Gluon fusion correction to $HW^+W^-/HZZ$ production in the POWHEG-BOX

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Abstract

The study of the Higgs boson properties is one of the most important tasks to be accomplished in the next years, at the Large Hadron Collider (LHC) and at future colliders such as the Future Circular Collider in hadron-hadron mode (FCC-hh), the potential 100 TeV follow-up of the LHC machine. In this view the precise study of the Higgs couplings to weak gauge bosons is crucial and requires as much information as possible. After the recent calculation of the next-to-leading order QCD corrections to the production cross sections and differential distributions of a Standard Model Higgs boson in association with a pair of weak bosons, matched with parton shower in the POWHEG-BOX framework, we present the gluon fusion correction $gg \rightarrow HW^+W^-(HZZ)$ to the process $pp \rightarrow HW^+W^-(HZZ)$. This correction can be sizeable and amounts to +3% (+10%) in the $HW^+W^-$ process and +5% (+18%) in the $HZZ$ process at the LHC (FCC-hh). We present results on total cross sections and distributions at the LHC and at the FCC-hh.

Keywords: Higgs, weak bosons, QCD corrections, LHC, FCC-hh, parton shower

1. Introduction

After the discovery of a Higgs boson with a mass of $\sim$ 125 GeV in the Run I of the Large Hadron Collider (LHC) at CERN [1, 2], the study of its properties has begun, in particular to test whether they deviate from the predictions of the Standard Model (SM) mechanism [3–5]. The latest results at 13 TeV still display a compatibility with the SM hypothesis [6–8]. Developing the most exhaustive survey of possible deviations from the SM is thus an important task. In this view the coupling between a Higgs boson and weak bosons is a crucial part of this survey. The production of a Higgs boson in association with a pair of weak gauge bosons [9–12] can be used to probe the Higgs gauge couplings [13], which is also directly related to the triple gauge bosons vertex [14].

The next-to-leading order (NLO) QCD corrections to various $H + VV'$ processes at the LHC have now been calculated: $HW^+W^-$ production [15, 16], $HW^\pm Z$ production [16, 17], associated production with a massive gauge boson $W/Z$ and a photon [18, 19], and finally $HZZ$ production [16]. The matching with parton shower was also completed in 2015 for all processes except those involving a photon [16]. The gluon fusion correction to $HW^+W^-$, $gg \rightarrow HW^+W^-$, exists in the literature [15] and amounts to $\sim +4\%$ to the total cross section at the LHC for a fixed central scale.

This Letter is a follow-up to Ref. [16] and completes the picture by presenting for the first time the gluon fusion correction to $HZZ$ production and the matching with parton shower of the gluon fusion corrections to $HW^+W^-$ and $HZZ$ productions in the SM, in the POWHEG-BOX framework [20, 21]. The paper is organised as follows: in Section 2 the calculation and the tools used are presented, then in Section 3 the numerical results are presented, both for the LHC and the Future Circular Collider in hadron-hadron mode (FCC-hh), the potential machine which would follow the LHC with an energy of 100 TeV. A short conclusion will be given in Section 4.

2. Description of the calculation

The leading order (LO) processes $pp \rightarrow HW^+W^-$ and $pp \rightarrow HZZ$, together with their NLO QCD corrections, have been discussed in Ref. [16]. We only discuss in this Letter the LO gluon fusion correction $pp \rightarrow gg \rightarrow HVV$ at proton-proton colliders, where $VV'$ stands either for $W^+W^-$ or for $ZZ$. It is formally a next-to-next-to-leading order contribution to the full hadronic cross section $pp \rightarrow HVV$, nevertheless we will combine it with the NLO QCD calculation of the quark channels $pp \rightarrow q\bar{q} \rightarrow HVV$ as done for $W^+W^-$ and $ZZ$ production processes, see for example Ref. [22] and references therein. The gluon fusion correction for the $HW^+W^-$ process was calculated in Ref. [15] and it was shown that it has an impact of $\sim +4\%$ at $M_H = 120$ GeV for a central scale $\mu = (M_H + 2M_W)/2$.

