THE FLORIDA STATE UNIVERSITY

COLLEGE OF ARTS & SCIENCES

W BOSON PRODUCTION CHARGE ASYMMETRY

IN THE ELECTRON CHANNEL

By

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Abstract

We present a measurement of the W boson production charge asymmetry in $p\bar{p}$ collisions in the electron channel through $W \rightarrow e\nu_e$ decays using data collected with the DØ detector. The collision of a u quark with a $\bar{d}$ quark can produce a W^+ boson while the collision of a $\bar{u}$ quark and a d quark can produce a W^- boson. These particles decay rapidly but we are able to measure their asymmetry by studying the resulting final state electrons and neutrinos. These results will be used to further constrain fits to parton distribution functions (PDFs) and improve the accuracy of future predictions for new physics.

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I. Introduction

A. The Standard Model

The Standard Model of particle physics is the theory that explains the fundamental particles and the interactions between them. In the Standard Model, a baryon is a subatomic particle that is made up of three quarks. A proton is a baryon. In order to understand the way the proton works, we must first understand the details inside the proton. Parton distribution functions (PDFs) are used to describe the properties of the quarks that make up the proton [1][2].

The particles in the Standard Model are split into two groups. The first groups, fermions, are the building blocks of matter and these particles have odd, half integer spin. The second groups, bosons, have integer spin and are the particles that mediate the fundamental forces of nature. There are four fundamental forces of nature: strong, weak, electromagnetic, and gravitational, but the standard model only includes the first three of these forces. The strong interaction charge is called color and the interaction of colored particles through the strong force is mediated by gluons. There are three colors and three anti-colors which are represented by 'red' (antired), 'green' (antigreen), and 'blue' (antiblue). If all three colors are combined, the resulting particle is color neutral. If a color and anticolor are combined, the resulting particle is also color neutral. The weak force can only act over a small distance and is mediated by W and Z bosons. The W and Z bosons are far more massive than the other bosons, resulting in the short interaction distance. Finally, the electromagnetic force between particles possessing an electric or magnetic charge is mediated by the massless photon. Since the photon is massless, the range of the electromagnetic force is infinite [1].

The two families of fermions are leptons and quarks which are then divided into three separate generations. The leptons are the electron and the electron neutrino, the muon and the muon neutrino, and the tau and the tau neutrino. Leptons do not interact via the strong force. The electron, muon, and tau leptons interact via the electromagnetic and weak forces. The neutrinos only interact via the weak force. The quarks are up and down, charm and strange, and top and bottom. Quarks are able to interact through all the fundamental forces [1]. Figure 1 is an illustration of the SM particles.

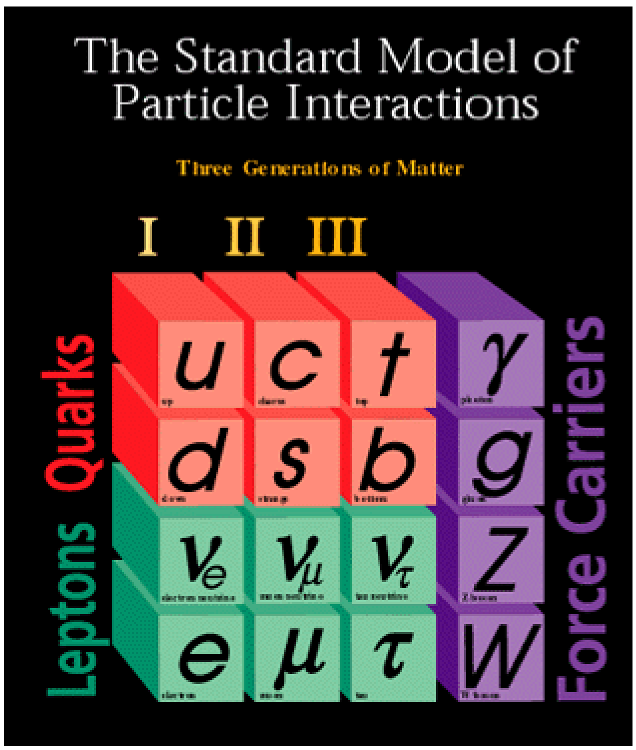

Figure 1: A diagram of The Standard Model of Particle Physics. Each column of quarks and leptons represents one generation [3].

