PROCEEDINGS OF SCIENCE

NLO QCD+EW for V+jets

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In this contribution recent results regarding the NLO electroweak corrections for vector boson production in association with jets are presented. Besides discussing the phenomenology of the fixed-order results, their incorporation in existing NLO QCD parton shower matched and merged calculations, which can directly be used in experimental analyses, will be shown.

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1. Introduction

The production of electroweak gauge bosons, frequently accompanied by one or multiple jets, plays a key role in the physics programme of the Large Hadron Collider. When decaying into leptons, the comparatively clean final state offers unique opportunities to test the Standard Model at the highest precisions. Simultaneously, vector boson production in association with multiple jets represents a large and therefore important background to many new physics searches.

As predictions for vector boson plus jets at next-to leading order (NLO) in QCD [1, 2, 3, 4, 5, 6, 7] are widely available, and the calculation of $V+1$jet final states is even known at next-to-next-to leading order (NNLO) [8, 9, 10, 11, 12, 13], electroweak (EW) corrections become increasingly important. They are relevant both for precision observables and measurements in the TeV regime where large Sudakov logarithms can lead to sizeable reductions of cross sections [14, 15, 16, 17, 18, 19]. While specific calculations for low multiplicity processes were available for some time [20, 21, 22, 23, 24], the recent automation of the generation of one-loop scattering amplitudes delivered the flexibility to calculate NLO EW corrections for processes with multiple jets in the final state [25, 26, 27, 28]. Automated implementations of the pure virtual Sudakov corrections are also available [29].

2. Next-to-leading order electroweak corrections

Next-to leading order electroweak corrections to (off-shell) vector boson ($V=W,Z,\gamma$) plus multijet production exhibit a rich internal structure. Apart from the occurrence of loop diagrams with multiple (different) internal masses, interferences from diagrams of different order in the QCD and EW couplings, g_s and e, are encountered as soon as four external quarks are present in the process. Thus, QCD and EW corrections cannot solely be classified as corrections due to real and virtual parton or photon emissions, respectively, but have to be defined through a power counting of the couplings involved: given a Born process at $\mathscr{O}(\alpha_s^n\alpha^m)$, NLO QCD corrections are defined as corrections of $\mathscr{O}(\alpha_s^{n+1}\alpha^m)$ while NLO EW corrections are of $\mathscr{O}(\alpha_s^n\alpha^{m+1})$. Consequently, NLO EW real corrections also involve processes with no external photons but an emergent pair of quarks or a gluon.

To calculate the NLO QCD and EW corrections to $W+n$jets ($n=1,2,3$) we use the fully automated frameworks of MUNICH+OPENLOOPS and SHERPA+OPENLOOPS . Therein, OPENLOOPS [30, 31] provides the renormalised one-loop matrix elements while either MUNICH or SHERPA [32, 33] arrange for phase space integration and process management. While MUNICH uses OPENLOOPS matrix elements for the Born and real emission matrix elements as well as in its Catani-Seymour [34, 35] subtraction, SHERPA employs its own internal matrix element generators AMEGIC [36] and COMIX [37]. This duality of approaches is used to provide independent cross checks of the results. OPENLOOPS uses the COLLIER [38] tensor reduction library, employing CUTTOOLS [39] and ONELOOP [40] for re-evaluating unstable phase space points.

