

EFT global fit of Higgs couplings at e^+e^- colliders

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DESY & IHEP

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[arXiv:1704.02333] G. Durieux, C. Grojean, JG, K. Wang

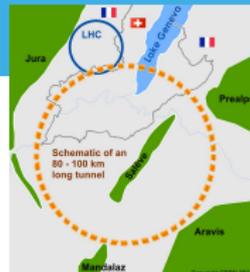
Introduction

- ▶ Higgs and nothing else? What next?
- ▶ An e^+e^- collider is an obvious direction to go.
(Or go directly for a 100 TeV hadron collider?)
- ▶ Higgs factory ($e^+e^- \rightarrow hZ$ at 240-250 GeV, $e^+e^- \rightarrow \nu\bar{\nu}h$ at higher energies), and many more other measurements.
- ▶ The scale of new physics Λ is large \Rightarrow EFT is a good description at low energy.
- ▶ A global analysis of the Higgs coupling constraints, in the EFT framework.
(See also talks by Jonathan R. Ellis and Christophe Grojean earlier today.)

Future e^+e^- colliders

► Circular colliders

- The Future Circular Collider (FCC-ee) at CERN.
- The Circular Electron-Positron Collider (CEPC) in China.
- 91 GeV(Z-pole), 160 GeV(WW), 240 GeV(hZ) and 350 GeV(tt).
- Large luminosity.
- A natural step towards a 100 TeV hadron collider.



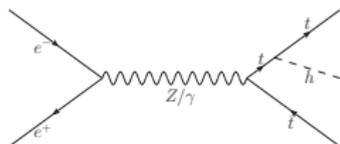
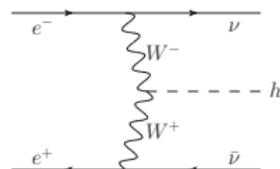
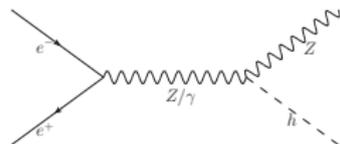
► Linear colliders

- The International Linear Collider (ILC) in Japan.
- The Compact Linear Collider (CLIC) at CERN.
- ILC: 250 GeV, 350 GeV, 500 GeV (and possibly 1 TeV).
- CLIC: 350(380) GeV, 1.4(1.5) TeV and 3 TeV.
- Can go to higher \sqrt{s} , and also implement longitudinal beam polarizations.

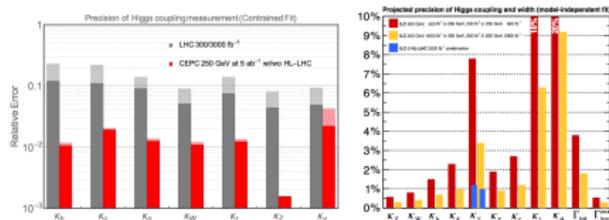


Higgs measurements

- ▶ $e^+e^- \rightarrow hZ$, cross section maximized at around 250 GeV.
- ▶ $e^+e^- \rightarrow \nu\bar{\nu}h$, cross section increases with energy.
- ▶ $e^+e^- \rightarrow t\bar{t}h$, can be measured with $\sqrt{s} \gtrsim 500$ GeV.
- ▶ Di-Higgs processes ($e^+e^- \rightarrow Zhh$, $e^+e^- \rightarrow \nu\bar{\nu}hh$) are left for future studies.



κ framework vs. EFT



From the CEPC preCDR and
 “Physics Case for the ILC”
 ([arXiv:1506.05992])

- ▶ Conventionally, the constraints on Higgs couplings are obtained from global fits in the so-called “ κ ” framework.

$$g_h^{\text{SM}} \rightarrow g_h^{\text{SM}}(1 + \kappa).$$

- ▶ Anomalous couplings such as $hZ^{\mu\nu}Z_{\mu\nu}$ or $hZ_\mu\partial_\nu Z^{\mu\nu}$ are assumed to be zero.
- ▶ $\kappa \rightarrow$ EFT
 - ▶ Assuming $v \ll \Lambda$, leading contribution from BSM physics are well-parameterized by D6 operators.
 - ▶ Gauge invariance is built in the parameterization.
- ▶ Lots of parameters! (Is it practical to perform a global fit?)

