Partial NLO electroweak corrections to Higgs pair production in gluon fusion

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Table of Contents

Table of Contents

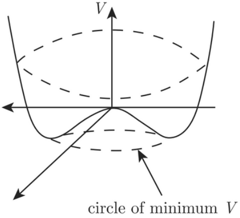
Higgs self-coupling λ

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

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



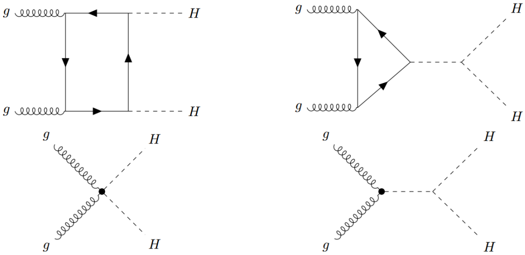
After spontaneous symmetry breaking

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

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

Higgs pair production

At the LHC, $\sqrt{s}$ =14TeV,
trilinear coupling: $pp \to HH$, 33fb (see ZhaoDan's talk)
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, because the EW corrections are more difficult to compute and its contributions are estimated to be small, only a few percent.
Calculation methods: full top mass dependence, heavy top limit (HTL)



QCD corrections in HTL

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
N^{3}LO	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$	$220.2^{+0.53\%}_{-2.4\%}$	$4439^{+0.51\%}_{-1.8\%}$

87%

18%

3%

Chen, Li, Shao, Wang, 2020

N^{3}LO corrections are of the same order of magnitude as the NLO EW corrections.

Higgs pair production

HTL:

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

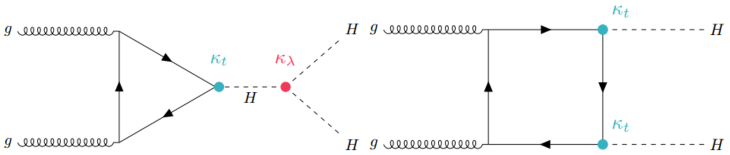
full top mass dependence:

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

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.



$$\kappa_\lambda = \frac{\lambda_{\mathrm{HHH}}}{\lambda_{\mathrm{HHH,SM}}}$$

$-1.24 < \kappa_\lambda < 6.49$ CMS, 2022

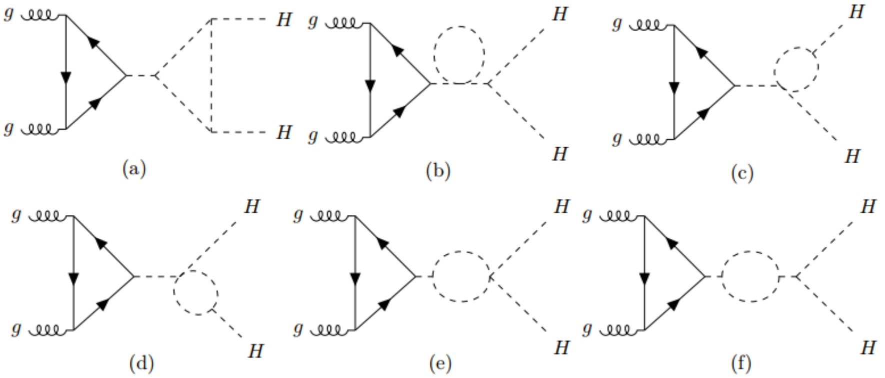
$-0.4 < \kappa_\lambda < 6.3$ ATLAS, 2022

$$\sigma = \mathrm{c}_0 \times \lambda^0 + \mathrm{c}_1 \times \lambda^1 + \mathrm{c}_2 \times \lambda^2$$
$$+ \mathrm{c}_3 \times \lambda^1 + \mathrm{c}_4 \times \lambda^2 + \mathrm{c}_5 \times \lambda^3 + \mathrm{c}_6 \times \lambda^4 + \ldots$$

Although the higher-order EW corrections are suppressed, the impact of these corrections may be significant due to the large range of κ_λ.

