Fermi National Accelerator Laboratory

Measurement of the Transverse Momentum Distributions of W and Z Bosons Produced in p̄p Collisions at $\sqrt{s} = 1.8$ TeV

B. Abbott et al.

The D0 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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Measurement of the Transverse Momentum Distributions of W and Z Bosons Produced in $\overline{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

The DØ Collaboration *

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

(June 10, 1999)

Abstract

We present measurements of the transverse momentum distribution of W and Z bosons produced in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The data were collected with the DØ detector at Fermilab during 1994-1996 Tevatron run. The results are in good agreement with theoretical predictions based on the perturbative QCD and soft gluon resummation combined calculation over the entire measured p_T range ($p_T = 0 - 200$ GeV/c).

B. Abbott,[45] M. Abolins,[42] V. Abramov,[18] B.S. Acharya,[11] I. Adam,[44] D.L. Adams,[54]
M. Adams,[28] S. Ahn,[27] V. Akimov,[16] G.A. Alves,[2] N. Amos,[41] E.W. Anderson,[34]
M.M. Baarmand,[47] V.V. Babintsev,[18] L. Babukhadia,[20] A. Baden,[38] B. Baldin,[27]
S. Banerjee,[11] J. Bantly,[51] E. Barberis,[21] P. Baringer,[35] J.F. Bartlett,[27] A. Belyaev,[17]
S.B. Beri,[9] I. Bertram,[19] V.A. Bezzubov,[18] P.C. Bhat,[27] V. Bhatnagar,[9]
M. Bhattacharjee,[47] G. Blazey,[29] S. Blessing,[25] P. Bloom,[22] A. Boehnlein,[27] N.I. Bojko,[18]
F. Borcherding,[27] C. Boswell,[24] A. Brandt,[27] R. Breedon,[22] G. Briskin,[51] R. Brock,[42]
A. Bross,[27] D. Buchholz,[30] V.S. Burtovoi,[18] J.M. Butler,[39] W. Carvalho,[2] D. Casey,[42]
Z. Casilum,[47] H. Castilla-Valdez,[14] D. Chakraborty,[47] S.V. Chekulaev,[18] W. Chen,[47]
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A.R. Clark,[21] W.G. Cobau,[38] J. Cochran,[24] L. Coney,[32] W.E. Cooper,[27] D. Coppage,[35]
C. Cretsinger,[46] D. Cullen-Vidal,[51] M.A.C. Cummings,[29] D. Cutts,[51] O.I. Dahl,[21]
K. Davis,[20] K. De,[52] K. Del Signore,[41] M. Demarteau,[27] D. Denisov,[27] S.P. Denisov,[18]
H.T. Diehl,[27] M. Diesburg,[27] G. Di Loreto,[42] P. Draper,[52] Y. Ducros,[8] L.V. Dudko,[17]
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S. Eno,[38] G. Eppley,[54] P. Ermolov,[17] O.V. Eroshin,[18] H. Evans,[44] V.N. Evdokimov,[18]
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E. Flattum,[27] G.E. Forden,[20] M. Fortner,[29] K.C. Frame,[42] S. Fuess,[27] E. Gallas,[27]
A.N. Galyaev,[18] P. Gartung,[24] V. Gavrilov,[16] T.L. Geld,[42] R.J. Genik II,[42] K. Genser,[27]
C.E. Gerber,[27] Y. Gershtein,[51] B. Gibbard,[48] B. Gobbi,[30] B. Gómez,[5] G. Gómez,[38]
P.I. Goncharov,[18] J.L. González Solís,[14] H. Gordon,[48] L.T. Goss,[53] K. Gounder,[24]
A. Goussiou,[47] N. Graf,[48] P.D. Grannis,[47] D.R. Green,[27] J.A. Green,[34] H. Greenlee,[27]
S. Grinstein,[1] P. Grudberg,[21] S. Grünendahl,[27] G. Guglielmo,[50] J.A. Guida,[20]
J.M. Guida,[51] A. Gupta,[11] S.N. Gurzhiev,[18] G. Gutierrez,[27] P. Gutierrez,[50] N.J. Hadley,[38]
H. Haggerty,[27] S. Hagopian,[25] V. Hagopian,[25] K.S. Hahn,[46] R.E. Hall,[23] P. Hanlet,[40]
S. Hansen,[27] J.M. Hauptman,[34] C. Hays,[44] C. Hebert,[35] D. Hedin,[29] A.P. Heinson,[24]
U. Heintz,[39] R. Hernández-Montoya,[14] T. Heuring,[25] R. Hirosky,[28] J.D. Hobbs,[47]
B. Hoeneisen,[6] J.S. Hoftun,[51] F. Hsieh,[41] Tong Hu,[31] A.S. Ito,[27] S.A. Jerger,[42] R. Jesik,[31]
T. Joffe-Minor,[30] K. Johns,[20] M. Johnson,[27] A. Jonckheere,[27] M. Jones,[26] H. Jöstlein,[27]
S.Y. Jun,[30] C.K. Jung,[47] S. Kahn,[48] D. Karmanov,[17] D. Karmgard,[25] R. Kehoe,[32]
S.K. Kim,[13] B. Klima,[27] C. Klopfenstein,[22] B. Knuteson,[21] W. Ko,[22] J.M. Kohli,[9]
D. Koltick,[33] A.V. Kostritskiy,[18] J. Kotcher,[48] A.V. Kotwal,[44] A.V. Kozelov,[18]
E.A. Kozlovsky,[18] J. Krane,[34] M.R. Krishnaswamy,[11] S. Krzywdzinski,[27] M. Kubantsev,[36]
S. Kuleshov,[16] Y. Kulik,[47] S. Kunori,[38] F. Landry,[42] G. Landsberg,[51] A. Leflat,[17] J. Li,[52]
Q.Z. Li,[27] J.G.R. Lima,[3] D. Lincoln,[27] S.L. Linn,[25] J. Linnemann,[42] R. Lipton,[27]
A. Lucotte,[47] L. Lueking,[27] A.K.A. Maciel,[29] R.J. Madaras,[21] R. Madden,[25]
L. Magaña-Mendoza,[14] V. Manankov,[17] S. Mani,[22] H.S. Mao,[4] R. Markeloff,[29]
T. Marshall,[31] M.I. Martin,[27] R.D. Martin,[28] K.M. Mauritz,[34] B. May,[30] A.A. Mayorov,[18]
R. McCarthy,[47] J. McDonald,[25] T. McKibben,[28] J. McKinley,[42] T. McMahon,[49]
H.L. Melanson,[27] M. Merkin,[17] K.W. Merritt,[27] C. Miao,[51] H. Miettinen,[54] A. Mincer,[45]
C.S. Mishra,[27] N. Mokhov,[27] N.K. Mondal,[11] H.E. Montgomery,[27] M. Mostafa,[1]
H. da Motta,[2] C. Murphy,[28] F. Nang,[20] M. Narain,[39] V.S. Narasimham,[11] A. Narayanan,[20]
H.A. Neal,[41] J.P. Negret,[5] P. Nemethy,[45] D. Norman,[53] L. Oesch,[41] V. Oguri,[3] N. Oshima,[27]
D. Owen,[42] P. Padley,[54] A. Para,[27] N. Parashar,[40] Y.M. Park,[12] R. Partridge,[51] N. Parua,[7]
M. Paterno,[46] B. Pawlik,[15] J. Perkins,[52] M. Peters,[26] R. Piegaia,[1] H. Piekarz,[25]