Fig. 1 presents the NLO QCD and NLO EW corrections on the transverse momentum of the W boson and the leading jet in events with at least one jet. The inclusive corrections are shown on the left. As can be seen, the NLO QCD corrections alone amount to an increase in the cross section of several hundred percent at large p_{T} [41]. This effect originates in the opening

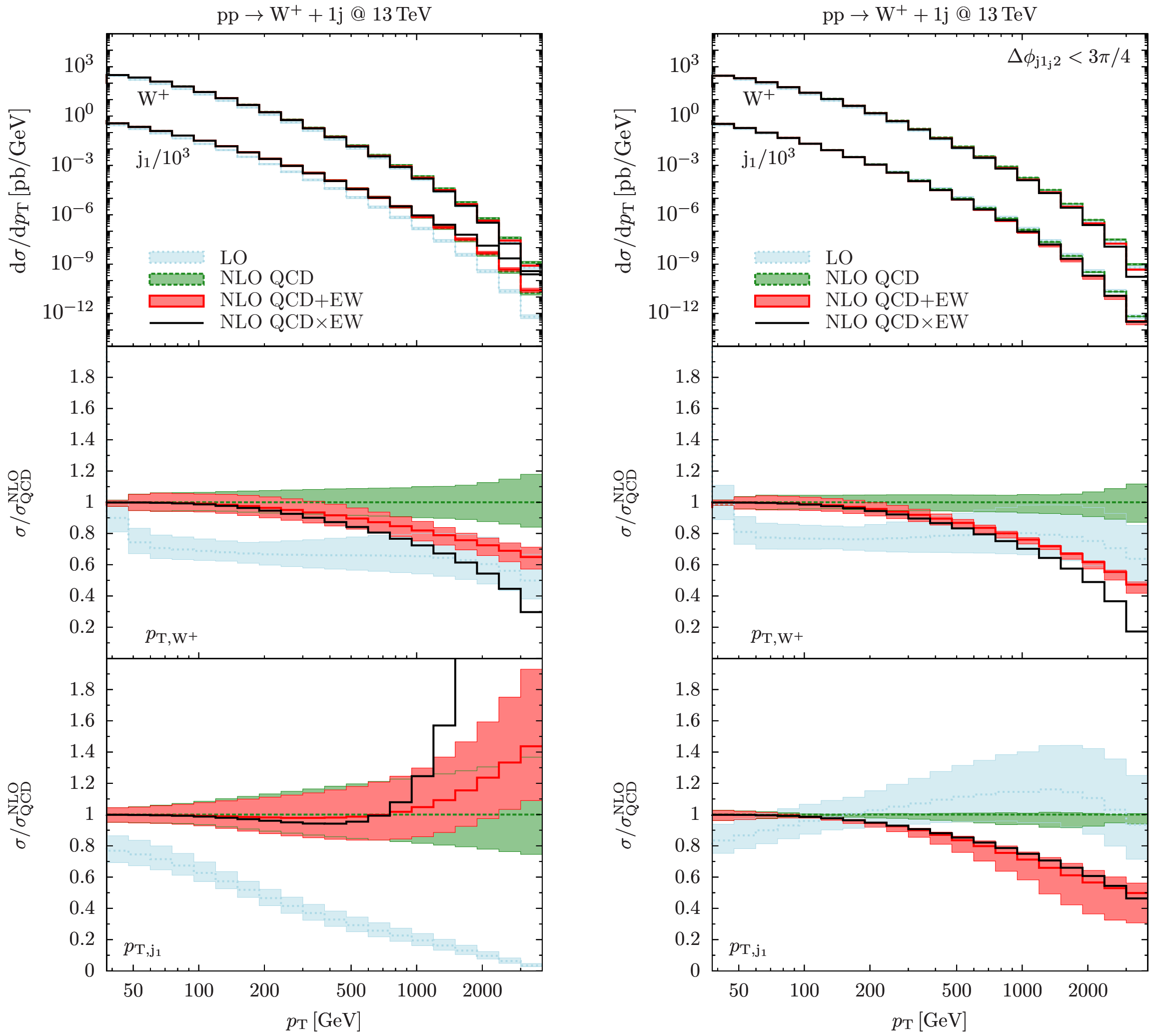

Figure 1: NLO QCD and EW corrections to the W-boson and leading jet transverse momenta in $pp \to W^+ j$ at 13 TeV at the LHC. While both types of corrections are dominated by real radiation $pp \to W^+ jj$ topologies featuring back-to-back dijet topologies and subsequently atypically large K-factors in the inclusive case (left), vetoing such configurations (right) recovers the standard behaviour.

