Transverse Mass Distribution and Charge Asymmetry in W Boson Production to Third Order in QCD

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Charged gauge boson production at hadron colliders is a fundamental benchmark for the extraction of electroweak parameters and the understanding of the proton structure. To enable precision phenomenology for this process, we compute the third-order (N^3 LO) QCD corrections to the rapidity distribution and charge asymmetry in W boson production and to the transverse mass distribution of its decay products. Our results display substantial QCD corrections in kinematic regions relevant for Tevatron and LHC measurements. We compare the numerical magnitude of the N^3 LO corrections with uncertainties from electroweak input parameters and illustrate their potential impact on the determination of the W boson mass.

INTRODUCTION

Charged electroweak (EW) gauge bosons W± are produced copiously through the charged-current Drell-Yan process at hadron colliders 1. Measurements of the inclusive and differential properties of W production play a central role in tests of the Standard Model (SM) of particle physics and in the search for novel physics effects beyond it, allowing precision determinations of electroweak parameters such as the W boson mass and weak mixing angle, and of parton distribution functions (PDFs) in the proton. In the past, measurements have been performed at the Fermilab Tevatron and the Large Hadron Collider (LHC), substantially improving our knowledge about the SM 2–9.

Very recently, using a sample of approximately 4 million W bosons collected at the Tevatron, the CDF Collaboration reported a new measurement of the W boson mass using template fits to the transverse mass distribution in W boson decays and the transverse momentum distribution of the decay leptons 10. The new measurement displays significant tension with the SM expectation and has an unprecedentedly small uncertainty of ±9.4 MeV. The new result calls for a careful assessment of the theoretical predictions for the charged-current Drell-Yan process and their associated uncertainties.

Due to their importance for SM measurements, precision predictions for Drell-Yan production have been among the first applications of perturbative QCD at next-to-leading order (NLO, 11), next-to-next-to-leading order (NNLO, 12), and the inclusive corrections were accomplished at third order (N^3 LO) accuracy in QCD 13 recently. Fully differential NNLO QCD corrections 14–17, including the kinematics of the decay leptons, have been available for a while and are routinely used in the experimental analysis of Drell-Yan data.

Significant efforts have also gone in the derivation of EW 18–20 and mixed QCD-EW corrections 21–25 for W production and into the combination of fixed-order predictions with resummation of large logarithmic corrections 26–29.

In this letter we present for the first time differential predictions for W production at N^3 LO in QCD, including the gauge boson rapidity distributions and associated charge asymmetry as well as the transverse mass distribution. Compared to NNLO, we find large N^3 LO corrections to the rapidity distributions with non-overlapping scale uncertainty bands. For the normalized transverse mass distribution, which plays an important role in the W mass measurement, we observe a high perturbative stability of the predictions from NNLO to N^3 LO. We quantify the impact of varying EW input parameters around the peak region of the transverse mass distribution, finding substantial effects that could have an important impact on future precision EW measurements using charged-current Drell-Yan production.

METHODOLOGY

In this letter, we calculate the differential cross section dσ_{DY}, of charged-current production using the q_T-subtraction formalism 30:

\[ dσ^{N^3 LO}_{DY} = \mathcal{F}^{N^3 LO}_{DY} ⊗ dσ^{LO}_{DY, q_T < q_T^{cut}} + dσ^{NNLO}_{DY, jet, q_T > q_T^{cut}}, \]

(1)

where a slicing parameter q_T^{cut} is introduced to separate unresolved and resolved contributions. Our study is based on an established framework at N^3 LO 31, 32 which integrates the unresolved and resolved contributions in a computationally demanding manner. The in-
The unresolved contribution \( F^{N^{3}LO}_{DY} \otimes d\sigma^{LO}_{DY}\big|_{q_T < q_T^{\text{cut}}} \) denotes the fixed-order prediction for producing a W boson with transverse momentum \( q_T \) less than \( q_T^{\text{cut}} \) within Soft-Collinear Effective Theory (SCET) \[34\] \[38\]. It can be expanded into logarithmic terms \( \alpha_s \ln(q_T^{\text{cut}}/M_W) \) and constant terms. All logarithmic terms can be predicted through to \( N^{3}LO \) \[32\] \[39\] using the rapidity renormalization group formalism \[40\]. The key ingredients to achieve \( N^{3}LO \) accuracy for color-singlet production are the constant terms. They arise from the boundary conditions for the renormalization group equation, namely the rapidity-divergent transverse-momentum-dependent soft function \[41\] and beam functions \[42\] \[41\] at three loops, as well as the massless QCD form factor \[45\] \[47\].