Y. Pischalnikov,[33] B.G. Pope,[42] H.B. Prosper,[25] S. Protopopescu,[48] J. Qian,[41]
P.Z. Quintas,[27] R. Raja,[27] S. Rajagopalan,[48] O. Ramirez,[28] N.W. Reay,[36] S. Reucroft,[40]
M. Rijssenbeek,[47] T. Rockwell,[42] M. Roco,[27] P. Rubinov,[30] R. Ruchti,[32] J. Rutherfoord,[20]
A. Sánchez-Hernández,[14] A. Santoro,[2] L. Sawyer,[37] R.D. Schamberger,[47] H. Schellman,[30]
J. Sculli,[45] E. Shabalina,[17] C. Shaffer,[25] H.C. Shankar,[11] R.K. Shivpuri,[10] D. Shpakov,[47]
M. Shupe,[20] R.A. Sidwell,[36] H. Singh,[24] J.B. Singh,[9] V. Sirotenko,[29] E. Smith,[50]
R.P. Smith,[27] R. Snihur,[30] G.R. Snow,[43] J. Snow,[49] S. Snyder,[48] J. Solomon,[28]
M. Sosebee,[52] N. Sotnikova,[17] M. Souza,[2] N.R. Stanton,[36] G. Steinbrück,[50]
R.W. Stephens,[52] M.L. Stevenson,[21] F. Stichelbaut,[48] D. Stoker,[23] V. Stolin,[16]
D.A. Stoyanova,[18] M. Strauss,[50] K. Streets,[45] M. Strovink,[21] A. Sznajder,[2] P. Tamburello,[38]
J. Tarazi,[23] M. Tartaglia,[27] T.L.T. Thomas,[30] J. Thompson,[38] D. Toback,[38] T.G. Trippe,[21]
P.M. Tuts,[44] V. Vaniev,[18] N. Varelas,[28] E.W. Varnes,[21] A.A. Volkov,[18] A.P. Vorobiev,[18]
H.D. Wahl,[25] J. Warchol,[32] G. Watts,[51] M. Wayne,[32] H. Weerts,[42] A. White,[52]
J.T. White,[53] J.A. Wightman,[34] S. Willis,[29] S.J. Wimpenny,[24] J.V.D. Wirjawan,[53]
J. Womersley,[27] D.R. Wood,[40] R. Yamada,[27] P. Yamin,[48] T. Yasuda,[27] P. Yepes,[54] K. Yip,[27]
C. Yoshikawa,[26] S. Youssef,[25] J. Yu,[27] Y. Yu,[13] Z. Zhou,[34] Z.H. Zhu,[46] M. Zielinski,[46]
D. Zieminska,[31] A. Zieminski,[31] V. Zutshi,[46] E.G. Zverev,[17] and A. Zylberstejn[8]

