

Effective field theories in future Higgs factories

Jiayin Gu (顾嘉荫)

DESY/IHEP

The 3rd CEPC Physics Software Meeting
November 30, 2016

current work with G. Durieux, C. Grojean, K. Wang

Introduction

- ▶ Higgs and nothing else?
- ▶ The scale of new physics Λ is large \Rightarrow EFT is a good description at low energy.
- ▶ We want a Higgs factory! ($e^+e^- \rightarrow hZ$ at 240-250 GeV)
- ▶ A global fit to EFT parameters is desired, but one may get poor results due to a large degeneracy among many parameters.
- ▶ To resolve the large degeneracy one should try to include all possible measurements (and also make reasonable assumptions).

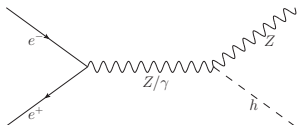
Future e^+e^- colliders

- ▶ Circular colliders
 - ▶ The Circular Electron-Positron Collider (CEPC) in China.
 - ▶ The Future Circular Collider (FCC-ee) at CERN.
 - ▶ Possible runs at 240 GeV (Higgs factory), Z-pole, and 350 GeV.
 - ▶ Large luminosity.
 - ▶ The tunnel can be used for a hadron collider with $\sqrt{s} \sim 100$ TeV in the future!
- ▶ Linear collider
 - ▶ The International Linear Collider (ILC) in Japan.
 - ▶ Smaller luminosity, but can achieve a much larger center of mass energy (500 GeV, and possibly 1 TeV).
 - ▶ Longitudinal beam polarization.

What measurements can be done in a Higgs Factory?

- ▶ A circular collider at 240 GeV or a linear collider at 250 GeV.
- ▶ Rate measurements in $e^+e^- \rightarrow hZ$, both $\sigma(hZ)$ and $\sigma(hZ) \times \text{BR}(h \rightarrow xx)$.
- ▶ Angular distributions in $e^+e^- \rightarrow hZ$.
- ▶ WW fusion ($e^+e^- \rightarrow \nu\bar{\nu}h$).
- ▶ $e^+e^- \rightarrow WW$. ($\sigma(WW) \sim 10^2 \times \sigma(hZ)$. Buy one get one free!)
- ▶ The beam polarization option in a linear collider can effectively increase the total number of independent observables.

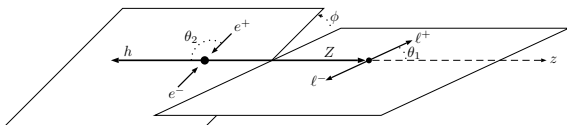
- ▶ other running options of a future e^+e^- collider
 - ▶ Electroweak precision measurements at Z -pole (a better version of LEP).
 - ▶ $\sqrt{s} \sim 350$ GeV ($t\bar{t}$ threshold); $\sqrt{s} \sim 500$ GeV or above (ILC).

rate measurements in $e^+e^- \rightarrow hZ$ 

measurement	precision	
	CEPC	ILC
$\sigma(hZ)$	0.50%	2.5%
	$\sigma(hZ) \times \text{BR}$	
$h \rightarrow bb$	0.21% (0.24%)	1%
$h \rightarrow c\bar{c}$	2.5%	6.9%
$h \rightarrow gg$	1.3%	8.5%
$h \rightarrow \tau\tau$	1.0%	3.6%
$h \rightarrow WW^*$	1.0%	8.1%
$h \rightarrow ZZ^*$	4.3%	26%
$h \rightarrow \gamma\gamma$	9.0%	23-30%
$h \rightarrow \mu\mu$	17%	
$h \rightarrow Z\gamma$	$\sim 25\%$ (4σ)	

- ▶ CEPC with 5 ab^{-1} data at 240 GeV (preCDR).
- ▶ ILC with 250 fb^{-1} data at 250 GeV (TDR).
- ▶ Rates can be measured very precisely!
- ▶ It is possible to directly measure the total cross section $\sigma(hZ)$ at e^+e^- colliders.

