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
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Abstract

We present measurements of the transverse momentum distribution of W and Z bosons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the DØ detector at Fermilab. The results are consistent with predictions based on the combined QCD perturbative and resummation calculation over the entire p_T range. The transverse momentum of the Z boson can distinguish between different phenomenological models available for the small p_T region.

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B. Abbott,[40] M. Abolins,[37] V. Abramov,[15] B.S. Acharya,[8] I. Adam,[39] D.L. Adams,[48] M. Adams,[24] S. Ahn,[23] H. Aihara,[17] G.A. Alves,[2] N. Amos,[36] E.W. Anderson,[30] R. Astur,[42] M.M. Baarmand,[42] V.V. Babintsev,[15] L. Babukhadia,[16] A. Baden,[33] V. Balamurali,[28] B. Baldin,[23] S. Banerjee,[8] J. Bantly,[45] E. Barberis,[17] P. Baringer,[31] J.F. Bartlett,[23] A. Belyaev,[14] S.B. Beri,[6] I. Bertram,[26] V.A. Bezzubov,[15] P.C. Bhat,[23] V. Bhatnagar,[6] M. Bhattacharjee,[42] N. Biswas,[28] G. Blazey,[25] S. Blessing,[21] P. Bloom,[18] A. Boehnlein,[23] N.I. Bojko,[15] F. Borcherding,[23] C. Boswell,[20] A. Brandt,[23] R. Breedon,[18] R. Brock,[37] A. Bross,[23] D. Buchholz,[26] V.S. Burtovoi,[15] J.M. Butler,[34] W. Carvalho,[2] D. Casey,[37] Z. Casilum,[42] H. Castilla-Valdez,[11] D. Chakraborty,[42] S.-M. Chang,[35] S.V. Chekulaev,[15] L.-P. Chen,[17] W. Chen,[42] S. Choi,[10] S. Chopra,[36] B.C. Choudhary,[20] J.H. Christenson,[23] M. Chung,[24] D. Claes,[38] A.R. Clark,[17] W.G. Cobau,[33] J. Cochran,[20] L. Coney,[28] W.E. Cooper,[23] C. Cretsinger,[41] D. Cullen-Vidal,[45] M.A.C. Cummings,[25] D. Cutts,[45] O.I. Dahl,[17] K. Davis,[16] K. De,[46] K. Del Signore,[36] M. Demarteau,[23] D. Denisov,[23] S.P. Denisov,[15] H.T. Diehl,[23] M. Diesburg,[23] G. Di Loreto,[37] P. Draper,[46] Y. Ducros,[5] L.V. Dudko,[14] S.R. Dugad,[8] A. Dyshkant,[15] D. Edmunds,[37] J. Ellison,[20] V.D. Elvira,[42] R. Engelmann,[42] S. Eno,[33] G. Eppley,[48] P. Ermolov,[14] O.V. Eroshin,[15] V.N. Evdokimov,[15] T. Fahland,[19] M.K. Fatyga,[41] S. Feher,[23] D. Fein,[16] T. Ferbel,[41] G. Finocchiaro,[42] H.E. Fisk,[23] Y. Fisyak,[43] E. Flattum,[23] G.E. Forden,[16] M. Fortner,[25] K.C. Frame,[37] S. Fuess,[23] E. Gallas,[46] A.N. Galyaev,[15] P. Gartung,[20] V. Gavrilov,[13] T.L. Geld,[37] R.J. Genik II,[37] K. Genser,[23] C.E. Gerber,[23] Y. Gershtein,[13] B. Gibbard,[43] B. Gobbi,[26] B. Gómez,[4] G. Gómez,[33] P.I. Goncharov,[15] J.L. González Solís,[11] H. Gordon,[43] L.T. Goss,[47] K. Gounder,[20] A. Goussiou,[42] N. Graf,[43] P.D. Grannis,[42] D.R. Green,[23] H. Greenlee,[23] S. Grinstein,[1] P. Grudberg,[17] S. Grünendahl,[23] G. Guglielmo,[44] J.A. Guida,[16] J.M. Guida,[45] A. Gupta,[8] S.N. Gurzhiev,[15] G. Gutierrez,[23] P. Gutierrez,[44] N.J. Hadley,[33] H. Haggerty,[23] S. Hagopian,[21] V. Hagopian,[21] K.S. Hahn,[41] R.E. Hall,[19] P. Hanlet,[35] S. Hansen,[23] J.M. Hauptman,[30] D. Hedin,[25] A.P. Heinson,[20] U. Heintz,[23] R. Hernández-Montoya,[11] T. Heuring,[21] R. Hirosky,[24] J.D. Hobbs,[42] B. Hoeneisen,[4,*] J.S. Hoftun,[45] F. Hsieh,[36] Ting Hu,[42] Tong Hu,[27] T. Huehn,[20] A.S. Ito,[23] E. James,[16] J. Jaques,[28] S.A. Jerger,[37] R. Jesik,[27] J.Z.-Y. Jiang,[42] T. Joffe-Minor,[26] K. Johns,[16] M. Johnson,[23] A. Jonckheere,[23] M. Jones,[22] H. Jöstlein,[23] S.Y. Jun,[26] C.K. Jung,[42] S. Kahn,[43] G. Kalbfleisch,[44] D. Karmanov,[14] D. Karmgard,[21] R. Kehoe,[28] M.L. Kelly,[28] S.K. Kim,[10] B. Klima,[23] C. Klopfenstein,[18] W. Ko,[18] J.M. Kohli,[6] D. Koltick,[29] A.V. Kostritskiy,[15] J. Kotcher,[43] A.V. Kotwal,[39] A.V. Kozelov,[15] E.A. Kozlovsky,[15] J. Krane,[38] M.R. Krishnaswamy,[8] S. Krzywdzinski,[23] S. Kuleshov,[13] S. Kunori,[33] F. Landry,[37] G. Landsberg,[23] B. Lauer,[30] A. Leflat,[14] J. Li,[46] Q.Z. Li-Demarteau,[23] J.G.R. Lima,[3] D. Lincoln,[23] S.L. Linn,[21] J. Linnemann,[37] R. Lipton,[23] F. Lobkowicz,[41] S.C. Loken,[17] A. Lucotte,[42] L. Lueking,[23] A.L. Lyon,[33] A.K.A. Maciel,[2] R.J. Madaras,[17] R. Madden,[21] L. Magaña-Mendoza,[11] V. Manankov,[14] S. Mani,[18] H.S. Mao,[23,†] R. Markeloff,[25] T. Marshall,[27] M.I. Martin,[23] K.M. Mauritz,[30] B. May,[26] A.A. Mayorov,[15] R. McCarthy,[42] J. McDonald,[21] T. McKibben,[24] J. McKinley,[37] T. McMahon,[44] H.L. Melanson,[23] M. Merkin,[14] K.W. Merritt,[23] H. Miettinen,[48] A. Mincer,[40] C.S. Mishra,[23] N. Mokhov,[23] N.K. Mondal,[8] H.E. Montgomery,[23] P. Mooney,[4] H. da Motta,[2] C. Murphy,[24] F. Nang,[16] M. Narain,[23] V.S. Narasimham,[8] A. Narayanan,[16] H.A. Neal,[36] J.P. Negret,[4] P. Nemethy,[40] D. Norman,[47] L. Oesch,[36] V. Oguri,[3] E. Oliveira,[2] E. Oltman,[17] N. Oshima,[23] D. Owen,[37] P. Padley,[48] A. Para,[23] Y.M. Park,[9] R. Partridge,[45] N. Parua,[8] M. Paterno,[41] B. Pawlik,[12]