(DØ Collaboration)

[1]Universidad de Buenos Aires, Buenos Aires, Argentina
[2]LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
[3]Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[4]Institute of High Energy Physics, Beijing, People's Republic of China
[5]Universidad de los Andes, Bogotá, Colombia
[6]Universidad San Francisco de Quito, Quito, Ecuador
[7]Institut des Sciences Nucléaires, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France
[8]DAPNIA/Service de Physique des Particules, CEA, Saclay, France
[9]Panjab University, Chandigarh, India
[10]Delhi University, Delhi, India
[11]Tata Institute of Fundamental Research, Mumbai, India
[12]Kyungsung University, Pusan, Korea
[13]Seoul National University, Seoul, Korea
[14]CINVESTAV, Mexico City, Mexico
[15]Institute of Nuclear Physics, Kraków, Poland
[16]Institute for Theoretical and Experimental Physics, Moscow, Russia
[17]Moscow State University, Moscow, Russia
[18]Institute for High Energy Physics, Protvino, Russia
[19]Lancaster University, Lancaster, United Kingdom
[20]University of Arizona, Tucson, Arizona 85721
[21]Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
[22]University of California, Davis, California 95616
[23]University of California, Irvine, California 92697
[24]University of California, Riverside, California 92521
[25]Florida State University, Tallahassee, Florida 32306

[26]University of Hawaii, Honolulu, Hawaii 96822

[27]Fermi National Accelerator Laboratory, Batavia, Illinois 60510

[28]University of Illinois at Chicago, Chicago, Illinois 60607

[29]Northern Illinois University, DeKalb, Illinois 60115

[30]Northwestern University, Evanston, Illinois 60208

[31]Indiana University, Bloomington, Indiana 47405

[32]University of Notre Dame, Notre Dame, Indiana 46556

[33]Purdue University, West Lafayette, Indiana 47907

[34]Iowa State University, Ames, Iowa 50011

[35]University of Kansas, Lawrence, Kansas 66045

[36]Kansas State University, Manhattan, Kansas 66506

[37]Louisiana Tech University, Ruston, Louisiana 71272

[38]University of Maryland, College Park, Maryland 20742

[39]Boston University, Boston, Massachusetts 02215

[40]Northeastern University, Boston, Massachusetts 02115

[41]University of Michigan, Ann Arbor, Michigan 48109

[42]Michigan State University, East Lansing, Michigan 48824

[43]University of Nebraska, Lincoln, Nebraska 68588

[44]Columbia University, New York, New York 10027

[45]New York University, New York, New York 10003

[46]University of Rochester, Rochester, New York 14627

[47]State University of New York, Stony Brook, New York 11794

[48]Brookhaven National Laboratory, Upton, New York 11973

[49]Langston University, Langston, Oklahoma 73050

[50]University of Oklahoma, Norman, Oklahoma 73019

[51]Brown University, Providence, Rhode Island 02912

[52]University of Texas, Arlington, Texas 76019

[53]Texas A&M University, College Station, Texas 77843

[54]Rice University, Houston, Texas 77005

I. INTRODUCTION

At the Fermilab Tevatron, W and Z bosons are produced in high energy $\bar{p}p$ collisions. The study of the production of W and Z bosons provides an avenue to explore QCD, the theory of strong interactions. The benefits of using intermediate vector bosons to study perturbative QCD are large momentum transfer, distinctive event signatures, low backgrounds, and a well understood electroweak vertex. In this paper we present measurements of the W and Z transverse momentum distribution based on data taken by the DØ collider detector during the 1994–1996 Tevatron running period.

