# Measurement of the ratio of the differential cross sections for $W$ and $Z$ boson production as a function of transverse momentum in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

The DØ Collaboration *
*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
(February 7, 2008)

arXiv:hep-ex/0106027v1 5 Jun 2001

## Abstract

We report on a preliminary measurement of the ratio of the differential cross sections for $W$ and $Z$ boson production as a function of transverse momentum in proton-antiproton collisions at $\sqrt{s} = 1.8$ TeV. It has been shown that the ratio between $W$ and $Z$ observables can be reliably calculated using perturbative QCD, even when the individual observables are not. We present the first comparison between the measurement of a $W$ and $Z$ observable ratio and a purely perturbative calculation. The use of the ratio reduces both experimental and theoretical uncertainites and might result in smaller overall uncertainties on the measured $W$ mass and width, compared to currently used methods at hadron colliders.

*Submitted to the *International Europhysics Conference on High Energy Physics*, July 12-18, 2001, Budapest, Hungary,
and *XX International Symposium on Lepton and Photon Interactions at High Energies* July 23 – 28, 2001, Rome, Italy.

V.M. Abazov,[23] B. Abbott,[58] A. Abdesselam,[11] M. Abolins,[51] V. Abramov,[26] B.S. Acharya,[17] D.L. Adams,[60] M. Adams,[38] S.N. Ahmed,[21] G.D. Alexeev,[23] G.A. Alves,[2] N. Amos,[50] E.W. Anderson,[43] Y. Arnoud,[9] M.M. Baarmand,[55] V.V. Babintsev,[26] L. Babukhadia,[55] T.C. Bacon,[28] A. Baden,[47] B. Baldin,[37] P.W. Balm,[20] S. Banerjee,[17] E. Barberis,[30] P. Baringer,[44] J. Barreto,[2] J.F. Bartlett,[37] U. Bassler,[12] D. Bauer,[28] A. Bean,[44] M. Begel,[54] A. Belyaev,[35] S.B. Beri,[15] G. Bernardi,[12] I. Bertram,[27] A. Besson,[9] R. Beuselinck,[28] V.A. Bezzubov,[26] P.C. Bhat,[37] V. Bhatnagar,[11] M. Bhattacharjee,[55] G. Blazey,[39] S. Blessing,[35] A. Boehnlein,[37] N.I. Bojko,[26] F. Borcherding,[37] K. Bos,[20] A. Brandt,[60] R. Breedon,[31] G. Briskin,[59] R. Brock,[51] G. Brooijmans,[37] A. Bross,[37] D. Buchholz,[40] M. Buehler,[38] V. Buescher,[14] V.S. Burtovoi,[26] J.M. Butler,[48] F. Canelli,[54] W. Carvalho,[3] D. Casey,[51] Z. Casilum,[55] H. Castilla-Valdez,[19] D. Chakraborty,[39] K.M. Chan,[54] S.V. Chekulaev,[26] D.K. Cho,[54] S. Choi,[34] S. Chopra,[56] J.H. Christenson,[37] M. Chung,[38] D. Claes,[52] A.R. Clark,[30] J. Cochran,[34] L. Coney,[42] B. Connolly,[35] W.E. Cooper,[37] D. Coppage,[44] S. Crépé-Renaudin,[9] M.A.C. Cummings,[39] D. Cutts,[59] G.A. Davis,[54] K. Davis,[29] K. De,[60] S.J. de Jong,[21] K. Del Signore,[50] M. Demarteau,[37] R. Demina,[45] P. Demine,[9] D. Denisov,[37] S.P. Denisov,[26] S. Desai,[55] H.T. Diehl,[37] M. Diesburg,[37] G. Di Loreto,[51] S. Doulas,[49] P. Draper,[60] Y. Ducros,[13] L.V. Dudko,[25] S. Duensing,[21] L. Duflot,[11] S.R. Dugad,[17] A. Duperrin,[10] A. Dyshkant,[39] D. Edmunds,[51] J. Ellison,[34] V.D. Elvira,[37] R. Engelmann,[55] S. Eno,[47] G. Eppley,[62] P. Ermolov,[25] O.V. Eroshin,[26] J. Estrada,[54] H. Evans,[53] V.N. Evdokimov,[26] T. Fahland,[33] S. Feher,[37] D. Fein,[29] T. Ferbel,[54] F. Filthaut,[21] H.E. Fisk,[37] Y. Fisyak,[56] E. Flattum,[37] F. Fleuret,[30] M. Fortner,[39] H. Fox,[40] K.C. Frame,[51] S. Fu,[53] S. Fuess,[37] E. Gallas,[37] A.N. Galyaev,[26] M. Gao,[53] V. Gavrilov,[24] R.J. Genik II,[27] K. Genser,[37] C.E. Gerber,[38] Y. Gershtein,[59] R. Gilmartin,[35] G. Ginther,[54] B. Gómez,[5] G. Gómez,[47] P.I. Goncharov,[26] J.L. González Solís,[19] H. Gordon,[56] L.T. Goss,[61] K. Gounder,[37] A. Goussiou,[28] N. Graf,[56] G. Graham,[47] P.D. Grannis,[55] J.A. Green,[43] H. Greenlee,[37] S. Grinstein,[1] L. Groer,[53] S. Grünendahl,[37] A. Gupta,[17] S.N. Gurzhiev,[26] G. Gutierrez,[37] P. Gutierrez,[58] N.J. Hadley,[47] H. Haggerty,[37] S. Hagopian,[35] V. Hagopian,[35] R.E. Hall,[32] P. Hanlet,[49] S. Hansen,[37] J.M. Hauptman,[43] C. Hays,[53] C. Hebert,[44] D. Hedin,[39] J.M. Heinmiller,[38] A.P. Heinson,[34] U. Heintz,[48] T. Heuring,[35] M.D. Hildreth,[42] R. Hirosky,[63] J.D. Hobbs,[55] B. Hoeneisen,[8] Y. Huang,[50] R. Illingworth,[28] A.S. Ito,[37] M. Jaffré,[11] S. Jain,[17] R. Jesik,[28] K. Johns,[29] M. Johnson,[37] A. Jonckheere,[37] M. Jones,[36] H. Jöstlein,[37] A. Juste,[37] W. Kahl,[45] S. Kahn,[56] E. Kajfasz,[10] A.M. Kalinin,[23] D. Karmanov,[25] D. Karmgard,[42] Z. Ke,[4] R. Kehoe,[51] A. Khanov,[45] A. Kharchilava,[42] S.K. Kim,[18] B. Klima,[37] B. Knuteson,[30] W. Ko,[31] J.M. Kohli,[15] A.V. Kostritskiy,[26] J. Kotcher,[56] B. Kothari,[53] A.V. Kotwal,[53] A.V. Kozelov,[26] E.A. Kozlovsky,[26] J. Krane,[43] M.R. Krishnaswamy,[17] P. Krivkova,[6] S. Krzywdzinski,[37] M. Kubantsev,[45] S. Kuleshov,[24] Y. Kulik,[55] S. Kunori,[47] A. Kupco,[7] V.E. Kuznetsov,[34] G. Landsberg,[59] W.M. Lee,[35] A. Leflat,[25] C. Leggett,[30] F. Lehner,[37,*] J. Li,[60] Q.Z. Li,[37] X. Li,[4] J.G.R. Lima,[3] D. Lincoln,[37] S.L. Linn,[35] J. Linnemann,[51] R. Lipton,[37] A. Lucotte,[9] L. Lueking,[37] C. Lundstedt,[52] C. Luo,[41] A.K.A. Maciel,[39] R.J. Madaras,[30] V.L. Malyshev,[23] V. Manankov,[25] H.S. Mao,[4] T. Marshall,[41] M.I. Martin,[39] R.D. Martin,[38] K.M. Mauritz,[43] B. May,[40] A.A. Mayorov,[41] R. McCarthy,[55] T. McMahon,[57] H.L. Melanson,[37] M. Merkin,[25] K.W. Merritt,[37] C. Miao,[59] H. Miettinen,[62] D. Mihalcea,[39] C.S. Mishra,[37] N. Mokhov,[37] N.K. Mondal,[17] H.E. Montgomery,[37] R.W. Moore,[51] M. Mostafa,[1] H. da Motta,[2] E. Nagy,[10] F. Nang,[29] M. Narain,[48] V.S. Narasimham,[17] H.A. Neal,[50] J.P. Negret,[5] S. Negroni,[10] T. Nunnemann,[37] D. O'Neil,[51] V. Oguri,[3] B. Olivier,[12] N. Oshima,[37] P. Padley,[62] L.J. Pan,[40] K. Papageorgiou,[38] A. Para,[37] N. Parashar,[49] R. Partridge,[59] N. Parua,[55] M. Paterno,[54] A. Patwa,[55] B. Pawlik,[22]

