Measurement of the ratio of 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

DØ Collaboration

V.M. Abazov [w], B. Abbott [bf], A. Abdesselam [k], M. Abolins [ay], V. Abramov [z],
B.S. Acharya [q], D.L. Adams [bh], M. Adams [al], S.N. Ahmed [u], G.D. Alexeev [w],
G.A. Alves [b], N. Amos [ax], E.W. Anderson [aq], Y. Arnoud [i], M.M. Baarmand [bc],
V.V. Babintsev [z], L. Babukhadia [bc], T.C. Bacon [ab], A. Baden [au], B. Baldin [ak], P.W. Balm [t],
S. Banerjee [q], E. Barberis [ad], P. Baringer [ar], J. Barreto [b], J.F. Bartlett [ak], U. Bassler [l],
D. Bauer [ab], A. Bean [ar], F. Beaudette [k], M. Begel [bb], A. Belyaev [ai], S.B. Beri [o],
G. Bernardi [l], I. Bertram [aa], A. Besson [i], R. Beuselinck [ab], V.A. Bezzubov [z], P.C. Bhat [ak],
V. Bhatnagar [k], M. Bhattacharjee [bc], G. Blazey [am], S. Blessing [ai], A. Boehnlein [ak],
N.I. Bojko [z], F. Borcherding [ak], K. Bos [t], A. Brandt [bh], R. Breedon [ae], G. Briskin [bg],
R. Brock [ay], G. Brooijmans [ak], A. Bross [ak], D. Buchholz [an], M. Buehler [al], V. Buescher [n],
V.S. Burtovoi [z], J.M. Butler [av], F. Canelli [bb], W. Carvalho [c], D. Casey [ay], Z. Casilum [bc],
H. Castilla-Valdez [s], D. Chakraborty [am], K.M. Chan [bb], S.V. Chekulaev [z], D.K. Cho [bb],
S. Choi [ah], S. Chopra [bd], J.H. Christenson [ak], M. Chung [al], D. Claes [az], A.R. Clark [ad],
J. Cochran [ah], L. Coney [ap], B. Connolly [ai], W.E. Cooper [ak], D. Coppage [ar],
S. Crépé-Renaudin [i], M.A.C. Cummings [am], D. Cutts [bg], G.A. Davis [bb], K. Davis [ac],
K. De [bh], S.J. de Jong [u], K. Del Signore [ax], M. Demarteau [ak], R. Demina [as], P. Demine [i],
D. Denisov [ak], S.P. Denisov [z], S. Desai [bc], H.T. Diehl [ak], M. Diesburg [ak], S. Doulas [aw],
Y. Ducros [m], L.V. Dudko [y], S. Duensing [u], L. Duflot [k], S.R. Dugad [q], A. Duperrin [j],
A. Dyshkant [am], D. Edmunds [ay], J. Ellison [ah], V.D. Elvira [ak], R. Engelmann [bc], S. Eno [au],
G. Eppley [bj], P. Ermolov [y], O.V. Eroshin [z], J. Estrada [bb], H. Evans [ba], V.N. Evdokimov [z],
T. Fahland [ag], S. Feher [ak], D. Fein [ac], T. Ferbel [bb], F. Filthaut [u], H.E. Fisk [ak], Y. Fisyak [bd],
E. Flattum [ak], F. Fleuret [ad], M. Fortner [am], H. Fox [an], K.C. Frame [ay], S. Fu [ba], S. Fuess [ak],
E. Gallas [ak], A.N. Galyaev [z], M. Gao [ba], V. Gavrilov [x], R.J. Genik II [aa], K. Genser [ak],
C.E. Gerber [al], Y. Gershtein [bg], R. Gilmartin [ai], G. Ginther [bb], B. Gómez [e], G. Gómez [au],
P.I. Goncharov [z], J.L. González Solís [s], H. Gordon [bd], L.T. Goss [bi], K. Gounder [ak],
A. Goussiou [ab], N. Graf [bd], G. Graham [au], P.D. Grannis [bc], J.A. Green [aq], H. Greenlee [ak],
Z.D. Greenwood [at], S. Grinstein [a], L. Groer [ba], S. Grünendahl [ak], A. Gupta [q],

