Higgs/top/EW precision measurements at future e+e-: combined EFT analysis with renormalization mixing

based on arXiv:2006.14631;
collaboration with
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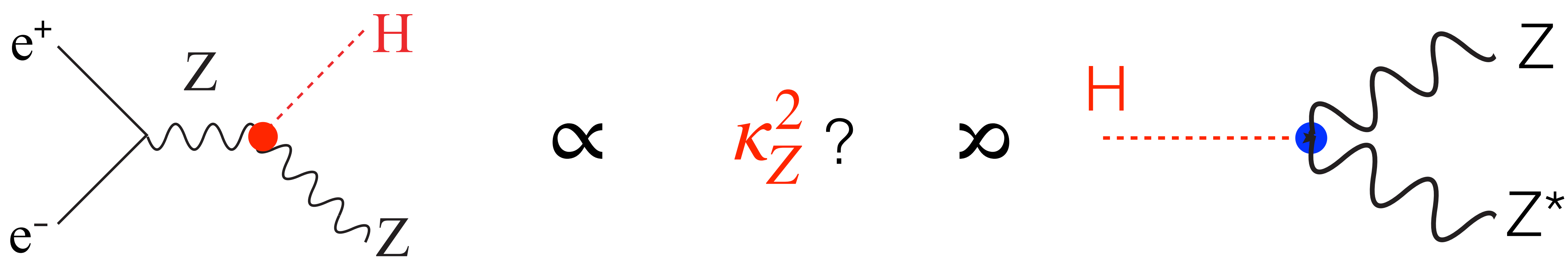
CEPC Workshop 2020, October 26, 2020

outline

- Introduction to SMEFT fit @ e+e-
- Top-quark effects in Higgs/EW processes
- Combined fit & results
- Summary

A question in kappa formalism:

$$\frac{\sigma(e^+e^- \to Zh)}{SM} = \frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \qquad \textbf{?}$$

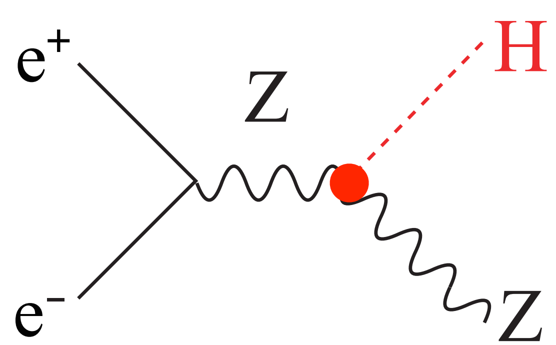


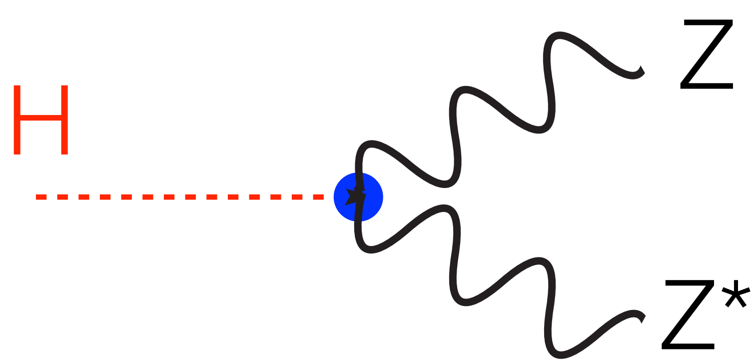
- can deviations from SM be both represented by single κ_Z?

the answer is model dependent

- if BSM induces new Lorentz structures in hZZ interaction

$$\delta\mathcal{L} = (1+\eta_Z)\frac{m_Z^2}{v} h Z_\mu Z^\mu + \zeta_Z \frac{h}{2v} Z_{\mu\nu} Z^{\mu\nu}$$





$$\sigma(e^+e^- \to Zh) = (SM)\cdot (1 + 2\eta_Z + (5.5)\zeta_Z)$$

$$\neq$$

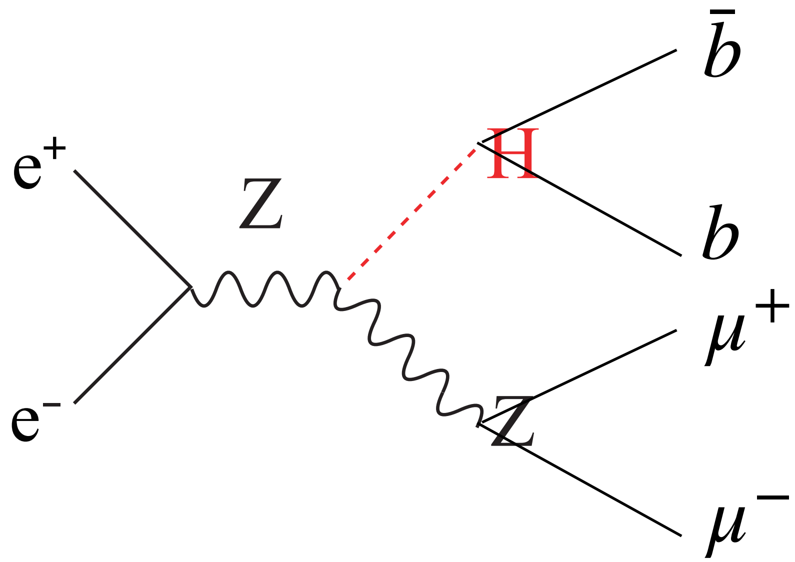
$$\Gamma(h \to ZZ^*) = (SM)\cdot (1 + 2\eta_Z - (0.50)\zeta_Z)$$

- need a better, more theoretical sound framework

global perspective for precision meas. @ future e+e-

- different new physics effects can appear in a same observable

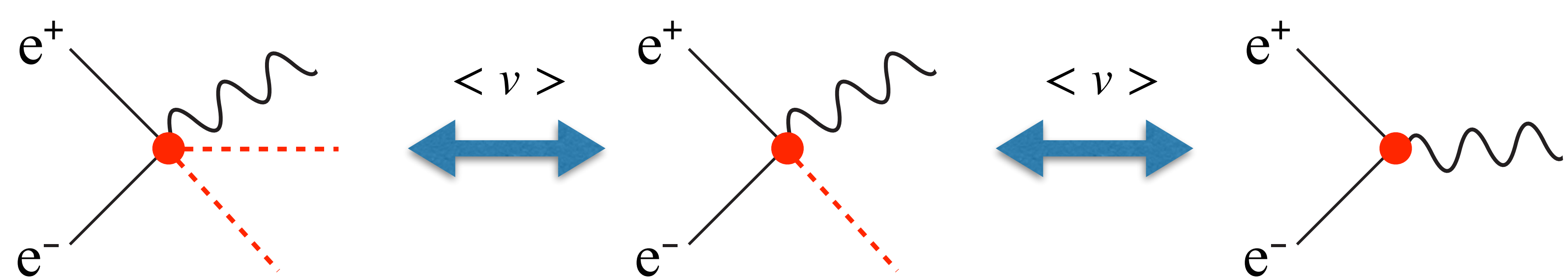
  e.g. suppose we discover a deviation in rate meas. σxBr



- hbb coupling?
- hZZ coupling?
- Zμμ coupling?
- Zee coupling?
- new diagrams?