The resolved contribution above \( q_T^{\text{cut}} \) is computed using the NNLOJET code for charged-current Drell-Yan-plus-jet production at NNLO \[48\] \[49\]. It is fully differential at NNLO accuracy by employing the antenna subtraction method \[60\] \[62\]. Sufficient numerical precision is mandatory to enable the cancellation between resolved and unresolved contributions at \( q_T^{\text{cut}} \). This is achieved through dedicated optimization \[29\] \[33\] \[39\] of phase space generation and subtraction terms to enable robust coverage in the unresolved regions for small values of the slicing parameter \( q_T^{\text{cut}} \). The cancellation of \( q_T^{\text{cut}} \)-dependent terms between resolved and unresolved contributions in \[1\] is accurate only up to power-suppressed terms at \( O(\alpha_s(q_T^{\text{cut}}/M_W)^3) \) which are unaccounted for in the unresolved piece. These terms are found to be sufficiently suppressed to no longer affect the final result for \( q_T^{\text{cut}} \sim 1.5 \) \((0.75) \) GeV at the LHC (Tevatron), which is validated for each LHC (Tevatron) observable by varying \( q_T^{\text{cut}} \) by \( \pm 0.5 \) \((0.25) \) GeV.

The decay of the W boson into a charged lepton and a neutrino is described at leading order with a Breit-Wigner parametrisation of the W propagator using a fixed width. To assess the impact of higher order QCD corrections and EW input parameters, we use the PDG \[53\] values \( M_W = 80.379 \) GeV and \( \Gamma_W = 2.085 \) GeV as the default setup and compare predictions with variations of \( M_W \) and \( \Gamma_W \).

**RESULTS**

Applying the \( q_T \)-subtraction method described above, we study charged-current Drell-Yan production at fully differential \( N^{3}LO \) accuracy in proton-proton collisions with center-of-mass energy at \( 13 \) TeV. We use the central member of NNPDF3.1 and NNPDF4.0 NNLO PDFs \[51\] \[55\] with \( \alpha_s(M_Z) = 0.118 \) throughout the calculation and the scale evolution is performed with LHAPDF \[56\]. The electroweak couplings are determined using the \( G_\mu \) scheme with: \( M_Z = 91.1876 \) GeV, \( \Gamma_Z = 2.4952 \) GeV, \( G_F = 1.1663787 \times 10^{-5} \) GeV\(^{-2} \) \[55\]. The CKM parameters are taken at their PDG values \[55\] in all Tevatron predictions, while a diagonal CKM matrix is used for LHC predictions. For absolute cross sections, the CKM effects are negligible for LHC energies \((0.2\%) \) but relevant at \( 2\% \) level at Tevatron energies (largely due to the different partonic composition in proton-antiproton collisions). For normalized distributions without fiducial cuts, the CKM effects are negligible throughout. The central factorisation and renormalisation scales are chosen to be the invariant mass of final state leptons, \( \mu_F = \mu_R = m_{\ell\ell} \). To estimate theoretical uncertainties, we adopt the 7-point scale variation of \( \mu_F \) and \( \mu_R \) by a factor of two while enforcing \( 1/2 \leq \mu_F/\mu_R \leq 2 \).

In Fig. \[1\] we show the rapidity distributions of the

![Graphical representation of W boson rapidity distributions from LO to N\(3\)LO accuracy at the LHC.](image-url)
and is defined as

$$A_W(|y_W|) = \frac{\sigma/d|y_W| - \sigma/d|y_W|}{\sigma/d|y_W| + \sigma/d|y_W|}$$  \hspace{1cm} (2)$$

In Fig. 2 we display the predictions of $A_W(|y_W|)$ at 13 TeV center of mass energy with up to N3LO corrections. We independently vary the scale choices between the numerator and the denominator of Eq. (2) while requiring $1/2 \leq \mu/\mu' \leq 2$ for any pair of scales, leading to 31 combinations. Their envelope is used to estimate the theoretical uncertainty. We observe positive N3LO corrections of about 2% relative to the NNLO predictions. The N3LO contribution is not flat in rapidity. In contrast to the individual rapidity distributions, the charge asymmetry converges well from NLO to N3LO with scale variation uncertainty reduced to about ±1.5% at N3LO.

Finally, we consider the transverse mass distribution in charged-current Drell-Yan production. The transverse mass is constructed as

$$m_T W = \sqrt{2E_T^\ell E_T^\nu (1 - \cos \Delta \phi)},$$  \hspace{1cm} (3)$$

with $E_T^\ell$ denoting the transverse energies of the final state charged lepton and neutrino and $\Delta \phi$ being their azimuthal angle difference. It is a characteristic observable in measurements of $M_W$ and $\Gamma_W$ at hadron colliders, since its distribution peaks around $M_W$ and the shape of its tail is sensitive to $\Gamma_W$. Precise predictions for the $m_T^W$ distribution are vital for the measurement of W boson mass and width, which are based on fitting theory templates for the normalized distribution to data in the experimental analysis. The most recent measurement of $M_W$ by the CDFII collaboration reports $\pm 9.4$ MeV overall uncertainty among which $\pm 5.2$ MeV arises from theoretical modelling. The different sources of modelling uncertainties have subsequently been revisited, largely supporting the CDFII approach while however not accounting for the state-of-the-art fixed-order predictions in mixed QCD-EW and fixed-order QCD corrections.

