Effective field theories in future Higgs factories

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DESY/IHEP

Workshop on CEPC Physics
December 15, 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! ($e^+e^- \to hZ$ 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

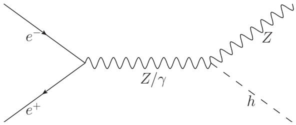
- Circular colliders
  - The Circular Electron-Positron Collider (CEPC) in China.
  - The Future Circular Collider (FCC-ee) at CERN.
  - Possible runs at 240 GeV (Higgs factory), Z-pole, and 350 GeV.
  - Large luminosity.
  - The tunnel can be used for a hadron collider with $\sqrt{s} \sim 100$ TeV in 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 $e^+e^- \to hZ$, both $\sigma(hZ)$ and $\sigma(hZ) \times \mathrm{BR}(h \to xx)$.
- Angular distributions in $e^+e^- \to hZ$.
- WW fusion production of Higgs ($e^+e^- \to \nu\bar{\nu}h$).
- $e^+e^- \to WW$. ($\sigma(WW) \sim 10^2 \times \sigma(hZ)$. 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).

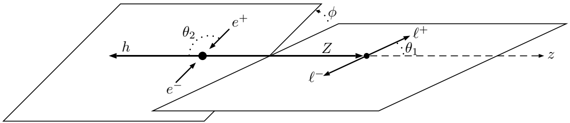
rate measurements in $e^+e^- \to hZ$



	precision	
meausrement	CEPC	ILC
$\sigma(hZ)$	0.50%	2.0%
	$\sigma(hZ) \times \mathrm{BR}$	
$h \to b\bar{b}$	0.21% (0.24%)	1.2%
$h \to c\bar{c}$	2.5%	8.3%
$h \to gg$	1.3%	7.0%
$h \to \tau\tau$	1.0%	3.2%
$h \to WW^*$	1.0%	6.4%
$h \to ZZ^*$	4.3%	19%
$h \to \gamma\gamma$	9.0%	34%
$h \to \mu\mu$	17%	72%
$h \to Z\gamma$	$\sim 25\%$ (4σ)	$\lesssim 100\%$?

- CEPC with $5\,\mathrm{ab}^{-1}$ data at 240 GeV and ILC with $250\,\mathrm{fb}^{-1}$ data at 250 GeV.
- ILC can also run at higher energies and may have luminosity upgrade.
- Rates can be measured very precisely!
- Both $\sigma(hZ)$ and $\sigma(hZ) \times \mathrm{BR}$ can be measured.
- $h \to Z\gamma$ is important!

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

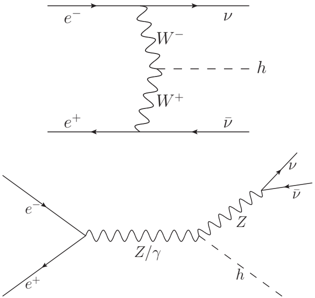


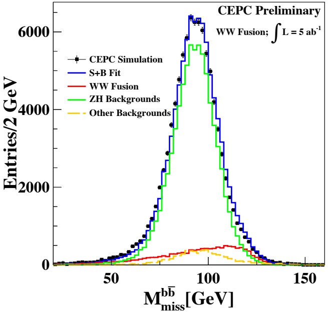
- Angular distributions in $e^+e^- \to hZ$ can provide information in addition to the rate measurement alone.
- Previous studies
  - [arXiv:1406.1361] Beneke, Boito, Wang
  - [arXiv:1512.06877] N. Craig, JG, Z. Liu, K. Wang
- 6 independent asymmetry observables from 3 angles

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

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

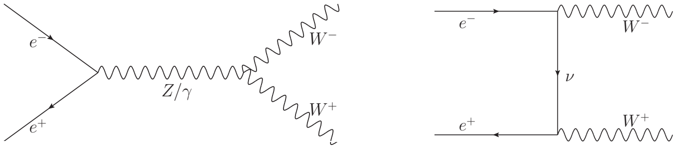
$e^+e^- \to \nu\bar{\nu}h$





- 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 $\delta g_{1,Z}$, $\delta\kappa_\gamma$, λ_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 $\sim 9\times10^7$ $e^+e^- \to WW$ 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?

