A Global View on the Higgs Self-coupling at Future (Lepton) Colliders

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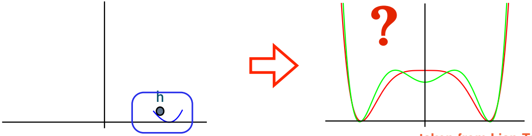
based on [arXiv:1711.03978], S. Di Vita, G. Durieux, C. Grojean, JG, Z. Liu, G. Panico, M. Riembau, T. Vantalon

Introduction

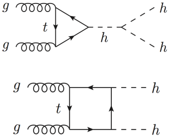
- The Higgs Self-coupling is important!
  - Deviation from SM ⇒ indication of new physics.
  - Tells us more about the Higgs potential.
  - Electroweak phase transition.



taken from Lian-Tao Wang's slides

- The triple Higgs coupling can be measured from the double Higgs process (*e.g.* $gg \to hh$).

- The reach at the (HL-)LHC is limited.
  - $\mathcal{O}(10)$ now and $\mathcal{O}(1)$ at HL-LHC.
- Good reach at a 100 TeV collider.
  - $\lesssim 5\%$ (see *e.g.* the CERN Yellow Report [arXiv:1606.09408]).



Future lepton colliders

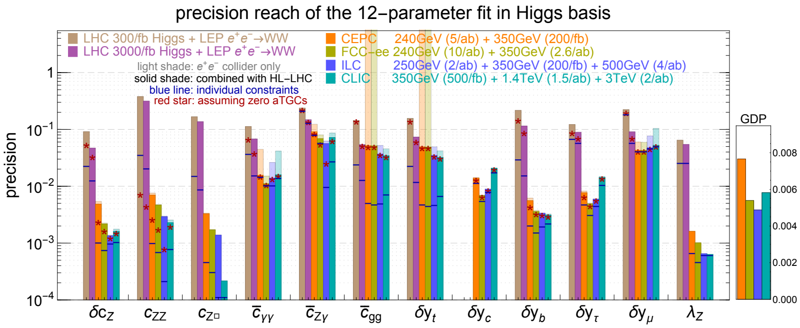
- Linear colliders
  - ILC (up to 500 GeV, maybe 1 TeV?) and CLIC (up to 3 TeV).
  - Direct measurements with $e^+e^- \to Zhh$, $e^+e^- \to \nu\bar{\nu}hh$.
  - $\sim$ 20-30%, depending on the scenario.
  - **What if other Higgs couplings are not SM-like?**
- Circular colliders (CEPC & FCC-ee)
  - Higgs factory at $\sim$ 240-250 GeV, up to $\sim$ 350-380 GeV.
  - Probe the triple Higgs coupling indirectly via the loop contribution in $e^+e^- \to hZ$.
  - TLEP (FCC-ee) 240 GeV: $\sim$ 30%, assuming all other Higgs couplings are SM-like ([arXiv:1312.3322] M. McCullough).
  - **What if other Higgs couplings are not SM-like?**
- A global fit of Higgs couplings in the EFT framework!

The “12-parameter” EFT global analysis

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

- SM + D6 operators (a good description at low energy if the scale of new physics is high).
- Include all possible Higgs measurements, production (hZ, $\nu\bar{\nu}h$, $t\bar{t}h$) and decays.
- Make reasonable assumptions
  - CP even, no fermion dipole interaction, NP only modifies the diagonal entries of the Yukawa matrix,
  - **no corrections to Z-pole observables** and W mass.
- See also
  - [arXiv:1510.04561, 1701.04804] Ellis *et al.*,
  - [arXiv:1708.08912, 1708.09079] Peskin *et al.*,
  - [arXiv:1711.04046] HKUST group *et al.*

Results of the “12-parameter” fit



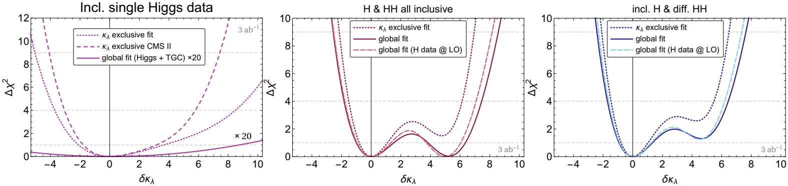
- We work in the Higgs basis (LHCHXSWG-INT-2015-001, A. Falkowski).
- Strong constraints on Higgs EFT parameters at future lepton colliders!