In the parton model at lowest order, W and Z intermediate vector bosons are produced in head-on collisions of $q\bar{q}$ constituents of the proton and antiproton, and have little transverse momentum ($p_T << M_W$, M_Z). Consequently, the fact that observed bosons have large transverse momentum (p_T) is attributed to the production of one or more gluons or quarks along with the bosons. At high transverse momentum ($p_T > 20$ GeV/c), the cross section is dominated by the radiation of a single parton with large transverse momentum. Perturbative QCD is therefore expected to be reliable in this regime [1]. At low transverse momentum ($p_T < 10$ GeV/c), multiple soft gluon emission is expected to dominate the cross section. A soft gluon resummation technique [2–5] is therefore used to make QCD predictions. Neither the resummed nor the fixed order calculation describes the distribution for all values of p_T. Conventionally, one switches from the resummed calculation to the fixed-order calculation at $p_T \approx Q$ [2,5]. Thus, a measurement of the transverse momentum distribution may be used to check the soft gluon resummation calculations in the low p_T range, and to test the perturbative QCD calculations at high p_T.

II. INTRODUCTION TO THEORY

In standard fixed order perturbative QCD, the partonic cross section is calculated by expanding in terms of the strong coupling constant (α_s) [1], where each power of α_s corresponds to the radiation of a single gluon or quark into the final state. This procedure works well in the high p_T region, where $p_T^2 \approx Q^2$. However, as $p_T \to 0$, this fixed order calculation of the cross section diverges due to the presence of correction terms that go as $\log^n(Q^2/p_T^2)$. Physically, this failure of fixed order perturbation theory at low p_T is due to soft gluon radiation from the initial partons that is not properly accounted for in the standard expansion. This difficulty in performing the calculation can be remedied by reordering the perturbation series through a technique called resummation, where the cross section is calculated in terms of the large logarithms, rather than strictly in terms of powers of α_s. The resulting calculation is an all orders calculation, i.e., each piece in the new sum contains terms to all orders in α_s. However, the largest terms dropped in the latest calculation are $O(\alpha_s^2)$, so it is considered to be accurate to $O(\alpha_s^2)$.

In final form, the calculation is carried out via a Fourier transform in impact parameter space (b-space), with the following relation describing the differential cross section [2-5]:

$$\frac{d^2\sigma}{dp_T^2 dy} \sim \int_0^\infty d^2b\, e^{i\vec{p}_T \cdot \vec{b}} W(b, Q) + Y(b, Q) \tag{1}$$

where $W(b,Q)$ contains the results of resumming the perturbative series, and $Y(b,Q)$ adds back to the calculation the pieces that are perturbative in α_s, but not singular at $p_T = 0$ [3].

Although the resummation technique extends the applicability of perturbative QCD to lower values of p_T, a more fundamental barrier is encountered when p_T approaches Λ_{QCD}. In this region non-perturbative aspects of the strong force dominate the production of vector bosons and in general perturbative QCD is expected to fail. This implies that the resummed calculation becomes undefined above some value of $b = b_{max}$. In order to extend the calculation to the low p_T region a parameterization which accounts for the non-perturbative effects is introduced. This extension is accomplished by cutting off the integral in Eq. 1 at some value b_{max} and replacing $W(b,Q)$ with $W(b_*,Q)e^{-S_{NP}(b,Q)}$, where $b_* = b/\sqrt{1 + b/b_{max}}$. This effectively cuts off the contribution of $W(b,Q)$ near b_{max}, leaving the cross section dominated by the function being introduced $S_{NP}(b,Q)$, known as the *non-perturbative Sudakov form factor*. S_{NP} has the generic renormalization group invariant form [3]:

$$S_{NP}(b,Q) = h_1(b, x_A) + h_1(b, x_B) + h_2(b)\ln\left(\frac{Q^2}{Q_o^2}\right) \tag{2}$$

where x_A and x_B are the momentum fractions of the incoming partons, b is Fourier conjugate to the transverse momentum (impact parameter), Q_o is an arbitrary momentum scale and $h_1(b,x)$ and $h_2(b)$ are phenomenological functions to be determined from experiment [2,4,5]. We used the Sudakov factor functional form from Ladinsky and Yuan [5]:

$$S_{NP}^{LY}(b,Q) = g_1 b^2 + g_2 b^2 \ln\left(\frac{Q^2}{Q_o^2}\right) + g_3 b\ln(100 x_A x_B) \tag{3}$$