of an alternative channel of production of a W boson in association with two jets encountered in the real corrections: a hard and nearly back-to-back dijet system radiates a comparably soft W boson. As these configurations can be interpreted as a NLO real EW boson emission corrections to dijet production, it inherits its large initial cross section and dominates in the high-p_T region of the leading jet, but not of the W boson. Consequently, its accuracy is reduced to be effectively leading order. Similar observations can be made for the NLO EW corrections. This artefact is best remedied by a multijet merged approach, treating the troublesome dijet plus W configurations at next-to leading order as well. In the absence of such a merging in a fixed-order calculation the offending contributions can simply be vetoed, e.g. by requiring the azimuthal separation of the two leading jets to be at most $\frac{3\pi}{4}$. The results for such a vetoed calculation are shown on the right hand side of Fig. 1. Here, modest NLO QCD and typical Sudakov-type NLO EW corrections are

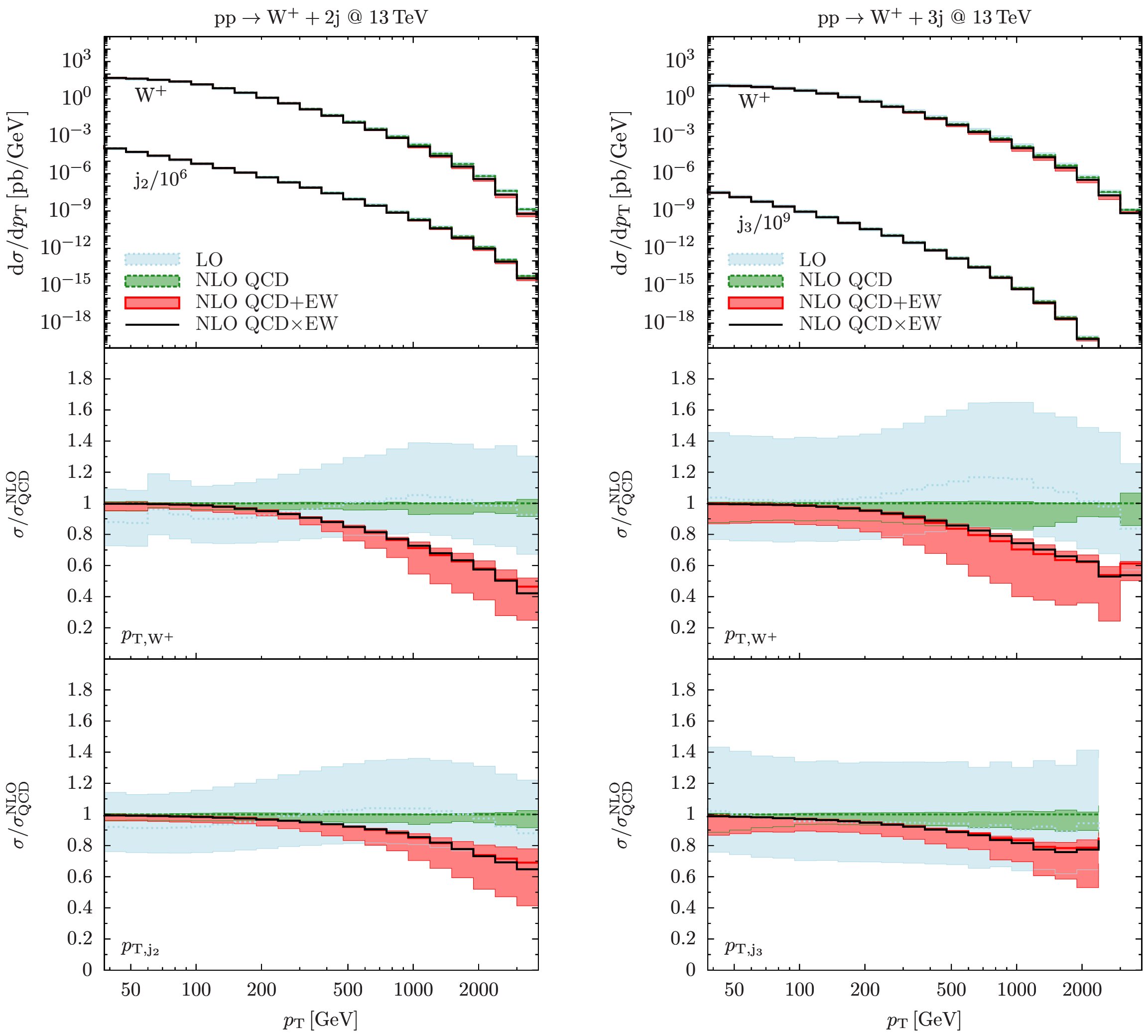

Figure 2: NLO QCD and EW corrections to the W-boson and subleading and third leading jet transverse momenta, respectively, in $pp \to W^+jj$ (left) and $pp \to W^+jjj$ (right) at 13 TeV at the LHC.

recovered.

NLO QCD and EW corrections for the transverse momentum and the second and third leading jet in the higher multiplicity $W+2j$ and $W+3j$ events, respectively, are displayed in Fig. 2. As the Sudakov-type NLO EW corrections in the TeV regime become smaller for each subleading jet, so they do for the W boson itself. The results of [26] using on-shell bosons were quantitatively reproduced with an off-shell calculation using the full leptonic final state in [27].

These results were then directly used to produce theoretical predictions for the Z/γ-ratio in dependence on the (reconstructed) boson transverse momentum [44, 42, 45] in events with at least one jet accompanying the reconstructed Z boson or the photon, cf. Fig. 3 (left). As can be seen, the pure NLO QCD calculation predicts a slightly too large ratio. The electroweak correction, acting differently in both processes due to the different EW charge of the Z boson as compared to the photon, lower the ratio and improve the data description significantly.

Similarly, analyses focussed on finding W boson emissions off high-p_T jets [46], simplified

