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Mainz Institute for Theoretical Physics

Towards v2.0 of the CEPC EFT fit

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CEPC Physics Workshop, PKU CHEP
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to appear J. de Blas, G. Durieux, C. Grojean, JG, A. Paul

(also see my talk in the EW session on Thursday...)

EFT fit v1.0

- Why EFT fit?
  - A systematic parameterization of BSM contributions to Higgs couplings. (If $v \ll \Lambda$, leading order contributions are parametrized by D6 operators.)
  - EFT vs. "κ": EFT automatically includes the hVV anomalous couplings and imposes gauge invariance (and custodial symmetry).
- Higgs ($e^+e^- \to hZ$, $e^+e^- \to \nu\bar{\nu}h$, Higgs decays) and diboson ($e^+e^- \to WW$) measurements.
  - $e^+e^- \to WW$ probes the anomalous triple gauge couplings (aTGCs).
- A lot of parameters! We can reduce the parameter space by assuming the new physics ...
  - is CP-even,
  - does not generate dipole interaction of fermions,
  - has no corrections to Z-pole observables and W mass/width/BR.
- Only 12 combinations of operators are relevant for the measurements considered (with the inclusion of the Yukawa couplings of t, c, b, τ, μ).

EFT fit v1.0

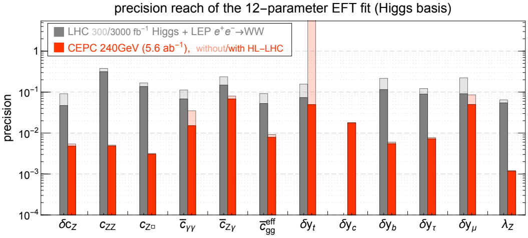
- Higgs basis (LHCHXSWG-INT-2015-001, A. Falkowski) with the following 12 parameters,

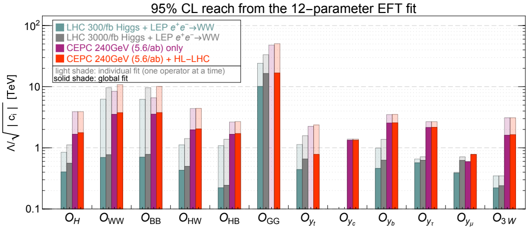
$$\delta c_Z\,,\quad c_{ZZ}\,,\quad c_{Z\Box}\,,\quad c_{\gamma\gamma}\,,\quad c_{Z\gamma}\,,\quad c_{gg}\,,\quad \delta y_t\,,\quad \delta y_c\,,\quad \delta y_b\,,\quad \delta y_\tau\,,\quad \delta y_\mu\,,\quad \lambda_Z\,.$$

- The Higgs basis is defined in the broken electroweak phase.
  - $\delta c_Z \leftrightarrow hZ^\mu Z_\mu, \quad c_{ZZ} \leftrightarrow hZ^{\mu\nu}Z_{\mu\nu}, \quad c_{Z\Box} \leftrightarrow hZ_\mu \partial_\nu Z^{\mu\nu}.$
- Couplings of h to W are written in terms of couplings of h to Z and γ.
- 3 aTGC parameters ($\delta g_{1,Z}$, $\delta\kappa_\gamma$, λ_Z), 2 written in terms of Higgs parameters.
- It can be easily mapped to the following basis with D6 operators.

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2\rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R + \text{h.c.} \quad (u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R + \text{h.c.} \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R + \text{h.c.} \quad (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$

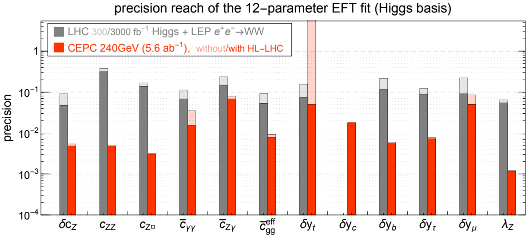
EFT fit v1.0

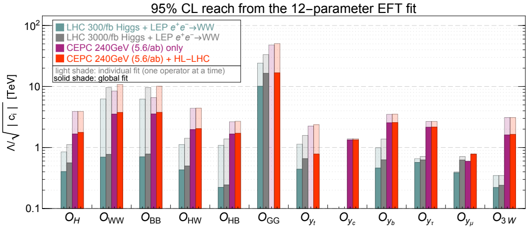




- Results in the CEPC Higgs whitepaper (arXiv:1810.09037) and the CDR.

