PROCEEDINGS OF SCIENCE

Higher-order corrections in multiboson production

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Multiboson production provides a crucial test of the gauge structure of the Standard Model. In this proceeding we present a method to reach NNLO QCD and NLO EW accuracy matched to parton showers using the MiNNLO$_{\rm PS}$ framework [1]. We show results for the specific case of $W^{\pm}Z$ production with fully leptonic decays, which plays a fundamental role among multiboson processes because of the clean experimental signature and large cross section. We propose different combination schemes between QCD and EW corrections matched to parton showers and we present a phenomenological analysis for LHC collisions, showing that NNLO QCD corrections are dominant in the bulk of the cross section while EW effects become non-negligible in the tails of kinematic distributions. We also present a comparison with recent ATLAS data, finding very good agreement with our theoretical predictions.

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1. Introduction

Multiboson production provides a fundamental test of the gauge structure of the electroweak (EW) sector of the Standard Model (SM), and its interplay with the scalar one. In this proceeding we present a method to reach NNLO QCD and NLO EW accuracy matched to parton showers using the MiNNLO$_{\rm PS}$ method [1]. We consider $W^{\pm}Z$ production with fully leptonic decays, which plays a crucial role among multiboson processes thanks to the large cross section and the clean experimental signature.

2. The method

We consider $W^{\pm}Z$ production with leptonic decays of the two vector bosons, $pp \to \ell^+\ell^-\ell'^{\pm}\nu_{\ell'}$, with $\ell' \neq \ell$ and $\ell' = \ell$. To reach NNLO QCD and NLO EW accuracy matched to partons showers, we follow a three-step procedure:

First: We separately generate NNLO QCD and NLO EW accurate results. NNLO QCD results are obtained using the MiNNLO$_{\rm PS}$ method [2, 3]. The fully differential MiNNLO$_{\rm PS}$ cross section for the production of a colour singlet F is obtained from a Powheg calculation [4–6] for F+J, where J is a light jet, as follows:

$$\mathrm{d}\sigma_{\rm F}^{\rm MiNNLO_{PS}} = \mathrm{d}\Phi_{\rm FJ}\, \bar{B}^{\,\rm MiNNLO_{PS}} \times \left\{ \Delta_{\rm pwg}(\Lambda_{\rm pwg}) + \mathrm{d}\Phi_{\rm rad}\, \Delta_{\rm pwg}(p_{\rm T,rad})\, \frac{R_{\rm FJ}}{B_{\rm FJ}} \right\} . \tag{1}$$

The curly bracket represents the Powheg emission probability for the first emission, which is produced with the correct matrix element. $B_{\rm FJ}$ and $R_{\rm FJ}$ are the squared tree-level and real matrix elements for FJ production, respectively. $\Delta_{\rm pwg}$ is the Powheg Sudakov form factor (with $\Lambda_{\rm pwg} = 0.89\,\mathrm{GeV}$). The $\bar{B}^{\,\rm MiNNLO_{PS}}$ function reads

$$\bar{B}^{\,\rm MiNNLO_{PS}} = e^{-S} \left\{ \frac{\mathrm{d}\sigma_{\rm FJ}^{(1)}}{\mathrm{d}\Phi_{\rm FJ}} \left(1 + S^{(1)}\right) + \frac{\mathrm{d}\sigma_{\rm FJ}^{(2)}}{\mathrm{d}\Phi_{\rm FJ}} + \left(D - D^{(1)} - D^{(2)}\right) \times F^{\rm corr} \right\} , \tag{2}$$

where $\mathrm{d}\sigma_{\rm FJ}^{(1,2)}$ represent the LO and NLO differential FJ cross sections, S is an appropriate Sudakov form factor ($S^{(1)}$ is the $O(\alpha_s)$ coefficient in its expansion), and $(D - D^{(1)} - D^{(2)})$ represents the α_s^3 correction needed to reach NNLO accuracy. This term is obtained from $p_{\rm T}$-resummation

$$\mathrm{d}\sigma_{\rm F}^{\rm res} = \frac{\mathrm{d}}{\mathrm{d}p_{\rm T}} \left\{ e^{-S} \mathcal{L} \right\} = e^{-S} \left\{ -S' \mathcal{L} + \mathcal{L}' \right\} \equiv e^{-S}\, D\,, \tag{3}$$

where $\mathcal{L}$ is the luminosity factor up to NNLO. The $(D - D^{(1)} - D^{(2)})$ contribution is spread over the full FJ phase space according to a suitable function $F^{\rm corr}$. More details on the method can be found in [2, 3]. For the generation of NLO EW accurate events, we use the standard Powheg approach.