The “12-parameter” framework in EFT

- ▶ Assume the new physics
 - ▶ is CP-even,
 - ▶ does not generate dipole interaction of fermions,
 - ▶ only modifies the diagonal entries of the Yukawa matrix,
 - ▶ has **no corrections to Z-pole observables** and W mass (more justified if the machine will run at Z-pole).
- ▶ Additional measurements
 - ▶ Triple gauge couplings from $e^+e^- \rightarrow WW$. (The LEP constraints will be improved at future colliders.)
 - ▶ Angular observables in $e^+e^- \rightarrow hZ$.
 - ▶ $h \rightarrow Z\gamma$ is also important.
- ▶ Only 12 combinations of operators are relevant for the measurements considered (with the inclusion of the Yukawa couplings of t, c, b, τ, μ).
- ▶ All 12 EFT parameters can be constrained reasonable well in the global fit!

EFT basis

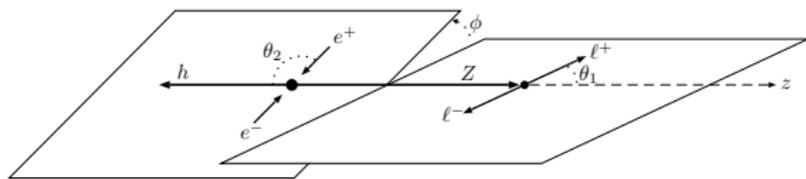
- ▶ We work in the Higgs basis (LHCHXSWG-INT-2015-001, A. Falkowski) with the following 12 parameters,

$$\delta c_Z, c_{ZZ}, c_{Z\Box}, c_{\gamma\gamma}, c_{Z\gamma}, c_{gg}, \delta y_t, \delta y_c, \delta y_b, \delta y_\tau, \delta y_\mu, \lambda_Z.$$

- ▶ The Higgs basis is defined in the broken electroweak phase.
 - ▶ $\delta c_Z \leftrightarrow hZ^\mu Z_\mu$, $c_{ZZ} \leftrightarrow hZ^{\mu\nu} Z_{\mu\nu}$, $c_{Z\Box} \leftrightarrow hZ_\mu \partial_\nu Z^{\mu\nu}$.
- ▶ Couplings of h to W are written in terms of couplings of h to Z and γ .
- ▶ 3 aTGC parameters ($\delta g_{1,Z}, \delta \kappa_\gamma, \lambda_Z$), 2 written in terms of Higgs parameters.
- ▶ It can be easily mapped to the following basis with D6 operators.