S.N. Gurzhiev [z], G. Gutierrez [ak], P. Gutierrez [bf], N.J. Hadley [au], H. Haggerty [ak],
S. Hagopian [ai], V. Hagopian [ai], R.E. Hall [af], P. Hanlet [aw], S. Hansen [ak], J.M. Hauptman [aq],
C. Hays [ba], C. Hebert [ar], D. Hedin [am], J.M. Heinmiller [al], A.P. Heinson [ah], U. Heintz [av],
T. Heuring [ai], M.D. Hildreth [ap], R. Hirosky [bk], J.D. Hobbs [bc], B. Hoeneisen [h], Y. Huang [ax],
R. Illingworth [ab], A.S. Ito [ak], M. Jaffré [k], S. Jain [q], R. Jesik [ab], K. Johns [ac], M. Johnson [ak],
A. Jonckheere [ak], M. Jones [aj], H. Jöstlein [ak], A. Juste [ak], W. Kahl [as], S. Kahn [bd],
E. Kajfasz [j], A.M. Kalinin [w], D. Karmanov [y], D. Karmgard [ap], Z. Ke [d], R. Kehoe [ay],
A. Khanov [as], A. Kharchilava [ap], S.K. Kim [r], B. Klima [ak], B. Knuteson [ad], W. Ko [ae],
J.M. Kohli [o], A.V. Kostritskiy [z], J. Kotcher [bd], B. Kothari [ba], A.V. Kotwal [ba],
A.V. Kozelov [z], E.A. Kozlovsky [z], J. Krane [aq], M.R. Krishnaswamy [q], P. Krivkova [f],
S. Krzywdzinski [ak], M. Kubantsev [as], S. Kuleshov [x], Y. Kulik [bc], S. Kunori [au], A. Kupco [g],
V.E. Kuznetsov [ah], G. Landsberg [bg], W.M. Lee [ai], A. Leflat [y], C. Leggett [ad], F. Lehner [ak,1],
J. Li [bh], Q.Z. Li [ak], X. Li [d], J.G.R. Lima [c], D. Lincoln [ak], S.L. Linn [ai], J. Linnemann [ay],
R. Lipton [ak], A. Lucotte [i], L. Lueking [ak], C. Lundstedt [az], C. Luo [ao], A.K.A. Maciel [am],
R.J. Madaras [ad], V.L. Malyshev [w], V. Manankov [y], H.S. Mao [d], T. Marshall [ao],
M.I. Martin [am], K.M. Mauritz [aq], B. May [an], A.A. Mayorov [ao], R. McCarthy [bc],
T. McMahon [be], H.L. Melanson [ak], M. Merkin [y], K.W. Merritt [ak], C. Miao [bg],
H. Miettinen [bj], D. Mihalcea [am], C.S. Mishra [ak], N. Mokhov [ak], N.K. Mondal [q],
H.E. Montgomery [ak], R.W. Moore [ay], M. Mostafa [a], H. da Motta [b], E. Nagy [j], F. Nang [ac],
M. Narain [av], V.S. Narasimham [q], H.A. Neal [ax], J.P. Negret [e], S. Negroni [j],
T. Nunnemann [ak], D. O'Neil [ay], V. Oguri [c], B. Olivier [l], N. Oshima [ak], P. Padley [bj],
L.J. Pan [an], K. Papageorgiou [al], A. Para [ak], N. Parashar [aw], R. Partridge [bg], N. Parua [bc],
M. Paterno [bb], A. Patwa [bc], B. Pawlik [v], J. Perkins [bh], M. Peters [aj], O. Peters [t], P. Pétroff [k],
R. Piegaia [a], B.G. Pope [ay], E. Popkov [av], H.B. Prosper [ai], S. Protopopescu [bd], J. Qian [ax],
R. Raja [ak], S. Rajagopalan [bd], E. Ramberg [ak], P.A. Rapidis [ak], N.W. Reay [as], S. Reucroft [aw],
M. Ridel [k], M. Rijssenbeek [bc], F. Rizatdinova [as], T. Rockwell [ay], M. Roco [ak], C. Royon [m],
P. Rubinov [ak], R. Ruchti [ap], J. Rutherfoord [ac], B.M. Sabirov [w], G. Sajot [i], A. Santoro [b],
L. Sawyer [at], R.D. Schamberger [bc], H. Schellman [an], A. Schwartzman [a], N. Sen [bj],
E. Shabalina [al], R.K. Shivpuri [p], D. Shpakov [aw], M. Shupe [ac], R.A. Sidwell [as], V. Simak [g],
H. Singh [ah], J.B. Singh [o], V. Sirotenko [ak], P. Slattery [bb], E. Smith [bf], R.P. Smith [ak],
R. Snihur [an], G.R. Snow [az], J. Snow [be], S. Snyder [bd], J. Solomon [al], V. Sorín [a],
M. Sosebee [bh], N. Sotnikova [y], K. Soustruznik [f], M. Souza [b], N.R. Stanton [as],
G. Steinbrück [ba], R.W. Stephens [bh], F. Stichelbaut [bd], D. Stoker [ag], V. Stolin [x], A. Stone [at],
D.A. Stoyanova [z], M. Strauss [bf], M. Strovink [ad], L. Stutte [ak], A. Sznajder [c], M. Talby [j],
W. Taylor [bc], S. Tentindo-Repond [ai], S.M. Tripathi [ae], T.G. Trippe [ad], A.S. Turcot [bd],
P.M. Tuts [ba], V. Vaniev [z], R. Van Kooten [ao], N. Varelas [al], L.S. Vertogradov [w],
F. Villeneuve-Seguier [j], A.A. Volkov [z], A.P. Vorobiev [z], H.D. Wahl [ai], H. Wang [an],
Z.-M. Wang [bc], J. Warchol [ap], G. Watts [bl], M. Wayne [ap], H. Weerts [ay], A. White [bh],

