

# Partial NLO electroweak corrections to Higgs pair production in gluon fusion

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# Table of Contents

- 1 Introduction
- 2 Calculation methods
- 3 Numerical results
- 4 Summary

# Table of Contents

1 Introduction

2 Calculation methods

3 Numerical results

4 Summary

# Higgs self-coupling $\lambda$

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

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

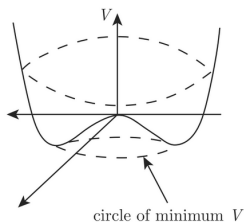
with

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

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,  $\sqrt{s} = 14\text{TeV}$ ,

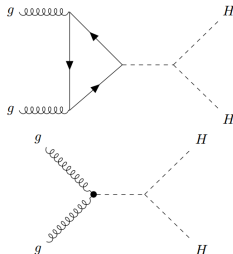
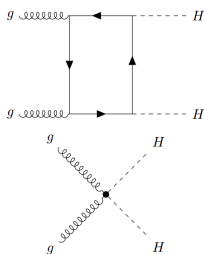
trilinear coupling:  $pp \rightarrow HH$ , 33fb (see Dan Zhao's talk)

quartic coupling:  $pp \rightarrow HHH$ , 0.09fb [Maltoni, Vryonidou, Zaro, 2014](#)

Higgs pair production modes: ggF (dominant), VBF,  $t\bar{t}HH$ , VHH

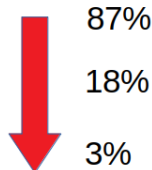
A lot of higher-order corrections have been computed, mainly in the QCD part, because the EW corrections are more difficult to compute and its contributions are estimated to be small, only a few percent.

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 <sup>+31%</sup> <sub>-22%</sub>	17.06 <sup>+31%</sup> <sub>-22%</sub>	98.22 <sup>+26%</sup> <sub>-19%</sub>	2015 <sup>+19%</sup> <sub>-15%</sub>
NLO	25.81 <sup>+18%</sup> <sub>-15%</sub>	31.89 <sup>+18%</sup> <sub>-15%</sub>	183.0 <sup>+16%</sup> <sub>-14%</sub>	3724 <sup>+13%</sup> <sub>-11%</sub>
NNLO	30.41 <sup>+5.3%</sup> <sub>-7.8%</sub>	37.55 <sup>+5.2%</sup> <sub>-7.6%</sub>	214.2 <sup>+4.8%</sup> <sub>-6.7%</sub>	4322 <sup>+4.2%</sup> <sub>-5.3%</sub>
N <sup>3</sup> LO	31.31 <sup>+0.66%</sup> <sub>-2.8%</sub>	38.65 <sup>+0.65%</sup> <sub>-2.7%</sub>	220.2 <sup>+0.53%</sup> <sub>-2.4%</sub>	4439 <sup>+0.51%</sup> <sub>-1.8%</sub>



Chen, Li, Shao, Wang, 2020

N<sup>3</sup>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](#)

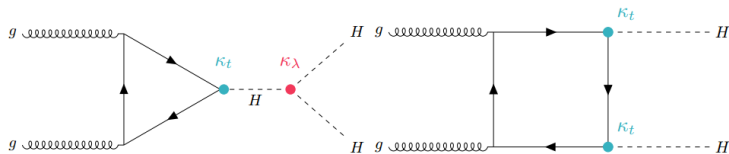
Higgs boson exchange in the top quark loop: [Davies, Mishima, Schönwald, Steinhauser et al, 2022](#)

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  $\kappa$ , are used in particle physics to quantify the deviations from the SM predictions for the interactions of fundamental particles.



