Study of the $Z \rightarrow ee$ differential cross section as a function of $Z$ rapidity at $\sqrt{s} = 10$ TeV

The CMS Collaboration

Abstract

We present estimates for the measurement of the shape of the rapidity distribution for $Z$ bosons produced in proton-proton collisions with the CMS detector at $\sqrt{s}$ of 10 TeV. We consider integrated luminosity scenarios from 10 to 100 pb$^{-1}$. The results of this measurement will provide input to constrain the parton density function of the proton at the LHC for many measurements and searches.
1 Introduction

We report on the expected sensitivity of the measurement of the shape of the rapidity distribution for Z bosons produced at the LHC and decaying to electron-positron pairs recorded by the CMS detector. This measurement provides constraints on the parton density functions at $\sqrt{s}$ of 10 TeV which are independent of jet measurement effects and which can be directly compared to similar measurements performed using Tevatron collisions at center-of-mass energies of 2 TeV[1] and 1.8 TeV[2].

This measurement is performed by evaluating the following expression for each bin $i$ of the rapidity ($Y \equiv \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$) distribution:

$$\frac{1}{\sigma} \frac{d\sigma(Z \to e^+e^-)}{dY_i} = \frac{(\epsilon \times A)}{N - B} \cdot \frac{N_i - B_i}{\Delta_i(\epsilon \times A_i)}$$

In this expression, $N_i$ is the number of Z candidates observed in data, $B_i$ is the estimated number of background candidates, $\Delta_i$ is the bin width, and $(\epsilon \times A_i)$ is the product of the efficiency and acceptance for detecting and fully reconstructing a Z boson with a rapidity within the $Y_i$ bin.

The $(\epsilon \times A)$ is determined using efficiencies for single electron reconstruction and identification which are evaluated from data. These efficiencies are determined using tag-and-probe techniques applied to Z boson decays. The individual electron efficiencies are convolved using fast Monte Carlo techniques to determine the total $(\epsilon \times A)$ for the Z as a function of boson rapidity.

2 Monte Carlo Data Samples

The signal $pp \to Z/\gamma^* + X \to e^+e^- + X$ Monte Carlo simulation used in this study used the Pythia 6 [3] event generator. The CTEQ6L1[4] parton distribution functions are used to describe the momenta of the partons in the colliding protons.

We studied the following simulated datasets to investigate the Standard Model backgrounds for this analysis:

- $W \to e\nu$ events.
- $\gamma + \text{jets}$ events, with photon transverse momentum $> 15$ GeV/c.
- $Z \to \tau\tau + \text{jets}$ events.
- $t\bar{t}$ events.
- QCD dijets were simulated by combining two samples which enriched the electromagnetic content of the event to enhance the possibility of generating a fake electron. The first sample includes events where a b or c quark decays to an electron/neutrino pair while the second contains events in which relatively-isolated energetic electromagnetic particles are required at generator level. The two samples were defined in a mutually exclusive manner.

All background events were produced using the Pythia 6 event generator as well.
3 Event Selection

All the $Z \rightarrow e^+e^-$ decays are selected from the events which pass the loosely isolated single electron High Level Trigger (HLT) which has a transverse energy threshold of 15 GeV. In the selected $Z$ decays, one electron is required to be within the tracking region with requirements of isolation, electron cluster shape, and track matching. The second electron is either an electron in the joint acceptance of the crystal calorimeter and the tracker, or in the forward calorimeter (HF). All lepton pairs, whether used for background subtraction or for signal, are required to have $50 \text{ GeV}/c^2 < M_{ee} < 150 \text{ GeV}/c^2$. The mass window for the signal is $70 \text{ GeV}/c^2 < M_{ee} < 110 \text{ GeV}/c^2$. For analysis purposes, the detector acceptance is defined as given in Table 1.