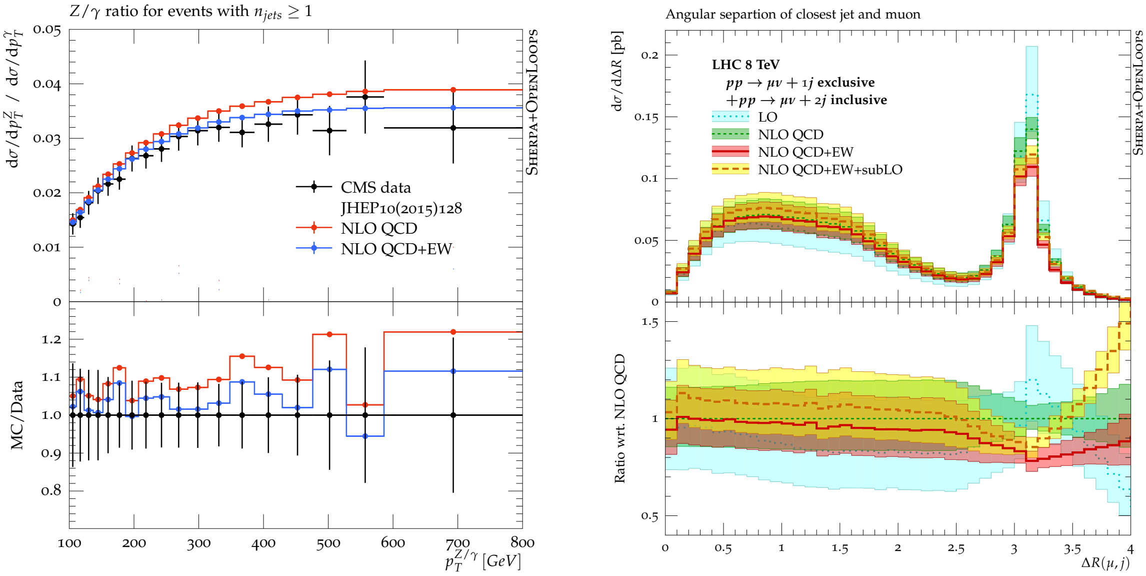

Figure 3: *Left*: Ratio of the transverse momentum of the reconstructed Z-boson and the photon in $pp \to \ell^+\ell^- j$ and $pp \to \gamma j$, respectively, compared to data taken by the CMS collaboration at the LHC at 8 TeV [42]. *Right*: Angular separation of the muon and the closest jet in $pp \to W + \text{jets}$ production with $p_\mathrm{T}^{j_1} > 500\,\mathrm{GeV}$ at the LHC at 8 TeV, a comparison to data can be found in [43].

for the limited reach at 8 TeV, primarily measure the angular separation of the muon and the closest jet. As in this observables the region $\Delta R \gtrsim \pi$ is already defined in $W + 1j$ production but $\Delta R \lesssim \pi$ is only populated with $W + 2j$ events, an exclusive-sums approach (using $p_\mathrm{T}^{j_2,\text{cut}} = 100\,\mathrm{GeV}$ as discriminator) is taken. Fig. 3 (right) displays the NLO QCD+EW prediction for this observable including comparatively large subleading Born contributions. The yet unpublished study in [43] shows excellent agreement with data, especially where electroweak corrections are sizeable.

3. Electroweak corrections in particle-level event generation

