PROCEEDINGS OF SCIENCE

Vector-boson production at the LHC: QCD and electroweak effects

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A profound understanding of vector-boson production processes is of crucial importance at the LHC. The corresponding cross sections are large, and the final states are easy to reconstruct due to the clean signatures in the leptonic decay modes. Therefore, such processes play an important role as backgrounds in a large variety of new-physics signals, and they may furthermore help to better understand the well-established Standard-Model physics in a hadron-collider environment. We review the recent progress in the theoretical description of higher-order QCD and electroweak effects in vector-boson production at the LHC, discussing the Drell–Yan process, vector-boson pair production and vector-boson production with associated jets.

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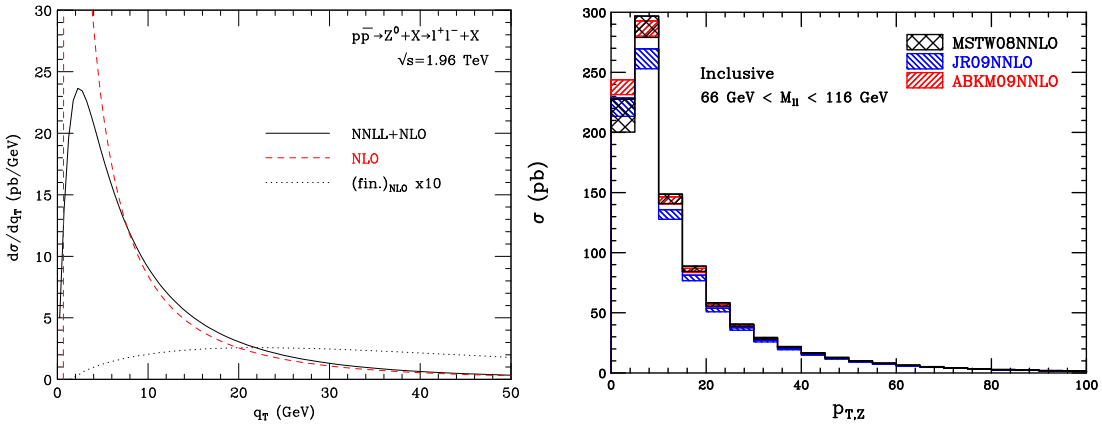

Figure 1: Left: Comparison of the resummed result at NNLL accuracy to the fixed-order computation at the Tevatron [5] for the Drell–Yan process. The fixed-order prediction fails for $q_{\mathrm{T}} < 10\,\mathrm{GeV}$. $((\mathrm{fin.})_{\mathrm{NLO}}$: Non-logarithmically-enhanced contributions). Right: Distribution of the Z-boson transverse momentum at NNLO accuracy for different PDF sets at the LHC (`FEWZ` [8]).

1. The Drell–Yan process

A proper understanding of the charged-current (CC) and neutral-current (NC) single vector-boson production process $\mathrm{pp} \to \mathrm{W}^{\pm}/\mathrm{Z}, \gamma^* \to l\nu_l/l\bar{l}$ is an important task at the LHC. Such processes have a clean leptonic signature and are therefore well suited for luminosity monitoring and detector calibration purposes. Moreover, Z-boson production will allow for a precise determination of the effective weak mixing angle at the LHC by measuring appropriate forward-backward asymmetries, while W-boson production is primarily used to precisely determine the W-boson mass M_{W} and width Γ_{W}, and to constrain the parton distribution functions (PDFs) by analyzing the $\mathrm{W}^-/\mathrm{W}^+$-ratio or the W-boson charge asymmetry $A_{\mathrm{W}}^l \equiv (\mathrm{d}\sigma_{l^+}/\mathrm{d}\eta_l - \mathrm{d}\sigma_{l^-}/\mathrm{d}\eta_l)/(\mathrm{d}\sigma_{l^+}/\mathrm{d}\eta_l + \mathrm{d}\sigma_{l^-}/\mathrm{d}\eta_l)$, respectively.

