# Measurement of the shape of the boson rapidity distribution for $p\bar{p} \to Z/\gamma^* \to e^+e^- + X$ events produced at $\sqrt{s}$ of 1.96 TeV

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(Dated: February 14, 2007)

We present a measurement of the shape of the boson rapidity distribution for $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^- + X$ events at a center-of-mass energy of 1.96 TeV. The measurement is made for events with electron-positron mass $71 < M_{ee} < 111$ GeV and uses 0.4 fb$^{-1}$ of data collected at the Fermilab Tevatron collider with the D0 detector. This measurement significantly reduces the uncertainties on the rapidity distribution in the forward region compared with previous measurements. Predictions of NNLO QCD are found to agree well with the data over the full rapidity range.

PACS numbers: 13.60.Hb, 13.38.Dg, 13.85.Qk

## I. INTRODUCTION

Kinematic distributions of $Z/\gamma^*$ bosons produced in hadronic collisions provide a wealth of information on the fundamental interactions involved. At leading order, $Z/\gamma^*$ bosons are produced through the annihilation of a quark and an anti-quark, with the partons in the proton and anti-proton carrying momentum fractions $x_1$ and $x_2$, respectively. In turn, the rapidity of the boson, defined as $y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$, where $E$ is the energy of the boson and $p_L$ is the component of its momentum along the beam direction, is directly related to the momentum fractions by

$$x_{1,2} = \frac{M_{Z/\gamma^*}}{\sqrt{s}} e^{\pm y}.$$

Here, $M_{Z/\gamma^*}$ is the mass of the boson, and $\sqrt{s}$ is the center of mass energy. These kinematic distributions can be precisely reconstructed when the boson decays leptonically since the leptons can be accurately reconstructed, and the backgrounds to di-lepton final states are small. For low rapidity bosons, the leptons also have small pseudorapidity,

$$\eta = - \ln \left( \tan \left( \theta/2 \right) \right),$$

where $\theta$ is the polar angle and is measured relative to the proton beam. High rapidity bosons are more likely to have initial states that have maximal $|x_1 - x_2|$ for the incident partons.

Although calculations are available at next-to-next-to-leading-order in QCD (NNLO) for $d\sigma/dy$ for $p\bar{p} \rightarrow Z/\gamma^* \rightarrow \ell\bar{\ell} + X$ [1], few measurements of the differential cross section exist [2]. The forward rapidity region ($|y| > 1.5$) suffers from a smaller cross section and lower acceptance than the central rapidity region ($|y| < 1.5$), and has not yet been well tested. The forward region probes quarks with low $x$ and high 4-momentum transfer squared $Q^2$ ($Q^2 \approx M_Z^2$) as well as quarks with very large $x$. Parton distribution functions (PDFs) in this regime are mainly determined by jet cross section data, which have very different experimental and theoretical systematic uncertainties than the electron measurements presented here, and by inclusive lepton scattering data taken mostly at much lower $Q^2$, which must be evolved to high momentum transfer scales using the DGLAP equations [3].

We measure the normalized differential cross section

$$\frac{1}{\sigma} \left( \frac{d\sigma}{dy} \right)_i = \frac{(\epsilon \times A)_{\text{avg}}}{N_{\text{total}}^{\text{obs}} - N_{\text{total}}^{\text{bg}}} \frac{N_i^{\text{obs}} - N_i^{\text{bg}}}{\Delta_i (\epsilon \times A)_i},$$

where the index $i$ indicates the boson rapidity bin. In the first term on the right hand side, $\epsilon_{\text{avg}}$ is the average efficiency and $A_{\text{avg}}$ is the average acceptance for kinematic and geometric cuts. $N_{\text{total}}^{\text{obs}}$ is the total number of candidate bosons, and $N_{\text{total}}^{\text{bg}}$ is the total number of background events in the sample. In the second term, $\epsilon_i$, $A_i$, $N_i^{\text{obs}}$,

and $N_i^{\text{bg}}$ are the same as before, but determined in each bin $i$. $\Delta_i$ is the bin width. Dividing by the total number of events reduces many of the systematic uncertainties, particularly those due to luminosity.

The D0 detector [4] allows efficient detection of electrons [5] at the large pseudorapidities needed to study high rapidity $Z/\gamma^*$ bosons. It has a central tracking system, consisting of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing [6] at pseudorapidities $|\eta_D| < 3$ and $|\eta_D| < 2.5$, respectively. The quantity $\eta_D$ is $\eta$ measured from the center of the detector. A liquid-argon and uranium calorimeter allows reconstruction of electrons, photons, jets, and missing transverse energy. The calorimeter is divided into a central section (CC) covering $|\eta_D| \lesssim 1.1$ , and two end calorimeters (EC) that extend coverage to $|\eta_D| \approx 4.2$. Each calorimeter is housed in a separate cryostat [7]. An outer muon system, covering $|\eta_D| < 2$, consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T iron toroids, followed by two similar layers after the toroids [8]. The luminosity is measured using plastic scintillator arrays placed in front of the EC cryostats. The trigger and data acquisition systems are designed to accommodate the high luminosities of Run II.

## II. EVENT SELECTION

This measurement utilizes a data set of 0.4 fb$^{-1}$ collected at the Fermilab Tevatron between 2002 and 2004. The data are from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We consider candidate $Z/\gamma^*$ events that decay into an electron-positron pair with a reconstructed invariant mass $71 < M_{ee} < 111$ GeV. The range used is $\pm 20$ GeV about the mass of the $Z$ boson.