The values of g_i were determined by Ladinsky and Yuan by fitting to low energy Drell-Yan data and a small sample of $Z \to ee$ data from 1994-96 run at CDF [9], yielding $g_1 = 0.11^{+0.04}_{-0.03}$ GeV^2, $g_2 = 0.4^{+0.1}_{-0.2}$ GeV^2 and $g_3 = -1.5^{+0.1}_{-0.2}$ GeV^{-1}, where $b_{max} = 0.5$ GeV^{-1} and $Q_o = 1.6$ GeV, and the CTEQ2M pdfs were used.

III. MEASUREMENT OF THE DIFFERENTIAL CROSS SECTIONS

In this paper we present measurements of the p_T spectra of W and Z bosons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV with the DØ detector [6] at Fermilab. The transverse momentum spectra of W and Z bosons have been measured previously by the UA1 [7], UA2 [8], CDF [9] and DØ [10] collaborations, but with smaller data samples than the ones reported on here.

The W and Z samples have been selected from data taken during the 1994-96 run of the Tevatron, and correspond to an integrated luminosity of ≈ 80 pb^{-1} for W and ≈ 110 pb^{-1} for Z. The measurements of the W and Z boson p_T spectra used the decay modes $W \to e\nu$ and $Z \to e^+e^-$. Electrons were detected in hermetic, uranium liquid-argon calorimeters with an energy resolution of about $15\%/\sqrt{E(\text{GeV})}$. The calorimeters have a transverse granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, where η is the pseudorapidity and ϕ is the azimuthal angle. Electrons were accepted in the regions $|\eta| < 1.1$ (central) and $1.5 < |\eta| < 2.6$ (forward). In reconstructing the p_T of the W boson, we assume that the transverse momentum of the neutrino is given by the calorimetric measurement of the missing transverse energy ($E\!\!\!/_T$) in

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the event. Electrons from W and Z boson decays tend to be isolated. Thus, we required the cut

$$\frac{E_{tot}(0.4) - E_{EM}(0.2)}{E_{EM}(0.2)} < 0.15,$$

where $E_{tot}(0.4)$ is the energy within $\Delta R < 0.4$ of the cluster centroid ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$) and $E_{EM}(0.2)$ is the energy in the EM calorimeter within $\Delta R < 0.2$.

At trigger level, the Z analysis required two electrons, one with transverse energy (E_T) greater than 20 GeV and the second with E_T greater than 16 GeV. Off-line for a "loose" electron we required that $E_T > 25$ GeV and that the transverse and longitudinal shower shapes be consistent with those expected for an electron (based on test beam measurements). For a "tight" electron we also required a good match between a reconstructed track in the drift chamber system and the shower position in the calorimeter. For the Z boson sample we required one electron to be "tight" and the other to be either "tight" or "loose"; at least one of the two electrons had to be in the central region. To be acceptable candidates for Z production, both decay electrons are required to be isolated. The dielectron invariant mass was required to lie in the range $75 - 105$ GeV/c^2. These selection cuts were passed by 6407 Z candidates.

In the case of the W boson analysis, a single electron with E_T greater than 20 GeV was required at trigger level. Off-line, a tighter requirement on the electron quality was introduced to reduce the background level from QCD events, especially at high transverse momentum. Electron identification was based on a likelihood technique. Candidates were first identified by finding isolated clusters of energy in the EM calorimeter with a matching track in the central detector. We then cut on a likelihood constructed from the following four variables: the χ^2 from a covariance matrix which measures the consistency of the calorimeter cluster shape with that of an electron shower; the electromagnetic energy fraction (defined as the ratio of the portion of the energy of the cluster found in the EM calorimeter to its total energy); a measure of the consistency between the track position and the cluster centroid; and the ionization dE/dx along the track. For the W boson sample we required one isolated electron in the central region and $\not{E}_T > 25$ GeV. The event is rejected if there is a second electron and the dielectron invariant mass lies in the range $75 - 105$ GeV/c^2. A total of 41173 W candidates passed these cuts in the central region.

