Trilinear Higgs boson coupling variations for di-Higgs production with full NLO QCD predictions in Powheg

G. Heinrich[1], S. Jones[2], M. Kerner[3], G. Luisoni[1] and L. Scyboz[1]

[1] Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
[2] Theoretical Physics Department, CERN, Geneva, Switzerland
[3] Physik-Institut, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland

E-mail: gudrun@mpp.mpg.de, s.jones@cern.ch, mkerner@physik.uzh.ch, luisonig@gmail.com, scyboz@mpp.mpg.de

Abstract. The couplings of the Higgs boson to other particles are increasingly well measured by the ATLAS and CMS experiments. The Higgs boson trilinear self-coupling however is still largely unconstrained, mainly due to the low cross-section for Higgs boson pair production. We present inclusive and differential results for the NLO QCD corrections to Higgs boson pair production with the full top-quark mass dependence, where the Higgs trilinear coupling is varied to non-SM values. The calculation of the two-loop virtual contributions has been performed numerically using CPUs and GPUs. The fixed-order calculation is supplemented by parton showering within the Powheg-BOX-V2 event generator, and both Pythia8 and Herwig7 parton-shower algorithms are implemented in a preliminary study of shower effects.

1. Introduction

Impressive experimental constraints have been set on the Higgs boson couplings to vector bosons and heavy fermions [1, 2, 3, 4]. The Higgs potential, in contrast, leaves more room for New Physics. In particular, the Higgs boson trilinear self-coupling λ can be experimentally constrained by exclusion limits on Higgs boson pair production $pp \to hh$ [5, 6], where the best limit on $\kappa_\lambda = \lambda/\lambda_{\rm SM}$ is currently given by ATLAS with $-5.0 < \kappa_\lambda < 12.1$ at 95% confidence level. Higher-order corrections to Higgs pair production were first calculated in the heavy top-quark mass limit (HTL) $m_t \to \infty$, where the top-quark degrees of freedom are integrated out [7, 8, 9, 10]. The NLO QCD corrections with the full top-quark mass dependence were only computed more recently [11, 12, 13]. The latter are based on numerical evaluations of the two-loop contribution to $gg \to hh$. For non-SM values of the Higgs couplings, results were computed at NLO QCD in the full theory for a class of extensions of the SM in Ref. [14].

In the following, an implementation of the full NLO QCD corrections into the Powheg-BOX-V2 event generator [15, 16, 17] is presented. In this framework, the Higgs trilinear self-coupling can be varied, as well as the top-Higgs Yukawa coupling. Total cross sections are computed for $\sqrt{s} = 13, 14$ and $27\,\text{TeV}$ at the (HE-)LHC. Differential results are shown for $\sqrt{s} = 14\,\text{TeV}$. The fixed-order calculation is then matched to both Pythia8 [18] and Herwig7 [19, 20] parton showers. For a more detailed description, the reader is referred to Ref. [21].

2. Description of the calculation

The calculation is based on the setup presented in Ref. [22] for the case of the SM. The leading-order amplitude has been computed analytically. The real-emission contributions were implemented using an interface [23] between the `Powheg-BOX` and GoSam [24, 25], where the reduction of the one-loop amplitude has been performed with `Ninja` [26], using master integrals from `golem95C` [27, 28], `OneLOop` [29] and `VBFNLO` [30, 31]. The two-loop amplitude for the full virtual contribution was adapted from Refs. [11, 12], which used an extension of the GoSam package to two loops [32]. There, the integral reduction was performed with Reduze2 [33], and the integrals were numerically evaluated with SecDec3 [34]. For a faster convergence, the integration was performed within a Quasi-Monte-Carlo implementation using a rank-1 shifted lattice rule [35, 36]. The integrals were computed with 16 dual NVidia Tesla K20Xm GPUs. The top-quark and Higgs masses have been set to $m_t = 173$ GeV and $m_h = 125$ GeV. Thus, the integrals depend only on the two Mandelstam invariants $\hat{s}$ and $\hat{t}$.