J.T. White [bi], D. Whiteson [ad], J.A. Wightman [aq], D.A. Wijngaarden [u], S. Willis [am],
S.J. Wimpenny [ah], J. Womersley [ak], D.R. Wood [aw], Q. Xu [ax], R. Yamada [ak], P. Yamin [bd],
T. Yasuda [ak], Y.A. Yatsunenko [w], K. Yip [bd], S. Youssef [ai], J. Yu [ak], Z. Yu [an], M. Zanabria [e],
X. Zhang [bf], H. Zheng [ap], B. Zhou [ax], Z. Zhou [aq], M. Zielinski [bb], D. Zieminska [ao],
A. Zieminski [ao], V. Zutshi [bd], E.G. Zverev [y], A. Zylberstejn [m]

[a] *Universidad de Buenos Aires, Buenos Aires, Argentina*
[b] *LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[c] *Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[d] *Institute of High Energy Physics, Beijing, People's Republic of China*
[e] *Universidad de los Andes, Bogotá, Colombia*
[f] *Charles University, Center for Particle Physics, Prague, Czech Republic*
[g] *Institute of Physics, Academy of Sciences, Center for Particle Physics, Prague, Czech Republic*
[h] *Universidad San Francisco de Quito, Quito, Ecuador*
[i] *Institut des Sciences Nucléaires, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France*
[j] *CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France*
[k] *Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS, Orsay, France*
[l] *LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France*
[m] *DAPNIA/Service de Physique des Particules, CEA, Saclay, France*
[n] *Universität Mainz, Institut für Physik, Mainz, Germany*
[o] *Panjab University, Chandigarh, India*
[p] *Delhi University, Delhi, India*
[q] *Tata Institute of Fundamental Research, Mumbai, India*
[r] *Seoul National University, Seoul, South Korea*
[s] *CINVESTAV, Mexico City, Mexico*
[t] *FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands*
[u] *University of Nijmegen/NIKHEF, Nijmegen, The Netherlands*
[v] *Institute of Nuclear Physics, Kraków, Poland*
[w] *Joint Institute for Nuclear Research, Dubna, Russia*
[x] *Institute for Theoretical and Experimental Physics, Moscow, Russia*
[y] *Moscow State University, Moscow, Russia*
[z] *Institute for High Energy Physics, Protvino, Russia*
[aa] *Lancaster University, Lancaster, United Kingdom*
[ab] *Imperial College, London, United Kingdom*
[ac] *University of Arizona, Tucson, AZ 85721, USA*
[ad] *Lawrence Berkeley National Laboratory and University of California, Berkeley, CA 94720, USA*
[ae] *University of California, Davis, CA 95616, USA*
[af] *California State University, Fresno, CA 93740, USA*
[ag] *University of California, Irvine, CA 92697, USA*
[ah] *University of California, Riverside, CA 92521, USA*
[ai] *Florida State University, Tallahassee, FL 32306, USA*
[aj] *University of Hawaii, Honolulu, HI 96822, USA*
[ak] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[al] *University of Illinois at Chicago, Chicago, IL 60607, USA*
[am] *Northern Illinois University, DeKalb, IL 60115, USA*
[an] *Northwestern University, Evanston, IL 60208, USA*
[ao] *Indiana University, Bloomington, IN 47405, USA*
[ap] *University of Notre Dame, Notre Dame, IN 46556, USA*
[aq] *Iowa State University, Ames, IO 50011, USA*
[ar] *University of Kansas, Lawrence, KS 66045, USA*
[as] *Kansas State University, Manhattan, KS 66506, USA*
[at] *Louisiana Tech University, Ruston, LA 71272, USA*
[au] *University of Maryland, College Park, MD 20742, USA*
[av] *Boston University, Boston, MA 02215, USA*
[aw] *Northeastern University, Boston, MA 02115, USA*

