Probing the Higgs with angular observables at future e^+e^- colliders

Jiayin Gu

Fudan University

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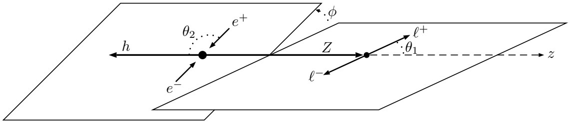
[arXiv:1512.06877] Nathaniel Craig, JG, Zhen Liu, Kechen Wang

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



- Angular distributions in $e^+e^- \to hZ$ can provide information in addition to the one from rate measurements.
- Theory framework [arXiv:1406.1361] M. Beneke, D. Boito, Y.-M. Wang
- Pheno study [arXiv:1512.06877] N. Craig, JG, Z. Liu, K. Wang
- Focusing on leptonic decays of Z (good resolution, small background, statistical uncertainty dominates).

Asymmetry observables

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

$$\mathcal{A}_{\phi}^{(1)} = \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\, \mathrm{sgn}(\sin\phi)\, \frac{d\sigma}{d\phi}\,,$$

$$\mathcal{A}_{\phi}^{(2)} = \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\, \mathrm{sgn}(\sin(2\phi))\, \frac{d\sigma}{d\phi}\,,$$

$$\mathcal{A}_{\phi}^{(3)} = \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\, \mathrm{sgn}(\cos\phi)\, \frac{d\sigma}{d\phi}\,,$$

$$\mathcal{A}_{\phi}^{(4)} = \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\, \mathrm{sgn}(\cos(2\phi))\, \frac{d\sigma}{d\phi}\,,$$

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

- 6 independent asymmetry observables from 3 angles.
- Assuming statistical uncertainties only: $\sigma_A = \sqrt{\frac{1-\bar{A}}{N}}$.

The dimension-6 operators

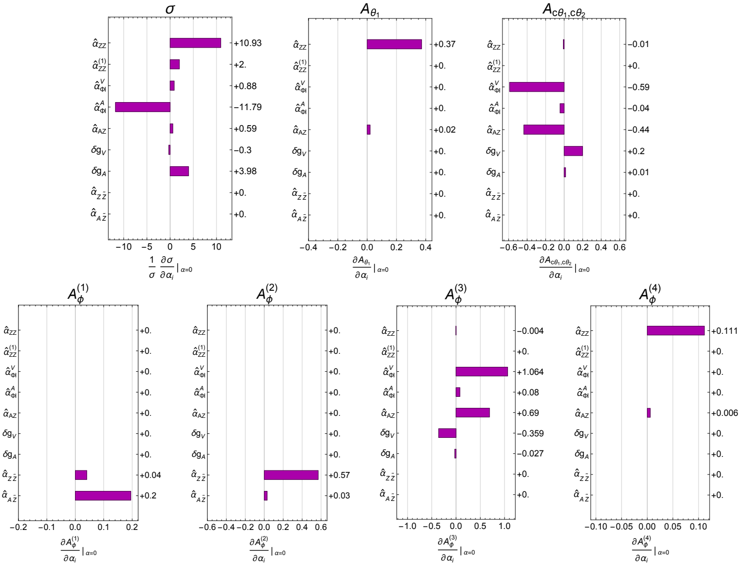
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W^I_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}^{(1)}_{\Phi\ell}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

- Warsaw basis.
- Operators that only modifies the Higgs BR are not considered.

