Beyond Higgs Couplings

Probing the Higgs with Angular Observables at Future e^+e^- Colliders

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Miniworkshop on MC for e^+e^- colliders
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based on current work with Nathaniel Craig, Zhen Liu and Kechen Wang

Introduction

Angular observables

Higgs effective field theory

Expected precision

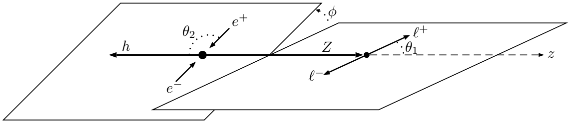
Constraints on new physics

Conclusion

Introduction

- The precision Higgs data can provide strong constraint on new physics.
- So far most studies are based on rate measurements.
- Angular distribution of the events can provide additional information.
- Theoretical calculations have been done in *e.g.* 1406.1361(Beneke, Boito, Wang) using Higgs effective field theory.
- No existing phenomenology study yet.

Angular observables in HZ production



- Three angles in each event.
- It is convenient to define asymmetry observables in the form

$$\mathcal{A} = \frac{N_+ - N_-}{N_+ + N_-} \, .$$

- Focusing on leptonic decay of Z (good resolution, small background).

Angular observables in HZ production

$$
\begin{aligned}
\mathcal{A}_{\theta_1} &= \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1 \;\mathrm{sgn}(\cos(2\theta_1))\,\frac{d\sigma}{d\cos\theta_1}\,,\\
\mathcal{A}_{\phi}^{(1)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi \;\mathrm{sgn}(\sin\phi)\,\frac{d\sigma}{d\phi}\,,\\
\mathcal{A}_{\phi}^{(2)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi \;\mathrm{sgn}(\sin(2\phi))\,\frac{d\sigma}{d\phi}\,,\\
\mathcal{A}_{\phi}^{(3)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi \;\mathrm{sgn}(\cos\phi)\,\frac{d\sigma}{d\phi}\,,\\
\mathcal{A}_{\phi}^{(4)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi \;\mathrm{sgn}(\cos(2\phi))\,\frac{d\sigma}{d\phi}\,,\\
\mathcal{A}_{c\theta_1,c\theta_2} &= \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\,\mathrm{sgn}(\cos\theta_1)\int_{-1}^{1} d\cos\theta_2\,\mathrm{sgn}(\cos\theta_2)\,\frac{d^2\sigma}{d\cos\theta_1\,d\cos\theta_2}\,.
\end{aligned}
$$

Higgs effective field theory

$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi) W^I_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi) B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}^{(1)}_{\Phi\,\ell} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar\ell\gamma^\mu\ell)$	$\mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi) W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}^{(3)}_{\Phi\,\ell} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar\ell\gamma^\mu\tau^I\ell)$	$\mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi) \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar e\gamma^\mu e)$	$\mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi) \widetilde{B}_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{4L} = (\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell)$	$\mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi) \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

Table: A complete basis of dimension-6 operators contributing to $e^+e^- \to Zh$. Here the τ^I are the Pauli matrices.

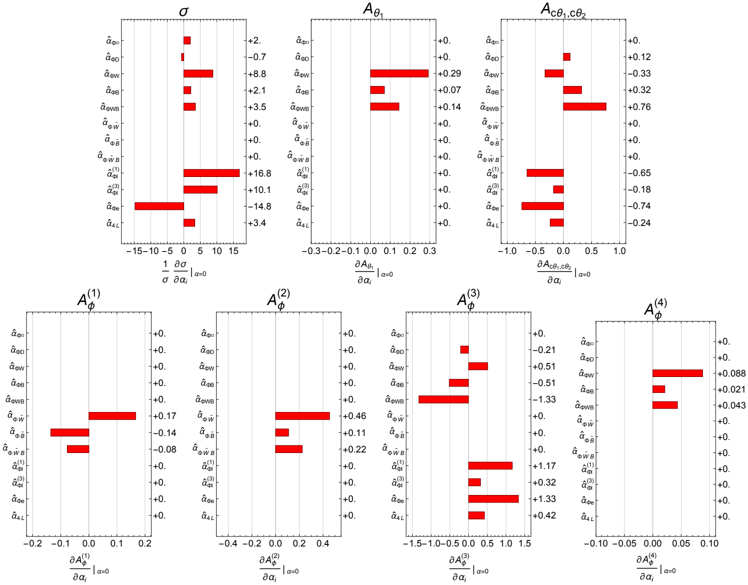
- Starting with dimension-6 operators, we can derive the Higgs effective Lagrangian