- same new physics effect can appear in different observables

$$i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu L)$$



$e^+e^- \rightarrow Zhh$ $e^+e^- \rightarrow Zh$ Z-pole

SM Effective Field Theory @ future e+e-

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Delta\mathcal{L}$$

$$= \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i-4}} O_i$$

- assumption: $m_{BSM} >> m_{EW}$
- most general effects from BSM represented by a set of higher dimensional ops.
- respect SU(3)xSU(2)xU(1) gauge symmetries
- consistently relate BSM effects in Higgs, W/Z, top, 2-fermion processes: provide a global view of roles of various measurements @ future e+e-

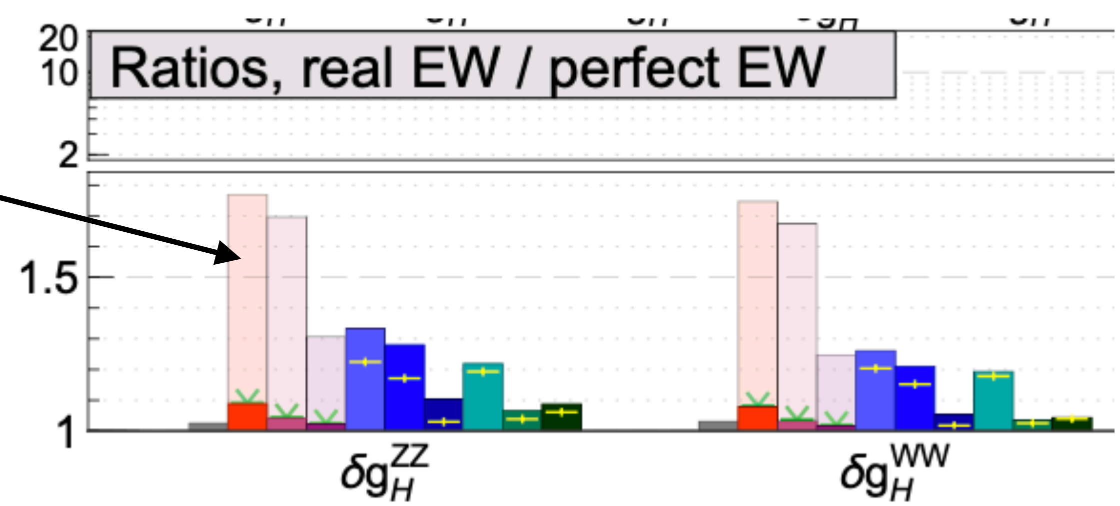
important implications for future e+e-

- great synergies with (HL-)LHC measurements
  - Higgs rare decays; Top-quark EW couplings; TGC / QGC; etc

- CEPC / FCC-ee: important role by ***Z-pole run***, ~x2 better δg_{HVV}

- ILC/ CLIC: important role by ***beam polarizations***, made up ∫L

Z-pole



[de Blas et al, arXiv:1907.04311]

[ESG] $SMEFT_{ND}$	ILC250	CLIC380	CEPC	FCC-ee240
∫L•ab	2	1	5.6	5
δg_{HZZ}	0.39%	0.5%	0.45%	0.47%
δg_{Hbb}	0.78%	0.99%	0.63%	0.71%
$\delta g_{H\tau\tau}$	0.81%	1.3%	0.66%	0.69

combined fit for Higgs/EWPO/WW @ future e+e-

(Barklow et al, arXiv:1708.09079, 1708.08912; + papers by other groups)

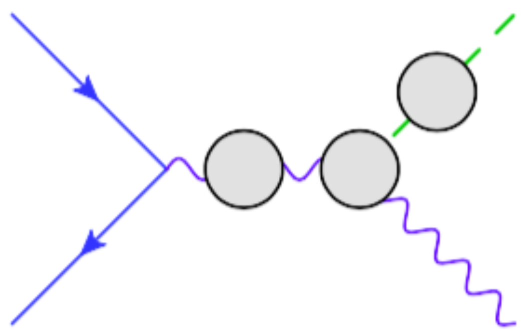
$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi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

Φ: higgs field
W, B: SU(2), U(1) gauge
L, e: left/right electron

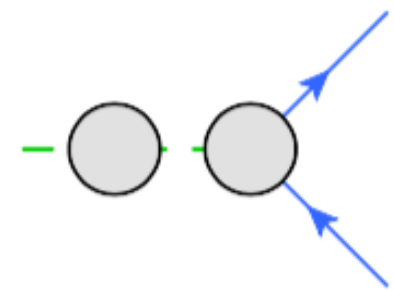
- in total 23 parameters: 17 D-6 operators
  + 4 SM parameters (g, g’, v, λ) + 2 for Higgs exotic decays

- a complete subset (**@LO**) for Higgs physics @ future e+e-

what happens at next leading order for SMEFT



WH,ZH



H→bb

Zhang, et al,
arXiv:1804.09766,
1807.02121

- at e+e-, NLO ~ O(α), 1% level
- for NLO from W/Z/γ/H, operators constrained to ~<0.01, overall effect will be < 0.1%
- for NLO from top, operators would be much less constrained, currently ~ O(1) -> overall effect 1% -> potential impact in global fit on Higgs coupling precision

our approach to include NLO top effects

S.Jung, J.Lee, M.Perello, JT, M.Vos, arXiv:2006.14631

- we didn't try to include full NLO effects for all observables
- mainly include effects that have log-dependence on Q-scale
- captured by Renormalization Group Evolution (mixing)

$$\dot{c}_i \equiv 16\pi^2 \frac{\mathrm{d}c_i}{\mathrm{d}\ln\mu} = \gamma_{ij} c_j$$

[Alonso, Jekins, Manohar, Trott, 2013]

c_i: Higgs operators; c_j: Top operators; γ_{ij}: anomalous dimensions

- convenient to include such top-quark effects in all Higgs/EWPO/WW observables that have been considered previously

top-quark operators (added to previous SMEFT fit)

(no 4-fermion operators considered)

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

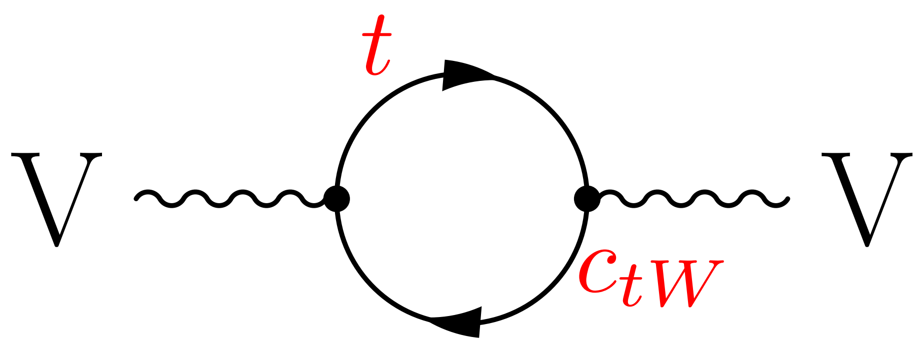
$$\mathcal{O}_{Hq}^{(3)} = (\Phi^\dagger i \overleftrightarrow{D}^a_\mu \Phi)(\bar{Q}\gamma^\mu \tau^a Q), \qquad \mathcal{O}_{Ht} = (\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{t}\gamma^\mu t),$$

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

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

$$\Delta\mathcal{L}_{\rm top} = y_t \frac{c_{tH}}{v^2}\mathcal{O}_{tH} + \frac{c_{Hq}^{(1)}}{v^2}\mathcal{O}_{Hq}^{(1)} + \frac{c_{Hq}^{(3)}}{v^2}\mathcal{O}_{Hq}^{(3)} + \frac{c_{Ht}}{v^2}\mathcal{O}_{Ht} + \frac{c_{Htb}}{v^2}\mathcal{O}_{Htb} + \frac{c_{tW}}{v^2}\mathcal{O}_{tW} + \frac{c_{tB}}{v^2}\mathcal{O}_{tB}$$

effect of top operators: example



log-dependence

higgs operator

$$\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger \Phi W^a_{\mu\nu} W^{a\mu\nu}$$