J. Perkins,[60] M. Peters,[36] O. Peters,[20] P. Pétroff,[11] R. Piegaia,[1] B.G. Pope,[51] E. Popkov,[48] H.B. Prosper,[35] S. Protopopescu,[56] J. Qian,[50] R. Raja,[37] S. Rajagopalan,[56] E. Ramberg,[37] P.A. Rapidis,[37] N.W. Reay,[45] S. Reucroft,[49] M. Ridel,[11] M. Rijssenbeek,[55] F. Rizatdinova,[45] T. Rockwell,[51] M. Roco,[37] P. Rubinov,[37] R. Ruchti,[42] J. Rutherfoord,[29] B.M. Sabirov,[23] G. Sajot,[9] A. Santoro,[2] L. Sawyer,[46] R.D. Schamberger,[55] H. Schellman,[40] A. Schwartzman,[1] N. Sen,[62] E. Shabalina,[38] R.K. Shivpuri,[16] D. Shpakov,[49] M. Shupe,[29] R.A. Sidwell,[45] V. Simak,[7] H. Singh,[34] J.B. Singh,[15] V. Sirotenko,[37] P. Slattery,[54] E. Smith,[58] R.P. Smith,[37] R. Snihur,[40] G.R. Snow,[52] J. Snow,[57] S. Snyder,[56] J. Solomon,[38] V. Sorín,[1] M. Sosebee,[60] N. Sotnikova,[25] K. Soustruznik,[6] M. Souza,[2] N.R. Stanton,[45] G. Steinbrück,[53] R.W. Stephens,[60] F. Stichelbaut,[56] D. Stoker,[33] V. Stolin,[24] A. Stone,[46] D.A. Stoyanova,[26] M. Strauss,[58] M. Strovink,[30] L. Stutte,[37] A. Sznajder,[3] M. Talby,[10] W. Taylor,[55] S. Tentindo-Repond,[35] S.M. Tripathi,[31] T.G. Trippe,[30] A.S. Turcot,[56] P.M. Tuts,[53] P. van Gemmeren,[37] V. Vaniev,[26] R. Van Kooten,[41] N. Varelas,[38] L.S. Vertogradov,[23] F. Villeneuve-Seguier,[10] A.A. Volkov,[26] A.P. Vorobiev,[26] H.D. Wahl,[35] H. Wang,[40] Z.-M. Wang,[55] J. Warchol,[42] G. Watts,[64] M. Wayne,[42] H. Weerts,[51] A. White,[60] J.T. White,[61] D. Whiteson,[30] J.A. Wightman,[43] D.A. Wijngaarden,[21] S. Willis,[39] S.J. Wimpenny,[34] J. Womersley,[37] D.R. Wood,[49] R. Yamada,[37] P. Yamin,[56] T. Yasuda,[37] Y.A. Yatsunenko,[23] K. Yip,[56] S. Youssef,[35] J. Yu,[37] Z. Yu,[40] M. Zanabria,[5] H. Zheng,[42] Z. Zhou,[43] M. Zielinski,[54] D. Zieminska,[41] A. Zieminski,[41] V. Zutshi,[56] E.G. Zverev,[25] and A. Zylberstejn[13]