$$\mathcal{L}_{\rm eff} \supset c^{(1)}_{ZZ}\, hZ_\mu Z^\mu + c^{(2)}_{ZZ}\, h\, Z_{\mu\nu} Z^{\mu\nu} + c_{Z\widetilde{Z}} h\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu} + c_{AZ} h\, Z_{\mu\nu} A^{\mu\nu} + c_{A\widetilde{Z}} h Z_{\mu\nu}\widetilde{A}^{\mu\nu}$$
$$+ hZ_\mu\bar\ell\gamma^\mu\,(c_V + c_A\gamma_5)\,\ell + Z_\mu\bar\ell\gamma^\mu(g_V - g_A\gamma_5)\ell - g_{\rm em} Q_\ell A_\mu\bar\ell\gamma^\mu\ell\,.$$

Angular observables in terms of Wilson coefficients

- Using the Higgs effective Lagrangian we can derive the cross section and angular observables as functions of the Wilson coefficients.
- Keeping the linear order terms of the Wilson coefficients ($\hat{\alpha}_k = \frac{v^2}{\Lambda^2}\alpha_k$, $\sqrt{s} = 240$ GeV).

$$
\begin{aligned}
\sigma[\mathrm{fb}] \approx\ & 7.82 + 16\,\hat{\alpha}_{\Phi\Box} - 5.3\,\hat{\alpha}_{\Phi D} + 69\,\hat{\alpha}_{\Phi W} + 17\,\hat{\alpha}_{\Phi B} + 27\,\hat{\alpha}_{\Phi WB} \\
& + 132\,\hat{\alpha}^{(1)}_{\Phi\,\ell} + 79\,\hat{\alpha}^{(3)}_{\Phi\,\ell} - 115\,\hat{\alpha}_{\Phi\,e} + 26\,\hat{\alpha}_{4L}\,, \\
\mathcal{A}_{\theta_1} \approx\ & -0.447 + 0.29\,\hat{\alpha}_{\Phi W} + 0.070\,\hat{\alpha}_{\Phi B} + 0.14\,\hat{\alpha}_{\Phi WB}\,, \\
\mathcal{A}^{(1)}_{\phi} \approx\ & 0.17\,\hat{\alpha}_{\Phi\widetilde{W}} - 0.14\,\hat{\alpha}_{\Phi\widetilde{B}} - 0.077\,\hat{\alpha}_{\Phi W\widetilde{B}}\,, \\
\mathcal{A}^{(2)}_{\phi} \approx\ & 0.46\,\hat{\alpha}_{\Phi\widetilde{W}} + 0.11\,\hat{\alpha}_{\Phi\widetilde{B}} + 0.22\,\hat{\alpha}_{\Phi W\widetilde{B}}\,, \\
\mathcal{A}^{(3)}_{\phi} \approx\ & 0.0105 - 0.21\,\hat{\alpha}_{\Phi D} + 0.51\,\hat{\alpha}_{\Phi W} - 0.51\,\hat{\alpha}_{\Phi B} - 1.33\,\hat{\alpha}_{\Phi WB} \\
& + 1.17\,\hat{\alpha}^{(1)}_{\Phi\,\ell} + 0.32\,\hat{\alpha}^{(3)}_{\Phi\,\ell} + 1.33\,\hat{\alpha}_{\Phi\,e} + 0.42\,\hat{\alpha}_{4L}\,, \\
\mathcal{A}^{(4)}_{\phi} \approx\ & 0.0961 + 0.088\,\hat{\alpha}_{\Phi W} + 0.021\,\hat{\alpha}_{\Phi B} + 0.043\,\hat{\alpha}_{\Phi WB}\,, \\
\mathcal{A}_{c\theta_1, c\theta_2} \approx\ & -0.0581 + 0.12\,\hat{\alpha}_{\Phi D} - 0.33\,\hat{\alpha}_{\Phi W} + 0.32\,\hat{\alpha}_{\Phi B} + 0.76\,\hat{\alpha}_{\Phi WB} \\
& - 0.65\,\hat{\alpha}^{(1)}_{\Phi\,\ell} - 0.18\,\hat{\alpha}^{(3)}_{\Phi\,\ell} - 0.74\,\hat{\alpha}_{\Phi\,e} - 0.24\,\hat{\alpha}_{4L}\,.
\end{aligned}
$$


