Measurement of $d\sigma/dy$ of Drell-Yan e^+e^- pairs in the Z Mass Region from $p\bar{p}$ Collisions at $\sqrt{s}$=1.96 TeV

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We report on a CDF measurement of the total cross section and rapidity distribution, $d\sigma/dy$, for $q\bar{q} \to \gamma^*/Z \to e^+e^-$ events in the Z boson mass region ($66 < M_{ee} < 116$ GeV/c^2) produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with 2.1 fb^{-1} of integrated luminosity. The measured cross section of 257 ± 16 pb and $d\sigma/dy$ distribution are compared with Next-to-Leading-Order(NLO) and Next-to-Next-to-Leading-Order(NNLO) QCD theory predictions with CTEQ and MRST/MSTW parton distribution functions (PDFs). There is good agreement between the experimental total cross section and $d\sigma/dy$ measurements with theoretical calculations with the most recent NNLO PDFs.

Keywords : Z Boson Rapidity $d\sigma/dy$ PDFs

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1. INTRODUCTION

Accurate predictions using perturbative quantum chromodynamics (QCD) are critical for understanding experimental results at hadron colliders. Such predictions depend on the accuracy of input parton distribution functions (PDFs), which at present cannot be calculated and are obtained from analysis of data from a broad range of processes. Precise knowledge of PDFs will be particularly important for analysis of data at the Large Hadron Collider (LHC) where new phenomena may be revealed via small deviations from Standard Model (SM) predictions. The Drell-Yan process [1], in which quark-antiquark annihilations form intermediate γ^* or Z (γ^*/Z) vector bosons decaying to lepton pairs, is particularly useful in providing information on PDFs at $Q^2 = M_{\ell\ell}^2$, where $M_{\ell\ell}$ is the invariant mass of the dilepton pair. In the leading order (LO) approximation, the momentum fractions x_1, x_2 carried by the initial state quarks in the proton and antiproton, respectively, are related to the rapidity y [2] of the γ^*/Z boson via the equation $x_{1,2} = (M_{\ell\ell}/\sqrt{s})e^{\pm y}$, where $\sqrt{s}$ is the center of mass energy. Dilepton pairs produced at large y originate from collisions in which one parton carries a large and the other a small momentum fraction x. A measurement of $d\sigma/dy$ at large y tests PDFs at high x, a region not well constrained by current results. Therefore, precise measurements of W and Z boson rapidity distributions at the Tevatron determine the size of higher order QCD terms and can be used to further refine current PDF models. Furthermore since the Z production cross section is predicted with an accuracy of $\approx 2\%$ [3], precise measurements of the rate of Z production at the Tevatron and the LHC can be used to determine the integrated luminosity [4] more precisely than the traditional method of using the total inelastic cross section. This has particular applicability to sub-processes initiated by a quark and an anti-quark and can reduce the uncertainty in the determination of LHC and Tevatron cross sections.

The most recent Tevatron measurement of $d\sigma/dy$ for e^+e^- pairs in the Z boson mass region was performed by the D0 [5] experiment, using a data-set corresponding to 0.4 fb^{-1} of integrated luminosity. Here, we report on a new measurement of $d\sigma/dy$ at the Tevatron with an integrated luminosity of 2.1 fb^{-1}. The measured rapidity range extends to $|y| \sim 2.9$, close to the kinematic limit of $|y| = 3.0$ for Z boson production at $\sqrt{s} = 1.96$ TeV. The $d\sigma/dy$ distribution is compared to the predictions of perturbative QCD calculations in Next-to-Leading-Order (NLO) and Next-to-Next-to-Leading-Order (NNLO) with different PDF models.