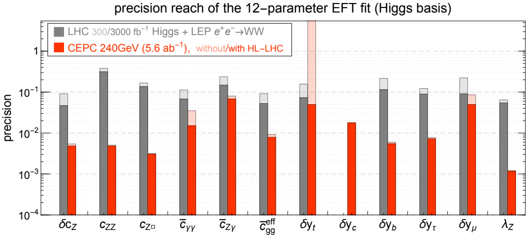
EFT fit v1.0

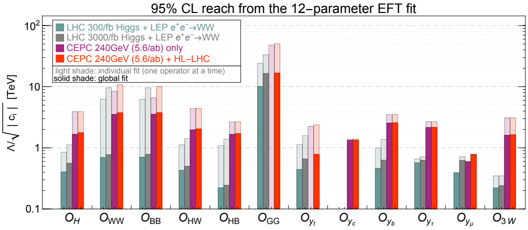




- Results in the CEPC Higgs whitepaper (arXiv:1810.09037) and the CDR.
- Now we wait for 20 years until all the data is taken ...
-

EFT fit v1.0



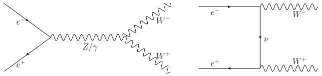


- See the CEPC Higgs whitepaper (arXiv:1810.09037) and the CDR.
- ~~Now we wait for 20 years until all the data has been taken ...~~
- **Still a lot of work to be done before that!**

What's new in v2.0?

- Z-pole & W mass/width/BR:
  perfect $\Rightarrow$ realistic (CEPC)!
  - **Directly** constraints on EW operators.
  - **Indirect** impact on Higgs operators.
  - Higgs+aTGCs (12 parameters)
    $\Rightarrow$ Higgs+aTGCs**+EW** (28 parameters)
    (impose $U(2)$ on 1st and 2nd generation quarks, exclude $Zt\bar{t}$ and Wtb couplings)

- An improved diboson ($e^+e^- \rightarrow WW$) analysis.
  - Going beyond the TGC-dominance assumption.
  - Binned methods $\Rightarrow$ optimal observables
    (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - Still an idealized theorists' analysis...
    (no background, no systematics...)



What's new in v2.0?

- Updated **(much better)** HL-LHC Higgs measurements!
- Basis choices...
  - Higgs basis: Define parameters in the broken EW phase so we can interpret them as Higgs couplings.
  - Can we take this idea further and just define some “effective couplings”?
  - **Make your EFT look as much like “kappa” as possible!** ([arXiv:1708.08912], [arXiv:1708.09079], Peskin *et al.*)

How to make your banana look like an apple

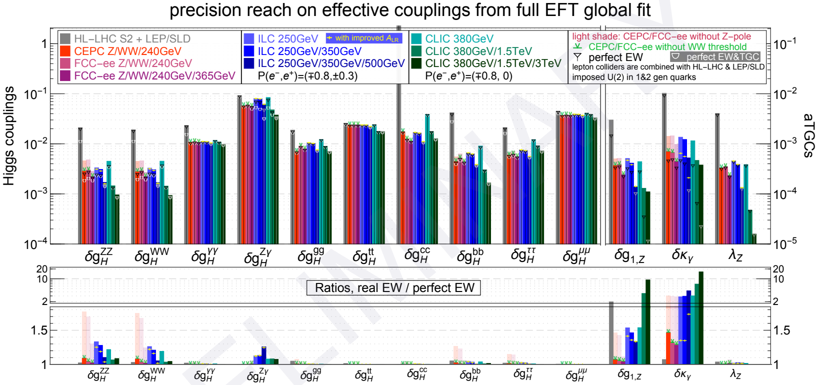
- EFT fit results projected on Effective Higgs couplings
  - $g(hZZ)$, $g(hWW)$ are defined at the scale of the relavent Higgs decay.
    $g(hZZ) \propto \sqrt{\Gamma(h \to ZZ)}\,, \quad g(hWW) \propto \sqrt{\Gamma(h \to WW)}\,.$
  - Not necessarily a basis, but can be made into a basis. (Maybe call it the "Peskin basis"?)
  - **It looks like κ but it is not κ!** (both intuitive and confusing....)
- Used in ILC and FCC-ee official documents and the ECFA report.
- Also useful for comparing results in different basis...

