Double Higgs production

HL/HE LHC workshop
CERN - 18.06.2018

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Based on work with T. Han, F. Kling, T. Plehn, M. Takeuchi arxiv:1802.04312
Motivation

The properties of the Higgs sector are uniquely determined in the SM. Any deviation would be a smoking gun signature for physics beyond SM.

**Goal:** few percent precision in Higgs couplings measurements

Huge experimental & theoretical effort

Higgs couplings to fermions and gauge bosons so far compatible with SM
The properties of the Higgs sector are uniquely determined in the SM. Any deviation would be a smoking gun signature for physics beyond SM.

**Goal: few percent precision in Higgs couplings measurements**

Huge experimental & theoretical effort

- Higgs couplings to fermions and gauge bosons so far compatible with SM
- However, we still lack understanding of Higgs potential

\[ V(h) = \frac{m_h^2}{2} h^2 + \lambda_3 h^3 + \lambda_4 h^4 + \ldots \]

- Elementary scalar self-interaction has never been measured
- Could probe the nature of the EW phase transition: 1st vs. 2nd order
Double Higgs production fundamental to reconstruct Higgs potential
Double Higgs decays

HH displays phenomenologically rich variety of final states:

Huge theoretical & experimental effort exploring promising final states: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, 4$b$, $b\bar{b}WW$...

Theoretical studies as well as current analyses point to $b\bar{b}\gamma\gamma$ as the most promising signature at LHC

Complementarity

<table>
<thead>
<tr>
<th></th>
<th>$H(b\bar{b})$</th>
<th>$H(\gamma\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Largest Branching ratio</td>
<td>Limited Branching ratio</td>
<td></td>
</tr>
<tr>
<td>High b-tagging efficiency</td>
<td>Excellent mass resolution</td>
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Double Higgs decays

HH displays phenomenologically rich variety of final states:

HL-LHC projections:

\[ \kappa_\lambda = \frac{\lambda}{\lambda_{SM}} \] @95% CL

<table>
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<tr>
<th></th>
<th>ATL-PHYS-PUB-2015-046</th>
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<tbody>
<tr>
<td>bb\gamma\gamma_{w/o\ sys}</td>
<td>[-0.8, 7.7]</td>
</tr>
<tr>
<td>bb\tau\tau</td>
<td>[-4.0, 12.0]</td>
</tr>
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<td>4b</td>
<td>[-3.5, 11]</td>
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ATLAS Simulation Preliminary

ATL-PHYS-PUB-2017-001
Double Higgs decays

HH displays phenomenologically rich variety of final states:

**HL-LHC projections:**

\[
\kappa_\lambda = \frac{\lambda}{\lambda_{SM}} \quad @ 95\% CL
\]

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<tr>
<th>Final State</th>
<th>Exclusion Region</th>
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Despite of the huge effort, it is far from satisfactory in probing the Higgs potential, HH falls short in precision in comparison to other Higgs property measurements.

Clear motivation for a higher energy colliders

Future colliders

HL-LHC: 14 TeV 3 ab⁻¹  HE-LHC: 27 TeV 15 ab⁻¹  100 TeV 30 ab⁻¹

Factor 4 at 27 TeV in cross section and factor 40 at 100 TeV

Accounting for the projected luminosities, this implies in an event increase

DG, Han, Kling, Plehn, Takeuchi (2018)

Increased energy and luminosity turns Higgs pair production into a valid channel for precision measurements
Where the sensitivities come from?

Three distinctive phase space regimes:

\[ m_{hh}^{(th)} \approx 2m_h \]

\[ \frac{\alpha_s}{12\pi v} \left( \frac{\kappa_\lambda \lambda_{SM}}{s - m_h^2} - \frac{1}{v} \right) \rightarrow \frac{\alpha_s}{12\pi v^2} (\kappa_\lambda - 1)^{\text{SM}} = 0 \]

\[ m_{hh}^{(abs)} \approx 2m_t \]

\[ m_{hh}^{(high)} \gg m_h, m_t \]

Where do the sensitivities come from?

Barr, Dolan, Englert, Lima, Spannowsky (2014)

DG, Han, Kling, Plehn, Takeuchi (2018)
Detector level analysis

The Higgs tend to produce soft decays $p_{Tb} \sim m_h/2$. Cheap to produce extra harder jet at HE colliders.