<table>
<thead>
<tr>
<th>$\eta_d$ min</th>
<th>$\eta_d$ max</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.018</td>
<td>0.423</td>
<td>ECAL Barrel Module 1</td>
</tr>
<tr>
<td>0.461</td>
<td>0.770</td>
<td>ECAL Barrel Module 2</td>
</tr>
<tr>
<td>0.806</td>
<td>1.127</td>
<td>ECAL Barrel Module 3</td>
</tr>
<tr>
<td>1.163</td>
<td>1.460</td>
<td>ECAL Barrel Module 4</td>
</tr>
<tr>
<td>1.558</td>
<td>2.48</td>
<td>ECAL Endcap with Tracker coverage</td>
</tr>
<tr>
<td>3.1</td>
<td>4.6</td>
<td>HF (no Tracker)</td>
</tr>
</tbody>
</table>

Since the electrons from the $Z$ decays are isolated from the rest of the particles in the event, strict isolation in the tracker, ECAL, and HCAL is used to reject fake electrons from hadronic jets. The isolation is performed by summing the total transverse momentum in tracks or hits with a within a larger cone but excluding tracks or ECAL hits within an inner region or with very low momentum.

In addition to the isolation requirements, we use the $\eta$ covariance of the energy deposited in ECAL and the difference between the angular positions at the vertex (from the tracker) extrapolated to the ECAL and that measured using the ECAL data to help reject jet backgrounds. Fake electrons from jets will generally have both neutral and charged components and the shower shape will be wider than for an electron and the actual position at ECAL will differ from that predicted by track at the vertex.

The electrons in HF are reconstructed by taking advantage of the two sets of measurements made in each tower[5]. Each tower in the HF is read out by two set of fibers, one which reads the full depth of the calorimeter (the long fibers) and one which reads only the deeper portion of the absorber (the short fibers). This arrangement was made to flatten the jet response of HF between hadrons and electromagnetic particles, but as the channels are read out separately we are able to use these variables for identification. Electromagnetic showers will have lost most of their energy before reaching the short fibers, while hadrons will have nearly the same response in both channels.

Electrons within the HF are clustered using $3 \times 3 \eta \times \phi$ clusters seeded by high-$E_T$ towers. For the purposes of identification, the cluster software defines the cluster core as the seed tower plus the highest $E_T$ neighboring tower, provided it has at least half the $E_T$ of the seed. Shape variables are calculated for each cluster, including the ratio of the transverse energy in the 5x5 towers containing the cluster to the cluster itself. The primary identification variables used are the ratio of the $E_T$ of the cluster core to the $E_T$ of the cluster (a transverse shower variable) and the ratio of the cluster $E_T$ in the short fibers to the $E_T$ in the long fibers (a longitudinal variable).

The selection criteria are highly effective in removing background from the sample while retaining the $Z$ events. All electron candidates in the final sample must pass the full set of iden-
tification and isolation requirements appropriate to the section of the detector involved. The events which include HF, with the associated lack of tracker coverage, can be expected to have different background and signal mass resolution, so we consider ECAL-ECAL and ECAL-HF events separately in the analysis. Any event can be only one of the two and ECAL-ECAL is given priority, since this channel has the smaller backgrounds. A full breakdown of the events by type after selection is given in Table 2.

Table 2: Numbers of signal and background events selected by the ECAL-ECAL and ECAL-HF signal definitions after all requirements for 100pb\(^{-1}\) of integrated luminosity. Errors on the background events are determined by the number of simulated events available.

<table>
<thead>
<tr>
<th>Sample</th>
<th>ECAL-ECAL</th>
<th>ECAL-HF</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD dijets, 20 &lt; p(_T) &lt; 170 GeV</td>
<td>24.2 ± 17.1</td>
<td>487.7 ± 76.3</td>
</tr>
<tr>
<td>tt</td>
<td>33.0 ± 3.3</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>Z → (\tau\tau)</td>
<td>9.0 ± 1.0</td>
<td>1.2 ± 0.4</td>
</tr>
<tr>
<td>W → eν</td>
<td>37.4 ± 6.8</td>
<td>54.8 ± 8.3</td>
</tr>
<tr>
<td>(\gamma) +jets, p(_T) &gt; 15 GeV</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>Total Background</td>
<td>103.6 ± 18.7</td>
<td>544.7 ± 76.5</td>
</tr>
<tr>
<td>Signal</td>
<td>32500</td>
<td>6283</td>
</tr>
</tbody>
</table>