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

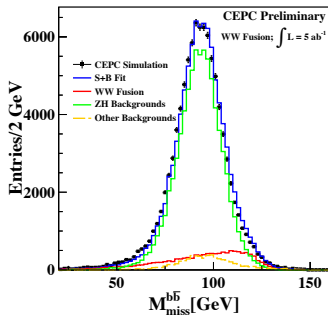
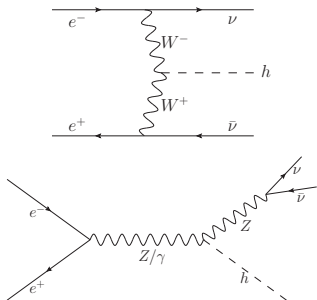


- ▶ Angular distributions in $e^+e^- \rightarrow hZ$ can provide information in addition to the rate measurement alone.
- ▶ Previous studies
 - ▶ [1406.1361] Beneke, Boito, Wang
 - ▶ [1512.06877] N. Craig, JG, Z. Liu, K. Wang
- ▶ 6 independent asymmetry observables from 3 angles

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

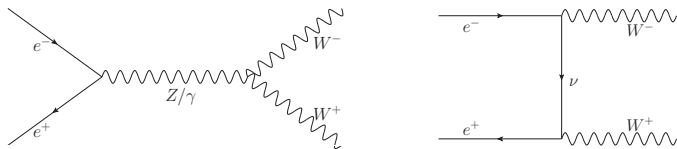
- ▶ Focusing on leptonic decays of Z (good resolution, small background, statistical uncertainty dominates).

$$e^+e^- \rightarrow \nu\bar{\nu}h$$



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

$e^+e^- \rightarrow WW$



- ▶ $e^+e^- \rightarrow WW$ offers a great way to probe the anomalous triple gauge couplings (aTGCs, parameterized by $\delta g_{1,Z}$, $\delta \kappa_\gamma$, λ_Z).
- ▶ $\delta g_{1,Z}$ and $\delta \kappa_\gamma$ are related to Higgs observables.
- ▶ CEPC with 5 ab^{-1} data at 240 GeV can collect $\sim 9 \times 10^7$ $e^+e^- \rightarrow WW$ 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 $e^+e^- \rightarrow WW$ is measured more precisely than the Z-pole measurements, is it still ok to assume the fermion gauge couplings are SM-like?

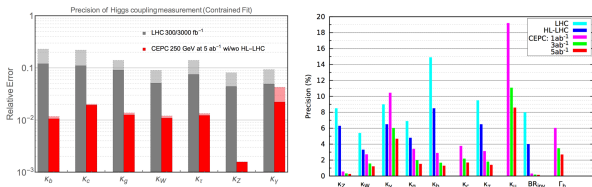
The “10-parameter” framework in the Higgs basis

- ▶ Starting with all the D6 operators that can contribute to the above measurements.
- ▶ Assuming new physics is CP-even, flavor universal.
- ▶ Assuming 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:

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

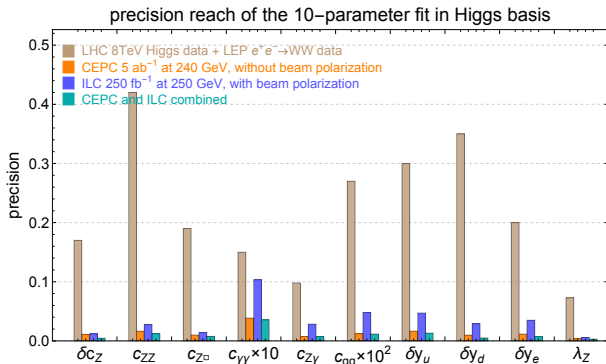
- ▶ Strong independent constraints can be obtained for all 10 coefficients!
- ▶ [1505.00046] Falkowski
[1508.00581] Falkowski, Gonzalez-Alonso, Greljo, Marzocca

Higgs basis vs. the “ κ -frame”



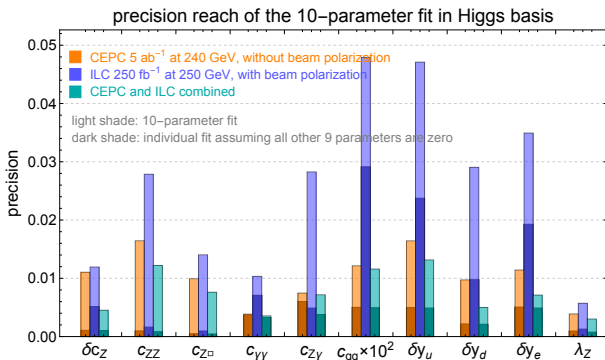
- ▶ Conventionally, many studies of Higgs couplings use the so-called “ κ -frame”.
- ▶ The Higgs basis is more general and consistent than the “ κ -frame”.
 - ▶ It allows couplings with different Lorentz structures, such as $hZ^{\mu\nu}Z_{\mu\nu}$ or $hZ_{\mu}\partial_{\nu}Z^{\mu\nu}$ (parameterized 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.
- ▶ Higgs invisible/exotic decays are not considered at the moment, but can be implemented in the future.

