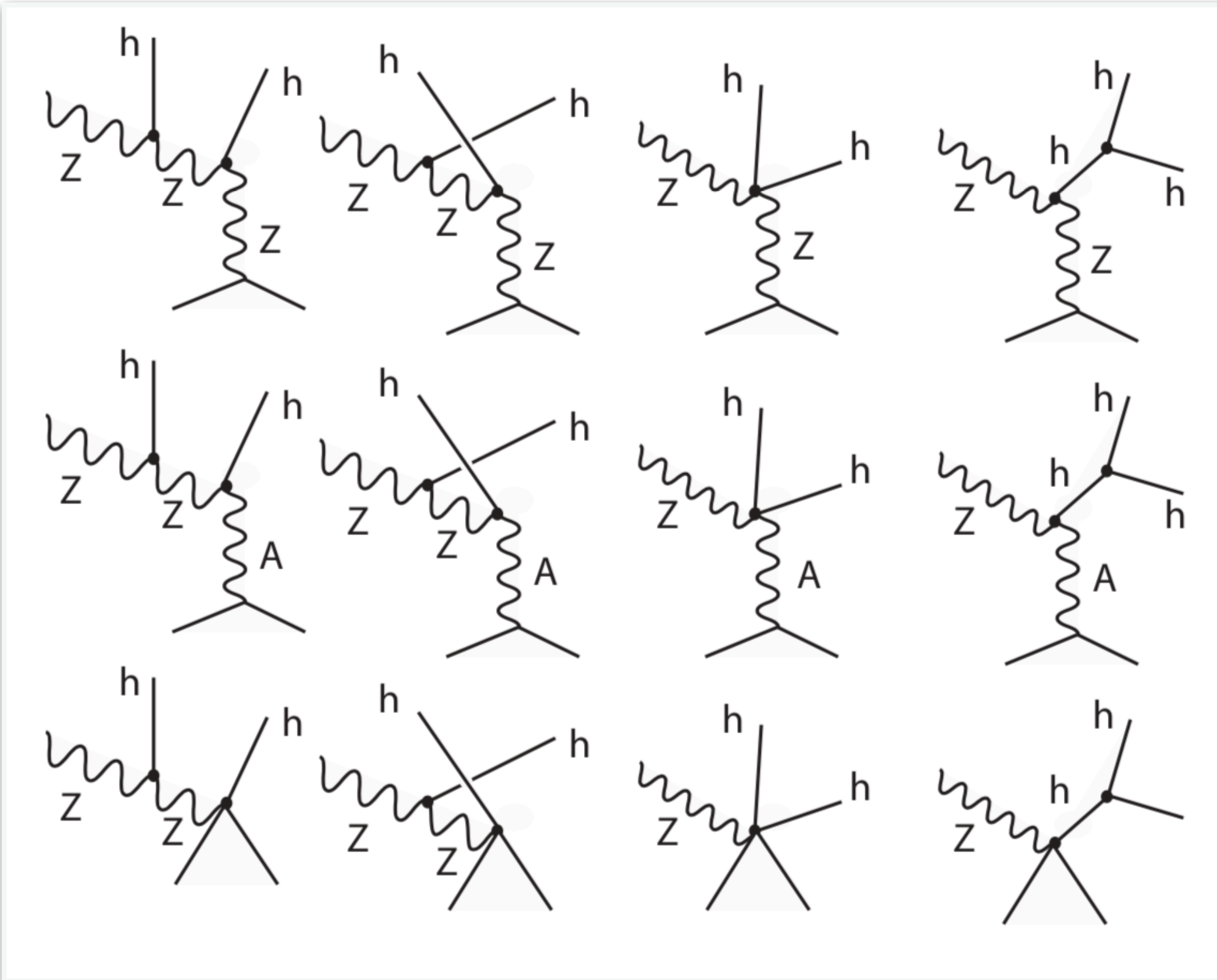
For example,



$$\lambda_3 = \frac{1}{6} V'''(v)$$

Quantum interference makes it complicated

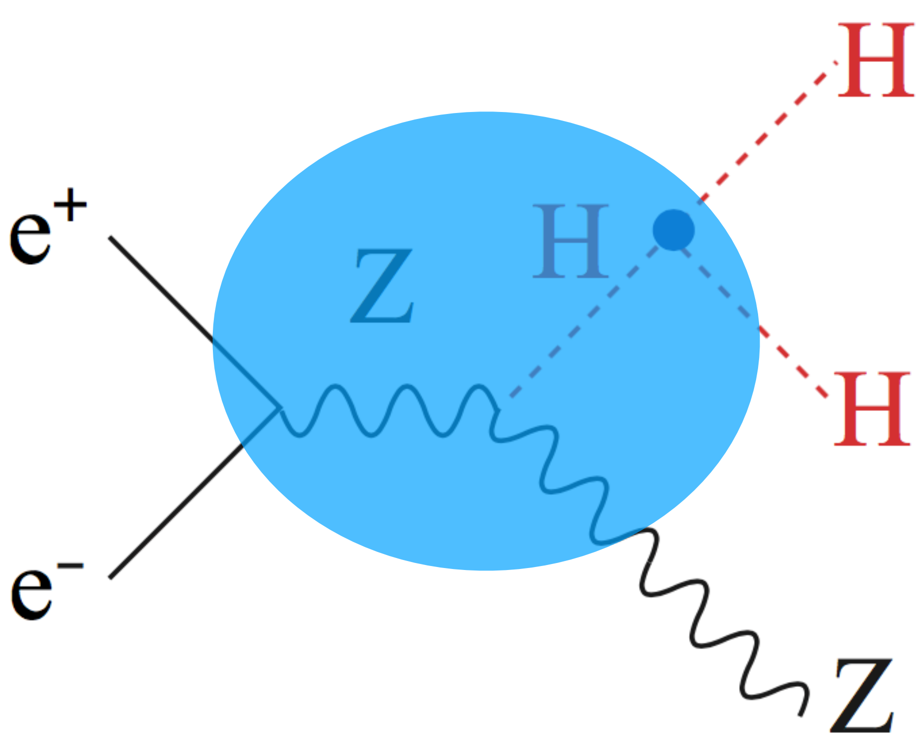


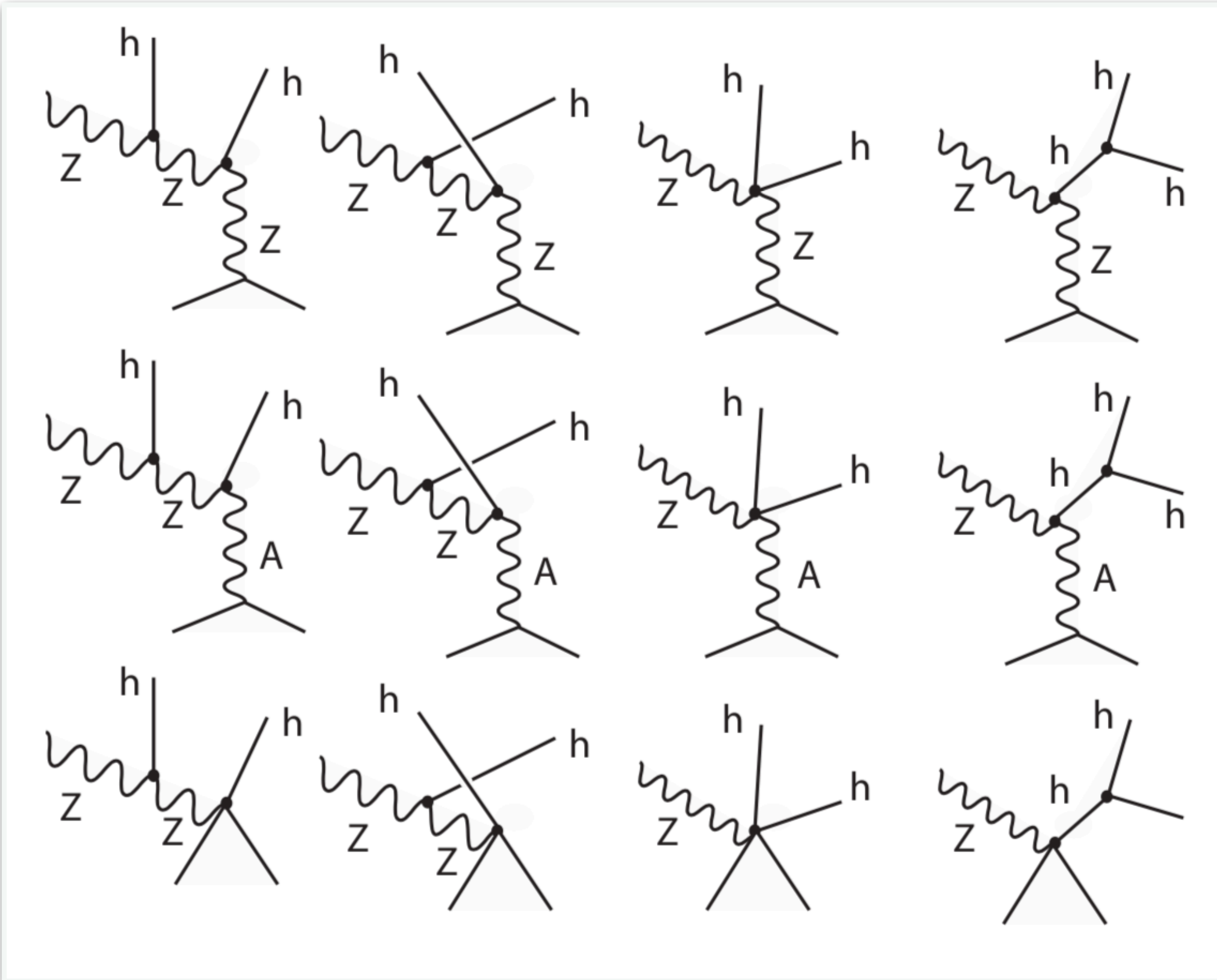


Barklow et al.
1708.08912, 1708.09070

- Higgs potential is just one of those diagrams.
- How can we extract Higgs potential out of mess?

Unknown mess makes it very challenging





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- Higgs potential is just one of those diagrams.
- How can we extract Higgs potential out of ***unknown*** mess?

Higgs Effective Theory

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

Barklow et al.
1708.08912, 1708.09070

$c_{bH,\, cH,\, \tau H,\, \mu H,\, gH}$ $\quad \delta g, \delta g', \delta v, \delta\lambda \quad$ $a_{\rm inv},\ a_{\rm oth},\ \mathcal{C}_{W,Z},$

Durieux, Grojean et al.
1907.04311,1711.03978,
1704.02333,1704.02953,
Wang et al. 1711.04046

For Higgs + EW observables at tree-level,
15 Higgs operators + 4 SM parameters + 4 Higgs widths
= 23 parameters.

