PROCEEDINGS OF SCIENCE

Parton shower and finite top quark mass effects in HH production

Matthias Kerner*
Max Planck Institute for Physics, Föhringer Ring 6, 80805 München, Germany
E-mail: kerner@mpp.mpg.de

We present predictions for Higgs boson pair production at next-to-leading order in QCD matched to the PYTHIA parton shower retaining the full dependence on the top-quark mass. The contribution of the virtual amplitude, which is only known numerically, is interfaced to both the POWHEG-BOX and MADGRAPH5_AMC@NLO frameworks via a grid. We compare the results obtained in both frameworks and we discuss the effect of the top-quark mass on the level of differential cross sections.

25th International Workshop on Deep Inelastic Scattering and Related Topics
3-7 April 2017
University of Birmingham, Birmingham, UK

*Speaker.

PoS(DIS2017)297

1. Introduction

While studying pair production of Higgs bosons at the LHC is a challenging task, it is also very important for scrutinizing the mechanism of electroweak symmetry breaking, since the contributions of Higgs boson self interactions appearing in this process can be directly related to the Higgs potential. Therefore, an accurate prediction of the production cross section is required, which is dominated by the gluon fusion mechanism via a top-quark loop. In contrast to the single-Higgs case, however, the Higgs Effective Field Theory (HEFT) approach, where the limit $m_t \to \infty$ is considered, only leads to a poor description of di-Higgs production, since the majority of the cross section is obtained in the phase-space region above the production threshold for top-quark pairs.

The leading order process [1] already requires the calculation of one-loop box diagrams with internal masses, and for the next-to-leading order (NLO) corrections the evaluation of corresponding two-loop integrals is required. Since these integrals are not known analytically, only approximated NLO results were available for a long time. In Ref. [2] the NLO cross section has been calculated in the heavy top limit and rescaled by a factor of B_{FT}/B_{HEFT}, where B_{FT} and B_{HEFT} are the squared Born matrix elements in the full theory and HEFT, respectively. This approach is therefore called Born-improved (B.i.) HEFT. To include further top-quark mass effects, expansions of the NLO contributions in $1/m_T^2$ [3, 4, 5] have been performed. In Refs. [6, 7] the full top-quark mass dependence has been included in the real radiation, which will be denoted by FTapprox in the following. Furthermore, the NNLO cross section [8, 9, 4, 10] and resummation effects [11, 12] have been studied in the HEFT.

Recently, the NLO correction including the full top-mass dependence has been calculated in Refs. [13, 14] using numerical methods for the evaluation of the two-loop amplitude. This result has been combined with NLL transverse-momentum resummation in Ref. [15] and with a parton shower in Ref. [16], using both the POWHEG-BOX [17, 18] and the MADGRAPH5_AMC@NLO framework [19, 20]. In this talk, we present the results obtained in Refs. [13, 14, 16].

2. Calculation

We only outline the calculation of the virtual amplitude and the methods used to interface it to a parton shower. For more details on the calculation and on the implementation of leading order and real radiation contributions we refer to Refs. [13, 14, 16, 6, 7] and references therein.

To construct the virtual amplitude, we implemented a multi-loop extension of the program GOSAM [21, 22] to obtain algebraic expressions of the amplitude. Using the program REDUZE [23], we reduced the appearing planar integrals to a finite basis [24] of master integrals; for the non-planar integrals, however, we didn't achieve a full reduction. All integrals have been evaluated with SECDEC [25] using a quasi-Monte-Carlo algorithm [26, 27] for the numerical integration.

Since the numerical evaluation of the virtual two-loop amplitude requires a median runtime of about 2 h on a cluster, a direct interface of the amplitude to the parton shower frameworks is impracticable. We therefore constructed a two-dimensional grid in the Mandelstam variables $\hat{s}$ and $\hat{t}$ to interpolate the virtual amplitude based on 3741 precomputed results. With the variable