(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] *Charles University, Center for Particle Physics, Prague, Czech Republic*
[7] *Institute of Physics, Academy of Sciences, Center for Particle Physics, Prague, Czech Republic*
[8] *Universidad San Francisco de Quito, Quito, Ecuador*
[9] *Institut des Sciences Nucléaires, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France*
[10] *CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France*
[11] *Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS, Orsay, France*
[12] *LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France*
[13] *DAPNIA/Service de Physique des Particules, CEA, Saclay, France*
[14] *Universität Mainz, Institut für Physik, Mainz, Germany*
[15] *Panjab University, Chandigarh, India*
[16] *Delhi University, Delhi, India*
[17] *Tata Institute of Fundamental Research, Mumbai, India*
[18] *Seoul National University, Seoul, Korea*
[19] *CINVESTAV, Mexico City, Mexico*
[20] *FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands*
[21] *University of Nijmegen/NIKHEF, Nijmegen, The Netherlands*
[22] *Institute of Nuclear Physics, Kraków, Poland*
[23] *Joint Institute for Nuclear Research, Dubna, Russia*
[24] *Institute for Theoretical and Experimental Physics, Moscow, Russia*

[25]*Moscow State University, Moscow, Russia*
[26]*Institute for High Energy Physics, Protvino, Russia*
[27]*Lancaster University, Lancaster, United Kingdom*
[28]*Imperial College, London, United Kingdom*
[29]*University of Arizona, Tucson, Arizona 85721*
[30]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720*
[31]*University of California, Davis, California 95616*
[32]*California State University, Fresno, California 93740*
[33]*University of California, Irvine, California 92697*
[34]*University of California, Riverside, California 92521*
[35]*Florida State University, Tallahassee, Florida 32306*
[36]*University of Hawaii, Honolulu, Hawaii 96822*
[37]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[38]*University of Illinois at Chicago, Chicago, Illinois 60607*
[39]*Northern Illinois University, DeKalb, Illinois 60115*
[40]*Northwestern University, Evanston, Illinois 60208*
[41]*Indiana University, Bloomington, Indiana 47405*
[42]*University of Notre Dame, Notre Dame, Indiana 46556*
[43]*Iowa State University, Ames, Iowa 50011*
[44]*University of Kansas, Lawrence, Kansas 66045*
[45]*Kansas State University, Manhattan, Kansas 66506*
[46]*Louisiana Tech University, Ruston, Louisiana 71272*
[47]*University of Maryland, College Park, Maryland 20742*
[48]*Boston University, Boston, Massachusetts 02215*
[49]*Northeastern University, Boston, Massachusetts 02115*
[50]*University of Michigan, Ann Arbor, Michigan 48109*
[51]*Michigan State University, East Lansing, Michigan 48824*
[52]*University of Nebraska, Lincoln, Nebraska 68588*
[53]*Columbia University, New York, New York 10027*
[54]*University of Rochester, Rochester, New York 14627*
[55]*State University of New York, Stony Brook, New York 11794*
[56]*Brookhaven National Laboratory, Upton, New York 11973*
[57]*Langston University, Langston, Oklahoma 73050*
[58]*University of Oklahoma, Norman, Oklahoma 73019*
[59]*Brown University, Providence, Rhode Island 02912*
[60]*University of Texas, Arlington, Texas 76019*
[61]*Texas A&M University, College Station, Texas 77843*
[62]*Rice University, Houston, Texas 77005*
[63]*University of Virginia, Charlottesville, Virginia 22901*
[64]*University of Washington, Seattle, Washington 98195*

[*] *Visitor from University of Zurich, Zurich, Switzerland.*

## I. INTRODUCTION

The DØ Collaboration has recently published [1,2] measurements of the differential cross sections for $W$ and $Z$ boson production as a function of transverse momentum $p_T$. Both measurements are in good agreement with combined resummed and perturbative QCD models, such as those in references [3–5]. For the analyses based on data taken by DØ during 1992–1996 (Tevatron Run 1), we have used the resummed calculation of Ref. [4] fitted to our own Drell–Yan data to determine the non-perturbative phenomenological parameters of the theory. The resummed calculation was then used to predict $W$ boson observables such as the electron and neutrino transverse momenta. These predictions are used as input to a Monte Carlo model of $W$ boson production and decay, which is used in our published measurements of the $W$ boson mass [6] and $W$ boson production cross section [7].