Top is next important

- The top is next important contributor.
  - practically, next largest through loop effects with yt
  - theoretically, most important to hierarchy problem

- Top is badly constrained at low energy w/o direct-top.
  - Thus, loop suppression may not be big enough.

- → We will include top effects model independently into the model-independent Higgs precision program.

Questions

- **Above all, is Higgs precision robust or ruined by top effects?**

  - What collider capabilities are (more) essential?

- **Can we achieve indirect top precision before direct-top measurements?**

Top sector by EFT ops

- 7 Top EFT operators.

$$\mathcal{O}_{tH} = (\Phi^\dagger \Phi)(\bar{Q} t \tilde{\Phi}), \qquad \mathcal{O}_{Hq}^{(1)} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{Q}\gamma^\mu Q),$$

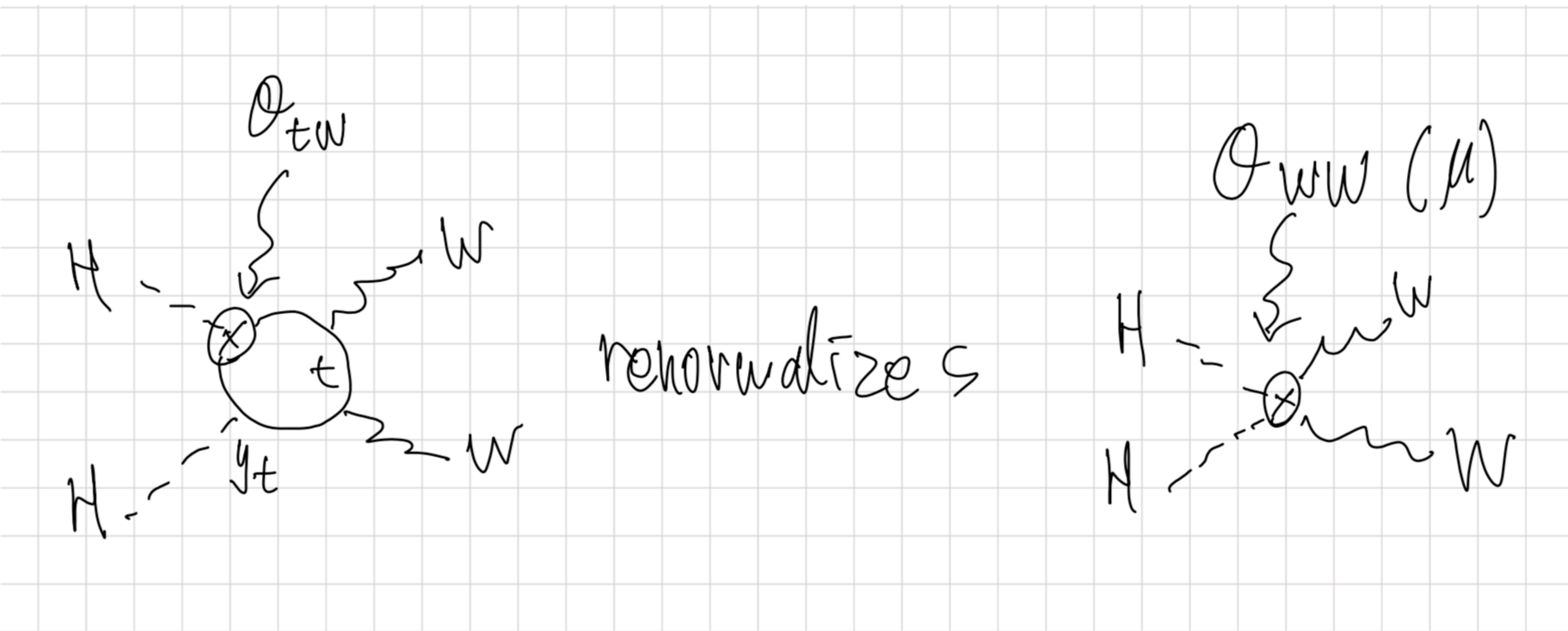
$$\mathcal{O}_{Hq}^{(3)} = (\Phi^\dagger i \overleftrightarrow{D}^a_\mu \Phi)(\bar{Q}\gamma^\mu \tau^a Q), \qquad \mathcal{O}_{Ht} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{t}\gamma^\mu t),$$