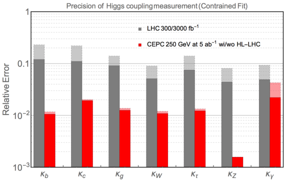
The "10-parameter" framework in the Higgs basis

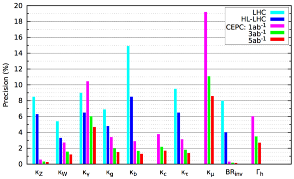
- Start with all the D6 operators that can contribute to the above measurements.
- Assume the new physics
  - is CP-even,
  - does not generate dipole interaction of fermions,
  - has no corrections to Z-pole observables and W mass (more justified if the machine will run at Z-pole),
  - is flavor universal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

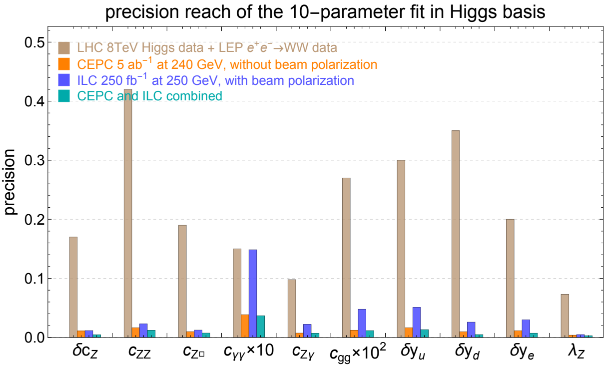
Higgs basis vs. the "κ-frame"





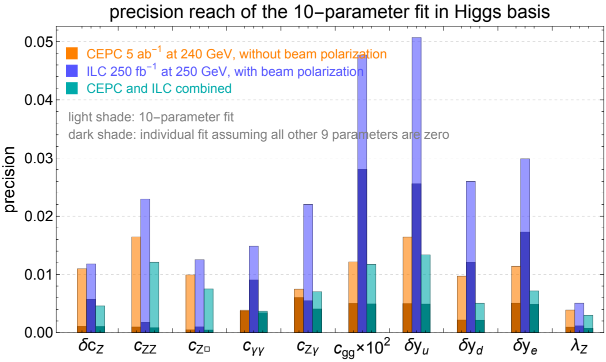
- Conventionally, many studies of Higgs couplings use the so-called "κ-frame."
- The Higgs basis is more general and consistent than the "κ-frame."
  - It allows couplings with different Lorentz structures, such as $hZ^{\mu\nu}Z_{\mu\nu}$ or $hZ_\mu \partial_\nu Z^{\mu\nu}$ (parameterized by c_{ZZ} and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

Results of the “10-parameter” fit



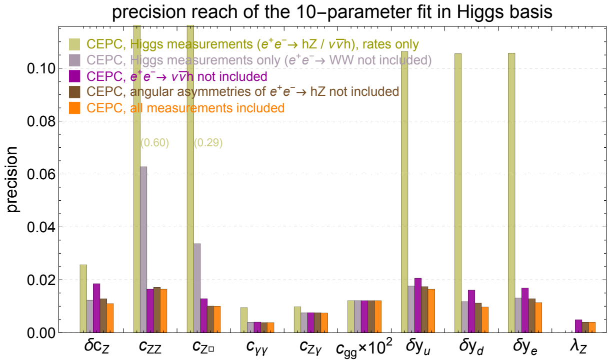
- Much better than the current results! (Taken from [arXiv:1508.00581] Falkowski, Gonzalez-Alonso, Greljo, Marzocca, obtained from LHC 8 TeV Higgs data and LEP $e^+e^- \to WW$ data.)
- Haven't compared with HL-LHC data yet... (nontrivial to estimate the reach at HL-LHC)