Results of the “10-parameter” fit



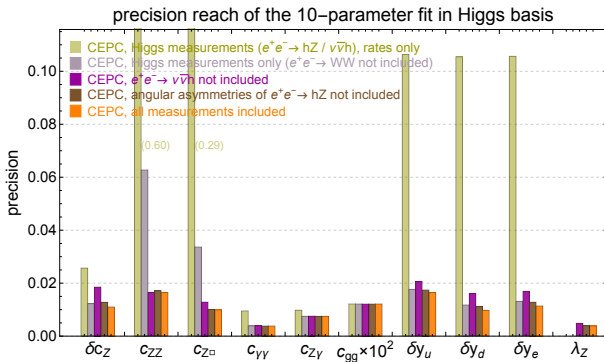
- ▶ Much better than the current results! (Taken from [1508.00581] Falkowski, Gonzalez-Alonso, Greljo, Marzocca, obtained from LHC 8 TeV Higgs data and LEP $e^+e^- \rightarrow WW$ data.)
- ▶ Haven't compared with HL-LHC data yet... (nontrivial to estimate the reach at HL-LHC)

Results of the “10-parameter” fit



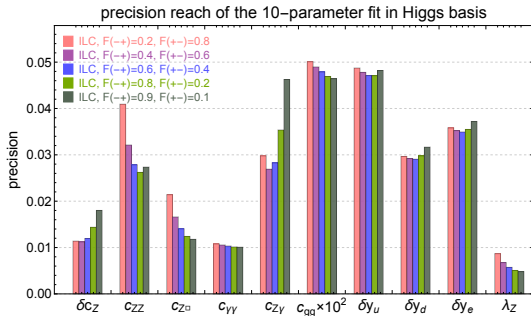
- ▶ CEPC: circular collider, large luminosity
- ▶ ILC: linear collider, beam polarization (60% of total Luminosity goes to $P(e^-, e^+) = (-0.8, +0.3)$, 40% goes to $P(e^-, e^+) = (+0.8, -0.3)$.)
- ▶ Complementarity!

The importance of combining all measurements



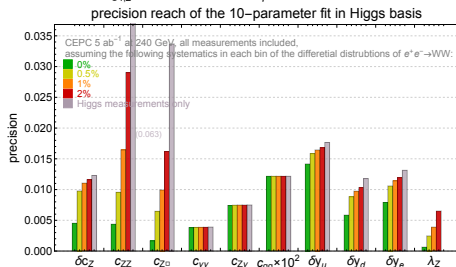
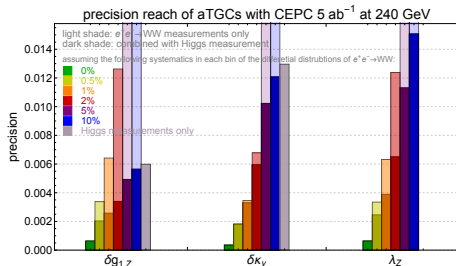
- ▶ The results are much worse if we only include the rates of Higgs measurements alone!
- ▶ There is some overlap in the information from different measurements.

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



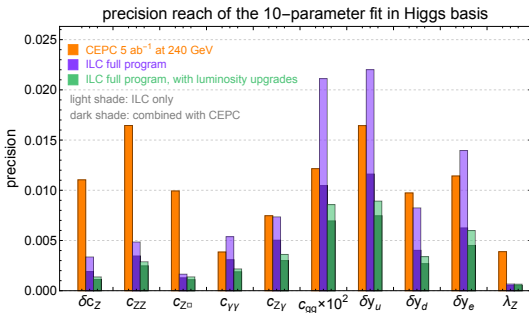
- ▶ Two polarization configurations are considered, $P(e^-, e^+) = (-0.8, +0.3)$ and $(+0.8, -0.3)$.
- ▶ $F(-+)$ in the range of 0.6-0.8 gives an optimal overall results.