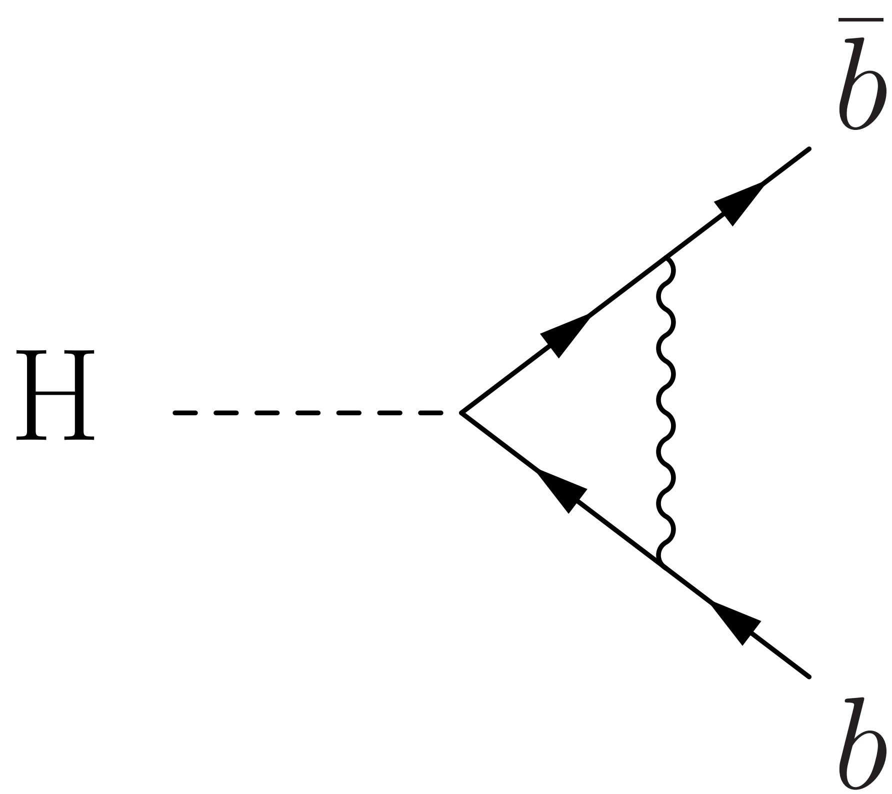
top operator

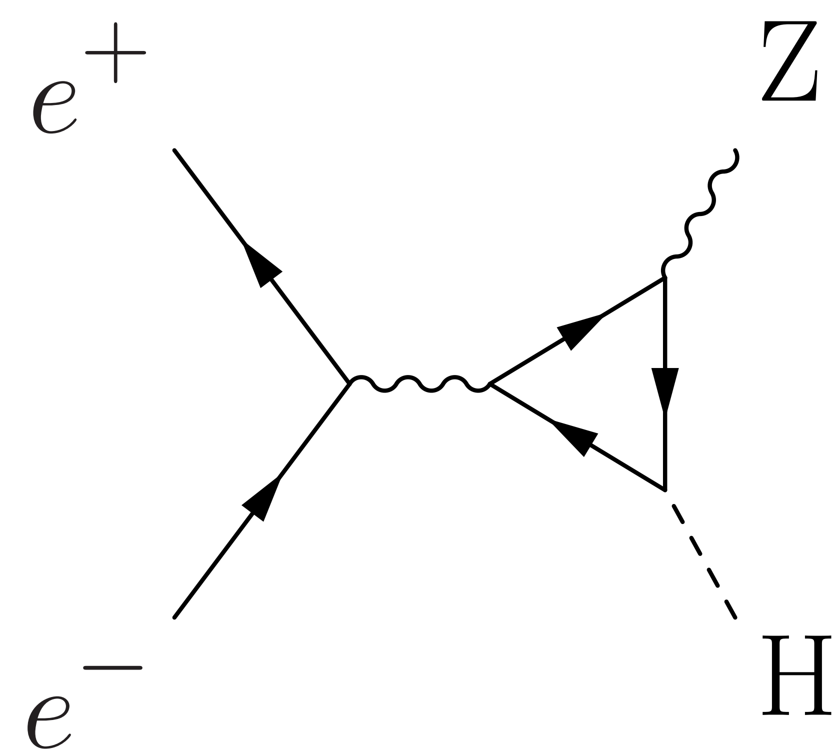
$$\frac{c_{tW}}{v^2}(\bar{Q}\sigma^{\mu\nu} t)\tau^a \tilde{\Phi} W^a_{\mu\nu}$$

$$\dot{c}_{WW} = \frac{1}{4}(-2 g y_t N_c c_{tW})$$

effect of top operators: example

finite term not log-dependent, hence not captured in our approach





more detailed power-counting rule

	Higgs loop production/decay	other observables	top production
SM	finite 1-loop	tree-level	tree-level
Higgs operator	tree-level from $c_{WW,WB,BB}$ finite 1-loop from other operators	tree-level	none
top operator	log 1-loop via $\dot{c}_{WW,WB,BB}$ log 2-loop via other $\dot{c}$ finite 1-loop via tree-shift of y_t, g_{Ztt}	log 1-loop via $\dot{c}$	tree-level

key: include leading contributions from top-quark operators

effect of top operators: example

RG evolution

$$\dot{c}_H = (12y_t^2 N_c - 4g^2 N_c) c_{Hq}^{(3)} - 12 y_t y_b N_c c_{Htb}$$

$$\dot{c}_{BB} = \frac{1}{4t_W^2}(-4g' y_t (Y_q + Y_u) N_c c_{tB})$$

$$\dot{c}_{HL} = \frac{1}{2} Y_l g'^2 \left(\frac{16}{3} Y_q N_c c_{Hq}^{(1)} + \frac{8}{3} Y_u N_c c_{Ht} \right)$$

$$\ldots$$

LO: without top-op

$$\delta\Gamma(h \to WW^*) = -24 c_{WW} - 7.8 c_H$$

NLO: with top-op

$$\delta\Gamma(h \to WW^*) += 3.1 c_{HQ}^{(3)} - 0.09 c_{Htb} - 0.36 c_{tW}$$

choice of scale for various observables

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

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

some at multiple scales:

$$\delta\sigma(Zh \to Zb\bar{b})(Q = 250) = \delta\sigma(Zh)(Q = 250) + \delta\Gamma(b\bar{b})(Q = m_h) - \delta\Gamma_{\rm tot}(Q = m_h). \tag{2.25}$$