2. EVENT SELECTION AND ANALYSIS METHOD

The data sample corresponds to an integrated luminosity of 2.1 fb^{-1} collected by the CDF II Detector at Fermilab [6] during 2004-2007. CDF II uses a 1.4 T solenoidal magnetic spectrometer surrounded by projective-tower-geometry calorimeters and outer muon detectors. Charged particle directions and momenta are measured by an open-cell drift chamber (COT), a silicon vertex detector (SVX), and an intermediate silicon layer (ISL). The coverage of COT tracking in pseudorapidity is $|\eta| < 1.2$ [2]. Reconstructed tracks are used to determine the $p\bar{p}$ collision point along the beam line (z_{vertex}), which is required to be within $z = \pm 60$ cm of the detector. The energies and directions [2] of electrons, photons, and jets are measured by two separate calorimeters: central ($|\eta| < 1.1$) and plug ($1.1 < |\eta| < 3.6$). Each calorimeter has an electromagnetic (EM) compartment with a shower maximum detector followed by a hadronic (HAD) compartment. Three topologies of e^+e^- pairs are considered: two central electrons (CC), one central and one plug electron (CP), and two plug electrons (PP). The inclusion of PP events allows the measurement of Z bosons in the forward rapidity region which corresponds to high and low parton momentum fractions.

Data are collected using a three-level trigger system [6] and trigger paths with either one central electron or two electrons (central or plug) with transverse energy $E_T > 18$ GeV. Electron identification requirements [7] are imposed to select signal events and to suppress background. Both electron candidates are required to be isolated from any other calorimetric activity. The fraction of energy in the HAD calorimeter towers behind the EM shower is required to be small [7], as expected for an EM shower. Electron candidates with $E_T > 25$ GeV for CC and PP events, and $E_T > 20$ GeV for CP events, are selected in the central ($|\eta| < 1.1$), and plug ($1.2 < |\eta| < 2.8$) fiducial regions of the calorimeters. Central electron candidates must have a COT track that extrapolates to a shower cluster in the EM calorimeter and a track momentum consistent with the calorimeter measurement. Central and plug electron candidates are required to have EM-like transverse shower profiles using the shower maximum detectors. In order to reduce background we require that at least one of the plug elec-

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trons in PP events has a track reconstructed in the SVX that points to the EM cluster in the calorimeter. The efficiency of having at least one electron matched to an SVX track is about 85%. The selected number of CC, CP, and PP events with $66 < M_{ee} < 116$ GeV/c^2 is 50752, 86203, and 31415, respectively.

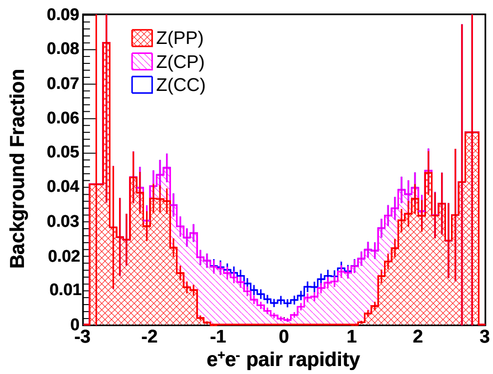

FIG. 1: The distribution of background events as a function of rapidity for CC, CP and PP e^+e^- candidates (shown as a fraction of all candidate events selected in this analysis). The error bars include the statistical and systematic uncertainty.

3. BACKGROUNDS

The main backgrounds are QCD dijet and photon plus jet events in the plug region (because of the limited tracking at large $|\eta|$). The jet background is measured separately in each e^+e^- pair topology by statistically separating electrons from jets on the basis of the transverse energy profile distributions in the calorimeter and the invariant mass distribution of e^+e^- pairs [7]. The distribution of background events as a function of rapidity for CC, CP and PP e^+e^- candidates (shown as a fraction of all candidate events selected in this analysis) is shown in Fig. 1. The fractional contribution of the total background to the number of selected events is $0.24 \pm 0.03\%$ (stat $\oplus$ syst) for CC, $1.55 \pm 0.44\%$ for CP, and $3.40 \pm 0.75\%$ for PP events. The background from electroweak (WW, WZ, W+jets, and $Z \rightarrow \tau^+\tau^-$) and $t\bar{t}$ processes is estimated from simulation to be $0.41 \pm 0.02\%$.