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

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

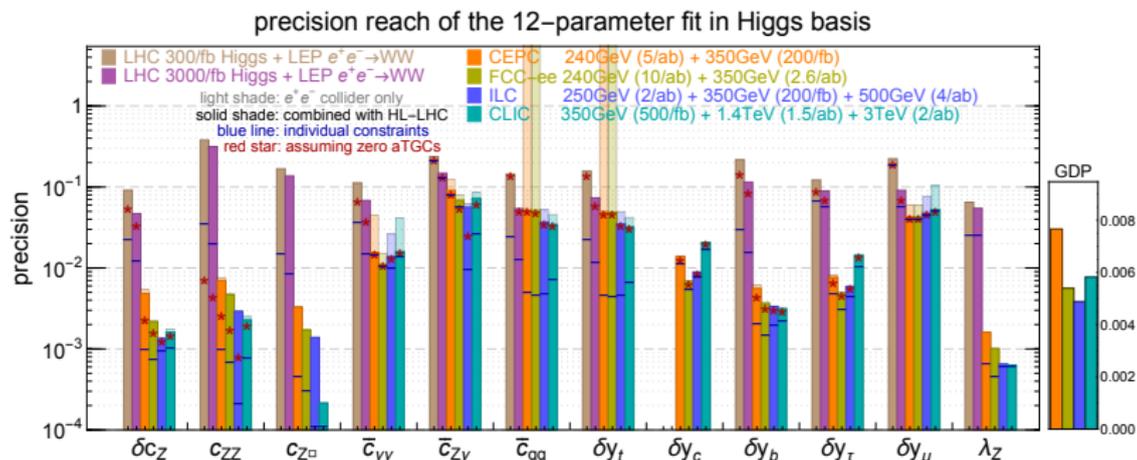


- ▶ Angular distributions in $e^+e^- \rightarrow hZ$ can provide information in addition to the rate measurement alone.
- ▶ Previous studies
 - ▶ [arXiv:1406.1361] M. Beneke, D. Boito, Y.-M. Wang
 - ▶ [arXiv:1512.06877] N. Craig, JG, Z. Liu, K. Wang
- ▶ 6 independent asymmetry observables from 3 angles

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

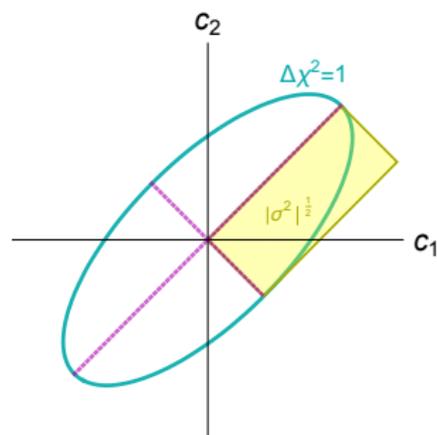
- ▶ Focusing on leptonic decays of Z (good resolution, small background, statistical uncertainty dominates).

Results of the “12-parameter” fit



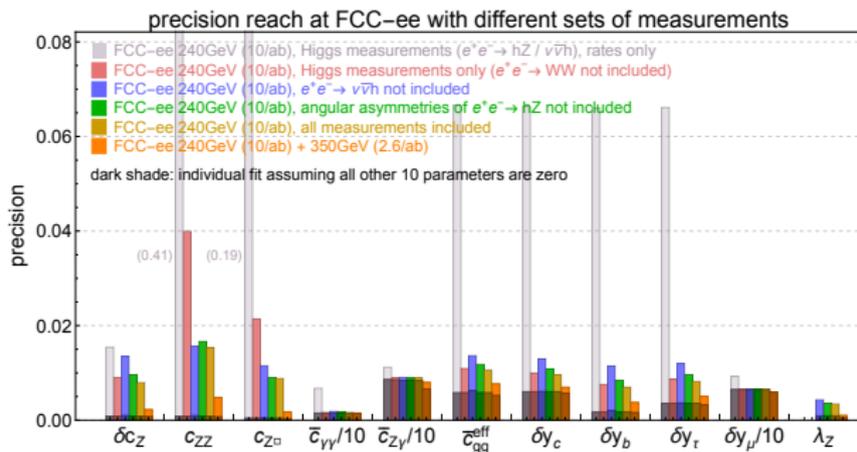
- ▶ Assuming the following run plans (no official plan for CEPC 350 GeV run yet)
 - ▶ CEPC 240 GeV(5/ab) + 350 GeV(200/fb)
 - ▶ FCC-ee 240 GeV(10/ab) + 350 GeV(2.6/ab)
 - ▶ ILC 250 GeV(2/ab) + 350 GeV(200/fb) + 500 GeV(4/ab)
 - ▶ CLIC 350 GeV(500/fb) + 1.4 TeV(1.5/ab) + 3 TeV(2/ab)

