Probing the scalar potential via double Higgs boson production at hadron colliders

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Based on JHEP 04 (2019) 016

RADCOR 2019
Avignon, September 9-13, 2019
SM Higgs potential & New Physics

Higgs potential & EWSB in the SM,

\[ V^{\text{SM}}(\Phi) = -\mu^2 (\Phi^\dagger \Phi) + \lambda (\Phi^\dagger \Phi)^2 \]

EWSB \Rightarrow V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4.

The mass and the self-couplings of the Higgs boson depend only on \( \lambda \) and
\[ v = (\sqrt{2} G_\mu)^{-1/2}, \]
\[ m_H^2 = 2\lambda v^2; \quad \lambda_3^{\text{SM}} = \lambda_4^{\text{SM}} = \lambda. \]

\[ m_H = 125 \text{ GeV} \text{ and } v \sim 246 \text{ GeV}, \Rightarrow \boxed{\lambda \approx 0.13}. \]

Presence of new physics at higher energy scales can contribute to the Higgs potential and modify the Higgs self-couplings.

*Independent measurements of \( \lambda_3 \) and \( \lambda_4 \) are crucial.*
Direct determination of Higgs self-couplings

Information on $\lambda_3$ and $\lambda_4$ can be extracted by studying multi-Higgs production processes.

[Frederix et al. '14, 1408.6542]
Very challenging due to small cross sections: $\sim 33$ fb ($HH$), $\sim 0.1$ fb ($HHH$)

*Compare it with the single Higgs production ($gg \rightarrow H$) cross section: $\sim 50$ pb*
Current and future experimental sensitivity ($\kappa_\lambda = \lambda_3/\lambda_3^{\text{SM}}$)

Di-Higgs production

- ATLAS: $\mu < 6.7$ (exp 10.4) @ 95% CL
- CMS: $\mu < 22$ (exp 13) @ 95% C.L.
- Limits at 95% CL on self-coupling scale factor $\kappa_\lambda$:
  - ATLAS: $-5.0 < \kappa_\lambda < 12.1$
  - CMS: $-11.8 < \kappa_\lambda < 18.8$

ATLAS (HL-LHC, $2b2\gamma$): [ATL-PHYS-PUB-2017-001],

$\kappa_\lambda < -0.8$ and $\kappa_\lambda > \sim 7.7$

Bounds are sensitive to $\kappa_t$ value.
Indirect determination of $\lambda_3$ in single Higgs

Gorbahn, Haisch: 1607.03773; Degrassi, Giardino, Maltoni, Pagani: 1607.04251; Bizon, Gorbahn, Haisch, Zanderighi: 1610.05771; Di Vita, Grojean, Panico, Riembau, Vantalon: 1704.01953; Maltoni, Pagani, AS, Zhao: 1709.08649

Master formula: Anomalous trilinear coupling ($\kappa_3 = \lambda_3/\lambda_{3}^{\text{SM}}$)

$$
\Sigma_{\text{NLO}}^{\text{BSM}} = Z_{H}^{\text{BSM}} \left[ \Sigma_{\text{LO}} (1 + \kappa_3 C_1 + \delta Z_H) + \Delta_{\text{NLO}}^{\text{SM}} \right]
$$

$$
Z_{H}^{\text{BSM}} = \frac{1}{1 - (\kappa_3^2 - 1)\delta Z_H}, \quad \delta Z_H = -1.536 \times 10^{-3}
$$
Current and future reach at the LHC

13 TeV:

\[-4.7 < \kappa_3 < 12.6\]

HL-LHC:

\[-2 \lesssim \kappa_3 \lesssim 8\]
CMS Projections: HL-LHC

tH + ttH: using the calculation of Maltoni, Pagani, AS, Zhao:
1709.08649

[CMS-PAS-FTR-18-020]

Question: Can we extend this strategy to double Higgs production?
Maltoni, Pagani, Zhao: 1802.07616; Bizon, Haisch, Rottoli: 1810.04665; Borowka, Duhr, Maltoni, Pagani, AS, Zhao: 1811.12366
Indirect determination of $\lambda_4$ in double Higgs

At LO, the $gg \to HH$ amplitude is sensitive to only $\lambda_3$.

$\lambda_4$ affects $gg \to HH$ amplitude at two-loop level via NLO EW corrections.