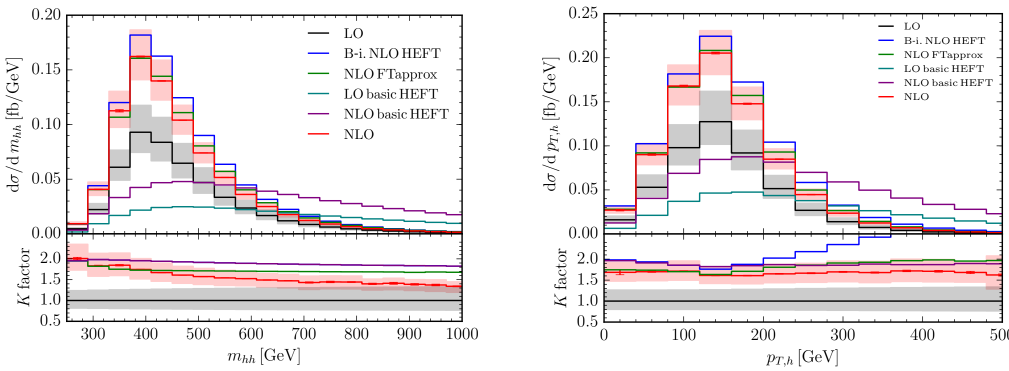

Figure 1: Fixed order distribution of the invariant mass of the Higgs boson pair and the transverse momentum of a randomly selected Higgs in the full theory and using various approximations.

transformations

$$c_\theta = |\cos\theta| = \left|\frac{\hat{s}+2\hat{t}-2m_h^2}{\hat{s}\beta(\hat{s})}\right|, \qquad x = f(\beta(\hat{s})) \quad \text{with} \quad \beta = \left(1-\frac{4m_h^2}{\hat{s}}\right)^{\frac{1}{2}}, \tag{2.1}$$

we obtain a nearly uniform distribution of phase-space points in the variables x and c_θ if the function f is chosen according to the cumulative distribution function of phase-space points. As a first interpolation step, we then define a regular grid in the new variables and estimate the amplitude results at these points via a linear interpolation of the close-by precomputed points. The so defined grid points are then used as input for the second interpolation step, where we use the python *SciPy* [28] package to perform a Clough-Tocher interpolation [29] for estimating amplitude results at arbitrary phase-space points. This two-step procedure avoids large interpolation artefacts caused by fluctuations of the precomputed results, which are only known with few percent level precision.

The grid for the virtual amplitude is then interfaced to the POWHEG-BOX and the MADGRAPH5_AMC@NLO framework where they are combined with the real emission contribution and supplemented with the PYTHIA 8 [30, 31] parton shower.

3. Results

We present results for Higgs boson pair production at the LHC with a center of mass energy of $\sqrt{s} = 14\,\text{TeV}$. We set $m_h = 125\,\text{GeV}$ and $m_t = 173\,\text{GeV}$ and we use the PDF4LHC15 [32] pdf set with the corresponding value of α_s. In Fig. 1 we present differential fixed order results. It can be seen that the pure HEFT result leads to a wrong shape of the distributions with large contributions in the high m_{hh} and $p_{T,h}$ regions and the rescaling done in the B.i. HEFT is required to obtain the correct shape of the distributions. In the high $p_{T,h}$ region, however, the B.i. HEFT prediction still shows large differences compared to the full NLO result. This difference is caused partly by an ambiguity in the mapping of real emission kinematics to corresponding Born events, such that the rescaling of the LO amplitude is not unique. Including the top-quark mass effects also in the real emission contributions (FTapprox) further improves the predictions, but still shows deviations from the full NLO result, in particular in the tail of the m_{hh} distribution.

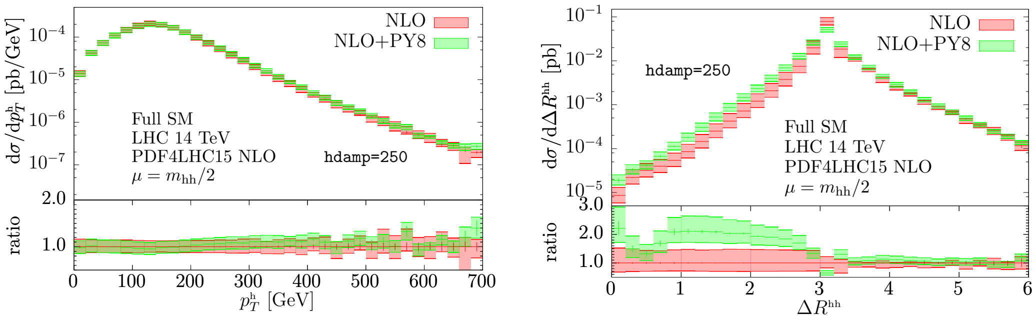

Figure 2: Effect of the parton shower on the transverse momentum of a Higgs boson and the radial separation of the two Higgs bosons.

