

q_T Uncertainties for W and Z Production¹

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Abstract. Analysis of semi-inclusive DIS hadroproduction suggests broadening of transverse momentum distributions at small x below $10^{-3} \sim 10^{-2}$, which can be modeled in the Collins-Soper-Sterman formalism by a modification of impact parameter dependent parton densities. We investigate these consequences for the production of electroweak bosons at the Tevatron and the LHC. If substantial small- x broadening is observed in forward Z^0 boson production in the Tevatron Run-2, it will strongly affect the predicted q_T distributions for W^\pm and Z^0 boson production at the LHC.

INTRODUCTION: As we move from the Tevatron collider at 1.96 TeV to the Large Hadron Collider (LHC) at 14 TeV, we encounter an unexplored kinematic regime. In this regime we may discover phenomena with significant consequences for precision measurements and searches for new physics.

In this paper,² we analyze the consequences of anomalous transverse momentum (q_T) broadening driven by possible small- x effects in W and Z boson production at the Tevatron and LHC. At present, the form of the q_T distributions of W , Z , and Higgs boson production at the LHC is largely unknown, in part because limited experimental data on q_T distributions is available in Drell-Yan-like processes at small x . If we turn to the crossed deep inelastic scattering (DIS) process, q_T broadening was observed at the HERA ep collider in the small x region: $x = 10^{-4} \sim 10^{-2}$ [2, 3, 4, 5]. We use these results to predict the effects in hadron-hadron processes. The resulting modifications in the transverse momentum distributions may affect the measurements of the W boson mass and width, as well as the W and Z boson background in the search for new gauge bosons. The q_T broadening may also affect the detection of the Higgs boson at the LHC by altering its q_T distribution and the relevant QCD background.

PARAMETERIZING THE BROADENING: We now characterize the q_T broadening which was observed in semi-inclusive DIS processes and consider implications for the

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² The results presented here are based on Ref. [1]; refer to this reference for a detailed description of the process and more extensive references.

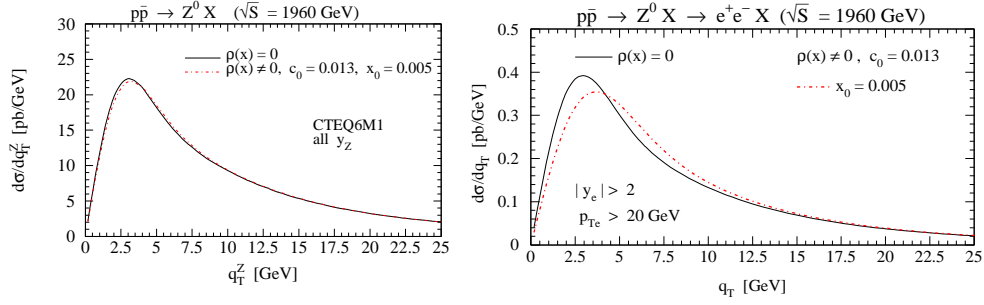


Figure 1. Transverse momentum distributions of Z bosons in the Tevatron Run-2: (A) integrated over the full range of Z boson rapidity y ; (B) for events with both decay electrons registered in the forward ($y_{e^+} > 2$, $y_{e^-} > 2$) or backward ($y_{e^+} < -2$, $y_{e^-} < -2$) detector regions. The solid curve is the standard CSS cross section, calculated using the BLNY parametrization [6] of the non-perturbative Sudakov factor. The dashed curve includes the additional term responsible for the q_T broadening in the small- x region.

(crossed) Drell-Yan process. We examine the resummed transverse momentum distribution for the Drell-Yan process, following the notations of Refs. [1, 7]

$$\frac{d\sigma}{dydq_T^2} = \frac{\sigma_0}{S} \int \frac{d^2b}{(2\pi)^2} e^{-i\vec{q}_T \cdot \vec{b}} \tilde{W}(b, Q, x_A, x_B) + Y(q_T, Q, x_A, x_B). \quad (1)$$

Here $x_{A,B} \equiv Qe^{\pm y}/\sqrt{S}$, y is the rapidity, the integral is the Fourier-Bessel transform of a resummed form factor \tilde{W} given in impact parameter (b) space, and Y is the regular part of the fixed-order cross section (Y is small at $q_T \rightarrow 0$). The form factor \tilde{W} is given by a product of a Sudakov exponent $e^{-S(b,Q)}$ and generalized parton distributions $\overline{\mathcal{P}}(x, b)$:

$$\tilde{W}(b, Q, x_A, x_B) = \frac{\pi}{S} \sum_{a,b} \sigma_{ab}^{(0)} e^{-S(b,Q)} \overline{\mathcal{P}}(x_A, b) \overline{\mathcal{P}}(x_B, b).$$

