# Effective field theories in future Higgs factories

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# Introduction

- **Goal:** Perform a global fit of EFT parameters to the data from a future ($e^+e^-$) Higgs factory.
- **Problem:** One may get poor results from the global fit due to a large degeneracy among many parameters.
- **Solution:** Include all possible measurements (and also make reasonable assumptions).

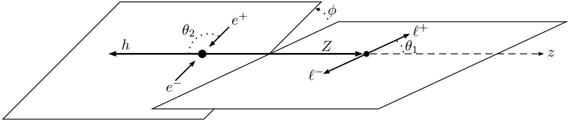
# Future $e^+e^-$ colliders

- Circular colliders
  - The Future Circular Collider (FCC-ee) at CERN.
  - The Circular Electron-Positron Collider (CEPC) in China.
  - CEPC: $5\,\mathrm{ab}^{-1}$ data at $240$ GeV (Higgs factory), likely to also run at $350$ GeV (luminosity undecided, we use a conservative value of $200\,\mathrm{fb}^{-1}$). Possible run at $Z$-pole?
  - FCC-ee can potentially do even better.
- Linear collider
  - The International Linear Collider (ILC) in Japan.
  - With luminosity upgrades, the ILC can collect $2\,\mathrm{ab}^{-1}$ at 250 GeV, $200\,\mathrm{fb}^{-1}$ at 350 GeV and $4\,\mathrm{ab}^{-1}$ at 500 GeV.
  - Longitudinal beam polarizations ($|P(e^-)| = 80\%$, $|P(e^+)| = 30\%$).

# What measurements can we include?

- Rate measurements in $e^+e^- \to hZ$, both $\sigma(hZ)$ and $\sigma(hZ) \times \mathrm{BR}(h \to xx)$.
- Angular distributions in $e^+e^- \to hZ$.
- $WW$ fusion production of Higgs ($e^+e^- \to \nu\bar{\nu}h$).
- $e^+e^- \to WW$. (A lot of "free data" at 240 GeV.)
- Measurements at higher energies and/or with beam polarizations.
- Electroweak precision measurements at $Z$-pole (not included in our study but may have an impact).

# 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] Beneke, Boito, 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).

# A few remarks on the measurements

- The measurements of the decay $h \to Z\gamma$ plays an important role in the global fit. ($\sigma(hZ) \times \mathrm{BR(h \to Z\gamma)}$ estimated to be $\sim 25\%$ at CEPC.)
- $e^+e^- \to \nu\bar{\nu}h$
  - At 240 GeV it is hard to separate the *WW* fusion process from $e^+e^- \to hZ, Z \to \nu\bar{\nu}$.
  - It is not consistent to focus on one process and treat the other one as SM-like!
- $e^+e^- \to WW$
  - 2 of the 3 aTGCs are generated by operators that also contribute to Higgs physics.
  - $\sigma(WW) \sim 10^2 \times \sigma(hZ)$ at 240 GeV.
  - Dedicated experimental studies are needed to determine the systematic uncertainties and extract the constraints on aTGCs.
  - If $e^+e^- \to WW$ is measured at the same level of precision with the *Z*-pole measurements, the "TGC dominance assumption" may no longer be valid.

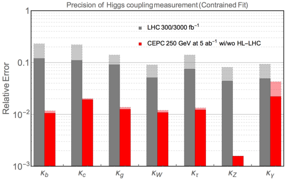
# The “10-parameter” framework in the Higgs basis

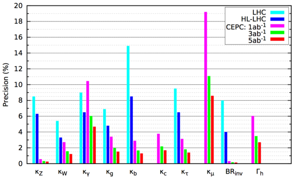
- Start with all the D6 operators that can contribute to the above measurements.
- Assume the new physics
  - is CP-even,
  - does not generate dipole interaction of fermions,
  - is flavor universal (for Yukawa couplings, we assume $\delta y_u = \delta y_c = \delta y_t$, etc.),
  - has no corrections to $Z$-pole observables and $W$ mass (more justified if the machine will run at $Z$-pole).
- We are left with 10 operators, parameterized in the Higgs basis by:

$$\delta c_Z\,, \quad c_{ZZ}\,, \quad c_{Z\Box}\,, \quad c_{\gamma\gamma}\,, \quad c_{Z\gamma}\,, \quad c_{gg}\,, \quad \delta y_u\,, \quad \delta y_d\,, \quad \delta y_e\,, \quad \lambda_Z\,.$$