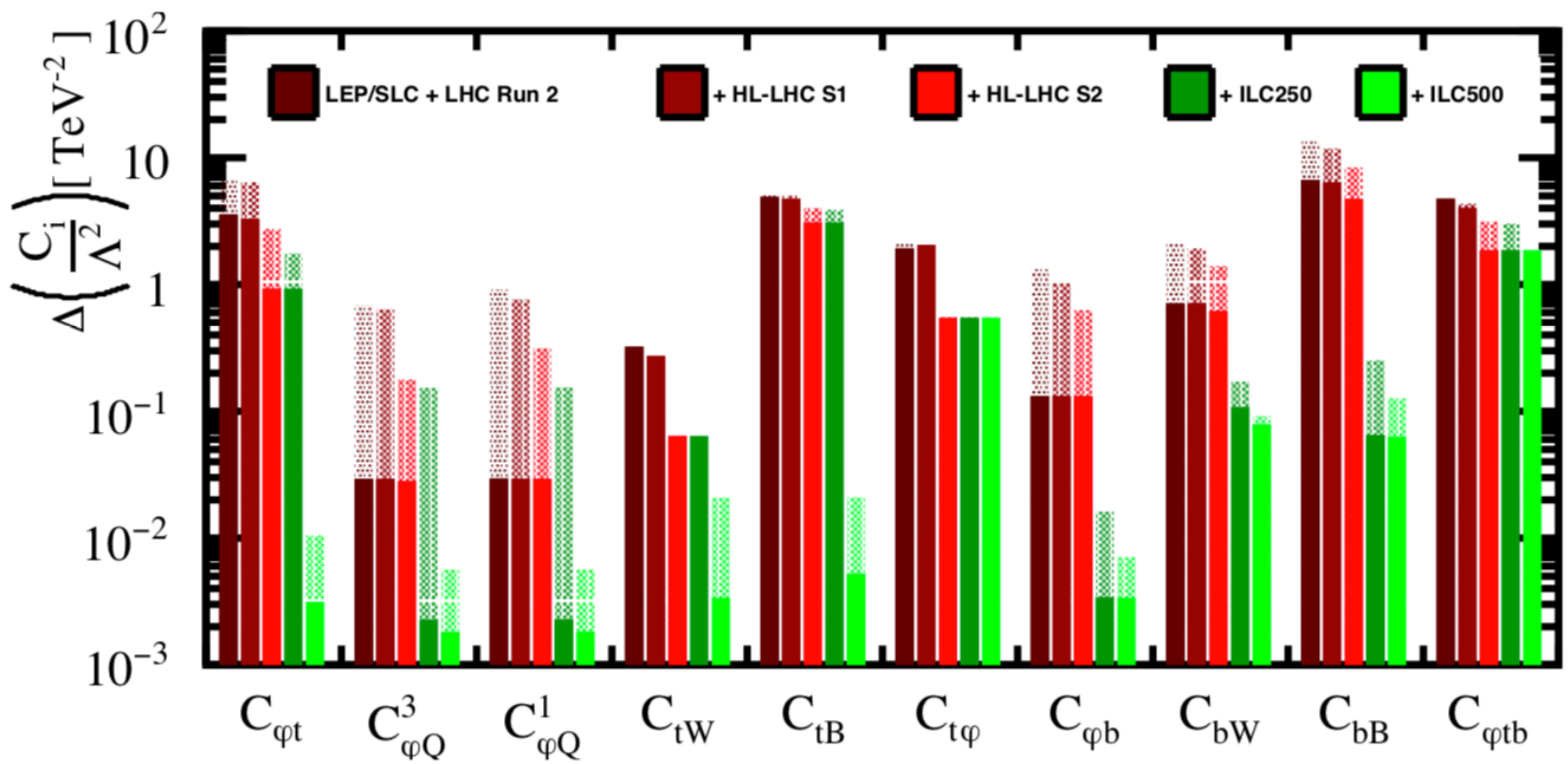
results (I): $\sqrt{s}$ = 250 GeV e+e-

- with the same set of observables (as previous global fit), at 250 GeV running only, the global fit will not converge at any of the Higgs factories
- e.g. Higgs couplings could not be determined unambiguously

not surprising, but no worry

results (II): ILC250 + LHC

- LHC will provide us valuable top data sets
- top operators will be constrained to some extent at (HL-)LHC

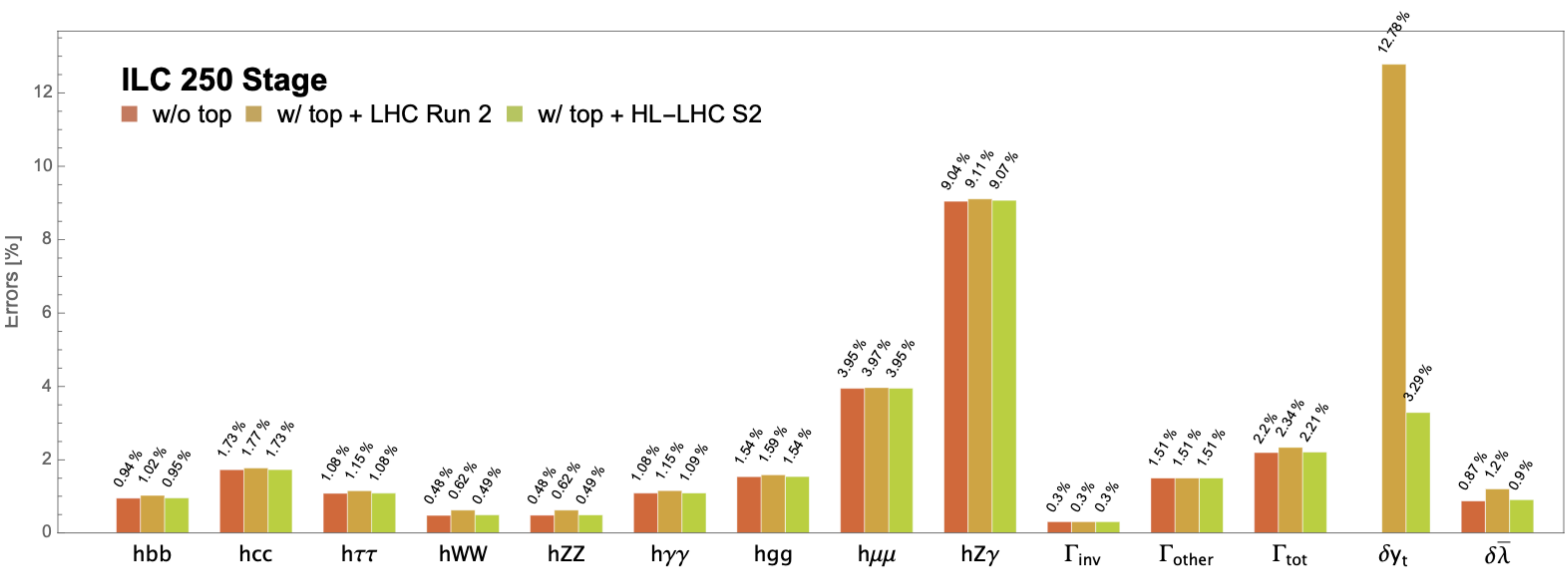


[Durieux, et al, arXiv:1907.10619]

results (II): ILC250 + LHC

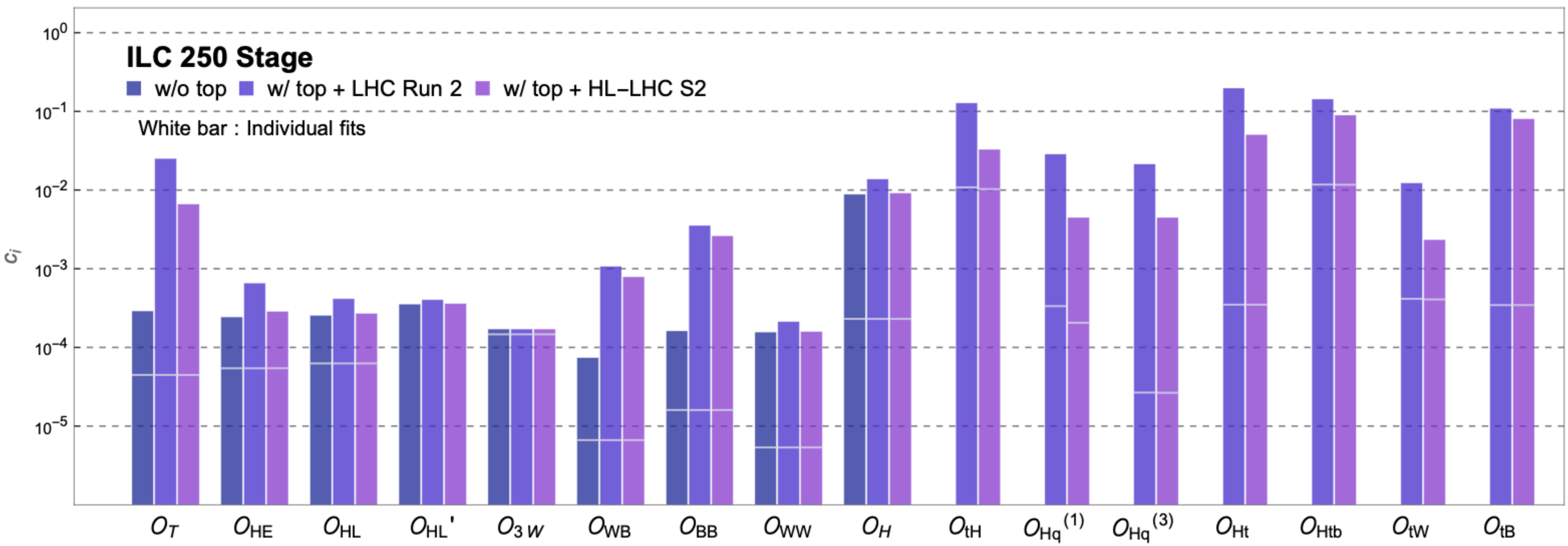
- with the help of LHC top data, Higgs coupling precisions @ ILC250 are almost restored