The absolute normalization of the trigger and selection efficiencies were determined using $Z \to e^+e^-$ DØ collider events in which one of the electrons satisfied the trigger and selection criteria. The second electron then provided an unbiased sample with which to measure the efficiencies. The variation in the electron selection efficiency as a function of p_T has been determined using a signal Monte Carlo sample from HERWIG, smeared for detector resolutions and overlayed with events taken in random $p\overline{p}$ collisions (zero bias). A parametric Monte Carlo program [11] was used to simulate the DØ detector response and calculate the kinematic and geometric acceptance as a function of p_T. The detector resolutions used in the Monte Carlo were determined from data, and were parameterized as a function of energy and angle. The relative response of the hadronic and EM calorimeters was studied using the transverse momentum of the Z boson as measured by the p_T of the two electrons compared to the hadronic recoil system in the Z event. This parameterized representation of the DØ detector was used to smear the predictions by detector effects and compare it to
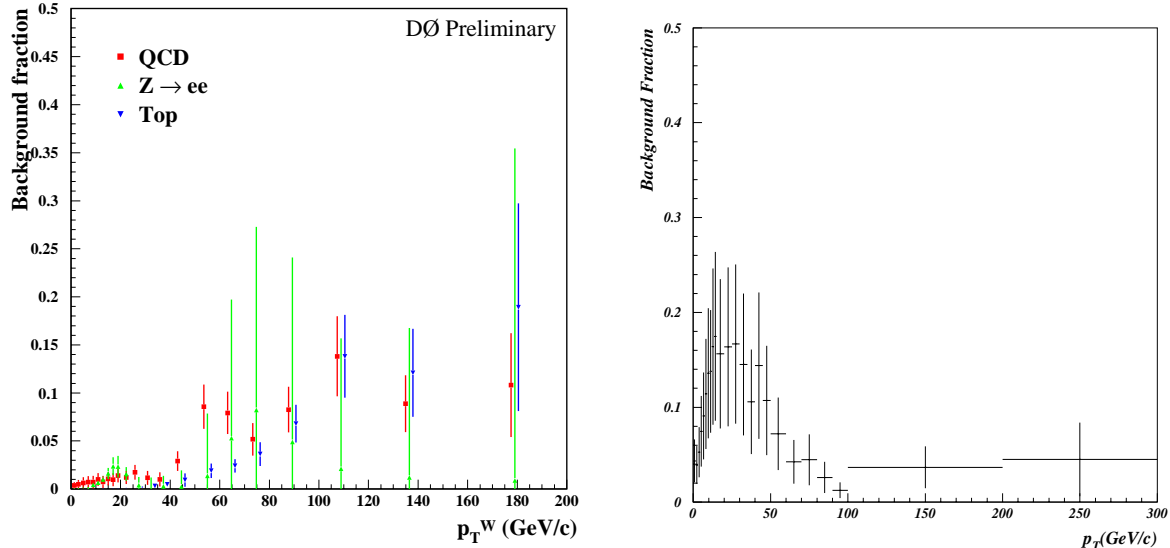
FIG. 1. Left: The background fraction to the $W \to e\nu$ signal from QCD, $Z \to ee$, and top production as a function of the p_T of the W. Right: The background fraction from QCD processes to the $Z \to ee$ signal as a function of the p_T of the Z.

our measured results.

The major source of background for both the W and the Z sample is QCD multi–jet and photon–jet events: the amount of background in the samples and its shape as a function of p_T was obtained directly from DØ data.

The total amount of QCD background in the inclusive W sample is $\approx 1\%$. The normalized QCD background was subtracted bin-by-bin from the W boson candidate sample transverse momentum spectrum. Additional corrections were made to account for top quark background events (0.1%) and for $Z \to e^+e^-$ events (0.8%), where one of the electrons was lost or not identified. Since p_T^W was measured from the recoiling hadrons, the events originating from $W \to \tau\nu$ (where $\tau \to e\nu\nu$) contributed properly to the differential distribution; this source of background therefore was included in the Monte Carlo simulation of the p_T^W distribution.

The total background for the Z sample is $\approx 2\%$ for events in which both electrons are in the central region and $\approx 7\%$ when one electron is in the central region and the other is in the forward region. Backgrounds to $Z \to ee$ production from $Z \to \tau\tau$, top quark and diboson production have been estimated from Monte Carlo samples and are negligible. Figure 1 shows the background fractions as a function of p_T for both the W and Z samples.