GDP



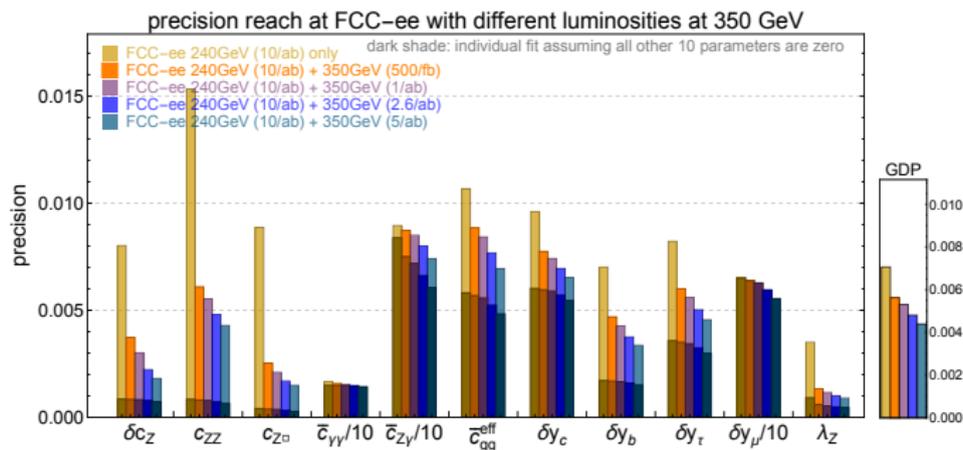
- ▶ Global Determinant Parameter ($\text{GDP} \equiv \sqrt[2n]{\det \sigma^2}$).
- ▶ Ratios of GDPs are basis-independent.
- ▶ Small GDP \rightarrow better precision!

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.
- ▶ Measurements at different energies can be very helpful.

Impact of the 350 GeV run



- ▶ Advantages of the 350 GeV run
 - ▶ Much better measurement of the WW fusion process ($e^+e^- \rightarrow \nu\bar{\nu}h$).
 - ▶ Probing $e^+e^- \rightarrow hZ$ at a different energy.
 - ▶ Improving constraints on aTGCs ($e^+e^- \rightarrow WW$).
- ▶ Very helpful in resolving the degeneracies among parameters!

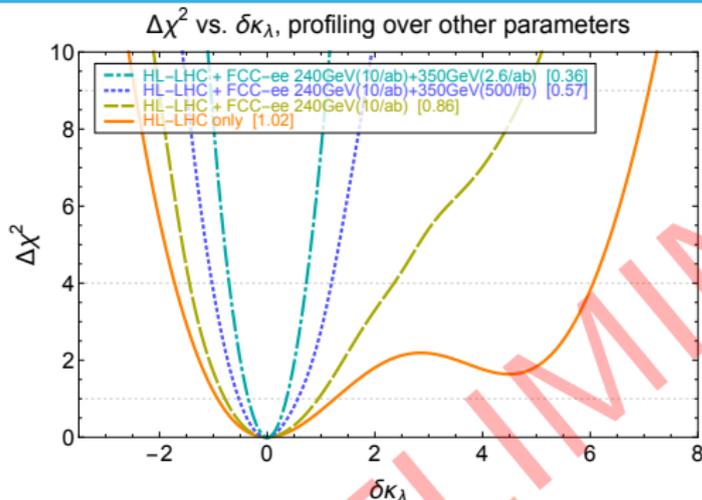
The Higgs self-coupling at e^+e^- colliders

(current work with N. Craig, S. Di Vita, G. Durieux, C. Grojean, Z. Liu, G. Panico, M. Riembau, T. Vantalon)

- ▶ **HL-LHC: $\sim \mathcal{O}(1)$ determination.** ($\kappa_\lambda \in [-0.8, 7.7]$ at 95% CL from Atlas projection for the $b\bar{b}\gamma\gamma$ channel, ATL-PHYS-PUB-2017-001)
- ▶ **Ways to probe the triple Higgs coupling at e^+e^- colliders**
 - ▶ **Linear colliders: direct measurements with $e^+e^- \rightarrow Zh h, e^+e^- \rightarrow \nu\bar{\nu}hh$.**
 - ▶ ILC: 26.6% at 500 GeV (4 ab^{-1}) [C. F. Dürig, PhD thesis, Hamburg U. (2016)]
 - ▶ CLIC: 24%-32% at 1.4 TeV (1.5 ab^{-1}) and 12%-16% at 3 TeV (2 ab^{-1}) (Higgs Physics at CLIC [arXiv:1608.07538]).
 - ▶ **Circular colliders: probe indirectly via the loop contribution in $e^+e^- \rightarrow hZ$** ([arXiv:1312.3322] M. McCullough).
 - ▶ FCC-ee 240 GeV: $|\delta\kappa_\lambda| \lesssim 28\%$ assuming all other Higgs couplings are SM-like.
 - ▶ **What if other Higgs couplings are not SM-like?**
- ▶ **Can we obtain robust constraints on $\delta\kappa_\lambda$ at circular colliders?**
Yes we can!
 - ▶ A global fit of 12+1 parameters. **Very preliminary results!**
 - ▶ FCC-ee 240 GeV (10 ab^{-1}) alone, $\delta\kappa_\lambda$ almost not constrained! ($|\delta\kappa_\lambda| \lesssim 650\%$)
 - ▶ FCC-ee 240 GeV (10 ab^{-1}) + 350 GeV (500 fb^{-1}), $|\delta\kappa_\lambda| \lesssim 73\%$.
 - ▶ FCC-ee 240 GeV (10 ab^{-1}) + 350 GeV (2.6 ab^{-1}), $|\delta\kappa_\lambda| \lesssim 39\%$.