[ax] *University of Michigan, Ann Arbor, MI 48109, USA*

[ay] *Michigan State University, East Lansing, MI 48824, USA*

[az] *University of Nebraska, Lincoln, NE 68588, USA*

[ba] *Columbia University, New York, NY 10027, USA*

[bb] *University of Rochester, Rochester, NY 14627, USA*

[bc] *State University of New York, Stony Brook, NY 11794, USA*

[bd] *Brookhaven National Laboratory, Upton, NY 11973, USA*

[be] *Langston University, Langston, OK 73050, USA*

[bf] *University of Oklahoma, Norman, OK 73019, USA*

[bg] *Brown University, Providence, RI 02912, USA*

[bh] *University of Texas, Arlington, TX 76019, USA*

[bi] *Texas A&M University, College Station, TX 77843, USA*

[bj] *Rice University, Houston, TX 77005, USA*

[bk] *University of Virginia, Charlottesville, VA 22901, USA*

[bl] *University of Washington, Seattle, WA 98195, USA*

Abstract

We report on a 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. This measurement uses data recorded by the DØ detector at the Fermilab Tevatron in 1994–1995. It represents the first investigation of a proposal that ratios between W and Z observables can be calculated reliably using perturbative QCD, even when the individual observables are not. Using the ratio of differential cross sections reduces both experimental and theoretical uncertainties, and can therefore provide smaller overall uncertainties in the measured mass and width of the W boson than current methods used at hadron colliders. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The DØ Collaboration has recently published [1,2] measurements of 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 Refs. [3–5]. For the analyses of data taken during 1992–1996 (Fermilab Tevatron Run 1), we have used the resummed calculation of Ref. [4] fitted to our observed $Z \to e^+e^-$ differential cross section to extract 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 mo-

menta and as input to a Monte Carlo model of W boson production and decay, which we used to extract the mass [6] and production cross section [7] of the W boson.

Ref. [8] proposes an alternative method of predicting W boson observables from measured Z boson quantities. This is based on the theoretical ratio of the W to Z boson differential cross sections with respect to variables that have been scaled by their corresponding vector boson masses. Because production properties of W and Z bosons are very similar, the large radiative corrections that affect the individual distributions cancel in the ratio. The ratio can therefore be calculated reliably using perturbative QCD (pQCD), with no need for resummation, even at small values of the transverse momenta of the vector bosons, for which the radiative corrections factorize from the hard process and therefore cancel in the ratio. The theoretical uncertainties stemming from the perturbative

expansion are consequently well-understood, and are smallest at very low p_T.

The basic proposal of Ref. [8] is to use pQCD calculations and the measured Z boson observables to extract the W boson observables. Compared to the standard method used previously to extract W boson observables, the present 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 from Run 2 of the Tevatron.

Corroborating the agreement of the pQCD calculation with data is vital if the new procedure is to be used to improve the measurement of the W boson mass in future collider runs. In this Letter, we will check the validity of the method using the measured differential cross sections for W and Z boson production as a function of transverse momentum. Both distributions were measured at the Tevatron [1,2,9], where the systematic uncertainty on the p_T^W at lowest transverse momentum is four times larger than the corresponding uncertainty in p_T^Z. The uncertainty in p_T^Z is dominated by statistics. Hence, once large samples of Z boson events become available, it is expected that, if theoretical uncertainties can be kept small, using the pQCD prediction and the well-measured p_T^Z distribution to predict the p_T^W distribution should lead to smaller overall uncertainties on the measured mass and width of the W boson, relative to current methods used at hadron colliders.