A grid for the two-loop amplitude was constructed in both variables using 5291 pre-sampled phase-space points. We split the amplitude in two contributions: diagrams containing the trilinear Higgs coupling are called *triangle-like*, and those that do not are called *box-like* (see Fig. 1 for two diagrams at NLO).

Figure 1. Triangle-like (left) and box-like (right) diagrams contribute to the full amplitude. The former contain the Higgs self-coupling, while the latter do not.

At any order in QCD, the squared matrix-element can thus be written as a second-order polynomial in λ:

$$M_\lambda \equiv |\mathcal{M}_\lambda|^2 = \mathcal{M}_B^* \mathcal{M}_B + \lambda \left(\mathcal{M}_B^* \mathcal{M}_T + \mathcal{M}_T^* \mathcal{M}_B \right) + \lambda^2 \mathcal{M}_T^* \mathcal{M}_T \,. \tag{1}$$

The two-loop amplitude for an arbitrary value of λ can be reconstructed from the squared matrix-element computed for three different values of λ. In our case, we chose $\kappa_\lambda = \lambda_{\mathrm{BSM}}/\lambda_{\mathrm{SM}} \in \{-1, 0, 1\}$. A new grid is generated at runtime for the user-defined value of λ, where the amplitude for each pre-sampled phase-space point is calculated as:

$$M_\lambda = M_0 \cdot (1 - \lambda^2) + \frac{M_1}{2} \cdot (\lambda + \lambda^2) + \frac{M_{-1}}{2} \cdot (-\lambda + \lambda^2) \,. \tag{2}$$

The grid produced for the two-loop amplitude is fed to an interpolation framework, which interfaces the result at *any* phase-space point $M_\lambda(\hat{s}, \hat{t})$ to `Powheg`.

3. Total and differential cross-sections for variations of the trilinear coupling

The results given below are produced using the PDF4LHC15_nlo_30_pdfas sets [37, 38, 39, 40] interfaced to `Powheg` via `LHAPDF6` [41], with the corresponding value of α_s. The top-quark mass is renormalised in the on-shell scheme and is set to $m_t = 173$ GeV, as in the virtual amplitude. The mass of the Higgs boson is fixed to $m_h = 125$ GeV, and the top-quark and Higgs widths are set to zero. Jets are clustered using the anti-k_T algorithm [42] as implemented in `FastJet` [43, 44], with a jet distance parameter of $R = 0.4$ and a minimum transverse momentum requirement of $p_T = 20$ GeV. The central renormalisation and factorisation scales are set to $\mu_R = \mu_F = \mu_0 = m_{\rm hh}/2$. Scale uncertainties are estimated by 2-point variations $\mu_R = \mu_F = c\,\mu_0$, with $c \in \{0.5, 2.0\}$.

Total cross-sections for Higgs pair production at the (HE-)LHC are shown in Table 1, for centre-of-mass energies of $\sqrt{s} = 13, 14$ and 27 TeV and different values of the Higgs self-coupling $\kappa_\lambda = \lambda_{\rm BSM}/\lambda_{\rm SM}$. They are accompanied by their relative scale uncertainties, which are of the order $\mathcal{O}(10-20\%)$. Notably, the K-factors at 14 TeV show a sizeable dependence on the trilinear coupling κ_λ. In the HTL at NLO QCD, Ref. [45] suggested a variation of the K-factors with κ_λ of the order $\mathcal{O}(2-3\%)$. In the full theory, the K-factors are found to vary between 1.56 and 2.15 for variations of the trilinear coupling $-5 \le \kappa_\lambda \le 12$, see Fig. 2.

