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

Jiayin Gu

DESY & IHEP

FCC Week
May 30, 2017

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 $\Lambda$ 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), \(240 \text{ GeV}(hZ)\) and 350 GeV(t\(t\)).
  - 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.
Introduction

Global fit in the EFT framework

Results

Conclusion

$k$ 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 “$k$” framework.

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

- Anomalous couplings such as $hZ^{\mu\nu}Z_{\mu\nu}$ or $hZ_{\mu}^{\nu}Z^{\mu\nu}$ are assumed to be zero.

- $k \rightarrow$ 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 $t, c, b, \tau, \mu$).

- 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 \( \gamma \).

- 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.

\[
\begin{align*}
\mathcal{O}_H &= \frac{1}{2} (\partial_\mu |H^2|)^2 \\
\mathcal{O}_{WW} &= g^2 |H|^2 W_\mu W_\nu \ W_\mu W_\nu \\
\mathcal{O}_{BB} &= g' |H|^2 B_\mu B_\nu \\
\mathcal{O}_{HW} &= ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W_\mu W_\nu \\
\mathcal{O}_{HB} &= ig'(D^\mu H)^\dagger (D^\nu H) B_\mu B_\nu \\
\mathcal{O}_{GG} &= g_s^2 |H|^2 G^{A,\mu\nu} G^{A,\mu\nu} \\
\mathcal{O}_{y_u} &= y_u |H|^2 \bar{Q}_L H u_R \\
\mathcal{O}_{y_d} &= y_d |H|^2 \bar{Q}_L H d_R \\
\mathcal{O}_{y_e} &= y_e |H|^2 \bar{L}_L H e_R \\
\mathcal{O}_{3W} &= \frac{1}{3!} g_{\epsilon abc} W_\mu W_\nu W_\rho W^{a\nu\rho\mu} \
\end{align*}
\]
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

- 6 independent asymmetry observables from 3 angles

\[ A_{\theta_1}, \ A_{\phi}^{(1)}, \ A_{\phi}^{(2)}, \ A_{\phi}^{(3)}, \ A_{\phi}^{(4)}, \ A_{c\theta_1,c\theta_2}. \]

- 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)
Global Determinant Parameter (GDP $\equiv \frac{2^n}{\sqrt{\text{det} \sigma^2}}$).

- 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 $e^+ e^- \rightarrow Zhh$, $e^+ e^- \rightarrow \nu\bar{\nu}hh$.
    - 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: $|\delta K_\lambda| \lesssim 28\%$ assuming all other Higgs couplings are SM-like.
    - What if other Higgs couplings are not SM-like?

- **Can we obtain robust constraints on $\delta K_\lambda$ at circular colliders?**
  - **Yes we can!**
    - A global fit of 12+1 parameters. **Very preliminary results!**
    - FCC-ee 240 GeV (10 ab$^{-1}$) alone, $\delta K_\lambda$ almost not constrained! ($|\delta K_\lambda| \lesssim 650\%$)
    - FCC-ee 240 GeV (10 ab$^{-1}$) + 350 GeV (500 fb$^{-1}$), $|\delta K_\lambda| \lesssim 73\%$.
    - FCC-ee 240 GeV (10 ab$^{-1}$) + 350 GeV (2.6 ab$^{-1}$), $|\delta K_\lambda| \lesssim 39\%$. 
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. Vantalon)

\[ \Delta \chi^2 \text{ vs. } \delta \kappa_\lambda, \text{ profiling over other parameters} \]

- "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:1502.00539] Azatov, Contino, Panico, Son

<table>
<thead>
<tr>
<th>one-sigma uncertainty of ( \delta \kappa_\lambda )</th>
<th>FCC-ee alone</th>
<th>with HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>full</td>
<td>linear</td>
</tr>
<tr>
<td></td>
<td>full</td>
<td>linear</td>
</tr>
<tr>
<td></td>
<td>+1.26</td>
<td>-0.92</td>
</tr>
<tr>
<td></td>
<td>+0.95</td>
<td>-0.78</td>
</tr>
<tr>
<td></td>
<td>+0.56</td>
<td>-0.53</td>
</tr>
<tr>
<td></td>
<td>+0.36</td>
<td>-0.35</td>
</tr>
</tbody>
</table>

Jiayin Gu

DESY & IHEP

EFT global fit of Higgs couplings at \( e^+ e^- \) colliders
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 $\Gamma_{ZZ^*}$ and $\Gamma_{WW^*}$ 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.
Introduction

Global fit in the EFT framework

Results

Conclusion

\[ e^+ e^- \rightarrow WW \]

- \[ e^+ e^- \rightarrow WW \] offers a great way to probe the anomalous triple gauge couplings (aTGCs, parameterized by \( \delta g_{1,Z}, \delta \kappa_\gamma, \lambda_Z \)).