Triple Higgs coupling in the EFT framework

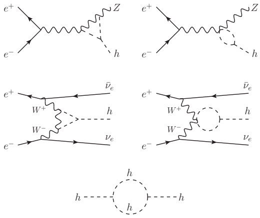
- A global fit with 12+1 parameters!
- Triple Higgs coupling

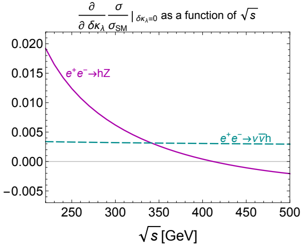
$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}, \quad \delta\kappa_\lambda \equiv \kappa_\lambda - 1 \; = c_6 - \frac{3}{2} c_H, \quad \text{with } \mathcal{L} \supset -\frac{c_6 \lambda}{v^2} (H^\dagger H)^3$$

- HL-LHC: [arXiv:1704.01953] Di Vita, Grojean, Panico, Riembau, Vantalon
  - Single Higgs measurements alone could not constrain $\delta\kappa_\lambda$ well under a global framework.
  - Other parameters contributing to the double-Higgs process can be well constrained by single Higgs measurements.
  - Differential observables in HH process helps resolve the 2nd minimum.



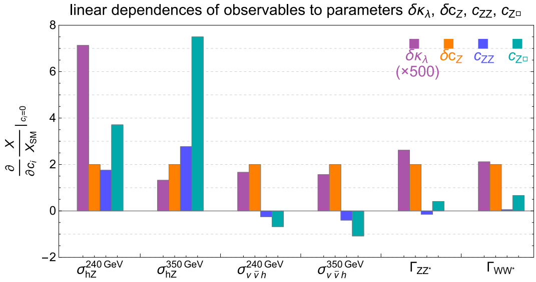
Triple Higgs coupling at low energy (240/250 GeV & 350 GeV)





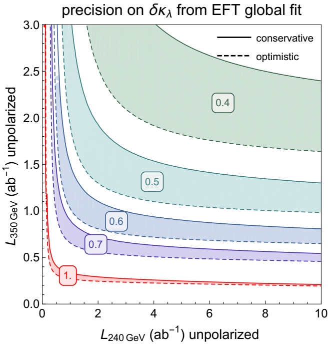
- CEPC, FCC-ee, or earlier stages of ILC.
- 350 GeV is above the threshold of $e^+e^- \to Zhh$, but the cross section is too small.
- One loop corrections to all Higgs couplings (production and decay).
- 240 GeV: hZ near threshold (more sensitive to $\delta\kappa_\lambda$).

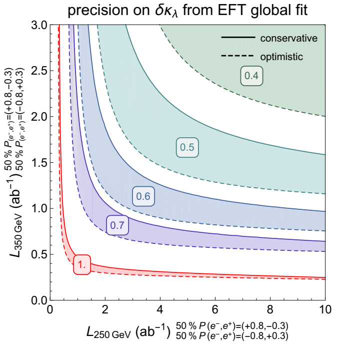
How to discriminate $\delta\kappa_\lambda$ with other parameters



- Different parameters have different energy dependences.
  - δc_Z ($hZ^\mu Z_\mu$) modifies the SM HZZ coupling.
  - $e^+e^- \to hZ$ is more sensitive to c_{ZZ} ($hZ^{\mu\nu}Z_{\mu\nu}$), $c_{Z\Box}$ ($hZ_\mu\partial_\nu Z^{\mu\nu}$) at higher energies.
  - c_{ZZ} and $c_{Z\Box}$ have negative coefficients for WW fusion (virtual Ws).
  - $h \to WW^*/ZZ^*$ also have some discriminating power.
- The 350 GeV run turns out to be crucial! (Good measurement of the *WW* fusion process, and *hZ* at a different energy.)