Second: We shower our events using Pythia8 [7] and we apply a veto procedure. We let the parton shower generate QCD and QED emissions in the whole allowed phase space and then we accept or reject the event according to its shower history. When showering NNLO QCD accurate events, we restrict the phase space of QCD emissions according to the usual Powheg veto, i.e.

QCD emissions produced by Pythia8 must have a transverse momentum smaller than the one of the radiation produced by Powheg. In this case, QED radiation is unconstrained. By contrast, when showering NLO EW accurate results we apply a veto on QED emissions while QCD radiation is unconstrained. Note that here we use the the multiple-radiation scheme of Powheg [8].

Third: We combine $\mathrm{NNLO}_{\mathrm{QCD}}$+PS and $\mathrm{NLO}_{\mathrm{EW}}$+PS results at the level of differential distributions using the following combination schemes:

1. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} + \delta\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD+EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} \to$ DEFAULT ADDITIVE
2. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} + \delta\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}}$
3. $\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} + \delta\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$
4. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} \times \text{K-NLO}_{\mathrm{EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} \to$ DEFAULT MULTIPLICATIVE
5. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} \times \text{K-NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}}$
6. $\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} \times \text{K-NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$
7. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \text{K-NLO}_{\mathrm{EW}}^{(\mathrm{f.o.})}$

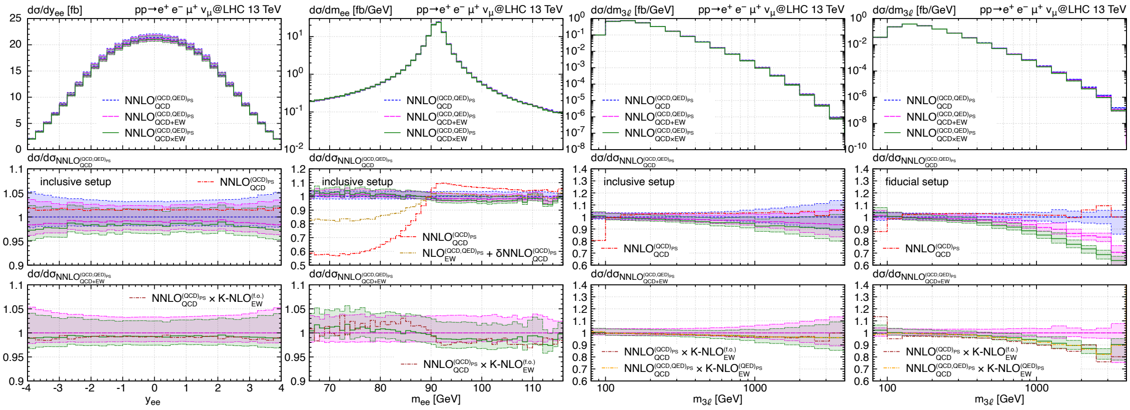
where $\mathrm{(N)NLO}_{\mathrm{X}}^{(\mathrm{Y})_{\mathrm{PS}}}$, with $\mathrm{X} \in \{\mathrm{QCD, EW}\}$ and $\mathrm{Y} \in \{\mathrm{QCD, QED, QCD\ and\ QED}\}$, refers to the (N)NLO calculation in X perturbation theory matched to Y parton showers. Moreover, $\delta\mathrm{N(N)LO}_{\mathrm{X}}{}^{(\mathrm{Y})_{\mathrm{PS}}} = \mathrm{N(N)LO}_{\mathrm{X}}^{(\mathrm{Y})_{\mathrm{PS}}} - \mathrm{LO}_{\mathrm{X}}^{(\mathrm{Y})_{\mathrm{PS}}}$, and $\text{K-N(N)LO}_{\mathrm{X}}^{(\mathrm{Y})_{\mathrm{PS}}} = \mathrm{N(N)LO}_{\mathrm{X}}^{(\mathrm{Y})_{\mathrm{PS}}}/\mathrm{LO}_{\mathrm{X}}^{(\mathrm{Y})_{\mathrm{PS}}}$. These combinations are NNLO QCD and NLO EW accurate and consistently matched to QCD and QED parton showers. Note that in 7 the EW K-factor is obtained at fixed order.