The $gg \rightarrow HVV$ contribution is a one-loop contribution already at the lowest order and proportional to $\alpha_s^2$. It consists of triangle, box and pentagon loops of quarks. Our calculation is done with five active massless flavours for the running of the strong coupling constant $\alpha_s$, and we use diagonal Cabibbo-Kobayashi-Maskawa (CKM) matrix...
elements for the $HW^+W^-$ process. Diagrams involving a Yukawa coupling between a light quark and a Higgs boson are discarded, so that in the pentagon loops only the top quark contributes. We use the 't Hooft-Feynman gauge. We depict in Fig. 1 some generic diagrams, in particular the pentagon class involving the quark-quark-Higgs coupling.

The full one-loop amplitude is ultraviolet (UV) and infrared (IR) finite and is convoluted with the gluon parton distribution functions (PDF) to obtain the hadronic cross section as

$$\sigma_{gg} = \int dx_1 dx_2 [g(x_1, \mu_F)g(x_2, \mu_F)\sigma_{gg \to HVV}],$$

where $g(x, \mu_F)$ denotes the gluon PDF with momentum fraction $x$ and factorisation scale $\mu_F$. The PDF evolution is taken at NLO as well as the running of $\alpha_s$. The one-loop amplitude is generated with FeynArts-3.7 [24]. The scalar integrals as well as the reduction of tensor coefficients down to scalar integrals are calculated using the techniques developed in Refs. [25–27] and implemented with FormCalc-8.4 [23], adapted to the FormCalc framework thanks to an in-house routine. The final code is implemented in the framework of the POWHEG-BOX [21]. To improve the stability of the calculation of the amplitudes a technical cut has been implemented,

$$k_{ij} \geq k_{\text{cut}}, \quad k_{ij} = \min(\tilde{k}_{ij}, p_{T,i}, p_{T,j}),$$

$$\tilde{k}_{ij} = \frac{3}{5} \min(p_{T,i}, p_{T,j}) \sqrt{\Delta y_{ij}^2 + \Delta \phi_{ij}^2},$$

where $(ij)$ runs on the pairs of final-state particles $(i \neq j)$, $\Delta y_{ij}$ and $\Delta \phi_{ij}$ are the rapidity and angular separations between the particle $i$ and $j$, $p_{T,i}$ is the transverse momentum of particle $i$, and $k_{\text{cut}} = 10^{-2}$. It has been checked that the result does not depend on the value of $k_{\text{cut}}$ (as long as $k_{\text{cut}}$ is small enough). We use the same phase-space parametrisation that was used in our previous work [16]. It has been explicitly checked that the amplitudes are UV and IR finite. In addition, adopting the same framework as in Ref. [15] for the $HW^+W^-$ process, a good agreement has been found between their results and our calculation.

3. Numerical results at the LHC and at the FCC

Following strictly the framework of our previous work [16], we use the following set of input parameters,

$$G_F = 1.16637 \times 10^{-5} \text{ GeV}^{-2}, \quad M_W = 80.385 \text{ GeV},$$

$$M_Z = 91.1876 \text{ GeV}, \quad M_t = 172.5 \text{ GeV},$$

$$M_H = 125 \text{ GeV}, \quad \alpha_s^{\text{NLO}}(M_Z^2) = 0.118,$$

where all but $M_H$ is taken from Ref. [29]. The CKM matrix is assumed to be diagonal and the masses of all the quarks but the top quark are approximated as zero. Following the latest PDF4LHC Recommendation [30] we use in the LHAPDF6 framework [31] the NLO PDF set family PDF4LHC15_nlo. To define the jets we use FastJet [32, 33] and the parton shower is done with Pythia 6.4 [34]. The central scale is defined as the $HVV$ invariant mass, $\mu_R = \mu_F = \mu_0$ with $\mu_0^{HW} = M_{HW+W^-}, \mu_0^{HZZ} = M_{HZZ}$. The running of $\alpha_s$ is done at NLO throughout the whole Letter.

Using this set of parameters we obtain at the LHC at 14 TeV a $\sim +3\%$ correction to the LO $pp \to HW^+W^-$ cross section and a $\sim +5\%$ correction to the LO $pp \to HZZ$ cross section. At the FCC-lh at 100 TeV we obtain $\sim +10\%$ and $\sim +18\%$ corrections respectively. The correction increases, in both channels, with increasing centre-of-mass (c.m.) energies. The total QCD corrections, including the NLO contributions calculated in Ref. [16], eventually amount to $\sim +30\%$ $(\sim +28\%)$ for the $HW^+W^-$ (HZZ) channel at the LHC and to $\sim +38\%$ $(\sim +34\%)$ for the $HW^+W^-$ (HZZ) channel at the FCC-lh.

