PROCEEDINGS OF SCIENCE

Higgs Self-Coupling and Yukawa Corrections to Higgs Boson Pair Production

Matthias Kerner[a,*]

[a]*Institute for Theoretical Physics, Karlsruhe Institute of Technology (KIT), 76128 Karlsruhe, Germany*

E-mail: matthias.kerner@kit.edu

We present a calculation of the Higgs Self-Coupling and Yukawa Corrections, contributing to the electroweak NLO corrections to Higgs boson pair production. The two-loop integrals are calculated numerically with pySecDec and we show how the choice of master integrals influences the evaluation time of the amplitude. The renormalization of our model, which is obtained from the SM by including only the top quark, Higgs boson and gluon fields, is discussed.

Loops and Legs in Quantum Field Theory (LL2024)
14-19, April, 2024
Wittenberg, Germany

*Speaker

https://pos.sissa.it/

PoS(LL2024)016

1. Introduction

The production of Higgs boson pairs is the prime process to constrain the trilinear Higgs coupling λ_{HHH} and it will allow to shrink the current limits [1, 2] obtained by the ATLAS and CMS collaboration to $0.1 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 2.3$ at the high-luminosity LHC [3].

Reaching these limits also requires accurate theoretical predictions and therefore higher-order corrections to the process $gg \to HH$, which has first been calculated at Leading Order (LO) in Refs. [4, 5], need to be included. The Next-to-Leading Order (NLO) QCD corrections including the full top-quark mass dependence have been obtained in Refs. [6–10] and matched to parton showers [11–14]. QCD corrections beyond NLO have been calculated in the heavy-top-limit [15–17], or in a combination of large-m_t and high-energy expansions [18], and combined with the top-mass effects at NLO in Refs. [19–22]. Reducing the large top-mass renormalisation scheme uncertainty [14, 23] of about 20% at NLO, requires the calculation of the top-mass effects at NNLO. First contributions to these three-loop contributions have been calculated recently [24–26].

In addition to higher-order QCD predictions, NLO electroweak (EW) predictions are required for accurate predictions. Various groups have calculated parts of the NLO EW corrections [27–34]. The full NLO EW corrections have been presented in Ref. [35], and in Ref. [36] using a large top-quark mass expansion up to $1/m_t^8$.

In this contribution, the calculation of the EW contributions resulting from Higgs Self-Coupling and Yukawa corrections, presented in Ref. [32], is summarized.

2. Model and Renormalisation

To calculate the Higgs Self-Coupling and Yukawa corrections to the process $gg \to HH$ at NLO, we use the gaugeless limit $(g, g') \to (0, 0)$ of the Standard Model and we only consider contributions of the Higgs field, top-quark and gluons. We therefore start from the bare Lagrangian

$$\begin{aligned}\mathcal{L}_0 =& -\frac{1}{4}\mathcal{G}_{0,\mu\nu}\mathcal{G}_0^{\mu\nu} + (D_\mu\Phi_0)^\dagger(D^\mu\Phi_0) + \mu^2\Phi_0^\dagger\Phi_0 + \frac{\lambda_0}{4}(\Phi_0^\dagger\Phi_0)^2 \\ &+ i\bar{Q}_{L,0}\not{D}Q_{L,0} + i\bar{t}_{R,0}\not{D}t_{R,0} - (y_{t,0}\bar{Q}_{L,0}\Phi_0^c t_{R,0} + \text{h.c.}),\end{aligned} \tag{1}$$

with

$$Q_{L,0} = \begin{pmatrix} t_{L,0} \\ 0 \end{pmatrix}, \tag{2}$$

After symmetry breaking and using unitary gauge, this leads to

$$\begin{aligned}=& -\frac{1}{4}\mathcal{G}_{0,\mu\nu}\mathcal{G}_0^{\mu\nu} + \frac{1}{2}(\partial_\mu H_0)^\dagger(\partial^\mu H_0) - \frac{m_{H,0}^2}{2}H_0^2 - \frac{m_{H,0}^2}{2v_0}H_0^3 - \frac{m_{H,0}^2}{8v_0^2}H_0^4 \\ &+ i\bar{t}_0\not{D}t_0 - m_{t,0}\bar{t}_0t_0 - \frac{m_{t,0}}{v_0}H_0\bar{t}_0t_0 + \text{constant}\end{aligned} \tag{3}$$

with

$$m_{H,0}^2 = 2\mu_0^2\,,\ m_{t,0} = \frac{y_{t,0}v_0}{\sqrt{2}} \quad \text{and} \quad v_0^2 = -\frac{2m_{H,0}^2}{\lambda_0}\,. \tag{4}$$