The interplay between Higgs and TGC



- ▶ $\delta g_{1,Z}, \delta \kappa_\gamma \leftrightarrow c_{ZZ}, c_{Z^0}, c_{\gamma\gamma}, c_{Z\gamma}$
- ▶ We try different assumptions on the systematic uncertainties (in each bin with the differential distribution divided into 20 bins).
- ▶ Detailed study of $e^+e^- \rightarrow WW$ required to estimate the systematic uncertainties!

Comparison with the Full ILC program



- ▶ The ILC measurements at higher \sqrt{s} can be very helpful in resolving
 - ▶ $\delta c_Z \leftrightarrow hZ^\mu Z_\mu$, $c_{ZZ} \leftrightarrow hZ^{\mu\nu} Z_{\mu\nu}$, $c_{Z\Box} \leftrightarrow hZ_\mu \partial_\nu Z^{\mu\nu}$.
- ▶ The following numbers are used for “ILC full program” and “ILC full program with luminosity upgrades”, both with $P(e^-, e^+) = (-0.8, +0.3)$,
 - ▶ 250 fb^{-1} at 250 GeV, 330 fb^{-1} at 350 GeV and 500 fb^{-1} at 500 GeV,
 - ▶ 2 ab^{-1} at 250 GeV, 200 fb^{-1} at 350 GeV and 4 ab^{-1} at 500 GeV.

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 $e^+e^- \rightarrow hZ$ (production and Higgs decay),
 - ▶ Angular distributions in $e^+e^- \rightarrow hZ$,
 - ▶ WW fusion ($e^+e^- \rightarrow \nu\bar{\nu}h$),
 - ▶ $e^+e^- \rightarrow WW$.
 - ▶ Measurements with 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!
- ▶ Complementarity between a circular collider and a linear collider.
- ▶ Still a lot of work to be done!

backup slides

Asymmetry observables

$$\begin{aligned}
 \mathcal{A}_{\theta_1} &= \frac{1}{\sigma} \int_{-1}^1 d\cos\theta_1 \operatorname{sgn}(\cos(2\theta_1)) \frac{d\sigma}{d\cos\theta_1}, \\
 \mathcal{A}_{\phi}^{(1)} &= \frac{1}{\sigma} \int_0^{2\pi} d\phi \operatorname{sgn}(\sin\phi) \frac{d\sigma}{d\phi}, \\
 \mathcal{A}_{\phi}^{(2)} &= \frac{1}{\sigma} \int_0^{2\pi} d\phi \operatorname{sgn}(\sin(2\phi)) \frac{d\sigma}{d\phi}, \\
 \mathcal{A}_{\phi}^{(3)} &= \frac{1}{\sigma} \int_0^{2\pi} d\phi \operatorname{sgn}(\cos\phi) \frac{d\sigma}{d\phi}, \\
 \mathcal{A}_{\phi}^{(4)} &= \frac{1}{\sigma} \int_0^{2\pi} d\phi \operatorname{sgn}(\cos(2\phi)) \frac{d\sigma}{d\phi}, \tag{1}
 \end{aligned}$$

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

The “10-parameter” framework in the Higgs basis

- ▶ The relevant terms in the EFT Lagrangian are

$$\mathcal{L} \supset \mathcal{L}_{hVV} + \mathcal{L}_{hff} + \mathcal{L}_{\text{tgc}}, \quad (3)$$

- ▶ the Higgs couplings with a pair of gauge bosons

$$\begin{aligned} \mathcal{L}_{hVV} = & \frac{h}{v} \left[(1 + \delta c_W) \frac{g^2 v^2}{2} W_\mu^+ W_\mu^- + (1 + \delta c_Z) \frac{(g^2 + g'^2) v^2}{4} Z_\mu Z_\mu \right. \\ & + c_{WW} \frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + c_{W\Box} g^2 (W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}) \\ & + c_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^2 + c_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{Z\gamma} \frac{e\sqrt{g^2 + g'^2}}{2} Z_{\mu\nu} A_{\mu\nu} \\ & \left. + c_{ZZ} \frac{g^2 + g'^2}{4} Z_{\mu\nu} Z_{\mu\nu} + c_{Z\Box} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A_{\mu\nu} \right]. \quad (4) \end{aligned}$$

The “10-parameter” framework in the Higgs basis

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

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

- ▶ Assuming flavor universality, the Yukawa couplings are written as

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

TGC

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

- ▶ $V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$ for $V = W^\pm, Z, A,$. Imposing Gauge invariance one obtains $\delta\kappa_Z = \delta g_{1,Z} - t_{\theta_W}^2 \delta\kappa_\gamma$ 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

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