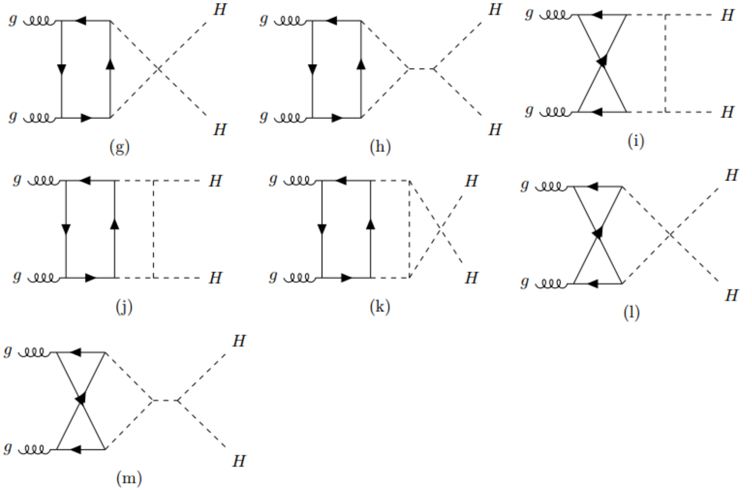
Table of Contents

NLO diagrams: Higgs-Higgs reducible part



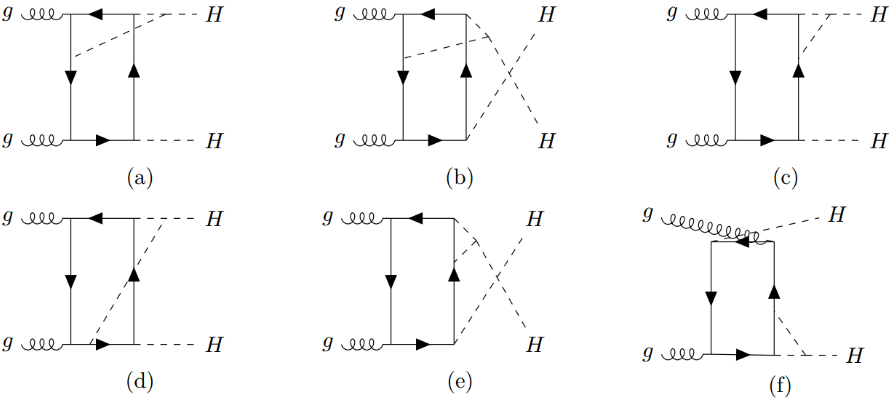
The sum of reducible diagrams contains divergences, which can be canceled by 3-Higgs vertex counterterms and propagator counterterms. This can be used as a check for these calculations.

NLO diagrams: Higgs-Higgs irreducible part



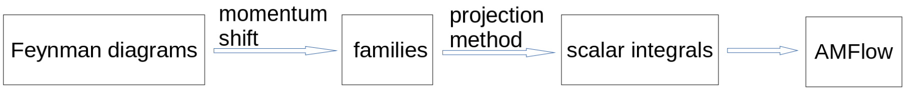
These diagrams are separately divergent, but their sum is finite.

NLO diagrams: Higgs-Yukawa part



Each of these Feynman diagrams is finite.

Calculation methods



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

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

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

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

Table of Contents

Numerical results

Input parameters:
$m_H = 125$GeV, $m_t = 173.05$GeV, $v = 246.22$GeV
$\mu_R = \mu_F = m_{HH}/2$
PDF: $\mathrm{PDF4LHC15\_nlo\_100\_pdfas}$

Scalar integrals are calculated by AMFlow. Liu, Ma, 2022
We calculated the squared matrix-element at some phase points, then we used the Lagrange interpolation to calculate the cross-section.

For the LO cross-section, we compared the results with those calculated by OpenLoops and found them to be consistent, with a difference of 10^{-4}.
Buccioni, Lang, Lindert, Maierhöfer et al, 2019

Numerical results: Higgs-Higgs part

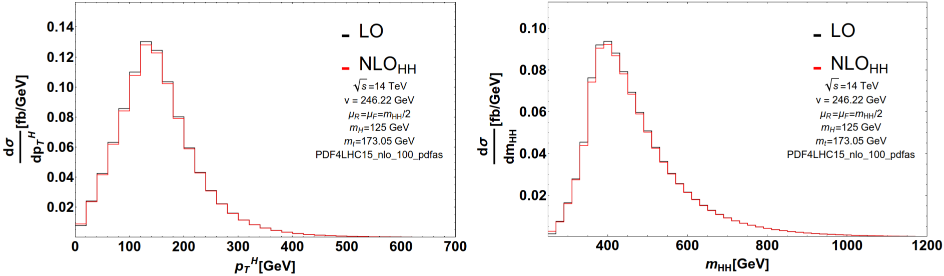
Cross-section:

LO: 19.86 fb

$\delta_{\mathrm{NLO\_HH}} = -0.2784$ fb

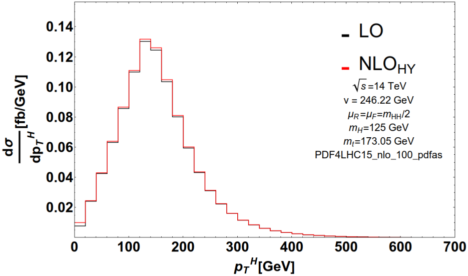
$\mathrm{NLO}_{\mathrm{HH}}$: 19.58 fb

$\delta_{\mathrm{NLO\_HH}}/\mathrm{LO} = -1.4\%$



Numerical results: Higgs-Yukawa part

$\delta_{\mathrm{NLO\_HY}} = 0.2578$ fb
$\mathrm{NLO_{HY}}$: 20.11 fb
$\delta_{\mathrm{NLO\_HY}}/\mathrm{LO} = 1.3\%$



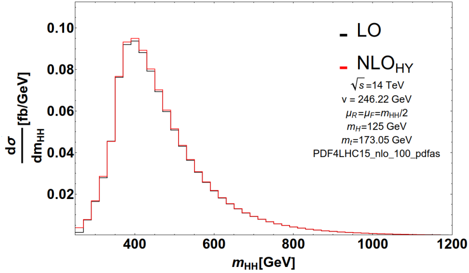


Table of Contents

Summary

- Measuring Higgs self-couplings is of great importance.
- Trilinear Higgs self coupling can be probed through Higgs boson pair production, the dominant mode is ggF. Because the $\mathrm{N^3LO}$ QCD corrections are of the same order of magnitude as the NLO EW corrections, and the range of κ_λ is large, we need to consider the EW corrections.
- We computed partial NLO EW corrections and presented the cross-sections for two types of Feynman diagrams, as well as the differential cross-sections with respect to m_{HH} and Higgs p_t. The contribution of Higgs-Higgs type diagrams is -1.4%, and the contribution of Higgs-Yukawa type diagrams is 1.3%, making the NLO EW corrections proportional to λ very small.

Thank you!