The last section demonstrated the size and impact of next-to leading order electroweak corrections. However, they need to be incorporated in particle level event generators in order to be directly applied in experimental analyses. As a proper generic NLO QCD+EW matching to parton showers is still to be formulated, the following outlines an approximation that is designed to capture the dominant Sudakov-type corrections in the TeV regime as well as non-logarithmic ones over the whole phase space.

The basis for this approximation is Sherpa's MEPs@Nlo [47, 48, 49, 50] multijet merging algorithm at NLO QCD accuracy. As it bases on an Mc@Nlo-type approach [51, 52, 53, 54, 55, 56] for matching the NLO QCD computation to the parton shower [57], its $\overline{\mathrm{B}}$-function, labelled $\overline{\mathrm{B}}_\mathrm{QCD}$ in the following, can be extended for the n parton final state to

$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)\,. \tag{3.1}$$

Herein, $\mathrm{V}_{n,\mathrm{EW}}(\Phi_n)$ are the renormalised one-loop electroweak corrections while $\mathrm{I}_{n,\mathrm{EW}}(\Phi_n)$ are the approximated real emission corrections integrated over the one-particle emission phase space,

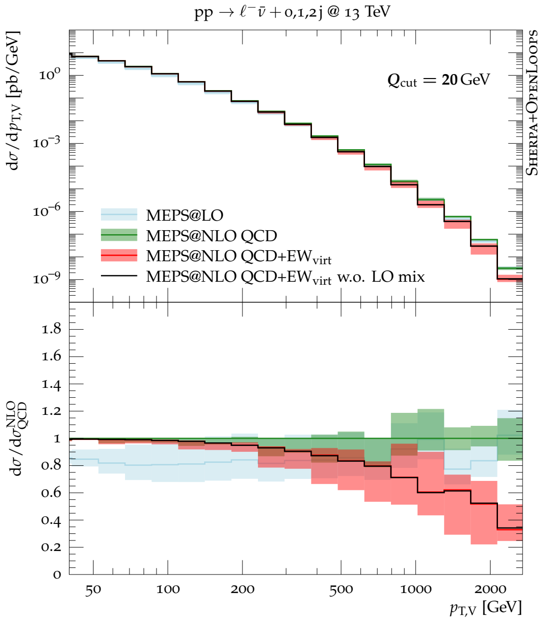

Figure 4: Incorporation of approximate NLO EW corrections into the standard NLO QCD multijet merging for the transverse momenta of the reconstructed W-boson (left) and leading jet (right) in $pp \to \ell^- \bar{\nu}_\ell + \text{jets}$ at 13 TeV at the LHC.

