PROCEEDINGS OF SCIENCE

Z+jet production at the LHC: Electroweak radiative corrections

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The investigation of weak bosons V ($V = \mathrm{W}^{\pm}, \mathrm{Z}$) produced with or without associated hard QCD jets will be of great phenomenological interest at the LHC. Owing to the large cross sections and the clean decay signatures of the vector bosons, weak-boson production can be used to monitor and calibrate the luminosity of the collider, to constrain the PDFs, or to calibrate the detector. Moreover, the Z+jet(s) final state constitutes an important background to a large variety of signatures of physics beyond the Standard Model.

To match the excellent experimental accuracy that is expected at the LHC, we have worked out a theoretical next-to-leading-order analysis of V+jet production at hadron colliders. The focus of this talk will be on new results on the full electroweak corrections to $\mathrm{Z}(\rightarrow l^- l^+)$+jet production at the LHC. All off-shell effects are included in our approach, and the finite lifetime of the Z boson is consistently accounted for using the complex-mass scheme. In the following, we briefly introduce the calculation and discuss selected phenomenological implications of our results.

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1. Introduction

The survey of Standard Model weak-boson production is an important task in the era of LHC physics. The investigation of inclusive Z-boson production is of special importance, since the production cross section is comparably large, and the two charged leptons in the final state allow for a precise event reconstruction, e.g. for a precise measurement of the invariant mass M_{ll} and the transverse momentum $p_{\mathrm{T},ll}$ of the intermediate boson. Therefore, such events are well suited to monitor and to calibrate the luminosity of the collider, to determine the lepton energy scale and the detector resolution, as well as to test the linearity of the detector response. Finally, the Drell–Yan process also plays an important role in a precise determination of the W-boson mass and width.

At the LHC, Z bosons will often be accompanied by one or more hard QCD jets. On the one hand, such processes constitute a significant background to various scenarios of physics beyond the Standard Model that might be discovered at the LHC. On the other hand, the study of V+jets ($V = \mathrm{W}/\mathrm{Z}$) events at the LHC may help us to gain a deeper understanding of QCD and jet physics in general.

The next-to-leading-order (NLO) QCD corrections to Z+jet and Z+2jets production at hadron colliders are known for a long time [1, 2]. They are implemented in Monte Carlo generators [2] and recently Z+jet production has been matched with parton showers [3]. In the past year, NLO QCD results for V+3jets and even W+4jets production were presented [4]. However, until now only the purely virtual weak corrections to on-shell Z+jet production have been calculated for the LHC [5], including next-to-leading-logarithmic and next-to-next-to-leading-logarithmic approximations. In Ref. [5], the focus was on the high-energy behaviour of the cross section and the dominating universal high-energy logarithms. Complementary to those results, in this work we present the full NLO electroweak (EW) corrections to off-shell Z+1jet production at the LHC, taking into account the leptonic decay of the Z boson to allow for a realistic event definition.

2. Details of the calculation

In this section we briefly introduce the setup of the calculation which closely follows the setup explained in detail in Ref. [6] in the context of W+jet production. For more process-specific details on Z+jet production we refer the reader to our forthcoming publication on the subject.

At tree level, three partonic channels contribute to the processes $\mathrm{pp/p\bar{p}} \to \mathrm{Z}/\gamma + \mathrm{jet} \to l^- l^+ +$ jet,

$$(i) \quad q\bar{q} \to \mathrm{Z}/\gamma + \mathrm{g}\,, \qquad (ii) \quad q\mathrm{g} \to \mathrm{Z}/\gamma + q\,, \qquad (iii) \quad \mathrm{g}\bar{q} \to \mathrm{Z}/\gamma + \bar{q}\,,$$

with $q = \mathrm{u,d,c,s,b}$ denoting the active quarks. The QCD parton in the final state (quark or gluon) will eventually be detected as a hard jet in the hadronic calorimeter after hadronization.

The finite lifetime of the Z boson is accounted for by including the corresponding decay width Γ_Z in the Z-boson propagator. We work in the *complex-mass scheme (CMS) for unstable particles* [7], which enables a consistent and gauge-invariant treatment of finite-lifetime effects in one-loop calculations. In the CMS, the vector-boson masses M_V are consequently replaced by complex parameters, $M_V^2 \to \mu_V^2 = M_V^2 - \mathrm{i} M_V \Gamma_V$, in the propagators *and* in the definition of all derived quantities, for example the weak mixing angle, i.e. $\cos\theta_\mathrm{w}^2 \equiv \mu_\mathrm{W}^2/\mu_\mathrm{Z}^2$.