The main difference between the production properties of the W and the Z bosons arises from the difference in their masses. We will therefore introduce variables that are scaled by the corresponding vector boson mass M_V. The ratio of differential cross sections for the scaled W and Z boson transverse momenta (p_T^W/M_W and p_T^Z/M_Z) is defined as

$$R_{p_T} = \left[\frac{d\sigma^W}{d(p_T^W/M_W)} \right] \Big/ \left[\frac{d\sigma^Z}{d(p_T^Z/M_Z)} \right], \quad (1)$$

where $d\sigma^V/dp_T^V$ is the standard differential cross section for vector boson production $\sigma(p\bar{p} \to V + X)$ as a function of transverse momentum p_T^V. Eq. (1) can be used to predict the differential cross section

for W bosons with respect to the non-scaled transverse momentum [8]:

$$\frac{d\sigma^W}{dp_T^W}\bigg|_{\text{predicted}} = \frac{M_Z}{M_W} \times R_{p_T} \times \frac{d\sigma^Z}{dp_T^Z}\bigg|_{\text{measured}}^{p_T^Z = \frac{M_Z}{M_W} p_T^W}, \quad (2)$$

where R_{p_T} is calculated using pQCD. In this Letter, we present the first measurement of R_{p_T}, and compare it to the calculation of Ref. [8]. For completeness, we repeat the exercise presented in Ref. [8] and use our measured differential Z boson cross section in Eq. (2), and R_{p_T} from Ref. [8], to obtain the differential W boson cross section and compare it to our published result [1].

2. Data selection

We keep 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 in measuring R_{p_T}. The uncertainty in the integrated luminosity of the data samples (4.3%) is the dominant uncertainty in the individual cross sections. It cancels completely when taking the ratio, as long as the same data sets are used to select the final W and Z boson candidate samples. In this analysis, we keep the event selections and corrections for background, efficiency, acceptance, and detector resolutions identical to those in the published results [1,2], but require total overlap in the data-taking runs for the W and Z boson event samples. In addition, we exclude events at collision times with large beam losses from the Main Ring accelerator [7]. These beam losses can create significant energy deposits in the calorimeter that produce events with large false transverse momentum imbalance that could pass our W boson selection criteria. Due to these additional requirements, the Z boson sample was reduced from 6407 to 4881 events. About half of the events were lost due to tightening of beam quality conditions, and half because the W trigger was not available or was prescaled. The W sample was reduced from 50488 to 50264 events when we removed runs for which the W trigger was prescaled. The final integrated luminosity for both samples is (84.5 ± 3.6) 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 are 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 mimic the presence of a neutrino. The way multijet or photon-jet events mimic *W* or *Z* boson events is quite different, and the methods used to estimate background are independent. We therefore cannot cancel any contribution to the error in the ratio arising from background estimates.

Acceptance and unfolding corrections are applied using a parameterized Monte Carlo [6]. The main contribution to the error is from the modeling of the detector. For the *W* analysis, we rely completely on the measurement of the energy of the recoiling hadrons, whereas for the *Z* boson measurement we use the electromagnetic energy deposited by the electrons. We therefore do not benefit from cancellation of errors in the acceptance/unfolding procedure.

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 [10], is common for *W* and *Z* boson events. The uncertainty in this trigger therefore cancels completely in the ratio. However, its contribution to the error in the efficiency is negligible (0.5% out of a total of 3.5%).

Although the triggers and the offline electron identification criteria used in the *W* and *Z* boson analyses are different, the main contribution (3%) to the error in the efficiency comes from a common source, the so-called $u_{||}$ efficiency [6]. This inefficiency arises when the energy flow close to the electron increases as recoiling hadrons approach the electron. It is therefore a topological effect produced by the proximity of the electron to the jet, and has the largest effect at a boson transverse momentum of about 20 GeV [2]. The $u_{||}$ efficiency is calculated on an electron-by-electron basis using the parameterized Monte Carlo. The error in the $u_{||}$ efficiency is estimated from *W* and *Z* boson events, generated in HERWIG [12], and overlaid

with data taken from randomly selected $p\bar{p}$ collisions. Because this inefficiency depends on the proximity of electrons to jets, it is difficult to estimate how much of the uncertainty in the $u_{||}$ efficiency cancels in the ratio. To determine if further investigation of any possible cancellation of the uncertainty in $u_{||}$ efficiency was warranted, we estimated the effect on R_{p_T} of a complete cancellation of the contribution from the uncertainty in $u_{||}$ efficiency. This produced a maximum reduction of uncertainty in R_{p_T} of less than 5%. We therefore concluded that no cancellations beyond the uncertainty in the luminosity would improve significantly the measurement of R_{p_T}.