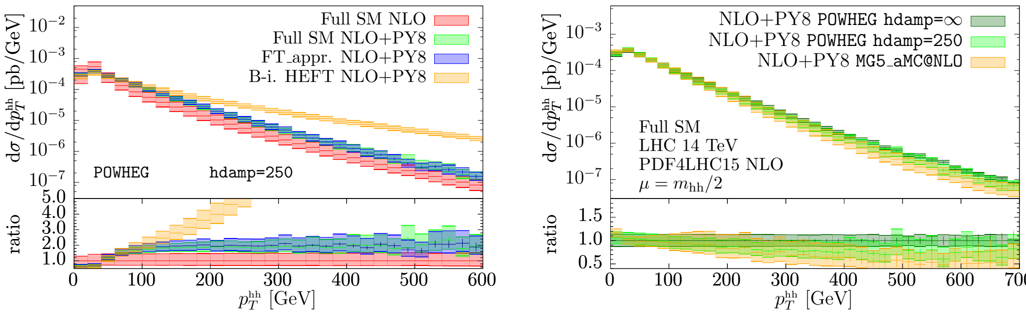

Figure 3: Parton shower effect on the transverse momentum of the di-Higgs system. The left plot shows results obtained in the full theory and various approximations. The right plot shows a comparison of POWHEG-BOX and the MG5_AMC@NLO results.

Fig. 2 shows the effect of the parton shower on the $p_{T,h}$ and ΔR_{hh} distributions using the POWHEG-BOX framework, where the real radiation R is split into a singular and a regular region according to

$$R_{sing} = R \times F, \quad R_{reg} = R \times (1-F), \qquad \text{with } F = h_{damp}^2/(p_{T,hh}^2 + h_{damp}^2), \tag{3.1}$$

and only the singular part is exponentiated in the parton shower. The parton shower enhances the tail of the $p_{T,h}$ distribution while slightly decreasing the contributions close to the peak at $p_{T,h} \approx 130\,\text{GeV}$. In the ΔR_{hh} distribution, the parton shower leads to a large enhancement in the region $\Delta R_{hh} < \pi$, which can only be filled by real radiation.

Parton shower effects of similar size are obtained in the $p_{T,hh}$ distribution shown in Fig. 3, where the tail is enhanced by a factor of 2 compared to the fixed order result when using the POWHEG method. Setting $h_{damp} = \infty$ would further enhance the tail, which can be seen in the right plot. In the MG5_AMC@NLO framework the definition of the shower starting scale changed in version 2.5.3, leading to different behaviour of the $p_{T,hh}$ distribution. While previous versions, where the scale was picked based on $\sqrt{\hat{s}}$, lead to results similar to the ones obtained with POWHEG-BOX, newer versions choose the shower starting scale based on H_T which reduces the enhancements of the tail. Since the $p_{T,hh}$ distribution is entirely generated by real radiation, the FTapprox leads to similar behaviour as the full calculation. The B.i. HEFT, however, leads to huge deviations from the full result, showing the importance of the top-mass effects in HH production.

4. Conclusions

We have presented results for Higgs boson pair production at next-to-leading order in QCD, retaining the full dependence of the top-quark mass including matching to a parton shower. The top-quark mass effects reduce the total cross section by 14% and modify the shape of distributions relative to NLO results obtained in the HEFT appoach. While we observe only a small effect of the parton shower on inclusive variables, we obtain large corrections, up to a factor of 2-3, for observables sensitive to additional radiation.

Acknowledgments

I would like to thank Sophia Borowka, Nicolas Greiner, Gudrun Heinrich, Stephen Jones, Gionata Luisoni, Johannes Schlenk, Ulrich Schubert, Eleni Vryonidou and Tom Zirke for the collaboration.

References

[1] E. W. N. Glover and J. J. van der Bij, *Higgs Boson Pair Production via Gluon Fusion*, *Nucl. Phys.* **B309** (1988) 282.

[2] S. Dawson, S. Dittmaier, and M. Spira, *Neutral Higgs boson pair production at hadron colliders: QCD corrections*, *Phys. Rev.* **D58** (1998) 115012, [hep-ph/9805244].

[3] J. Grigo, J. Hoff, K. Melnikov, and M. Steinhauser, *On the Higgs boson pair production at the LHC*, *Nucl. Phys.* **B875** (2013) 1–17, [arXiv:1305.7340].

[4] J. Grigo, J. Hoff, and M. Steinhauser, *Higgs boson pair production: top quark mass effects at NLO and NNLO*, *Nucl. Phys.* **B900** (2015) 412, [arXiv:1508.00909].

[5] G. Degrassi, P. P. Giardino, and R. GrÃűber, *On the two-loop virtual QCD corrections to Higgs boson pair production in the Standard Model*, *Eur. Phys. J.* **C76** (2016), no. 7 411, [arXiv:1603.00385].