Run Scenarios

$\int \mathcal{L}dt$ [ab^{-1}]					
unpolarized	Z-pole	WW thres.	240 GeV	350 GeV	365 GeV
CEPC	8	2.6	5.6		
FCC-ee	150	10	5	0.2	1.5
ILC			250 GeV	350 GeV	500 GeV
$P(e^-, e^+) = (-0.8, +0.3)$			0.9	0.135	1.6
$P(e^-, e^+) = (+0.8, -0.3)$			0.9	0.045	1.6
CLIC			380 GeV	1.5 TeV	3 TeV
$P(e^-, e^+) = (-0.8, 0)$			0.5	2	4
$P(e^-, e^+) = (+0.8, 0)$			0.5	0.5	1

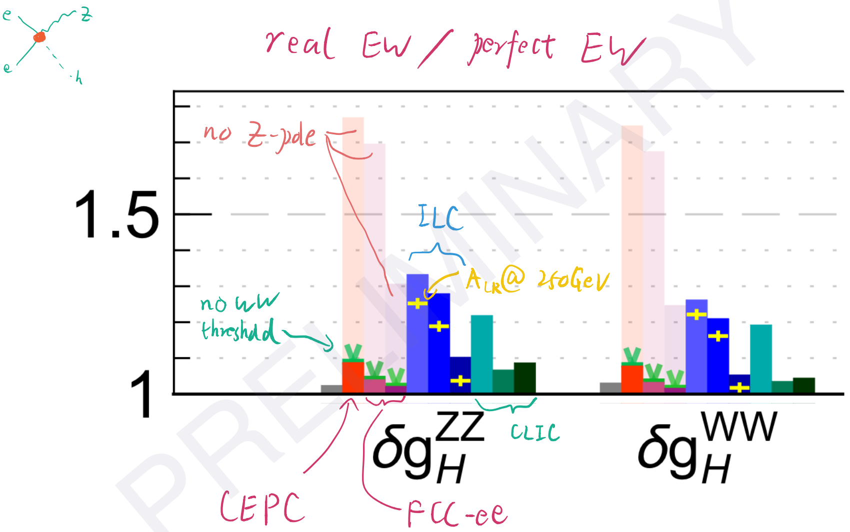
- FCC-ee has a top threshold run and also better EW programs.
- Linear colliders have the option of longitudinal beam polarizations.

“Full fit” projected on the Higgs couplings (and aTGCs)



- 28-parameter fit, projected on the Higgs couplings & aTGCs.
- Lepton colliders are combined with HL-LHC & LEP/SLD.
- The *hZZ* and *hWW* couplings are not independent!

Z-pole run is also important for Higgs couplings!

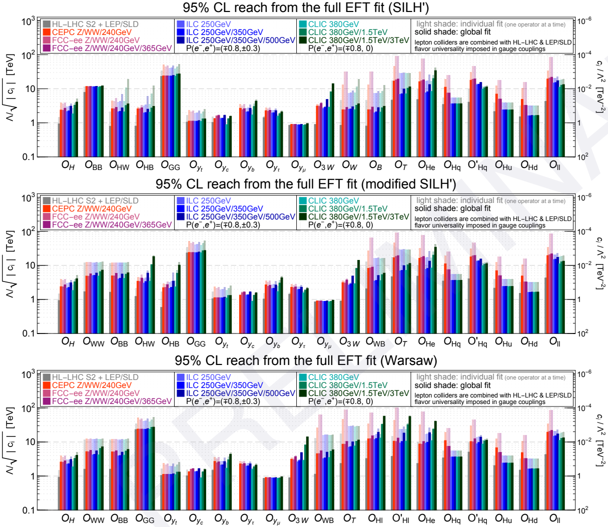


D6 operators

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{q}_L \tilde{H} u_R + \text{h.c.} \quad (u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{q}_L H d_R + \text{h.c.} \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{l}_L H e_R + \text{h.c.} \quad (e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$	$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$
$\mathcal{O}'_{Hq} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$

