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Electroweak corrections to $\mathrm{W}+\mathrm{jet}$ hadroproduction including leptonic W-boson decays

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This talk summarizes the first calculation of the next-to-leading-order electroweak corrections to W-boson + jet hadroproduction including leptonic W-boson decays [1]. The W-boson resonance is treated consistently using the complex-mass scheme, and all off-shell effects are taken into account. The corresponding next-to-leading-order QCD corrections have also been recalculated. All the results are implemented in a flexible Monte Carlo code. Selected numerical results for this Standard Model benchmark process are presented for the LHC.

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PoS(EPS-HEP 2009)341

1. Introduction

The production of electroweak (EW) W and Z bosons with subsequent leptonic decays is one of the cleanest and most frequent Standard Model (SM) processes at the Tevatron and the LHC. The charged-current Drell–Yan process allows for a precision measurement of the W-boson mass and width, can deliver important constraints in the fit of the parton distribution functions, may serve as a luminosity monitor at the LHC, and offers the possibility to search for new charged W′ gauge bosons. For more details we refer the reader for example to Ref. [2] and references therein, or the numerous talks on physics with EW gauge bosons at this conference.

At hadron colliders, the EW gauge bosons are (almost) always produced together with additional QCD radiation. The production cross section of W bosons in association with a hard, visible jet,

$$\mathrm{pp}/\mathrm{p}\,\overline{\mathrm{p}} \rightarrow \mathrm{W} + \mathrm{jet} \rightarrow l\nu_l + \mathrm{jet} + X, \tag{1.1}$$

is still large. The jet recoil can lead to strongly boosted W bosons, i.e. to events with high p_{T} charged leptons and/or neutrinos. Hence, $\mathrm{W}+\mathrm{jet(s)}$ production is not only a SM candle process, it is also an important background for a large class of new physics searches based on missing transverse momentum. Moreover, the process offers the possibility for precision tests concerning jet dynamics in QCD.

To match the prospects and importance of this process class, an excellent theoretical accuracy has already been achieved for the prediction of inclusive W-boson production including NNLO calculations, resummation, parton-shower matching, NLO EW corrections, and leading higher-order corrections. The production of W bosons in association with jets is now known in NLO QCD up to 3 jets [3]. An extensive list of references can be found in Ref. [1].

So far, the EW corrections in the SM have been assessed for $\mathrm{W}+1\,\mathrm{jet}$ production in an on-shell approximation where the W boson is treated as a stable external particle [4]. For W bosons at large transverse momentum, i.e. at large center-of-mass energy, this is a good approximation since the EW corrections are dominated by large universal Sudakov logarithms.

In this work, we present a calculation of the NLO EW corrections for the physical final state in W-boson hadroproduction, i.e. $\mathrm{pp}/\mathrm{p}\,\overline{\mathrm{p}} \rightarrow l\nu_l + \mathrm{jet} + X$. In contrast to the on-shell approximation, all off-shell effects due to the finite width of the W boson are included. Moreover, we can incorporate the experimental event selection based on the charged-lepton momentum and the missing transverse momentum of the neutrino in our fully flexible Monte Carlo code which is able to calculate binned distributions for all physically relevant $\mathrm{W}+1\,\mathrm{jet}$ observables. Our calculation is completely generic in the sense that it can predict observables which are dominated by W bosons close to their mass shell as well as observables for which the exchanged W boson is far off-shell. Moreover, we have recalculated the NLO QCD corrections at $\mathscr{O}(\alpha_s^2\alpha^2)$, supporting a phase-space dependent choice for the factorization and renormalization scales.

The calculation of the EW corrections for W production in association with a hard jet is also a step towards a better understanding of the interplay between QCD and EW corrections for W production in general. This understanding—including a full treatment of off-shell W bosons—is mandatory to match the envisaged experimental accuracy for the W-mass measurement at the Tevatron and the LHC.

2. The Calculation

In this section we highlight specific aspects of the calculation which are particularly important for the presented corrections and which are not part of the standard framework for NLO corrections. For an extensive discussion of the calculational setup we refer the reader to Ref. [1].

