Measurement of the Shape of the Boson-Transverse Momentum Distribution 
in $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^- + X$ Events Produced at $\sqrt{s} = 1.96$ TeV


PRL 100, 102002 (2008)
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102002-2
We present a measurement of the shape of the $Z/\gamma^*$ boson transverse momentum ($q_T$) distribution in $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+ e^- + X$ events at a center-of-mass energy of 1.96 TeV using 0.98 fb$^{-1}$ of data collected with the D0 detector at the Fermilab Tevatron collider. The data are found to be consistent with the resummation prediction at low $q_T$, but above the perturbative QCD calculation in the region of $q_T > 30$ GeV/$c$. 
Using events with $q_T < 30 \text{ GeV}/c$, we extract the value of $g_2$, one of the nonperturbative parameters for the resummation calculation. Data at large boson rapidity $y$ are compared with the prediction of resummation and with alternative models that employ a resummed form factor with modifications in the small Bjorken $x$ region of the proton wave function.

A complete understanding of weak vector boson production is essential for maximizing the sensitivity to new physics at hadron colliders. Studies of the $Z/\gamma^*$ boson production play a particularly valuable role in that its kinematics can be precisely determined through measurement of its leptonic decays. Throughout this Letter, we use the notation “$Z$ boson” to mean “$Z/\gamma^*$ boson,” unless specified otherwise.

$Z$ boson production also serves as an ideal testing ground for predictions of quantum chromodynamics (QCD), since the boson’s transverse momentum, $q_T$, can be measured over a wide range of values and can be correlated with its rapidity. At large $q_T$ (approximately greater than $30 \text{ GeV}/c$), the radiation of a single parton with large transverse momentum dominates the cross section, and fixed-order perturbative QCD (pQCD) calculations [1], currently available at next-to-next-to leading order (NNLO) [2], should yield reliable predictions. At lower $q_T$, multiple soft-gluon emission cannot be neglected, and the fixed-order perturbation calculation no longer gives accurate results. A soft-gluon resummation technique developed by Collins, Soper, and Sterman (CSS) [3] gives reliable predictions in the low-$q_T$ region. A prescription has been proposed [4] for matching the low- and high-$q_T$ regions in order to provide a continuous prediction for all values of $q_T$. The CSS resummation formalism allows the inclusion of contributions from large logarithms of the form $\ln^2(q_T^2/Q^2)$ to all orders of perturbation theory in an effective resummed form factor, where $Q^2$ represents the invariant mass corresponding to the four-momentum transfer. The CSS resummation can be done either in impact parameter ($b$) space or in transverse momentum ($q_T$) space. In the case of $b$-space resummation, this form factor can be parameterized with the following nonperturbative function first introduced by Brock, Landry, Ndolosky, and Yuan (BLNY) [5]:

$$S_{NP}(b, Q^2) = \left[ g_1 + g_2 \ln\left(\frac{Q^2}{2Q_0^2}\right) + g_3 \ln(100x_1x_2) \right] b^2,$$

(1)

where $x_1$ and $x_2$ are the fractions of the incident hadron momenta carried by the colliding partons, $Q_0$ is a scale typical of the onset of nonperturbative effects, and $g_1$, $g_2$, and $g_3$ are phenomenological nonperturbative parameters that must be obtained from fits to the data. The $Z$ boson $q_T$ distribution at the Fermilab Tevatron is by far most sensitive to the value of $g_2$ and quite insensitive to the value of $g_3$. Thus, a measurement of the $Z$ boson $q_T$ spectrum can be used to test this formalism and to determine the value of $g_2$.

Recent studies of data from deep inelastic scattering (DIS) experiments [6,7] indicate that the resummed form factor in the above equation may need to be modified for processes involving a small-$x$ parton in the initial state. Reference [8] indicates how such a modification would influence the $q_T$ distributions of vector and Higgs bosons produced in hadronic collisions. A wider $q_T$ distribution is predicted for $Z$ bosons with large rapidity (called “small-$x$ broadening”). $Z$ bosons produced at the Tevatron in the rapidity range $2 < |y| < 3$ probe processes involving a parton with $0.002 < x < 0.006$, and can be used to test the modified form factor at small $x$.

$Z$ boson $q_T$ distributions have been published previously by the CDF [9] and D0 [10] collaborations using about 100 pb$^{-1}$ of data at $\sqrt{s} = 1.8$ TeV. In this Letter, we report a new measurement with larger statistics and improved precision. This measurement is also the first to present a $q_T$ distribution for large-rapidity $Z$ bosons.

The data sample used in this measurement was collected using a set of inclusive single-electron triggers with the D0 detector [11] at the Fermilab Tevatron collider, and the integrated luminosity is 980 ± 60 pb$^{-1}$ [12].

Our selection criteria for $Z$ bosons require two isolated electromagnetic clusters that have a shower shape consistent with that of an electron. Electron candidates are required to have transverse momentum greater than 25 GeV/c. The electron pairs must have a reconstructed invariant mass $70 < M(\text{ee}) < 110 \text{ GeV}/c^2$. If an event has both its candidate electrons in the central calorimeter (CC events), each electron must be spatially matched to a reconstructed track. Because the tracking efficiency decreases with rapidity in the endcap region, events with one or two endcap calorimeter electron candidates (CE and EE events, respectively) are required to have at least one electron with a matching track. After these requirements, 23 959 CC, 30 344 CE, and 9598 EE events are selected; 5412 of these have a $Z$ boson with $|y| > 2$.