Reference [8] proposes an alternative method of predicting $W$ boson observables from measured $Z$ boson quantities using the theoretical ratio of the $W$ to $Z$ boson differential cross sections with respect to variables that have been scaled by the corresponding vector boson masses. Because $W$ and $Z$ boson production properties are very similar, the large radiative corrections that affect the individual distributions cancel when calculating the ratio. The ratio can therefore be reliably calculated using perturbative QCD (pQCD), with no need for resummation, even for small values of the transverse momenta of the vector bosons. In fact, as the transverse momentum of the vector boson becomes smaller, the radiative corrections factorize from the hard process and cancel when taking the ratio. The theoretical uncertainties are therefore well understood, and smallest, at very low $p_T$.

The basic proposal is to combine pQCD calculations with the measured $Z$ boson observables to extract the $W$ boson observables. This method is exemplified and tested here using the $W$ and $Z$ boson differential cross sections as a function of transverse momentum. The main difference between the $W$ and the $Z$ boson production properties is due to the difference in the $W$ and $Z$ boson masses. We therefore work with vector boson variables that have been scaled by the corresponding vector boson mass $m_V$.

The ratio of differential cross sections with respect to the scaled $W$ and $Z$ boson transverse momenta $p_T^W/m_W$ and $p_T^Z/m_Z$ is defined as

$$R_{p_T} = \left(\frac{d\sigma^W}{dp_T^W/m_W}\right) \Big/ \left(\frac{d\sigma^Z}{dp_T^Z/m_Z}\right), \tag{1.1}$$

where $d\sigma^V/dp_T^V$ is the differential cross section for vector boson production $\sigma(p\bar{p} \to V + X)$ with respect to the vector boson transverse momentum $p_T^V$. Equation 1.1 can be used to predict the differential cross section for $W$ bosons with respect to the non-scaled transverse momentum:

$$\left.\frac{d\sigma^W}{dp_T^W}\right|_{\text{predicted}} = \frac{m_Z}{m_W} \times R_{p_T} \times \left.\frac{d\sigma^Z}{dp_T^Z}\right|_{\text{measured}}^{p_T^Z = \frac{m_Z}{m_W} p_T^W}, \tag{1.2}$$

where $R_{p_T}$ is calculated using pQCD. In this paper, we present the first measurement of $R_{p_T}$, and confront it with the calculation of Ref. [8].

Next, we use our measured differential $Z$ boson cross section, Eq. 1.2 and Ref. [8] to obtain the differential $W$ boson cross section and compare it to our published result [1].

Compared to the method previously used to extract $W$ boson observables, the present ratio method reduces both theoretical and experimental systematic uncertainties. However, it introduces a statistical contribution to the uncertainty from the number of events in the $Z$ boson candidate sample. Such a trade–off will eventually result in smaller overall uncertainties, especially when used with the high statistics samples expected during Run 2 at the Tevatron.

## II. DATA SELECTION

We keep the modifications to the published DØ analyses [1,2] to a minimum, but, at the same time, we try to cancel as many experimental uncertainties as possible when measuring the ratio $R_{p_T}$. The uncertainty in the integrated luminosity of the data samples (4.3%) is the dominant uncertainty in the individual cross section measurements. It cancels completely when taking the ratio, as long as the same data sets are used to select the $W$ and $Z$ boson candidate samples. In this analysis, we keep the event selection and corrections for background, efficiency, acceptance and detector resolutions identical to the ones in the published results [1,2], but require that the same data–taking runs be included in the $W$ and $Z$ boson event samples. In addition, we exclude events for which large beam losses from the Main Ring accelerator were expected [7]. These beam losses can create significant energy deposits in the calorimeter, resulting in events with large false transverse momentum imbalance, that could pass our $W$ selection cuts. Due to these additional requirements, the $Z$ boson sample is reduced from 6407 to 4881 events. About half of the event losses are due to the tightening of the beam quality conditions, while the other half are events taken during runs for which there was no $W$ trigger present or it was prescaled. The $W$ sample is reduced from 50488 to 50264 events when we remove runs for which the $W$ trigger was prescaled. The integrated luminosity for both samples is $(84.5 \pm 3.6)\mathrm{pb}^{-1}$.

We have investigated whether additional sources of error could be cancelled in the ratio. There are four sources of systematic error that contribute to the $W$ and $Z$ boson cross sections. These arise from uncertainties in the background estimate, the event selection efficiency and the unfolding procedure used to correct for acceptance and detector resolution.

The dominant sources of background in both the $W$ and the $Z$ boson analyses come from multijet and photon–jet events, where the jets pass our electron identification criteria. In the case of the $W$, a large imbalance in the transverse energy has to arise to fake the presence of a neutrino. The mechanisms for multijet or photon–jet events to fake a $W$ or a $Z$ boson event are different, and the methods used to estimate the background are completely independent. We therefore cannot cancel any contribution to the error in the ratio from the background estimates.