In the limit of small b , we can write $\overline{\mathcal{P}}(x, b)$ in the form: $\overline{\mathcal{P}}(x, b) \simeq (\mathcal{C} \otimes f)(x, b_0/b) e^{-\rho(x)b^2}$, where $\mathcal{C}(x, b_0/b)$ are coefficient functions, $f(x, \mu)$ are k_T -integrated parton distributions, and $b_0 = 2e^{-\gamma_E}$.

The expressions for $\overline{\mathcal{P}}(x, b)$ differ from the conventional form by the introduction of the term $e^{-\rho(x)b^2}$, which will provide an additional q_T broadening with an x dependence specified by $\rho(x)$. This phenomenological characterization of the q_T broadening follows the corresponding analysis of the effect observed at HERA. This q_T broadening may approximate x -dependent higher-order contributions that are not included in the finite-order (NLO) expression for $(\mathcal{C} \otimes f)$. We parametrize $\rho(x)$ in the following functional form:

$$\rho(x) = c_0 \left(\sqrt{\frac{1}{x^2} + \frac{1}{x_0^2}} - \frac{1}{x_0} \right)$$

such that $\rho(x) \sim c_0/x$ for $x \ll x_0$, and $\rho(x) \sim 0$ for $x \gg x_0$. This parameterization ensures that the formalism reduces to the usual CSS form for large x ($x \gg x_0$) and introduces an additional source of q_T broadening (growing as $1/x$) at small x ($x \ll x_0$).

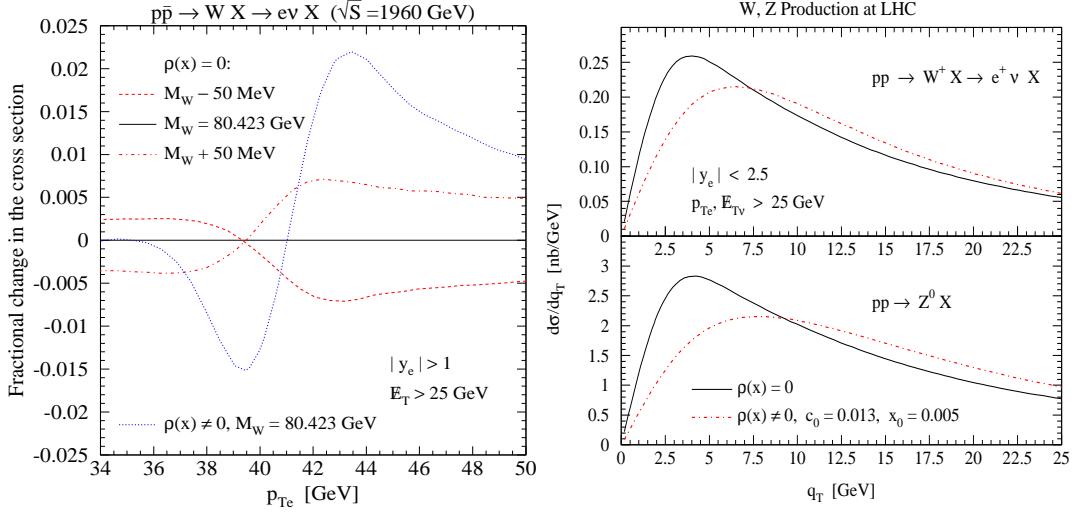


Figure 2. A) The fractional difference in the distribution $d\sigma/dp_{T_e}$ for the forward-rapidity sample of electrons ($|y_e| > 1$) at the Tevatron. B) Transverse momentum distributions of (i) W^+ bosons and (ii) Z^0 bosons at the Large Hadron Collider.

The parameter c_0 determines the magnitude of the broadening for a given x , while x_0 specifies the value of x below which the broadening effects become important. Based on the observed dependence $\rho(x) \sim 0.013/x$ at $x \lesssim 10^{-2}$ in SIDIS energy flow data, we choose $c_0 = 0.013$ and $x_0 = 0.005$ as a representative choice for our calculations.

