DI-BOSON PRODUCTION BEYOND NLO QCD AND ANOMALOUS COUPLINGS*

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In this paper, 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].

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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 paper, following the LOOPSIM approach [3], we will merge VV and VV+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+jet production processes. The merged sample is simultaneously accurate at NLO for both the VV and VV+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 of $\log(p_{\mathrm{T}}^2/M_W^2)$ 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 $\bar{n}$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 $\alpha_{\mathrm{s}}(m_Z) = 0.11707$. As a central value for the factorization and renormalization scales, we chose $\mu_{\mathrm{F,R}} = \frac{1}{2}\,(\sum p_{\mathrm{T,partons}} + \sqrt{p_{\mathrm{T},V_1}^2 + m_{V_1}^2} +$

[1] We use $\bar{n}$ to refer to our approximated results.

$\sqrt{p_{\mathrm{T},V_2}^2 + m_{V_2}^2}$), 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 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 ± 0.5 around the central value $R_{\mathrm{LS}} = 1$. 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.

Figure 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

$$H_{\mathrm{T}} = \sum p_{\mathrm{T,jets}} + \sum p_{\mathrm{T},l}\,. \tag{1}$$

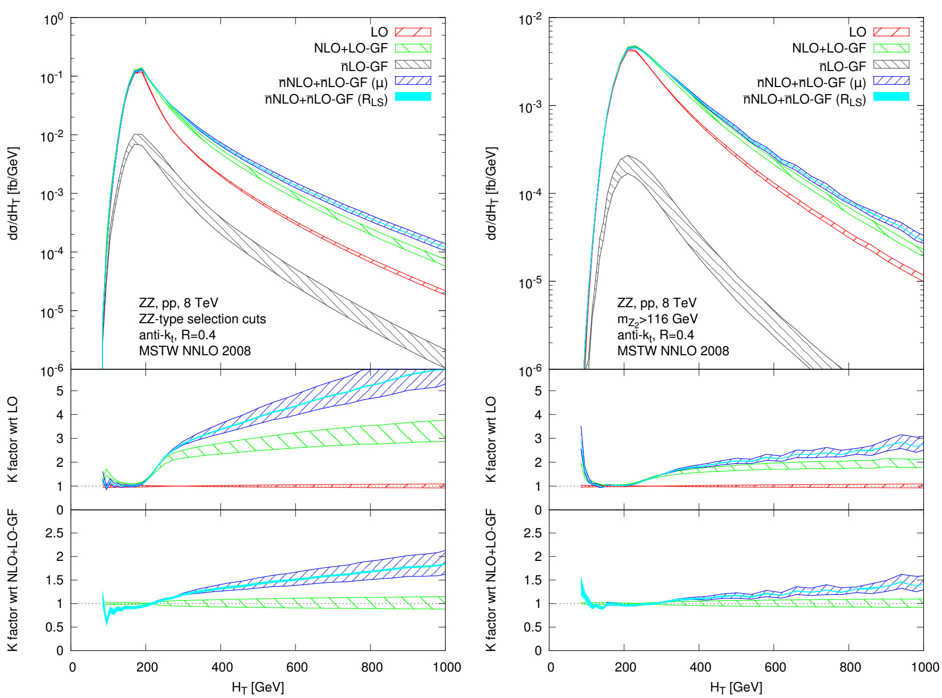

Fig. 1. Differential cross sections and K-factors for the effective mass observable H_{T}, defined in Eq. (1), for the LHC at $\sqrt{s} = 8$ TeV. The bands correspond to varying $\mu_{\mathrm{F}} = \mu_{\mathrm{R}}$ by factors $1/2$ and 2 around the central value. The solid bands give the uncertainty related to the R_{LS} parameter varied between 0.5 and 1.5. The distribution is a sum of contributions from the same-flavor decay channels ($4e$ and 4μ) and the different-flavor channel ($2e2\mu$) in ZZ production.

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 GeV $< m_{\mathrm{inv},Z_i} <$ 116 GeV and label the pair closer (further) to the on-shell value m_Z as $Z_{1(2)}$. One can observe the large $\bar{n}$NLO contributions, which clearly exceed the scale uncertainties, and the small LOOPSIM uncertainty provided by the R_{LS} variation. 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 of $\log(p^2_{\mathrm{T,jet}}/M_Z^2)$. On the right, one observes smaller corrections once we reduce the size of the appearing logs by imposing $m_{\mathrm{inv},Z_2} >$ 116 GeV. The plots also show results at $\bar{n}$LO for the gluon loop-induced contributions, which formally contribute at NNLO and use the amplitudes of Ref. [9].