The potentially resonant W bosons require a proper inclusion of the finite gauge-boson width in the propagators. We use the complex-mass scheme [5]. In this approach the W-boson mass (as well as the Z-boson mass) is consistently considered as a complex quantity,

$$\mu_{\mathrm{W}}^2 = M_{\mathrm{W}}^2 - \mathrm{i} M_{\mathrm{W}} \Gamma_{\mathrm{W}}, \tag{2.1}$$

defined as the location of the propagator pole in the complex plane, where M_{W} is the conventional real mass and Γ_{W} denotes the W-boson width. This leads to complex couplings and, in particular, a complex weak mixing angle. The underlying (real) Lagrangian does not change since the introduced width is compensated by adding a corresponding complex counterterm. The scheme fully respects all relations that follow from gauge invariance.

The experimental event definition for final-state muons usually selects so-called “bare” muons which are measured without taking into account collinear bremsstrahlung photons. Technically, the two collinear particles are not recombined into a single pseudo-particle and the observable is not collinear safe. Therefore, the KLN theorem does not apply and the corresponding EW corrections include terms which are enhanced by logarithms of the (small) muon mass. The enhanced corrections are phenomenologically relevant and cannot be calculated by the standard subtraction methods which assume collinear safety. Accordingly, we use an extended dipole subtraction method [6] which has been specifically designed to deal with non-collinear safe observables. The logarithms are extracted analytically and we can still work with matrix elements in the massless muon approximation.

To form collinear-safe quantities, also photons and QCD partons have to be recombined into a single jet if they are sufficiently collinear. However, the recombination induces a problem if the bremsstrahlung photon and a gluon are accidentally collinear. In this case, soft gluons can still pass the jet selection due to the recombination procedure. Hence, a soft-gluon divergence is induced that would be canceled by the virtual QCD corrections to W + photon production. To avoid the singularity, one has to distinguish W + photon and W + jet production by means of a more precise event definition employing a cut on the maximal energy or transverse momentum fraction of a photon inside a given jet. However, this procedure spoils the collinear safety of the event definition in partonic processes with final-state quarks. Using again the subtraction formalism [6] to extract the problematic collinear terms, the appearance of an unphysical quark-mass logarithm in the final result signals the necessity to include non-perturbative physics to properly describe the emission of a photon by a quark. The relevant collinear physics can be factorized from the underlying hard process and can be cast into a process-independent quark-to-photon fragmentation function [7], which has been measured at LEP in photon+jet events [8]. We employ this fragmentation function to achieve both, a realistic event selection and a theoretically consistent result.

To reach the accuracy of $\mathscr{O}(\alpha_{\mathrm{s}}\alpha^3)$ throughout the calculation we have also included the photon-induced partonic processes and the respective NLO QCD corrections. Also non-trivial interference terms between EW and QCD diagrams within the real corrections have been included

PoS(EPS-HEP 2009)341

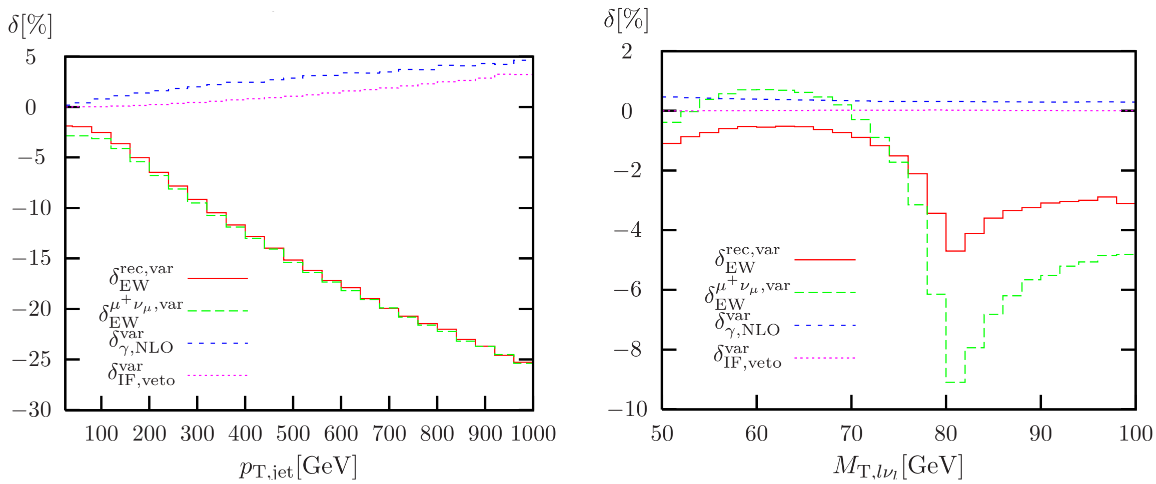

Figure 1: Various corrections to the transverse momentum distribution of the leading jet (left) and to the transverse-mass distribution of the leptons (right). See text for details.

at this order. However, these contributions are phenomenologically irrelevant and will not be discussed in detail in this talk.