To optimize the acceptance for electrons at large $\eta$, two strategies are used. The first is to require only one of the electrons be matched to a reconstructed track. Requiring a track-matched electron helps to reduce background from jets misidentified as electrons, while removing the track requirement on the second electron extends the $\eta$ coverage beyond that of the tracking system. The second strategy takes advantage of the length of the bunches containing the incident protons and antiprotons, which has a design length of 37 cm. For our dataset, the $z$ coordinate [9] of the primary interactions have a Gaussian distribution with an rms ranging from $29 \pm 2$ cm to $24 \pm 1$ cm. The rms varies with respect to run conditions and time. At large values of vertex $|z|$, some of the decay products will travel back through the detector towards smaller $|z|$ values. These particles pass through much of the active volume of the tracking system. Typically, these events have low background and have the highest boson rapidities.

Events are considered only if a single electron trigger fired. The efficiency is $(99.0 \pm 0.3)\%$ per electron for

particles with transverse momentum $p_T > 30$ GeV and $|\eta_D| < 2$. From these events, di-electron candidates are selected by requiring two isolated electromagnetic objects which have shower shapes consistent with those of electrons. A candidate electron is considered to be isolated when greater than 85% of its energy is contained within a cone of 0.2 in $\eta - \phi$ space. Also, they must have deposited more than 90% of their energy in the electromagnetic portion of the calorimeter. One electron must have $p_T > 15$ GeV while the other electron has $p_T > 25$ GeV. Electrons are defined to be in the CC (EC) region of the calorimeter if they are within $|\eta_D| < 0.9$ ($1.5 < |\eta_D| < 3.2$). In the CC region, electrons are not used if they pass near EM calorimeter module boundaries. As mentioned previously, at least one of the electrons in each di-electron pair must be spatially matched to a reconstructed track. In addition, all CC-region electrons are required to have a track match, so that both legs of a CC-CC event have a track match. A total of 19,306 events pass these selection criteria.

## III.   EFFICIENCIES AND BACKGROUNDS

Single electron efficiencies are measured from this data sample using a "tag-and-probe method." This method involves selecting a sample of $Z \to e^+e^-$ candidate events by applying tight selection criteria to one of the electron candidates, the "tag leg," and very loose selection criteria to the other electron candidate, "the probe leg." The reconstructed mass of the tag and probe pair are required to be close to that of a $Z$ boson. The tag leg has tighter cuts to reduce the amount of background and to increase the probability that the event is really a boson decay event, and not from jets that are misidentified as electrons. The probe leg has looser cuts and is used to test the selection cut in question. While the efficiencies are measured with data, Monte Carlo events are used to test for biases in the efficiency measurements. For this purpose, $Z/\gamma^*$ Monte Carlo events are generated with PYTHIA [10] and are processed with a full D0 detector simulation based on the GEANT software package [11], which models the interactions of particles with matter. Efficiencies are measured for identification of particles like photons and electrons that shower in the electromagnetic calorimeter ("EM particles"), shower shape cuts, trigger, and track-matching probability. All efficiencies are studied as a function of the $\eta_D$ of the probe electron. In addition, some of the efficiencies are measured with respect to additional quantities such as $p_T$ of the probe, vertex $z$ position of the event, boson $y$, or run number. Single electron efficiencies are relatively flat in $\eta_D$ for the CC region, and the values are typically larger than 90%. In the EC region, the efficiencies are sensitive to changes in the calorimeter geometry, to the finite coverage of the tracking system, and to the shape of the distribution of event vertices. Due to this sensitivity, effects of variations in the width of the vertex $z$ distribution of the course of

Run II are taken into account with a width-dependent efficiency.

For the acceptance determination, we use the RESBOS Monte Carlo event generator [12] with CTEQ6.1M input PDFs [13, 14]. RESBOS computes the differential cross section including NLO QCD corrections and uses resummation for the low $p_T$ region. The simulated events then are processed with PHOTOS [15] to account for QED final state radiation (FSR). The events then are passed through a parameterized detector simulation which has been tuned to our data set. To properly apply efficiencies in the Monte Carlo, events are weighted based on the relative integrated luminosity per run. Figure 1 compares data to the Monte Carlo simulation; the simulated signal plus background reproduces the data well. The $\epsilon \times A$ per rapidity bin is summarized in Table I.

The main source of background arises from events with jets where one or more of the jets are misidentified as an electron. The size of the background is less than 0.8% for events where both electrons are detected in the central calorimeter (CC-CC) and less than 6% for the remainder of the data set. The background for CC-CC events is significantly smaller due to the track-match requirement on both electrons. The jet background is subtracted by fitting the di-lepton mass distribution with the sum of background and signal shapes. The signal shapes are taken from the same tuned Monte Carlo as used for the acceptance. Two different methods to determine the background shape are used. For $|y| < 2$, the background is determined separately for each rapidity bin. The total background is measured in the low statistics regions of $y > 2$ and $y < -2$ separately. The small numbers of events in these areas do not permit the background fits to be performed on a bin-by-bin basis. In each of the high rapidity regions the background fraction is assumed to be constant for subsets of CC-CC, CC-EC, and EC-EC events. The background per bin then is determined using the number of candidate events per bin collected in each subset and the background fraction for that subset.

