Improved constraint on Higgs boson self-couplings with quartic and cubic power dependence in the cross section

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Higgs self-coupling λ

After the discovery of Higgs boson, an important experimental goal is the measurement of the Higgs potential, which is closely related to electroweak symmetry breaking (EWSB). It can be probed by measuring the Higgs self coupling. In the SM, the Higgs potential is

$$V = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

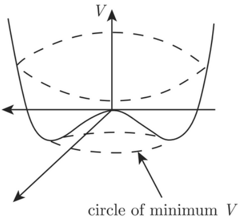
with

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h+v \end{pmatrix}$$

After spontaneous symmetry breaking

$$V \sim \frac{1}{2}\left(\underline{\underline{2\lambda v^2}}\right)h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

$$m_H^2 = 2\lambda v^2$$



Higgs pair production

At the LHC, $\sqrt{s}$ =14TeV,
trilinear coupling: $pp \to HH$, 33fb
quartic coupling: $pp \to HHH$, 0.09fb   Maltoni, Vryonidou, Zaro, 2014
Higgs pair production modes: ggF (dominant), VBF, $t\bar{t}HH$, VHH
A lot of higher-order corrections have been computed, mainly in the QCD part. However, recently there has been a gradual increase in the calculations of EW corrections.

Higgs pair production

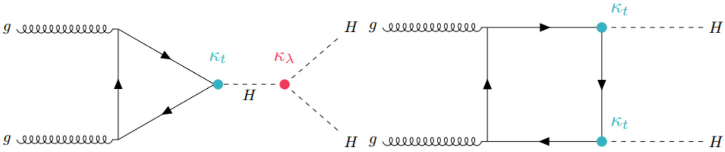
HTL:
NNLO: De Florian, Mazzitelli, 2013
N3LO: Chen, Li, Shao, Wang, 2019
N3LO+N3LL: Ajjath, Shao, 2022

full top mass dependence:
NLO: Borowka, Greiner, Heinrich, Jones, 2016
NLO: Baglio, Campanario, Glaus, Mühlleitner et al, 2018

Probing the scalar potential via double Higgs boson production at hadron colliders: Borowka, Duhr, Maltoni, Pagani et al, 2018
Higgs boson exchange in the top quark loop: Davies, Mishima, Schönwald, Steinhauser et al, 2022
Top-Yukawa-induced EW corrections: Mühlleitner, Schlenk, Spira, 2022
NLO EW corrections in an expansion for large-m_t: Davies, Schönwald, Steinhauser, Zhang, 2023
Full NLO EW corrections to ggF: Bi, Huang, Huang, Ma, Yu, 2023

Experiment

Coupling modifiers, often denoted as κ, are used in particle physics to quantify the deviations from the SM predictions for the interactions of fundamental particles.



$$\kappa_{\lambda_{3H}} = \frac{\lambda_{3H}}{\lambda_{3H,SM}}$$

$-0.6 < \kappa_{\lambda_{3H}} < 6.6$ ATLAS, 2022

$-1.24 < \kappa_{\lambda_{3H}} < 6.49$ CMS, 2022

$$\sigma = c_0 \times \lambda_{3H}^0 + c_1 \times \lambda_{3H}^1 + c_2 \times \lambda_{3H}^2$$
$$+ c_3 \times \lambda_{4H}^1 + c_4 \times \lambda_{3H}^2 + c_5 \times \lambda_{3H}^3 + c_6 \times \lambda_{3H}^4 + \ldots$$

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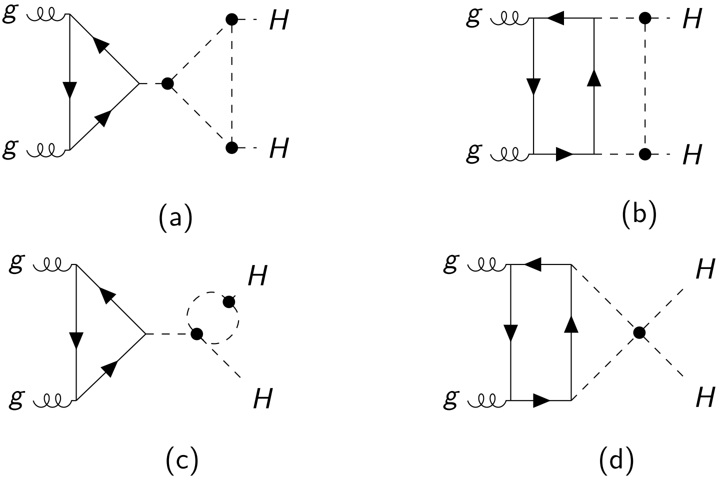
NLO EW corrections: ggF part