4 Determination of Single Electron Efficiencies

The efficiency for reconstructing an electron is partitioned into several contributions which are measured separately and in sequence using the tag-and-probe technique from data. For electrons reconstructed in the crystal calorimeter within tracker acceptance, we define four sequential terms in the offline efficiency. The first step starts with superclusters, which are then matched to tracks.

\[
\epsilon_{\text{offline}} = \frac{N(\text{Superclusters})}{N(\text{Electrons})} \times \frac{N(\text{Track matched})}{N(\text{Superclusters})} \times \frac{N(\text{Isolated})}{N(\text{Track matched})} \times \frac{N(\text{Electron Id})}{N(\text{Isolated})} \tag{2}
\]

The trigger used for this measurement is a single electron trigger. This trigger is confined to the crystal calorimeter and is determined with respect to the offline efficiencies.

\[
\epsilon_{\text{full}} = \epsilon_{\text{offline}} \times \frac{N(L1 + HLT)}{N(\text{offline})} \tag{3}
\]

In the case of forward electrons (in the HF), no tracking is available and the efficiency becomes:

\[
\epsilon_{\text{hf}} = \frac{N(\text{HF Clusters})}{N(\text{Electrons})} \times \frac{N(\text{HF Electron Identification})}{N(\text{HF Clusters})} \tag{4}
\]

The efficiencies for the individual selection criteria and the trigger are determined from data using the “tag-and-probe” method. The method relies on a sample of Z → e\(^+\)e\(^-\) decays, similar to the analysis sample and containing many of the same events. One electron, the “tag,” must pass strict identification requirements, and also be associated with a single electron trigger. The tag electron is combined with a “probe” electron, whose definition depends on
Determination of the Efficiency \times Acceptance

For the purposes of this analysis, it is necessary to bin the efficiencies in variables which may depend on the rapidity of the Z. The most important variables for the binning of the efficiency are the electron’s polar location with in the detector ($\eta_d$) and its transverse momentum ($p_T$). Single electron efficiencies were measured in bins of these variables. Most efficiencies were binned in a single dimension using the variable on which the efficiency has the strongest dependence. The $p_T$ was selected for the isolation efficiency separately for the ECAL Barrel (EB) and Endcap (EE) and $\eta_d$ was chosen for the electron identification and trigger efficiencies. The supercluster creation and track matching efficiencies evidenced non-trivial dependency on both $p_T$ and $\eta_d$, so two-dimensional binning was performed.

5 Determination of the Efficiency \times Acceptance

The individual electron efficiencies, which are determined as functions of detector space and electron transverse momentum, must be combined to determine the total efficiency as a function of Z-boson rapidity. The $(e \times A)$ for each bin of rapidity is determined by applying the measured electron efficiencies to Monte Carlo events generated by Pythia and smeared using a fast simulation package tuned to the detector resolutions using Z peak data. This process is effectively a Monte Carlo evaluation of the $P(\eta_d, p_T; Y)$ which includes the effect of acceptance. The $e_e(\eta_d, p_T)$ function represents the total efficiency for an electron with the given detector position and momentum.

The final $(e \times A)$ is shown in Figure 1. The effect of each of the various selection requirements on the analysis can be seen in Figure 1(a), while the contribution to the final $(e \times A)$ from the two separate Z definitions (ECAL-ECAL and ECAL-HF) can be seen in Figure 1(b) along with the predicted shape of the rapidity distribution. The inclusion of the HF electrons in this analysis clearly expands the acceptance for this measurement very significantly and future work to include ECAL electrons which are outside the tracker coverage should allow for even higher acceptances in the region around $|Y| = 2.5$.