The bare fields and masses of the top quark and Higgs boson can be related to renormalized quantities via

$$H_0 = \sqrt{Z_H} H = \sqrt{1+\delta_H} H, \qquad t_0 = \sqrt{Z_t} t = \sqrt{1+\delta_t} t, \tag{5}$$

$$m^2_{H,0} = m^2_H (1+\delta m^2_H), \qquad m_{t,0} = m_t (1+\delta m_t) \tag{6}$$

and we fix the renormalization constants using the on-shell scheme. The inverse of v_0 can be interpreted as the coupling constant of our model. It can be renormalized via

$$v_0 + \Delta v = v(1+\delta_v) + \Delta v, \tag{7}$$

where we also absorb a shift Δv due to tadpole contributions using the Fleischer-Jegerlehner tadpole scheme [37]. To facilitate comparison of our results with other calculations, we fix δ_v according to the G_μ scheme [38]. Alternatively, it could be fixed by requiring finiteness of the renormalized vertices, leading to

$$\delta_v|_{\text{UV}} = -\frac{3m_H^4 + 2m_H^2 m_t^2 N_c - 8m_t^4 N_c}{32\pi^2 m_H^2 v^2 \epsilon} \tag{8}$$

in all cases. This, however, would not uniquely fix the finite terms of δ_v.

3. Calculation

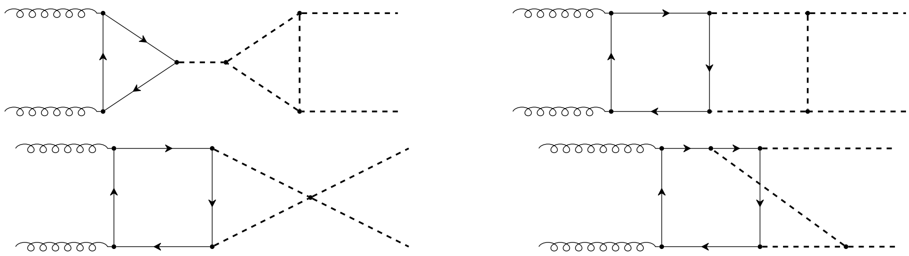

Figure 1: Representative two-loop diagrams contributing to the Higgs Self-Coupling and Yukawa Corrections considered here.

To calculate the amplitude, we first generate the Feynman diagrams using QGRAF [39]. Some example diagrams are shown in Fig. 1. We generate a form factor decomposition of the amplitude using ALIBRARY [40] and checked the resulting expressions with an independent calculation using REDUZE 2 [41] and find full agreement.

We then reduce the loop integrals to a basis of master integrals using RATRACER [42] and FIREFLY [43, 44] with integration-by-parts identities [45] generated by KIRA [46, 47]. Testing different choices for the master integral basis, we find a basis a finite integrals [48], where the dependence on the space-time dimension D factorizes from the kinematic dependence in the denominators of the reduction [49, 50], and furthermore, the top-level (7-propagator) integrals, as well as most of the 6-propagator integrals, don't contribute to the poles of the amplitude.

The master integrals are then evaluated numerically using PYSECDEC [51–54] to obtain the amplitude. For the bulk of phase-space points, we find that evaluating the loop integrals takes approximately five minutes on four Nvidia A100 GPUs to reach our target relative precision of 10^{-3} on the amplitude. It is worth mentioning that with an earlier, non-optimal choice of master integral basis, the integration time was typically $O(100\text{h})$ and hence finding a good basis is crucial to obtain a fast evaluation of the amplitude.

No real radiation contributions have to be taken into account, since in our approximation, these correction would involve the radiation of an additional Higgs boson, which can be experimentally distinguished from the HH final state.