3. Scaled *W* and *Z* boson cross sections

Eq. (1) can be written

$$R_{p_T}^{\text{th}} = \left(\frac{d\sigma^W}{dp_T^W} \right) \Big/ \left(\frac{d\sigma^Z}{d(p_T^Z \times M_W/M_Z)} \right),$$

where we use the mass ratio from the review of particle physics [11]

$$\frac{M_W}{M_Z} = 0.8820 \pm 0.0005.$$

In order to measure the scaled distributions without changing the p_T-binning of both the *W* and *Z* boson analyses, we keep the *W* bin boundaries (δ_i) identical to the ones in our published work, but because we require the same bin widths in 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 $\delta_i/0.8820$, and recompute the differential *Z* boson cross section accordingly.

Table 1 shows the modified results for the *W* and *Z* boson cross sections, with the statistical and systematic contributions to the uncertainties shown separately. It is clear that the error in the ratio is dominated by the systematic uncertainty in the *W* cross section.

4. Measurement of R_{p_T}

Based on the measured *W* and *Z* boson differential cross sections listed in Table 1, we extract the ratio of

Table 1
Summary of the measured W and Z boson differential production cross sections as a function of transverse momentum used to calculate the ratio. The error in the ratio is dominated by the systematic error in the W cross section

p_T bin (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

scaled cross sections as a function of p_T:

$$R_{p_T}^{\exp} = \left[\left(\frac{d\sigma^W}{dp_T^W}\right) \bigg/ \left(\frac{d\sigma^Z}{dp_T^Z}\right)\right] \times \frac{M_W}{M_Z}$$
$$\times \frac{B(Z \to ee)}{B(W \to e\nu)}.$$

It should be recognized that the prediction for R_{p_T} [8] was calculated for the ratio of the scaled W and Z boson differential cross sections $d\sigma^V/dp_T^V$, but we measure the differential cross sections multiplied by their branching fractions to electrons $(d\sigma^V/dp_T^V) \times B(V \to e)$. We therefore must multiply our measure-ment by the ratio of the Z to W boson branching fractions. Because the measurement of the W boson branching fraction from the Tevatron is obtained precisely from the ratio of W to Z production cross sections [7], we use the result from the LEP Electroweak Working Group [13] for the W branching fraction, to avoid a circularity problem. We take the value for the Z branching fraction from the review of particle physics [11].

$$B(W \to e\nu) = 0.1073 \pm 0.0025,$$
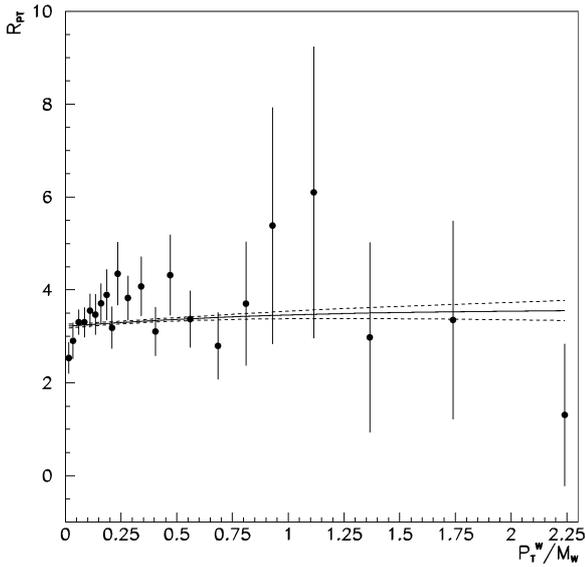$$B(Z \to ee) = 0.033632 \pm 0.000059.$$

Fig. 1. Ratio of scaled differential cross sections R_{p_T} for W and Z production. The solid line is the order α_S^2 theoretical prediction of Ref. [8], and the dotted lines are the one standard deviation uncertainties due to Monte Carlo integration. The error in the luminosity cancels completely in the ratio of the measured cross sections.

The result is shown in Fig. 1, and summarized in Table 2. The data are plotted at the value of p_T for which the theoretical prediction for R_{p_T} is equal to its average in the bin, following the prescription of Ref. [14]. We observe that the measured R_{p_T} agrees with the pQCD prediction [8]: the χ^2 for the comparison between data and theory is 18.3 for 21 degrees of freedom (63% probability). If we only consider the results in the first 12 bins, the χ^2 is 12.8 for 11 degrees of freedom, which corresponds to a probability of 31%.