Additional background contributions could come from events that produce two EM objects in the final state. We consider diboson events containing a $W$ plus a $W$, $Z$, or $\gamma$; $t\bar{t}$; and $Z/\gamma^* \to \tau\tau$ events where each $\tau$ decays to an electron. The combined contribution from these additional sources is negligible compared to the background from jets. The total number of background events per bin is presented in Table I.

## IV.   SYSTEMATIC UNCERTAINTIES

A number of contributions to the systematic uncertainty are considered. These include contributions that arise from the determination of the $\epsilon \times A$ correction and from the measurement of the background.

For estimating the background systematic uncertainty, two different background shapes are used in the fits. One is obtained from electron-positron events that fail the
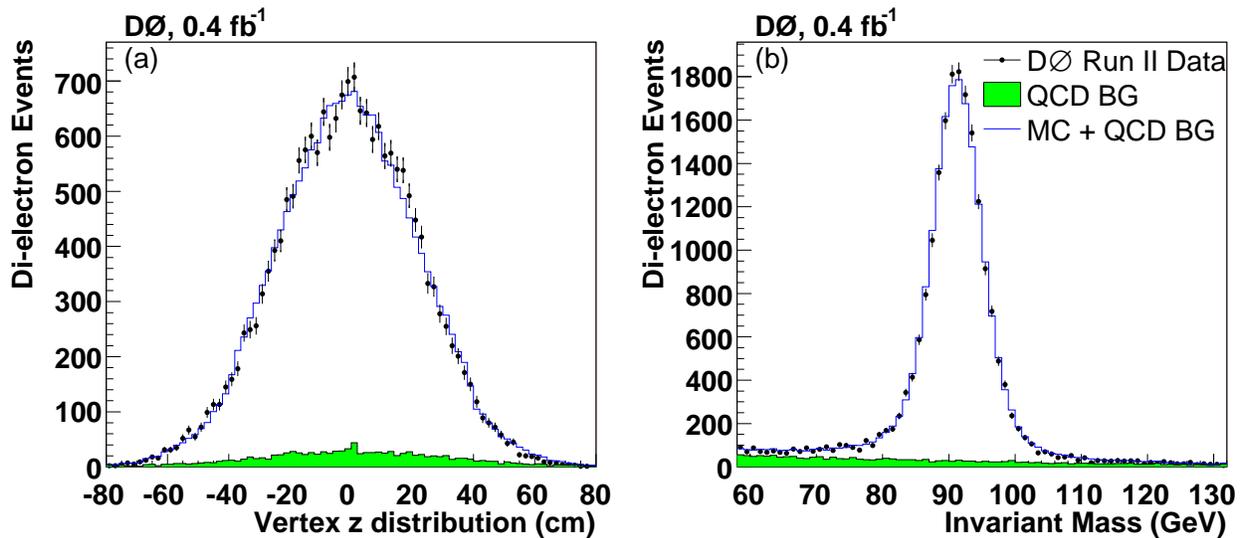
FIG. 1: Comparisons of data and Monte Carlo plus background are presented for (a) the vertex $z$ distribution and (b) the electron-positron invariant mass spectrum. The vertex $z$ plot shows data after all selection cuts. The data in the mass plot pass all selection criteria except for the mass cut. Uncertainties shown on the data points are statistical.

shower shape cuts; the other parameterizes the background shape as an exponential curve and incorporates it directly into the fit. The exponential fits result in about 13% more background. The average of the two methods is used as the background central value and the difference is split and assigned as a systematic uncertainty. An additional contribution to the background systematic uncertainty is derived by varying the constraints on the signal amplitude used in the background fits and redetermining the background.

The uncertainty on the differential cross section from the uncertainties on background ranges from $1.5 - 2.0\%$ for $|y| > 0.8$. In this region the data mainly come from the CC-EC and EC-EC configurations which, because only one track-match is required, tends to allow more background. For $|y| < 0.8$, which is dominated by CC-CC data, the uncertainty due to the background is less than 1%.

Several contributions due to the $\epsilon \times A$ measurement are taken into account. These include the uncertainties on single electron efficiencies, the electron energy scale and energy resolution, the PDFs, and the model of the vertex $z$ distribution.

For single electron efficiencies, several aspects contribute to the systematic uncertainty. The first two contributions are derived from data while the third is obtained using Monte Carlo events. Since efficiencies are measured using data, the size of our $Z/\gamma^*$ sample inherently has a limited precision. This statistical uncertainty is included as part of the systematic uncertainty. The next component of the efficiencies' systematic uncertainty comes from the background subtraction. To estimate this contribution, selection cuts are tightened on the tag electron to reduce the background at the ex-

pense of statistical precision. A comparison of the efficiencies with nominal and tighter cuts is used to estimate the systematic uncertainty from the background subtraction technique. Lastly, the tag-and-probe method used in the efficiency measurement may produce a biased result if the efficiency for the probe electron passing the selection criteria is correlated with that of the tag electron. We estimate the size of this bias with the PYTHIA Monte Carlo sample mentioned above, which includes a full detector simulation. Efficiencies measured using generator level information about the true particle identities are compared to the same efficiencies measured via tag-and-probe. The difference is used as a contribution to the systematic uncertainty.