$\lambda_{\rm BSM}/\lambda_{\rm SM}$	$\sigma_{\rm NLO}$@13TeV [fb]	$\sigma_{\rm NLO}$@14TeV [fb]	$\sigma_{\rm NLO}$@27TeV [fb]	K-factor@14TeV
-1	$116.71^{+16.4\%}_{-14.3\%}$	$136.91^{+16.4\%}_{-13.9\%}$	$504.9^{+14.1\%}_{-11.8\%}$	1.86
0	$62.51^{+15.8\%}_{-13.7\%}$	$73.64^{+15.4\%}_{-13.4\%}$	$275.29^{+13.2\%}_{-11.3\%}$	1.79
1	$27.84^{+11.6\%}_{-12.9\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	1.66
2	$12.42^{+13.1\%}_{-12.0\%}$	$14.75^{+12.0\%}_{-11.8\%}$	$59.10^{+10.2\%}_{-9.7\%}$	1.56
2.4	$11.65^{+13.9\%}_{-12.7\%}$	$13.79^{+13.5\%}_{-12.5\%}$	$53.67^{+11.4\%}_{-10.3\%}$	1.65
3	$16.28^{+16.2\%}_{-15.3\%}$	$19.07^{+17.1\%}_{-14.1\%}$	$69.84^{+14.6\%}_{-12.1\%}$	1.90
5	$81.74^{+20.0\%}_{-15.6\%}$	$95.22^{+19.7\%}_{-11.5\%}$	$330.61^{+17.4\%}_{-13.6\%}$	2.14

Table 1. Total cross-sections for Higgs boson pair production at NLO QCD at (HE-)LHC for centre-of-mass energies of $\sqrt{s} = 13, 14$ and 27 TeV. The scale uncertainties are given in percent.

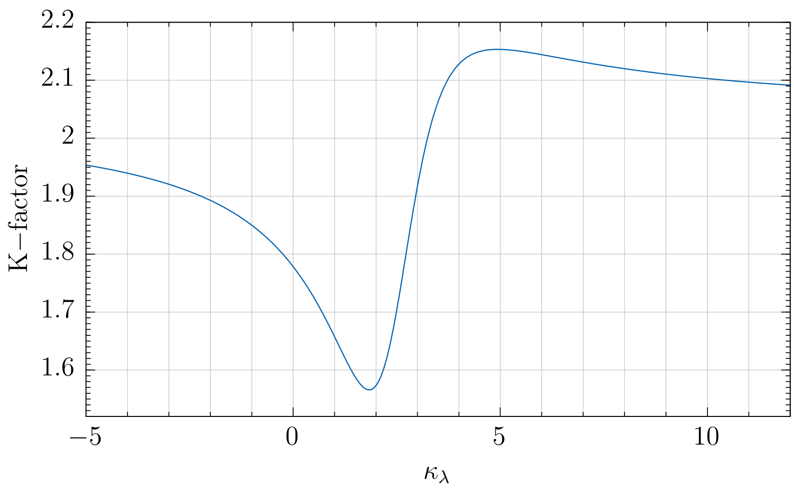

Figure 2. The dependence of the K-factor on the trilinear Higgs self-couplings κ_λ is given at $\sqrt{s} = 14\,$TeV in the full theory.

In Fig. 3, distributions of the invariant mass $m_{\rm hh}$ of the Higgs boson pair system are displayed for different values of κ_λ. They exhibit a characteristic dip around $m_{\rm hh} \sim 350\,$GeV for values of the trilinear coupling around $\kappa_\lambda = 2.4$. This value of the trilinear self-coupling corresponds to a maximally destructive interference between triangle-like and box-like diagrams. For $\kappa_\lambda = 1$, the maximal destructive interference happens at the hh production threshold and therefore does not manifest itself as a dip, while for κ_λ values larger than ~ 3 the triangle-type contributions start to dominate.