- \( \delta g_{1,Z} \) 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

- $\delta g_{1,Z} \, \delta \kappa_\gamma \leftrightarrow c_{ZZ} \, c_{Z\square} \, c_{\gamma\gamma} \, c_{Z\gamma}$

- 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!
Asymmetry observables

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

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

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

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

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

(1)

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

(2)
The “12-parameter” framework in the Higgs basis

- The relevant terms in the EFT Lagrangian are
  \[ \mathcal{L} \supset \mathcal{L}_{hVV} + \mathcal{L}_{hff} + \mathcal{L}_{tgc}, \]  
  \[ (3) \]

- the Higgs couplings with a pair of gauge bosons
  \[ \mathcal{L}_{hVV} = \frac{h}{\nu} \left[ (1 + \delta c_W) \frac{g^2 v^2}{2} W_\mu^+ W_\mu^- + (1 + \delta c_Z) \frac{(g^2 + g'^2) v^2}{4} Z_\mu Z_\mu \right. \]
  \[ + c_{WW} \frac{g^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + c_W \Box g^2 (W_{\mu\nu}^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}) \]
  \[ + c_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_\gamma \gamma \frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_Z \gamma \frac{e \sqrt{g^2 + g'^2}}{2} Z_{\mu\nu} A_{\mu\nu} \]
  \[ + c_{\gamma Z} \frac{g^2 + g'^2}{4} Z_{\mu\nu} Z_{\mu\nu} + c_{\Box Z} g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_\gamma \Box g' g Z_\mu \partial_\nu A_{\mu\nu} \]  
  \[ (4) \]
The “12-parameter” framework in the Higgs basis

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

\[
\delta c_W = \delta c_Z + 4 \delta m,
\]

\[
c_{WW} = c_{ZZ} + 2 s_{\theta_W}^2 c_{Z\gamma} + s_{\theta_W}^4 c_{\gamma\gamma},
\]

\[
c_{W\Box} = \frac{1}{g^2 - g'^2} \left[ g^2 c_{Z\Box} + g'^2 c_{ZZ} - e^2 s_{\theta_W}^2 c_{\gamma\gamma} - (g^2 - g'^2) s_{\theta_W}^2 c_{Z\gamma} \right],
\]

\[
c_{\gamma\Box} = \frac{1}{g^2 - g'^2} \left[ 2 g^2 c_{Z\Box} + (g^2 + g'^2) c_{ZZ} - e^2 c_{\gamma\gamma} - (g^2 - g'^2) c_{Z\gamma} \right],
\]

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

\[
\mathcal{L}_{hff} = -\frac{h}{v} \sum_{f=t,c,b,\tau,\mu} m_f (1 + \delta y_f) \bar{f}_R f_L + \text{h.c.}.
\]
\begin{align}
\mathcal{L}_{\text{tgc}} &= \, I g s_\theta W A^\mu (W^{-\nu} W_{\mu \nu}^+ - W^{+\nu} W_{\mu \nu}^-) \\
&+ I g (1 + \delta g^Z) c_\theta W Z^\mu (W^{-\nu} W_{\mu \nu}^+ - W^{+\nu} W_{\mu \nu}^-) \\
&+ I g \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{I g}{m_w^2} (\lambda_Z c_\theta W Z^{\mu \nu} + \lambda_\gamma s_\theta W A^{\mu \nu}) W_{\nu -} W_{\rho \mu}^+.
\end{align}

\[ \tag{7} \]

- \( V_{\mu \nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu \) for \( V = W^\pm, Z, A_\gamma \). 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 \( \lambda_Z \), 2 of them related to Higgs observables by

\[ \delta g_{1,Z} = \frac{1}{2(g^2 - g'^2)} \left[ -g^2 (g^2 + g'^2) c_{Z\square} - g'^2 (g^2 + g'^2) c_{ZZ} + e^2 g'^2 c_{\gamma \gamma} + g'^2 (g^2 - g'^2) c_{Z \gamma} \right] \]

\[ \delta_\kappa \gamma = - \frac{g^2}{2} \left( c_{\gamma \gamma} \frac{e^2}{g^2 + g'^2} + c_{Z \gamma} \frac{g^2 - g'^2}{g^2 + g'^2} - c_{ZZ} \right). \]  

\[ \tag{8} \]
### CEPC/FCC-ee Higgs rate measurements

<table>
<thead>
<tr>
<th></th>
<th>CEPC</th>
<th>FCC-ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>production</td>
<td>[240 GeV, 5 ab(^{-1})]</td>
<td>[350 GeV, 200 fb(^{-1})]</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>(Zh \nu\bar{\nu}h)</td>
<td>(Zh \nu\bar{\nu}h)</td>
</tr>
<tr>
<td>(\sigma \times \text{BR})</td>
<td>(0.50% - 2.4%)</td>
<td>(0.40% - 0.67%)</td>
</tr>
</tbody>
</table>

| \(h \rightarrow b\bar{b}\) | 0.21\%\(\star\) 0.39\%\(\diamondsuit\) | 2.0\% 2.6\% | 0.20\% 0.28\%\(\diamondsuit\) | 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 \(\diamondsuit\) 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