At hadron colliders, at least the knowledge of the next-to-leading-order (NLO) QCD corrections is crucial for the normalization of the total cross section, the reduction of the scale dependence, and to obtain realistic predictions for the shapes of differential cross sections. The QCD corrections to the Drell–Yan (DY) process have been studied extensively. The NLO contributions have been matched with parton showers [1, 2, 3] and combined with soft-gluon resummation [4, 5] to efficiently account for dominating contributions $\propto \alpha_{\mathrm{s}}^n \ln^m(M_V^2/q_{\mathrm{T}}^2)$ at small transverse momenta q_{T} of the vector bosons (see Fig. 1, left). Moreover, the corresponding next-to-next-to-leading-order (NNLO) two-loop corrections are known fully differentially (see Fig. 1, right) and have been implemented in Monte Carlo programs [6, 7, 8]. Even the $\mathrm{N^3LO}$ corrections are known in the soft-plus-virtual approximation [9], pushing the theoretical uncertainties due to perturbative QCD to the level of below 2% for this specific process class.

The corresponding NLO electroweak (EW) corrections have been investigated by many groups for the CC [10, 11, 12, 13, 14] and the NC [15, 16, 17] process, and tuned comparisons of different implementations have been performed. Universal higher-order corrections were included [18], and the predictions were studied in different input schemes, where corrections due to $\Delta\alpha$ and $\Delta\rho$ are

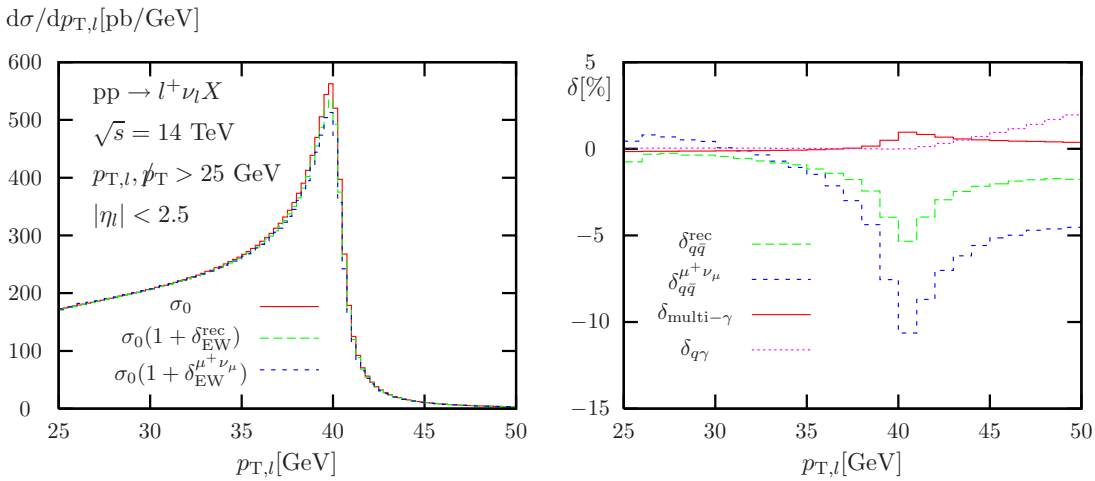

Figure 2: EW corrections to the lepton transverse momentum for the CC Drell–Yan process at the LHC [14]. Results are presented for bare muons ($\delta_{q\bar{q}}^{\mu^+\nu_\mu}$) and for electrons employing electron-photon recombination ($\delta_{q\bar{q}}^{\rm rec}$), respectively; the effects due to multi-photon radiation ($\delta_{\rm multi-\gamma}$) as well as photon-induced processes ($\delta_{q\gamma}$) are small.

absorbed in effective leading-order (LO) couplings. It was found that the relative EW corrections are nearly insensitive to the specific theoretical treatment of the vector-boson resonance and to the inclusion of virtual corrections within the MSSM, respectively [14, 17].

In general, the EW corrections at moderate energies are dominated by final-state photon radiation off leptons leading to a significant distortion of the line-shapes of the leptonic invariant-mass and transverse-momentum distributions (see Fig. 2), which strongly influences the precise determination of $M_{\rm W}$. Consequently, also the effect of multi-photon radiation has been investigated in a structure-function approach [19], and the corresponding contributions have been matched to the fixed-order $\mathcal{O}(\alpha)$ corrections within HORACE [20]. Moreover, first steps have been taken towards a combined QCD $\otimes$ EW (two-loop) analysis [21] to improve the EW accuracy to the level of better than 1%.

2. Vector-boson pair production

Vector-boson pair production processes $pp \to V_1V_2 \to 4l$ ($V_i = W^\pm, Z, \gamma$) play a key role in the understanding of irreducible backgrounds to Standard-Model (SM) Higgs production in the intermediate mass range. Moreover, they will allow us to probe the non-abelian structure of the SM at high scales, and may give hints to the existence of anomalous trilinear and quartic couplings, which are predicted to have a sizable effect at high energies accessible at the LHC. In addition, such processes constitute backgrounds to various new-physics signatures with leptons and missing transverse energy.

