Di-boson Production beyond NLO QCD and Anomalous Couplings*

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In these proceedings, we review results for several di-boson production processes beyond NLO QCD at high transverse momenta using the VBFNLO Monte-Carlo program together with the LOOPSIM method. Additionally, we show for the \( WZ \) production process how higher order QCD corrections can resemble anomalous coupling effects.

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1. Introduction

Di-boson production processes are important channels to test the Standard Model (SM) at the LHC. They have been studied intensively in the past years both from the theoretical and the experimental side. As a signal, they are sensitive to triple gauge boson couplings, and therefore, provide a unique avenue to quantify deviations from the SM predictions. Furthermore, they are a background to many SM and beyond standard model analyses. Due to the large size of the next-to-leading order (NLO) corrections and the expected percent precision measurement at the LHC, the theoretical community has pursued in the last years the task to provide next-to-next-to-leading order (NNLO) QCD results. This task has been almost completed in the last years and exact results at NNLO are known for most of the processes, not only for total cross sections \(^1\), but also for differential distributions \(^2\).

At the same time, due to the large collection of results known at NLO for processes with different jet multiplicities, a field by its own has emerged with the aim to merge in a consistent way processes with different jet multiplicities at NLO. In this letter, following the LOOPSIM approach \(^3\), we will

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merge $VV$ and $VV+\text{jet}$ samples and review results at approximate NNLO accuracy for several di-boson production processes. Furthermore, we will show preliminary results of anomalous couplings effects in $WZ$ production.

2. Ingredients of the Calculational Setup

Using the LOOPSIM approach, we merge samples at NLO accuracy, provided by the VBFNLO Monte Carlo program [4], for several $VV$ and $VV+\text{jet}$ production processes. The merged sample is simultaneously accurate at NLO for both the $VV$ and $VV+\text{jet}$ sample and provides results at NNLO accuracy for the $VV$ production process in certain regions of the phase space since it includes consistently the double-real and virtual-real contributions to the $VV$ NNLO contributions, simulating in a unitarity approach, the missing two loop corrections, such that by construction the merged sample is infrared finite. Thus the sample consistently includes all the new phase space regions opening up first at NNLO, including the double soft and collinear emission of the weak bosons, which leads to numerically large logarithms of the form $\log(p_t^2/M_W^2)$ and therefore to potentially large NNLO corrections. Furthermore, it includes consistently the new partonic sub-processes opening up at NNLO, in this case, $gg$ and $qq$ initiated processes. Thus in regions of phase space where the LO kinematics are not dominant and therefore the missing finite piece of the two loop corrections is suppressed, like in inclusive anomalous coupling searches, the merged sample should provide most of the NNLO contributions.

3. SM predictions

In the following, results for $ZZ$ and $WW$ production are given at $\bar{n}\text{NLO}$\(^{1}\). They were studied in Ref. [5] and Ref. [6], respectively. The input parameters and a detailed description of the analysis can be found there. We take into account the leptonic decay of the weak bosons including all off-shell and spin correlation effects. However, we refer to the processes by the on-shell production mode for simplicity.

Independently of the order of a prediction, we used the NNLO MSTW2008 [7] PDF set with $\alpha_s(m_Z) = 0.11707$. As central value for the factorization and renormalization scales we chose $\mu_{F,R} = \frac{1}{2} ( \sum p_{T,\text{partons}} + \sqrt{p_{T,V_1}^2 + m_{V_1}^2} + \sqrt{p_{T,V_2}^2 + m_{V_2}^2} )$, where $p_{T,V_i}$ and $m_{V_i}$ are the transverse momenta and invariant masses of the decaying vector bosons, respectively. The scale uncertainty is obtained by varying simultaneously the factorization and renormalization scale by a factor two around the central scale. Additionally, to

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\(^{1}\) We use $\bar{n}$ to refer to our approximated results.
Fig. 1. Differential cross sections and K factors for the effective mass observable $H_T$, defined in Eq. (1), for the LHC at $\sqrt{s} = 8$ TeV. The bands correspond to varying $\mu_F = \mu_R$ by factors 1/2 and 2 around the central value. The solid bands give the uncertainty related to the $R_{LS}$ parameter varied between 0.5 and 1.5. The distribution is a sum of contributions from same-flavor decay channels (4$e$ and 4$\mu$) and the different-flavor channel (2$e$2$\mu$) in ZZ production. 