J. Perkins,[46] M. Peters,[22] R. Piegaia,[1] H. Piekarz,[21] Y. Pischalnikov,[29] B.G. Pope,[37]
H.B. Prosper,[21] S. Protopopescu,[43] J. Qian,[36] P.Z. Quintas,[23] R. Raja,[23] S. Rajagopalan,[43]
O. Ramirez,[24] S. Reucroft,[35] M. Rijssenbeek,[42] T. Rockwell,[37] M. Roco,[23] P. Rubinov,[26]
R. Ruchti,[28] J. Rutherfoord,[16] A. Sánchez-Hernández,[11] A. Santoro,[2] L. Sawyer,[32]
R.D. Schamberger,[42] H. Schellman,[26] J. Sculli,[40] E. Shabalina,[14] C. Shaffer,[21]
H.C. Shankar,[8] R.K. Shivpuri,[7] M. Shupe,[16] H. Singh,[20] J.B. Singh,[6] V. Sirotenko,[25]
W. Smart,[23] E. Smith,[44] R.P. Smith,[23] R. Snihur,[26] G.R. Snow,[38] J. Snow,[44] S. Snyder,[43]
J. Solomon,[24] M. Sosebee,[46] N. Sotnikova,[14] M. Souza,[2] A.L. Spadafora,[17] G. Steinbrück,[44]
R.W. Stephens,[46] M.L. Stevenson,[17] D. Stewart,[36] F. Stichelbaut,[42] D. Stoker,[19]
V. Stolin,[13] D.A. Stoyanova,[15] M. Strauss,[44] K. Streets,[40] M. Strovink,[17] A. Sznajder,[2]
P. Tamburello,[33] J. Tarazi,[19] M. Tartaglia,[23] T.L.T. Thomas,[26] J. Thompson,[33]
T.G. Trippe,[17] P.M. Tuts,[39] V. Vaniev,[15] N. Varelas,[24] E.W. Varnes,[17] D. Vititoe,[16]
A.A. Volkov,[15] A.P. Vorobiev,[15] H.D. Wahl,[21] G. Wang,[21] J. Warchol,[28] G. Watts,[45]
M. Wayne,[28] H. Weerts,[37] A. White,[46] J.T. White,[47] J.A. Wightman,[30] S. Willis,[25]
S.J. Wimpenny,[20] J.V.D. Wirjawan,[47] J. Womersley,[23] E. Won,[41] D.R. Wood,[35] Z. Wu,[23,†]
H. Xu,[45] R. Yamada,[23] P. Yamin,[43] T. Yasuda,[35] P. Yepes,[48] K. Yip,[23] C. Yoshikawa,[22]
S. Youssef,[21] J. Yu,[23] Y. Yu,[10] B. Zhang,[23,†] Y. Zhou,[23,†] Z. Zhou,[30] Z.H. Zhu,[41]
D. Zieminska,[27] A. Zieminski,[27] E.G. Zverev,[14] and A. Zylberstejn[5]