3.1. Differential distributions

As an example of the impact of the gluon fusion correction on the differential distributions we present the Higgs transverse momentum $p_{T,H}$ for the $HW^+W^-$ channel and
the jet transverse momentum $p_{T,J}$ distributions for the $HZZ$ channel, in both cases at the LHC and at the FCC-hh. The other kinematic distributions can be easily obtained in the POWHEG-BOX framework. Note that the distributions are quite similar between both channels, so that for example the conclusions drawn in the $HW^+W^-$ for the $p_{T,H}$ distribution apply also in the $HZZ$ channel, but as expected from the corrections on the total cross sections the impact of gluon fusion contributions is more visible in the $HZZ$ channel than in the $HW^+W^-$ channel.

In Figure 2 we display the $p_{T,H}$ distributions at the LHC (left) and the FCC-hh (right), including the LO prediction (in black/dashed line) and the full prediction including both the NLO QCD corrections and the gluon fusion contribution (in red/solid line), as well as the gluon fusion contribution alone (in blue/dotted line) and with parton shower (PS) effects simulated with Pythia (in pink/thin dotted line). The inserts display the $K$-factor of the gluon fusion contributions, defined as $K = \sigma_{gg}/\sigma_{LO}$. The $gg$ corrections are quite small at the LHC, of the order of $+2\%$ to $+5\%$, linearly increasing from low to high $p_{T,H}$, but sizeable at the FCC-hh, from $+5\%$ to $\sim +18\%$. The PS effects are quite small on the $gg$ contribution but noticeable as a change in shape, leading to slightly smaller corrections at low $p_{T,H}$ and slightly larger corrections at high $p_{T,H}$.

In Figure 3 we display the $p_{T,H}$ distributions at the LHC (left) and the FCC-hh (right), including the PS effects everywhere. The NLO distribution is displayed in blue (thin dotted line), the full distribution including the $gg$ contribution is displayed in red (dashed line), and the $gg$ contribution alone is displayed in pink (dotted line). The insert displays the percent correction due to the $gg$ contribution with respect to the NLO prediction. The behaviour of the $gg$ contribution is similar to that in the $p_{T,H}$ distribution: linearly increasing with increasing $p_{T,H}$, and modest at the LHC but sizeable at the FCC-hh.

3.2. Total cross sections including theoretical uncertainties

As already demonstrated in Ref. [16] the total rates $pp \to HW^+W^-/HZZ$ are affected by theoretical uncertainties: 1) the scale uncertainty reflecting the confidence given to the calculation at a given perturbative order, calculated by varying the renormalisation scale $\mu_R$ and the factorisation scale $\mu_F$ in the range $1/2 \mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$; 2) the PDF+α_s uncertainty reflecting the impact of the experimental uncertainties on the fit leading to the determination of the PDFs. We calculate the theoretical uncertainties on the gluon fusion contribution as well as on its combination with the NLO QCD $qq$ contribution to the whole hadronic cross section, following Ref. [16].