- SILH' basis (eliminate $\mathcal{O}_{WW}$, $\mathcal{O}_{WB}$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Modified-SILH' basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Warsaw basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{HW}$ and $\mathcal{O}_{HB}$)

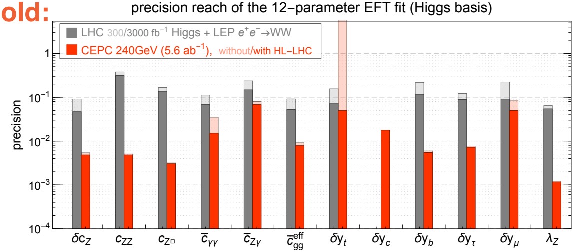
Pick your favorite basis!



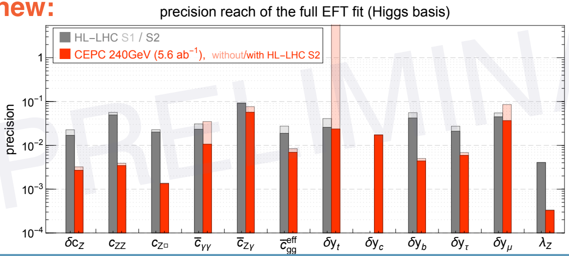
- Modified-SILH' is most convenient in the limit of perfect EW (Z-pole, W mass/width/BR).
- Now we can choose any of them...

CEPC: old *vs.* new (Higgs basis)

old:



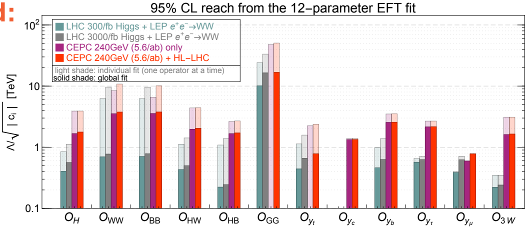
new:



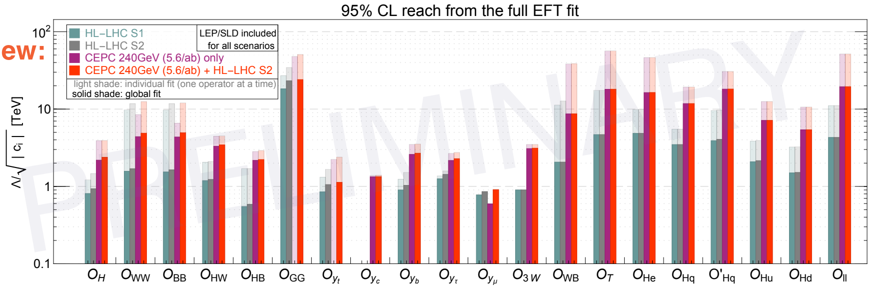
- Full fit: only the Higgs parameters are shown.
- HL-LHC: ATLAS and CMS are combined. (The correlation between ATLAS/CMS are not provided by the WG.)

CEPC: old *vs.* new (modified-SILH’ basis)

old:



new:



- Flavor universality imposed on gauge couplings for now (can be removed later).

Important messages

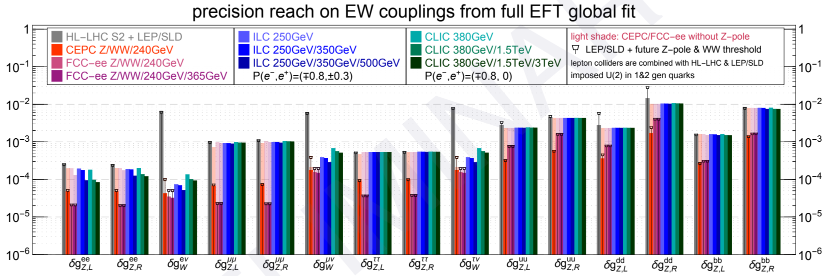
- The new projections of the HL-LHC Higgs measurement won't kill the physics case of CEPC.
- The CEPC Z-pole program is important for
  - probing EW couplings;
  - eliminating EW uncertainties in Higgs processes, allowing for a robust extraction of Higgs couplings. (For this purpose, the CEPC Z-pole program is "good enough.")
- **We need a realistic $e^+e^- \to WW$ analysis!**