$$\mathcal{O}_{Htb} = i(\tilde{\Phi}^\dagger D_\mu \Phi)(\bar{t}\gamma^\mu b),$$

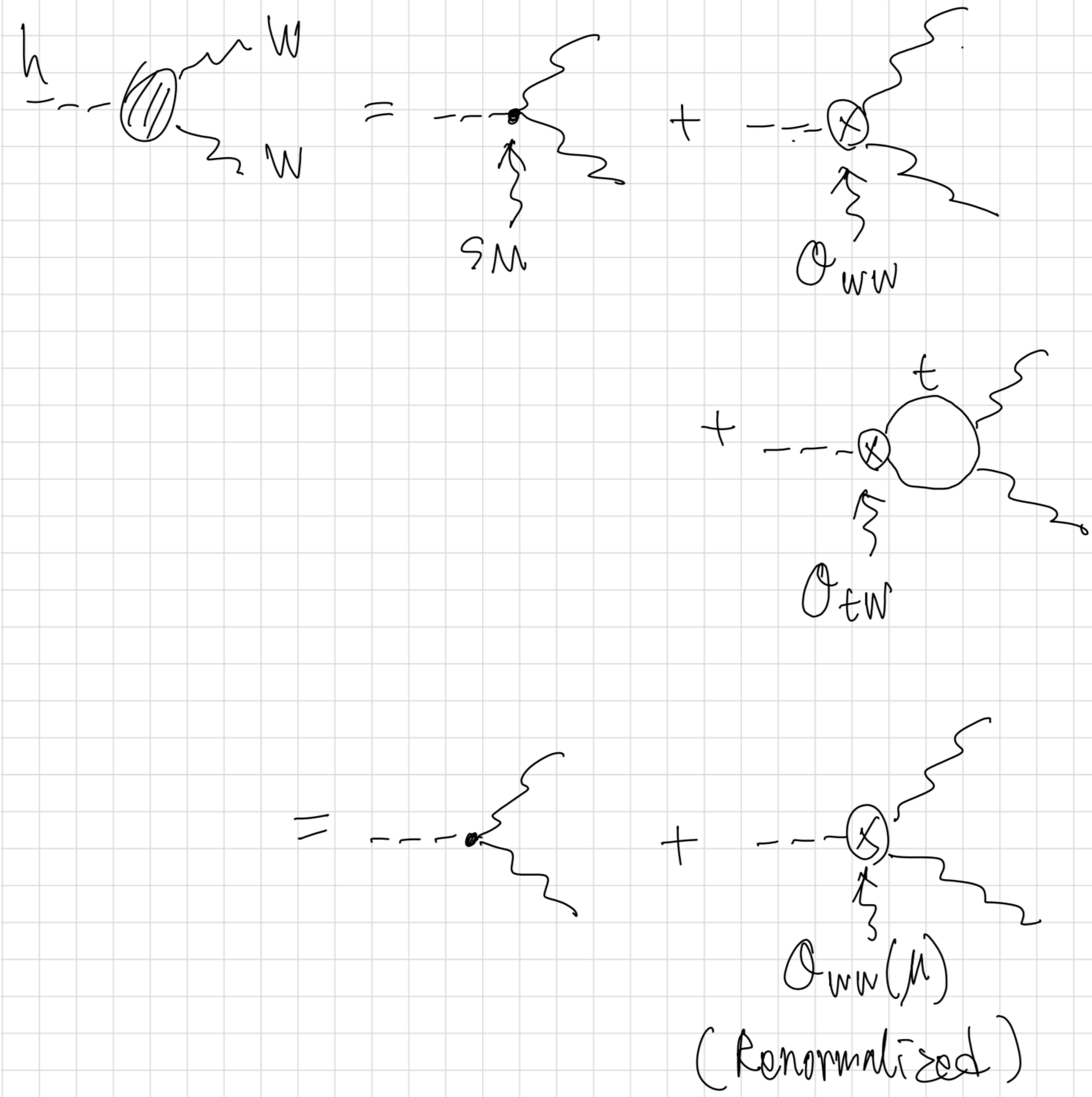
$$\mathcal{O}_{tW} = (\bar{Q}\sigma^{\mu\nu} t)\tau^a \tilde{\Phi} W^a_{\mu\nu}, \qquad \mathcal{O}_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\tilde{\Phi} B_{\mu\nu},$$

Top-loop effects on Higgs and EW

- via RG evolution and mixing btwn top and Higgs ops.
  - operator mixing is top's leading contributions.



Top-loop effects on Higgs and EW



Top-loop effects on Higgs and EW

- via RG evolution and mixing btwn top and Higgs ops.
  - operator mixing is top's leading contributions.

- Power counting rule:
  - Up to log-enhanced one-loop (compared to the LO)
  - No fixed-order one-loop effects

$$c_i(Q) \simeq c_i(Q') + \frac{1}{16\pi^2}\gamma_{ij}c_j(Q')\ln\frac{Q}{Q'}$$

- Not complete one-loop effects,
  - but consistent gauge-invariant subset, often dominant, easier to calculate, understand and handle.

Map of leading effects

observable	Higgs + EW	
tree-level (or LO) contribution	Higgs op	
one-loop contribution		

- A lot of recent works: Barklow et al. (1708.08912,1708.09079), Durieux/Grojean et al. (1907.04311,1711.03978,1704.02333,1704.02953), Wang et al. (1711.04046,1411.1054), Cheung et al. (1302.3794,1908.00753)

Map of leading effects

observable	Higgs + EW	Direct top
tree-level (or LO) contribution	Higgs op	top op
one-loop contribution		

- Vos et al. (1907.10619, 1807.02121)

Map of leading effects

observable	Higgs + EW	Direct top
tree-level (or LO) contribution	Higgs op	top op
one-loop contribution	Higgs op	top op

- Our topic today.
  - Inspired by earlier works by Zhang et al. (1804.09766, 1809.03520)