Typical two-loop Feynman diagrams of order λ_{3H}^3 (a), λ_{3H}^2 (b), $\lambda_{4H}\lambda_{3H}$ (c) and λ_{4H} (d), respectively.

Calculation methods

Feynman diagrams —(momentum shift)→ families —(projection method)→ scalar integrals → AMFlow

Liu, Ma, 2022

$g(p_1)g(p_2) \to H(p_3)H(p_4)$

$$s = (p_1 + p_2)^2, \quad t = (p_1 - p_3)^2, \quad u = (p_2 - p_3)^2$$

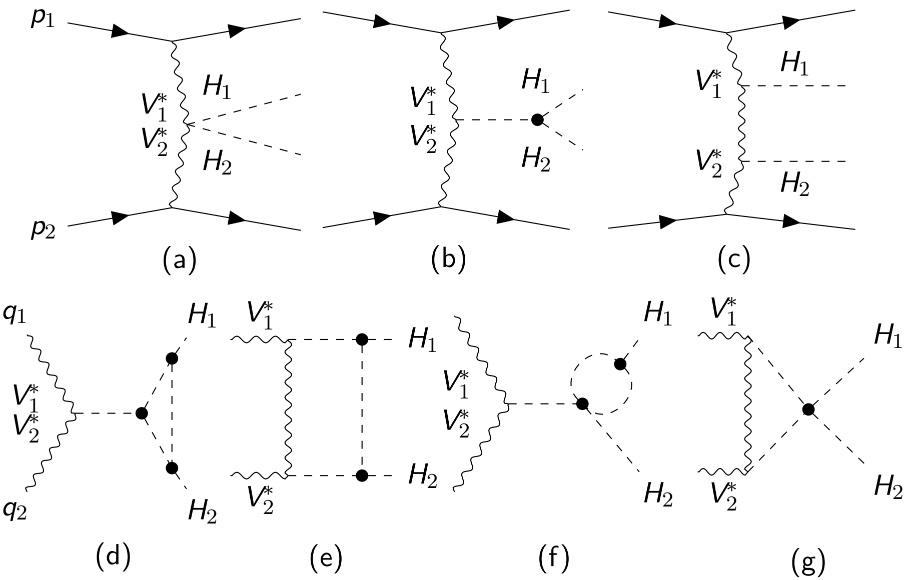
with

$$p_1^2 = p_2^2 = 0, \quad p_3^2 = p_4^2 = m_H^2, \quad s + t + u = 2m_H^2$$

tensor basis Plehn, Spira, Zerwas, 1996

$$\begin{aligned} T_1^{\mu\nu} =& g^{\mu\nu} - \frac{p_1^\nu p_2^\mu}{p_1 \cdot p_2} \\ T_2^{\mu\nu} =& g^{\mu\nu} + \frac{1}{p_T^2 (p_1 \cdot p_2)} \{ m_H^2 p_1^\nu p_2^\mu - 2(p_1 \cdot p_3) p_3^\nu p_2^\mu - 2(p_2 \cdot p_3) p_3^\mu p_1^\nu \\ & + 2(p_1 \cdot p_2) p_3^\nu p_3^\mu \} \end{aligned}$$

NLO EW corrections: VBF part



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Numerical results

Input parameters:
$m_H = 125$ GeV, $m_t = 173$ GeV, $v = (\sqrt{2}G_F)^{-1/2}$,
$G_F = 1.16637 \times 10^{-5}\ \mathrm{GeV}^{-2}$, $m_W = 80.379$ GeV, $m_Z = 91.1876$ GeV
ggF: $\mu_R = \mu_F = m_{HH}/2$
VBF: $\mu_R = \mu_F = \sqrt{-q_i^2}$, q_i is the four-momentum of the vector boson V
PDF: PDF4LHC15_nlo_100_pdfas

ggF: We set the two-dimensional grid as a function of the Higgs velocity β and $\cos\theta$ with θ the scattering angle, then we use the Lagrange interpolation to calculate the cross-section.