Results of the “10-parameter” fit



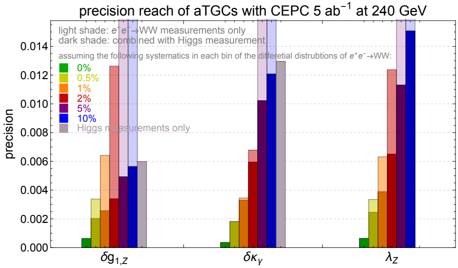
- CEPC: circular collider, large luminosity.
- ILC: linear collider, beam polarization (70% of total Luminosity goes to $P(e^-, e^+) = (-0.8, +0.3)$, 30% goes to $P(e^-, e^+) = (+0.8, -0.3)$).
- Complementarity!

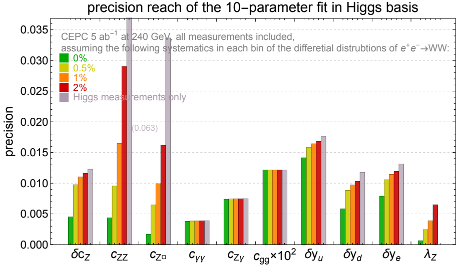
The importance of combining all measurements



- 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.

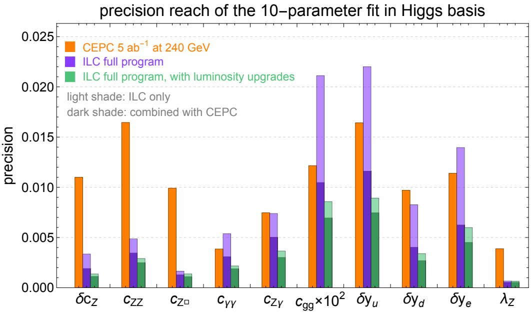
The interplay between Higgs and TGC





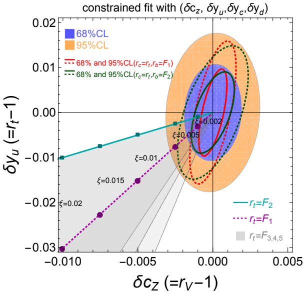
- $\delta g_{1,Z}\,,\ \delta\kappa_\gamma \leftrightarrow$ $c_{ZZ}\,,\ c_{Z\Box}\,,\ c_{\gamma\gamma}\,,\ c_{Z\gamma}$
- We try different assumptions on the systematic uncertainties (in each bin with the differential distribution divided into 20 bins).
- Detailed study of $e^+e^- \to WW$ required to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

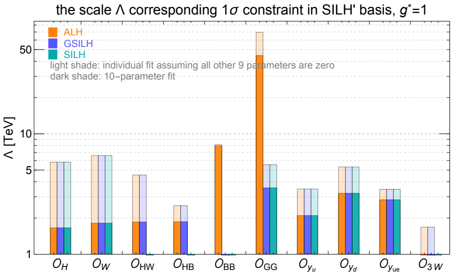
Comparison with the Full ILC program



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

Constraining models! (preliminary results)





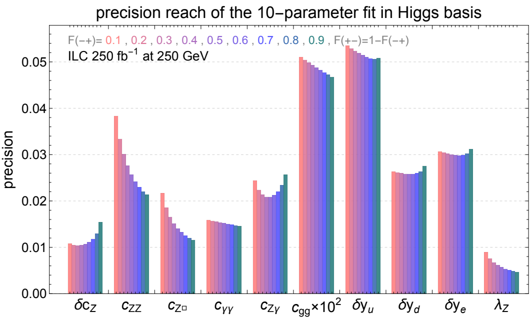
- Current work with Honglei Li, Zhen Liu, Shufang Su, Wei Su.
- Minimal Composite Higgs models with different fermion representation.
- Projected reach on the new physics scale in different types of strong interacting models. (See [arXiv:1603.03064] Liu, Pomarol, Rattazzi, Riva for more details.)

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 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

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

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

- 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

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

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

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