The acceptance and unfolding corrections are applied together using a parametric Monte Carlo [6]. The main contribution to the error comes from the detector modeling. For the $W$ analysis, we rely on the measurement of the energy of the recoiling hadrons, whereas the $Z$ boson measurement uses the measurement of the electromagnetic energy from the electrons. We therefore do not attempt any cancellation of errors in the acceptance/unfolding procedure either.

The uncertainty in the efficiency has contributions from the trigger and offline electron

identification. The Level 0 trigger, which requires the detection of an inelastic collision via simultaneous hits in the forward and backward Level 0 scintillation detectors [9], is common for $W$ and $Z$ boson events. The uncertainty in this trigger can therefore be completely cancelled in the ratio. However, its contribution to the error on the efficiency is negligible (0.5% out of a total of 3.5%).

Although the triggers and the offline electron identification used in the $W$ and $Z$ boson analyses are different, the main contribution to the error in the efficiency (3%) comes from a common source, the so-called $u_{||}$ efficiency [6]. This inefficiency arises when the energy flow close to the electron increases as the recoiling hadrons approach the electron. It is therefore a topological effect produced by the proximity of the electron to the jet, which has the largest effect at a boson transverse momentum of about 20 GeV [2]. The parameterization of the $u_{||}$ efficiency is done on an electron–by–electron basis in the parametric Monte Carlo. The error on the $u_{||}$ efficiency is estimated from Herwig [11] $W$ and $Z$ boson events, overlayed with data taken from randomly selected $p\bar{p}$ collisions. Because this inefficiency depends on the proximity between electrons and jets in the event, it is difficult to estimate *a priori* how much of the uncertainty in the $u_{||}$ efficiency cancels in the ratio. To determine if further investigations of the possible cancellation of the $u_{||}$ efficiency error are worthwhile, we estimated the effect on the $R_{p_T}$ measurement of cancelling the contribution from the $u_{||}$ efficiency error completely. This resulted in a maximum reduction on the uncertainty on the ratio of less than 5%. We therefore conclude that no error cancellations beyond the errors in the luminosity would improve the ratio measurement significantly.

## III. SCALED $W$ AND $Z$ BOSON CROSS SECTIONS

Equation (1.1) can be written

$$R^{th}_{p_T} = \left(\frac{d\sigma^W}{dp_T^W}\right) \Big/ \left(\frac{d\sigma^Z}{d(p_T^Z \times m_W/m_Z)}\right) = \left(\frac{d\sigma^W}{dp_T^W}\right) \Big/ \left(\frac{d\sigma^Z}{dp_T^{Z\prime}}\right), \tag{3.1}$$

where we have defined

$$p_T^{Z\prime} = \frac{m_W}{m_Z} p_T^Z. \tag{3.2}$$

We use the value from the Particle Data Book [10] for the mass ratio

$$\frac{m_W}{m_Z} = 0.8820 \pm 0.0005. \tag{3.3}$$

In order to measure the scaled distributions without changing the binning of both the $W$ and the $Z$ boson analyses, we kept the $W$ bin boundaries ($\delta_i$) identical to the ones used in the published result. Since we require the same bin widths for the scaled variables $p_T^W/m_W$ and $p_T^Z/m_Z$, we set the bin boundaries in the differential $Z$ boson cross section to

$$\delta_i \times \frac{m_Z}{m_W} = \delta_i/0.8820, \tag{3.4}$$

and recompute the differential $Z$ boson cross section.

Table I shows the modified results for the $W$ and $Z$ boson cross sections. The statistical and systematic contributions to the individual cross section uncertainties are shown separately. One can see that the error on the ratio will be dominated by the systematic error on the $W$ cross section.

## IV. MEASUREMENT OF $R_{P_T}$

Based on the measured $W$ and $Z$ boson differential cross sections listed in Table I, we extract the ratio of scaled cross sections

$$R_{p_T}^{exp} = \left[ \left( \frac{d\sigma^W}{dp_T^W} \right) \Big/ \left( \frac{d\sigma^Z}{dp_T^Z} \right) \right] \times \frac{m_W}{m_Z} \times \frac{Br(Z \to ee)}{Br(W \to e\nu)}. \tag{4.1}$$

Note that the prediction for $R_{p_T}$ [8] was calculated for the ratio of the scaled $W$ and $Z$ boson differential cross sections $d\sigma^V/dp_T^V$, and we measure the differential cross sections times their branching fractions to electrons $(d\sigma^V/dp_T^V) \times Br(V \to e)$. We therefore need to multiply our measurement by the ratio of the $Z$ to $W$ boson branching fractions, which we obtain from the particle data book [10]:

$$Br(Z \to ee) = 0.03367 \pm 0.00005 \tag{4.2}$$

$$Br(W \to e\nu) = 0.1066 \pm 0.0020. \tag{4.3}$$

The result is shown in Figure 1 and summarized in Table II. The data are plotted at the value of $p_T$ for which the theoretical prediction for $R_{p_T}$ is equal to its average over the bin, following the prescription of reference [12]. We observe that the measured differential cross section ratio agrees well with the purely pQCD theoretical prediction [8], even at small values of $p_T$. The $\chi^2$ test for the comparison between data and theory is 18.7 for 21 degrees of freedom.