To assess the uncertainties associated with the recombination method used by LOOPSIM, we show the uncertainty bands associated with variations of the clustering radius, $R_{LS}$, of $\pm 0.5$ around the central value $R_{LS} = 1$. $R_{LS}$ is used in LOOPSIM to establish the sequence of emissions, which is used later on to identify the Born type particles ($WZ, Vj$ or $jj$) of the event.

Fig. 1 for ZZ production, shows the differential distribution for the effective mass, $H_T$, defined as a scalar sum of transverse momenta of leptons and jets

$$H_T = \sum p_{T,jets} + \sum p_{T,l}. \quad (1)$$

The set of cuts closely follows the ATLAS [8] analysis for inclusive searches and is described in detail in Ref. [5]. In the left panel, we require that the invariant masses of the reconstructed $Z$ bosons satisfy the cut $66 \text{GeV} < m_{\text{inv},Z_i} < 116 \text{GeV}$ and label the pair closer (further) to the on-shell value $m_Z$ as $Z_{1(2)}$. One can observe the large $nNLO$ contributions, which clearly exceed the scale uncertainties, and the small LOOPSIM uncertainty pro-
Fig. 2. Differential cross sections and K-factors for the $p_T$ of the hardest lepton at $\sqrt{s} = 8$ TeV without (left) and with jet veto (right). Bands are defined as in Fig. 1. We include the channels $e^+\nu_e e^-\bar{\nu}_e$, $\mu^+\nu_\mu \mu^-\bar{\nu}_\mu$, $e^+\nu_e \mu^-\bar{\nu}_\mu$ and $\mu^+\nu_\mu e^-\bar{\nu}_e$.

The contribution from the gluon-fusion box and Higgs diagrams is included in the NLO and $\bar{n}$NLO curves. The left panels correspond to the inclusive sample, while the results shown in the right panel were obtained with vetoing events containing jets which fulfill the criteria $p_T,\text{jet} > 30$ GeV and $|\eta,\text{jet}| < 4.7$.

The origin of the size of the corrections is well understood and is due to the sensitivity of this observable to additional jet radiation, leading to enhanced logarithms of the form $\log(p_T,\text{jet}/M_Z^2)$. On the right, one observes smaller corrections once we reduce the size of the appearing logs by imposing $m_{\text{inv},Z} > 116$ GeV. The plots also show results at $\bar{n}$LO for the gluon loop-induced contributions, which formally contribute at NNNLO and use the amplitudes of Ref. [9].
Fig. 3. Differential cross sections and K-factors for the $p_T$ of the hardest lepton for the LHC at $\sqrt{s} = 13$ TeV without (left) and with a dynamical jet veto (right) for different values of the anomalous coupling parameter $F_w$ (in TeV$^{-2}$). The light-grey (green) and grey (blue) bands correspond, respectively, to the SM NLO and SM $\bar{n}$NLO contributions varying $\mu_F = \mu_R$ by factors 1/2 and 2 around the central value. The dark-grey (orange) band correspond to the SM $\bar{n}$NLO uncertainty related to the $R_{LS}$ parameter varied between 0.5 and 1.5. Dashed and solid lines refer to NLO and $\bar{n}$NLO, respectively.

the entire $\bar{n}$NLO-vetoed result has larger scale uncertainties than the NLO-vetoed curves. This reveals, partially, accidental cancellation happening at NLO. However, as discussed in Ref. [6], jet-vetoed exclusive samples are potentially subject to further corrections from the constant term of 2-loop diagrams which are not accounted for by the $R_{LS}$ uncertainty band.

4. Anomalous Couplings

In the following, we show how higher order corrections can fake anomalous couplings (AC) effects for $WZ$ production. We closely follow the setup defined in Ref. [11] and use the amplitudes from Ref. [12]. On the left plot of Fig. 3 we present the SM predictions for lepton $p_T$ distributions with a finite anomalous coupling parameter, $F_w = f_W/\Lambda^2$, corresponding to the dimension 6 operator $(D_\mu \Phi)^\dagger W^{\mu \nu} (D_\nu \Phi)$. The coupling values used are within the range allowed by the global fit to present data in Ref. [13]. We use a dipole form factor to preserve tree level unitarity, with a form factor scale derived from unitarity constraints. One can clearly see in the
left plot that higher order QCD contributions can fake AC effects, if NLO predictions are taken. On the right, to increase the sensitivity to AC, we apply a dynamical veto, $x_{\text{jet}} < 0.2$, as described in Ref. [14] and given by

$$x_{\text{jet}} = \sum_{\text{jets}} E_{T,i}/(\sum_{\text{jets}} E_{T,i} + \sum_{W,Z} E_{T,i}).$$

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