B. W boson production

In the DØ detector, protons collide with their antiparticles, the antiproton, at center of mass energy $\sqrt{s} = 1.96$ TeV. Because the energy of the interaction is so high, the actual collisions are between the quarks inside the protons and antiprotons. This study focuses on the production of

W bosons from the collision of these quarks. The W boson can either be positively or negatively charged. A W^+ boson can be produced from the collision of a u quark with a $\bar{d}$ quark while a W^- boson can be produced from the collision of a d quark with a $\bar{u}$ quark. The resulting W bosons decay almost immediately. A W^+ boson can decay into a positron (an antielectron) and an electron neutrino. A W^- boson can decay into an electron and an electron antineutrino. A diagram of the possible interactions can be seen in Figure 2. It is these resulting final state particles that we study to measure the W boson production charge asymmetry in the electron channel [1][4].

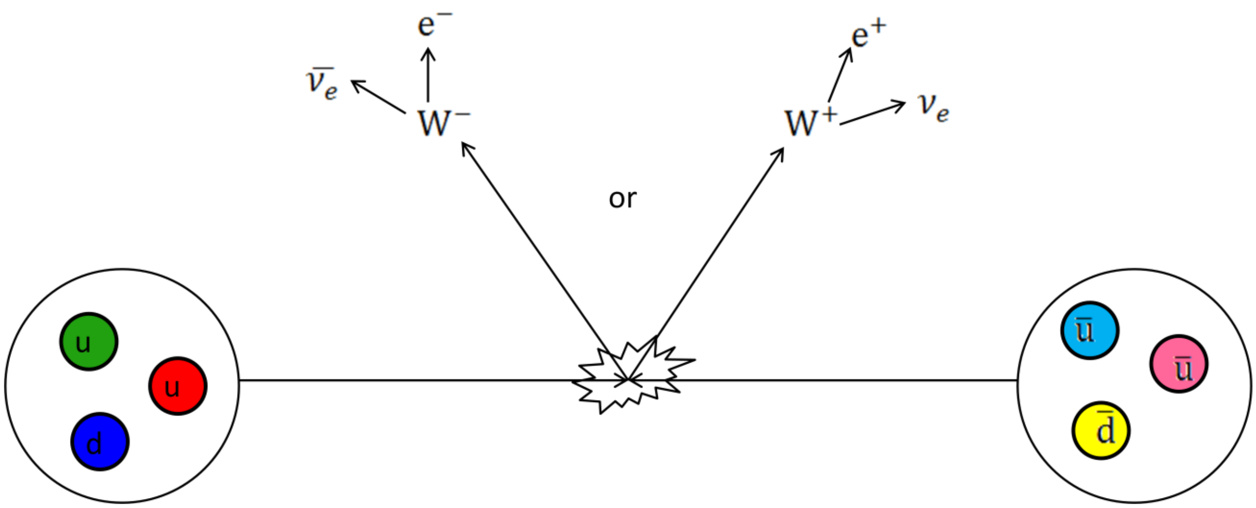

Figure 2: Diagram of W boson production and decay in the electron channel.

C. The Detector and Data Collection

In general, the u quark carries more of the momentum in a proton than the d quark due to the presence of the second u valence quark. Since we know that momentum is conserved, we can expect to find W^+ bosons created in the direction of the proton beam and W^- bosons created in the direction of the antiproton beam. We define the particle's pseudorapidity, or position with respect to the beam axis, as:

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

Where θ is the angle between the particle's momentum vector $\vec{p}$ and the beam axis. We use this relation to locate particles inside the detector [1][4].