Effective couplings

$$
\begin{aligned}
\alpha_{ZZ}^{(1)} &= \alpha_{\Phi\Box} - \frac{1}{2}\delta'_{G_F} + \frac{1}{4}\alpha_{\Phi D}\,, \\
\alpha_{ZZ} &= c_W^2\alpha_{\Phi W} + s_W^2\alpha_{\Phi B} + s_W c_W \alpha_{\Phi WB}\,, \\
\alpha_{Z\tilde{Z}} &= c_W^2\alpha_{\Phi\tilde{W}} + s_W^2\alpha_{\Phi\tilde{B}} + s_W c_W \alpha_{\Phi\tilde{W}B}\,, \\
\alpha_{AZ} &= 2s_W c_W(\alpha_{\Phi W} - \alpha_{\Phi B}) + (s_W^2 - c_W^2)\alpha_{\Phi WB}, \\
\alpha_{A\tilde{Z}} &= 2s_W c_W(\alpha_{\Phi\tilde{W}} - \alpha_{\Phi\tilde{B}}) + (s_W^2 - c_W^2)\alpha_{\Phi\tilde{W}B}\,, \\
\widehat{\alpha}_{\Phi\ell}^{V} &= \widehat{\alpha}_{\Phi e} + \left(\widehat{\alpha}_{\Phi\ell}^{(1)} + \widehat{\alpha}_{\Phi\ell}^{(3)}\right)\,, \\
\widehat{\alpha}_{\Phi\ell}^{A} &= \widehat{\alpha}_{\Phi e} - \left(\widehat{\alpha}_{\Phi\ell}^{(1)} + \widehat{\alpha}_{\Phi\ell}^{(3)}\right)\,, \\
\delta_{G_F} &= -\widehat{\alpha}_{4L} + 2\widehat{\alpha}_{\Phi\ell}^{(3)}\,, \\
\delta g_V &= -\widehat{\alpha}_{\Phi\ell}^{V} + \frac{\widehat{\alpha}_{\Phi D}}{4} + \frac{\delta_{G_F}}{2} + \frac{4s_W^2}{c_{2W}}\left[\frac{\widehat{\alpha}_{\Phi D}}{4} + \frac{c_W}{s_W}\widehat{\alpha}_{\Phi WB} + \frac{\delta_{G_F}}{2}\right]\,, \\
\delta g_A &= -\widehat{\alpha}_{\Phi\ell}^{A} - \frac{\widehat{\alpha}_{\Phi D}}{4} - \frac{\delta_{G_F}}{2}\,.
\end{aligned}
$$

Sensitivities to the effective couplings



Results

observable	SM expectation	Precision σ_A		
		$5\,\mathrm{ab}^{-1}$ CEPC	$30\,\mathrm{ab}^{-1}$ FCC-ee	Full Stat.
$\mathcal{A}_{\theta_1}$	-0.448	0.0060	0.0025	0.00078
$\mathcal{A}_{\phi}^{(1)}$	0	0.0067	0.0027	0.00087
$\mathcal{A}_{\phi}^{(2)}$	0	0.0067	0.0027	0.00087
$\mathcal{A}_{\phi}^{(3)}$	0.0136	0.0067	0.0027	0.00087
$\mathcal{A}_{\phi}^{(4)}$	0.0959	0.0067	0.0027	0.00086
$\mathcal{A}_{c\theta_1,c\theta_2}$	-0.0075	0.0067	0.0027	0.00087

indv. bounds	$\widehat{\alpha}_{ZZ}$	$\widehat{\alpha}_{ZZ}^{(1)}$	$\widehat{\alpha}_{\Phi\ell}^{V}$	$\widehat{\alpha}_{\Phi\ell}^{A}$	$\widehat{\alpha}_{AZ}$	δg_V	δg_A	$\widehat{\alpha}_{Z\widetilde{Z}}$	$\widehat{\alpha}_{A\widetilde{Z}}$
rate	0.00064	0.0035	0.0079	0.00059	0.012	0.023	0.0018	∞	∞
angles	0.016	∞	0.0058	0.078	0.0087	0.017	0.23	0.012	0.036
total	0.00064	0.0035	0.0047	0.00059	0.0070	0.014	0.0018	0.012	0.036

- $Z\to\mu^+\mu^-/e^+e^-$ and $H\to b\bar{b}$, signal only, $\sim 50\%$ selection efficiency.
- "Full Stat.": naively scale to all decay channel.
- Linear contributions only. $\widehat{\alpha}$ are normalized by $1/v^2$.

A few remarks

- Many of the CP even operators can be probed by EW measurements and Higgs rate measurements.
  - In a Higgs+EW global fit with CP-even dim-6 operators we do not find the *hZ* angular measurements to have a significant impact.
- Some of the angular observables are sensitive to CP-odd operators.
  - The sensitivities do not match the ones from electron EDM experiments ($\sim 10^{3-4}$ worse than the current EDM bounds), but Higgs measurements probe a different combinations of CP-odd operator coefficients.
- More studies can be done!
  - Hadronic Z channels
  - Truth level $\Rightarrow$ detector level
  - Optimal observables, machine learning ...