VBF: QCDLoop Ellis, Zanderighi, 2008
proVBFHH Dreyer, Karlberg, 2018

Numerical results

At the 13 TeV LHC,

$$\sigma^{\kappa_\lambda}_{\mathrm{ggF,LO}} = (\ 4.72\ \kappa^2_{\lambda_{3H}} - 23.0\ \kappa_{\lambda_{3H}} + 35.0\ )\ \ \mathrm{fb}$$

$$\sigma^{\kappa_\lambda}_{\mathrm{ggF,NNLO-FT}} = (\ 10.8\ \kappa^2_{\lambda_{3H}} - 49.6\ \kappa_{\lambda_{3H}} + 70.0\ )\ \ \mathrm{fb}$$

Di Micco, Schaarschmidt, 2019

$$\sigma^{\kappa_\lambda}_{\mathrm{VBF,LO}} = (\ 1.24\ \kappa^2_{\lambda_{3H}} - 4.03\ \kappa_{\lambda_{3H}} + 4.49\ )\ \ \mathrm{fb}$$

$$\sigma^{\kappa_\lambda}_{\mathrm{VBF,N3LO}} = (\ 1.22\ \kappa^2_{\lambda_{3H}} - 3.95\ \kappa_{\lambda_{3H}} + 4.43\ )\ \ \mathrm{fb}$$

The EW corrections that contain higher power dependence on the Higgs self-coupling are given by

$$\delta\sigma^{\kappa_\lambda}_{\mathrm{ggF,EW}} = (0.075\kappa^4_{\lambda_{3H}} - 0.158\kappa^3_{\lambda_{3H}} - 0.006\kappa^2_{\lambda_{3H}}\kappa_{\lambda_{4H}} - 0.058\kappa^2_{\lambda_{3H}} + 0.070\kappa_{\lambda_{3H}}\kappa_{\lambda_{4H}} - 0.149\kappa_{\lambda_{4H}})\ \ \mathrm{fb}$$

$$\delta\sigma^{\kappa_\lambda}_{\mathrm{VBF,EW}} = (0.0215\kappa^4_{\lambda_{3H}} - 0.0324\kappa^3_{\lambda_{3H}} - 0.0019\kappa^2_{\lambda_{3H}}\kappa_{\lambda_{4H}} - 0.0043\kappa^2_{\lambda_{3H}} + 0.0151\kappa_{\lambda_{3H}}\kappa_{\lambda_{4H}} - 0.0211\kappa_{\lambda_{4H}})\ \ \mathrm{fb}$$

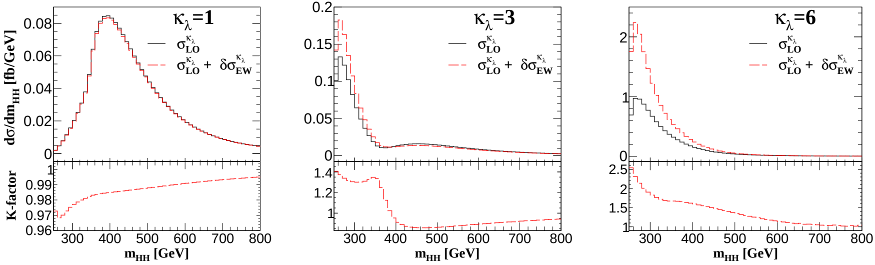
Numerical results

$\kappa_{\lambda_{3H}}$	$\kappa_{\lambda_{4H}}$	ggF			VBF		
		$\sigma_{\mathrm{LO}}^{\kappa_\lambda}$	$\sigma_{\mathrm{NNLO-FT}}^{\kappa_\lambda}$	$\delta\sigma_{\mathrm{EW}}^{\kappa_\lambda}$	$\sigma_{\mathrm{LO}}^{\kappa_\lambda}$	$\sigma_{\mathrm{NNNLO}}^{\kappa_\lambda}$	$\delta\sigma_{\mathrm{EW}}^{\kappa_\lambda}$
1	1	16.7	31.2	-0.225	1.71	1.69	-2.30×10^{-2}
3	1	8.59	18.4	1.28	3.59	3.53	8.35×10^{-1}
6	1	67.3	161	60.6	25.1	24.6	20.7
1	3	16.7	31.2	-0.393	1.71	1.69	-3.89×10^{-2}
1	6	16.7	31.2	-0.646	1.71	1.69	-6.27×10^{-2}
3	3	8.59	18.4	1.30	3.59	3.53	8.50×10^{-1}
6	6	67.3	161	61.0	25.1	24.6	20.7