4. Results

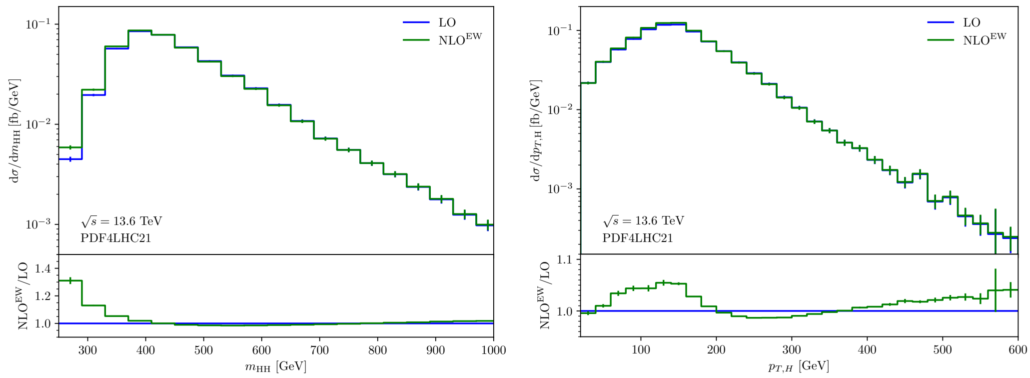

Figure 2: Invariant mass and transverse momentum distributions for Higgs boson pair production at LO and NLO$^{\text{EW}}$ including only the Yukawa and self-coupling type corrections. The QCD renormalisation and factorisation scales are set to $\mu_r = \mu_f = m_{HH}/2$.

To obtain the total and differential cross section, we reweight ~7000 unweighted LO eventss with the NLO$^{\text{EW}}$ contribution obtained from the virtual two-loop amplitude. For the LHC at a center-of-mass energy of $\sqrt{s} = 13.6\,\text{TeV}$ we find that the NLO$^{\text{EW}}$ corrections increase the cross total section by 1%. Differential results for the m_{HH} and $p_{T,H}$ distribution are shown in Fig. 2. For the m_{HH} distribution, we find corrections of up to 15% close to the production threshold, whereas for $m_{HH} > 400\,\text{GeV}$ the corrections decrease to the ±1% level. In the $p_{T,H}$ spectrum, we find a strong phase-space dependence with corrections of up to 5%.

5. Conclusion

We have presented a calculation of the subset of EW corrections to Higgs boson pair production stemming from additional Yukawa or Higgs self-interactions. The integrals appearing in the two-loop amplitude have been calculated numerically with pySecDec, after selecting a basis of finite master integrals, which avoids poles in the coefficients of the top-level integrals. We find that the NLO$^{\text{EW}}$ corrections increase the total cross section by 1%, and on the differential level, we find up to 15% corrections close to the production threshold.

Acknowledgments

I want to thank G. Heinrich, S. Jones, T. Stone and A. Vestner for the good collaboration. This research was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through grant 396021762 - TRR 257.

References

[1] ATLAS collaboration, G. Aad et al., *Combination of searches for Higgs boson pair production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, 2406.09971.

[2] CMS collaboration, A. Tumasyan et al., *A portrait of the Higgs boson by the CMS experiment ten years after the discovery.*, Nature **607** (2022) 60 [2207.00043].

[3] B. D. Micco, M. Gouzevitch, J. Mazzitelli and C. Vernieri, *Higgs boson potential at colliders: Status and perspectives*, Reviews in Physics **5** (2020) 100045.

[4] O. J. P. Eboli, G. C. Marques, S. F. Novaes and A. A. Natale, *TWIN HIGGS BOSON PRODUCTION*, Phys. Lett. B **197** (1987) 269.

[5] E. W. N. Glover and J. J. van der Bij, *HIGGS BOSON PAIR PRODUCTION VIA GLUON FUSION*, Nucl. Phys. B **309** (1988) 282.

[6] S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk et al., *Higgs Boson Pair Production in Gluon Fusion at Next-to-Leading Order with Full Top-Quark Mass Dependence*, Phys. Rev. Lett. **117** (2016) 012001 [1604.06447].

[7] S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk et al., *Full top quark mass dependence in Higgs boson pair production at NLO*, JHEP **10** (2016) 107 [1608.04798].

[8] J. Baglio, F. Campanario, S. Glaus, M. Mühlleitner, M. Spira and J. Streicher, *Gluon fusion into Higgs pairs at NLO QCD and the top mass scheme*, Eur. Phys. J. C **79** (2019) 459 [1811.05692].

[9] J. Davies, G. Heinrich, S. P. Jones, M. Kerner, G. Mishima, M. Steinhauser et al., *Double Higgs boson production at NLO: combining the exact numerical result and high-energy expansion*, JHEP **11** (2019) 024 [1907.06408].

[10] J. Baglio, F. Campanario, S. Glaus, M. Mühlleitner, J. Ronca, M. Spira et al., *Higgs-Pair Production via Gluon Fusion at Hadron Colliders: NLO QCD Corrections*, JHEP **04** (2020) 181 [2003.03227].

[11] G. Heinrich, S. P. Jones, M. Kerner, G. Luisoni and E. Vryonidou, *NLO predictions for Higgs boson pair production with full top quark mass dependence matched to parton showers*, JHEP **08** (2017) 088 [1703.09252].