3. Results and Conclusion

We define W + 1 jet events by requiring a jet and a charged lepton with transverse momentum $p_T > 25$ GeV as well as missing transverse momentum larger than 25 GeV. The jet and the lepton have to be central with a rapidity smaller then 2.5 in absolute value. The details of the event selection as well as the numerical input values for the calculation can be found in Ref. [1].

For the inclusive cross section, we find negative percent-level EW corrections. When we focus on events in the tails of the transverse momentum distributions of the charged lepton $p_{T,l}$ or the jet $p_{T,\text{jet}}$ (or the transverse mass distribution of the final-state leptons $M_{T,l\nu_l}$) we observe the well known universal Sudakov enhancement of EW corrections in the high-energy regime. As shown exemplarily in Figure 1, the EW correction rise to -25% at $p_T = 1$ TeV for the leading jet, both for bare muons $\delta_{\text{EW}}^{\mu^+\nu_\mu,\text{var}}$ as well as for lepton–photon recombination $\delta_{\text{EW}}^{\text{rec,var}}$. In the Sudakov regime, where the on-shell result is a good approximation, the transverse-momentum distribution for the leading jet in Figure 1 agrees at the percent level with the previous on-shell results [4].

For all results in this talk we employ a variable scale choice (var) which reflects the kinematics of the process and has been chosen to stabilize the QCD corrections (see Ref. [1]). Concerning the QCD corrections, we only briefly note that a veto against a second hard QCD jet has to be used to carefully define the W + 1 jet observable, in particular for the $p_{T,\text{jet}}$ distribution. Otherwise, the differential cross section is completely dominated by QCD dijet production, where a quark jet radiates a W boson, i.e. by a completely different process which is not related to a generic NLO contribution.

In Figure 1, we also show the small impact of the NLO QCD corrected photon induced processes $\delta_{\gamma,\text{NLO}}^{\text{var}}$ and of the interference terms $\delta_{\text{IF,veto}}^{\text{var}}$ for which also a sensible jet veto against a second hard jet has been applied.

PoS(EPS-HEP 2009)341

In contrast to the integrated cross sections, the transverse-mass distribution is quite sensitive to the specific treatment of final-state photons, in particular close to the Jacobian peak of the distribution at $M_{\mathrm{T},l\nu_l} \sim M_{\mathrm{W}}$, where the correction for bare muons reaches almost -10% (see Figure 1). As expected, the corrections for bare muons are larger since photons, being radiated collinearly to the charged lepton, carry away transverse momentum.

The region around the Jacobian peak is of particular interest for the precision determination of the W-boson mass. The EW corrections for the $M_{\mathrm{T},l\nu_l}$ distributions resemble the corrections for the inclusive W-boson sample for which no additional jet is required (see, e.g., Figure 2 in Ref. [9]). This result is expected since the transverse mass is rather insensitive to initial-state QCD radiation. Our calculation allows to quantitatively compare distributions for inclusive W-boson and W + 1 jet production in a future publication. As part of a full NNLO prediction of the mixed EW and QCD corrections for inclusive W production our results can provide a handle for an improved understanding of the interplay between EW and QCD corrections in the charged-current Drell–Yan process (see Ref. [10] for a recent account of this subject).

To summarize, we have extended the theoretical effort for the precise prediction for W-boson production at the Tevatron and the LHC by an important step: We have presented the first calculation of the full electroweak (EW) NLO corrections for W-boson hadroproduction in association with a hard jet where all off-shell effects are taken into account in the leptonic W-boson decay, i.e. we have studied final states with a jet, a charged lepton, and missing transverse momentum at NLO in the EW coupling constant within the SM. All results are implemented in a flexible Monte Carlo code which can model the experimental event definition at the NLO parton level.

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