For the parameterized detector simulation, the energy response and resolutions are tuned using the width and peak position of the electron-positron mass distribution from the data sample. Kinematic variables that are correlated with the boson rapidity are not used to tune the detector simulation parameters. Changing the tuning method leads to slight variations in the energy scale and resolution parameters. From these variations, we estimate the contribution due to uncertainties on the electron energy scale. The boson rapidity measurement is not sensitive to the energy resolution.

CTEQ6.1M PDFs are defined by twenty orthogonal parameters. Each parameter has an uncertainty which is shifted separately in the positive and negative direction to provide a set of forty PDFs for determination of the uncertainty. The acceptance is reevaluated with each PDF. Following the prescription presented in Ref. [14], we compare each acceptance to that obtained with the nominal PDF set. The differences are combined into a PDF uncertainty, with a distinction made for sets that
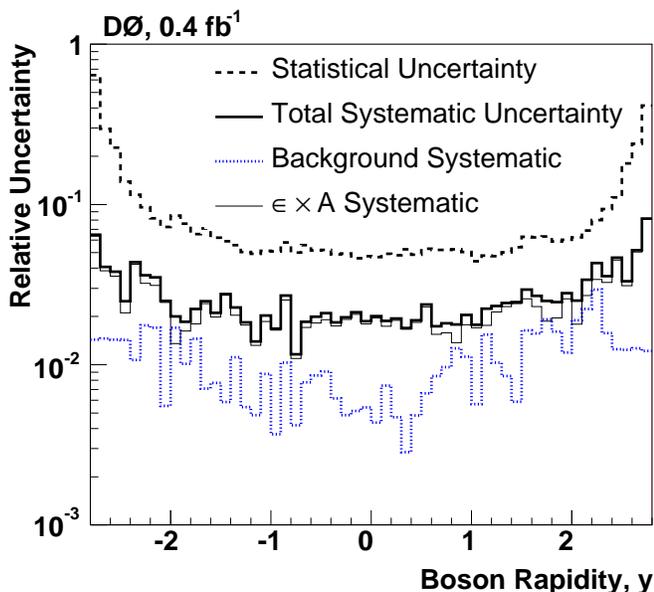
FIG. 2: Relative uncertainties plotted against the boson rapidity.



FIG. 3: DØ Run II measurement of $\frac{1}{\sigma} d\sigma/dy$ vs $y$. The inner (outer) error bars show the statistical (total) uncertainty.

increase or decrease the acceptance.

As mentioned above, the shape of the vertex $z$ distribution varies with time. The width of the distribution can depend on a number of factors. The beam tuning has changed this width over the course of Run II. Also, the time elapsed since beam injection can affect the width. Since the probability of an electron to have a track-match depends in part on the $z$ position of the primary vertex, knowledge of the vertex distribution can directly effect the acceptance correction. Samples of vertex $z$ distributions extracted from the data in blocks corresponding to different instantaneous luminosities are used to model the vertex distribution in the Monte Carlo simulation. Selection criteria that produce the widest and narrowest vertex distribution widths are used to estimate the systematic uncertainty.

The main contributions to the total systematic uncertainty depend on the boson rapidity. At small values of $|y|$, the main sources are the single electron efficiencies ($\approx 2\%$) and the vertex $z$ distribution ($< 1\%$). For midrange $|y|$, the largest contributions are due to the electron efficiencies and the background subtraction. The size of each is roughly 2%. In the high rapidity region, $|y| > 2$, the main sources are from the electron efficiencies, the background, and the PDFs. The combined uncertainty in this region ranges from 3% to 10% and increases with $|y|$. The relative total systematic uncertainty along with the contributions to the uncertainties from the background and the $\epsilon \times A$ are presented in Fig. 2. Contributions to the $\epsilon \times A$ uncertainty also are presented for each rapidity bin in Table II.

To cross check our result, we split the data into independent sets based on criteria that should not affect the result. These include dividing the data based upon
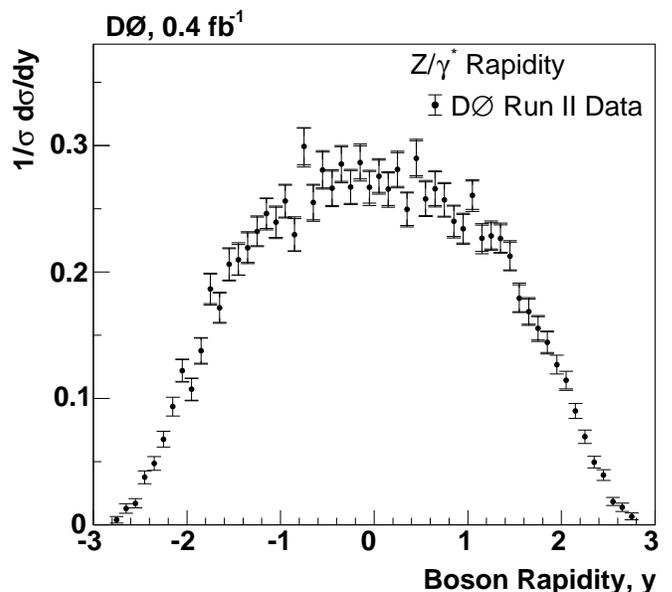
(a) time period for data collection, (b) different ranges of instantaneous luminosity, and (c) the calorimeter region in which the electrons are detected. Cross sections from independent subsets are compared to look for inconsistencies. Subsets in (a) are sensitive to hardware changes over the course of the data set and/or changes to the trigger menu used in collecting the data. Subsets in (b) have different vertex $z$ distributions and will not agree if the vertex distribution is modelled poorly. Subsets in group (c) compare data from three separate calorimeters. All of the cross checks give results that are consistent within uncertainties.

