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

\[
\frac{d\sigma}{dyd\vec{q}_T} = \frac{\sigma_0}{S} \int \frac{d^2 b}{(2\pi)^2} e^{-ib\cdot \vec{b}} \tilde{W}(b,Q,b_0,x_B) + Y(q_T,Q,x_A,x_B). \tag{1}
\]

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:

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

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 \( x \) (\( x \ll x_0 \)).
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 $x \to 1$.

**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 ($\approx 3.4 \text{ pb}$), 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 \(d\sigma/dp_T e\) over the transverse momentum \(p_T e\) of the decay charged leptons. The distribution \(d\sigma/dp_T e\) exhibits the typical Jacobian peak located at \(p_T e \approx M_W/2 \approx 40\) GeV. To better visualize percent-level changes in \(d\sigma/dp_T e\) associated with the broadening, we plot in Fig. 2(A) the fractional difference \((d\sigma^{\text{mod}}/d p_T e) / (d\sigma^{\text{std}}/d p_T e) - 1\) 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 \(p_T e\) 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.

**References**