- Strong independent constraints can be obtained for all 10 coefficients!
- [arXiv:1505.00046] Falkowski
  [arXiv:1508.00581] Falkowski, Gonzalez-Alonso, Greljo, Marzocca

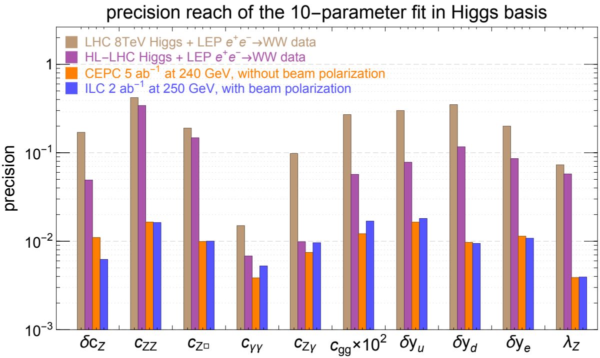
# EFT vs. the "$\kappa$-frame"





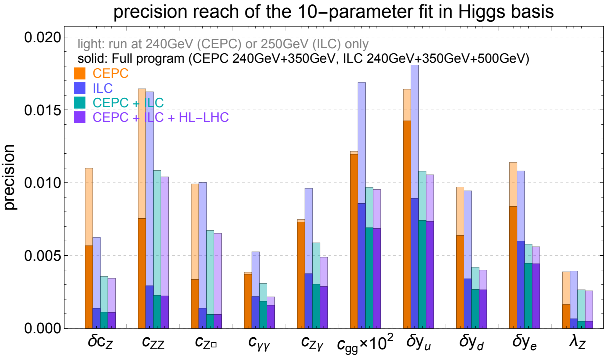
- Conventionally, many studies of Higgs couplings use the so-called "$\kappa$-frame."
- A framework based on EFT is more general and consistent than the "$\kappa$-frame."
  - It allows couplings with different Lorentz structures, such as $hZ^{\mu\nu}Z_{\mu\nu}$ or $hZ_\mu\partial_\nu Z^{\mu\nu}$ (parameterized by $c_{ZZ}$ and $c_{Z\Box}$).
  - Gauge invariance is built in the parameterization.
- More parameters $\Rightarrow$ more flat directions! Additional measurements are essential in resolving the flat directions.

# Results of the “10-parameter” fit



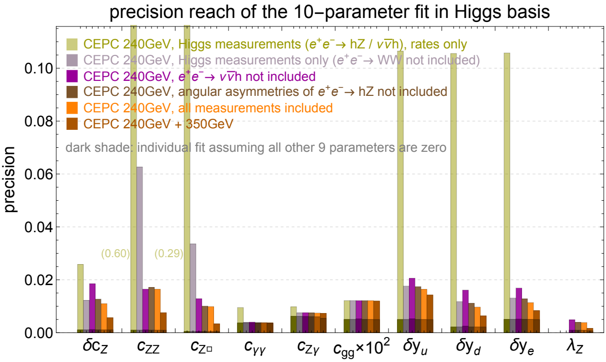
- Much better than LHC Higgs + LEP *WW* results!
- LHC diboson (TGC) results are not included at the moment.

# Results of the “10-parameter” fit



- Complementarity!
- Measurements at higher $\sqrt{s}$ can be very helpful in resolving
  - $\delta c_Z \leftrightarrow hZ^\mu Z_\mu, \quad c_{ZZ} \leftrightarrow hZ^{\mu\nu} Z_{\mu\nu}, \quad c_{Z\Box} \leftrightarrow hZ_\mu \partial_\nu Z^{\mu\nu}.$

# The importance of combining all measurements



- The results are much worse if we only include the rates of Higgs measurements alone!
- There is some overlap in the information from different measurements.

# Want list for the future

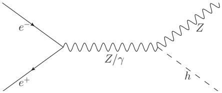
- Experimental studies of CEPC/FCC-ee on the extractions of aTGCs from $e^+e^- \to WW$ with realistic systematic uncertainties.
- A better study to determine the reach of HL-LHC?
- Extend the 10-parameter framework
  - Include CP-odd operators and relax the assumptions on flavor structure.
  - Include Higgs invisible/exotic decay?
  - Loop corrections (*e.g.* loop correction to the $hZZ$ vertex from Higgs trilinear couplings).
- Combine Higgs, diboson and $Z$-pole data and do a MEGA global fit? (a lot of work!)
- FCC-ee vs. CLIC ?