σ
A_{θ_1}
$A_{c\theta_1,c\theta_2}$
$A_\phi^{(1)}$
$A_\phi^{(2)}$
$A_\phi^{(3)}$
$A_\phi^{(4)}$
$\hat\alpha_{\Phi\Box}$ $\hat\alpha_{\Phi D}$ $\hat\alpha_{\Phi W}$ $\hat\alpha_{\Phi B}$ $\hat\alpha_{\Phi WB}$ $\hat\alpha_{\Phi\tilde W}$ $\hat\alpha_{\Phi\tilde B}$ $\hat\alpha_{\Phi\tilde W B}$ $\hat\alpha_{\Phi l}^{(1)}$ $\hat\alpha_{\Phi l}^{(3)}$ $\hat\alpha_{\Phi e}$ $\hat\alpha_{4L}$
σ: +2. −0.7 +8.8 +2.1 +3.5 +0. +0. +0. +16.8 +10.1 −14.8 +3.4
A_{θ_1}: +0. +0. +0.29 +0.07 +0.14 +0. +0. +0. +0. +0. +0. +0.
$A_{c\theta_1,c\theta_2}$: +0. +0.12 −0.33 +0.32 +0.76 +0. +0. +0. −0.65 −0.18 −0.74 −0.24
$A_\phi^{(1)}$: +0. +0. +0. +0. +0. +0.17 −0.14 −0.08 +0. +0. +0. +0.
$A_\phi^{(2)}$: +0. +0. +0. +0. +0. +0.46 +0.11 +0.22 +0. +0. +0. +0.
$A_\phi^{(3)}$: +0. −0.21 +0.51 −0.51 −1.33 +0. +0. +0. +1.17 +0.32 +1.33 +0.42
$A_\phi^{(4)}$: +0. +0. +0.088 +0.021 +0.043 +0. +0. +0. +0. +0. +0. +0.
$\frac{1}{\sigma}\frac{\partial\sigma}{\partial\alpha_i}|_{\alpha=0}$
$\frac{\partial A_{\theta_1}}{\partial\alpha_i}|_{\alpha=0}$
$\frac{\partial A_{c\theta_1,c\theta_2}}{\partial\alpha_i}|_{\alpha=0}$
$\frac{\partial A_\phi^{(1)}}{\partial\alpha_i}|_{\alpha=0}$
$\frac{\partial A_\phi^{(2)}}{\partial\alpha_i}|_{\alpha=0}$
$\frac{\partial A_\phi^{(3)}}{\partial\alpha_i}|_{\alpha=0}$
$\frac{\partial A_\phi^{(4)}}{\partial\alpha_i}|_{\alpha=0}$

Expected precision and statistical uncertainty

- $A \equiv \frac{N_+ - N_-}{N_+ + N_-} = \frac{2N_+}{N} - 1$, where N_+ has a binomial distribution with standard deviation $\sigma_{N_+} = \sqrt{N\,p(1-p)}$, where p is the probability for a event to be counted into N_+.

- 1σ uncertainty of A

$$\sigma_A = \sqrt{\frac{1-\bar{A}^2}{N}} \approx \frac{1}{\sqrt{N}}\,. \tag{1}$$

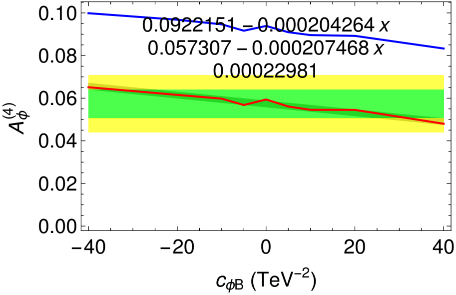
- With $\sqrt{s} = 240$ GeV and $5\,\mathrm{ab}^{-1}$ data, for the channel $e^- e^+ \to ZH \to \ell^+\ell^-\, b\bar{b}$, there are ~ 22100 events after cuts.

observable	SM expectation	σ_A for $5\,\mathrm{ab}^{-1}$
$\mathcal{A}_{\theta_1}$	-0.447	0.0060
$\mathcal{A}_{\phi}^{(1)}$	0	0.0067
$\mathcal{A}_{\phi}^{(2)}$	0	0.0067
$\mathcal{A}_{\phi}^{(3)}$	0.0105	0.0067
$\mathcal{A}_{\phi}^{(4)}$	0.0961	0.0067
$\mathcal{A}_{c\theta_1,c\theta_2}$	-0.00581	0.0067