RG operator mixing

- For Higgs operators i, from top operators j

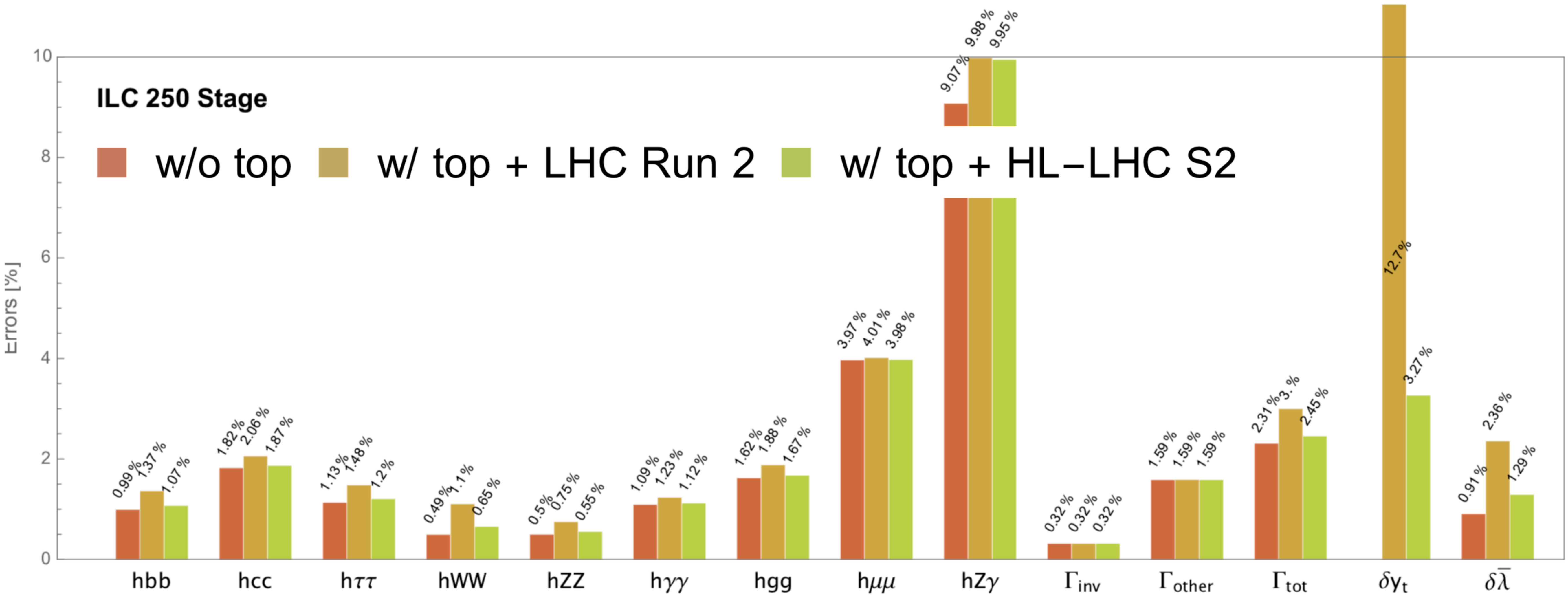
$$c_i(Q) = c_i(Q_0) + \frac{1}{16\pi^2}\gamma_{ij}c_j(Q_0)\ln\frac{Q}{Q_0}$$

- - Q0: a common scale at which Wilson coefficients are defined and we express constraints.

  - Q: scale of each observable.

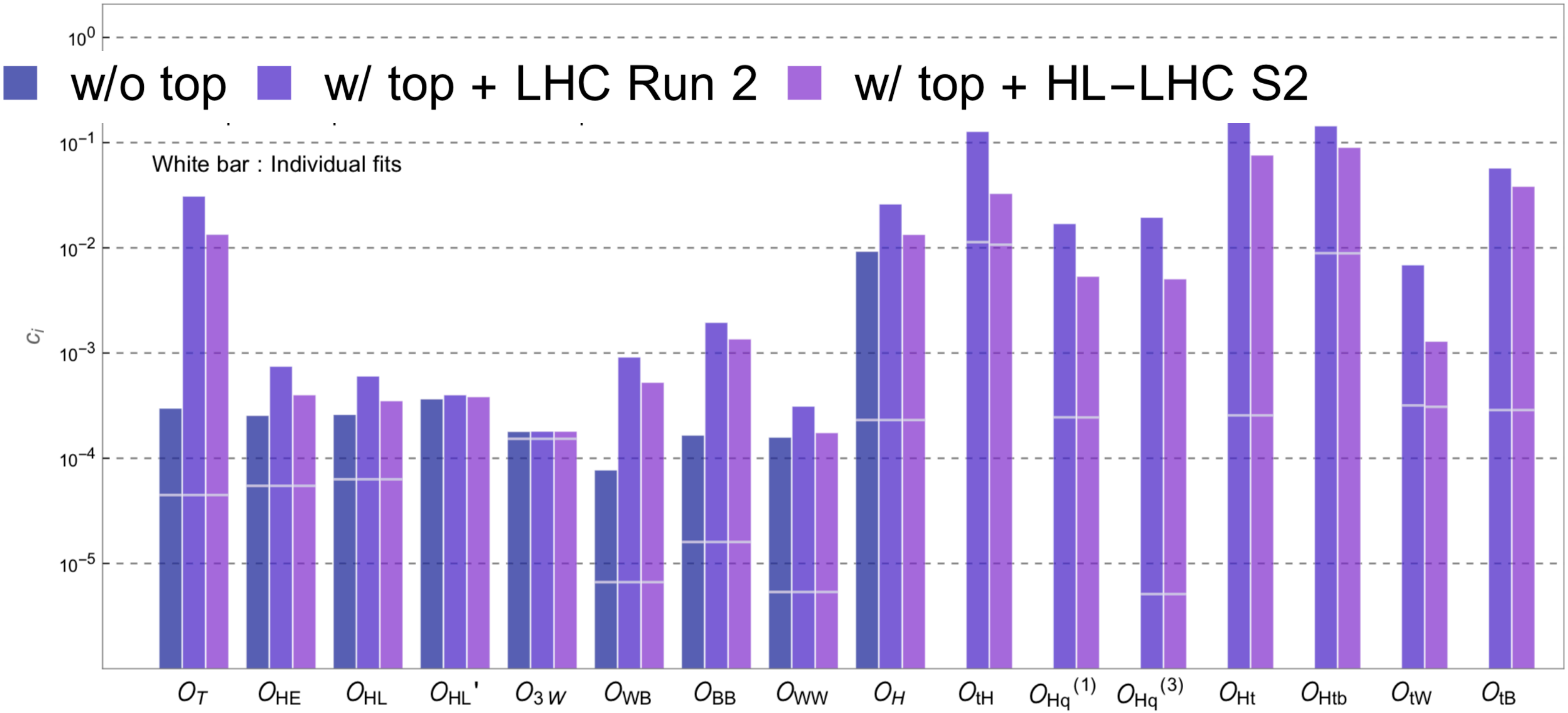
	G_F	EWPO	$\delta m_{W,Z,h}$	$\delta\Gamma(h)$	TGC (W^-W^+)	$\sigma(\nu\bar{\nu}h)$	$\sigma(Zh)$	$\sigma(Zhh)$
Q	m_μ	m_Z, m_W	$m_{W,Z,h}$	m_h	250, 500 GeV	250, 500 GeV	250, 500 GeV	500 GeV