4. ACCEPTANCE AND EFFICIENCIES

The acceptance is defined as the ratio of the number of Monte Carlo (MC) simulation events that pass selection criteria in each y bin of the reconstructed final state e^+e^- pair (including resolution smearing) to the number of MC generated events in each true y bin of the generated γ^*/Z boson. The resolution in the measurement of the e^+e^- invariant mass is 2.2 GeV/c^2, and the resolution in the measurement of y is 0.015. The acceptance is modeled using the PYTHIA [8] generator combined with a GEANT [11] simulation of the CDF detector.

The PYTHIA generator includes a LO QCD interaction ($q + \bar{q} \rightarrow \gamma^*/Z$), initial state QCD radiation, parton shower fragmentation, the $\gamma^*/Z \rightarrow e^+e^-$ decay, and photon radiation from the final state. The version of PYTHIA used at CDF has additional ad-hoc tuning [8] in order to accurately represent the Z boson transverse momentum distribution measured in data. To reconstruct the simulated events in the same way as data, the calorimetry energy scale, resolutions, and selection efficiencies used in the detector simulation are tuned using data.

Because the acceptance depends on modeling of the Z boson rapidity, transverse momentum and angular distributions of the electron pairs, it is important to correct for possible model dependences arising from the choice of the event generator or a particular PDF set. The uncorrected acceptance is calculated using the CTEQ5L [9] LO PDFs, and we compare relevant kinematic distributions in the MC simulation to those observed in the data to correct the acceptance for possible observed discrepancies.

While the generated rapidity spectrum is in good agreement with the data for $y < 2$, the data and simulation do not agree at larger values of y. To correct for this discrepancy, we modify the MC generated event spectrum (dN/dy) so that the final accepted MC spectrum matches the spectrum in data, as shown in Fig. 2. A comparison of the reconstructed transverse momentum spectra of the e^+e^- pairs in the data and the MC simulation reveals good agreement as shown in Fig. 3. Modifying the P_T spectrum in simulation to exactly follow the data leads to a negligible change in the calculated acceptance. A comparison of the average P_T of events in bins of y shows that the data is well modeled by the simulation. Similarly, a study of the angular distribution in θ (where θ is the polar angle of the final state electron in the Collins-Soper frame [10]) in data shows good agreement with the simulation as illustrated in Fig. 4.

The acceptance (A) and efficiencies (ϵ) are determined as a function of boson rapidity. The contributions of each topology to the product $A \times \epsilon$ are shown in Fig. 5.

5. DIFFERENTIAL AND TOTAL CROSS SECTIONS

The differential cross section is given by

$$\frac{d\sigma(\gamma^*/Z)}{dy}(y) = \frac{N_{sig}(y) - N_{bkg}(y)}{c(y)\Delta y \epsilon_{zvtx} \Sigma_i[(A_i \times \epsilon_i(y))\epsilon^i_{trig}(y)\mathcal{L}_i]}$$

where $N_{sig}(y) - N_{bkg}(y)$ is the number of events after subtracting background, $c(y)$ is a correction factor used in order to yield $d\sigma/dy$ at the center of the bin, and Δy is the y bin size ($\Delta y = 0.1$ up to $y = 2.7$ and $\Delta y = 0.2$ for the last bin, $2.7 < y \leq 2.9$). The sum index i runs over the e^+e^- topologies (CC, CP, PP), $A_i \times \epsilon_i(y)$ is the combined acceptance and event selection efficiency,