- note: top data from LHC Run 2 is not constraining enough



results (II): ILC250 + LHC

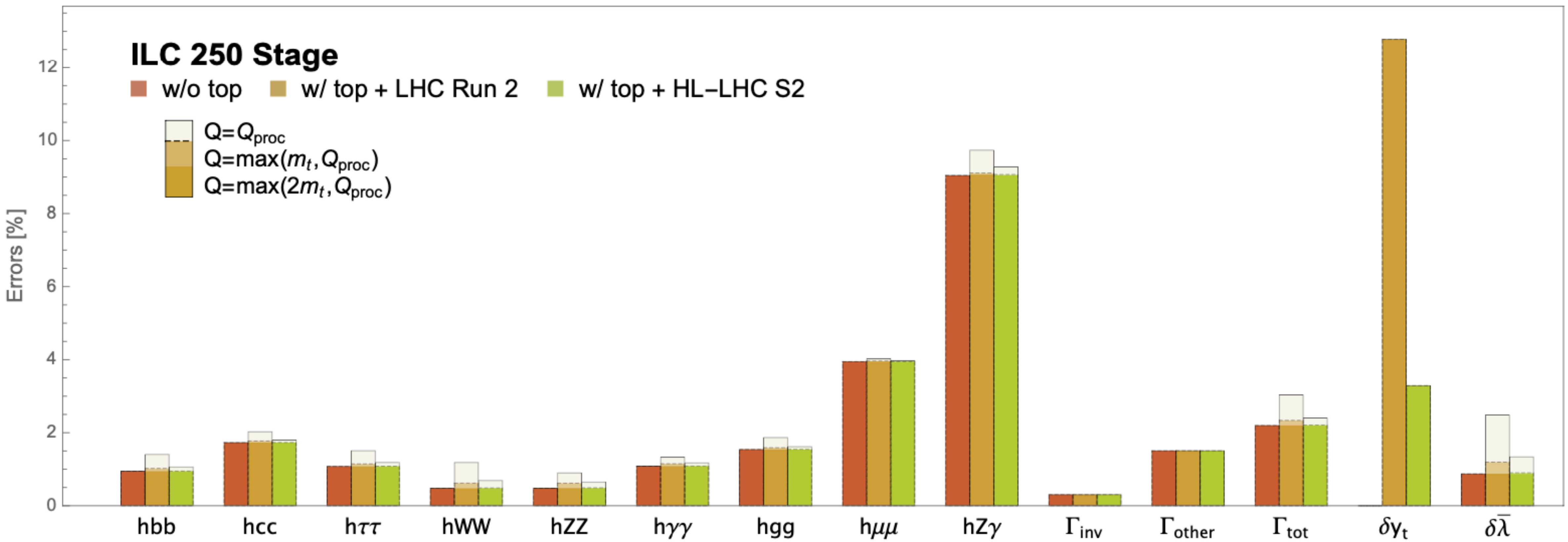
- constraints on some Higgs operators get significantly worse
- much stronger individual sensitivity to top-operators (notably 1% sensitivity to top-Yukawa coupling, O_{tH})



results (II): Q dependence

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

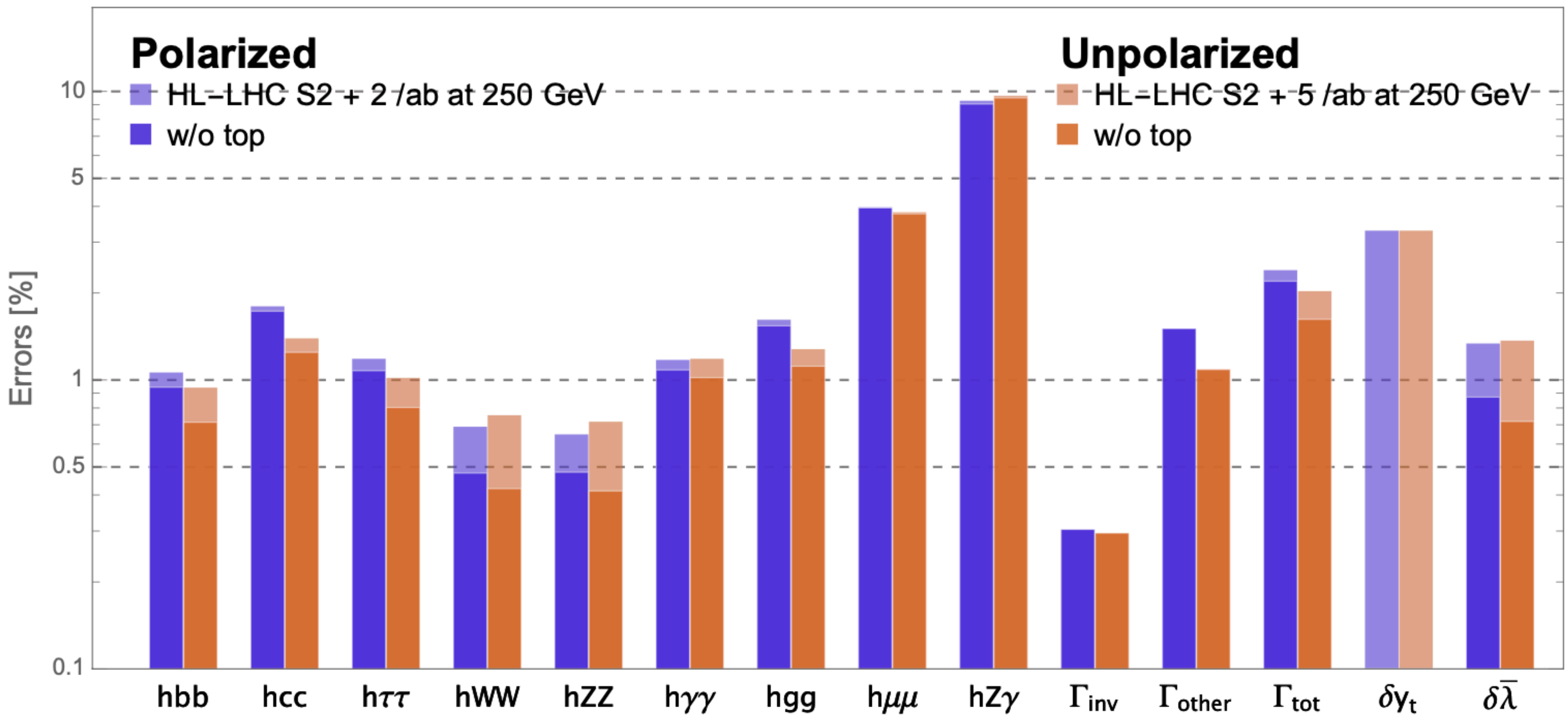
- different choice of Q reflects the errors from even higher order quantum corrections
- appearance of more different Q in observables, larger degradation on Higgs coupling precisions



our default choice Q=max(m_t, Q_{proc});
varied with Q=Q_{proc}, Q=max($2m_t$, Q_{proc})