The results are presented in Tables 1 and 2 as well as displayed in Figure 4. The scale uncertainties of the gluon fusion cross sections are quite large, of the order of $15\%$ to $30\%$. This was expected as this is a LO process. The combination of the gluon fusion channel with the NLO $qq$ cross section, however, displays limited uncertainties albeit larger than for the $qq$ channel alone, because of the sizeable impact of the $gg$ correction. The PDF+α_s uncertainty is nearly the same in the $qq$ contributions and in the full cross sections. We obtain a total theoretical uncertainty of $\sim \pm 4\% (\sim \pm 7\%)/\sim 8\%$ at the LHC (FCC-hh) for the $HW^+W^-$ channel, compared to $\sim \pm 4\% (\sim \pm 6\%)/\sim 7\%$ for the NLO QCD $qq$ contributions only [16]. In the case of the $HZZ$ channel we obtain a total theoretical uncertainty of $\sim \pm 4\% (\sim \pm 8\%)$ at the LHC (FCC-hh), compared to $\sim \pm 4\%/\sim 7\%$ for the NLO QCD $qq$ contributions only [16]. The impact of the gluon fusion contribution uncertainty is then negligible at LHC energies but noticeable at the FCC-hh. Note that in comparison with Ref. [16]
Figure 3: In the main frame: Jet transverse momentum $p_{T,j}$ (in GeV) distribution of the $pp \rightarrow HZZ$ cross section (in fb/GeV) at the 14 TeV LHC (left) and at the 100 TeV FCC-hh (right) calculated with the PDF4LHC15, full+PS, gg+PS PDF set and with the input parameters given in Eq. (3). In blue (thin dotted): the NLO distribution including PS effects; in red (dashed): the full distribution including NLO QCD corrections and the $gg$ contribution, corrected with PS effects; in pink (dotted): $gg$ contribution including PS effects. In the insert is displayed the correction $\Delta_{gg}$ (in %) due to the gluon fusion contribution in the full prediction with respect to the NLO+PS calculation.

Table 1: The total $HW^+W^-$ production cross section at the LHC and the FCC-hh (in fb) for given c.m. energies (in TeV) at the central scale $\mu_F = \mu_R = M_{HW^+}$. The first group of lines displays the $gg \rightarrow HW^+W^-$ contribution and the second displays the combination of this contribution with the NLO QCD $gg$ contribution taken from Ref. [16]. The corresponding shifts due to the theoretical uncertainties coming from scale variation, PDF+$\alpha_s$ errors as well as the total uncertainty, when all errors are added linearly, are also shown (in %).

| $\sqrt{s}$ [TeV] | $\sigma_{HW^+}^{gg}$ [fb] | Scale | PDF+$\alpha_s$ | Total |
|------------------|-----------------|-------|---------------|-------|
| 13               | 0.217           | +27%  | +4.2%         | +31%  |
| 14               | 0.262           | -21%  | -4.2%         | -25%  |
| 33               | 1.81            | +26%  | +3.5%         | +30%  |
| 100              | 13.8            | -20%  | -3.5%         | -24%  |
| $\sqrt{s}$ [TeV] | $\sigma_{HW^+}^{full}$ [fb] | Scale | PDF+$\alpha_s$ | Total |
|------------------|-----------------|-------|---------------|-------|
| 13               | 10.7            | +2.5% | +1.8%         | +4.3% |
| 14               | 12.1            | +2.4% | +1.7%         | +4.2% |
| 33               | 43.3            | -3.4% | -1.6%         | -5.0% |

The $HZZ$ channel dominates over the $HW^-Z$ channel not only at lower c.m. energies but also at higher c.m. energies, when the gluon fusion correction is included.

4. Conclusion

We have completed in this Letter the current picture of the QCD corrections to $HW^+W^-$ and $HZZ$ production at hadron colliders, including the matching to parton shower, by calculating the gluon fusion corrections $gg \rightarrow HW^+W^-/HZZ$. This is in particular the first calculation of the gluon fusion correction to $HZZ$ production. These gluon fusion contributions are sizeable, from $+5\%$ to $+18\%$ at LHC energies up to $+18\%$ at 100 TeV. Combining the NLO corrections to the $pp \rightarrow q\bar{q} \rightarrow HW^+W^-/HZZ$ cross sections already calculated in Ref. [16] with the gluon fusion channel, the QCD corrections amounts to $+30\%$ ($+38\%$) and $+28\%$ ($+34\%$) for the total cross section $pp \rightarrow HW^+W^-$ and $pp \rightarrow HZZ$ at the LHC (FCC-hh), respectively. The total theoretical uncertainty is nearly unmodified at LHC energies while the modification is bigger at the FCC-hh, from $+6\%/−7\%$ to $+7\%/−8\%$ for the $HW^+W^-$ channel and from $+5\%/−7\%$ to $+8\%$ for the $HZZ$ channel. The impact of the gluon fusion channel on the differential distributions matched to parton shower is found small at the LHC and sizeable at
the FCC-hh, following the pattern of the corrections on the total cross sections. A public release of the code in the POWHEG-BOX is expected in the near future.

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