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

$$-1.24 < \kappa_\lambda < 6.49 \quad \text{CMS, 2022}$$

$$-0.4 < \kappa_\lambda < 6.3 \quad \text{ATLAS, 2022}$$

$$\begin{aligned} \sigma = & c_0 \times \lambda^0 + c_1 \times \lambda^1 + c_2 \times \lambda^2 \\ & + c_3 \times \lambda^1 + c_4 \times \lambda^2 + c_5 \times \lambda^3 + c_6 \times \lambda^4 + \dots \end{aligned}$$

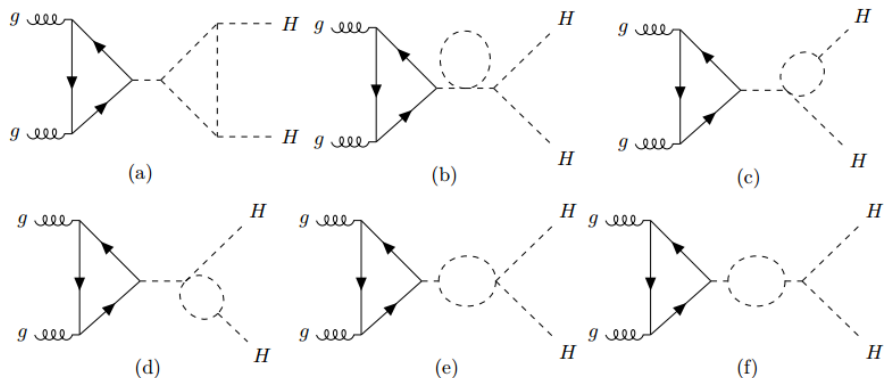
Although the higher-order EW corrections are suppressed, the impact of these corrections may be significant due to the large range of  $\kappa_\lambda$ .



# Table of Contents

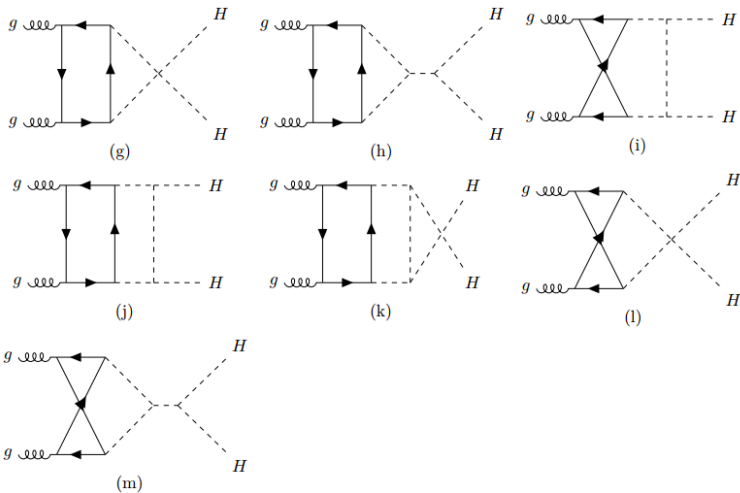
- 1 Introduction
- 2 Calculation methods**
- 3 Numerical results
- 4 Summary

# NLO diagrams: Higgs-Higgs reducible part



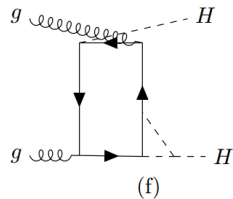
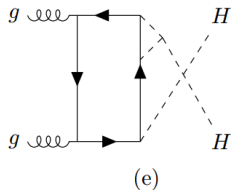
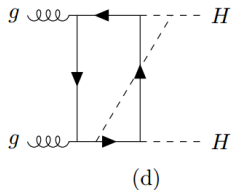
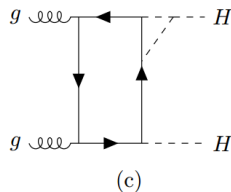
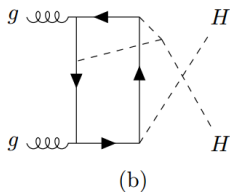
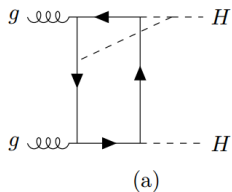
The sum of reducible diagrams contains divergences, which can be canceled by 3-Higgs vertex counterterms and propagator counterterms. This can be used as a check for these calculations.