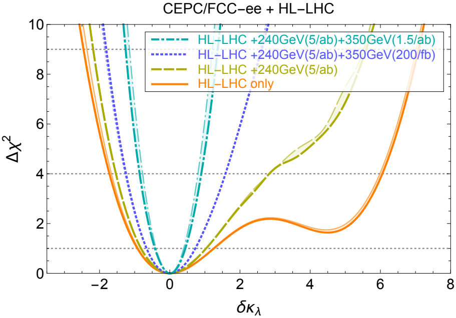
Triple Higgs coupling at 240/250 GeV & 350 GeV


precision on $\delta\kappa_\lambda$ from EFT global fit


precision on $\delta\kappa_\lambda$ from EFT global fit

- Runs at both 240/250 GeV and 350 GeV are needed to obtain good constraints on $\delta\kappa_\lambda$!
- The range is covered by different assumptions of the $e^+e^- \to WW$ measurements.

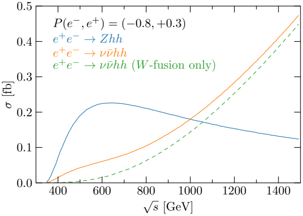
Complementarities between HL-LHC and CEPC/FCC-ee

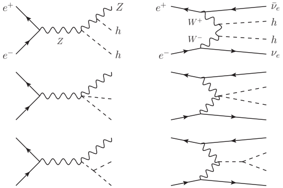


	CEPC alone		CEPC + HL-LHC	
	non-zero aTGCs	zero aTGCs	non-zero aTGCs	zero aTGCs
HL-LHC alone			$[-0.92, +1.26]$	$[-0.90, +1.24]$
240 GeV (5 ab^{-1})	$[-4.55, +4.72]$	$[-2.93, +3.01]$	$[-0.81, +1.04]$	$[-0.82, +1.03]$
+350 GeV (200 fb^{-1})	$[-1.08, +1.09]$	$[-1.04, +1.04]$	$[-0.66, +0.76]$	$[-0.66, +0.74]$
+350 GeV (1.5 ab^{-1})	$[-0.50, +0.49]$	$[-0.43, +0.43]$	$[-0.43, +0.44]$	$[-0.39, +0.40]$

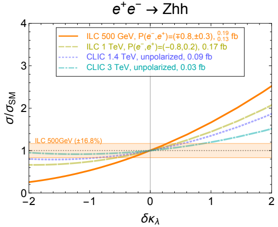
- Bounds are further improved if combined with HL-LHC measurements.
- If the 350 GeV run is not available, the 240 GeV run still provides nontrivial improvement to the LHC bounds.

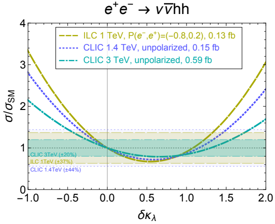
Double-Higgs measurements ($e^+e^- \to Zhh$ & $e^+e^- \to \nu\bar{\nu}hh$)

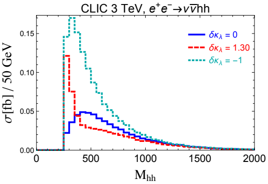




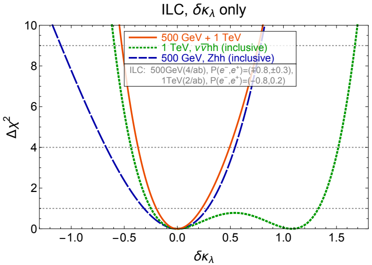
- Destructive interference in $e^+e^- \to \nu\bar{\nu}hh$! The square term is important.
- *hh* invariant mass distribution helps discriminate the “2nd solution.”