KINEMATICS: The small- x broadening occurs when one or both longitudinal momentum fractions $x_{A,B} \approx M_V e^{\pm y} / \sqrt{S}$ are of order or less than $x_0 = 0.005$. Lower values of x_A can be reached at the price of pushing x_B closer to unity, and vice versa; hence, we anticipate this effect will be enhanced as we move to either large boson rapidity $|y|$, or to small M_V / \sqrt{S} . The rate in the forward $|y|$ region is suppressed by the decreasing parton densities at $x \rightarrow 1$.

Z BOSONS AT THE TEVATRON: The broadening may be observed in the di-lepton channel in Z boson production in the Tevatron Run-2. The dominant contributions come from $x \sim M_Z / \sqrt{S} \sim 0.046 \gg x_0$, where the broadening function $\rho(x)$ is negligible. Consequently, the strategy here is to exclude contributions from the central-rapidity Z bosons, which are almost insensitive to the broadening. If no distinction between the central and forward Z bosons is made (e.g., as in the Run-1 analysis), the small- x broadening contributes at or below the level of the other uncertainties in the resummed form factor. Fig. 1(A) shows the Z boson distribution $d\sigma/dq_T$, integrated over the Z boson rapidity y without selection cuts on the decay leptons. The cross section with the broadening term (dashed line) essentially coincides with the cross section without such a term (solid line).

In contrast, the small- x broadening visibly modifies $d\sigma/dq_T$ at forward rapidities ($|y| < 2$), where one of the initial-state partons carries a small momentum fraction ($x \lesssim 0.005$). Fig. 2(B) displays the cross sections with the acceptance cuts $y_{e^\pm} > 2$ or $y_{e^\pm} < -2$ simultaneously imposed on both decay leptons. The cuts exclude central Z contributions and retain a fairly large cross section (≈ 3.4 pb), most of which falls

within the experimental acceptance region. Run-2 can discriminate between the curves in Fig. 1(B) given the improved acceptance and increased luminosity of the upgraded Tevatron collider; this result will have important implications for the W boson measurements, as we illustrate in the following section.

M_W MEASUREMENT: The q_T distribution of the W boson is important, as this influences the extraction of M_W from the distribution $d\sigma/dp_{Te}$ over the transverse momentum p_{Te} of the decay charged leptons. The distribution $d\sigma/dp_{Te}$ exhibits the typical Jacobian peak located at $p_{Te} \sim M_W/2 \approx 40$ GeV. To better visualize percent-level changes in $d\sigma/dp_{Te}$ associated with the broadening, we plot in Fig. 2(A) the fractional difference $(d\sigma^{mod}/dp_{Te}) / (d\sigma^{std}/dp_{Te}) - 1$ of the “modified” (*mod*) and “standard” (*std*) theory cross sections. The broadening of $d\sigma/dq_T$ shifts the Jacobian peak in the positive direction. At $|y_e| > 1$, the small- x broadening is large and exceeds the other theoretical uncertainties, and is comparable with a variation of M_W by more than 50 MeV. For $|y_e| < 1$ (not shown), the effect is comparable with a variation of M_W by ~ 20 MeV. In either case, if these effects are present, they must be taken into account for precision measurements.

W & Z BOSONS AT THE LHC: At the LHC, the small- x broadening can be observed in W and Z boson production at all rapidities because $x < 0.005$ for all y . Fig. 2(B-i) displays the q_T shift for the production of W bosons with experimental cuts for ATLAS. The shift is slightly larger in W^+ boson production as compared to W^- boson production (not shown) because of the flatter y distribution for W^+ bosons. The observed q_T broadening propagates into the leptonic transverse mass and transverse momentum distributions. The q_T shift for the production of Z bosons is comparable and displayed in Fig. 2(B-ii). A measurement of the rapidity dependence of q_T distributions at the LHC will test for the presence of such effects.

CONCLUSIONS: For the choice of parameters extracted from the fit to the HERA data, the q_T broadening may be discovered via the analysis of forward produced Z bosons at the Tevatron Run-2. Then the q_T broadening will shift the measured W boson mass in the p_{Te} method by ~ 20 MeV in the central region ($|y_e| < 1$), and more than 50 MeV in the forward region ($|y_e| > 1$). At the LHC, these effects produce a much harder q_T distribution for W and Z bosons and have important implications for the measurement of the W boson mass.

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