The NLO QCD corrections to vector-boson pair production are known for a long time, and a fully-exclusive computation of the two-loop corrections to $pp \to \gamma\gamma$ has been completed recently [22]. The NLO corrections have been matched with parton showers and combined with soft-

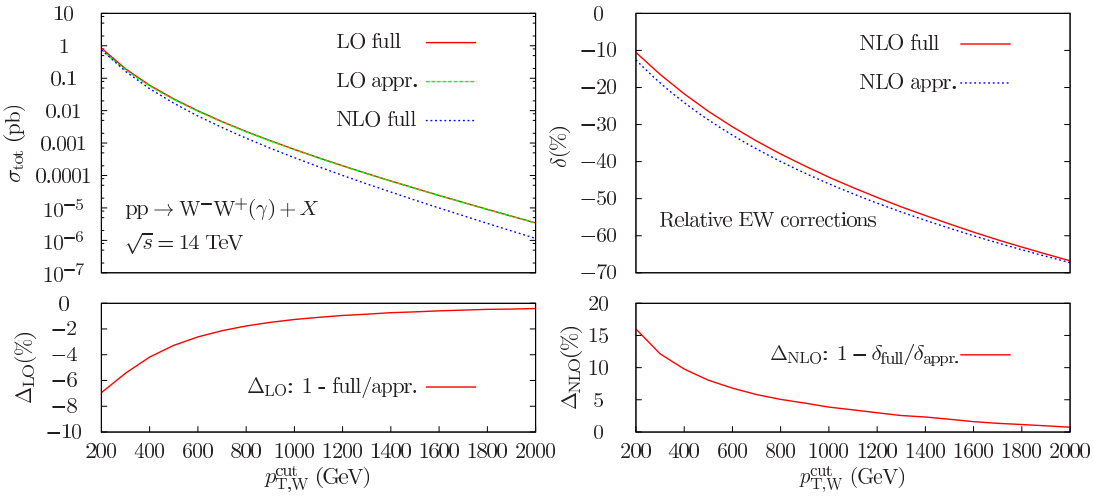

Figure 3: W-boson pair production at the LHC at 14 TeV; Left: Comparison of the full LO cross section to the high-energy approximation for different values of $p_{\rm T,W}^{\rm cut}$. Right: Same for the relative corrections (Approximate NLO corrections at NNLL accuracy). For $p_{\rm T,W}^{\rm cut} < 1\,$TeV, the approximate results become crude [26].

gluon resummation [1, 23], and the leptonic decays are accounted for in the narrow-width approximation, retaining all spin information. Although the corresponding cross sections are dominated by the $q\bar{q}$ channels, there are significant contributions from the loop-induced channels $gg \to V_1V_2$ at the LHC, especially if selection cuts for Higgs searches are applied, of up to 30% [24].

In the high-energy limit the corrections at $\mathcal{O}(\alpha)$ are known for all combinations of external vector bosons in the pole approximation [25] to facilitate a realistic phenomenological description of the final-state leptons. Recently, we have computed the full EW corrections to on-shell W-pair production at the LHC [26] and find sensible agreement with former approximate results [27] for center-off-mass energies beyond 2 TeV (see Fig. 3). For lower energies, however, the approximation becomes crude even at leading order. To this very process, also two-loop pieces are available in NNLL accuracy [27], leading to sizable positive corrections of about 10%.

3. Vector-boson production with associated jets

At the LHC, vector bosons are almost always produced together with one or more hard jets. Since the corresponding cross sections are still sizable, and due to the distinct leptonic final states, such processes may help to attain a profound understanding of SM physics in a hadron-collider environment. Moreover, V + jet(s) production also provides a good possibility to study QCD jet dynamics in great detail, and the corresponding signatures with jets, charged leptons and missing transverse energy have to be understood properly to discriminate hypothetical new-physics signals from the SM background.