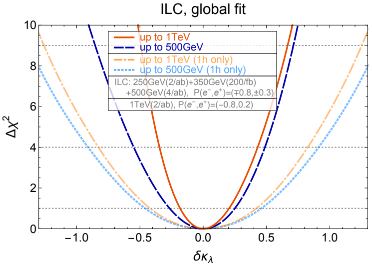




χ^2 vs. $\delta\kappa_\lambda$, ILC



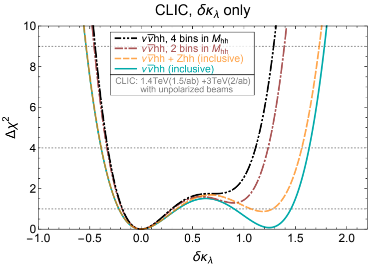
ILC, $\delta\kappa_\lambda$ only

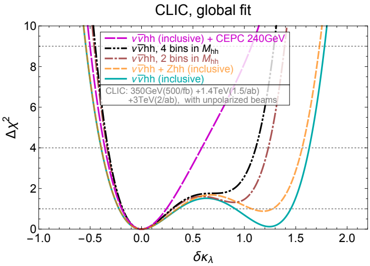


ILC, global fit

- Run senario: **250 GeV(2/ab) + 350 GeV(200/fb) + 500 GeV(4/ab)** + 1 TeV (2/ab)
  - 500 GeV (4 ab^{-1}): $\sigma(Zhh)$ measured to 16.8% [C. F. Dürig, PhD thesis, Hamburg U. (2016)]
  - 1 TeV (2 ab^{-1}): $\sigma(\nu\bar{\nu}hh)$ measured to 2.7σ significance $\Rightarrow\sim$ 37% [talk by Dürig at ALCW15]
- Complementarity between the 500 GeV run and the 1 TeV run.
- Single Higgs measurements provide non-negligible improvment.
  - up to 500 GeV: $[-0.31, +0.28] \rightarrow [-0.26, +0.25]$,
  - up to 1 TeV: $[-0.20, +0.23] \rightarrow [-0.18, +0.20]$,

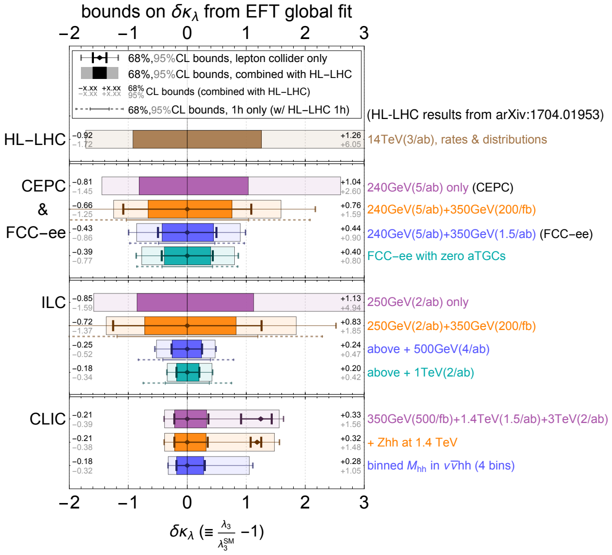
χ^2 vs. $\delta\kappa_\lambda$, CLIC





- Run scenario: **350 GeV(500/fb) + 1.4 TeV(1.5/ab) + 3 TeV(2/ab), assuming unpolarized beam**
  - $\sigma(\nu\bar{\nu}hh)$ measured to 44% at 1.4 TeV and 20% at 3 TeV (Higgs Physics at the CLIC Electron-Positron Linear Collider [arXiv:1608.07538])
  - $\sigma(Zhh)$ measured to $\sim$ 50% at 1.4 TeV (our own naive estimation).
- The measurement of *Zhh* or the M_{hh} distribution of $\nu\bar{\nu}hh$ can help resolve the “2nd solution.”
- The bounds on $\delta\kappa_\lambda$ can be further improved by having a *hZ* threshold run (*e.g.*, by combining with CEPC 240 GeV or ILC 250 GeV).

A summary of the (future) bounds on $\delta\kappa_\lambda$



Conclusion

- Lepton colliders are great tools to probe the triple Higgs coupling!

- To obtain robust constraints, we perform global analyses in the EFT framework.

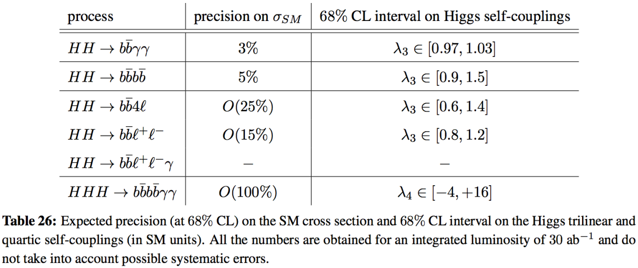
- Circular colliders (or ILC at low energy)
    - Probe the triple Higgs coupling via its loop contribution.
    - To obtain robust constraints, the 350 GeV run is very important!