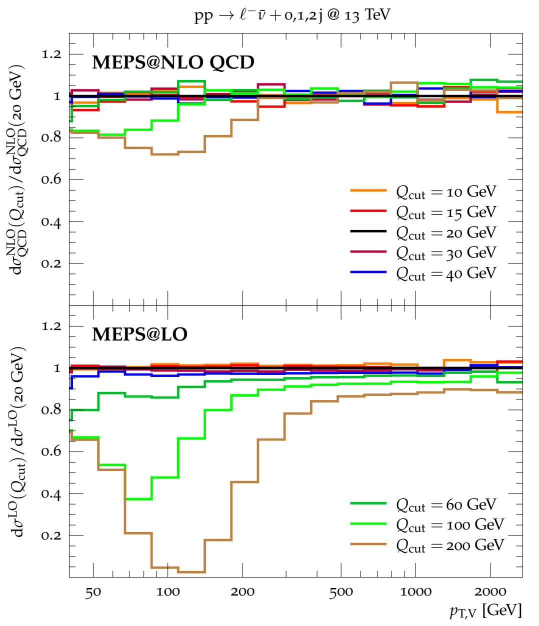

Figure 5: Dependence of the reconstructed W-boson (left) and leading jet (right) transverse momenta on the merging parameter Q_cut in the LO (bottom) and NLO (top) QCD multijet merged calculation for $pp \to \ell^- \bar{\nu}_\ell + \text{jets}$ at 13 TeV at the LHC.

such that their sum yields a finite result. Optionally, subleading Born contributions, $\mathrm{B}_{n,\text{mix}}$, can be included when numerically relevant. This approach neglects the kinematical impact of real photon radiation dominant in e.g. leptonic observables. It can be recovered, however, by making use of standard QED radiation tools [58] which have been shown to be superior to a fixed order calculation for these observables [45].

Fig. 4 now again shows the transverse momentum distribution of the W boson on the left hand side and the leading jet on the right hand side obtained when calculating $W+$jets production with the above outlined method including up to two jets at (approximate) next-to leading order accuracy. As can be seen, very similar quantitative electroweak corrections are recovered in the TeV regime. Further, due to the consistent treatment of one and two jet final states the issue of potentially large corrections at large transverse momenta has been resolved in the merged calculation and the typical behaviour for the leading jet is recovered. For this observable, also the subleading Born contributions are of importance as they significantly reduce the impact of the electroweak corrections due to their opposite sign.

For the above prediction the standard merging cut of $Q_{\text{cut}} = 20\,\text{GeV}$ has been used. Following the Q_{cut}-dependence analysis of the method provided in [49, 50] large uncancelled logarithms could in principle emerge. A direct quantification through varying the merging parameter Q_{cut} yields the results presented in Fig. 5, showing negligible dependences for a large range of Q_{cut} values if varied around a sufficiently small central value.

4. Conclusions

The automation of NLO EW corrections within the MUNICH+OPENLOOPS and SHERPA+OPENLOOPS frameworks provide indispensable input for many high precision or TeV regime analyses at Run II of the LHC. A method for incorporation of approximate NLO EW corrections into established multijet merging methods at NLO QCD accuracy has been introduced and is publicly available within SHERPA-2.2.1. This formulation allows for particle level, and therefore potentially detector simulated, fully realistic event simulation. It represents a first, albeit very useful, step towards a complete NLO QCD+EW matching and multijet merging.

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