[12] S. Jones and S. Kuttimalai, *Parton Shower and NLO-Matching uncertainties in Higgs Boson Pair Production*, *JHEP* **02** (2018) 176 [1711.03319].

[13] G. Heinrich, S. P. Jones, M. Kerner, G. Luisoni and L. Scyboz, *Probing the trilinear Higgs boson coupling in di-Higgs production at NLO QCD including parton shower effects*, *JHEP* **06** (2019) 066 [1903.08137].

[14] E. Bagnaschi, G. Degrassi and R. Gröber, *Higgs boson pair production at NLO in the POWHEG approach and the top quark mass uncertainties*, 2309.10525.

[15] D. De Florian and J. Mazzitelli, *Soft gluon resummation for Higgs boson pair production including finite M_t effects*, *JHEP* **08** (2018) 156 [1807.03704].

[16] D. de Florian, M. Grazzini, C. Hanga, S. Kallweit, J. M. Lindert, P. Maierhöfer et al., *Differential Higgs Boson Pair Production at Next-to-Next-to-Leading Order in QCD*, *JHEP* **09** (2016) 151 [1606.09519].

[17] J. Grigo, J. Hoff and M. Steinhauser, *Higgs boson pair production: top quark mass effects at NLO and NNLO*, *Nucl. Phys. B* **900** (2015) 412 [1508.00909].

[18] J. Davies, F. Herren, G. Mishima and M. Steinhauser, *Real corrections to Higgs boson pair production at NNLO in the large top quark mass limit*, *JHEP* **01** (2022) 049 [2110.03697].

[19] M. Grazzini, G. Heinrich, S. Jones, S. Kallweit, M. Kerner, J. M. Lindert et al., *Higgs boson pair production at NNLO with top quark mass effects*, *JHEP* **05** (2018) 059 [1803.02463].

[20] L.-B. Chen, H. T. Li, H.-S. Shao and J. Wang, *Higgs boson pair production via gluon fusion at N^3LO in QCD*, *Phys. Lett. B* **803** (2020) 135292 [1909.06808].

[21] L.-B. Chen, H. T. Li, H.-S. Shao and J. Wang, *The gluon-fusion production of Higgs boson pair: N^3LO QCD corrections and top-quark mass effects*, *JHEP* **03** (2020) 072 [1912.13001].

[22] A. A H and H.-S. Shao, *N^3LO+N^3LL QCD improved Higgs pair cross sections*, *JHEP* **02** (2023) 067 [2209.03914].

[23] J. Baglio, F. Campanario, S. Glaus, M. Mühlleitner, J. Ronca and M. Spira, *$gg \to HH$: Combined uncertainties*, *Phys. Rev. D* **103** (2021) 056002 [2008.11626].

[24] J. Davies, K. Schönwald and M. Steinhauser, *Towards $gg \to HH$ at next-to-next-to-leading order: Light-fermionic three-loop corrections*, *Phys. Lett. B* **845** (2023) 138146 [2307.04796].

[25] J. Davies, K. Schönwald, M. Steinhauser and M. Vitti, *Three-loop corrections to Higgs boson pair production: reducible contribution*, 2405.20372.

[26] J. Davies, *Higgs pair production at NNLO*, in *Loops and Legs in Quantum Field Theory*, 7, 2024, 2407.08264.

[27] S. Borowka, C. Duhr, F. Maltoni, D. Pagani, A. Shivaji and X. Zhao, *Probing the scalar potential via double Higgs boson production at hadron colliders*, *JHEP* **04** (2019) 016 [1811.12366].

[28] W. Bizoń, U. Haisch and L. Rottoli, *Constraints on the quartic Higgs self-coupling from double-Higgs production at future hadron colliders*, *JHEP* **10** (2019) 267 [1810.04665].

[29] W. Bizoń, U. Haisch, L. Rottoli, Z. Gillis, B. Moser and P. Windischhofer, *Addendum to: Constraints on the quartic Higgs self-coupling from double-Higgs production at future hadron colliders [JHEP 10 (2019) 267]*, *JHEP* **02** (2024) 170 [2402.03463].

[30] M. Mühlleitner, J. Schlenk and M. Spira, *Top-Yukawa-induced corrections to Higgs pair production*, *JHEP* **10** (2022) 185 [2207.02524].

[31] J. Davies, G. Mishima, K. Schönwald, M. Steinhauser and H. Zhang, *Higgs boson contribution to the leading two-loop Yukawa corrections to $gg \to HH$*, *JHEP* **08** (2022) 259 [2207.02587].

[32] G. Heinrich, S. Jones, M. Kerner, T. Stone and A. Vestner, *Electroweak corrections to Higgs boson pair production: The top-Yukawa and self-coupling contributions*, 2407.04653.