## V. RESULTS

A plot of $\frac{1}{\sigma} d\sigma/dy$ is given in Fig. 3 for $Z/\gamma^*$ events within a mass range of $71 < M_{ee} < 111$ GeV. The inner (outer) error bars show the statistical (total) uncertainty. In Fig. 4 the result is shown vs $|y|$. For bin centering we follow the prescription given in Ref. [16]. The center of the bin is located at the average value of the expected distribution over the bin. For this purpose we use the NNLO calculation generated from code made available from Ref. [1]. This is a small effect and for the two decimal places of precision used here, the procedure gives the same result as using the bin center. Due to the finite resolution of the D0 detector, some fraction of the events in a given rapidity bin originates from a neighboring bin. For this analysis, about 5% of the events migrate to each adjacent bin. Even though the effect is small, a migration correction is included in the $\epsilon \times A$ determination. The uncertainties in $\frac{1}{\sigma} d\sigma/dy$ are dominantly statistical for all measured rapidity bins.
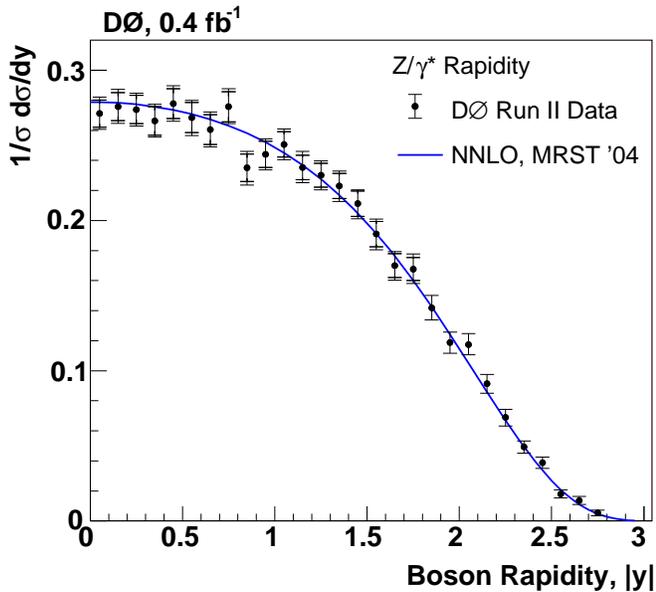
FIG. 4: DØ Run II measurement of $\frac{1}{\sigma}d\sigma/dy$ vs $|y|$. The inner (outer) error bars show the statistical (total) uncertainty. The curve is a NNLO calculation from [1] using MRST 2004 PDFs.

The values for the fraction of the cross section in each rapidity bin also are listed in Table I. No information on the bin-to-bin correlations is included in the table. Since the systematic uncertainty is small compared to the statistical uncertainty, a correlation matrix is not included. The curve in Fig. 4 is a NNLO calculation from Ref. [1] generated with MRST 2004 NNLO PDFs [17]. The calculation agrees well with our data, with a $\chi^2$/d.o.f. of 20.0/27. Our result improves upon previous measurements over the full range in $y$, especially in the forward region. Figure 5 shows the relative uncertainties from the most recent boson rapidity measurement [2] and from this analysis plotted vs $|y|$. For comparison purposes, Fig. 5 also includes the relative uncertainty due to PDFs for a NLO calculation of the differential cross section. This curve uses CTEQ6M uncertainty PDFs and code from Ref. [1]. The method is the same as that used for the determination of the PDF uncertainty on the $\epsilon \times A$ which was discussed earlier.

In summary, we have presented a measurement of $\frac{1}{\sigma}d\sigma/dy$ for $Z/\gamma^*$ measured with electron-positron events in the mass range $71 < M_{ee} < 111$ GeV. The measurement is the most precise measurement to date. It improves upon previous measurements and gives a significantly more precise measurement of the boson rapidity distribution in the high rapidity region which probes

the small $x$, high $Q^2$ portion of the parton distribution functions which is least constrained by other data. The fractional uncertainty in the highest rapidity bin is reduced by 30%. We find the result to be consistent with a recent NNLO calculation. The current measurement is performed with $(10–20)\%$ of the expected Run II integrated luminosity. An improved result is foreseen with
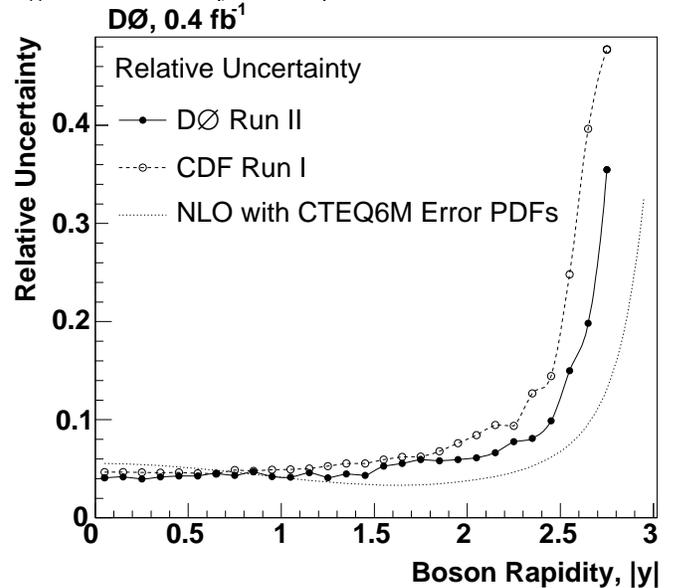