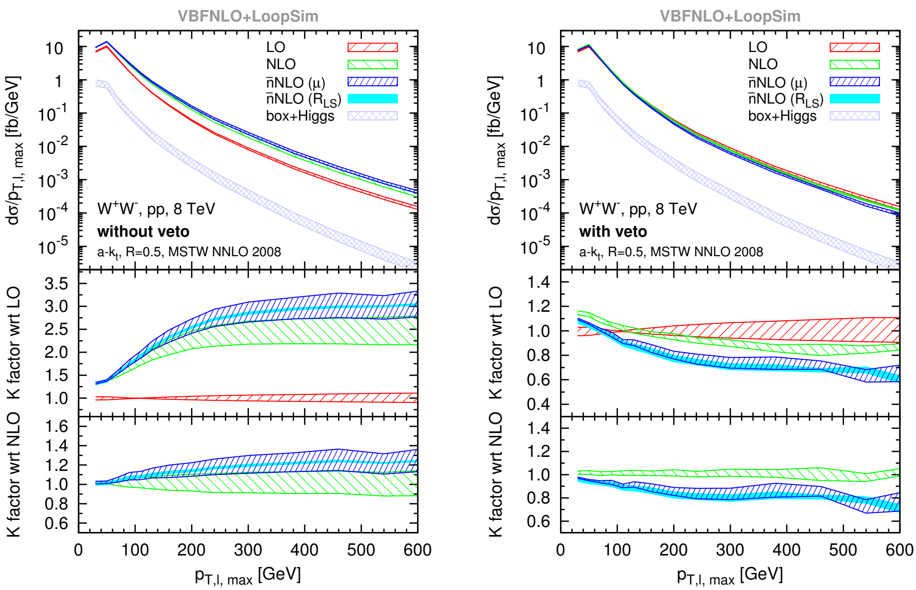

Fig. 2. Differential cross sections and K-factors for the p_{T} of the hardest lepton at $\sqrt{s}$ = 8 TeV without (left) and with jet veto (right). Bands are defined as in Fig. 1. We include the channels $e^+\nu_e e^-\bar{\nu}_e$, $\mu^+\nu_\mu\mu^-\bar{\nu}_\mu$, $e^+\nu_e\mu^-\bar{\nu}_\mu$ and $\mu^+\nu_\mu e^-\bar{\nu}_e$. 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 $p_{\mathrm{T,\,jet}} >$ 30 GeV and $|\eta_{\mathrm{jet}}| <$ 4.7.

In Fig. 2, we show the differential distribution for the hardest lepton for WW production with (left) and without (right) applying a fixed jet veto. To a large extent, our cuts match the ones by the CMS experiment in Ref. [10]. The loop-squared gluon-fusion box and Higgs contributions are separately shown. On the left, one can see that the $\bar{n}$NLO corrections are of the order of 30% and beyond the NLO scale uncertainties. On the right, we show results for the vetoed contributions to point out that exclusive samples are subject to potentially large negative Sudakov corrections and to show that 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 $R_{\rm LS}$ 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]. In the left plot of Fig. 3, we present the SM predictions for lepton $p_{\rm T}$ distributions with a finite anomalous coupling parameter, $F_w = f_W/\Lambda^2$, corresponding to the dimension 6 operator $(D_\mu\Phi)^\dagger\,\hat{W}^{\mu\nu}\,(D_\nu\Phi)$. 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, $x_{\rm jet} < 0.2$, as described in Ref. [14] and given by $x_{\rm jet} = \sum_{\rm jets} E_{{\rm T},i}/(\sum_{\rm jets} E_{{\rm T},i} + \sum_{W,Z} E_{{\rm T},i})$.

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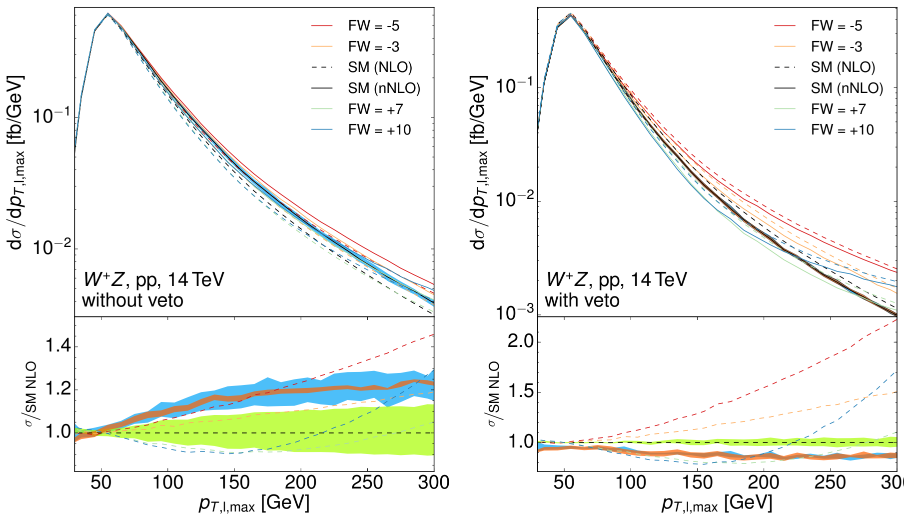

Fig. 3. Differential cross sections and K-factors for the p_{T} of the hardest lepton for the LHC at $\sqrt{s} = 13$ TeV without (left) and with a dynamical jet veto (right) for different values of the anomalous coupling parameter F_w (in TeV^{-2}). The light-gray (green) and gray (blue) bands correspond, respectively, to the SM NLO and SM $\bar{n}$NLO contributions varying $\mu_{\mathrm{F}} = \mu_{\mathrm{R}}$ by factors $1/2$ and 2 around the central value. The dark-gray (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.

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