More things to do

- top threshold run (can use FCC-ee as a reference)
  - Measuring Higgs processes at a different energy.
  - EW + Higgs + top combined fit. (maybe left for the future...)
- triple Higgs coupling
  - With runs at both 240 GeV and 350/365 GeV we can constrain it to $\sim 40\text{-}50\%$ in a global fit.
    [arXiv:1711.03978] Di Vita, Durieux, Grojean, JG, Liu, Panico, Riembau, Vantalon
  - The new HL-LHC projection is also $\sim 50\%$ (ATLAS & CMS all channels combined).
- more loop contributions
  - For the top loop contributions in Higgs processes, see *e.g.* [arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang.

backup slides

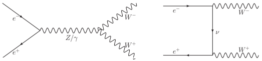
Reach on the Vff couplings (in Higgs basis)



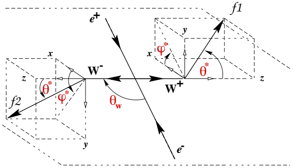
- *Zff* couplings are still best probed by future Z-pole runs.

A refined TGC analysis using Optimal Observables

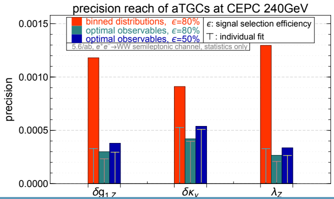
- TGCs are sensitive to the differential distributions!
  - Current method: fit to binned distributions of all angles.
  - Correlations among angles are ignored.



- What are optimal observables?
  (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - For a given sample, there is an upper limit on the precision reach of the parameters.
  - In the limit of large statistics (everything is Gaussian) and small parameters (leading order dominates), this "upper limit" can be derived analytically!

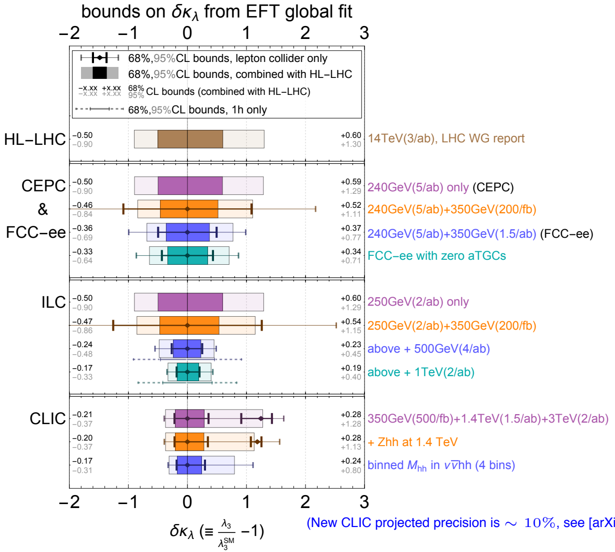


- $\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}|_{\rm SM} + \sum_i S(\Omega)_i\, g_i$. The optimal observables are simply the $S(\Omega)_i$.



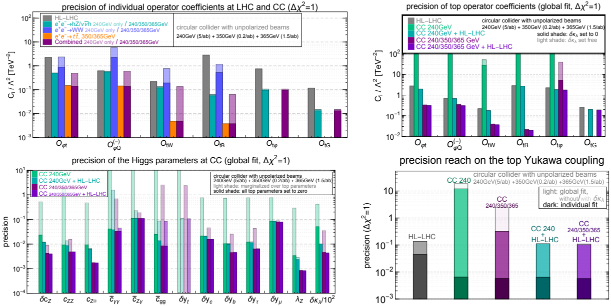
- Very idealized! How well can we actually do?
  - Choose a conservative 50% efficiency to compensate the omission of systematics...