FIG. 5: Relative uncertainties from this measurement and from the CDF Run I result. Also shown is the PDF uncertainty on the differential cross section using the CTEQ6M uncertainty PDF sets. The values for the CTEQ6M curve are generated with code from Ref. [1].

the inclusion of additional data, which will reduce the current still-dominant statistical uncertainty.

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[5] In this note, electrons refers to both electrons and positrons.

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TABLE I: Summary of the measurement of $\frac{1}{\sigma}\frac{d\sigma}{dy}$ per rapidity bin for $Z/\gamma^* \to e^+e^-$ events with mass $71 < M_{ee} < 111$ GeV.

| $|y|$ | $\frac{1}{N} \times \frac{dN}{dy}$ $\pm$ stat. $\pm$ syst. | Candidate Events | Background Events | $\epsilon \times A$ |
|---|---|---|---|---|
| 0.05 | $0.271 \pm 0.009 \,^{+0.006}_{-0.005}$ | 961 | $21.8 \pm 2.5$ | $0.176 \,^{+0.005}_{-0.006}$ |
| 0.15 | $0.276 \pm 0.009 \,^{+0.007}_{-0.006}$ | 961 | $28.1 \pm 3.3$ | $0.172 \,^{+0.005}_{-0.006}$ |
| 0.25 | $0.274 \pm 0.009 \,^{+0.005}_{-0.005}$ | 924 | $29.0 \pm 2.1$ | $0.166 \,^{+0.004}_{-0.004}$ |
| 0.35 | $0.266 \pm 0.010 \,^{+0.006}_{-0.005}$ | 879 | $33.7 \pm 2.8$ | $0.161 \,^{+0.004}_{-0.005}$ |
| 0.45 | $0.278 \pm 0.010 \,^{+0.007}_{-0.006}$ | 898 | $37.5 \pm 3.7$ | $0.158 \,^{+0.004}_{-0.004}$ |
| 0.55 | $0.269 \pm 0.010 \,^{+0.006}_{-0.007}$ | 870 | $50.6 \pm 3.5$ | $0.155 \,^{+0.005}_{-0.003}$ |
| 0.65 | $0.260 \pm 0.010 \,^{+0.006}_{-0.006}$ | 882 | $71.3 \pm 3.7$ | $0.159 \,^{+0.004}_{-0.004}$ |
| 0.75 | $0.276 \pm 0.010 \,^{+0.007}_{-0.005}$ | 967 | $74.4 \pm 4.2$ | $0.164 \,^{+0.003}_{-0.005}$ |
| 0.85 | $0.235 \pm 0.009 \,^{+0.006}_{-0.007}$ | 895 | $88.9 \pm 5.6$ | $0.175 \,^{+0.005}_{-0.004}$ |
| 0.95 | $0.244 \pm 0.009 \,^{+0.005}_{-0.006}$ | 988 | $79.0 \pm 5.4$ | $0.190 \,^{+0.005}_{-0.004}$ |
| 1.05 | $0.251 \pm 0.008 \,^{+0.006}_{-0.006}$ | 1095 | $75.2 \pm 3.8$ | $0.207 \,^{+0.005}_{-0.006}$ |
| 1.15 | $0.235 \pm 0.008 \,^{+0.007}_{-0.006}$ | 1106 | $98.0 \pm 8.2$ | $0.218 \,^{+0.005}_{-0.007}$ |
| 1.25 | $0.230 \pm 0.008 \,^{+0.005}_{-0.006}$ | 1060 | $83.7 \pm 5.5$ | $0.216 \,^{+0.006}_{-0.005}$ |
| 1.35 | $0.223 \pm 0.008 \,^{+0.005}_{-0.006}$ | 965 | $94.6 \pm 4.3$ | $0.199 \,^{+0.006}_{-0.005}$ |
| 1.45 | $0.211 \pm 0.008 \,^{+0.004}_{-0.005}$ | 793 | $60.0 \pm 2.4$ | $0.177 \,^{+0.006}_{-0.003}$ |
| 1.55 | $0.191 \pm 0.008 \,^{+0.005}_{-0.006}$ | 694 | $69.5 \pm 5.4$ | $0.167 \,^{+0.005}_{-0.004}$ |
| 1.65 | $0.170 \pm 0.008 \,^{+0.005}_{-0.005}$ | 644 | $72.4 \pm 5.1$ | $0.171 \,^{+0.006}_{-0.005}$ |
| 1.75 | $0.168 \pm 0.008 \,^{+0.006}_{-0.006}$ | 689 | $79.5 \pm 6.3$ | $0.185 \,^{+0.005}_{-0.006}$ |
| 1.85 | $0.142 \pm 0.007 \,^{+0.005}_{-0.004}$ | 614 | $57.3 \pm 5.4$ | $0.200 \,^{+0.005}_{-0.007}$ |
| 1.95 | $0.119 \pm 0.006 \,^{+0.004}_{-0.004}$ | 559 | $55.5 \pm 3.9$ | $0.216 \,^{+0.006}_{-0.006}$ |
| 2.05 | $0.117 \pm 0.006 \,^{+0.005}_{-0.004}$ | 551 | $37.3 \pm 5.7$ | $0.223 \,^{+0.007}_{-0.009}$ |
| 2.15 | $0.091 \pm 0.005 \,^{+0.004}_{-0.004}$ | 459 | $36.4 \pm 5.6$ | $0.235 \,^{+0.010}_{-0.007}$ |
| 2.25 | $0.069 \pm 0.004 \,^{+0.003}_{-0.004}$ | 352 | $33.2 \pm 5.7$ | $0.236 \,^{+0.011}_{-0.008}$ |
| 2.35 | $0.049 \pm 0.004 \,^{+0.002}_{-0.002}$ | 232 | $15.4 \pm 2.1$ | $0.224 \,^{+0.012}_{-0.008}$ |
| 2.45 | $0.039 \pm 0.003 \,^{+0.002}_{-0.002}$ | 162 | $10.4 \pm 1.1$ | $0.199 \,^{+0.010}_{-0.012}$ |
| 2.55 | $0.018 \pm 0.003 \,^{+0.001}_{-0.001}$ | 61 | $3.9 \pm 0.4$ | $0.162 \,^{+0.008}_{-0.011}$ |
| 2.65 | $0.014 \pm 0.003 \,^{+0.001}_{-0.001}$ | 35 | $2.2 \pm 0.2$ | $0.123 \,^{+0.008}_{-0.012}$ |
| 2.75 | $0.005 \pm 0.002 \,^{+0.0004}_{-0.0004}$ | 10 | $0.6 \pm 0.1$ | $0.085 \,^{+0.009}_{-0.008}$ |