More on the Higgs self-coupling

(current work with N. Craig, S. Di Vita, G. Durieux, C. Grojean, Z. Liu, G. Panico, M. Riembau, T. Vantalón)



▶ “Synergy” of the double Higgs measurements at HL-LHC and the single Higgs measurements at FCC-ee.

- ▶ HL-LHC: Both single and double Higgs measurements, inclusive and differential.

[arXiv:1704.01953] Di Vita, Grojean, Panico, Riembau, Vantalón

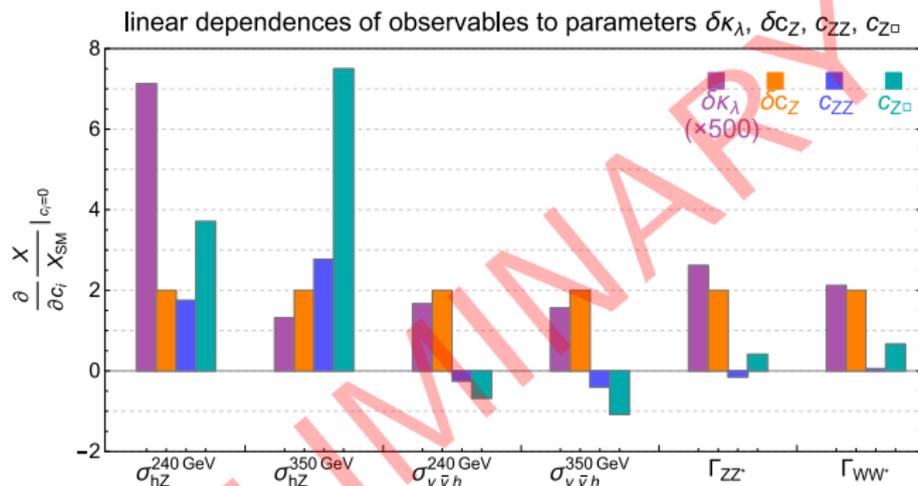
[arXiv:1502.00539] Azatov, Contino, Panico, Son

one-sigma uncertainty of $\delta\kappa_\lambda$	FCC-ee alone		with HL-LHC	
	full	linear	full	linear
-	-	-	+1.26 -0.92	± 1.02
240 GeV(10/ab)	+6.6 -6.4	± 6.5	+0.95 -0.78	± 0.86
240 GeV(10/ab)+350 GeV(500/fb)	+0.73 -0.73	± 0.73	+0.56 -0.53	± 0.57
240 GeV(10/ab)+350 GeV(2.6/ab)	+0.39 -0.39	± 0.39	+0.36 -0.35	± 0.36