results (III): effects from beam polarizations

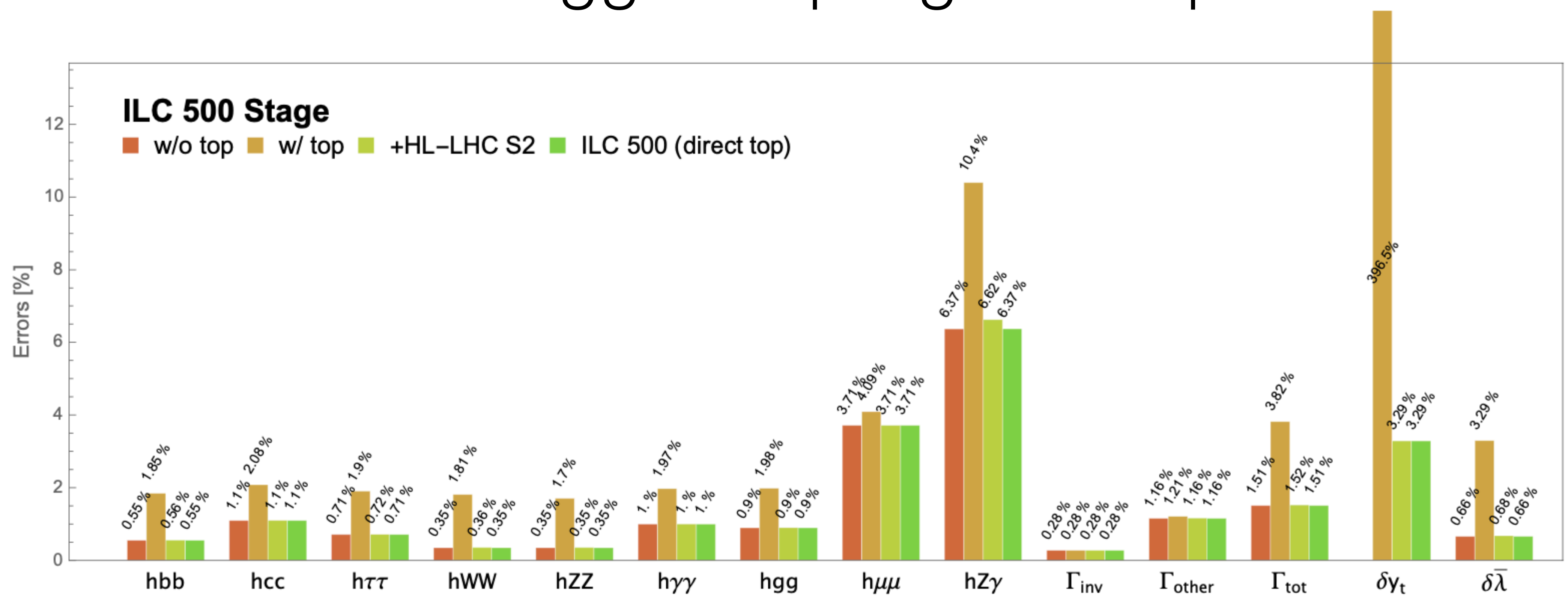
- beam polarizations double independent observables, in general more robust against uncertainty from top-operators

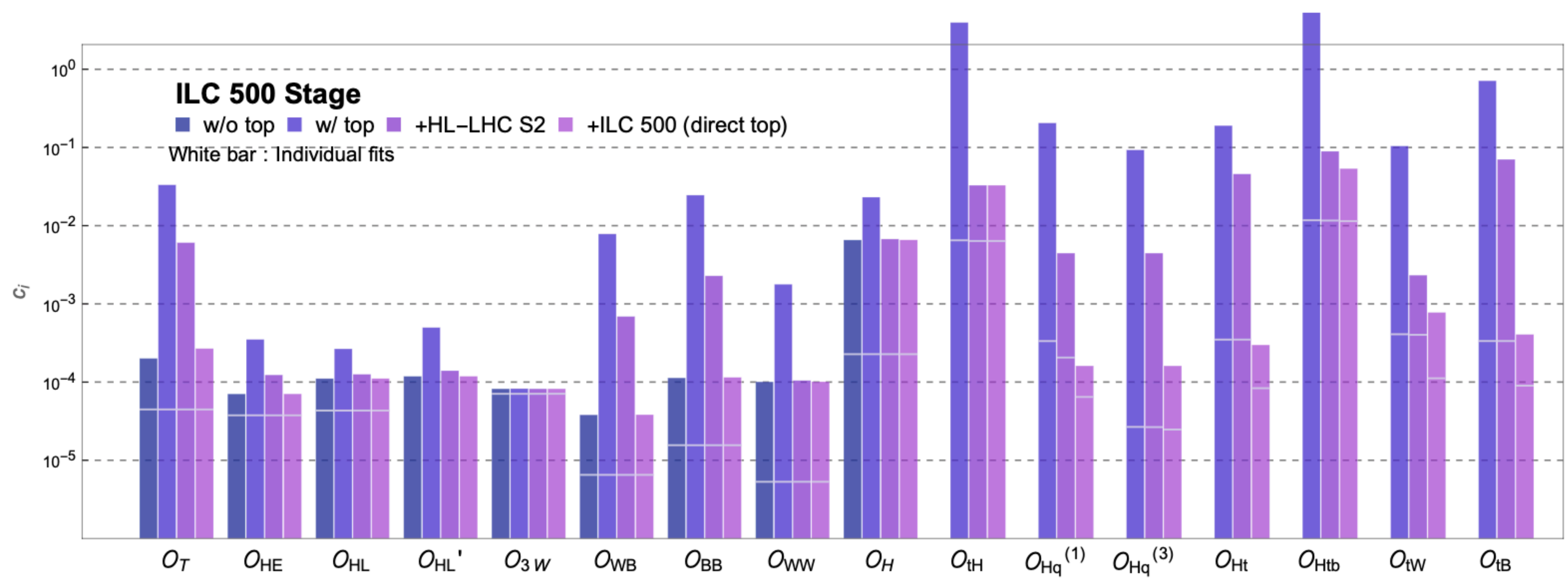


for Q=Q_{proc}

results (IV): ILC250+LHC+ILC500

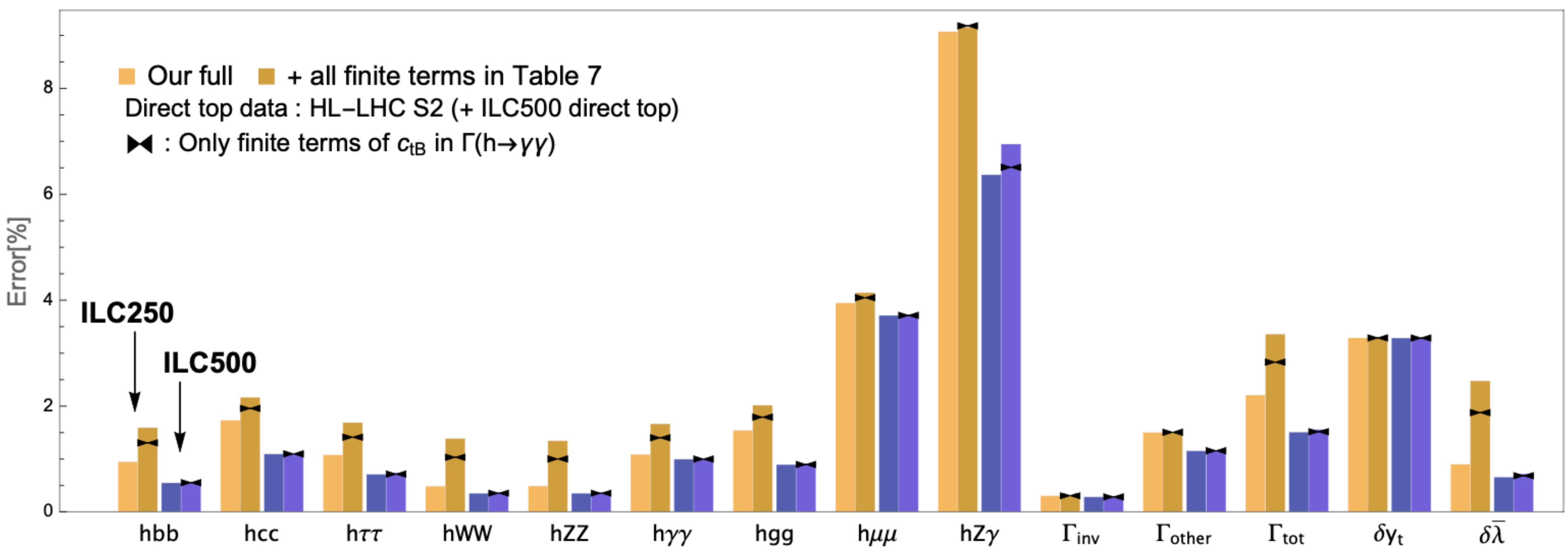
- precisions of both Higgs couplings and operators restored