The result for the W p_T distribution, shown in Figure 2, is compared to the theoretical calculation by Arnold and Kauffman [2], smeared by detector resolutions. The W data shows good agreement with this combined QCD perturbative and resummation calculation over the whole range of p_T. In the case of the Z, we correct the measured cross section for the effects of detector smearing. Figure 3 compares the final, smearing-corrected Z p_T distribution to the calculation by Ladinsky and Yuan [5]. In addition, Figure 4 compares the p_T^Z measurement to the fixed-order perturbative theory [1]. In comparing to the NLO
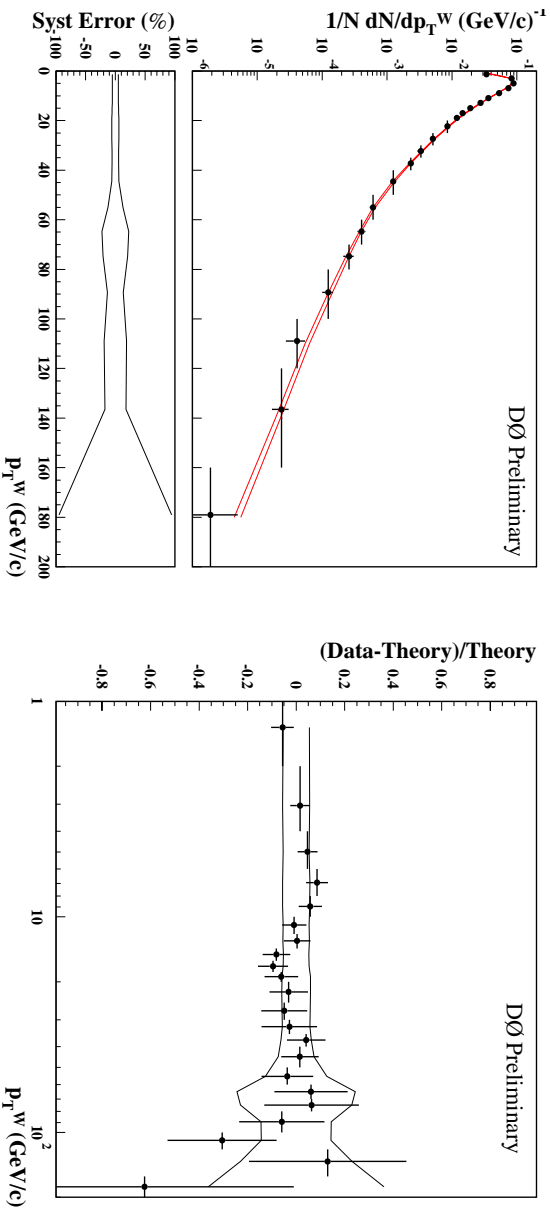
FIG. 2. Left: DØ W p_T result (solid points) with statistical uncertainty. The theoretical calculation by Arnold-Kauffman [2] has been smeared for detector resolutions and is shown as two lines corresponding to the $\pm 1\sigma$ variations of the uncertainties in the detector modeling. Data and theory are independently area normalized to unity. The fractional systematic uncertainty on the data is shown as a band in the lower portion of the plot. Right: The ratio (Data-Theory)/Theory shown as a function of p_T^W with its statistical uncertainty as error bars. The total systematic uncertainties, shown as a band, were obtained by adding in quadrature the contributions from data (background and efficiency) and from the detector modeling.