- Linear colliders
    - The measurements of $e^+e^- \to Zhh$ and $e^+e^- \to \nu\bar{\nu}hh$ are complementary.
    - Differential observables in $e^+e^- \to \nu\bar{\nu}hh$ can be helpful.
    - Other parameters are well constrained by single Higgs measurements.

backup slides

Reach at Hadron colliders

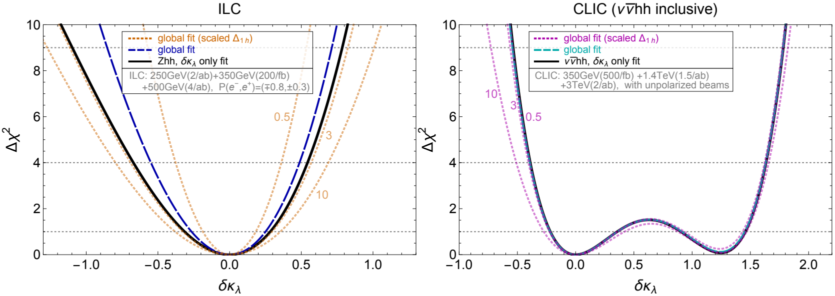
- HL-LHC: $\kappa_\lambda \in [-0.8, 7.7]$ at 95% CL from Atlas projection for the $b\bar{b}\gamma\gamma$ channel, ATL-PHYS-PUB-2017-001
- 100 TeV collider (from the CERN Yellow Report [arXiv:1606.09408])



process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

Table 26: Expected precision (at 68% CL) on the SM cross section and 68% CL interval on the Higgs trilinear and quartic self-couplings (in SM units). All the numbers are obtained for an integrated luminosity of 30 ab^{-1} and do not take into account possible systematic errors.

Impact of the single Higgs measurements



- What if the single Higgs measurements are much better or much worse?
- Much better: can further improve the bounds on $\delta\kappa_\lambda$ from double-Higgs measurements.
- Much worse: can significantly worsen the bounds on $\delta\kappa_\lambda$ from double-Higgs measurements.

EFT basis

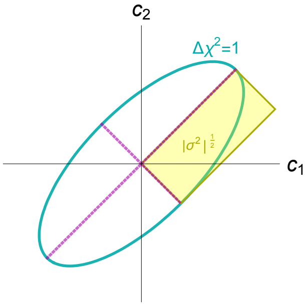
- We work in the Higgs basis (LHCHXSWG-INT-2015-001, A. Falkowski) with the following 12 parameters,

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

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

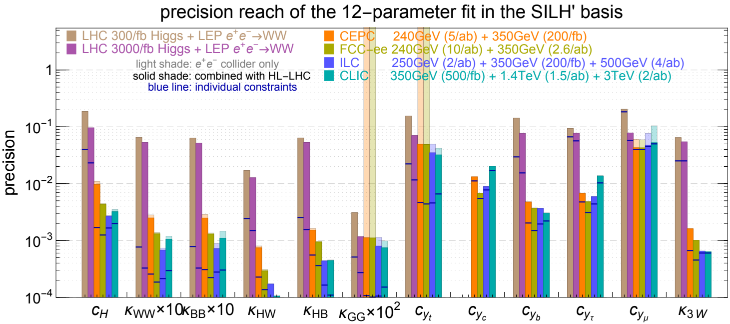
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \|H^2\|)^2$	$\mathcal{O}_{GG} = g_s^2 \|H\|^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \|H\|^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \tilde{H} u_R$
$\mathcal{O}_{BB} = g'^2 \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d}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

GDP



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

If you don’t like the Higgs basis...

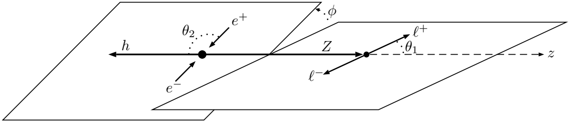


precision reach of the 12−parameter fit in the SILH' basis

- Results in the SILH’(-like) basis ($\mathcal{O}_{W,\,B} \to \mathcal{O}_{WW,\,WB}$)

$$\mathcal{L}_{\rm D6} = \frac{c_H}{v^2}\mathcal{O}_H + \frac{\kappa_{WW}}{m_W^2}\mathcal{O}_{WW} + \frac{\kappa_{BB}}{m_W^2}\mathcal{O}_{BB} + \frac{\kappa_{HW}}{m_W^2}\mathcal{O}_{HW} + \frac{\kappa_{HB}}{m_W^2}\mathcal{O}_{HB} + \frac{\kappa_{GG}}{m_W^2}\mathcal{O}_{GG} + \frac{\kappa_{3W}}{m_W^2}\mathcal{O}_{3W} + \sum_{f=t,c,b,\tau,\mu}\frac{c_{y_f}}{v^2}\mathcal{O}_{y_f}\,.$$