3. Phenomenological results

We consider $pp \to \mu^+\nu_\mu e^+e^-$ at 13 TeV LHC collisions. Our inputs are defined in section 3.1 of the original publication [1]. We use two different setups: in the `inclusive setup`, we consider $66\,\mathrm{GeV} < m_{e^+e^-} < 116\,\mathrm{GeV}$, while in the `fiducial setup` we require $|m_{e^+e^-} - m_Z| < 10\,\mathrm{GeV}$, $p_{T,e^\pm} > 15\,\mathrm{GeV}$, $p_{\mathrm{T},\mu} > 20\,\mathrm{GeV}$, $|\eta_\ell| < 2.5$, $m_{\mathrm{T},W} > 30\,\mathrm{GeV}$, $\Delta R_{e^+e^-} > 0.2$, $\Delta R_{e^\pm\mu} > 0.3$.

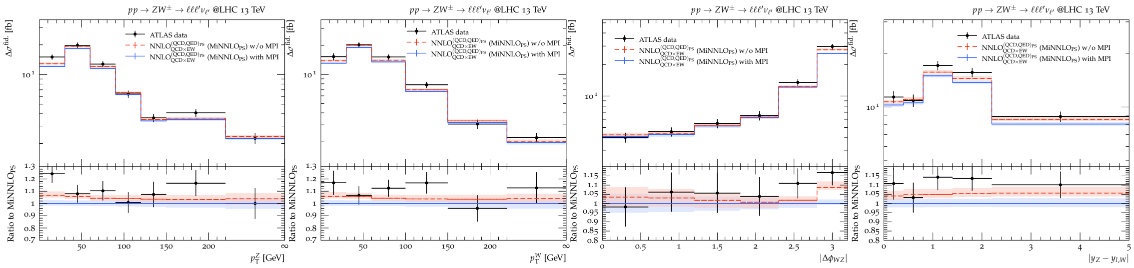
We start from the rapidity distribution $y_{e^+e^-}$ of the reconstructed Z boson in the `inclusive setup` (fig. 1a). Pure QED effects are of order −1–2%, while weak corrections are of order −2–3%. Our default additive and multiplicative combinations are in perfect agreement with $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \text{K-NLO}_{\mathrm{EW}}^{(\mathrm{f.o.})}$, as this observable in not affected by photon emissions after the first one. In fig. 1b we show the invariant mass $m_{e^+e^-}$ of the reconstructed Z boson in the `inclusive setup`. The pure QCD combination $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$ misses important collinear QED effects, which are of order 40% in the low mass region ($m_{e^+e^-} \simeq 70$ GeV). The same conclusion holds for $\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} + \delta\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$, as the QED shower is not included on top of the NNLO calculation. Note that our default multiplicative and additive results are in excellent agreement with both $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$ and $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \text{K-NLO}_{\mathrm{EW}}^{(\mathrm{f.o.})}$. In figs. 1c and 1d, we present the invariant mass $m_{3\ell}$ of the three charged leptons in the `inclusive setup` and `fiducial setup`, respectively. We observe that EW effects become larger when fiducial cuts are applied. This behaviour is associated to very

Figure 1



(a) **(b)** **(c)** **(d)**

Figure 2



(a) **(b)** **(c)** **(d)**

forward regions where EW Sudakov logarithms are suppressed. When considering a fiducial setup, these regions are excluded and we thus observe an enhancement of EW effects.

In fig. 2 we present a comparison with ATLAS data [9] using as nominal prediction the default multiplicative scheme $\mathrm{NNLO}^{(\mathrm{QCD},\mathrm{QED})_{\mathrm{PS}}}_{\mathrm{QCD}\times\mathrm{EW}}$. The corresponding Rivet analysis [10] is provided on the `HEPdata` webpage https://www.hepdata.net/record/ins1720438. The results refer to the differential cross section for $W^{\pm}Z$ production averaged over all combinations of electrons and muons in the final state. We present the transverse momentum of the Z boson $p_{\mathrm{T},Z}$ (2a), the transverse momentum of the W boson $p_{\mathrm{T},W}$ (2b), the opening azimuthal angle between the Z and the W bosons $\Delta\phi_{WZ}$ (2c) and the absolute difference in rapidity between the Z boson and the charged lepton coming from the W decay $|y_Z - y_{\ell_W}|$ (2d). We present results with (blue curve) and without (red curve) multi-particle interactions (MPI). We observe a very good agreement between our predictions and data, both in the bulk of the cross section, where QCD is dominant, and in the tails of distributions, where EW effects are crucial. Note that MPI effects determine a shift of our predictions of -5%.

4. Conclusions

We presented a method to reach NNLO QCD and NLO EW accuracy consistently matched to parton showers using the MiNNLO$_{\mathrm{PS}}$ method. We showed phenomenological results for $W^{\pm}Z$ production for 13 TeV LHC collisions and we performed a comparison with ATLAS data, finding a good agreement with our predictions.

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