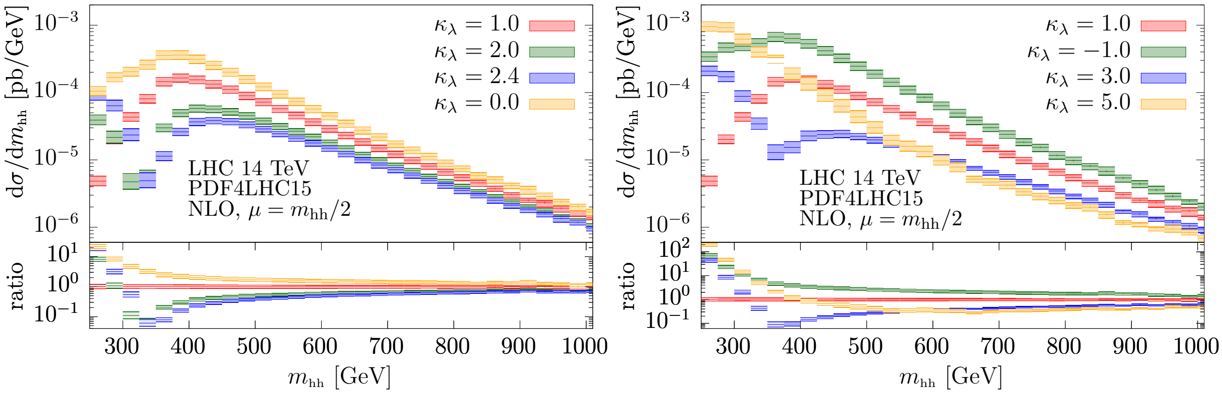

Figure 3. Distributions of the Higgs boson pair invariant mass m_{hh} for various values of κ_λ at $\sqrt{s} = 14\,\text{TeV}$. The uncertainty bands are from scale variations as described in the text.

Note that since the contributions can be separated in triangle- and box-like diagrams, the top-Higgs Yukawa coupling y_t can easily be varied within the same code. A non-SM value of y_t yields in Eq. (1):

$$|\mathcal{M}_\lambda|^2 = y_t^4 \left[\mathcal{M}_B^* \mathcal{M}_B + \frac{\kappa_\lambda}{y_t} \left(\mathcal{M}_B^* \mathcal{M}_T + \mathcal{M}_T^* \mathcal{M}_B \right) + \left(\frac{\kappa_\lambda}{y_t} \right)^2 \mathcal{M}_T^* \mathcal{M}_T \right] . \tag{3}$$

The cross-section can be computed by setting κ_λ in the code to the desired value of the ratio κ_λ / y_t, and rescaling the result by an overall factor y_t^4. For example, $\sigma(y_t = 1.2, \kappa_\lambda = 1) = (1.2)^4\, \sigma(y_t = 1, \kappa_\lambda = 1/1.2)$. Fig. 4 shows the distribution of m_{hh} for values of the top-Higgs Yukawa coupling that are still not experimentally excluded [4].

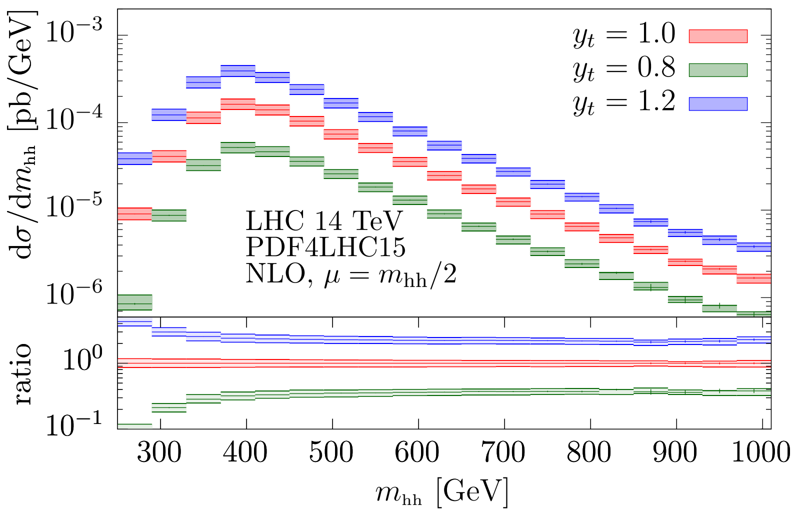

Figure 4. The distribution of the Higgs boson pair invariant mass m_{hh} for values of the top-Higgs Yukawa coupling $y_t \in \{0.8, 1, 1.2\}$.