Fig. 3 presents the normalized $W^\pm$ boson transverse mass distribution at the Tevatron. With the newly computed N3LO corrections, it establishes a new state-of-the-art in the precise description of this observable. The inclusive distribution without fiducial cuts is displayed in the upper frame, while the fiducial cuts on charged lepton and neutrino of the CDFII analysis are applied in the lower frame: $p_T, E_T > [30, 55]$ GeV, $|\eta| < 1$ and $p_T, W > 15$ GeV. For the N3LO coefficient, we compensate the linear $q_T^\text{cut}$-dependence due to the fiducial cuts through a recoil prescription, where the unresolved contribution in Eq. (1) is active if all fiducial requirements are satisfied after boosting Born kinematical to finite $q_T$ below $q_T^\text{cut}$. At N3LO, corrections are very uniform in the peak region for both inclusive and fiducial distribution, while displaying some kinematical

FIG. 2: W boson charge asymmetry distribution from LO to N3LO at the LHC. The colored bands represent theory uncertainties from 31 scale variations. The bottom panel is the ratio with respect to NNLO.
dependence at low $m_{T}^{W^{\pm}}$ below 12 GeV in the inclusive distribution and below 68 GeV in the fiducial distribution. Starting from NNLO, we observe a stabilization of scale uncertainties to the level of $\pm 1\%$.

Our newly derived predictions for the $m_{T}^{W^{\pm}}$ distribution allow us to compare different sources of theory uncertainty arising from higher perturbative orders and from variations of the input parameters for $M_W$ and $\Gamma_W$ in Fig. 4. For this purpose, we consider the PDG baseline values $M_W = 80.379$ GeV and $\Gamma_W = 2.085$ GeV, supplemented by the values of $M_W$ according to the measurement from CDFII (80.433 GeV) and L3 (80.27 GeV), as well as a variation of $\Gamma_W$ within the PDG uncertainty of $\pm 42$ MeV.

The top panel of Fig. 4 demonstrates that the normalized $m_{T}^{W^{\pm}}$ fiducial distribution changes substantially in shape when going from NLO to NNLO, but remains more stable especially away from the peak region upon inclusion of the newly derived N$^3$LO corrections. The sensitivity to the input parameters can thus be reliably quantified based on the NNLO predictions. The middle panel compares the normalized $m_{T}^{W^{\pm}}$ distributions for fixed $\Gamma_W = 2.085$ GeV and $M_W$ values from CDFII and L3, thus quantifying the magnitude and shape of the resulting variations in the distribution. As expected, a strong sensitivity on $M_W$ around the peak region is observed. Compared to the change in the normalized distribution from NLO to NNLO, we observe that an NLO-based template fit could experience a slight pull towards larger values of $M_W$ to compensate for missing NNLO corrections. These variations are to be contrasted with the lower panel of Fig. 4, where $\Gamma_W$ is varied by its PDG uncertainty of $\pm 42$ MeV for fixed PDG $M_W$, which basically affects the distributions only above the peak re-
region, with a magnitude comparable to the effect of the $M_W$ variation. In contrast to the sensitivity on $\Gamma_W$ of the CDFII measurement recently reported in [65], a more realistic assessment of the uncertainties from $\Gamma_W$ may thus be warranted.

CONCLUSIONS

In this letter, we have produced state-of-the-art predictions for differential distributions in the charged-current Drell-Yan production to third order in perturbative QCD. We used the $q_T$-subtraction method at $N^3$LO, by combining an NNLO calculation for the production of a charged Drell-Yan pair at large $q_T$ and leading-power factorised predictions from SCET at small $q_T$. The robust numerical quality of both contributions allowed us to consistently check the cancellation of the $q_T^{\text{inst}}$ dependence in our predictions.

We presented differential distributions for the rapidity charge asymmetry at the LHC and for $m_T^{W\pm}$ at the Tevatron. Our results display modest $N^3$LO corrections in asymmetries and normalized distributions, that are usually within the uncertainties of the NNLO predictions. $N^3$LO perturbative uncertainties estimated by scale variations are found to be about $\pm 1\%$ to $\pm 1.5\%$ throughout. Distortions to the shape of the distributions are minimal at $N^3$LO and only become visible outside the peak region of the $m_T^{W\pm}$ distribution.

On the CDFII fiducial $m_T^{W\pm}$ distribution [10], we studied the impact of perturbative corrections and of variations of $W$ and $M_W$ within their respective experimental uncertainties led on the other hand to characteristic shifts in the shape of the normalized transverse mass distributions at a level between 2% to 6% around the peak region.

With the newly derived $N^3$LO corrections, our results establish a new state-of-the-art for the perturbative description of $W$ boson production at hadron colliders. They yield perturbative QCD uncertainties at the sub-per-cent level, which combine with recent results on QCD resummation, electroweak as well as mixed QCDxEW corrections to enable precision physics studies with upcoming LHC data.

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