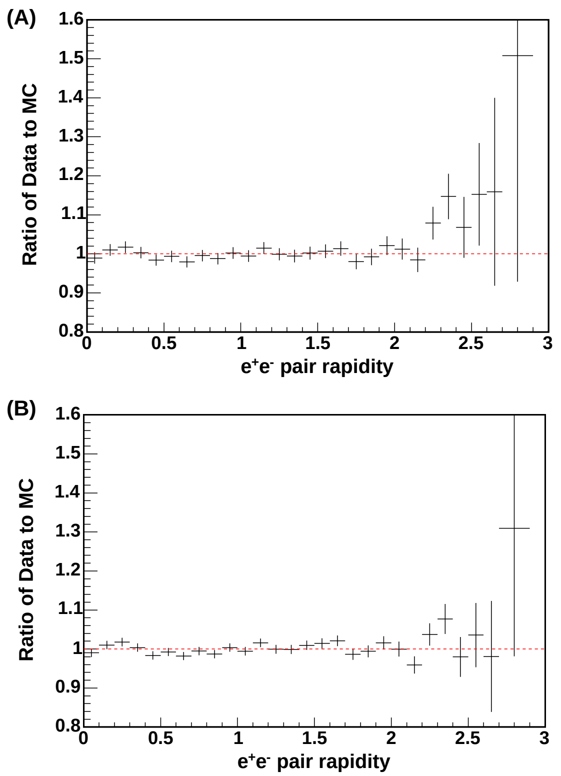

FIG. 2: The ratio of the rapidity distributions dN/dy of reconstructed e^+e^- pairs in data to the results from the simulation using PYTHIA, CTEQ5L LO PDFs and CDF W/Z tuning parameters [8]. (A) PYTHIA before modification of the rapidity distribution. (B) PYTHIA after modification of the rapidity distribution .

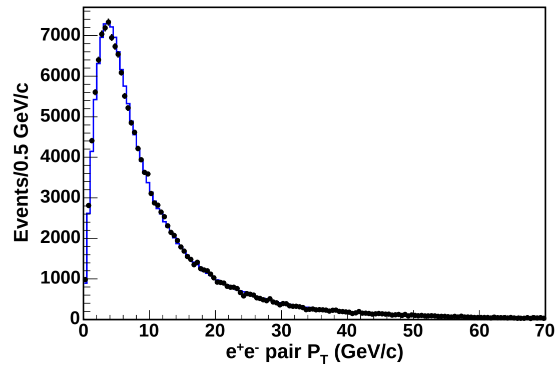

FIG. 3: The reconstructed transverse momentum distribution of e^+e^- pairs (after all event selection cuts) compared to the results from the simulation using PYTHIA, CTEQ5L LO PDFs and CDF W/Z tuning parameters [8]. The black points are data and the blue solid line is the PYTHIA MC prediction.

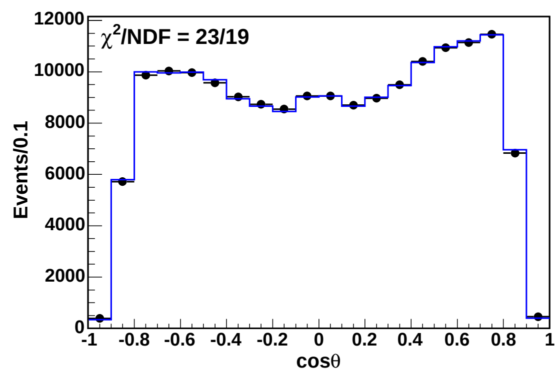

FIG. 4: The reconstructed polar angle distribution of e^+e^- pairs (after all event selection cuts) compared to the results from the simulation using PYTHIA, CTEQ5L LO PDFs and CDF W/Z tuning parameters [8]. The black points are data and the blue solid line is the PYTHIA MC prediction.

$\epsilon^i_{trig}(y)$ is the trigger efficiency, $\mathcal{L}_i$ is the total integrated luminosity for each topology, and ϵ_{zvtx} is the acceptance for the $p\bar{p}$ collision vertex to occur within $z = \pm 60$ cm of the center of the detector. The ϵ_{zvtx} in the data taken before June 2006 is $95.8 \pm 0.2\%$ and after that is $96.8 \pm 0.2\%$.

Systematic uncertainties in $d\sigma/dy$ originate from uncertainties in the estimates of the acceptance, backgrounds, electron identification efficiency, SVX tracking efficiency, and modeling of material in the detector. Uncertainties associated with correcting the acceptance for differences between kinematic distributions in data and simulation are found to be negligible. The total systematic uncertainty is $\sim$ 1.0% of $d\sigma/dy$ for $|y| < 2.5$, increasing to 10.0% at $|y| = 2.9$. The uncertainty on the integrated luminosity (lum.) is 6%.