EFT framework is necessary in order to vary cubic and quartic couplings independently in a consistent way.

\[
V^{\text{NP}}(\Phi) \equiv \sum_{n=3}^{\infty} \frac{c_{2n}}{\Lambda^{2n-4}} \left( \Phi^\dagger \Phi - \frac{1}{2} v^2 \right)^n.
\]

This also ensures gauge invariance and UV finiteness in our calculation.
NP Paramterization

\[ V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4 + \lambda_5 \frac{H^5}{v} + O(H^6), \]

\[ \kappa_3 \equiv \frac{\lambda_3}{\lambda_3^{SM}} = 1 + \frac{c_6 v^2}{\lambda \Lambda^2} \equiv 1 + \bar{c}_6, \]

\[ \kappa_4 \equiv \frac{\lambda_4}{\lambda_4^{SM}} = 1 + \frac{6 c_6 v^2}{\lambda \Lambda^2} + \frac{4 c_8 v^4}{\lambda \Lambda^4} \equiv 1 + 6 \bar{c}_6 + \bar{c}_8. \]

We can trade \( \kappa_3 \) and \( \kappa_4 \) with parameters \( \bar{c}_6 \) and \( \bar{c}_8 \).

\[ \bar{c}_6 \equiv \frac{c_6 v^2}{\lambda \Lambda^2} = \kappa_3 - 1, \]

\[ \bar{c}_8 \equiv \frac{4 c_8 v^4}{\lambda \Lambda^4} = \kappa_4 - 1 - 6(\kappa_3 - 1). \]
The Phenomenological quantity of interest

Inclusive/differential cross section

\[ \sigma_{NLO}^{\text{pheno}} = \sigma_{LO} + \Delta\sigma_{\bar{c}_6} + \Delta\sigma_{\bar{c}_8}, \]

EFT insertion at one-loop :

\[ \sigma_{LO} = \sigma_0 + \sigma_1 \bar{c}_6 + \sigma_2 \bar{c}_6^2, \]

EFT insertions at two-loop :

\[ \Delta\sigma_{\bar{c}_6} = \bar{c}_6^2 \left[ \sigma_{30} \bar{c}_6 + \sigma_{40} \bar{c}_6^2 \right] + \bar{c}_{20} \bar{c}_6^2, \]

\[ \Delta\sigma_{\bar{c}_8} = \bar{c}_8 \left[ \sigma_{01} + \sigma_{11} \bar{c}_6 + \sigma_{21} \bar{c}_6^2 \right], \]

Taking an agnostic view on possible values of \( \kappa_3 \) and \( \kappa_4 \), we have ignored the SM EW corrections, and have kept highest powers of \( \bar{c}_6 \) in \( \Delta\sigma_{\bar{c}_6} \).

The quantity \( \Delta\sigma_{\bar{c}_8} \) is the most relevant part of our computation and it solely induces the sensitivity on \( \bar{c}_8 \).

We assume that higher order QCD corrections factorize from two-loop EW effects.
Relevant two-loop topologies

Non-factorizable, factorizable and counterterms:
Non-factorizable contributions

The most challenging part of the calculation:

\[
\begin{align*}
M_a &= 2(M_{a1} + M_{a2} + M_{a3}), \\
M_b &= 2M_{b1} + M_{b2}, \\
M_c &= M_b \times \frac{6v^2}{\lambda_4} \frac{\lambda_3^2}{s - m_H^2},
\end{align*}
\]
Projection to spin-0 and spin-2 form factors

For both one-loop and two-loop $gg \rightarrow HH$ amplitudes:

$$\mathcal{M}^{\mu_1 \mu_2} \epsilon_{1, \mu_1} \epsilon_{2, \mu_2} = \delta^{c_1 c_2} \mathcal{A}_0^{\mu_1 \mu_2} \epsilon_{1, \mu_1} \epsilon_{2, \mu_2} F_0 + \delta^{c_1 c_2} \mathcal{A}_2^{\mu_1 \mu_2} \epsilon_{1, \mu_1} \epsilon_{2, \mu_2} F_2.$$ 

$$\mathcal{A}_0^{\mu_1 \mu_2} = \sqrt{\frac{2}{d-2}} \left( g^{\mu_1 \mu_2} - \frac{p_1^{\mu_2} p_2^{\mu_1}}{p_1 \cdot p_2} \right),$$

$$\mathcal{A}_2^{\mu_1 \mu_2} = \sqrt{\frac{d-2}{2(d-3)}} \left( - \frac{d-4}{d-2} \left[ g^{\mu_1 \mu_2} - \frac{p_1^{\mu_2} p_2^{\mu_1}}{p_1 \cdot p_2} \right] + g^{\mu_1 \mu_2} \right.$$ 
$$\left. + \frac{(p_3 \cdot p_3) p_1^{\mu_2} p_2^{\mu_1}}{p_3^2 (p_1 \cdot p_2)} + (2 p_1 \cdot p_2) p_3^{\mu_1} p_3^{\mu_2} - (2 p_1 \cdot p_3) p_2^{\mu_1} p_3^{\mu_2} - (2 p_2 \cdot p_3) p_3^{\mu_1} p_1^{\mu_2} \right) \bigg\}.$$ 

$$\Rightarrow F_{0,a}, F_{0,b}, F_{0,c} \text{ and } F_{2,a}$$

The box-triangle amplitudes depend only on the spin-0 form factor.

