PROCEEDINGS OF SCIENCE

Higgs Off-shell Effects at NLO

Raoul Röntsch[*†]
Karlsruhe Institute of Technology
E-mail: raoul.roentsch@kit.edu

We describe a recent computation of next-to-leading order (NLO) QCD corrections to the gluonic production of two massive vector bosons, including both prompt $gg \to VV$ production and the Higgs-mediated production $gg \to H^* \to VV$, as well as their interference. Both massless and massive quark loops are considered, with the NLO corrections to the latter being treated in a large mass expansion. We present results in the sizable window between the Higgs and top production thresholds. The NLO corrections are large and similar in size for the signal, background, and interference processes. The NLO corrections are also roughly constant in the invariant mass of the diboson pair, except near the $2m_V$ threshold, where the corrections to the interference change dramatically.

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[*]Speaker.
[†]In collaboration with F. Caola, M. Dowling, K. Melnikov, and L. Tancredi [1]

1. Introduction

ICHEP 2016 saw the first Higgs results from Run II of the LHC being presented. Efforts to understand the nature of the Higgs boson are principally focused on on-shell production, since this is where the majority of events lie. However, roughly 10% of events in the $H \to VV$ decay channel are produced off-shell, above the $2m_V$ threshold [2]. Such events present further opportunities to study the properties of the Higgs. For example, the fact that the Higgs mechanism unitarizes massive scattering amplitudes leads to large and destructive interference between prompt and Higgs-mediated amplitudes at high energies, which may be probed using off-shell events.

Another possibility is the proposal by Caola and Melnikov [3] to use ratios of on- and off-shell cross sections to indirectly constrain the Higgs width. Using this method, ATLAS and CMS find bounds $\Gamma_H < 23$ MeV and $\Gamma_H < 13$ MeV respectively [4, 5]. By contrast, direct constraints are limited by detector resolution to $\Gamma_H \sim 1$ GeV. These constraints are not model-independent; in particular, they assume that the on- and off-shell couplings are identical [6, 7]. However, new physics effects which violate this assumption will usually present themselves in other ways as well, meaning that the assumption can be experimentally validated. Furthermore, one can construct energy-dependent couplings, either in an anomalous coupling or effective field theory approach, and simultaneously constrain the Higgs width together with these, leading to a more model-independent bound. Initial steps in this direction have been taken by CMS [8].

An accurate extraction of the Higgs width relies on a good theoretical prediction in the off-shell region. As of the beginning of 2016, the interference effects were only known to leading-order (LO) in pertubative QCD. Higher order effects are thought to be large, as for on-shell Higgs production. Currently, experimental analyses rescale the LO interference by the signal k-factor and assign a systematic uncertainty to this approximation. Clearly this approach is not ideal, and a calculation at next-to-leading order (NLO) is desirable. Two such NLO calculations have been presented recently [1, 9]; this talk is based on the former.

2. Details of the calculation

We consider the loop-induced processes $gg \to H^* \to VV$ and $gg \to VV$, which we refer to as the signal and background amplitudes respectively. The signal amplitude contains only massive quarks in the loop, while the background amplitude includes both massless and massive quark loops. Thus the $gg \to VV$ production cross section can be written as $\sigma_{\text{full}} = \sigma_{\text{sigl}} + \sigma_{\text{bkgd}} + \sigma_{\text{intf}}$, where σ_{intf} arises from the interference between signal and background amplitudes, and can be negative, while σ_{sigl} and σ_{bkgd} are positive-definite. However, only the sum σ_{full} is physical.

At NLO, one-loop real radiation corrections and two-loop virtual corrections are required. All LO and NLO contributions have been computed [10–22], with the exception of the two-loop correction to background amplitudes proceeding through a massive loop, which is beyond current calculational techniques. We therefore expand in s/m_t^2 for both the real radiation and virtual corrections to the massive background amplitudes [23]. We confirm, as anticipated, that this expansion is accurate provided the invariant mass of the diboson pair $m_{4\ell} < 2m_t$, and provided that we restrict all jets to $p_{T,j} < 150$ GeV. We emphasize that this is not a major setback, as this still leaves a large window $m_H \lesssim m_{4\ell} \lesssim 2m_t$ in which interference effects can be studied at NLO accuracy.