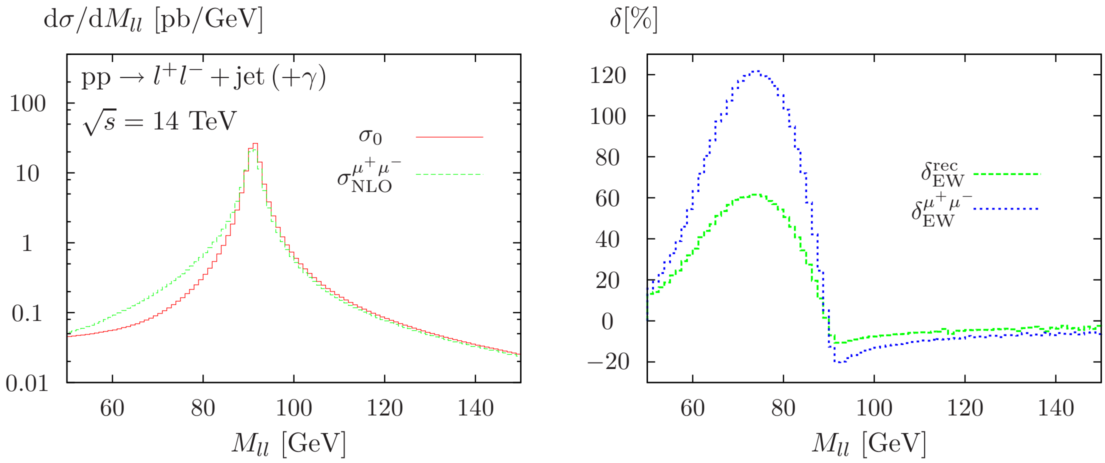

Figure 1: EW corrections (right) to the invariant-mass distribution of the lepton pair (left). Corrections for bare muons ($\delta_{\mathrm{EW}}^{\mu^+\mu^-}$) and for recombination of collinear lepton–photon pairs ($\delta_{\mathrm{EW}}^{\mathrm{rec}}$) are shown.

The computation of the full $\mathscr{O}(\alpha)$ corrections to Z+jet production requires the calculation of real bremsstrahlung corrections due to photon emission as well as the calculation of one-loop virtual corrections. Both real and virtual corrections give rise to so-called *infrared (IR) singularities* connected with soft and/or collinear photon emission. These singularities are regularized either dimensionally or alternatively via small lepton and quark masses and an infinitesimal photon mass λ and appear as $\ln m_l$, $\ln m_q$, and $\ln\lambda$ terms in intermediate steps of the calculation. In mass regularization the $\ln\lambda$-dependence drops out after combining virtual and real contributions, and residual $\ln m_q$-terms attributed to initial-state photon radiation off quarks are absorbed in the renormalized parton distribution functions (PDFs) similar to a QCD factorization prescription. Since we discard events with collinear parton–photon pairs in the final state if the photon is sufficiently hard to distinguish Z+jet from Z+photon production, the calculation is not collinear safe. Hence, it is necessary to introduce a *photon fragmentation function* [8, 6] to avoid unphysical $\ln m_q$-terms in the physical cross section, which indicate that the collinear quark–photon physics cannot be understood in a purely perturbative approach.

In contrast to the quark masses, the lepton masses have a well-defined physical meaning and allow for the purely perturbative calculation of *collinear-safe* and *non-collinear-safe* observables with respect to collinear lepton–photon splittings. We consider event definitions with and without recombination of collinear lepton–photon configurations in the electron and (bare) muon final state, respectively, observing corrections enhanced by $\ln m_\mu$-terms in the latter case (see Section 3). We use an extended version [9] of the dipole subtraction formalism which allows one to analytically extract the $\ln m_\mu$-terms for non-collinear-safe observables.