Tools: QGRAF, FORM
Numerical evaluation of form factors

The form factors are computed using \texttt{pySecDec}.
Borowka, Heinrich, Jahn, Jones, Kerner, Schlenk: 1703.09692, 1712.05755

Correctness of the calculation is ensured by various checks:

- UV finiteness of the form factors
- The large $m_t$ limit of box-triangle amplitude
- Reduction of double-box into box triangle in heavy propagator limit

For phenomenological predictions at colliders, the form factors are required to be computed for many phase space points which can become very time consuming.
Numerical evaluation of form factors

We build grids for form factors which can be interpolated for an efficient phase space integration.

One-dimensional grid is sufficient for box-triangle spin-0 form factor.

The double box spin-0 form factor, depends on $s$ as well as on $\theta$. The $\theta$ dependence is found to be very weak below top pair threshold.

The double box spin-2 form factor displays a large $\theta$ dependence, however, this form factor is suppressed wrt the spin-0 form factor.
Effect on inclusive cross section

For $\alpha_s$, $\mu_R = \mu_F = \frac{1}{2} m(HH)$ while $\mu_{EFT} = 2m_H$.

One-loop:

\[
\begin{array}{|c|c|c|c|}
\hline
\sqrt{s} \; [\text{TeV}] & \sigma_0 \; [\text{fb}] & \sigma_1 \; [\text{fb}] & \sigma_2 \; [\text{fb}] \\
\hline
14 & 19.49 & -15.59 & 5.414 \\
 & & (-80.0\%) & (27.8\%) \\
100 & 790.8 & -556.8 & 170.8 \\
 & & (-70.5\%) & (21.6\%) \\
\hline
\end{array}
\]

Two-loop:

\[
\begin{array}{|c|c|c|c|c|c|c|}
\hline
\sqrt{s} \; [\text{TeV}] & \tilde{\sigma}_{20} \; [\text{fb}] & \sigma_{30} \; [\text{fb}] & \sigma_{40} \; [\text{fb}] & \sigma_{01} \; [\text{fb}] & \sigma_{11} \; [\text{fb}] & \sigma_{21} \; [\text{fb}] \\
\hline
14 & 0.7112 & -0.5427 & 0.0620 & 0.3514 & -0.0464 & -0.1433 \\
 & (3.6\%) & (-2.8\%) & (0.3\%) & (1.8\%) & (-0.2\%) & (-0.7\%) \\
100 & 24.55 & -16.53 & 1.663 & 12.932 & -0.88 & -4.411 \\
 & (3.1\%) & (-2.1\%) & (0.2\%) & (1.6\%) & (-0.1\%) & (-0.6\%) \\
\hline
\end{array}
\]

Cross sections grow considerably with energy. The contributions (numbers in brackets) from $\bar{c}_6$ and $\bar{c}_8$ slowly decrease wrt the SM LO prediction.
Effect on differential cross section

One-loop

Two-loop

The dashed lines show absolute values of -ve contributions.
Projections for 100 TeV \( pp \) collider

For \( \kappa_3 = 1 \), at 95\% CL

\[-6 \lesssim \kappa_4 \lesssim 18 \] \quad \text{[Direct from } HHH(4b2\gamma)\text{]}

\[-4.2 \lesssim \kappa_4 \lesssim 6.7 \] \quad \text{[Indirect from } HH(2b2\gamma)\text{]}
Summary and conclusions

- The determination of Higgs potential is one of the most important goals of HL-LHC and future colliders.

- Due to low rates for multi-Higgs production, it is very challenging to measure Higgs self-couplings.

- Alternative strategies are needed to improve sensitivity on Higgs self-couplings. Higher order EW effects in single and double Higgs production are indirectly sensitive to cubic and quartic couplings respectively.

- We have calculated two-loop EW effects in $gg \rightarrow HH$ which are sensitive to cubic and quartic couplings using an EFT framework.

- Our study indicates that at 100 TeV $pp$ collider, the $HH$ channel would be more sensitive to independent variation in self-couplings than $HHH$ channel.

Thank You.