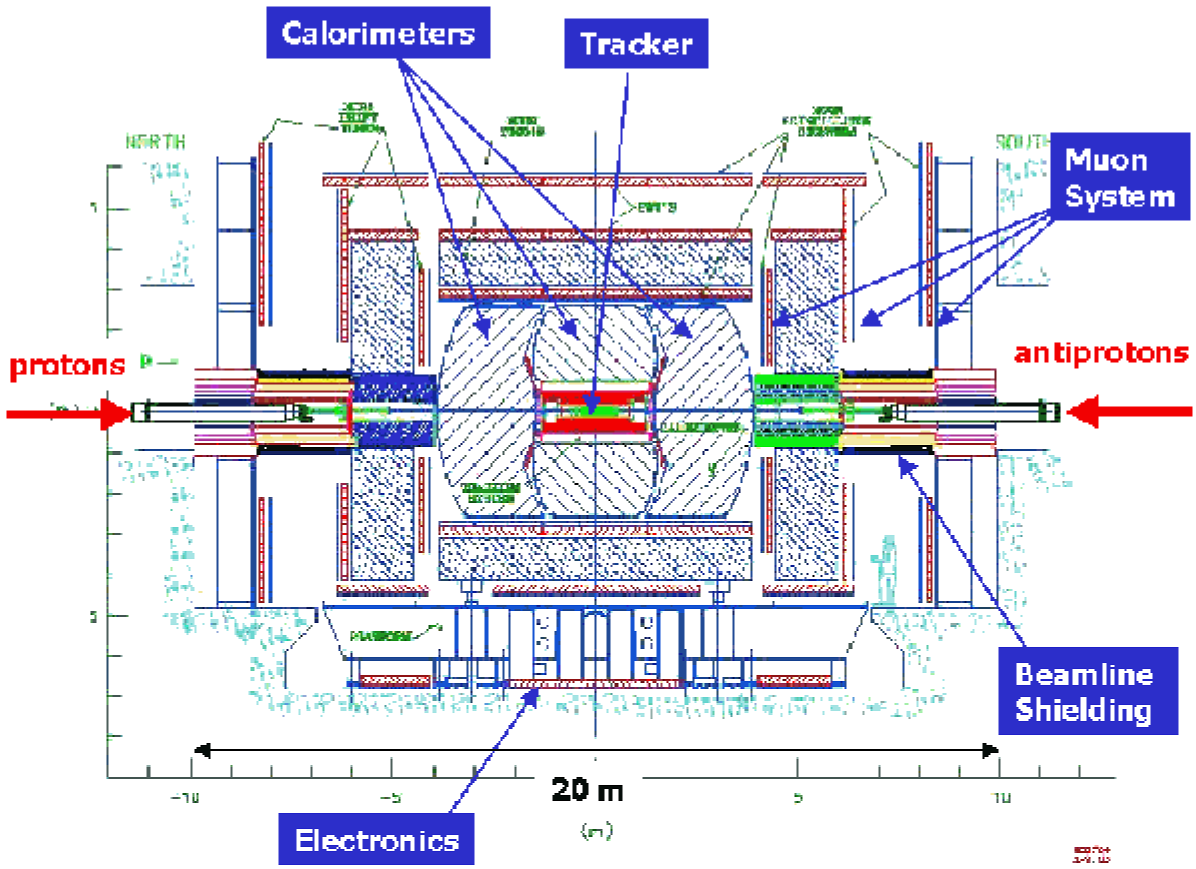

Figure 3: Side view of the DØ detector that shows that protons enter the detector from the left (circle the Tevatron clockwise) and antiprotons from the right (circle the Tevatron counterclockwise)[5].

Due to the design of DØ, not every particle will go through the same amount of detector which forces us to treat particles differently depending on where the reading came from [1][4]. Logically, we get the best readings from particles that go through the most amount of detector and the worst readings from particles that go through the least. A discussion of the different treatment of particles will take place in the Analysis section.

DØ is a general purpose detector located at Fermilab. It began running in 1992 and then was upgraded in 2001. After this upgrade it ran until the fall of 2011. The protons and antiprotons enter the detector and collide at the center. The tracking system is closest to the collision point and is made up of the central fiber tracker (CFT) and the silicon microstrip tracker (SMT). These tracking systems are inside a 2 T magnetic field that is produced by a solenoidal magnet. Surrounding the tracker is the calorimeter. A calorimeter is used to measure the position and energy of the particles. When an electron travels through the calorimeter they interact with it. During this interaction they will lose energy by way of photon emission through bremsstrahlung radiation. These photons go into a cycle of electron-positron pair production which in turn creates more photons to continue the pair production. This cycle will go on until the energy is small enough for the electrons and positrons to begin ionizing. Thus, by adding up the energy of the particles created in this cycle we can determine the energy of the initial electron (the energies will be equal). Because the beams cross so often, it is not possible to record all events. Therefore, there is a trigger system that activates only if an event has characteristics of the physics we are interested in. The last stage of the trigger system takes the information to a computer farm where it reconstructs the event [1].

II. Analysis

A. Selection Cuts

Each electron studied from the data is classified as a different type based on its position in the detector. This type is determined by the number of layers of the CFT that the electron crosses. We divide the types as follows [1][4]:

Type 1: Electrons that are found in the central section of the calorimeter and travel through all of the CFT. These electrons travel through the most amount of the detector meaning that we get the best measurement of Type 1 electrons.

Type 2: Electrons that are found in the forward section of the calorimeter. These electrons also pass through all of the CFT.