## V. EXTRACTION OF $d\sigma^W/dp_T^W$

Based on Eq. 1.2, we use the calculated ratio $R_{p_T}$ from reference [8], together with the measured $d\sigma^Z/dp_T^Z$, to predict the $W$ boson transverse momentum spectrum and compare it with our previously measured $d\sigma^W/dp_T^W$ [1]. The result is shown in Figure 2. The measured differential cross section is plotted at the center of the bin. The ratio method prediction upper and lower 68% confidence level limits are plotted as histograms. The extracted transverse momentum distribution agrees very well with the measurement; the Kolmogorov–Smirnov probability [13] $\kappa$ is equal to 1.

## VI. CONCLUSIONS

We have measured the ratio of the scaled differential cross sections for $W$ to $Z$ boson production for the first time, and compared it to a purely pQCD prediction. Our preliminary

measurement shows good agreement with theory over the whole $p_T$ spectrum, even at small values of $p_T$.

We have used the theoretical prediction for $R_{p_T}$, together with our measurement of the differential $Z$ boson production cross section, to obtain the $W$ differential cross section. This prediction agrees well with our published result.

This method for predicting $W$ properties should eventually result in smaller overall uncertainties on the measured $W$ mass and width, compared to currently used methods at hadron colliders, once the high statistics $Z$ boson samples expected during Run 2 at the Tevatron become available.

## ACKNOWLEDGEMENTS

We thank Stephane Keller for interesting discussions leading to this measurement and Walter Giele for providing the theoretical prediction and assistance with technical details to complete this measurement. We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à L'Energie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES and CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United Kingdom), Ministry of Education (Czech Republic), and the A.P. Sloan Foundation.

## REFERENCES


[1] DØ Collaboration, V. M. Abazov *et al.* Accepted by Phys. Lett. **B**, FERMILAB-Pub-00/268-E, hep-ex/0010026.

[2] DØ Collaboration, B. Abbott *et al.* Phys. Rev. **D61**, 032004 (2000), and Phys. Rev. Lett. **84**, 2792 (2000).

[3] P. Arnold and R. Kauffman, Nucl. Phys. **B349**, 381 (1991).

[4] G. A. Ladinsky and C. P. Yuan Phys. Rev. **D50**, 4239 (1994).

[5] R. K. Ellis and S. Veseli, Nucl. Phys. **B511**, 649 (1998).

[6] DØ Collaboration, S. Abachi *et al.* Phys. Rev. Letters **77**, 3309 (1996); Phys. Rev. **D58**, 12002 (1998); Phys. Rev. Letters **80**, 3008 (1998); Phys. Rev. **D58**, 092003 (1998); Phys. Rev. **D62**, 092006 (2000); Phys. Rev. Lett. **84**, 222 (2000).

[7] DØ Collaboration, B. Abbott *et al.* Phys. Rev. **D 61**, 072001 (2000).

[8] W. T. Giele and S. Keller, Phys. Rev. **D57**, 4433 (1998).

[9] DØ Collaboration, S. Abachi *et al.* Nucl. Instrum. Methods **A 338**, 185 (1994).

[10] D. Groom *et al.* The European Physical Journal **C15** (2000).

[11] G. Marchesini *et al.* Comput. Phys. Commun. **67**, 465 (1992).

[12] G. Lafferty and T. Wyatt, Nuclear Instruments and Methods **A 355**, 541 (1995).

[13] This test returns a confidence level $\kappa$ that is uniformly distributed between 0 and 1 if the two spectra derive from the same parent distribution. See, e.g., A. G. Frodesen, O. Skjeggestad, and H. Tøfte, "Probability and Statistics in Particle Physics." Columbia University Press, New York (1979).

TABLE I. Summary of the measured differential $W$ and $Z$ bosons production cross sections as a function of transverse momentum used to calculate the ratio. The error on the ratio is dominated by the systematic error on the $W$ cross section.