(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]Universidad de los Andes, Bogotá, Colombia
[5]DAPNIA/Service de Physique des Particules, CEA, Saclay, France
[6]Panjab University, Chandigarh, India
[7]Delhi University, Delhi, India
[8]Tata Institute of Fundamental Research, Mumbai, India
[9]Kyungsung University, Pusan, Korea
[10]Seoul National University, Seoul, Korea
[11]CINVESTAV, Mexico City, Mexico
[12]Institute of Nuclear Physics, Kraków, Poland
[13]Institute for Theoretical and Experimental Physics, Moscow, Russia
[14]Moscow State University, Moscow, Russia
[15]Institute for High Energy Physics, Protvino, Russia
[16]University of Arizona, Tucson, Arizona 85721
[17]Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
[18]University of California, Davis, California 95616
[19]University of California, Irvine, California 92697
[20]University of California, Riverside, California 92521
[21]Florida State University, Tallahassee, Florida 32306
[22]University of Hawaii, Honolulu, Hawaii 96822
[23]Fermi National Accelerator Laboratory, Batavia, Illinois 60510

[24]University of Illinois at Chicago, Chicago, Illinois 60607
[25]Northern Illinois University, DeKalb, Illinois 60115
[26]Northwestern University, Evanston, Illinois 60208
[27]Indiana University, Bloomington, Indiana 47405
[28]University of Notre Dame, Notre Dame, Indiana 46556
[29]Purdue University, West Lafayette, Indiana 47907
[30]Iowa State University, Ames, Iowa 50011
[31]University of Kansas, Lawrence, Kansas 66045
[32]Louisiana Tech University, Ruston, Louisiana 71272
[33]University of Maryland, College Park, Maryland 20742
[34]Boston University, Boston, Massachusetts 02215
[35]Northeastern University, Boston, Massachusetts 02115
[36]University of Michigan, Ann Arbor, Michigan 48109
[37]Michigan State University, East Lansing, Michigan 48824
[38]University of Nebraska, Lincoln, Nebraska 68588
[39]Columbia University, New York, New York 10027
[40]New York University, New York, New York 10003
[41]University of Rochester, Rochester, New York 14627
[42]State University of New York, Stony Brook, New York 11794
[43]Brookhaven National Laboratory, Upton, New York 11973
[44]University of Oklahoma, Norman, Oklahoma 73019
[45]Brown University, Providence, Rhode Island 02912
[46]University of Texas, Arlington, Texas 76019
[47]Texas A&M University, College Station, Texas 77843
[48]Rice University, Houston, Texas 77005

I. INTRODUCTION

W and Z bosons, the carriers of the weak force, are directly produced in high energy $\overline{p}p$ collisions at the Fermilab Tevatron, which operates at a center of mass energy of $\sqrt{s} = 1.8$ TeV. In addition to probing electroweak physics, 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. All of these features combine to provide higher-precision studies of the strong interaction than those that can generally be obtained from studying events with only jet final states. 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 1992–1996 Tevatron running period.