Type 3: Electrons that are found in the forward section of the calorimeter that do not pass through all of the CFT.

Type 4: Electrons that are found in the forward section of the calorimeter and pass through no portion of the CFT whatsoever.

By splitting the electrons into different types we are able to define a different set of cuts for each type of electron. This is necessary to preserve the statistics while improving the rate of correct charge identification.

The cuts are as follows [1][4]:

Type 1 and Type 2:

-Track fit reduced χ^2 < 9.95

- N_{smt} > 1 (number of smt hits)

- N_{cft} > 8 (number of cft hits)

Type 3:

-Track fit reduced χ^2 < 9.95

- N_{smt} > 0

- N_{cft} > 0

Type 4:

-Track fit reduced χ^2 < 9.95

- N_{smt} > 8

- Curvature Significance > 2

Electrons are also split into tight electrons and loose electrons. The tight and loose electron cuts are used to determine the signal efficiency, the EM jet-like probability, and the charge mis-identification which will be discussed later. To be considered a tight electron rather than a loose electron, the particle must pass slightly stricter cuts [1][4].

Loose Cuts:

- EMFrac > 0.9

- Isolation < 0.15

- H-Matrix(7) < 50 for CC, $|\eta_{det}| < 1.1$

- H-Matrix(8) < 75 for EC, $1.5 < |\eta_{det}| < 3.2$

- $E_T > 25$ GeV

- Track Match Probability $P(\chi^2) > 0.001$

- Track $E_T > 10$ GeV

Tight Cuts:

All the same as loose except:

- H-Matrix(7) < 10 for CC, $|\eta_{det}| < 1.1$

- H-Matrix(8) < 10 for EC, $1.5 < |\eta_{det}| < 3.2$

Here η_{det} is the pseudorapidity of the cluster of the calorimeter with respect to the center of the detector.

Finally we need to add requirements for the signal sample of this analysis. The W boson candidate events need to have [1][4]:

- One tight electron with $p_T > 25$ GeV

- Missing Transverse Energy > 25 GeV (from the neutrino)

-Transverse Mass of the W boson > 50 GeV

The transverse mass of the W boson is not recorded by the detector and needs to be reconstructed, as described in the next section.

B. Transverse Mass Reconstruction

The W bosons that are created in these events decay so rapidly that we are not able to obtain readings of them with the detector. However, we need to make sure we are selecting events in which we are actually creating a W boson. To do this we have to reconstruct the transverse mass of the electron and neutrino's parent particle. The equation for reconstruction is:

$$M_w^{T\,2} = 2p_T^e \not{E}_T^{\nu}(1 - \cos\Delta\varphi)$$

$\Delta\varphi$ is the azimuthal angle between the electron and the missing transverse energy [1][4]. The reconstructed plot can be seen in Figure 4.

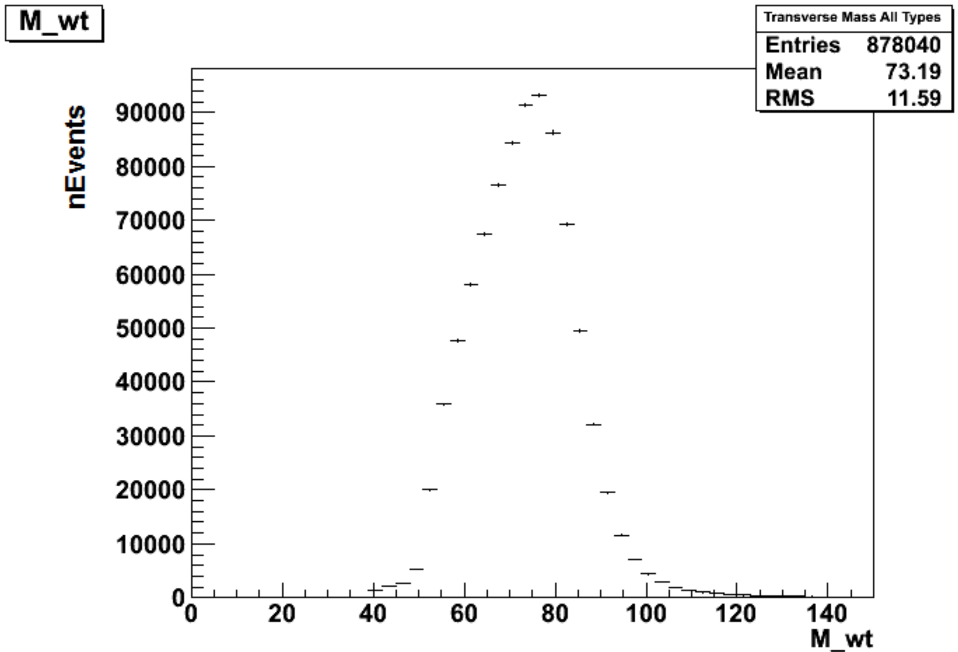

Figure 4: Transverse mass of reconstructed W boson. The recorded mass of the W boson is around 80 GeV which is where this plot falls off.