Besides the $(e \times A)$ distribution, the convolution process generates distributions of kinematic variables of the individual leptons as well as the dilepton mass distribution and the transverse momentum of the dilepton system. These distributions have the effects of electron efficiency and acceptance applied to them and thus should be directly comparable to the full Monte Carlo and, when data are available, to the data. The comparison validates the convolution process, showing that it produces distributions which agree in multiple variables besides the core rapidity distribution.
Figure 1: The \((\epsilon \times A)\) for the signal as determined by convolving the single electron efficiencies using the Monte Carlo distributions for Z electrons.
6 Evaluation of Systematic Error Contributions

The systematic uncertainties in this measurement arise from the individual efficiencies used in the \((\epsilon \times A)\) calculation as well as from uncertainties and potential miscalibrations in the Monte Carlo used for the calculation. The effect of each of these uncertainties is propagated to the \((\epsilon \times A)\) curve. Uncertainties related to the background subtraction are considered as well.

6.1 Error Contributions from Single-Electron Efficiencies

The statistical uncertainties from the finite numbers of events available for the efficiency determinations are propagated through the \((\epsilon \times A)\) calculation. Using the information gathered in the tag-and-probe process, we create pseudoexperiments which use different efficiency distributions. Each bin of a single electron efficiency is defined by a numerator \(n\) (number of electrons which passed the identification requirement) and denominator \(d\) (number of electrons which were considered). These parameters form a binomial distribution. Accordingly, we sample the binomial probability function to create each bin of efficiency for each pseudoexperiment. For each pseudoexperiment, the \((\epsilon \times A)\) is recalculated and normalized by \((\epsilon \times A)\). The process is repeated several hundred times to determine the effect of the statistical uncertainties on the final \((\epsilon \times A)\). The results are shown in Fig. 2 for the nominal 100 pb\(^{-1}\) of luminosity.

6.2 Parton Density Function Uncertainties

This analysis measurement is sensitive to parton density functions (PDFs). To better illustrate contributions due to PDFs in this analysis, we rearrange terms of the Eq. 1, and rewrite it as Eq. 6:

\[
\frac{1}{\sigma} \frac{d\sigma(Z \rightarrow e^+e^-)}{dY_i} = \left[ \frac{N_i - B_i}{N - B} \right] \cdot \frac{(\epsilon \times A)}{\Delta_i(\epsilon \times A)} \tag{6}
\]

Differences coming from the parton density functions which are measurable by this analysis will result in a change in the distribution of the \(N_i/N\) term of Eq. 6. However, variation in the parton density functions might also affect the \((\epsilon \times A)\) distribution. Such an effect would be model-dependent and could act to exaggerate or even cancel the PDF sensitivity. We therefore evaluate the systematic uncertainty arising from the variation of \((\epsilon \times A)\) with PDF variation by using the Next-to-Leading Order (NLO) accuracy generator POWHEG\([6]\) and the CTEQ6.5 PDF set\([8]\).

For each PDF variation, we generated ten million events of \(pp \rightarrow Z + X \rightarrow e^+e^- + X\) with \(\sqrt{s}\) of 10 TeV. Simultaneously, the reweighting method \([9]\) was used to obtain event weights for every other PDF in the set, providing us with 400 million events for each PDF variation. Samples were then passed through the analysis steps described in previous sections. Values of \((\epsilon \times A)\) as function of \(Z\) boson rapidity were obtained for each of 40 PDF variations.

For each PDF, a fractional difference was calculated for each bin from the median value for the bin. The fractional difference is shown in Figure 3. Contributions of the fractional differences were added in quadrature into a cumulative fractional difference. Positive and negative cumulative fractional differences are separately combined. In the central rapidity region this difference is on the order of 0.1 percent, while this effect becomes only slightly larger towards highest \(|Y|\) values.
6.3 Final State Radiation and Other Sources of Bin Migration

When a final state radiation photon is radiated at a large angle from the electron and falls outside its cluster, the rapidity of the reconstructed Z can be altered. Several detector effects can also alter the reconstructed Z rapidity, such as: the emission of the bremsstrahlung photons, the energy loss in the tracker, the intrinsic resolution of the energy measurement and of the tracker position measurement. Such effects can alter the rapidity spectrum by letting events migrate across the bins which were defined in Equation 1.