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

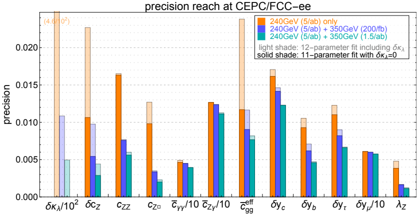


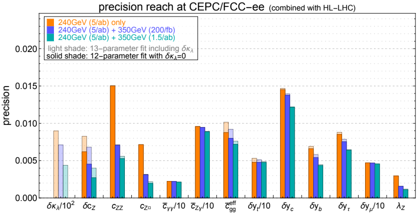
- Angular distributions in $e^+e^- \to hZ$ can provide information in addition to the rate measurement alone.
- Previous studies
  - [arXiv:1406.1361] M. Beneke, D. Boito, Y.-M. Wang
  - [arXiv:1512.06877] N. Craig, JG, Z. Liu, K. Wang
- 6 independent asymmetry observables from 3 angles

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

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

Impact of $\delta\kappa_\lambda$ on the other parameters





- Adding one more parameter could worsen the bounds on others.
- The effect is under control if the degeneracies are well-resolved.
- The HL-LHC bounds on $\delta\kappa_\lambda$ can also help.

The “12-parameter” framework in the Higgs basis

- The relevant terms in the EFT Lagrangian are

$$\mathcal{L} \supset \mathcal{L}_{hVV} + \mathcal{L}_{hff} + \mathcal{L}_{\rm tgc} \,, \qquad (1)$$

- the Higgs couplings with a pair of gauge bosons

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

The “12-parameter” framework in the Higgs basis

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

$$
\begin{aligned}
\delta c_W &= \delta c_Z + 4\delta m\,, \\
c_{WW} &= c_{ZZ} + 2 s_{\theta_W}^2 c_{Z\gamma} + s_{\theta_W}^4 c_{\gamma\gamma}\,, \\
c_{W\Box} &= \frac{1}{g^2 - g'^2}\left[g^2 c_{Z\Box} + g'^2 c_{ZZ} - e^2 s_{\theta_W}^2 c_{\gamma\gamma} - (g^2 - g'^2) s_{\theta_W}^2 c_{Z\gamma} \right]\,, \\
c_{\gamma\Box} &= \frac{1}{g^2 - g'^2}\left[2g^2 c_{Z\Box} + (g^2 + g'^2) c_{ZZ} - e^2 c_{\gamma\gamma} - (g^2 - g'^2) c_{Z\gamma} \right]\,, \qquad (3)
\end{aligned}
$$

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

$$
\mathcal{L}_{hff} = -\frac{h}{v} \sum_{f=t,c,b,\tau,\mu} m_f (1 + \delta y_f) \bar{f}_R f_L + \text{h.c.}\,. \qquad (4)
$$

TGC

$$\begin{aligned}\mathcal{L}_{\rm tgc} \;=\;\; & igs_{\theta_W} A^{\mu}(W^{-\nu}W^{+}_{\mu\nu} - W^{+\nu}W^{-}_{\mu\nu}) \\ & + ig(1+\delta g_1^Z)c_{\theta_W} Z^{\mu}(W^{-\nu}W^{+}_{\mu\nu} - W^{+\nu}W^{-}_{\mu\nu}) \\ & + ig\left[(1+\delta\kappa_Z)c_{\theta_W} Z^{\mu\nu} + (1+\delta\kappa_\gamma)s_{\theta_W} A^{\mu\nu}\right] W^{-}_{\mu} W^{+}_{\nu} \\ & + \frac{ig}{m_W^2}(\lambda_Z c_{\theta_W} Z^{\mu\nu} + \lambda_\gamma s_{\theta_W} A^{\mu\nu}) W_{v}^{-\rho} W^{+}_{\rho\mu}\,, \end{aligned} \tag{5}$$