Conclusion

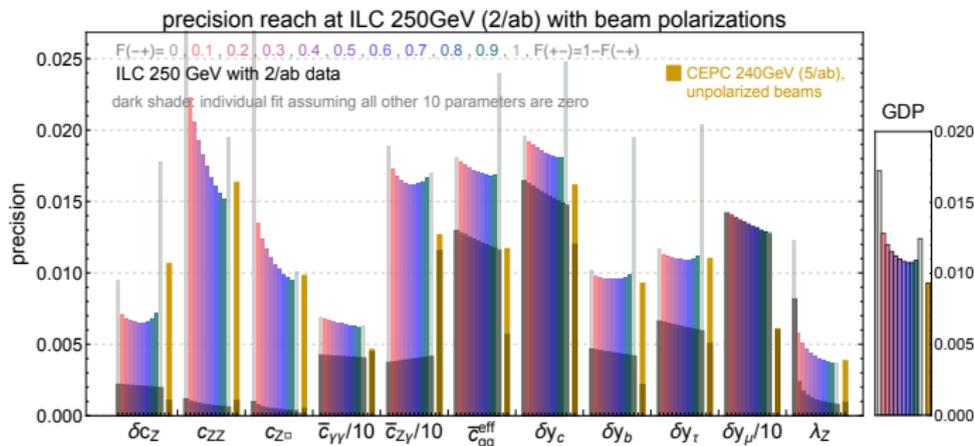
- ▶ After the discovery of Higgs at the LHC, a plausible “next step” is to build an e^+e^- collider to perform Higgs precision measurements.
- ▶ $\kappa \rightarrow$ EFT.
- ▶ Many parameters! Crucial to include all possible measurements (and make reasonable assumptions!)
 - ▶ $e^+e^- \rightarrow hZ$ (rate and asymmetries), $e^+e^- \rightarrow \nu\bar{\nu}h$, $e^+e^- \rightarrow t\bar{t}h$, $e^+e^- \rightarrow WW$, measurements at different energies or with different beam polarization.
- ▶ We can obtain strong and robust constraints on the coefficients of the relevant dimension-6 operators!
 - ▶ If discrepancy is observed, we can also try to discriminate different operators!
- ▶ Unanswered questions...
 - ▶ What's the impact of a future Z-pole run?
 - ▶ How well can aTGCs be constrained from $e^+e^- \rightarrow WW$? (Experimental studies desired.)
 - ▶ Include Higgs invisible/exotic decay?

backup slides

Dependence on $\delta\kappa_\lambda$ 

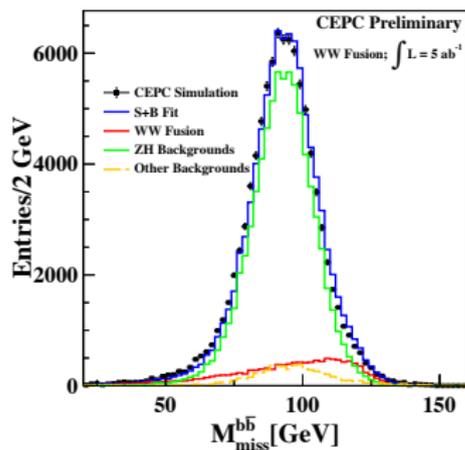
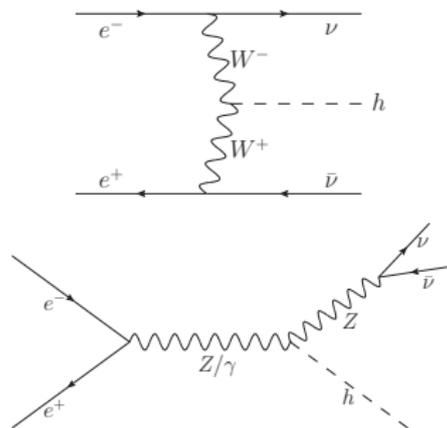
- ▶ WW fusion and hZ at 350 GeV are key to discriminate $\delta\kappa_\lambda$ from other parameters.
- ▶ The measurements of Higgs decay to ZZ and WW also have some discriminating power. (Note that Γ_{ZZ^*} and Γ_{WW^*} are not really observables...)