A summary of the projected reaches on $\delta\kappa_\lambda$ (with updated HL-LHC projection)



(New CLIC projected precision is $\sim 10\%$, see [arXiv:1901.05897] Roloff *et al.*)

Top operators in loops [arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang



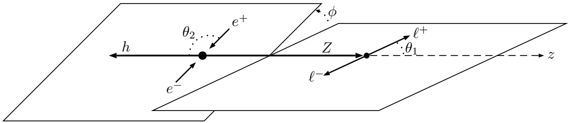
$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\,(\varphi^\dagger\varphi) + h.c.,$$
$$O^{(1)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q),$$
$$O^{(3)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{Q}\gamma^\mu\tau^I Q),$$
$$O_{\varphi t} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t),$$
$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c.,$$
$$O_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\,\tilde{\varphi}B_{\mu\nu} + h.c.,$$
$$O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\,\tilde{\varphi}G^A_{\mu\nu} + h.c.\,.$$

- (See Marcel’s talk for general top EFT analyses at future lepton colliders.)
- Higgs precision measurements have sensitivity to the top operators in the loops, but it is challenging to discriminate many parameters in a global fit.
- HL-LHC helps, but a Top threshold run is better.
- Indirect bounds on the top Yukawa coupling.

EW measurements

- *Z*-pole
  - $\sim 10^{11} - 10^{12}$ *Z*s at CEPC/FCC-ee.
  - How many *Z*s do we really need?
    - “EW Operators”: more is always better (but systematics will dominate at some point).
    - “Higgs Operators”: need the EW operators to be constrained sufficiently well.
- $e^+e^- \to WW$, threshold scan, or “free data” at 240 GeV and above
  - ***W* mass**
    - from threshold scan, or from *W* reconstruction at higher energies
  - ***W* width**
    - direct measurement with threshold scan
    - can be derived from BR measurements, assuming *W* has no exotic decay.
  - ***W* branching ratios**
  - anomalous Triple Gauge Couplings (**aTGCs**)
    - Not well measured at threshold (dominated by the *t*-channel diagram).
    - Is the TGC dominance assumption valid?
    - **Optimal observables** can be used to extract the maximum amount of information in the *WW* differential distributions. (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)

angular observables in $e^+e^- \to hZ$

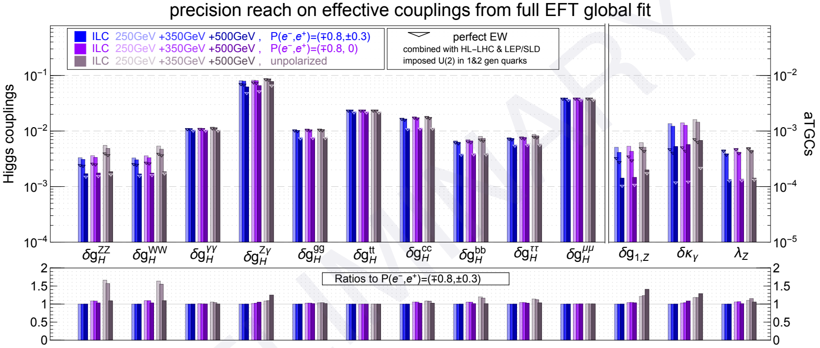


- Angular distributions in $e^+e^- \to hZ$ can provide information in addition to the rate measurement alone.
- Previous studies
  - [arXiv:1406.1361] M. Beneke, D. Boito, Y.-M. Wang
  - [arXiv:1512.06877] N. Craig, JG, Z. Liu, K. Wang
- 6 independent asymmetry observables from 3 angles

$$\mathcal{A}_{\theta_1}\,,\quad \mathcal{A}_{\phi}^{(1)}\,,\quad \mathcal{A}_{\phi}^{(2)}\,,\quad \mathcal{A}_{\phi}^{(3)}\,,\quad \mathcal{A}_{\phi}^{(4)}\,,\quad \mathcal{A}_{c\theta_1,c\theta_2}\,.$$

- Focusing on leptonic decays of Z (good resolution, small background, statistical uncertainty dominates).
- Optimal observables can further improve the sensitivity.

ILC polarization



- Polarized beams: assuming the luminosity is equally divided into $(-,+)$ and $(+,-)$ polarizations.
- Beam polarizations can probe different combinations of EFT parameters in $e^+e^- \to hZ$ (and so can runs at different energies).