TABLE II: Contributions to the systematic uncertainty for $\epsilon \times A$ are shown in bins of $|y|$. Details of the contributions are described in the text.

| $|y|$ | $\epsilon \times A$ | $\delta$(total) | $\delta$ ($e^-$ eff.) stat. | method | $\delta$(PDF) | $\delta$($E$ scale) | $\delta$(vtx $z$) |
|---|---|---|---|---|---|---|---|
| 0.05 | 0.176 | $^{+0.005}_{-0.006}$ | $\pm 0.0004$ | $^{+0.004}_{-0.004}$ | $^{+0.002}_{-0.002}$ | $^{+0.0009}_{-0.0002}$ | $^{+0.0016}_{-0.0034}$ |
| 0.15 | 0.172 | $^{+0.005}_{-0.006}$ | $\pm 0.0004$ | $^{+0.004}_{-0.004}$ | $^{+0.002}_{-0.002}$ | $^{+0.0010}_{-0.0006}$ | $^{+0.0015}_{-0.0033}$ |
| 0.25 | 0.166 | $^{+0.004}_{-0.004}$ | $\pm 0.0004$ | $^{+0.004}_{-0.004}$ | $^{+0.002}_{-0.001}$ | $^{+0.0007}_{-0.0011}$ | $^{+0.0012}_{-0.0018}$ |
| 0.35 | 0.161 | $^{+0.004}_{-0.005}$ | $\pm 0.0004$ | $^{+0.003}_{-0.004}$ | $^{+0.002}_{-0.003}$ | $^{+0.0002}_{-0.0004}$ | $^{+0.0012}_{-0.0017}$ |
| 0.45 | 0.158 | $^{+0.004}_{-0.004}$ | $\pm 0.0004$ | $^{+0.003}_{-0.003}$ | $^{+0.002}_{-0.003}$ | $^{+0.0006}_{-0.0002}$ | $^{+0.0017}_{-0.0003}$ |
| 0.55 | 0.155 | $^{+0.005}_{-0.003}$ | $\pm 0.0004$ | $^{+0.003}_{-0.003}$ | $^{+0.002}_{-0.002}$ | $^{+0.0015}_{-0.0007}$ | $^{+0.0017}_{-0.0002}$ |
| 0.65 | 0.159 | $^{+0.004}_{-0.004}$ | $\pm 0.0004$ | $^{+0.003}_{-0.004}$ | $^{+0.002}_{-0.002}$ | $^{+0.0013}_{-0.0002}$ | $^{+0.0007}_{-0.0013}$ |
| 0.75 | 0.164 | $^{+0.003}_{-0.005}$ | $\pm 0.0004$ | $^{+0.003}_{-0.003}$ | $^{+0.001}_{-0.003}$ | $^{+0.0011}_{-0.0003}$ | $^{+0.0007}_{-0.0013}$ |
| 0.85 | 0.175 | $^{+0.005}_{-0.004}$ | $\pm 0.0004$ | $^{+0.003}_{-0.004}$ | $^{+0.004}_{-0.001}$ | $^{+0.0013}_{-0.0004}$ | $^{+0.0008}_{-0.0004}$ |
| 0.95 | 0.190 | $^{+0.005}_{-0.004}$ | $\pm 0.0004$ | $^{+0.003}_{-0.004}$ | $^{+0.003}_{-0.001}$ | $^{+0.0002}_{-0.0013}$ | $^{+0.0008}_{-0.0005}$ |
| 1.05 | 0.207 | $^{+0.005}_{-0.006}$ | $\pm 0.0004$ | $^{+0.004}_{-0.004}$ | $^{+0.002}_{-0.003}$ | $^{+0.0007}_{-0.0005}$ | $^{+0.0022}_{-0.0035}$ |
| 1.15 | 0.218 | $^{+0.005}_{-0.007}$ | $\pm 0.0004$ | $^{+0.003}_{-0.005}$ | $^{+0.002}_{-0.003}$ | $^{+0.0014}_{-0.0005}$ | $^{+0.0023}_{-0.0036}$ |
| 1.25 | 0.216 | $^{+0.006}_{-0.005}$ | $\pm 0.0004$ | $^{+0.004}_{-0.004}$ | $^{+0.003}_{-0.001}$ | $^{+0.0013}_{-0.0004}$ | $^{+0.0024}_{-0.0030}$ |