# NLO diagrams: Higgs-Higgs irreducible part



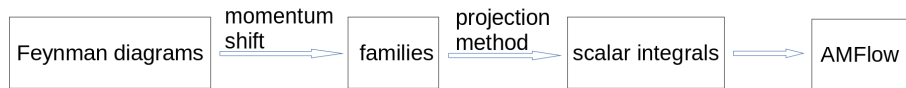
These diagrams are separately divergent, but their sum is finite.

# NLO diagrams: Higgs-Yukawa part



Each of these Feynman diagrams is finite.

# Calculation methods



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

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

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](#)

$$T_1^{\mu\nu} = g^{\mu\nu} - \frac{p_1^\nu p_2^\mu}{p_1 \cdot p_2}$$

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

# Table of Contents

- 1 Introduction
- 2 Calculation methods
- 3 Numerical results**
- 4 Summary

# Numerical results

Input parameters:

$$m_H = 125\text{GeV}, m_t = 173.05\text{GeV}, v = 246.22\text{GeV}$$

$$\mu_R = \mu_F = m_{HH}/2$$

PDF: 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  $10^{-3}$ .

[Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, Zhang, Zoller, 2019](#)

# Numerical results: Higgs-Higgs part

Preliminary results:

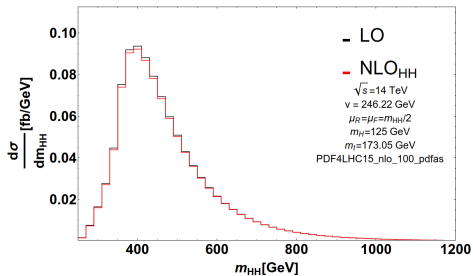
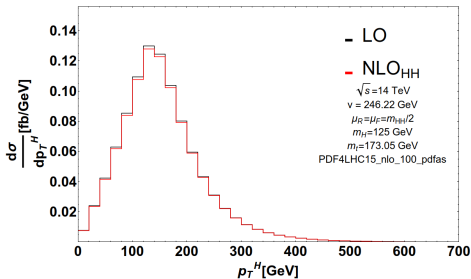
cross-section:

LO: 19.82 fb

$\delta_{\text{NLO}_{\text{HH}}} = -0.2777 \text{ fb}$

NLO<sub>HH</sub>: 19.54 fb

$\delta_{\text{NLO}_{\text{HH}}}/\text{LO} = -1.4\%$



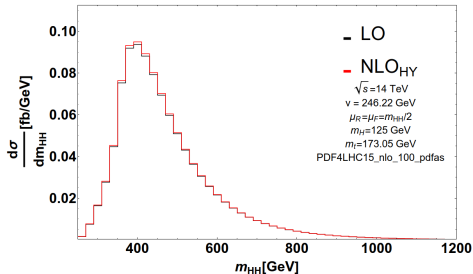
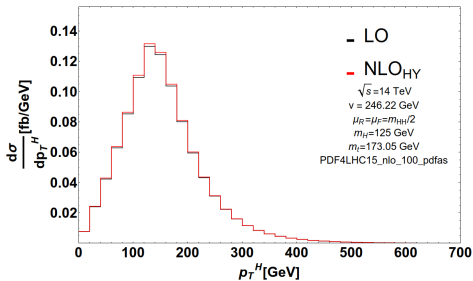


# Numerical results: Higgs-Yukawa part

$$\delta_{\text{NLO}_{\text{HY}}} = 0.2334 \text{ fb}$$

$$\text{NLO}_{\text{HY}}: 20.06 \text{ fb}$$

$$\delta_{\text{NLO}_{\text{HY}}}/\text{LO} = 1.2\%$$



# Table of Contents

- 1 Introduction
- 2 Calculation methods
- 3 Numerical results
- 4 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 N<sup>3</sup>LO QCD corrections are of the same order of magnitude as the NLO EW corrections, and the range of  $\kappa_\lambda$  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  $p_t$ . Preliminary results show that the contribution of Higgs-Higgs type diagrams is  $-1.4\%$ , and the contribution of Higgs-Yukawa type diagrams is  $1.2\%$ , making the NLO EW corrections proportional to  $\lambda$  very small.