4. Parton-shower matched results

We now consider NLO distributions matched to a parton shower. The Les Houches Events (LHE) [46] files produced by `Powheg` are used as input to the `Pythia8.235` and `Herwig7.1.4` parton showers. In the case of `Herwig7`, both the default angular-ordered $\tilde{q}$ and the dipole showers are compared. The radiation-regulating `hdamp` parameter in `Powheg` is set to `hdamp` $=$ 250 GeV. Multiple-parton interactions and hadronisation are switched off. The default tunes are used for both parton showers.

Fig. 5 displays the transverse momentum of the Higgs boson pair p_T^{hh} and the separation between the two Higgs bosons $\Delta R^{\mathrm{hh}} = \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2}$. Considering first the distribution of p_T^{hh}, both `Herwig7` parton showers (PH7-$\tilde{q}$ and PH7-dipole) generate similar results and reproduce the fixed-order NLO prediction in the far-p_T^{hh} range. In contrast, `Pythia8` agrees with `Herwig7` only for small transverse momenta, while it produces much harder radiation in the tail of the distribution. The same comments apply to the ΔR^{hh} observable in the region $0 < \Delta R^{\mathrm{hh}} < \pi$ where shower contributions are important. Large parton-shower matching uncertainties in Higgs boson pair production have already been discussed in Ref. [47].

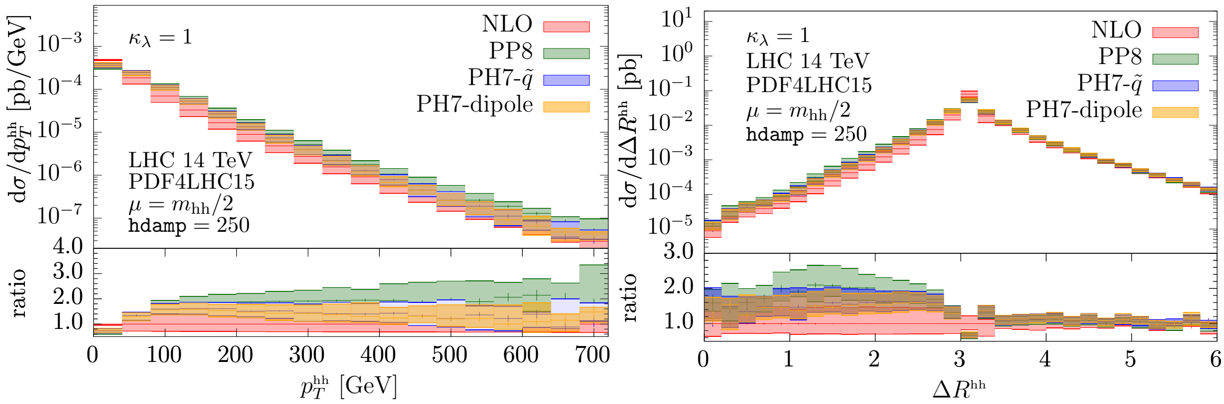

Figure 5. The transverse momentum p_T^{hh} of the Higgs boson pair and the separation between the two Higgs bosons ΔR^{hh} are shown for the fixed-order NLO calculation and three parton showers, in the $\kappa_\lambda = 1$ case.