| Bins (GeV) | $\frac{d\sigma(W\to e\nu)}{dp_T^W}$ (pb/GeV) | Stat Error (pb/GeV) | Syst Error (pb/GeV) | $\frac{d\sigma(Z\to e^+e^-)}{dp_T^Z}$ (pb/GeV) | Stat Error (pb/GeV) | Syst Error (pb/GeV) |
|---|---|---|---|---|---|---|
| 0-2 | 109.48 | 4.61 | 12.35 | 11.94 | 0.53 | 0.35 |
| 2-4 | 206.21 | 6.85 | 24.64 | 19.63 | 0.65 | 0.57 |
| 4-6 | 171.32 | 5.65 | 9.29 | 14.34 | 0.53 | 0.44 |
| 6-8 | 133.60 | 4.65 | 9.46 | 11.19 | 0.48 | 0.36 |
| 8-10 | 103.48 | 4.04 | 6.95 | 8.05 | 0.41 | 0.27 |
| 10-12 | 77.46 | 3.46 | 7.25 | 6.18 | 0.37 | 0.21 |
| 12-14 | 63.58 | 3.20 | 4.16 | 4.74 | 0.33 | 0.15 |
| 14-16 | 47.77 | 2.77 | 4.29 | 3.39 | 0.28 | 0.11 |
| 16-18 | 37.67 | 2.42 | 2.73 | 3.27 | 0.28 | 0.17 |
| 18-20 | 30.50 | 2.20 | 1.74 | 1.94 | 0.22 | 0.11 |
| 20-25 | 22.02 | 1.23 | 1.22 | 1.59 | 0.12 | 0.08 |
| 25-30 | 13.94 | 0.93 | 1.07 | 0.946 | 0.097 | 0.051 |
| 30-35 | 9.51 | 0.73 | 0.84 | 0.848 | 0.092 | 0.043 |
| 35-40 | 6.79 | 0.63 | 0.51 | 0.435 | 0.066 | 0.022 |
| 40-50 | 3.96 | 0.37 | 0.31 | 0.325 | 0.040 | 0.016 |
| 50-60 | 1.82 | 0.25 | 0.25 | 0.180 | 0.029 | 0.009 |
| 60-70 | 1.14 | 0.20 | 0.23 | 0.0848 | 0.0197 | 0.0045 |
| 70-80 | 0.749 | 0.178 | 0.170 | 0.0385 | 0.0129 | 0.0020 |
| 80-100 | 0.310 | 0.059 | 0.088 | 0.0141 | 0.0054 | 0.0008 |
| 100-120 | 0.0822 | 0.0287 | 0.0255 | 0.00764 | 0.00383 | 0.00032 |
| 120-160 | 0.0433 | 0.0119 | 0.0118 | 0.00358 | 0.00180 | 0.00018 |
| 160-200 | 0.00769 | 0.00545 | 0.00482 | 0.00163 | 0.00111 | 0.00010 |

TABLE II. Measured $R_{p_T}$. The uncertainty in the luminosity of the $W$ and $Z$ samples cancels completely when taking the ratio. No further error cancellation is attempted.

| Bins (GeV) | $p_T$ (GeV) | $R_{p_T}$ | Error |
|---|---|---|---|
| 0-2 | 1.21 | 2.555 | 0.340 |
| 2-4 | 2.81 | 2.927 | 0.388 |
| 4-6 | 4.83 | 3.327 | 0.273 |
| 6-8 | 6.84 | 3.326 | 0.323 |
| 8-10 | 8.85 | 3.580 | 0.360 |
| 10-12 | 10.86 | 3.494 | 0.439 |
| 12-14 | 12.87 | 3.739 | 0.426 |
| 14-16 | 14.88 | 3.921 | 0.550 |
| 16-18 | 16.89 | 3.208 | 0.450 |
| 18-20 | 18.90 | 4.380 | 0.683 |
| 20-25 | 22.52 | 3.854 | 0.479 |
| 25-30 | 27.34 | 4.105 | 0.640 |
| 30-35 | 32.57 | 3.125 | 0.529 |
| 35-40 | 37.89 | 4.348 | 0.875 |
| 40-50 | 45.03 | 3.395 | 0.615 |
| 50-60 | 55.09 | 2.814 | 0.727 |
| 60-70 | 65.14 | 3.731 | 1.342 |
| 70-80 | 74.79 | 5.419 | 2.566 |
| 80-100 | 89.67 | 6.140 | 3.160 |
| 100-120 | 109.77 | 2.995 | 2.060 |
| 120-160 | 139.93 | 3.374 | 2.151 |
| 160-200 | 180.14 | 1.317 | 1.539 |