Two $H(bb)$ decay products not always found in hardest two jets.

We simulate all samples (Signal & Background) merged up to one jet.

Divide analysis in two sub-samples: (bb,bbj) & (bjb,jbb).

DG, Han, Kling, Plehn, Takeuchi (2018)
Probing the Higgs potential

Doing a binned log-likelihood analysis for the $m_{hh}$ distribution at 27 TeV and 100 TeV for $pp \rightarrow h(bb)\gamma\gamma$.

HH discovery pushed from 2.8 ab$^{-1}$ to 2.3 ab$^{-1}$ at 27 TeV HE-LHC

Photon and b-jet invariant mass resolution important for the detector design

HH discovery: 27 TeV 2.3 - 5 ab$^{-1}$; 100 TeV collider 0.2 - 0.3 ab$^{-1}$
Probing the Higgs potential

Doing a binned log-likelihood analysis for the $m_{hh}$ distribution at 27 TeV and 100 TeV for $pp \rightarrow h(bb)h(\gamma\gamma)$

DG, Han, Kling, Plehn, Takeuchi (2018)

$\kappa_{\lambda}$ shape analysis removes degeneracies from rate-based measurement

Uncertainty measurement for the Higgs self-coupling:
- HE-LHC: $\kappa_{\lambda} \approx 1 \pm 15\%$ (1$\sigma$), 30% (2$\sigma$)
- FCC-100TeV: $\kappa_{\lambda} \approx 1 \pm 5\%$ (1$\sigma$), 10% (2$\sigma$)

HE-LHC give very competitive results
Probing the Higgs potential

Dependence on detector parameter choice

Conservative: HL-LHC performance projections from ATL-PHYS-PUB-2016-026

More optimistic parameter choice: FCC CERN Yellow Report

Only moderate changes on the bounds for these parameter choices
Double Higgs production in EFT

Dim-6 Lagrangian relevant to HH production:

\[ \mathcal{L}_{\text{non-lin}} \supset -m_t \bar{t} t \left( c_t \frac{h}{v} + c_{2t} \frac{h^2}{v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g^2}{4\pi^2} \left( c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu}^a G^{a\mu\nu} \]

- **Non-linear EFT:** \( c_t, c_{2t}, c_3, c_g, c_{2g} \) independent parameters
- **Linear EFT (Higgs is a doublet):** \( c_g, c_t, c_3 \) independent parameters. \( c_g = c_{gg}; \ c_{2t} = -\frac{3m_t}{2v} c_t \)

EFT - divide and conquer:

- \( c_t, c_g \) can be constrained by single Higgs production
- \( c_3, c_{2g}, c_{2t} \) need HH production for constraints

Azatov, Contino, Panico, Son (2015)
Double Higgs production in EFT

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\[ \sim c_t^2 \frac{\alpha_s}{4\pi} y_t^2 \]

\[ \sim c_{2t} \frac{\alpha_s}{4\pi} y_t^2 \left( \log \frac{m_t^2}{\hat{s}} + i\pi \right)^2 \]

\[ \sim c_2 \frac{\alpha_s}{4\pi} y_t^2 \left( \log \frac{m_h^2}{\hat{s}} + i\pi \right)^2 \]

\[ \sim c_g c_3 \frac{\alpha_s}{4\pi} \frac{m_h^2}{v^2} \]

\[ \sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2} \]

Shape analysis can significantly improve the fits:

Azatov, Contino, Panico, Son (2015)
Summary

Triple Higgs couplings is a key benchmark for the LHC and future colliders

- The HE-LHC and FCC combination of increased energy and luminosity turn the Higgs pair production into a valid channel for **precision measurements**. Finally probe the Higgs potential!

- The $m_{hh}$ shape analysis remove degeneracies and enhance the triple coupling sensitivity

- HE-LHC would rapidly reach a $5\sigma$ observation with $2.3\ \text{ab}^{-1}$. It displays competitive sensitivities to FCC

  \[ \mu_\lambda \approx 1 \pm 15\% \ (1\sigma), \ 30\% \ (2\sigma) \]

  \[ \mu_\lambda \approx 1 \pm 5\% \ (1\sigma), \ 10\% \ (2\sigma) \]
Thank you for your attention!