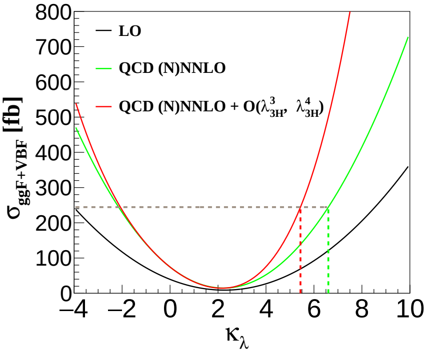
Cross sections (in fb) of ggF and VBF Higgs boson pair production.

Numerical results

The distributions of Higgs pair invariant mass in the ggF and VBF channels, at LO and with $\delta\sigma_{\rm EW}^{\kappa_\lambda}$ corrections at the 13 TeV LHC. We have used $\kappa_{\lambda_{3\rm H}} = \kappa_{\lambda_{4\rm H}} = \kappa_\lambda$.



Numerical results



The upper limit of $\kappa_{\lambda_{3H}}$ by the ATLAS (CMS) collaboration is reduced from 6.6 (6.49) to 5.4 (5.37). If the scale uncertainties are considered, the upper limit spans in the range (6.5, 6.8) in the ATLAS result, which would decrease to (5.4, 5.6) after including higher power dependence. In the CMS result, the upper limit changes from (6.40, 6.67) to (5.31, 5.48).

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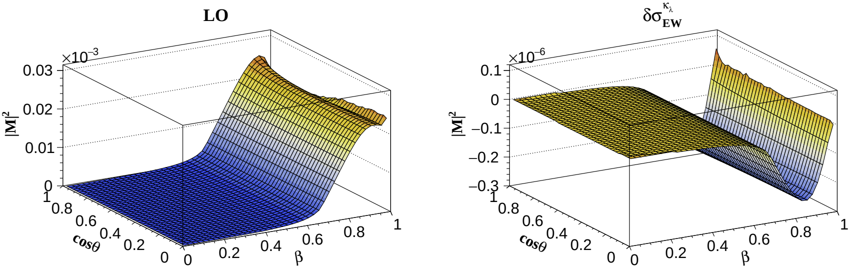
Summary

- Measuring Higgs self-couplings is of great importance.
- We find that the function form of the cross section should be generalized to include quartic and cubic dependence on the self-coupling instead of just quadratic dependence.
- With this refined functional form, we demonstrate that the upper limit on the trilinear Higgs self-coupling normalized by the SM value is reduced from 6.6 (by ATLAS) and 6.49 (by CMS) to 5.4 and 5.37, respectively.

Backup



The LO squared amplitudes (left) and λ dependent EW corrections (right).

Baglio, Campanario, Spira et al, 2020

If the scale uncertainties are considered, with $\mu_{R,F} = \xi \times m_{HH}/2$, $\xi \in \{0.5, 2\}$. At the 13 TeV LHC, when $\xi = 0.5$, we have

$$\sigma^{\kappa_\lambda}_{\rm ggF,LO} = (\ 5.96\ \kappa^2_{\lambda_{\rm 3H}} - 29.2\ \kappa_{\lambda_{\rm 3H}} + 44.7\ )\ \ {\rm fb}$$

$$\sigma^{\kappa_\lambda}_{\rm ggF,NNLO-FT} = (\ 11.5\ \kappa^2_{\lambda_{\rm 3H}} - 51.8\ \kappa_{\lambda_{\rm 3H}} + 72.1\ )\ \ {\rm fb}$$