3. Numerical results

In this section we discuss the distributions in the invariant mass M_{ll} and the transverse mass $M_{\mathrm{T},ll}$ of the final-state lepton pair, where we focus on the results for the LHC at 14 TeV. The event-selection criteria applied in our calculation are similar to the W+jet calculation which can be found

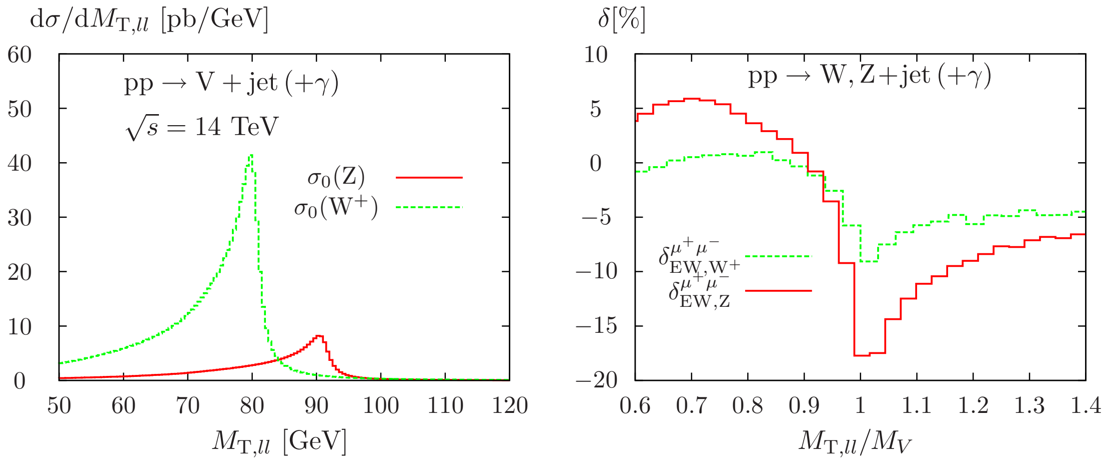

Figure 2: EW corrections (right) to the transverse-mass distribution of the lepton pair (left). Z+jet and W+jet production are compared for bare muons.

in Chapter (3.2) of Ref. [6]. For Z+jet production with two charged leptons in the final state, we ask for a transverse momentum $p_{\mathrm{T},l} > 25$ GeV and a rapidity $|y_l| < 2.5$ for both leptons. Moreover, we require a minimal invariant mass $M_{ll} > 50$ GeV.

Figure 1 shows the typical Breit–Wigner shape of the M_{ll} distribution at leading order (left) and the effect of the relative EW corrections (right). We observe dramatic positive corrections below the peak at M_{Z} which are even larger than in the single-Z case (see Fig. (12) in Ref. [10]), but exhibit a similar qualitative behaviour. These huge effects can easily be allocated to photon radiation off the final-state leptons, which systematically shifts events to lower values of M_{ll}, where the tree-level cross section is small. Of course, the relative corrections $\delta^{\mathrm{rec}}_{\mathrm{EW}}$ for collinear-safe observables (electrons in the final state) are much smaller than the corrections $\delta^{\mu^+\mu^-}_{\mathrm{EW}}$ for bare muons, since in the collinear-safe case electron and photon are recombined to a new (jet-like) quasi-particle that enters the cut procedure. Therefore, the kinematics is not changed drastically in the collinear phase-space region, where the matrix elements for photon emission are large.

The investigation of transverse-mass distributions allows one to directly compare W- and Z-boson production, since the analogue of $M_{\mathrm{T},ll}$ is also a well-defined observable for W bosons. Concerning the LO cross section, the left-hand side of Fig. 2 shows the Jacobian peak located at the vector-boson mass and the rapid decrease for larger values of $M_{\mathrm{T},ll}$. Again, the EW radiative corrections (right) are dominated by final-state photon emission; they induce positive contributions below and negative contributions at the position of the peak. Comparing the impact of the corresponding corrections for $\mathrm{Z}+\mathrm{jet}$ and $\mathrm{W}+\mathrm{jet}$ production, respectively, we observe that the effect is roughly a factor of two larger in the $\mathrm{Z}+\mathrm{jet}$ case, because—contrary to the $\mathrm{W}+\mathrm{jet}$ situation—there are two charged leptons in the final state that may emit a photon.

4. Summary

We have calculated the full $\mathcal{O}(\alpha)$ corrections to off-shell $\mathrm{Z}+\mathrm{jet}$ production with two charged leptons in the final state for the LHC and the Tevatron, where the finite width of the Z boson is consistently accounted for using the complex-mass scheme. Our approach is fully exclusive, allowing us to investigate any differential cross sections and apply any event-selection cuts that are of interest for experimentalists. The numerical analysis reveals moderate corrections to the total cross section as expected, but we find dramatic deviations in the line-shapes of fundamental leptonic observables. The quantitative behaviour of the corrections turns out to be significantly different compared to the single-Z production scenario, indicating that the indirect kinematic effects of the additional hard jet on purely leptonic observables have to be accounted for in a reliable analysis of LHC data.

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