Detector effects

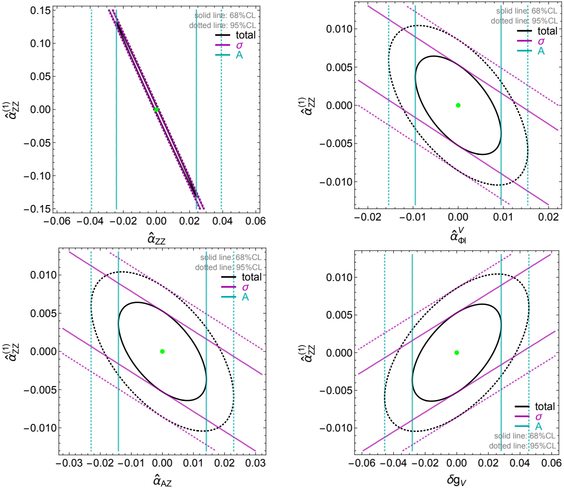
- For SM, we used the events generated with `Whizard` by our experimental colleagues. (Thanks!)
- For new physics, we used `Madgraph5` with dimenion-6 operator model file generated via `FeynRules`.
- For simulation, we focus on the process $e^- e^+ \to ZH \to \mu^- \mu^+ b\bar{b}$.
- Resolution, ISR effects (turned out to be small).
- $10^\circ < \theta_\mu < 170^\circ$, $81~\mathrm{GeV} < m_{\mu^-\mu^+} < 101~\mathrm{GeV}$, $120~\mathrm{GeV} < m_{\mathrm{recoil}} < 150~\mathrm{GeV}$, b-tagging.

Detector effects



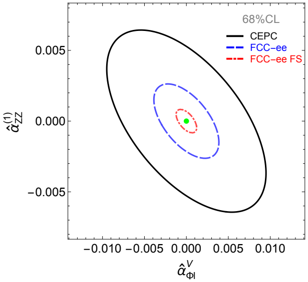
- The effects are much smaller than the statistical uncertainties except for $\mathcal{A}_\phi^{(4)}$ ($\sim 0.093 \to \sim 0.058$ with the cut$10^\circ < \theta_\mu < 170^\circ$).
- It shifts the central value but has little effects on the sensitivities to new physics (need to be further verified).
- We have justified that statistical uncertainties dominate in our study.

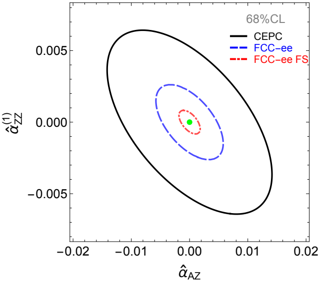
Constraining Wilson Coefficients



- $\sqrt{s} = 240$ GeV, $5\,\mathrm{ab}^{-1}$, $e^- e^+ \to ZH \to \ell^+\ell^-\, b\bar{b}$, ~ 22100 events.
- More parameters than constraints...
- $\hat{\alpha}_{ZZ}^{(1)}$ vs. another coefficient, assuming all others are zero.
- Useful for probing $HZ\gamma$ anomalous coupling.

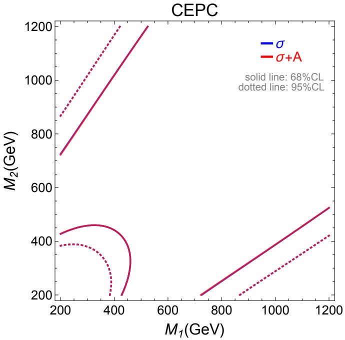
FCC-ee





- FCC-ee: $3\times$ CEPC luminosity at each IP, twice IPs (4 vs. 2).
- In principle one could use the full statistics (including other decay channels of Z and H), which requires further study.
- Plots made by simply scaling the statistics of CEPC by 6 (for FCC-ee) and 60 (for FCC-ee FS).

A (bad) example on model implication...



- Not so useful for probing Stop!
- Loop suppressed.
- The Wilson coefficients can be more sensitive to non-perturbative models.

Conclusion

- The angular observables in the HZ production at CEPC contain useful information about possible new physics and should be measured and studied.
- There are a wide range of interesting future directions.
- Hadronic channel of Z, other decay channels of Higgs...
- ILC can study this process at higher $\sqrt{s}$ and also with polarized beams.
- Asymmetry observables $\rightarrow$ distributions.
- We should try to extract as much information as we could from future colliders.