The impact of the bin migration on the measurement has been quantified using Monte Carlo samples to estimate the effect of final state radiation and the detector resolution. The migration matrix was constructed by comparing the true rapidity of the Z to that of the reconstructed Z. The matrix thus represents a set of probabilities for an event with a given tree-level rapidity to end up in the same or a different rapidity bin after all effects have been taken into account.

The actual impact on the final measurement is quantified by the difference, bin by bin, between the true Z rapidity spectrum and the Z rapidity spectrum obtained from the smeared electrons. Given the Poisson nature of the bin migration, one also wants to determine the significance of the expected migration effect compared to the statistical fluctuations which the effect will undergo with a given available integrated luminosity. Using the information of the migration matrix, we created pseudoexperiments implementing the random migration in and out of each rapidity bin, and determined the resulting content of each bin. We determined that the migration effect is limited to a few per cent in most of the rapidity range and, for 100 pb$^{-1}$, is comparable to its statistical uncertainty. Therefore we proceed by including the migration as contribution to the total uncertainty of the measurement, without trying to de-convolve it from the result.

6.4 Background Subtraction

Events with no real $Z \rightarrow e^+e^-$ decay which pass the selection criteria described earlier may alter the appearance of the reconstructed rapidity distribution of the Z boson. In addition to background events that contain at least one real high $p_T$ isolated electron, QCD processes may also generate electron signatures. Signal contamination from QCD background events is especially troublesome at large absolute rapidity, shown in Figure 4, where lack of tracker coverage reduces the ability to separate Z electrons from background.

We remove QCD and other background processes using the following data-driven technique using a fit to the dielectron mass distribution for events that pass our event selection. We assume that the background dielectron mass distribution will be featureless in our fit region, and take an exponential function to describe the shape. We model the signal $Z \rightarrow e^+e^-$ distribution with a Breit-Wigner convolved with a Gaussian (a combination also called a Voigtian). The opening angle between the candidate Z electrons modifies the shape of the background distribution below 70 GeV/c$^2$ so we take our fit region to be $70 < m_{ee} < 150$ GeV/c$^2$. The fit is performed separately for the ECAL-ECAL and ECAL-HF samples and combined for those bins which have contributions from both. Due to the small level of background expected, we combine bins of Z rapidity ($|Y|$) to increase the stability of the fit process. For HF-ECAL, we combine bins with the same $|Y|$ values, while for the ECAL-ECAL case, we fit the full $Y$ range and apply the result as a uniformly distributed background estimate.

This background estimation technique is data-driven, but we can validate this method using the available signal and background Monte Carlo samples. For each background fit, we create a data-like background dilepton mass distribution using the available Monte Carlo background
samples. We obtain the shape of the mass distribution by inverting the isolation and identification requirements on the background events, as these requirements have no effect on the shape in the fit region within the statistical accuracy of the background. None of the signal events pass after the cut inversion, which suggests this technique will be useful to help understand the background shape in data as well. This shape is then normalized to the number of properly weighted background events (from all available samples) present after the standard event selection in a given region of rapidity. The “expected” background distribution used for a given fit is then built bin by bin based on Poisson statistics and the number of events observed in the normalized background distribution.

We use our background distributions derived from this process to validate our data-driven treatment of the $Z \rightarrow e^+e^-$ background. For each fit bin, we combine the signal with our “expected” background and fit the distribution to the sum of a Voigtian and an exponential, allowing all parameters to float in the fit. The results of the fits for a representative selection of rapidity bins are shown in Figure 5. The expected background as estimated by the fit to the mass distribution is in reasonable agreement with the actual background levels.