<table>
<thead>
<tr>
<th>ILC</th>
<th>[250 GeV, 2 ab$^{-1}$]</th>
<th>[350 GeV, 200 fb$^{-1}$]</th>
<th>[500 GeV, 4 ab$^{-1}$]</th>
<th>[1 TeV, 1 ab$^{-1}$]</th>
<th>[1 TeV, 2.5 ab$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>production</td>
<td>$Zh$</td>
<td>$\nu\bar{\nu}h$</td>
<td>$Zh$</td>
<td>$\nu\bar{\nu}h$</td>
<td>$tth$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.71%</td>
<td>-</td>
<td>2.1%</td>
<td>-</td>
<td>1.1%</td>
</tr>
<tr>
<td>$h \to bb$</td>
<td>0.42%</td>
<td>3.7%</td>
<td>1.7%</td>
<td>1.7%</td>
<td>0.64%</td>
</tr>
<tr>
<td>$h \to c\bar{c}$</td>
<td>2.9%</td>
<td>-</td>
<td>13%</td>
<td>17%</td>
<td>4.6%</td>
</tr>
<tr>
<td>$h \to gg$</td>
<td>2.5%</td>
<td>-</td>
<td>9.4%</td>
<td>11%</td>
<td>3.9%</td>
</tr>
<tr>
<td>$h \to t\bar{t}$</td>
<td>1.1%</td>
<td>-</td>
<td>4.5%</td>
<td>24%</td>
<td>1.9%</td>
</tr>
<tr>
<td>$h \to WW^*$</td>
<td>2.3%</td>
<td>-</td>
<td>8.7%</td>
<td>6.4%</td>
<td>3.3%</td>
</tr>
<tr>
<td>$h \to ZZ^*$</td>
<td>6.7%</td>
<td>-</td>
<td>28%</td>
<td>22%</td>
<td>8.8%</td>
</tr>
<tr>
<td>$h \to \gamma\gamma$</td>
<td>12%</td>
<td>-</td>
<td>44%</td>
<td>50%</td>
<td>12%</td>
</tr>
<tr>
<td>$h \to \mu\mu$</td>
<td>25%</td>
<td>-</td>
<td>98%</td>
<td>180%</td>
<td>31%</td>
</tr>
<tr>
<td>$h \to Z\gamma$</td>
<td>34%</td>
<td>-</td>
<td>145%</td>
<td>-</td>
<td>49%</td>
</tr>
</tbody>
</table>


### CLIC Higgs rate measurements

<table>
<thead>
<tr>
<th>Production</th>
<th>[350 \text{ GeV, } 500 \text{ fb}^{-1}]</th>
<th>[1.4 \text{ TeV, } 1.5 \text{ ab}^{-1}]</th>
<th>[3 \text{ TeV, } 2 \text{ ab}^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma)</td>
<td>(Zh) 1.6%</td>
<td>(\nu\bar{\nu}h) -</td>
<td>(\nu\bar{\nu}h) -</td>
</tr>
<tr>
<td>(\sigma \times \text{BR})</td>
<td>0.84% 1.9%</td>
<td>0.4% 8.4%</td>
<td>0.3%</td>
</tr>
<tr>
<td>(h \to bb)</td>
<td>10.3% 14.3%</td>
<td>6.1% -</td>
<td>6.9%</td>
</tr>
<tr>
<td>(h \to c\bar{c})</td>
<td>4.5% 5.7%</td>
<td>5.0% -</td>
<td>4.3%</td>
</tr>
<tr>
<td>(h \to \tau\tau)</td>
<td>6.2% -</td>
<td>4.2% -</td>
<td>4.4%</td>
</tr>
<tr>
<td>(h \to W^+W^-)</td>
<td>5.1% -</td>
<td>1.0% -</td>
<td>0.7%</td>
</tr>
<tr>
<td>(h \to ZZ^*)</td>
<td>- -</td>
<td>5.6% -</td>
<td>3.9%</td>
</tr>
<tr>
<td>(h \to \gamma\gamma)</td>
<td>- -</td>
<td>15% -</td>
<td>10%</td>
</tr>
<tr>
<td>(h \to \mu\mu)</td>
<td>- -</td>
<td>38% -</td>
<td>25%</td>
</tr>
<tr>
<td>(h \to Z\gamma)</td>
<td>- -</td>
<td>42% -</td>
<td>30%</td>
</tr>
</tbody>
</table>

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