Electron identification efficiencies are measured using a combination of data and a GEANT-based [13] simulation of the D0 detector. The electron identification efficiencies are measured from $Z$ data. The dependence of the overall selection efficiency on the $Z$ boson $q_T$ is parameterized from the GEANT simulation. A measurement of this shape from the data agrees well with the simulation within statistical uncertainties.

The dominant backgrounds are from photon plus jet events and di-jet events, with photons and jets misidenti-
The measured spectrum is further corrected for detector resolution effects using the RUN (Regularized Unfolding) program [16] to obtain the true differential cross section. Its performance was verified by comparing the true and unfolded spectrum generated using pseudoexperiments. The measured Z qT resolution is about 2 GeV/c; the bin width we choose is 2.5 GeV/c for qT < 30 GeV/c. The typical correlation between adjacent bins is around 30%. Due to limited statistics, the chosen bin width is 10 GeV/c for 30 < qT < 100 GeV/c and 40 GeV/c for 100 < qT < 260 GeV/c.

Systematic uncertainties on the unfolded qT spectrum arise from uncertainties on the electron energy calibration, the electron energy resolution, the dependence of the overall selection efficiency on qT, and the effect of parton distribution functions (PDFs) on the acceptance. The uncertainties on the unfolded spectrum are estimated from the resulting change when the smearing parameters are varied within their uncertainties. CTEQ 6.1M is used as the default PDF. Uncertainties due to the PDFs are estimated using the procedure described in Ref. [17]. The uncertainty due to the choice of unfolding parameters in the RUN program is also estimated and included in the final systematic uncertainty.

The final results in the qT < 30 GeV/c range are shown in Fig. 1 for the inclusive sample and for the sample with |y| > 2. Each data point is plotted at the average value of the expected distribution over the bin [18]. For the theoretical calculation, we use RESBOS with published values of the nonperturbative parameters [5]. Good agreement between data and the prediction is observed for all rapidity ranges, which indicates that the BLNY parameterization works well for the low qT region.

Z boson events produced at large rapidities (|y| > 2) are also used to test the small-x prediction. We compare data with the theoretical predictions with and without the form factor as modified from studies of small-x DIS data [8]. All curves are normalized to 1 for qT < 30 GeV/c. The default values for the parameters g1, g2, and g3 [5] obtained from large-x data are used. The χ²/d.o.f. between the data and the RESBOS calculation using the default parameters is 0.8/1 for qT < 5 GeV/c and 11.1/11 for qT < 30 GeV/c, while that for the modified calculation is 5.7/1 for qT < 5 GeV/c and 31.9/11 for qT < 30 GeV/c. It remains to be seen if retuning of the nonperturbative parameters could improve the agreement for the modified calculations.

Figure 2 shows the measured differential cross section in the range qT < 260 GeV/c compared to (1) the RESBOS calculation with its default parameters [5], (2) RESBOS with a NLO to NNLO K factor by Arnold and Reno [19] incorporated into RESBOS by its authors, (3) a pQCD
The CSS model parameter most sensitive to the shape at low $q_T$ ($q_T < 30 \text{ GeV}/c$) is $g_2$. In a fit, we fix other phenomenological parameters to the values obtained in Ref. [5] and only vary $g_2$. A minimum $\chi^2$/d.o.f. of 9/11 between the model and the inclusive data for $q_T < 30 \text{ GeV}/c$ is found when $g_2 = 0.77 \pm 0.06 (\text{GeV}/c)^2$.

In conclusion, we have measured the normalized differential spectrum, $\frac{1}{\sigma} \frac{d\sigma}{dq_T}$, for $Z$ boson events produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with boson mass $40 < M < 200 \text{ GeV}/c^2$ and $q_T < 260 \text{ GeV}/c$. This represents the highest center-of-mass energy measurement of this quantity over the largest phase space available to date. The overall uncertainty of this measurement has been reduced compared with the previous measurements. We find that for $q_T < 30 \text{ GeV}/c$, the CSS resummation model used in RESBOS describes the data very well at all rapidities. Our data with $|y| > 2$ disfavor a variant of this model that incorporates an additional small-$x$ form factor when $g_3$, $g_2$, and $g_3$ from large-$x$ data is used. Using the BLNY parameterization for events with $q_T < 30 \text{ GeV}/c$, we obtain $g_2 = 0.77 \pm 0.06 (\text{GeV}/c)^2$, which is comparable with the current world average value [5]. We observe a disagreement between our data and NNLO calculations in the region $q_T > 30 \text{ GeV}/c$, where our distribution is higher than predicted by a factor of 1.25. However, the
NNLO calculation agrees in shape with our data when normalized at \( q_T = 30 \text{ GeV}/c \).

We thank C. Balazs, Q. H. Cao, P. Nadolsky, F. Petriello, and C. P. Yuan for many useful discussions. We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CAPES, CNPq, FAPERJ, FAPESP, and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); CONICET and UBAcYT (Argentina); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); CONICET and UBAcYT (Argentina); FOM (The Netherlands); Science and Technology Facilities Council (United Kingdom); MSMT and GACR (Czech Republic); CRC Program, CFI, NSERC, and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); Alexander von Humboldt Foundation; and the Marie Curie Program.

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[5] F. Landry et al., Phys. Rev. D 67, 073016 (2003). The values are \( g_1 = 0.21 \pm 0.01 \text{ (GeV}/c)^2 \), \( g_2 = 0.68 \pm 0.01 \text{ (GeV}/c)^2 \), \( g_3 = -0.6 \pm 0.05 \), \( Q_0 = 1.6 \text{ GeV}/c \).