# Conclusion

- After the discovery of Higgs at the LHC, a plausible “next step” is to build an $e^+e^-$ collider to perform Higgs precision measurements.
- Many measurements can be performed!
  - rate measurements in $e^+e^- \to hZ$ (production and Higgs decay),
  - angular distributions in $e^+e^- \to hZ$,
  - $WW$ fusion ($e^+e^- \to \nu\bar{\nu}h$),
  - $e^+e^- \to WW$,
  - measurements at different energies or with different beam polarization.
- By combining all the available measurements and making reasonable assumptions on the new physics, we can obtain strong independent constraints on all the relevant dimension-6 operators!
- Still a lot of work to be done!

# backup slides

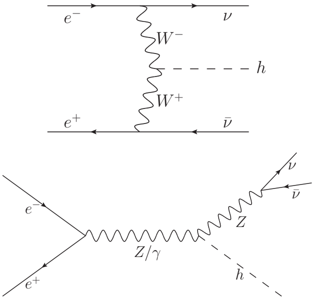
# rate measurements in $e^+e^- \to hZ$

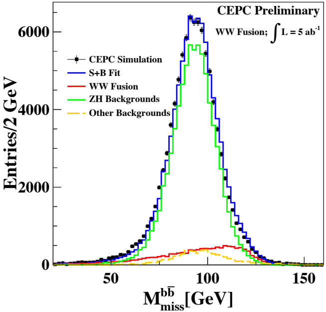


|  | precision |  |
|---|---|---|
| meausrement | CEPC<br>[240 GeV, $5\ \mathrm{ab}^{-1}$] | ILC<br>[250 GeV, $2\ \mathrm{ab}^{-1}$] |
| $\sigma(hZ)$ | 0.50% | 0.71% |
|  | $\sigma(hZ) \times \mathrm{BR}$ |  |
| $h \to b\bar{b}$ | 0.21% (0.24%) | 0.42% |
| $h \to c\bar{c}$ | 2.5% | 2.9% |
| $h \to gg$ | 1.3% | 2.5% |
| $h \to \tau\tau$ | 1.0% | 1.1% |
| $h \to WW^*$ | 1.0% | 2.3% |
| $h \to ZZ^*$ | 4.3% | 6.7% |
| $h \to \gamma\gamma$ | 9.0% | 12% |
| $h \to \mu\mu$ | 17% | 25% |
| $h \to Z\gamma$ | $\sim 25\%$ | $\sim 34\%$ |

- Rates can be measured very precisely!
- Both $\sigma(hZ)$ and $\sigma(hZ) \times \mathrm{BR}$ can be measured.
- $h \to Z\gamma$ is important!

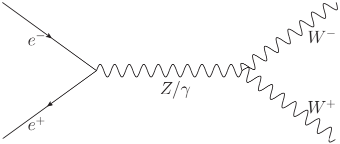
# $e^+e^- \to \nu\bar{\nu}h$

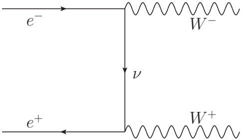




- It is hard to separate the $WW$ fusion process from $e^+e^- \to hZ, Z \to \nu\bar{\nu}$ at 240 GeV.
- It is not consistent to focus on one process and treat the other one as SM-like!
- We analyze the combined $e^+e^- \to \nu\bar{\nu}h$ process, assuming new physics can contribute to both processes. (The $h \to b\bar{b}$ decay channel is used.)