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



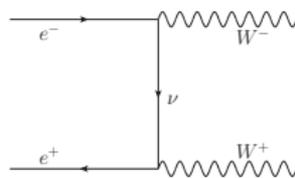
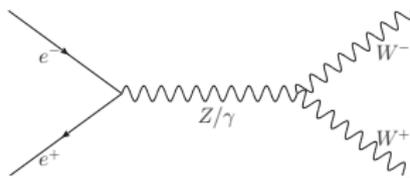
- ▶ Two polarization configurations are considered, $P(e^-, e^+) = (-0.8, +0.3)$ and $(+0.8, -0.3)$.
- ▶ $F(-+)$ in the range of 0.6-0.8 gives an optimal overall results.
- ▶ Runs with different polarizations probe different combinations of EFT parameters in Higgs production.

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



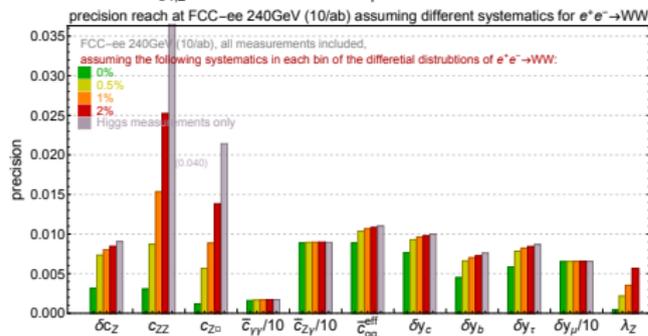
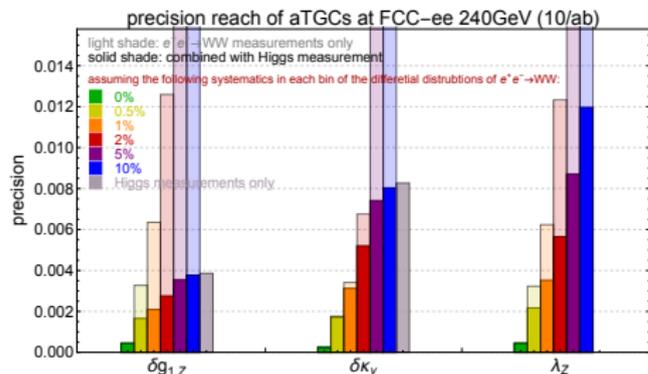
- ▶ It is hard to separate the WW fusion process from $e^+e^- \rightarrow hZ, Z \rightarrow \nu\bar{\nu}$ at 240 GeV.
- ▶ It is not consistent to focus on one process and treat the other one as SM-like!
- ▶ For CEPC/FCC-ee 240 GeV, we analyze the combined $e^+e^- \rightarrow \nu\bar{\nu}h$ process, assuming new physics can contribute to both processes.

$e^+e^- \rightarrow WW$



- ▶ $e^+e^- \rightarrow WW$ 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.
- ▶ With the 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 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 $e^+e^- \rightarrow WW$ required to estimate the systematic uncertainties!

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 “12-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

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

The “12-parameter” framework in the Higgs basis

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

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

- ▶ we only consider the diagonal elements in the Yukawa matrices relevant for the measurements considered,

$$\mathcal{L}_{hff} = -\frac{h}{v} \sum_{f=t,c,b,\tau,\mu} m_f (1 + \delta y_f) \bar{f}_R f_L + \text{h.c.} . \quad (6)$$

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

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

CEPC/FCC-ee Higgs rate measurements

	CEPC				FCC-ee			
	[240 GeV, 5 ab ⁻¹]		[350 GeV, 200 fb ⁻¹]		[240 GeV, 10 ab ⁻¹]		[350 GeV, 2.6 ab ⁻¹]	
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ	0.50%	-	2.4%	-	0.40%	-	0.67%	-
	$\sigma \times \text{BR}$				$\sigma \times \text{BR}$			
$h \rightarrow bb$	0.21% [★]	0.39% [◇]	2.0%	2.6%	0.20%	0.28% [◇]	0.54%	0.71%
$h \rightarrow c\bar{c}$	2.5%	-	15%	26%	1.2%	-	4.1%	7.1%
$h \rightarrow gg$	1.2%	-	11%	17%	1.4%	-	3.1%	4.7%
$h \rightarrow \tau\tau$	1.0%	-	5.3%	37%	0.7%	-	1.5%	10%
$h \rightarrow WW^*$	1.0%	-	10%	9.8%	0.9%	-	2.8%	2.7%
$h \rightarrow ZZ^*$	4.3%	-	33%	33%	3.1%	-	9.2%	9.3%
$h \rightarrow \gamma\gamma$	9.0%	-	51%	77%	3.0%	-	14%	21%
$h \rightarrow \mu\mu$	12%	-	115%	275%	13%	-	32%	76%
$h \rightarrow Z\gamma$	25%	-	144%	-	18%	-	40%	-