- $V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$ 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

$$\begin{aligned}\delta g_{1,Z} &= \frac{1}{2(g^2-g'^2)}\left[-g^2(g^2+g'^2)c_{Z\Box} - g'^2(g^2+g'^2)c_{ZZ} + e^2 g'^2 c_{\gamma\gamma} + g'^2(g^2-g'^2)c_{Z\gamma}\right] \\ \delta\kappa_\gamma &= -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{Z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{ZZ}\right)\,. \end{aligned} \tag{6}$$

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%	-
	$\sigma \times \mathrm{BR}$				$\sigma \times \mathrm{BR}$			
$h \to b\bar{b}$	0.21%*	0.39%$^{\diamond}$	2.0%	2.6%	0.20%	0.28%$^{\diamond}$	0.54%	0.71%
$h \to c\bar{c}$	2.5%	-	15%	26%	1.2%	-	4.1%	7.1%
$h \to gg$	1.2%	-	11%	17%	1.4%	-	3.1%	4.7%
$h \to \tau\tau$	1.0%	-	5.3%	37%	0.7%	-	1.5%	10%
$h \to WW^*$	1.0%	-	10%	9.8%	0.9%	-	2.8%	2.7%
$h \to ZZ^*$	4.3%	-	33%	33%	3.1%	-	9.2%	9.3%
$h \to \gamma\gamma$	9.0%	-	51%	77%	3.0%	-	14%	21%
$h \to \mu\mu$	12%	-	115%	275%	13%	-	32%	76%
$h \to Z\gamma$	25%	-	144%	-	18%	-	40%	-

Table: For $e^+e^- \to \nu\bar{\nu}h$, the precisions marked with a diamond $^{\diamond}$ are normalized to the cross section of the inclusive channel which includes both the *WW* fusion and $e^+e^- \to hZ, Z \to \nu\bar{\nu}$, 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	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$	$t\bar{t}h$
σ	0.71%	-	2.1%	-	1.1%	-	-	-	-	-	-
	$\sigma \times \mathrm{BR}$										
$h \to b\bar{b}$	0.42%	3.7%	1.7%	1.7%	0.64%	0.25%	9.9%	0.5%	6.0%	0.3%	3.8%
$h \to c\bar{c}$	2.9%	-	13%	17%	4.6%	2.2%	-	3.1%	-	2.0%	-
$h \to gg$	2.5%	-	9.4%	11%	3.9%	1.4%	-	2.3%	-	1.4%	-
$h \to \tau\tau$	1.1%	-	4.5%	24%	1.9%	3.2%	-	1.6%	-	1.0%	-
$h \to WW^*$	2.3%	-	8.7%	6.4%	3.3%	0.85%	-	3.1%	-	2.0%	-
$h \to ZZ^*$	6.7%	-	28%	22%	8.8%	2.9%	-	4.1%	-	2.6%	-
$h \to \gamma\gamma$	12%	-	44%	50%	12%	6.7%	-	8.5%	-	5.4%	-
$h \to \mu\mu$	25%	-	98%	180%	31%	25%	-	31%	-	20%	-
$h \to Z\gamma$	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	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$
σ	1.6%	-	-	-	-
	$\sigma \times \mathrm{BR}$				
$h \to b\bar{b}$	0.84%	1.9%	0.4%	8.4%	0.3%
$h \to c\bar{c}$	10.3%	14.3%	6.1%	-	6.9%
$h \to gg$	4.5%	5.7%	5.0%	-	4.3%
$h \to \tau\tau$	6.2%	-	4.2%	-	4.4%
$h \to WW^*$	5.1%	-	1.0%	-	0.7%
$h \to ZZ^*$	-	-	5.6%	-	3.9%
$h \to \gamma\gamma$	-	-	15%	-	10%
$h \to \mu\mu$	-	-	38%	-	25%
$h \to Z\gamma$	-	-	42%	-	30%

Table: We also include the estimations for $\sigma(hZ) \times \mathrm{BR}(h \to b\bar{b})$ 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 ($e^+e^- \to e^+e^-h$) are not included in our analysis.