Now that we have reconstructed the mass of the W boson we can add the transverse mass cut into our analysis.

C. Raw asymmetry

After the selection cuts are put in place, we are able to calculate the raw asymmetry. First, the asymmetry is found for each electron type. Then all four types are placed on the same plot. The equation for the raw asymmetry is:

$$A(\eta) = \frac{N_{+}(\eta) - N_{-}(\eta)}{N_{+}(\eta) + N_{-}(\eta)}$$

Where N_{+} is the number of positron events (W^{+} boson events), N_{-} is the number of electron events (W^{-} boson events). Figures 5 and 6 show the raw asymmetry of each type [1][4].

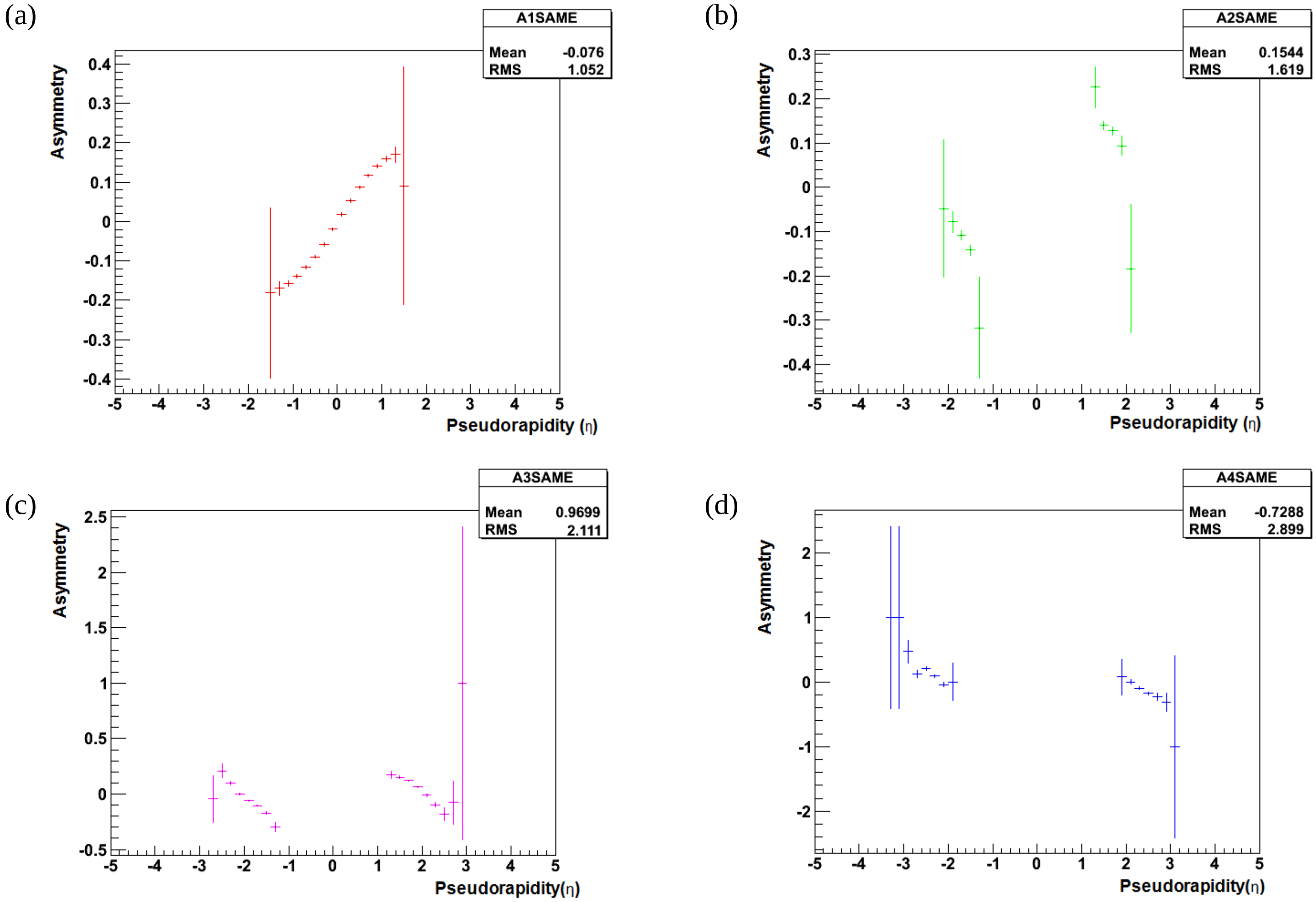

Figure 5: (a) Raw asymmetry of Type 1 electrons. (b) Raw asymmetry of Type 2 electrons. (c) Raw asymmetry of Type 3 electrons. (d) Raw asymmetry of Type 4 electrons.

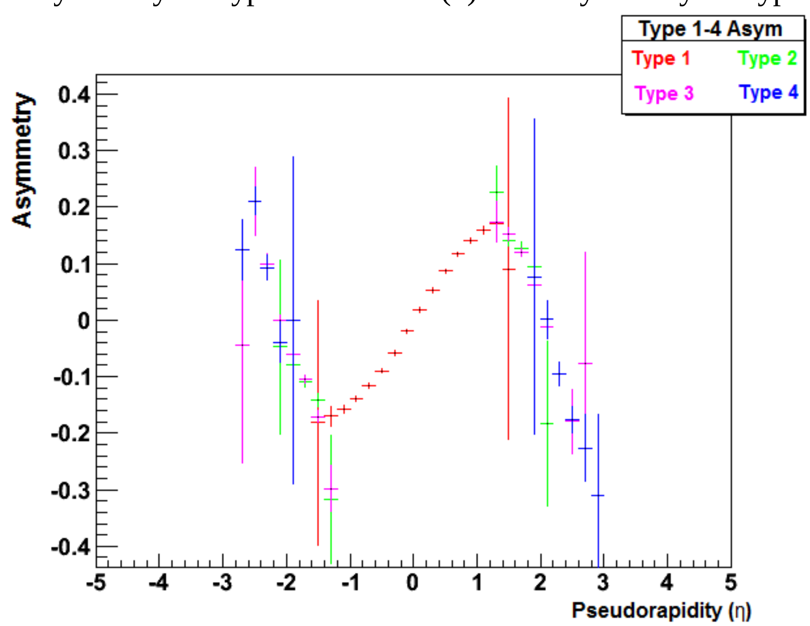

Figure 6: Combined plot of all four electron types to see the full asymmetry curve.

D. Weighted average asymmetry

We need to apply statistics to produce the full asymmetry plot since there are some bins in our histogram that contain more than one type of electron. To do this, we find the weighted average of each bin in our asymmetry plot. We find the weighted average of both the value of the asymmetry and the value of the uncertainty of that asymmetry [6].