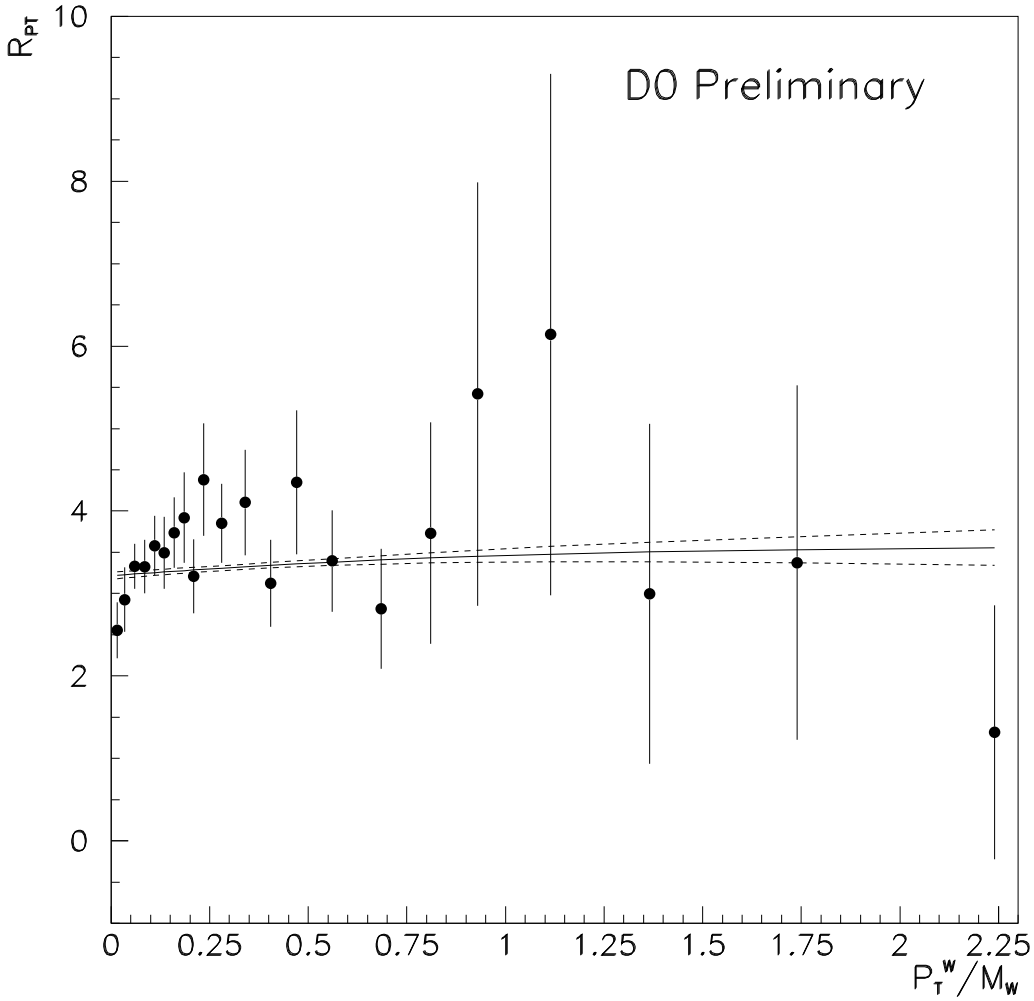


FIG. 1. Ratio of scaled differential cross sections for $W$ to $Z$ production. The solid line is the order $\alpha_S^2$ theoretical prediction of Ref. [8] and the dotted lines are the one sigma uncertainties due to Monte Carlo integration. The error on the luminosity cancels completely on the ratio of the measured cross sections. No further error cancellation is attempted.

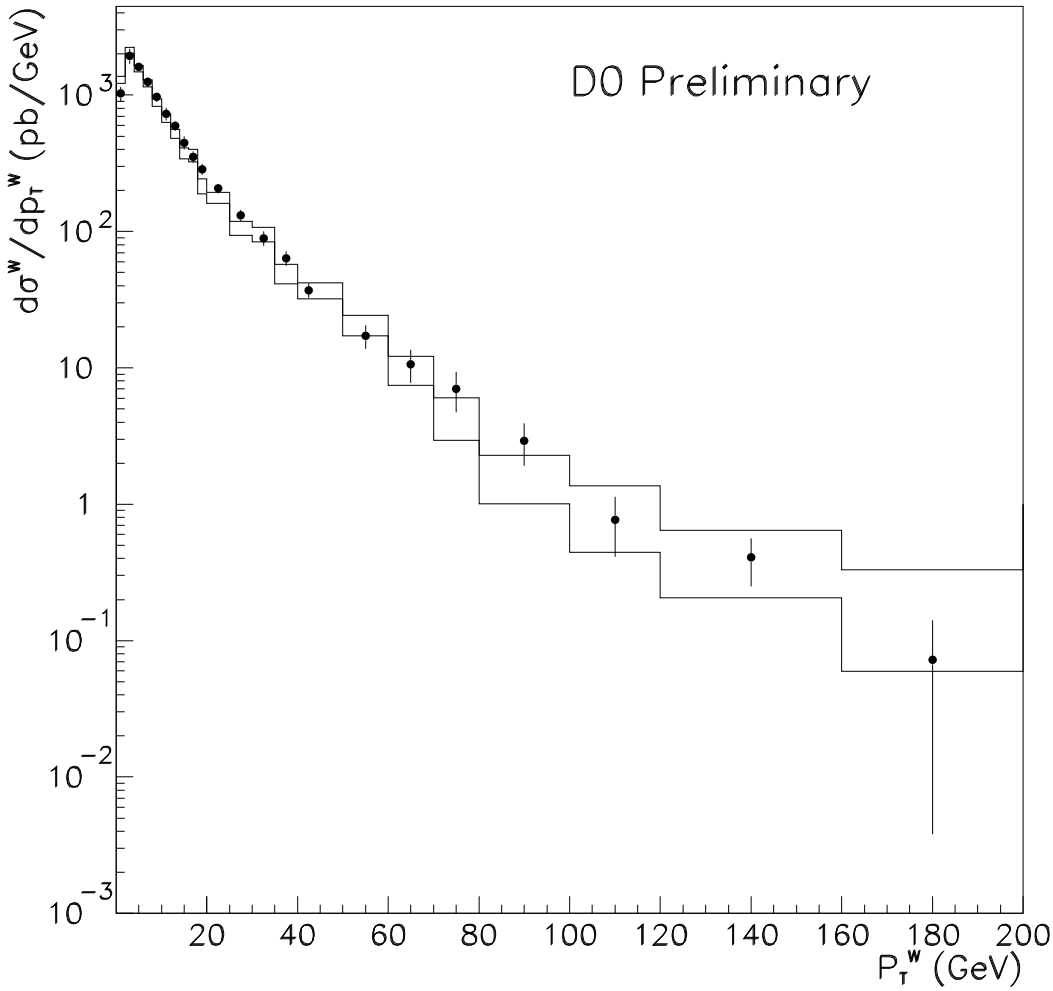


FIG. 2. Differential cross section for $W$ boson production as a function of $p_T^W$. The points are the DØ data; the error bars do not include the 4.3% error in the luminosity. The histograms represent the upper and lower 68% confidence level limits of the prediction [8] obtained from the ratio method.