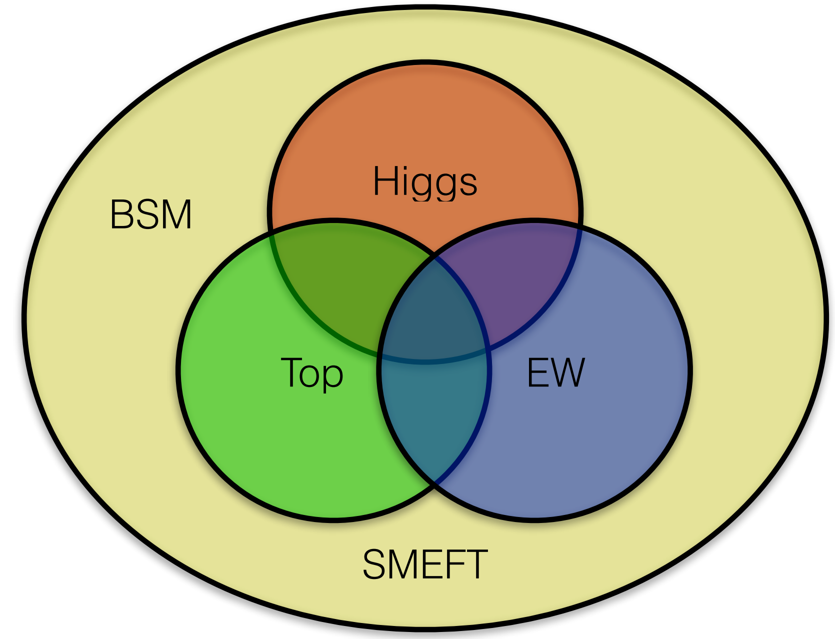


results (V): potential impact from finite one-loop effects

- could be significant @ 250 GeV, in particular for hZZ / hWW, x2-3 worse, though ~1-2% precision
- almost no difference once direct e+e- -> tt data is available



summary



- a combined Higgs/Top/EW analysis has been performed using the SMEFT framework
- NLO effects from top-quark play a significant role in the Higgs/EW processes
- top EW coupling measurements at (HL-)LHC are very important for future Higgs factories
- eventually e+e- -> t t-bar production will be very helpful to get most out of Higgs/EW measurements

backup

strategy to determine all the 23 parameters at e+e-

Electroweak Precision Observables (9)

+

Triple Gauge boson Couplings (3)

+

Higgs observables at LHC & e+e- (3+12x2)

2 for polarized

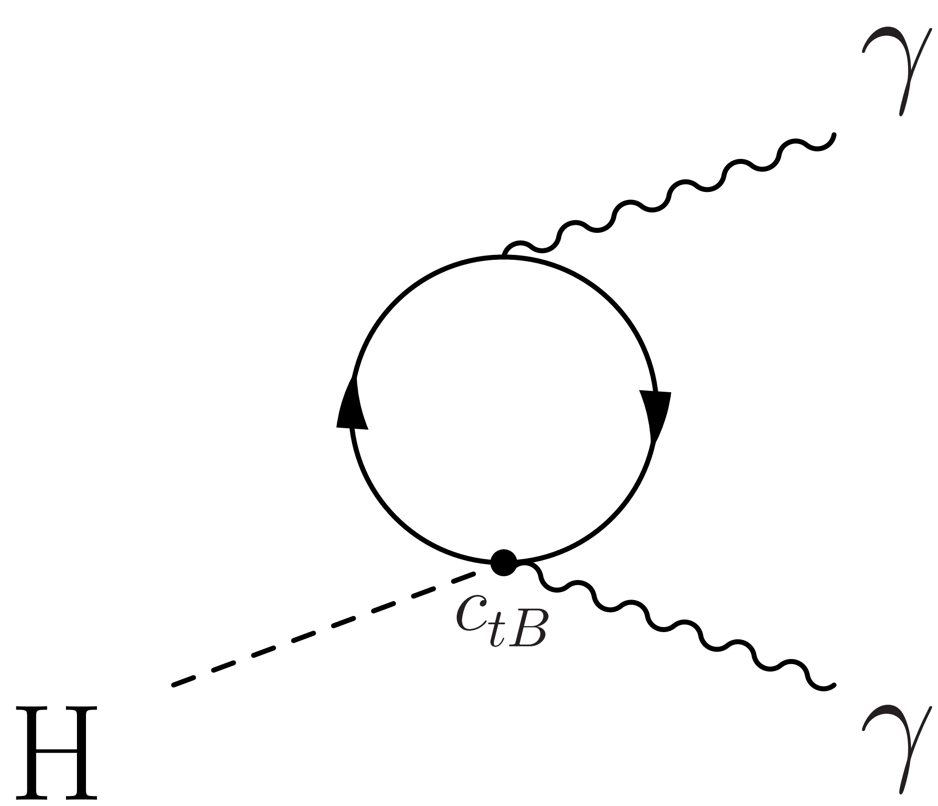
- all the 23 parameters can be determined ***simultaneously***

(details in backup)

some detailed understandings

$$\delta\Gamma(h \to \gamma\gamma) : + = -0.56c_{tH} + 1.2c_{HQ}^{(3)} - 0.04c_{Htb} + 33c_{tW} + 61c_{tB}$$

HL-LHC~600%

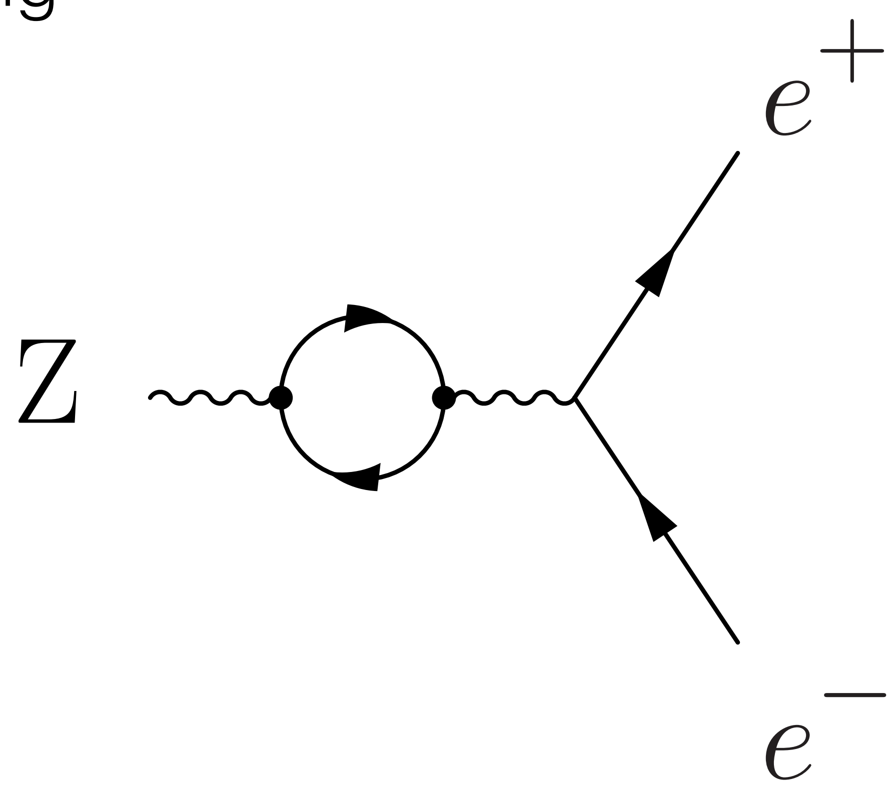


some detailed understandings

$$\delta A_l : + = 0.05 c_{HQ}^{(1)} - 0.2 c_{HQ}^{(3)} + 0.1 c_{Ht} + 1.8 c_{tW} - 0.3 c_{tB}$$