6. RESULTS

The measured $d\sigma/dy$ values, which are symmetric about $y = 0$, are shown versus $|y|$, with statistical and systematic uncertainties, in Fig. 6 and Table I. The total cross section, derived from integrating $d\sigma/dy$ up to $|y| = 2.9$, is $\sigma = 256.6 \pm 0.7(\text{stat.}) \pm 2.0(\text{syst.}) \pm 15.4(\text{lum.})$ pb. These results are compared to QCD predictions at LO with CTEQ5L [9], at NLO [17] with MRST2001 (NLO) [14], MRST2004 (NLO) [15], CTEQ6.1M (NLO) [12], CTEQ6.6M (NLO) [13], and MSTW2008 (NLO) [3] PDFs, and at NNLO [18] with MRST2006E (NNLO) [16] and MSTW2008 (NNLO) [3] PDFs. The measured total cross section is consistent with both NLO and NNLO calculations as shown in Table II.

In comparing the shape of the measured $d\sigma/dy$ to theory, the latter distributions are normalized to the measured total cross section of 256.6 pb. The ratios of the measured $d\sigma/dy$ to the QCD calculations at LO, NLO and NNLO with the above mentioned PDFs are shown in Figures 7, 8, and 9. The yellow bands in the fig-

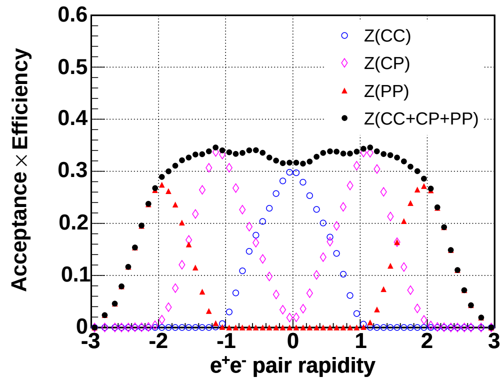

FIG. 5: The product of kinematic acceptance and event selection efficiency *vs.* the rapidity of the e^+e^- pair. The black points are the sum of all topologies.

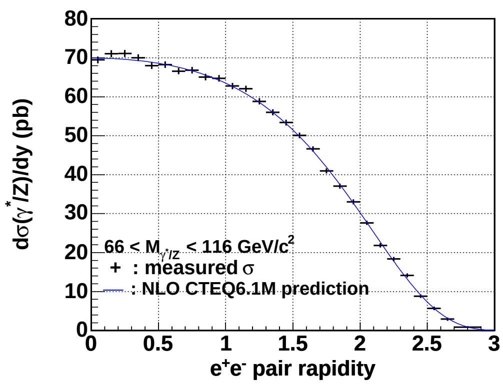

FIG. 6: The measured $d\sigma/dy$ for $p\bar{p} \rightarrow Z^0/\gamma^* \rightarrow e^+e^-$ over the entire rapidity range. The points are the measured cross section versus $|y|$ and the solid line is the theory prediction (scaled to the measured total cross section) for CTEQ6.1M(NLO) PDFs.

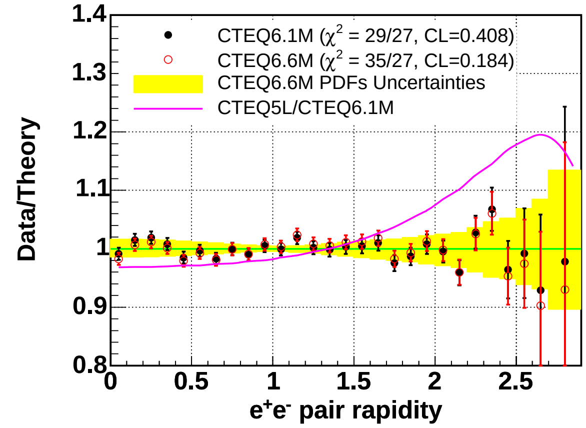

FIG. 7: The ratio of the experimental distribution of $d\sigma/dy$ (statistical and systematic uncertainties combined) to the theoretical predictions with CTEQ NLO PDFs (CTEQ6.1M and CTEQ6.6M). The yellow bands corresponds to the CTEQ6.6M PDFs 90% C.L. uncertainties. The χ^2 test includes the data statistical and systematical uncertainties.