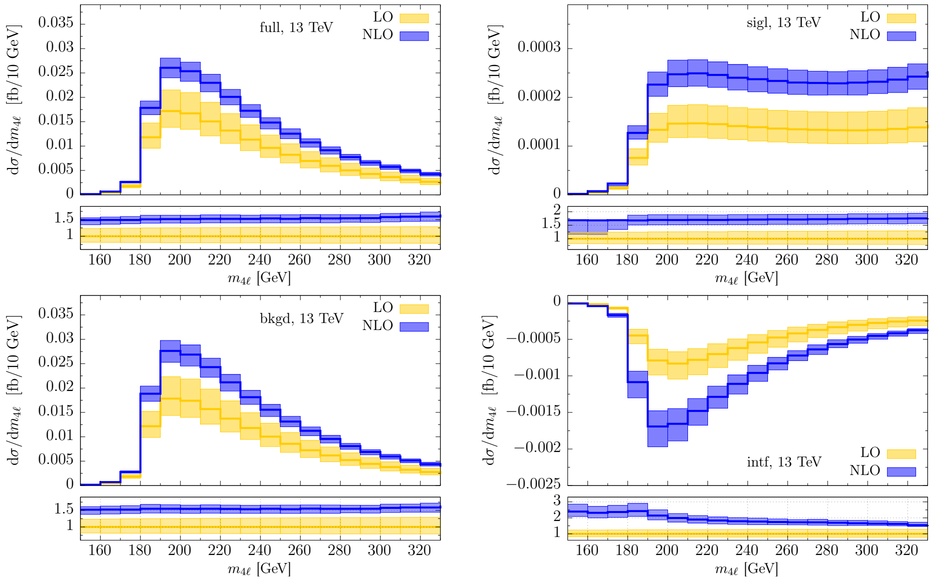

Figure 1: Four-lepton invariant mass distributions in $gg \to ZZ$ process at the 13 TeV LHC. The full result is shown as well as contributions of signal, background and interference separately. LO results are shown in yellow, NLO results are shown in blue, and scale variation is shown for $m_{4\ell}/4 < \mu < m_{4\ell}$ with a central scale $\mu = m_{4\ell}/2$. The lower pane shows the K-factors.

3. Results

We begin by presenting results for $gg \to ZZ \to e^+e^-\mu^+\mu^-$ production at the $\sqrt{s} = 13$ TeV LHC, to NLO in QCD. We use a dynamic scale $\mu_R = \mu_F = m_{4\ell}/2$ which we vary by a factor of two in either direction to estimate the scale uncertainty. We use minimal cuts 150 GeV $\leq m_{4\ell} \leq$ 340 GeV, $p_{T,j} < 150$ GeV, and 60 GeV $\leq m_{\ell\ell} \leq 120$ GeV. The first two cuts ensure that the heavy-loop expansion remains valid, while the third cut removes the contributions of off-shell photons.

The signal, background, interference, and full cross sections at LO and NLO are

$$\begin{aligned}
\sigma_{\mathrm{LO}}^{\mathrm{sigl}} &= 0.043^{+0.012}_{-0.009}\ \mathrm{fb}, & \sigma_{\mathrm{NLO}}^{\mathrm{sigl}} &= 0.074^{+0.008}_{-0.008}\ \mathrm{fb} \\
\sigma_{\mathrm{LO}}^{\mathrm{bkgd}} &= 2.90^{+0.77}_{-0.58}\ \mathrm{fb}, & \sigma_{\mathrm{NLO}}^{\mathrm{bkgd}} &= 4.49^{+0.34}_{-0.38}\ \mathrm{fb} \\
\sigma_{\mathrm{LO}}^{\mathrm{intf}} &= -0.154^{+0.031}_{-0.04}\ \mathrm{fb}, & \sigma_{\mathrm{NLO}}^{\mathrm{intf}} &= -0.287^{+0.031}_{-0.037}\ \mathrm{fb} \\
\sigma_{\mathrm{LO}}^{\mathrm{full}} &= 2.79^{+0.74}_{-0.56}\ \mathrm{fb}, & \sigma_{\mathrm{NLO}}^{\mathrm{full}} &= 4.27^{+0.32}_{-0.35}\ \mathrm{fb}.
\end{aligned} \tag{3.1}$$

The interference is negative and quite large, at the level of 5% of the total cross section, in spite of the relatively low mass scale. The scale uncertainty is 20%-30% at LO, which is reduced to around 10% at NLO. This implies that it would be difficult to observe the interference effect; however, it is possible to design specialized cuts to enhance the interference relative to the signal and background. We note also that the signal k-factor $K_{\mathrm{sigl}} = 1.72$ is slightly larger than that for the background $K_{\mathrm{bkgd}} = 1.55$, and that interference k-factor is close to the geometric mean of the signal and background k-factors, $K_{\mathrm{intf}} = 1.65 \simeq \sqrt{K_{\mathrm{sigl}}K_{\mathrm{bkgd}}}$.