II. INTRODUCTION TO THEORY

The transverse momentum (p_T) of W and Z intermediate vector bosons produced in proton-antiproton collisions is due to the production of one or more gluons or quarks along with the bosons. 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. 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 [1] is therefore expected to be reliable in this regime. A prescription [2] has been proposed for matching the low and high p_T regions to provide a continuous prediction for all p_T. 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.

In the high p_T region, where $p_{\mathrm{T}}^2 \approx Q^2$, the differential cross section is well described by standard fixed order perturbation theory, in which the cross section is expanded in terms of the strong coupling constant (α_s) [1]. In this case, each power of α_s corresponds to the radiation of a single gluon or quark into the final state. However, as $p_{\mathrm{T}} \to 0$, this fixed order calculation of the cross section diverges due to the presence of terms that go as $\log^n(Q^2/p_{\mathrm{T}}^2)$. Physically, this failure of fixed order perturbation theory at low p_T is due to soft gluon radiation from the initial partons being an important contributor to the transverse momentum of the vector boson. This difficulty in performing the perturbative calculation can be remedied by resumming the perturbation series 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 $O(\alpha_s^2)$.

Formally, 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]:

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

where

$$W(b,Q) \sim exp(-S(b,Q)), \tag{2}$$

$$S(b,Q) = \int_{b/b_o}^{Q^2} \frac{d\mu^2}{\mu^2}[\ln(\frac{Q^2}{\mu^2})A(\alpha_s(\mu)) + B(\alpha_s(\mu))]. \tag{3}$$

b_o is an arbitrary scale and $A(\alpha_s)$ and $B(\alpha_s)$ are coefficients determined from pQCD. $S(b,Q)$ is called the Sudakov form factor. It is via the exponentiation of $S(b,Q)$ that the sum over the logarithms is implemented. The Y term in Eq.1 is a correction from fixed order perturbation theory .

The resummed calculation becomes undefined at high b values (corresponding to very low p_T), where $b \geq 1/\Lambda_{QCD}$ and perturbation theory is expected to fail in general. A parameterization applicable to the low p_T region is introduced in order to account for the non-perturbative effects. Formally, this 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 $b_* = b/\sqrt{1+b/b_{max}}$ and S_{NP} is the non-perturbative function being introduced. It has been shown that the non-perturbative function has the following universal form [3] :

$$S_{NP}(b,Q) = h_1(b,x_A) + h_1(b,x_B) + h_2(b)\ln(\frac{Q}{2Q_o}) \tag{4}$$

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 the functions $h_1(b,x)$ and $h_2(b)$ must be determined from experiment.

The two suggested parameterizations for the non-perturbative function are [4] [5],

$$S_{NP}^{DWS}(b,Q) = g_1 b^2 + g_2 b^2 \ln(\frac{Q}{2Q_o}) \tag{5}$$

$$S_{NP}^{LY}(b,Q) = g_1 b^2 + g_2 b^2 \ln(\frac{Q}{2Q_o}) + g_3 b \ln(100 x_A x_B) \tag{6}$$

where g_i must be determined from experiment.

Fits to Drell-Yan data were performed in order to obtain values for the g_i parameters. Using Eq. 5, with the Duke and Owens parton distribution functions (PDFs), b_{max} = 0.5 GeV^{-1}, and Q_o = 2 GeV, Davies, Weber, and Stirling obtained the values g_1 = 0.15 GeV^2 and g_2 = 0.4 GeV^2 [4]. Using Eq. 6, with the CTEQ2M PDFs, b_{max} = 0.5 GeV^{-1} and Q_o = 1.6 GeV, Ladinsky and Yuan obtained the values $g_1 = 0.11^{+0.04}_{-0.03}$ GeV^2, $g_2 = 0.4^{+0.1}_{-0.2}$ GeV^2 and $g_3 = -1.5^{+0.1}_{-0.2}$ GeV^{-1} [5].