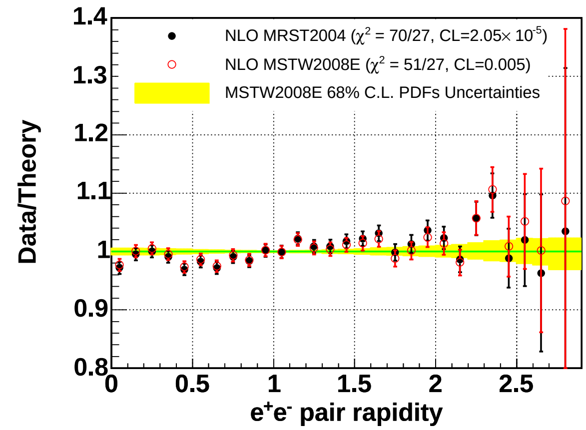

FIG. 8: The ratio of the experimental distribution of $d\sigma/dy$ (statistical and systematic uncertainties combined) to the theoretical predictions with MRST2004 and MSTW2008E NLO PDFs. The yellow bands corresponds to the MSTW2008E PDFs 68% C.L. uncertainties. The χ^2 test includes the data statistical and systematical uncertainties.

ures correspond to the uncertainties associated to the MSTW2008E (NLO and NNLO) PDFs, which are given with 68% C.L. errors and to the those associated to the other sets of PDFs, given with 90% C.L. errors. A χ^2 comparison (including statistical and systematic uncertainties) is shown in Table III. Better agreement is obtained for the MSTW (2008) PDF at NNLO compared to NLO. The NLO CTEQ6.1M, CTEQ6.6M, the NNLO MRST2006 and MSTW2008 PDFs all describe the data well. The older NLO MRST (2004) set provides a poorer description of the data and, as expected, so does the LO PDF, CTEQ5L. The MSTW(2008) PDF used a preliminary version of the data presented in this paper in their fit. The correlations [7, 19] between the uncertainties in different y bins are included in the χ^2 comparison.

In summary, high-statistics measurement of γ^*/Z production in the Z mass region and of its rapidity distribution are found to agree with theoretical calculations that use recent NLO and NNLO PDFs. (A preliminary version of these results has been used in the determination of the most recent PDFs). The precise measurement of the total production cross section, $\sigma = 256.6 \pm 0.7(\text{stat.}) \pm 2.0(\text{syst.}) \pm 15.4(\text{lum.})$ pb can be used to set the normalization of other processes at the Tevatron and the LHC.

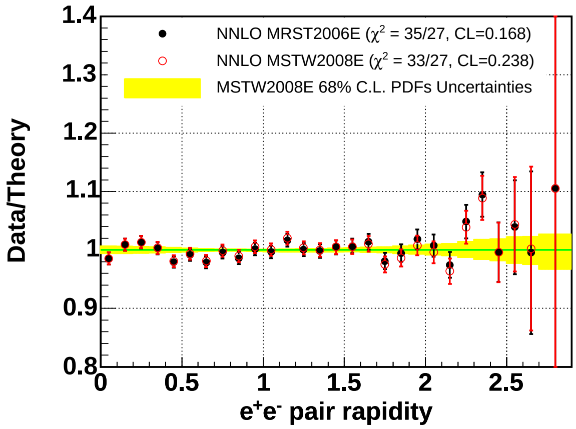

FIG. 9: The ratio of the experimental distribution of $d\sigma/dy$ (statistical and systematic uncertainties combined) to the theoretical predictions with MRST2006E and MSTW2008E NNLO PDFs. The yellow bands corresponds to the MSTW2008E PDFs 68% C.L. uncertainties. The χ^2 test includes the data statistical and systematical uncertainties.