We should mention that, at this time, the only uncertainty included in the theoretical prediction is the one arising from Monte Carlo integration. Additional uncertainties must be considered to determine whether the agreement between data and theory can be improved, in particular, if R_{p_T} should be calculated to higher orders, or whether non-perturbative effects are playing a role at lowest p_T. Once the theoretical uncertainties are improved, this would provide the means for estimating the integrated luminosity at which the ratio method will provide a superior measurement of the W boson mass.

Table 2

Measured R_{p_T}. The uncertainty in the luminosity for the W and Z samples cancels completely when taking the ratio

p_T bin (GeV)	p_T (GeV)	R_{p_T}	Total error
0−2	1.21	2.538	0.339
2−4	2.81	2.908	0.388
4−6	4.83	3.306	0.275
6−8	6.84	3.305	0.324
8−10	8.85	3.557	0.361
10−12	10.86	3.471	0.439
12−14	12.87	3.714	0.426
14−16	14.88	3.895	0.549
16−18	16.89	3.187	0.449
18−20	18.90	4.351	0.681
20−25	22.52	3.829	0.478
25−30	27.34	4.078	0.638
30−35	32.57	3.104	0.528
35−40	37.89	4.320	0.871
40−50	45.03	3.373	0.613
50−60	55.09	2.796	0.724
60−70	65.14	3.707	1.334
70−80	74.79	5.384	2.551
80−100	89.67	6.100	3.141
100−120	109.77	2.976	2.047
120−160	139.93	3.352	2.138
160−200	180.14	1.309	1.529

5. Extraction of $d\sigma^W / dp_T^W$

Based on Eq. (2), we use the calculated R_{p_T} in Ref. [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]. This is shown in Fig. 2, and is an update of the result given in Ref. [8] using our final data samples. For simplicity, we use the measured p_T^Z distribution from Table 1. A better prediction for p_T^W can be obtained from the combination of our published p_T^Z [2] and the corresponding measurement from CDF [9]. Fig. 2 shows the measured differential cross section plotted at the center of the bin.
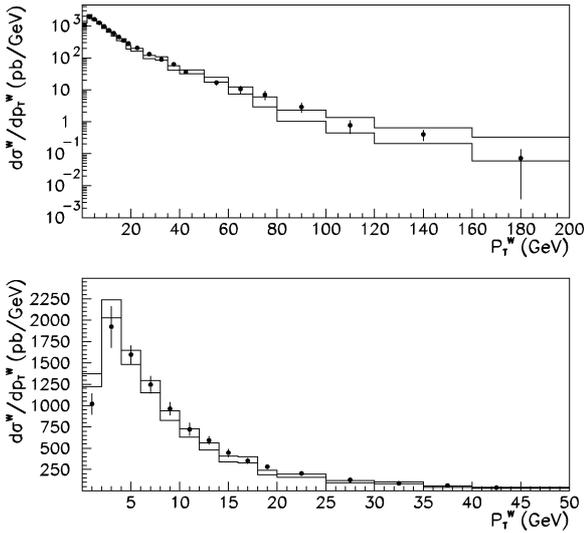
Fig. 2. Differential cross section for W boson production as a function of p_T^W shown for the entire p_T^W range (upper plot) and the low p_T^W region (lower plot). The points are the DØ data; the error bars do not include the 4.3% error in the luminosity. The histograms represent the upper and lower 68% confidence level limits of the prediction [8] obtained from the ratio method.

The upper and lower 68% confidence level limits for the prediction are plotted as histograms. The extracted transverse momentum distribution agrees well with the measurement: the Kolmogorov–Smirnov probability [15] κ is equal to 0.987.

6. Conclusions

We have measured the ratio of scaled differential cross sections R_{p_T} for W and Z boson production, and compared it to a purely pQCD prediction. We observe good agreement between data and theory over the entire p_T spectrum. For completeness, we have used the theoretical prediction for R_{p_T}, together with our measurement of the differential Z boson production cross section, to extract the differential cross section for W production. As expected, this prediction agrees with our published result. From this first study of the method of Ref. [8] for predicting W boson properties, we conclude that, once the high statistics samples of Z boson events expected from Run 2 at the Tevatron become available, this new approach should lead to smaller overall uncertainties on the measured mass

and width of the W boson, compared to current methods used at hadron colliders.

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