Physical Higgs coupling precision at ILC 250



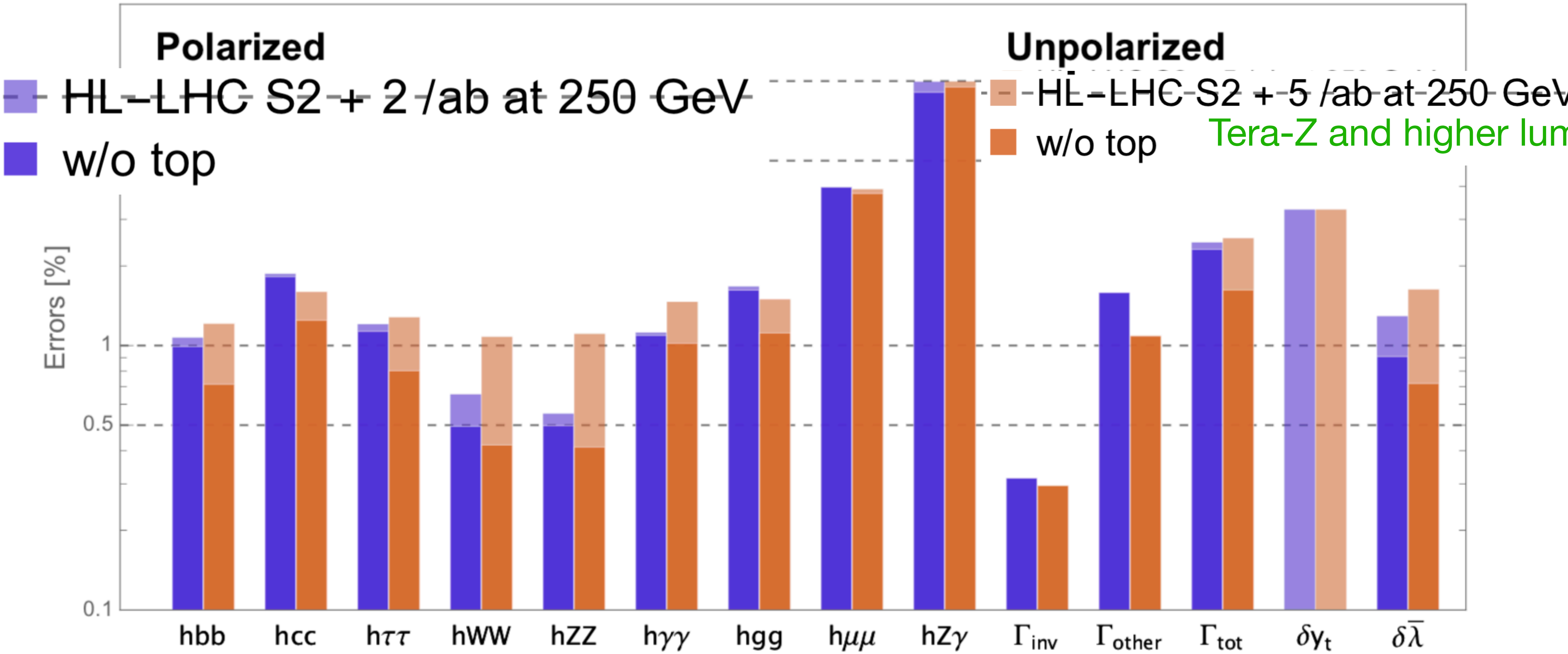
- Worsened by top effects, but can be mostly recovered with HL-LHC S2 direct-top data. (Most important conclusion!)
- Notably, no fit is possible at ILC 250 with only Higgs+EW!