The distributions in the invariant mass of the dibosons $m_{4\ell}$ is shown in Fig. 1 for the signal, background, and interference, as well as their sum. The k-factors are relatively flat, with the exception of the interference contribution around the $2m_Z$ threshold, where the k-factor drops from

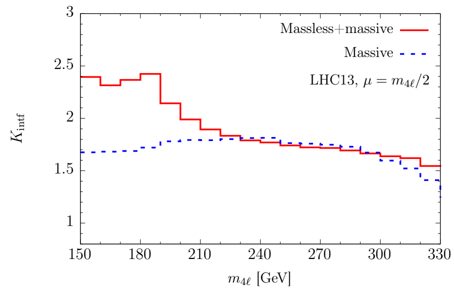

Figure 2: Comparison of full (massive+massless) and massive only interference K-factors as a function of $m_{4\ell}$ at the 13 TeV LHC.

about 2.5 at 160 GeV to about 2.0 at 200 GeV, and then flattens out. This effect is driven by the background amplitudes with massless quark loops. As can be seen in Fig. 2, removing these amplitudes so that the background amplitude contains massive loops only leads to a flat k-factor for the interference, including around the $2m_Z$ threshold.

The NLO correction to the interference contribution was also presented in Ref. [9], with the same qualitative behavior of the interference k-factor being observed. Moreover, Ref. [9] uses Padé approximants to extend the results beyond the $2m_t$ threshold, and find that the interference k-factor remains relatively flat beyond this threshold. It is not clear whether this approach is justified in this case, so the extension beyond the $2m_t$ threshold should be treated with caution. Ultimately, the only way to address this issue is by studying the NLO corrections with full mass dependence. As stated previously, this requires two-loop massive corrections to $gg \to VV$, which is extremely challenging.

We now turn to the process $gg \to WW \to \nu_e e^+ \mu^- \bar{\nu}_\mu$, again with particular emphasis on the interference between prompt- and Higgs-mediated production. The calculation is as for $gg \to ZZ$, with one important difference: in the case of WW production, there is no clear distinction between heavy and light quark loops, since bottom and top quarks mix in the loop. Thus, we neglect the third generation entirely. At LO, the third generation cross section is comparable to that from first the two generations at low energies, while at higher energies, the third generation produces the dominant contribution. Thus our results are to be viewed as incomplete, but they do give partial information on the impact of NLO QCD corrections to this process.

We use the same collider setup and scale choices as for $gg \to ZZ$. Since there is no mass expansion we are not obliged to use any cuts to ensure its validity; therefore, we choose not to impose any cuts on the final state particles, and present fully inclusive results. The cross sections are

$$\begin{aligned}
\sigma_{\text{LO}}^{\text{sigl}} &= 48.3^{+10.4}_{-8.4}\ \text{fb}, & \sigma_{\text{NLO}}^{\text{sigl}} &= 81.0^{+10.5}_{-8.2}\ \text{fb} \\
\sigma_{\text{LO}}^{\text{bkgd}} &= 49.0^{+12.8}_{-9.7}\ \text{fb}, & \sigma_{\text{NLO}}^{\text{bkgd}} &= 74.7^{+5.5}_{-6.2}\ \text{fb} \\
\sigma_{\text{LO}}^{\text{intf}} &= -2.24^{+0.44}_{-0.59}\ \text{fb}, & \sigma_{\text{NLO}}^{\text{intf}} &= -4.15^{+0.47}_{-0.54}\ \text{fb} \\
\sigma_{\text{LO}}^{\text{full}} &= 95.0^{+22.6}_{-17.6}\ \text{fb}, & \sigma_{\text{NLO}}^{\text{full}} &= 151.6^{+15.4}_{-13.9}\ \text{fb}.
\end{aligned} \tag{3.2}$$

Again, the interference is negative, although the impact is smaller, around 2% of the full cross section. The Higgs peak is not removed by cuts, as it was in the ZZ case, leading to a relatively