calculation, we observed strong disagreement at low p_T, as expected due to the divergence of the calculation at $p_T = 0$, and a significant enhancement of the cross section from soft gluon emission.
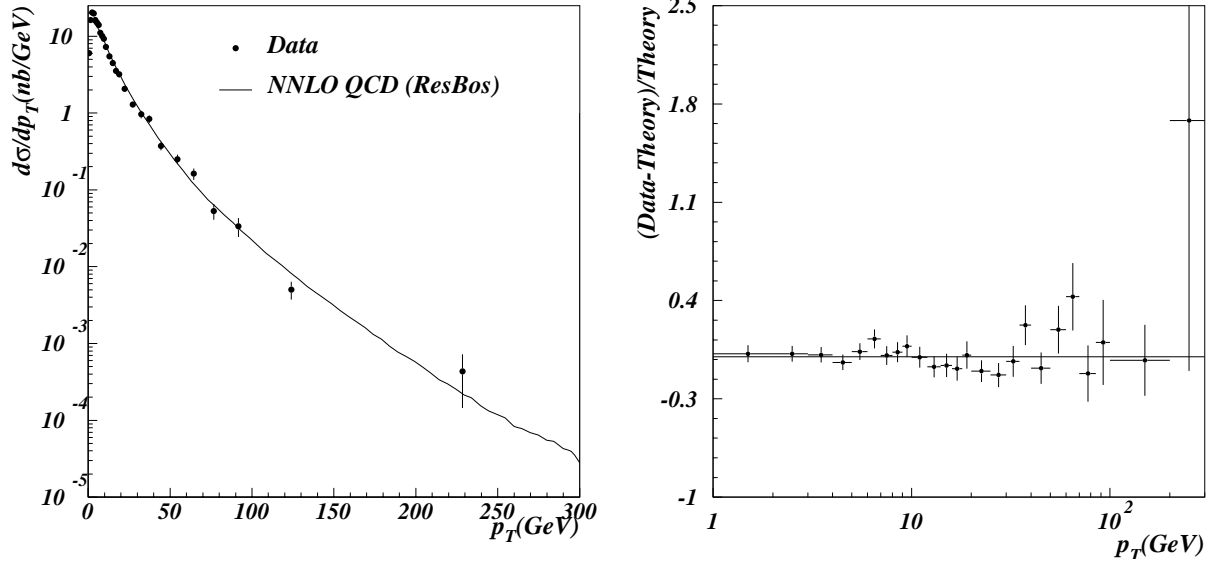
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FIG. 3. Left: DØ Z differential cross section (circles) as a function of p_T compared to the calculation by Ladinsky–Yuan [5]. Theory is normalized to the data. Right: The ratio (Data-Theory)/Theory as a function of p_T of the Z.
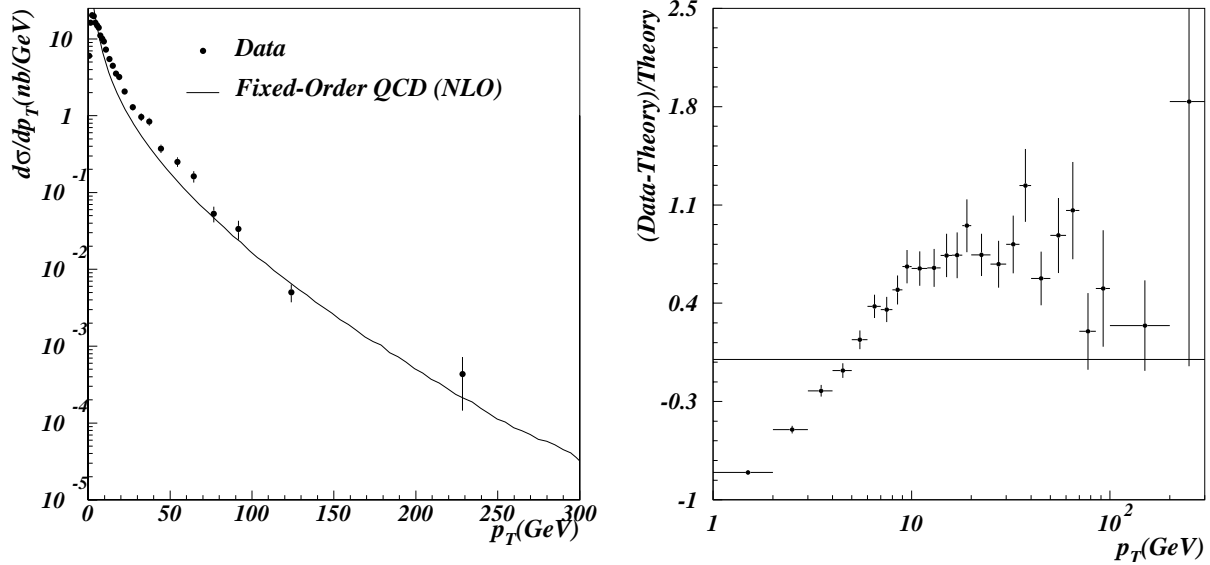

FIG. 4. Left: DØ Z p_T smearing-corrected data (solid points) with total uncertainty shown compared to the fixed-order (NLO) perturbative prediction [1]. The data is normalized to the DØ measured inclusive Z production cross section [12]; the theory is normalized to its own prediction [1]. Right: Fractional difference between the Z data and the fixed-order calculation as a function of p_T.

IV. CONCLUSIONS

Using data taken with the DØ detector during the 1994–1996 Tevatron collider run, we have presented measurements of the W and Z transverse momentum distributions that agree well with the combined QCD perturbative and resummation calculations.

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