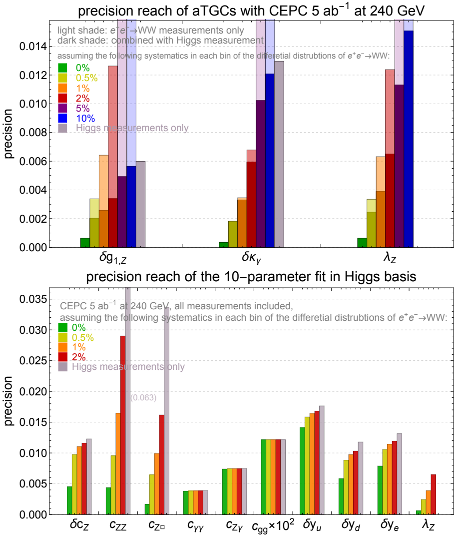
# $e^+e^- \to WW$





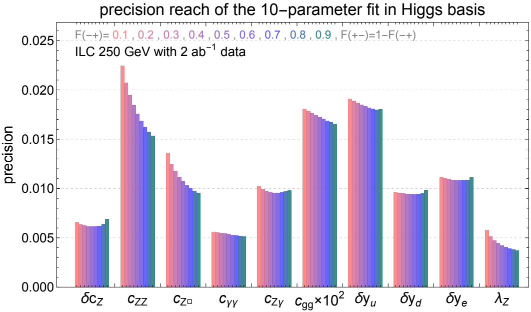
- $e^+e^- \to WW$ offers a great way to probe the anomalous triple gauge couplings (aTGCs, parameterized by $\delta g_{1,Z}$, $\delta\kappa_\gamma$, $\lambda_Z$).
- $\delta g_{1,Z}$ and $\delta\kappa_\gamma$ are related to Higgs observables.
- CEPC with $5\,\mathrm{ab}^{-1}$ data at 240 GeV can collect $\sim 9\times 10^7$ $e^+e^- \to WW$ events.
- With such large statistics, the aTGCs can be very well constrained ([1507.02238] Bian, Shu, Zhang), but with two potential issues:
  - Systematic uncertainties can be important!
  - If $e^+e^- \to WW$ is measured more precisely than the $Z$-pole measurements, is it still ok to assume the fermion gauge couplings are SM-like?

# The interplay between Higgs and TGC



- $\delta g_{1,Z}\,,\ \delta\kappa_\gamma \leftrightarrow$ $c_{ZZ}\,,\ c_{Z\Box}\,,\ c_{\gamma\gamma}\,,\ c_{Z\gamma}$
- We try different assumptions on the systematic uncertainties (in each bin with the differential distribution divided into 20 bins).
- Detailed study of $e^+e^-\to WW$ required to estimate the systematic uncertainties!

# What's the best way to divide the total luminosity into runs with different polarization?



- Two polarization configurations are considered, $P(e^-, e^+) = (-0.8, +0.3)$ and $(+0.8, -0.3)$.
- $F(-+)$ in the range of 0.6-0.8 gives an optimal overall results.
- Runs with different polarizations probe different combinations of EFT parameters in Higgs production. So do runs at different energies.

# Asymmetry observables

$$\begin{aligned}
\mathcal{A}_{\theta_1} &= \frac{1}{\sigma} \int_{-1}^{1} d\cos\theta_1 \, \mathrm{sgn}(\cos(2\theta_1)) \, \frac{d\sigma}{d\cos\theta_1} \, , \\
\mathcal{A}_{\phi}^{(1)} &= \frac{1}{\sigma} \int_{0}^{2\pi} d\phi \, \mathrm{sgn}(\sin\phi) \, \frac{d\sigma}{d\phi} \, , \\
\mathcal{A}_{\phi}^{(2)} &= \frac{1}{\sigma} \int_{0}^{2\pi} d\phi \, \mathrm{sgn}(\sin(2\phi)) \, \frac{d\sigma}{d\phi} \, , \\
\mathcal{A}_{\phi}^{(3)} &= \frac{1}{\sigma} \int_{0}^{2\pi} d\phi \, \mathrm{sgn}(\cos\phi) \, \frac{d\sigma}{d\phi} \, , \\
\mathcal{A}_{\phi}^{(4)} &= \frac{1}{\sigma} \int_{0}^{2\pi} d\phi \, \mathrm{sgn}(\cos(2\phi)) \, \frac{d\sigma}{d\phi} \, ,
\end{aligned} \tag{1}$$

$$\mathcal{A}_{c\theta_1, c\theta_2} = \frac{1}{\sigma} \int_{-1}^{1} d\cos\theta_1 \, \mathrm{sgn}(\cos\theta_1) \int_{-1}^{1} d\cos\theta_2 \, \mathrm{sgn}(\cos\theta_2) \frac{d^2\sigma}{d\cos\theta_1 \, d\cos\theta_2} \, , \tag{2}$$