There is a systematic uncertainty that arises from our assumption that an exponential function accurately describes the $Z \rightarrow e^+e^-$ background. To test our sensitivity to our choice of the background lineshape, we repeated the background estimation with the assumption that our background distribution could be described by a first order polynomial. For each fit bin we repeated our estimation of the background events in the signal region, and took the absolute difference between the results for a linear and an exponential background model as the systematic uncertainty associated with the background lineshape. A study of fit performance using toy Monte Carlo signal and background distributions validates the uncertainties assigned from the fit comparison.

Background in the HF from beam is expected to be at high $\eta$ values, most of which will fall beyond our acceptance value of $\eta = 4.6$. Tightening of this acceptance is possible to increase background exclusion with some loss in signal at the extremes of $|Y|$. In the presence of enhanced background, tightening the requirements on the ECAL should provide an efficient veto of background, while additional tightening of the HF electron ID requirements is also an option. Beam halo muons can also cause individual phototubes in HF to fire, somewhat mimicking electron behavior. The HCAL group has worked to identify such events and they can be excluded from the accepted HF candidates.

7 Results

The final result of the measurement for an integrated luminosity of 100 pb$^{-1}$ is shown in Figure 6 including the raw “data” distribution, the background-subtracted “data” distribution, and the final distribution after the application of the $(\epsilon \times A)$ . The distribution and relative importance of the various sources of uncertainty can be seen in Figure 7. The results at 100 pb$^{-1}$ emphasize the importance of background control in the HF region as well as the potential importance of including electrons from the crystal calorimeter from beyond the tracker acceptance. The final optimization of identification requirements for the ECAL-HF case will be driven by data as soon as it becomes available.

Since the underlying physics of the Z rapidity distribution is not expected to have dependence on the sign of the rapidity, we can fold the result around $|Y| = 0$. This process yields the results as shown in Figure 8 and tabulated in Table 3. These results include the full shape normalization, including the cancellation of the total cross-section. The detailed breakdown
of the fractional systematic error by bin in the folded distribution is given in Table 4. We also show results for an smaller data sample (10 pb\(^{-1}\)) in Fig. 10. These results indicate that a first observation of the Z rapidity shape becomes possible quite soon after start-up.

The utility of these measurements for setting constraints on the parton density functions can be seen in Figure 9 which shows the shape variation for the same set of CTEQ6.5 parton density functions used in Section 6.2 to determine the \((e \times A)\) uncertainty arising from the PDFs. The precision of the measurement with 100 \(\text{pb}^{-1}\) will be sufficient to begin to constrain the PDFs significantly at LHC energies. For comparison, the change in the result expected for a one sigma positive variation of one of the CTEQ PDF vectors (vector 13 [8]) is shown in red in Figure 8. While the full PDF analysis requires a combination of these results with all other results used for PDF fits, a simple \(\chi^2\) comparison of the base and the PDF variation with the data indicates a preference of the data for the base with a \(\Delta \chi^2 = 9.8\). If the comparison is done for \(|Y| \leq 3.0\) to avoid bins where the predicted bin migration is larger than 1%, the preference is \(\Delta \chi^2 = 7.4\), indicating a shape difference which persists over many bins.

References

[1] V. M. Abazov et al. [D0 Collaboration],
"Measurement of the shape of the boson rapidity distribution for p anti-p \(\rightarrow\) Z / gamma* \(\rightarrow\) e+ e- + X events produced at \(\sqrt{s}\) of 1.96-TeV,"

[2] A. A. Affolder et al. [CDF Collaboration],
"Measurement of d(\sigma)/dy for high mass Drell-Yan e+e- pairs from p\bar{p} collisions at \(\sqrt{s} =\) 1.8 TeV,"


"CTEQ6 parton distributions with heavy quark mass effects,"

Design, Performance and Calibration of CMS Forward Calorimeter Wedges,


Figure 2: Systematic errors on the $(\epsilon \times A)$ which are generated from the statistical uncertainties of the individual electron efficiencies, for the case of 100 pb$^{-1}$ of luminosity.

Table 3: The final result of the rapidity distribution measurement as a function of the absolute value of Z rapidity, giving the statistical and systematic errors for each bin.
Figure 3: Fractional difference of PDFs $\epsilon \times A$ from median $\epsilon \times A$, as a function of Z boson’s rapidity, individual and combined. Statistical error of MC is shown for reference.