[33] J. Davies, K. Schönwald, M. Steinhauser and H. Zhang, *Electroweak corrections to $gg \to HH$: Factorizable contributions*, in *Loops and Legs in Quantum Field Theory*, 7, 2024, 2407.05787.

[34] H. T. Li, Z.-G. Si, J. Wang, X. Zhang and D. Zhao, *Improved constraint on Higgs boson self-couplings with quartic and cubic power dependence in the cross section*, 2407.14716.

[35] H.-Y. Bi, L.-H. Huang, R.-J. Huang, Y.-Q. Ma and H.-M. Yu, *Electroweak Corrections to Double Higgs Production at the LHC*, *Phys. Rev. Lett.* **132** (2024) 231802 [2311.16963].

[36] J. Davies, K. Schönwald, M. Steinhauser and H. Zhang, *Next-to-leading order electroweak corrections to $gg \to HH$ and $gg \to gH$ in the large-m_t limit*, *JHEP* **10** (2023) 033 [2308.01355].

[37] J. Fleischer and F. Jegerlehner, *Radiative Corrections to Higgs Decays in the Extended Weinberg-Salam Model*, *Phys. Rev. D* **23** (1981) 2001.

[38] A. Biekötter, B. D. Pecjak, D. J. Scott and T. Smith, *Electroweak input schemes and universal corrections in SMEFT*, *JHEP* **07** (2023) 115 [2305.03763].

[39] P. Nogueira, *Automatic Feynman Graph Generation*, *J. Comput. Phys.* **105** (1993) 279.

[40] V. Magerya, "Amplitude library (Alibrary): gluing all the tools needed for computing multi-loop amplitudes in QCD and beyond." https://github.com/magv/alibrary.

[41] A. von Manteuffel and C. Studerus, *Reduze 2 - Distributed Feynman Integral Reduction*, 1201.4330.

[42] V. Magerya, *Rational Tracer: a Tool for Faster Rational Function Reconstruction*, 2211.03572.

[43] J. Klappert and F. Lange, *Reconstructing rational functions with FireFly*, *Comput. Phys. Commun.* **247** (2020) 106951 [1904.00009].

[44] J. Klappert, S. Y. Klein and F. Lange, *Interpolation of dense and sparse rational functions and other improvements in FireFly*, *Comput. Phys. Commun.* **264** (2021) 107968 [2004.01463].

[45] K. G. Chetyrkin and F. V. Tkachov, *Integration by parts: The algorithm to calculate β-functions in 4 loops*, *Nucl. Phys. B* **192** (1981) 159.

[46] P. Maierhöfer, J. Usovitsch and P. Uwer, *Kira—A Feynman integral reduction program*, *Comput. Phys. Commun.* **230** (2018) 99 [1705.05610].

[47] J. Klappert, F. Lange, P. Maierhöfer and J. Usovitsch, *Integral reduction with Kira 2.0 and finite field methods*, *Comput. Phys. Commun.* **266** (2021) 108024 [2008.06494].

[48] A. von Manteuffel, E. Panzer and R. M. Schabinger, *A quasi-finite basis for multi-loop Feynman integrals*, *Journal of High Energy Physics* **2015** (2015) .

[49] A. V. Smirnov and V. A. Smirnov, *How to choose master integrals*, *Nucl. Phys. B* **960** (2020) 115213 [2002.08042].

[50] J. Usovitsch, *Factorization of denominators in integration-by-parts reductions*, 2002.08173.

[51] S. Borowka, G. Heinrich, S. Jahn, S. P. Jones, M. Kerner, J. Schlenk et al., *pySecDec: a toolbox for the numerical evaluation of multi-scale integrals*, *Comput. Phys. Commun.* **222** (2018) 313 [1703.09692].

[52] S. Borowka, G. Heinrich, S. Jahn, S. P. Jones, M. Kerner and J. Schlenk, *A GPU compatible quasi-Monte Carlo integrator interfaced to pySecDec*, *Comput. Phys. Commun.* **240** (2019) 120 [1811.11720].

[53] G. Heinrich, S. Jahn, S. P. Jones, M. Kerner, F. Langer, V. Magerya et al., *Expansion by regions with pySecDec*, *Comput. Phys. Commun.* **273** (2022) 108267 [2108.10807].

[54] G. Heinrich, S. P. Jones, M. Kerner, V. Magerya, A. Olsson and J. Schlenk, *Numerical scattering amplitudes with pySecDec*, *Comput. Phys. Commun.* **295** (2024) 108956 [2305.19768].