Operator constraints at ILC 250



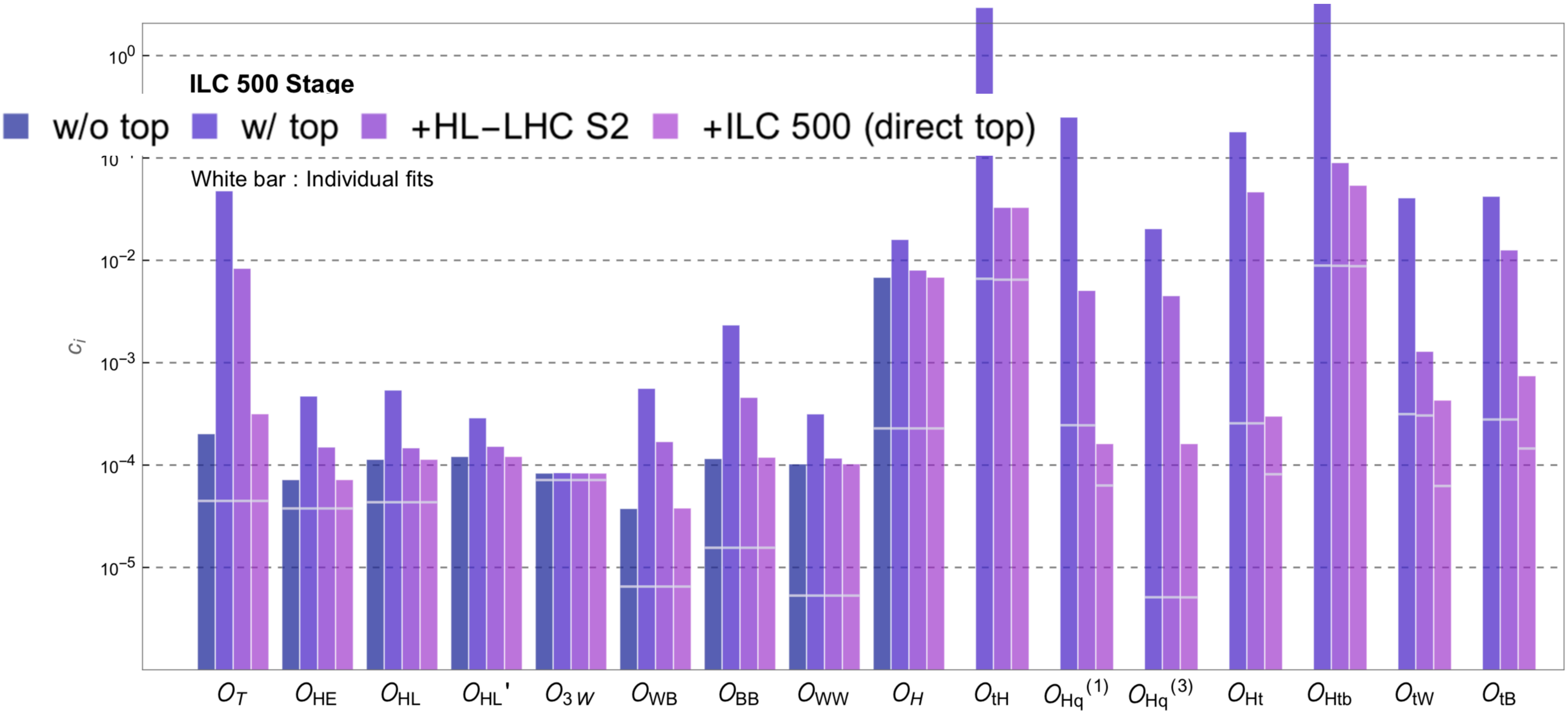
- Surprisingly, much more sensitive to top effects.
  - Higgs couplings are semi-directly measured.
  - Operator constraints are needed to fully characterize NP.

Role of polarization



- Polarization makes Higgs precision much more robust, as it doubles # of observables and reduces degeneracies. (Most surprising conclusion!)

Now indirect constraints at ILC 500



- Now indirect top constraints possible, but much worse.
- Top Yukawa ~ctH ~3.3% from HL-LHC S2, but 1~2% from 550+.

Higgs self coupling from Zhh

		$\langle(\delta\sigma_{Zhh})^2\rangle^{1/2}$
w/o top	ILC 250	2.67%
	ILC 250 + 500	2.13%
w/ top	HL-LHC + ILC 250	3.11%
	ILC 250 + 500 (indirect only)	14.3%
	+ HL-LHC	2.59%
	+ ILC 500-top	2.13%

- Self-coupling precision can be robust against top effects, as ILC 500 direct-top will be available.