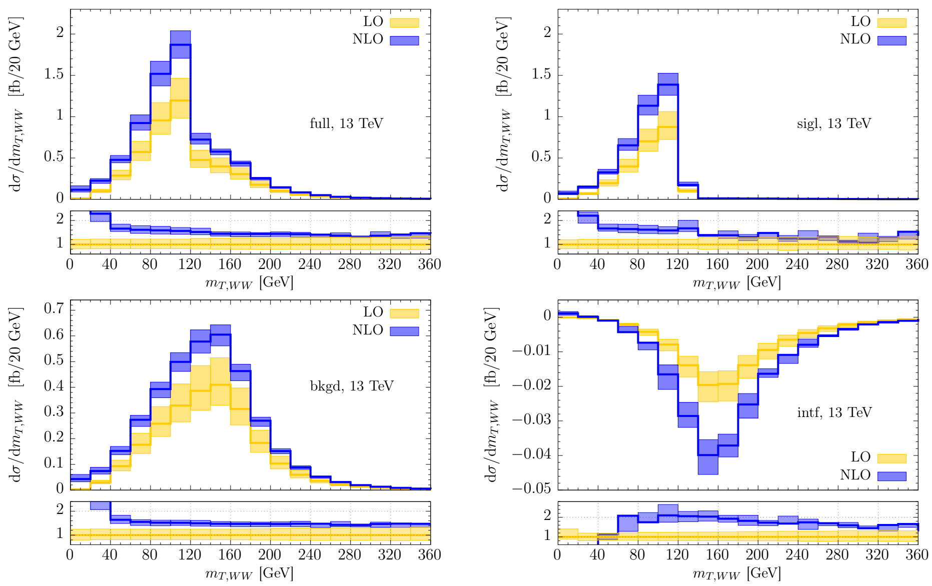

Figure 3: As for fig. 1, but showing the transverse mass $m_{T,WW}$ distributions in $gg \to WW$ process.

larger signal cross section. Clearly, one would need specialized cuts to study the interference. It is also interesting to note that the signal and background k-factors are similar to those found in ZZ production, $K_{\text{sigl}} = 1.68$ and $K_{\text{bkgd}} = 1.53$, while the interference k-factor is somewhat larger, $K_{\text{intf}} = 1.85$, meaning that the relation $K_{\text{intf}} \simeq \sqrt{K_{\text{sigl}} K_{\text{bkgd}}}$ no longer holds as precisely as for $gg \to ZZ$.

We now turn to differential distributions in the transverse mass of the WW system $m_{T,WW}$, shown in Fig. 3. Again, we observe relatively stable differential k-factors, except in the interference contribution around the $2m_W$ threshold, where a similar feature to that found in ZZ production is observed. Recalling that, in the ZZ case, this feature was driven by the interference with massless background amplitudes, we conjecture that the omitted third generation in $gg \to WW$ would give rise to a relatively flat k-factor, as observed for $gg \to ZZ$ (see Fig. 2). This suggests a way to include the third generation, by rescaling the LO third generation results by the approximate k-factor $\sqrt{K_{\text{sigl}} K_{\text{bkgd}}}$ and adding it to the NLO results for the first two generations.

4. Conclusion

We have presented NLO QCD corrections to $gg \to ZZ$ and $gg \to WW$. The focus is on interference effects, which are particularly important for off-shell Higgs production, although results are also presented using prompt-production or Higgs-mediated amplitudes only. The difficulties of computing two-loop massive $gg \to VV$ amplitudes leads us to use a heavy top expansion for $gg \to ZZ$, and to neglect the third generation entirely for $gg \to WW$. In the invariant-mass window 150 GeV $\leq m_{4\ell} \leq$ 340 GeV, we find moderate k-factors for ZZ production. We also observe that the interference k-factor can be approximated by $K_{\text{intf}} \simeq \sqrt{K_{\text{sigl}} K_{\text{bkgd}}}$, except in the region around the $2m_Z$ threshold, where the k-factor changes rapidly, apparently driven by massless background amplitudes. The NLO corrections are slightly larger for the interference contribution in $gg \to WW$, and the differential k-factor again changes rapidly near $2m_W$, while being relatively flat throughout the rest of phase space. The impact of the omitted third generation can be estimated by adding the rescaled LO contribution to the NLO results for the first two generations. Together with the heavy mass expansion used for $gg \to ZZ$, these provide the best estimate of massive $gg \to VV$ interference effects, until the massive two-loop amplitudes are computed.

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