~1%

A_{LR}: left-right asymmetry
in Z-e-e coupling



EFT input: EWPOs (7)

$$\underline{\alpha(m_Z), G_F, m_W, m_Z, m_h,} A_{LR}(\ell), \Gamma(Z \to \ell^+ \ell^-)$$

$$\delta e = \delta(4\pi\alpha(m_Z^2))^{1/2} = s_w^2 \delta g + c_w^2 \delta g' + \frac{1}{2}\delta Z_A$$

$$\delta G_F = \; - 2\delta v + 2c'_{HL}$$

$$\delta m_W = \delta g + \delta v + \frac{1}{2}\delta Z_W$$

(δX=ΔX/X)

$$\delta m_Z = c_w^2 \delta g + s_w^2 \delta g' + \delta v - \frac{1}{2} c_T + \frac{1}{2}\delta Z_Z$$

$$\delta m_h = \frac{1}{2}\delta\overline{\lambda} + \delta v + \frac{1}{2}\delta Z_h$$

$$\overline{\lambda} = \lambda(1 + \frac{3}{2}c_6)$$

$$s_w^2 = \sin^2\theta_w = \frac{g'^2}{g^2 + g'^2}$$

$$c_w^2 = \cos^2\theta_w = \frac{g^2}{g^2 + g'^2}$$

⟶ δg, δg', δv, δλ, c_T

EFT input: EWPOs (7)

$$\alpha(m_Z), G_F, m_W, m_Z, m_h, \underline{A_{LR}(\ell), \Gamma(Z \to \ell^+\ell^-)}$$

$$\delta\Gamma_\ell = \delta m_Z + 2\frac{g_L^2\delta g_L + g_R^2\delta g_R}{g_L^2 + g_R^2}$$

$$\delta A_\ell = \frac{4g_L^2 g_R^2(\delta g_L - \delta g_R)}{g_L^4 - g_R^4}$$

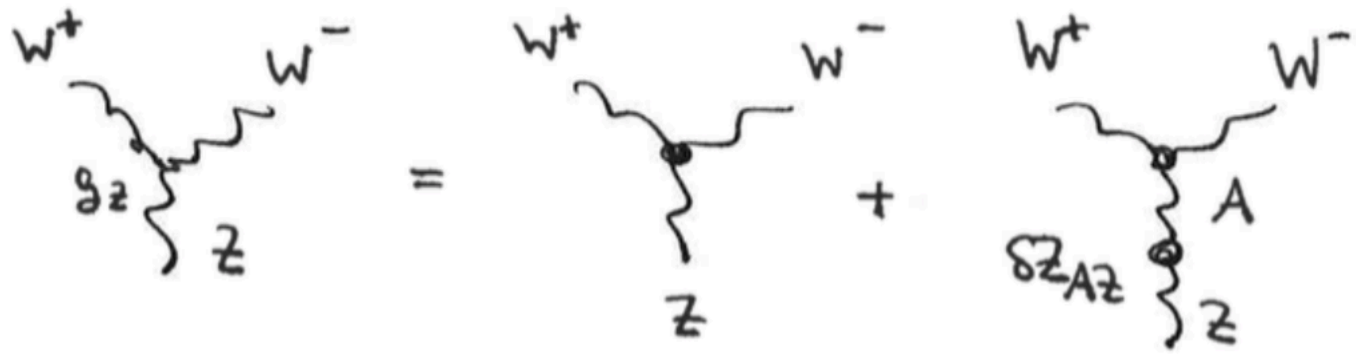
$$g_L = \frac{g}{c_w}\left[(-\frac{1}{2} + s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}(c_{HL} + c'_{HL}) - s_w c_w \delta Z_{AZ}\right]$$

$$g_R = \frac{g}{c_w}\left[(+s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}c_{HE} - s_w c_w \delta Z_{AZ}\right]$$

⟶ $c_{HL} + c'_{HL}$, c_{HE}

EFT input: TGC (3)

$$\Delta\mathcal{L}_{TGC} = ig_V\left\{V^\mu(\hat{W}^-_{\mu\nu}W^{+\nu} - \hat{W}^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu \hat{V}^{\mu\nu} + \frac{\lambda_V}{m_W^2}\hat{W}^{-\rho}_{\mu}\hat{W}^+_{\rho\nu}\hat{V}^{\mu\nu}\right\}$$

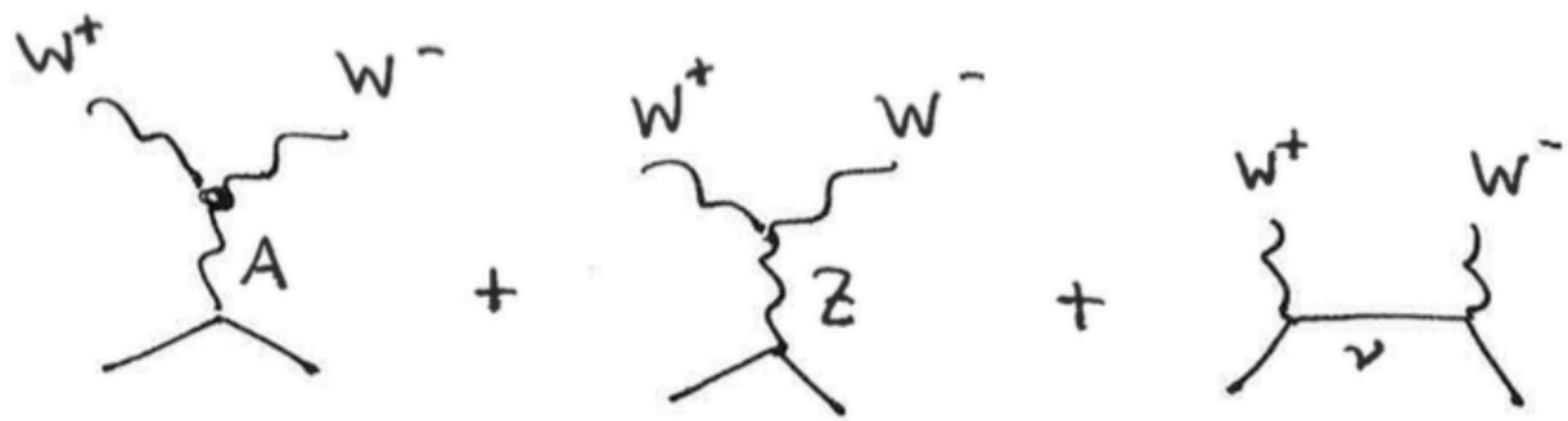


$$g_Z = gc_w(1 + \frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ})$$

$$\kappa_A = 1 + (8c_{WB})$$

$$\lambda_A = -6g^2 c_{3W}$$

EFT input: TGC (3)



$$\delta g_{Z,eff} = \delta g_Z + \frac{1}{c_w^2}((c_w^2 - s_w^2)\delta g_L + s_w^2 \delta g_R - 2\delta g_W)$$

$$\delta \kappa_{A,eff} = (c_w^2 - s_w^2)(\delta g_L - \delta g_R) + 2(\delta e - \delta g_W) + (8 c_{WB})$$

$$\delta \lambda_{A,eff} = -6 g^2 c_{3W}$$

$$g_W = g\ (1 + c'_{HL} + \frac{1}{2}\delta Z_W)$$

EFT input: BR(h->γγ)/BR(h->ZZ*), BR(h->γZ)/BR(h->ZZ*)

(2: HL-LHC)

$$\delta\Gamma(h \to \gamma\gamma) = 528\,\delta Z_A - c_H + 4\delta e + 4.2\,\delta m_h - 1.3\,\delta m_W - 2\delta v$$

$$\delta\Gamma(h \to Z\gamma) = 290\,\delta Z_{AZ} - c_H - 2(1 - 3s_W^2)\delta g + 6c_w^2\delta g' + \delta Z_A + \delta Z_Z$$
$$+9.6\,\delta m_h - 6.5\,\delta m_Z - 2\delta v$$

$$\delta\Gamma(h \to ZZ^*) = 2\eta_Z - 2\delta v - 13.8\delta m_Z + 15.6\delta m_h - 0.50\delta Z_Z - 1.02 C_Z + 1.18\delta\Gamma_Z$$

$$\delta Z_A = s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big) \qquad \delta Z_{AZ} = s_w c_w\Big((8c_{WW}) - (1 - \frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\Big)$$