The NLO QCD corrections for W/Z + 1 jet have been matched with parton showers [28], and the NLO corrections for W/Z + 2 jets are e.g. included in `MCFM` [29]. NLO results for W/Z + 3 jets have been presented by different collaborations [30], and even the NLO results for $W + 4$ jets could

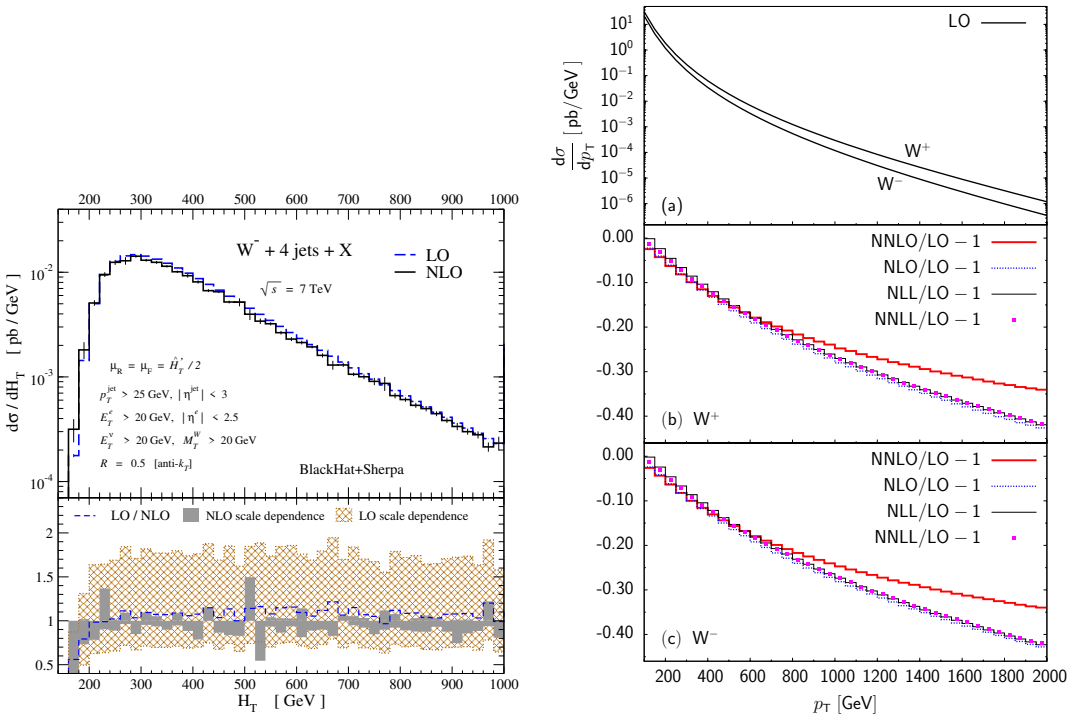

Figure 4: Left: NLO QCD corrections to W^- + 4 jets production at the LHC [31]; top: Differential distribution of the transverse energy $H_T \equiv \sum_j E_{T,j}^{jet} + E_T^e + E_T^\nu$; bottom: K-factor and scale dependence; note the marked reduction of scale uncertainties at NLO. Right: Relative EW corrections to the p_T distribution for on-shell $W^\pm$ + jet production at the LHC, and corresponding relative corrections [33]. (NNLO = NLO + 2-loop NLL; NLL and NNLL considered at one loop)

be worked out [31], using unitarity-based techniques for the automatized calculation of virtual amplitudes (see Fig. 4).

Various EW effects to W/Z + 1 jet production have been investigated, both in the on-shell [32, 33] and off-shell [34] scenario, where the leptonic decays of the vector bosons as well as finite-width effects are fully taken into account in the latter. As in the DY case, at high energies the corrections are dominated by universal large logarithms $\propto \alpha^L \ln^{2L-n}(M_V/\sqrt{s})$ ($\equiv$ N^{n}LL accuracy at L loops) which are known up to two loops in the NLL approximation (see Fig. 4), while at low and medium energies the corrections are nearly fully dominated by final-state photon radiation.

4. Conclusions

Precise theoretical predictions for vector-boson production at the LHC have been established during the recent years, where both fixed-order and resummed QCD and EW effects were considered. The accurate knowledge of Drell–Yan physics will help to further constrain the PDFs and probably enable the most accurate determination of M_W with an error of only 15 MeV at the LHC. Moreover, it will also open the door to a fruitful analysis of EW precision observables at hadron colliders. Apart from that, a profound theoretical knowledge of vector-boson pair production and V + jet(s) is mandatory to properly assess the SM backgrounds to Higgs-boson or $t\bar{t}$ production, as well as to various beyond-SM physics scenarios.

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