III. MEASUREMENT OF THE DIFFERENTIAL $D\sigma/DP_T$ CROSS SECTIONS

We present in this paper 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], and CDF [9] collaborations, but with smaller data samples than the ones reported on here.

The Ws have been selected from data taken during the 1993-94 run of the Tevatron, and correspond to an integrated luminosity of ≈ 12 pb^{-1}. The Zs have been selected from the 1994-96 data corresponding to an integrated luminosity of ≈ 110 pb^{-1}. 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 $15\%/\sqrt{E(\mathrm{GeV})}$. 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 $1.5 < |\eta| < 3.2$(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 ($\not\!\!E_T$) in the event.

At trigger level, the W analysis required a single electron with transverse energy (E_T) greater than 20 GeV; the Z analysis required two electrons, one with 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 W boson sample we required one central "tight" electron and $\not\!\!E_T > 25$ GeV. 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 central. The dielectron invariant mass had to lie in the range $75 - 105$ GeV/c^2. 7132 W candidates and 6407 Z candidates passed these selection cuts.

The absolute normalization of the trigger and selection efficiencies were determined using $Z \to e^+e^-$ 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 single electron selection efficiency as a function of p_T has been determined using a $Z \to ee$ Monte Carlo sample ran through a full detector simulation. A parametric Monte Carlo program [10] 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 parametrized 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 parametrized representation of the DØ detector was used to smear the theoretical prediction by detector effects and compare it to our measured p_T.

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 $\approx 4\%$. To cross–check this background estimate the transverse mass and the $\not\!\!E_T$ distributions of the final data sample were compared to a model of the expected distributions obtained from a combination of $W \to e\nu$ Monte Carlo events plus the estimated QCD background. The comparison was performed in three p_T^W bins: $0 - 30$ GeV$/c$, $30 - 60$ GeV$/c$, and > 60 GeV$/c$; the number of $W \to e\nu$ candidates in each bin was 6726, 282, and 124. The amount of QCD background in each p_T^W bin was estimated as $(2.9 \pm 1.6)\%$, $(20.9 \pm 11.7)\%$, and $(38.3 \pm 21.5)\%$, respectively. The goodness of the fit between the data and the model is evaluated by performing a χ^2_λ

test [11]. The numerical results for χ^2_λ/d.o.f. in each p_T^W bin are 20.2/25, 26.4/19, and 4.7/7 for the transverse mass fits and 5.4/9, 3.0/13, and 2.1/7 for the $\not{E}_T$ fits. They correspond to fit probabilities of 74%, 12%, 69%, 80%, 99%, and 95% respectively. We therefore conclude that the tests show good agreement between the data and the expectation. The normalized QCD background was subtracted bin by bin from the W boson candidate sample transverse momentum spectrum. Additional corrections (all less than 5%) were made to account for top quark background events and for $Z \to e^+e^-$ events 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 central and $\approx 7\%$ when one electron is central and the other is forward. 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.

Figure 2 shows the published [12] results for the W p_T; figures 3 and 4 show the preliminary results for the Z p_T. Figures 2 and 3 compare the measured results to the combined QCD resummed and perturbative calculation of the vector boson p_T. Only below 4 GeV/c do the true p_T distributions predicted by the two available models [2,5] exhibit a difference, which is masked in the W data by the resolution effects. The p_T^Z gets determined directly from the electrons E_T and is therefore sufficiently well-measured to discriminate between the two parameterizations. The W data shows good agreement with the combined QCD perturbative and resummation calculation. The Z data shows generally good agreement over the entire range, except for an approximately 2σ deviation near p_T^Z of 40 GeV/c.

In addition, figure 4 compares the p_T^Z measurement to pure NLO perturbative QCD over the entire range of p_T. One can observe the divergence of the theory from the data at low p_T, corroborating the known need for resummation calculations in that region.