The “12-parameter” framework in the Higgs basis

- The relevant terms in the EFT Lagrangian are

$$\mathcal{L} \supset \mathcal{L}_{hVV} + \mathcal{L}_{hff} + \mathcal{L}_{\rm tgc} \,, \tag{1}$$

- the Higgs couplings with a pair of gauge bosons

$$\begin{aligned}\mathcal{L}_{hVV} = \frac{h}{v}\Big[& (1+\delta c_W)\frac{g^2v^2}{2}W^+_\mu W^-_\mu + (1+\delta c_Z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu \\ & + c_{WW}\frac{g^2}{2}W^+_{\mu\nu}W^-_{\mu\nu} + c_{W\Box}\, g^2(W^-_\mu \partial_\nu W^+_{\mu\nu} + \mathrm{h.c.}) \\ & + c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^2_{\mu\nu} + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{Z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} \\ & + c_{ZZ}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} + c_{Z\Box}\, g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box}\, gg' Z_\mu \partial_\nu A_{\mu\nu}\Big] \,. \end{aligned} \tag{2}$$

The "12-parameter" framework in the Higgs basis

- Not all the couplings are independent, for instance one could write the following couplings as

$$\begin{aligned}
\delta c_W &= \delta c_Z + 4\delta m\,,\\
c_{WW} &= c_{ZZ} + 2s^2_{\theta_W} c_{Z\gamma} + s^4_{\theta_W} c_{\gamma\gamma}\,,\\
c_{W\Box} &= \frac{1}{g^2-g'^2}\left[g^2 c_{Z\Box} + g'^2 c_{ZZ} - e^2 s^2_{\theta_W} c_{\gamma\gamma} - (g^2-g'^2) s^2_{\theta_W} c_{Z\gamma}\right]\,,\\
c_{\gamma\Box} &= \frac{1}{g^2-g'^2}\left[2g^2 c_{Z\Box} + (g^2+g'^2) c_{ZZ} - e^2 c_{\gamma\gamma} - (g^2-g'^2) c_{Z\gamma}\right]\,,
\end{aligned} \tag{3}$$

- we only consider the diagonal elements in the Yukawa matrices relevant for the measurements considered,

$$\mathcal{L}_{hff} = -\frac{h}{v} \sum_{f=t,c,b,\tau,\mu} m_f (1+\delta y_f) \bar{f}_R f_L + \text{h.c.}\,. \tag{4}$$

TGC

$$\begin{aligned}\mathcal{L}_{\rm tgc} = \;& igs_{\theta_W} A^\mu (W^{-\nu} W^+_{\mu\nu} - W^{+\nu} W^-_{\mu\nu}) \\ & + ig(1+\delta g_1^Z) c_{\theta_W} Z^\mu (W^{-\nu} W^+_{\mu\nu} - W^{+\nu} W^-_{\mu\nu}) \\ & + ig\left[(1+\delta\kappa_Z) c_{\theta_W} Z^{\mu\nu} + (1+\delta\kappa_\gamma) s_{\theta_W} A^{\mu\nu}\right] W^-_\mu W^+_\nu \\ & + \frac{ig}{m_W^2}(\lambda_Z c_{\theta_W} Z^{\mu\nu} + \lambda_\gamma s_{\theta_W} A^{\mu\nu}) W^{-\rho}_v W^+_{\rho\mu} \,, \end{aligned} \quad (5)$$

- $V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$ for $V = W^\pm, Z, A,$. Imposing Gauge invariance one obtains $\delta\kappa_Z = \delta g_{1,Z} - t^2_{\theta_W}\delta\kappa_\gamma$ and $\lambda_Z = \lambda_\gamma$.
- 3 aTGCs parameters $\delta g_{1,Z}$, $\delta\kappa_\gamma$ and λ_Z, 2 of them related to Higgs observables by

$$\delta g_{1,Z} = \frac{1}{2(g^2-g'^2)}\left[-g^2(g^2+g'^2)c_{Z\Box} - g'^2(g^2+g'^2)c_{ZZ} + e^2 g'^2 c_{\gamma\gamma} + g'^2(g^2-g'^2)c_{Z\gamma}\right] \,,$$

$$\delta\kappa_\gamma = -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{Z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{ZZ}\right) \,. \quad (6)$$