Figure 4: The dielectron rapidity and mass distributions for background events passing the event selection criteria described in the note, with $50 < M_{ee} < 150$ GeV/c$^2$. The events have normalized to an integrated luminosity of 100 pb$^{-1}$.
Figure 5: The dielectron mass distribution for signal and background events for $Y_{ee}$ as indicated on each figure. The combined $Z \rightarrow e^+e^-$ and background distribution (points for the full distribution; the background distribution is represented by the dashed blue line) is fit to the sum of a Voigtian and an exponential (solid red for the background and black for the full fit) as indicated in the text. The fit covers the range $70 < m_{ee} < 150$ GeV/c$^2$ (the shaded region is excluded from the fit). The results in each plot have been normalized to 100 pb$^{-1}$.

Table 4: The fractional systematic error contributions per bin as a function of the absolute value of Z rapidity.

| $|Y_{min}|$ | $|Y_{max}|$ | Efficiency | Bin | PDF | Background |
|-------|-------|-----------|------|-----|------------|
|       |       | Statistics| Migration | Uncertainty | Estimation |
| 0.00  | 0.25  | 0.003     | 0.001 | 0.001 | 0.001      |
| 0.25  | 0.50  | 0.002     | 0.002 | 0.001 | 0.001      |
| 0.50  | 0.75  | 0.002     | 0.002 | 0.001 | 0.001      |
| 0.75  | 1.00  | 0.003     | 0.001 | 0.001 | 0.001      |
| 1.00  | 1.25  | 0.003     | 0.001 | 0.001 | 0.001      |
| 1.25  | 1.50  | 0.003     | 0.004 | 0.001 | 0.002      |
| 1.50  | 1.75  | 0.004     | 0.010 | 0.001 | 0.003      |
| 1.75  | 2.00  | 0.004     | 0.010 | 0.001 | 0.007      |
| 2.00  | 2.25  | 0.005     | 0.006 | 0.001 | 0.015      |
| 2.25  | 2.50  | 0.006     | 0.006 | 0.002 | 0.028      |
| 2.50  | 2.75  | 0.008     | 0.006 | 0.002 | 0.042      |
| 2.75  | 3.00  | 0.008     | 0.001 | 0.002 | 0.030      |
| 3.00  | 3.25  | 0.013     | 0.017 | 0.002 | 0.017      |
| 3.25  | 3.50  | 0.026     | 0.069 | 0.003 | 0.057      |
| 3.50  | 3.75  | 0.030     | 0.235 | 0.012 | 0.044      |
Figure 6: The final results for the rapidity measurement. The raw full simulation (“data”) distribution is shown with empty circles and the distribution corrected by \((e \times A)\) is shown with solid circles. The errors on the solid circles are shown for statistical and statistical+systematic separately. The prediction of CTEQ6.1 is shown for comparison. Results are shown for an integrated luminosity of 100 pb\(^{-1}\).

Figure 7: Comparison of the various contributions to the uncertainty in the final measurement as a function of the Z rapidity. The data statistical error is shown as a dashed line for comparison. Results are shown for an integrated luminosity of 100 pb\(^{-1}\).
Figure 8: The corrected final result distribution for the rapidity measurement as a function of the absolute value of Z rapidity (since the result is not expected to depend on the sign of the rapidity). The prediction for the positive variation of one of the CTEQ basis vectors (#13[8]) is shown in red. Results are shown for an integrated luminosity of 100 pb$^{-1}$.

Figure 9: Sensitivity to CTEQ6.5 PDF variations showing the vectors with largest sensitivity to the measurement.
Figure 10: The corrected final result distribution for the rapidity measurement as a function of the absolute value of $Z$ rapidity (since the result is not expected to depend on the sign of the rapidity). The prediction for PDF vector 13 positive variation is given in red. Results are shown for an integrated luminosity of $10 \text{ pb}^{-1}$. 