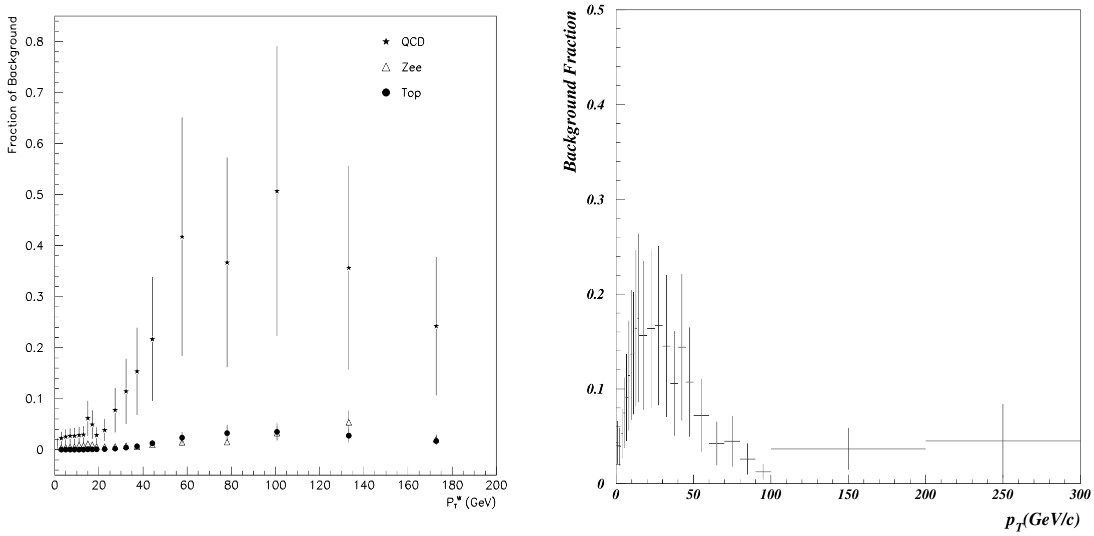

FIG. 1. Left: The background fraction to the $W \to e\nu$ signal from QCD, $Z \to ee$, and top production as a function of the p_T of the W. Right: The background fraction from QCD processes to the $Z \to ee$ signal as a function of the p_T of the Z.

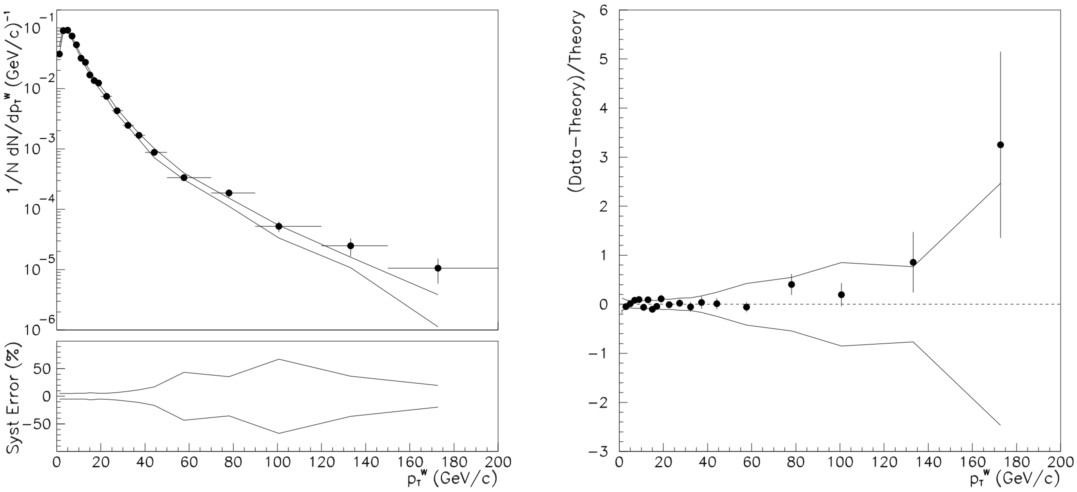

FIG. 2. Left: DØ result (solid points) with statistical uncertainty. The theoretical calculation by Davies-Weber-Stirling [2],with parameter values as discussed in the text, has been smeared for detector resolutions and is shown as two lines corresponding to the $\pm 1\sigma$ variations of the uncertainties in the detector modelling. 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 systematic uncertainties from data (background and efficiency) and from the detector modelling are added in quadrature and shown as a band.