5. Conclusion

We have presented a new program package for Higgs boson pair production at NLO QCD with full top-quark mass dependence. In this package, the trilinear Higgs self-coupling can be varied explicitly. Within the same code, simultaneous variations of the top-Higgs Yukawa coupling can also be produced. The public code for the `Powheg-BOX-V2` event generator can be found at the website `http://powhegbox.mib.infn.it` in the `User-Processes-V2/ggHH` subdirectory. In addition, approximations related to the heavy top limit (HTL) can be enabled for comparison purposes. We have found that the full m_t-dependent NLO QCD corrections lead to K-factors which exhibit a sizeable dependence on the value of the trilinear Higgs self-coupling, which is not present in the HTL. We have compared fixed-order predictions at NLO QCD to parton-shower matched results. Both the `Pythia8` and `Herwig7` ($\tilde{q}$ and dipole) parton showers can be matched directly to LHE files produced by `Powheg`. Full particle-level events can be produced with our framework, including Higgs boson decays and hadronisation.

References

[1] Aad G *et al.* (ATLAS, CMS) 2016 *JHEP* **08** 045 (*Preprint* `1606.02266`)

[2] Aaboud M *et al.* (ATLAS) 2018 *JHEP* **03** 095 (*Preprint* `1712.02304`)

[3] Sirunyan A M *et al.* (CMS) 2018 *Submitted to: Eur. Phys. J.* (*Preprint* 1809.10733)
[4] Sirunyan A M *et al.* (CMS) 2018 *Submitted to: Phys. Lett.* (*Preprint* 1812.06504)
[5] Sirunyan A M *et al.* (CMS) 2019 *Phys. Rev. Lett.* **122** 121803 (*Preprint* 1811.09689)
[6] ATLAS 2018 Combination of searches for Higgs boson pairs in *pp* collisions at 13 TeV with the ATLAS experiment. Tech. Rep. ATLAS-CONF-2018-043 CERN Geneva URL https://cds.cern.ch/record/2638212
[7] Dawson S, Dittmaier S and Spira M 1998 *Phys. Rev.* **D58** 115012 (*Preprint* hep-ph/9805244)
[8] de Florian D and Mazzitelli J 2013 *Phys. Rev. Lett.* **111** 201801 (*Preprint* 1309.6594)
[9] Grigo J, Melnikov K and Steinhauser M 2014 *Nucl. Phys.* **B888** 17–29 (*Preprint* 1408.2422)
[10] de Florian D, Grazzini M, Hanga C, Kallweit S, Lindert J M, Maierhöfer P, Mazzitelli J and Rathlev D 2016 *JHEP* **09** 151 (*Preprint* 1606.09519)
[11] Borowka S, Greiner N, Heinrich G, Jones S, Kerner M, Schlenk J, Schubert U and Zirke T 2016 *Phys. Rev. Lett.* **117** 012001 [Erratum: Phys. Rev. Lett.117,no.7,079901(2016)] (*Preprint* 1604.06447)
[12] Borowka S, Greiner N, Heinrich G, Jones S, Kerner M, Schlenk J and Zirke T 2016 *JHEP* **10** 107 (*Preprint* 1608.04798)
[13] Baglio J, Campanario F, Glaus S, Mühlleitner M, Spira M and Streicher J 2018 (*Preprint* 1811.05692)
[14] Buchalla G, Capozi M, Celis A, Heinrich G and Scyboz L 2018 *JHEP* **09** 057 (*Preprint* 1806.05162)
[15] Nason P 2004 *JHEP* **11** 040 (*Preprint* hep-ph/0409146)
[16] Frixione S, Nason P and Oleari C 2007 *JHEP* **11** 070 (*Preprint* 0709.2092)
[17] Alioli S, Nason P, Oleari C and Re E 2010 *JHEP* **06** 043 (*Preprint* 1002.2581)