[6] R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, P. Torrielli, E. Vryonidou, and M. Zaro, *Higgs pair production at the LHC with NLO and parton-shower effects*, *Phys. Lett.* **B732** (2014) 142–149, [arXiv:1401.7340].

[7] F. Maltoni, E. Vryonidou, and M. Zaro, *Top-quark mass effects in double and triple Higgs production in gluon-gluon fusion at NLO*, *JHEP* **11** (2014) 079, [arXiv:1408.6542].

[8] D. de Florian and J. Mazzitelli, *Two-loop virtual corrections to Higgs pair production*, *Phys. Lett.* **B724** (2013) 306–309, [arXiv:1305.5206].

[9] D. de Florian and J. Mazzitelli, *Higgs Boson Pair Production at Next-to-Next-to-Leading Order in QCD*, *Phys. Rev. Lett.* **111** (2013) 201801, [arXiv:1309.6594].

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

[11] D. Y. Shao, C. S. Li, H. T. Li, and J. Wang, *Threshold resummation effects in Higgs boson pair production at the LHC*, *JHEP* **07** (2013) 169, [arXiv:1301.1245].

[12] D. de Florian and J. Mazzitelli, *Higgs pair production at next-to-next-to-leading logarithmic accuracy at the LHC*, *JHEP* **09** (2015) 053, [arXiv:1505.07122].

[13] S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, U. Schubert, and T. Zirke, *Higgs Boson Pair Production in Gluon Fusion at Next-to-Leading Order with Full Top-Quark Mass Dependence*, *Phys. Rev. Lett.* **117** (2016), no. 1 012001, [arXiv:1604.06447]. [Erratum: Phys. Rev. Lett. 117, 079901 (2016)].

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

[15] G. Ferrera and J. Pires, *Transverse-momentum resummation for Higgs boson pair production at the LHC with top-quark mass effects*, *JHEP* **02** (2017) 139, [arXiv:1609.01691].

[16] 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*, arXiv:1703.09252.

[17] S. Frixione, P. Nason, and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070, [arXiv:0709.2092].

[18] S. Alioli, P. Nason, C. Oleari, and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043, [arXiv:1002.2581].

[19] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **1407** (2014) 079, [arXiv:1405.0301].

[20] V. Hirschi and O. Mattelaer, *Automated event generation for loop-induced processes*, *JHEP* **10** (2015) 146, [arXiv:1507.00020].

[21] G. Cullen, N. Greiner, G. Heinrich, G. Luisoni, P. Mastrolia, et al., *Automated One-Loop Calculations with GoSam*, *Eur.Phys.J.* **C72** (2012) 1889, [arXiv:1111.2034].

[22] G. Cullen et al., *GOSAM-2.0: a tool for automated one-loop calculations within the Standard Model and beyond*, *Eur. Phys. J.* **C74** (2014), no. 8 3001, [arXiv:1404.7096].

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

[24] A. von Manteuffel, E. Panzer, and R. M. Schabinger, *A quasi-finite basis for multi-loop Feynman integrals*, *JHEP* **02** (2015) 120, [arXiv:1411.7392].

[25] S. Borowka, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk, and T. Zirke, *SecDec-3.0: numerical evaluation of multi-scale integrals beyond one loop*, *Comput. Phys. Commun.* **196** (2015) 470–491, [arXiv:1502.06595].

[26] Z. Li, J. Wang, Q.-S. Yan, and X. Zhao, *Efficient Numerical Evaluation of Feynman Integral*, *Chinese Physics C* **40, No. 3** (2016) 033103, [arXiv:1508.02512].

[27] J. Dick, F. Y. Kuo, and I. H. Sloan, *High-dimensional integration: The quasi-monte carlo way*, *Acta Numerica* **22** (2013) 133–288.

[28] E. Jones, T. Oliphant, P. Peterson, et al., *SciPy: Open source scientific tools for Python*, 2001–2017. [Online; accessed 2017-03-22].

PoS(DIS2017)297

[29] R. Clough and J. Tocher, *Finite element stiffness matrices for analysis of plates in bending*, *Proceedings of Conference on Matrix Methods in Structural Analysis* (1965).

[30] T. Sjostrand, S. Mrenna, and P. Z. Skands, *A Brief Introduction to PYTHIA 8.1*, *Comput.Phys.Commun.* **178** (2008) 852–867, [arXiv:0710.3820].

[31] T. Sjostrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, *An Introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159–177, [arXiv:1410.3012].

[32] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, *J. Phys.* **G43** (2016) 023001, [arXiv:1510.03865].