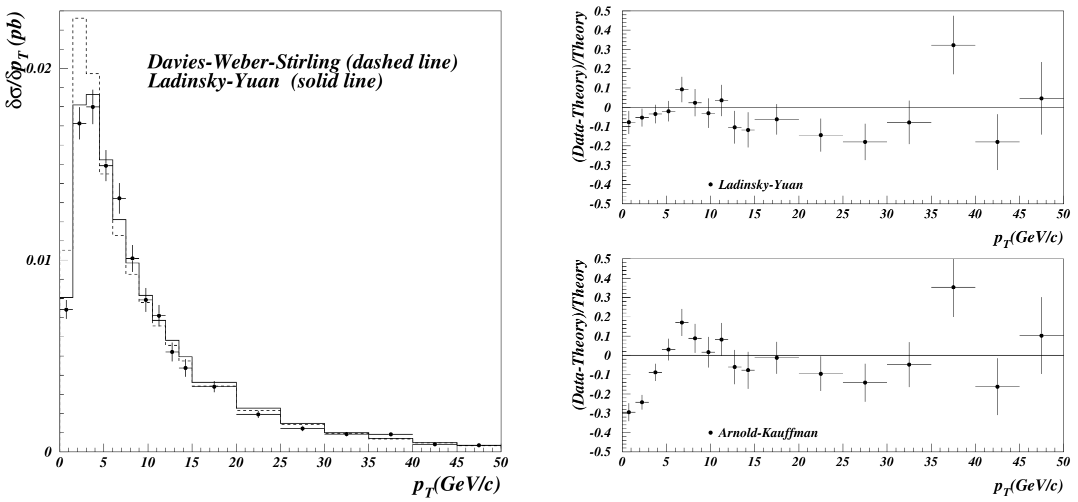

FIG. 3. Left: DØ data (solid points) with total uncertainty shown compared to two theoretical predictions, which are smeared for detector resolutions. The theoretical predictions shown are those of Davies-Weber-Stirling [2] and Ladinsky-Yuan [5], with parameter values as discussed in the text. The data is normalized to the DØ measured inclusive Z production cross section [12]; the theory is normalized to the data. Right: The ratio (Data-Theory)/Theory as a function of p_T of the Z shown for the two parameterizations of the non-perturbative function in the theory.

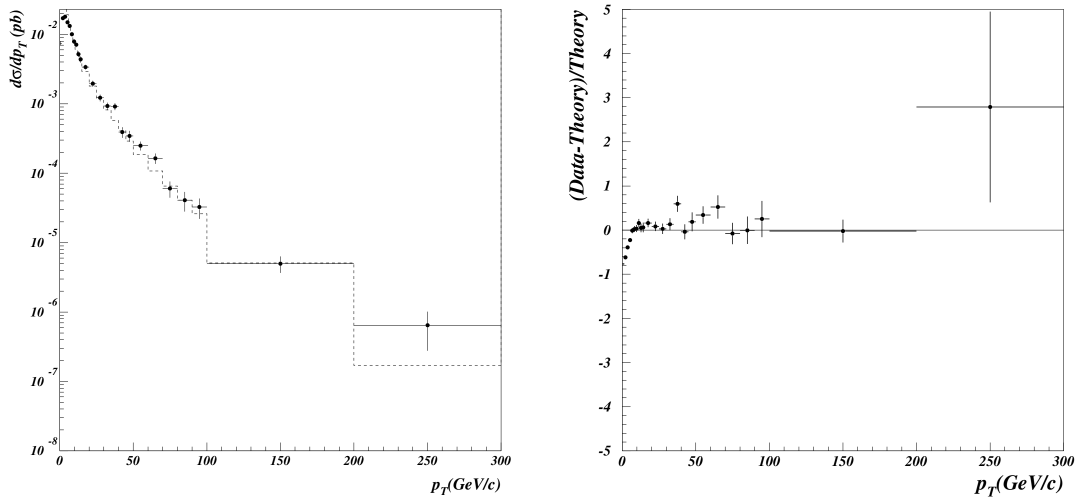

FIG. 4. Left: DØ data (solid points) with total uncertainty shown compared to the NLO perturbative prediction [1], which was smeared for detector resolutions. The data is normalized to the DØ measured inclusive Z production cross section [12]; the theory is normalized to its own prediction [1]. Right: The ratio (Data-Theory)/Theory as a function of p_T of the Z shows the known need for resummation in the very low–p_T region.

IV. CONCLUSIONS

Using data taken with the DØ detector during the 1992–1996 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. In addition, we have shown that the Z boson data distinguishes between different vector boson production models.

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* Visitor from Universidad San Francisco de Quito, Quito, Ecuador.
† Visitor from IHEP, Beijing, China.

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