[18] Sjostrand T, Ask S, Christiansen J R, Corke R, Desai N, Ilten P, Mrenna S, Prestel S, Rasmussen C O and Skands P Z 2015 *Comput. Phys. Commun.* **191** 159–177 (*Preprint* 1410.3012)
[19] Bellm J *et al.* 2016 *Eur. Phys. J.* **C76** 196 (*Preprint* 1512.01178)
[20] Bellm J *et al.* 2017 (*Preprint* 1705.06919)
[21] Heinrich G, Jones S P, Kerner M, Luisoni G and Scyboz L 2019 (*Preprint* 1903.08137)
[22] Heinrich G, Jones S P, Kerner M, Luisoni G and Vryonidou E 2017 *JHEP* **08** 088 (*Preprint* 1703.09252)
[23] Luisoni G, Nason P, Oleari C and Tramontano F 2013 *JHEP* **10** 083 (*Preprint* 1306.2542)
[24] Cullen G, Greiner N, Heinrich G, Luisoni G, Mastrolia P, Ossola G, Reiter T and Tramontano F 2012 *Eur. Phys. J.* **C72** 1889 (*Preprint* 1111.2034)
[25] Cullen G *et al.* 2014 *Eur. Phys. J.* **C74** 3001 (*Preprint* 1404.7096)
[26] Peraro T 2014 *Comput.Phys.Commun.* **185** 2771–2797 (*Preprint* 1403.1229)
[27] Binoth T, Guillet J P, Heinrich G, Pilon E and Reiter T 2009 *Comput. Phys. Commun.* **180** 2317–2330 (*Preprint* 0810.0992)
[28] Cullen G, Guillet J P, Heinrich G, Kleinschmidt T, Pilon E *et al.* 2011 *Comput.Phys.Commun.* **182** 2276–2284 (*Preprint* 1101.5595)
[29] van Hameren A 2011 *Comput.Phys.Commun.* **182** 2427–2438 (*Preprint* 1007.4716)
[30] Arnold K *et al.* 2009 *Comput. Phys. Commun.* **180** 1661–1670 (*Preprint* 0811.4559)
[31] Baglio J *et al.* 2014 (*Preprint* 1404.3940)
[32] Jones S P 2016 *PoS* **LL2016** 069 (*Preprint* 1608.03846)
[33] von Manteuffel A and Studerus C 2012 (*Preprint* 1201.4330)
[34] Borowka S, Heinrich G, Jones S P, Kerner M, Schlenk J and Zirke T 2015 *Comput. Phys. Commun.* **196** 470–491 (*Preprint* 1502.06595)
[35] Borowka S, Heinrich G, Jahn S, Jones S P, Kerner M and Schlenk J 2018 *Comp. Phys. Comm.* (*Preprint* 1811.11720)
[36] Jones S P 2019 *These Proceedings*
[37] Butterworth J *et al.* 2015 (*Preprint* 1510.03865)
[38] Dulat S, Hou T J, Gao J, Guzzi M, Huston J, Nadolsky P, Pumplin J, Schmidt C, Stump D and Yuan C P 2016 *Phys. Rev.* **D93** 033006 (*Preprint* 1506.07443)
[39] Harland-Lang L A, Martin A D, Motylinski P and Thorne R S 2015 *Eur. Phys. J.* **C75** 204 (*Preprint* 1412.3989)
[40] Ball R D *et al.* (NNPDF) 2015 *JHEP* **04** 040 (*Preprint* 1410.8849)
[41] Buckley A, Ferrando J, Lloyd S, Nordström K, Page B, Rüfenacht M, Schönherr M and Watt G 2015 *Eur. Phys. J.* **C75** 132 (*Preprint* 1412.7420)
[42] Cacciari M, Salam G P and Soyez G 2008 *JHEP* **04** 063 (*Preprint* 0802.1189)
[43] Cacciari M and Salam G P 2006 *Phys.Lett.* **B641** 57–61 (*Preprint* hep-ph/0512210)
[44] Cacciari M, Salam G P and Soyez G 2012 *Eur.Phys.J.* **C72** 1896 (*Preprint* 1111.6097)
[45] Gröber R, Mühlleitner M, Spira M and Streicher J 2015 *JHEP* **09** 092 (*Preprint* 1504.06577)
[46] Alwall J *et al.* 2007 *Comput. Phys. Commun.* **176** 300–304 (*Preprint* hep-ph/0609017)
[47] Jones S and Kuttimalai S 2018 *JHEP* **02** 176 (*Preprint* 1711.03319)