TABLE I: Differential cross sections for production of e^+e^- pairs in the mass range $66 < M_{ee} < 116$ GeV/c^2. The first and second uncertainties are statistical and systematical, respectively. The 6% luminosity uncertainty is not included. The quoted y values correspond to the center of the bin. The bin size is 0.1 up to $y = 2.7$ and 0.2 for the last bin.

y	$d\sigma/dy[pb]$	y	$d\sigma/dy[pb]$
0.05	$69.46 \pm 0.73 \pm 0.49$	1.55	$50.07 \pm 0.62 \pm 0.37$
0.15	$71.03 \pm 0.74 \pm 0.49$	1.65	$46.59 \pm 0.61 \pm 0.35$
0.25	$71.10 \pm 0.74 \pm 0.49$	1.75	$40.97 \pm 0.58 \pm 0.34$
0.35	$70.01 \pm 0.72 \pm 0.48$	1.85	$37.04 \pm 0.56 \pm 0.33$
0.45	$67.97 \pm 0.70 \pm 0.47$	1.95	$33.02 \pm 0.55 \pm 0.31$
0.55	$68.22 \pm 0.70 \pm 0.47$	2.05	$27.65 \pm 0.52 \pm 0.25$
0.65	$66.58 \pm 0.69 \pm 0.47$	2.15	$21.84 \pm 0.49 \pm 0.23$
0.75	$66.81 \pm 0.70 \pm 0.48$	2.25	$18.35 \pm 0.50 \pm 0.20$
0.85	$65.05 \pm 0.69 \pm 0.49$	2.35	$14.13 \pm 0.49 \pm 0.17$
0.95	$64.70 \pm 0.69 \pm 0.50$	2.45	$8.80 \pm 0.45 \pm 0.10$
1.05	$62.74 \pm 0.67 \pm 0.50$	2.55	$5.68 \pm 0.44 \pm 0.09$
1.15	$62.02 \pm 0.66 \pm 0.49$	2.65	$2.93 \pm 0.41 \pm 0.15$
1.25	$58.80 \pm 0.65 \pm 0.48$	2.80	$0.87 \pm 0.22 \pm 0.11$
1.35	$56.02 \pm 0.65 \pm 0.43$	2.95	–
1.45	$53.37 \pm 0.63 \pm 0.40$		

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TABLE II: A comparison of the measured total cross section for the production of e^+e^- pairs in the mass range $66 < M_{ee} < 116$ GeV/c^2 to theory calculations.

Model	*Total cross section*
CTEQ5L(LO)	183.3
MRST2001E(NLO)	$241.0^{+2.8}_{-3.4}$
MRST2004(NLO)	241.2
MSTW2008E(NLO)	$242.6^{+4.6}_{-5.5}$
CTEQ6.1M(NLO)	$236.1^{+9.3}_{-9.2}$
CTEQ6.6M(NLO)	$238.7^{+7.1}_{-7.0}$
MRST2006E(NNLO)	$251.6^{+2.8}_{-3.1}$
MSTW2008E(NNLO)	$248.7^{+5.1}_{-4.0}$
Data	$256.6 \pm 0.7 \pm 2.0 \pm 15.4$

TABLE III: A comparison of the shape of the measured $d\sigma/dy$ distribution to theoretical predictions with several choices of PDFs. The theoretical distributions are normalized to the measured total cross section of 256.6 pb. The χ^2 for 27 degrees of freedom includes statistical and systematic uncertainties.

Model	χ^2/DOF	*CL*
CTEQ5L(LO)	242/27	–
MRST2001E(NLO)	76/27	2.908×10^{-6}
MRST2004(NLO)	70/27	2.049×10^{-5}
MSTW2008E(NLO)	51/27	0.005
CTEQ6.1M(NLO)	29/27	0.408
CTEQ6.6M(NLO)	35/27	0.184
MRST2006E(NNLO)	35/27	0.168
MSTW2008E(NNLO)	33/27	0.238

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$y = \frac{1}{2} ln \frac{E+P_z}{E-P_z}$, where P and P_z are the magnitude and z component of the momentum, and E is the energy of the $e^+ + e^-$ pair.
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[19] CERN ROOT and C++ code for $d\sigma/dy$ and statistical and systematic uncertainty contributions from each source including correlations is available at `http://www-cdf.fnal.gov/physics/ewk/2009/dszdy/dszdy_sys.htm`