| 1.35 | 0.199 | $^{+0.006}_{-0.005}$ | $\pm 0.0004$ | $^{+0.004}_{-0.003}$ | $^{+0.004}_{-0.002}$ | $^{+0.0008}_{-0.0004}$ | $^{+0.0022}_{-0.0028}$ |
| 1.45 | 0.177 | $^{+0.006}_{-0.003}$ | $\pm 0.0004$ | $^{+0.005}_{-0.003}$ | $^{+0.003}_{-0.002}$ | $^{+0.0004}_{-0.0009}$ | $^{+0.0017}_{-0.0007}$ |
| 1.55 | 0.167 | $^{+0.005}_{-0.004}$ | $\pm 0.0004$ | $^{+0.005}_{-0.003}$ | $^{+0.002}_{-0.002}$ | $^{+0.0012}_{-0.0009}$ | $^{+0.0016}_{-0.0006}$ |
| 1.65 | 0.171 | $^{+0.006}_{-0.005}$ | $\pm 0.0005$ | $^{+0.004}_{-0.002}$ | $^{+0.003}_{-0.002}$ | $^{+0.0013}_{-0.0007}$ | $^{+0.0008}_{-0.0036}$ |
| 1.75 | 0.185 | $^{+0.005}_{-0.006}$ | $\pm 0.0005$ | $^{+0.003}_{-0.004}$ | $^{+0.004}_{-0.002}$ | $^{+0.0009}_{-0.0006}$ | $^{+0.0009}_{-0.0039}$ |
| 1.85 | 0.200 | $^{+0.005}_{-0.007}$ | $\pm 0.0006$ | $^{+0.002}_{-0.006}$ | $^{+0.003}_{-0.003}$ | $^{+0.0015}_{-0.0008}$ | $^{+0.0030}_{-0.0027}$ |
| 1.95 | 0.216 | $^{+0.006}_{-0.006}$ | $\pm 0.0006$ | $^{+0.004}_{-0.004}$ | $^{+0.003}_{-0.004}$ | $^{+0.0010}_{-0.0001}$ | $^{+0.0032}_{-0.0029}$ |
| 2.05 | 0.223 | $^{+0.007}_{-0.009}$ | $\pm 0.0008$ | $^{+0.004}_{-0.005}$ | $^{+0.004}_{-0.006}$ | $^{+0.0026}_{-0.0002}$ | $^{+0.0024}_{-0.0049}$ |
| 2.15 | 0.235 | $^{+0.010}_{-0.007}$ | $\pm 0.0009$ | $^{+0.006}_{-0.004}$ | $^{+0.007}_{-0.003}$ | $^{+0.0012}_{-0.0013}$ | $^{+0.0025}_{-0.0051}$ |
| 2.25 | 0.236 | $^{+0.011}_{-0.008}$ | $\pm 0.0010$ | $^{+0.008}_{-0.005}$ | $^{+0.005}_{-0.004}$ | $^{+0.0011}_{-0.0014}$ | $^{+0.0055}_{-0.0035}$ |
| 2.35 | 0.224 | $^{+0.012}_{-0.008}$ | $\pm 0.0013$ | $^{+0.008}_{-0.006}$ | $^{+0.007}_{-0.003}$ | $^{+0.0010}_{-0.0019}$ | $^{+0.0052}_{-0.0033}$ |
| 2.45 | 0.199 | $^{+0.010}_{-0.012}$ | $\pm 0.0017$ | $^{+0.004}_{-0.007}$ | $^{+0.008}_{-0.010}$ | $^{+0.0028}_{-0.0000}$ | $^{+0.0028}_{-0.0006}$ |
| 2.55 | 0.162 | $^{+0.008}_{-0.011}$ | $\pm 0.0016$ | $^{+0.005}_{-0.007}$ | $^{+0.005}_{-0.007}$ | $^{+0.0017}_{-0.0031}$ | $^{+0.0022}_{-0.0005}$ |
| 2.65 | 0.123 | $^{+0.008}_{-0.012}$ | $\pm 0.0015$ | $^{+0.004}_{-0.006}$ | $^{+0.005}_{-0.008}$ | $^{+0.0019}_{-0.0044}$ | $^{+0.0038}_{-0.0043}$ |
| 2.75 | 0.085 | $^{+0.009}_{-0.008}$ | $\pm 0.0015$ | $^{+0.002}_{-0.006}$ | $^{+0.006}_{-0.005}$ | $^{+0.0048}_{-0.0008}$ | $^{+0.0026}_{-0.0029}$ |