RG scale dependence

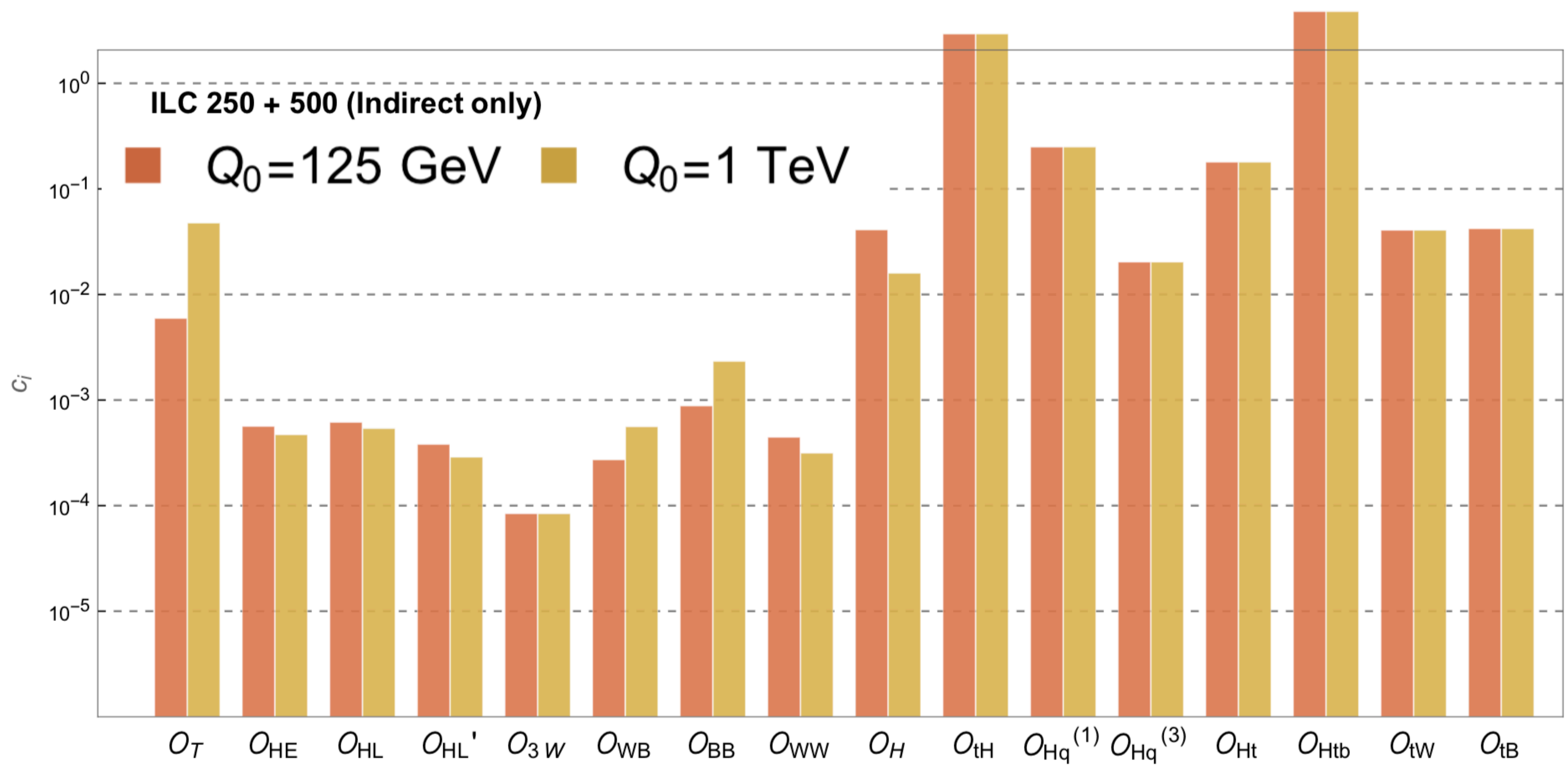
- Q0 is only a matter of choice.
- The fit results with different Q0 are physically equivalent, connected by RG evolution of covariance matrix.

$$\begin{aligned}\chi^2 &= \sum_{m,n} (\hat{O}_{exp} - \hat{O}_{thy})_m (\sigma^{-2})_{mn} (\hat{O}_{exp} - \hat{O}_{thy})_n \\ &= \sum_{I,J} c_I(Q_0)\, \mathcal{C}ov^{-1}_{IJ}(Q_0)\, c_J(Q_0) \\ &= \sum_{I,J} c_I(Q_0')\, \mathcal{C}ov^{-1}_{IJ}(Q_0')\, c_J(Q_0'),\end{aligned}$$

- \- In all, RG evolution and global-fit commute.
  \- Error contributions to phys observables are indep on Q0.
  \- Physical info are contained in the running btwn phys scales.

cT runs most vs. custodial sym

- cT runs most due to top effects. Custodial sym breaking?
- Yes, and no.



cT runs most vs. custodial sym

- cT runs most due to top effects. Custodial sym breaking?
- Yes, and no.
- First of all, non-oblique corrections exist.

$$\alpha\, S(m_Z) = 4s_0^2(8c_{WB} + c'_{HL}) + 4(-\frac{1}{2} + s_0^2)c_{HE} - 4s_0^2 c_{HL},$$
$$\alpha\, T(m_Z) = c_T - \frac{c_0^2 - s_0^2}{c_0^2} c_{HE} - 2\frac{s_0^2}{c_0^2} c_{HL}.$$

- Secondly, alphaT at mZ is indeed constrained to be small.

	$\alpha S(m_Z)$	$\alpha T(m_Z)$
without top operators	0.046 %	0.033 %
indirect-only (with any Q_0)	0.12 %	0.073 %
+ HL-LHC S2 + ILC 500-top	0.046 %	0.033 %

Conclusion

- Top-loop effects are influential.
  - But *polarization* and *direct-top* can recover Higgs precision.
  - Having polarization is preferred to further improving EWPO/TGC (at least at ILC 250).
- At ILC 250, fit is not possible w/o direct-top data.
  - ILC 500 indirect constraints on ops are weaker than direct.
- Operator constraints are needed to fully characterize New Physics.
  - Operator constraints are particularly sensitive to top effects.