$$\delta\sigma^{\kappa_\lambda}_{\rm ggF,EW} = (0.093\kappa^4_{\lambda_{\rm 3H}} - 0.197\kappa^3_{\lambda_{\rm 3H}} - 0.007\kappa^2_{\lambda_{\rm 3H}}\kappa_{\lambda_{\rm 4H}} - 0.078\kappa^2_{\lambda_{\rm 3H}} + 0.088\kappa_{\lambda_{\rm 3H}}\kappa_{\lambda_{\rm 4H}} - 0.188\kappa_{\lambda_{\rm 4H}})\ \ {\rm fb}$$

$$\sigma^{\kappa_\lambda}_{\rm VBF,LO} = (\ 1.32\ \kappa^2_{\lambda_{\rm 3H}} - 4.30\ \kappa_{\lambda_{\rm 3H}} + 4.83\ )\ \ {\rm fb}$$

$$\sigma^{\kappa_\lambda}_{\rm VBF,N3LO} = (\ 1.22\ \kappa^2_{\lambda_{\rm 3H}} - 3.95\ \kappa_{\lambda_{\rm 3H}} + 4.42\ )\ \ {\rm fb}$$

$$\delta\sigma^{\kappa_\lambda}_{\rm VBF,EW} = (0.0226\kappa^4_{\lambda_{\rm 3H}} - 0.0336\kappa^3_{\lambda_{\rm 3H}} - 0.0019\kappa^2_{\lambda_{\rm 3H}}\kappa_{\lambda_{\rm 4H}} - 0.0054\kappa^2_{\lambda_{\rm 3H}} + 0.0154\kappa_{\lambda_{\rm 3H}}\kappa_{\lambda_{\rm 4H}} - 0.0220\kappa_{\lambda_{\rm 4H}})\ \ {\rm fb}$$

Backup

when $\xi = 2$, we have

$$\sigma^{\kappa_\lambda}_{\rm ggF,LO} = (\ 3.79\ \kappa^2_{\lambda_{\rm 3H}} - 18.4\ \kappa_{\lambda_{\rm 3H}} + 27.8\ )\ \ {\rm fb}$$

$$\sigma^{\kappa_\lambda}_{\rm ggF,NNLO-FT} = (\ 10.2\ \kappa^2_{\lambda_{\rm 3H}} - 46.8\ \kappa_{\lambda_{\rm 3H}} + 66.1\ )\ \ {\rm fb}$$

$$\delta\sigma^{\kappa_\lambda}_{\rm ggF,EW} = (0.060\kappa^4_{\lambda_{\rm 3H}} - 0.128\kappa^3_{\lambda_{\rm 3H}} - 0.005\kappa^2_{\lambda_{\rm 3H}}\kappa_{\lambda_{\rm 4H}} - 0.044\kappa^2_{\lambda_{\rm 3H}} + 0.057\kappa_{\lambda_{\rm 3H}}\kappa_{\lambda_{\rm 4H}} - 0.120\kappa_{\lambda_{\rm 4H}})\ \ {\rm fb}$$

$$\sigma^{\kappa_\lambda}_{\rm VBF,LO} = (\ 1.17\ \kappa^2_{\lambda_{\rm 3H}} - 3.80\ \kappa_{\lambda_{\rm 3H}} + 4.20\ )\ \ {\rm fb}$$

$$\sigma^{\kappa_\lambda}_{\rm VBF,N3LO} = (\ 1.22\ \kappa^2_{\lambda_{\rm 3H}} - 3.96\ \kappa_{\lambda_{\rm 3H}} + 4.43\ )\ \ {\rm fb}$$

$$\delta\sigma^{\kappa_\lambda}_{\rm VBF,EW} = (0.0204\kappa^4_{\lambda_{\rm 3H}} - 0.0312\kappa^3_{\lambda_{\rm 3H}} - 0.0017\kappa^2_{\lambda_{\rm 3H}}\kappa_{\lambda_{\rm 4H}} - 0.0029\kappa^2_{\lambda_{\rm 3H}} + 0.0140\kappa_{\lambda_{\rm 3H}}\kappa_{\lambda_{\rm 4H}} - 0.0198\kappa_{\lambda_{\rm 4H}})\ \ {\rm fb}$$

The distributions of ggF (upper) and VBF (lower) channels