# The “10-parameter” framework in the Higgs basis

- The relevant terms in the EFT Lagrangian are

$$\mathcal{L} \supset \mathcal{L}_{hVV} + \mathcal{L}_{hff} + \mathcal{L}_{\rm tgc} \,, \tag{3}$$

- the Higgs couplings with a pair of gauge bosons

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

# The “10-parameter” framework in the Higgs basis

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

$$
\begin{aligned}
\delta c_W &= \delta c_Z + 4\delta m\,, \\
c_{WW} &= c_{ZZ} + 2 s_{\theta_W}^2 c_{Z\gamma} + s_{\theta_W}^4 c_{\gamma\gamma}\,, \\
c_{W\Box} &= \frac{1}{g^2 - g'^2}\left[ g^2 c_{Z\Box} + g'^2 c_{ZZ} - e^2 s_{\theta_W}^2 c_{\gamma\gamma} - (g^2 - g'^2) s_{\theta_W}^2 c_{Z\gamma} \right]\,, \\
c_{\gamma\Box} &= \frac{1}{g^2 - g'^2}\left[ 2g^2 c_{Z\Box} + (g^2 + g'^2) c_{ZZ} - e^2 c_{\gamma\gamma} - (g^2 - g'^2) c_{Z\gamma} \right]\,, \qquad (5)
\end{aligned}
$$

- Assuming flavor universality, the Yukawa couplings are written as

$$
\mathcal{L}_{hff} = -\frac{h}{v} \sum_{f\in u,d,e} \sum_{i=1}^{3} m_{f_i}(1 + \delta y_f) \bar{f}_{R,i} f_{L,i} + \mathrm{h.c.}\,, \qquad (6)
$$

# TGC

$$\begin{aligned}\mathcal{L}_{\rm tgc} \;=\;\; & igs_{\theta_W}A^{\mu}(W^{-\nu}W^{+}_{\mu\nu}-W^{+\nu}W^{-}_{\mu\nu}) \\ & + ig(1+\delta g_1^Z)c_{\theta_W}Z^{\mu}(W^{-\nu}W^{+}_{\mu\nu}-W^{+\nu}W^{-}_{\mu\nu}) \\ & + ig\left[(1+\delta\kappa_Z)c_{\theta_W}Z^{\mu\nu}+(1+\delta\kappa_\gamma)s_{\theta_W}A^{\mu\nu}\right]W^{-}_{\mu}W^{+}_{\nu} \\ & + \frac{ig}{m_W^2}(\lambda_Z c_{\theta_W}Z^{\mu\nu}+\lambda_\gamma s_{\theta_W}A^{\mu\nu})W_v^{-\rho}W^{+}_{\rho\mu}\,, \end{aligned} \tag{7}$$

- $V_{\mu\nu}\equiv\partial_\mu V_\nu-\partial_\nu V_\mu$ 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 $\lambda_Z$, 2 of them related to Higgs observables by

$$\begin{aligned}\delta g_{1,Z} &= \frac{1}{2(g^2-g'^2)}\left[-g^2(g^2+g'^2)c_{Z\Box}-g'^2(g^2+g'^2)c_{ZZ}+e^2g'^2c_{\gamma\gamma}+g'^2(g^2-g'^2)c_{Z\gamma}\right]\,, \\ \delta\kappa_\gamma &= -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2}+c_{Z\gamma}\frac{g^2-g'^2}{g^2+g'^2}-c_{ZZ}\right)\,. \end{aligned} \tag{8}$$

# A basis with D6 operators

| | |
|---|---|
| $\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$ | $\mathcal{O}_{GG} = g_s^2 \lvert H \rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$ |
| $\mathcal{O}_{WW} = g^2 \lvert H \rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$ | $\mathcal{O}_{y_u} = y_u \lvert H \rvert^2 \bar{Q}_L \tilde{H} u_R$ |
| $\mathcal{O}_{BB} = g'^2 \lvert H \rvert^2 B_{\mu\nu} B^{\mu\nu}$ | $\mathcal{O}_{y_d} = y_d \lvert H \rvert^2 \bar{Q}_L H d_R$ |
| $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$ | $\mathcal{O}_{y_e} = y_e \lvert H \rvert^2 \bar{L}_L H e_R$ |
| $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$ | $\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$ |