Table: For $e^+e^- \rightarrow \nu\bar{\nu}h$, the precisions marked with a diamond \diamond are normalized to the cross section of the inclusive channel which includes both the WW fusion and $e^+e^- \rightarrow hZ, Z \rightarrow \nu\bar{\nu}$, while the unmarked ones include WW fusion only.

ILC Higgs rate measurements

ILC

	[250 GeV, 2 ab ⁻¹]		[350 GeV, 200 fb ⁻¹]		[500 GeV, 4 ab ⁻¹]			[1 TeV, 1 ab ⁻¹]		[1 TeV, 2.5 ab ⁻¹]	
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	tth	$\nu\bar{\nu}h$	tth	$\nu\bar{\nu}h$	tth
σ	0.71%	-	2.1%	-	1.1%	-	-	-	-	-	-
	$\sigma \times \text{BR}$										
$h \rightarrow bb$	0.42%	3.7%	1.7%	1.7%	0.64%	0.25%	9.9%	0.5%	6.0%	0.3%	3.8%
$h \rightarrow c\bar{c}$	2.9%	-	13%	17%	4.6%	2.2%	-	3.1%	-	2.0%	-
$h \rightarrow gg$	2.5%	-	9.4%	11%	3.9%	1.4%	-	2.3%	-	1.4%	-
$h \rightarrow \tau\tau$	1.1%	-	4.5%	24%	1.9%	3.2%	-	1.6%	-	1.0%	-
$h \rightarrow WW^*$	2.3%	-	8.7%	6.4%	3.3%	0.85%	-	3.1%	-	2.0%	-
$h \rightarrow ZZ^*$	6.7%	-	28%	22%	8.8%	2.9%	-	4.1%	-	2.6%	-
$h \rightarrow \gamma\gamma$	12%	-	44%	50%	12%	6.7%	-	8.5%	-	5.4%	-
$h \rightarrow \mu\mu$	25%	-	98%	180%	31%	25%	-	31%	-	20%	-
$h \rightarrow Z\gamma$	34%	-	145%	-	49%	-	-	-	-	-	-

CLIC Higgs rate measurements

CLIC

	[350 GeV, 500 fb ⁻¹]		[1.4 TeV, 1.5 ab ⁻¹]		[3 TeV, 2 ab ⁻¹]
production	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$	tth	$\nu\bar{\nu}h$
σ	1.6%	-	-	-	-
	$\sigma \times \text{BR}$				
$h \rightarrow b\bar{b}$	0.84%	1.9%	0.4%	8.4%	0.3%
$h \rightarrow c\bar{c}$	10.3%	14.3%	6.1%	-	6.9%
$h \rightarrow g\bar{g}$	4.5%	5.7%	5.0%	-	4.3%
$h \rightarrow \tau\tau$	6.2%	-	4.2%	-	4.4%
$h \rightarrow WW^*$	5.1%	-	1.0%	-	0.7%
$h \rightarrow ZZ^*$	-	-	5.6%	-	3.9%
$h \rightarrow \gamma\gamma$	-	-	15%	-	10%
$h \rightarrow \mu\mu$	-	-	38%	-	25%
$h \rightarrow Z\gamma$	-	-	42%	-	30%

Table: We also include the estimations for $\sigma(hZ) \times \text{BR}(h \rightarrow b\bar{b})$ at high energies in [arXiv:1701.04804] (Ellis et al.), which are 3.3% (6.8%) at 1.4 TeV (3 TeV). For simplicity, the measurements of ZZ fusion ($e^+e^- \rightarrow e^+e^-h$) are not included in our analysis.