First, we extract the content and uncertainty for each pseudorapidity bin. The content is the value of the asymmetry and the uncertainty is the uncertainty in asymmetry. We do this for each type of electron. We check each type in each bin. If the value of the asymmetry in the bin is 0, then we set the value of the uncertainty to a very large number (1000000000) to preserve the asymmetry. We then obtain the weight of each type of electron in each bin by saying:

$$weightedAsymType\# = \frac{AsymType\#}{AsymType\#Error^2}$$

Then, if the weight is 0, that type does not contribute to the asymmetry in that bin. If the weight is not zero, the contribution of that type is given by:

$$weightOfType\# = \frac{1}{AsymType\#Error^2}$$

We then sum the weighted asymmetry of each type and the weight of each type as:

$$\begin{aligned} sumWeightedTypeAsym &= weightedAsymType1 + weightedAsymType2 + weightedAsymType3 \\ &\quad + weightedAsymType4 \end{aligned}$$

$$\begin{aligned} sumWeightOfTypes &= weightOfType1 + weightOfType2 + weightOfType3 \\ &\quad + weightOfType\ 4 \end{aligned}$$

The full weighted value of the asymmetry is then given by:

$$WeightedAsym = \frac{sumWeightedTypeAsym}{sumWeightOfTypes}$$

And the uncertainty of this measurement is given by:

$$Uncertainty = \sqrt{\frac{1}{sumWeightOfTypes}}$$

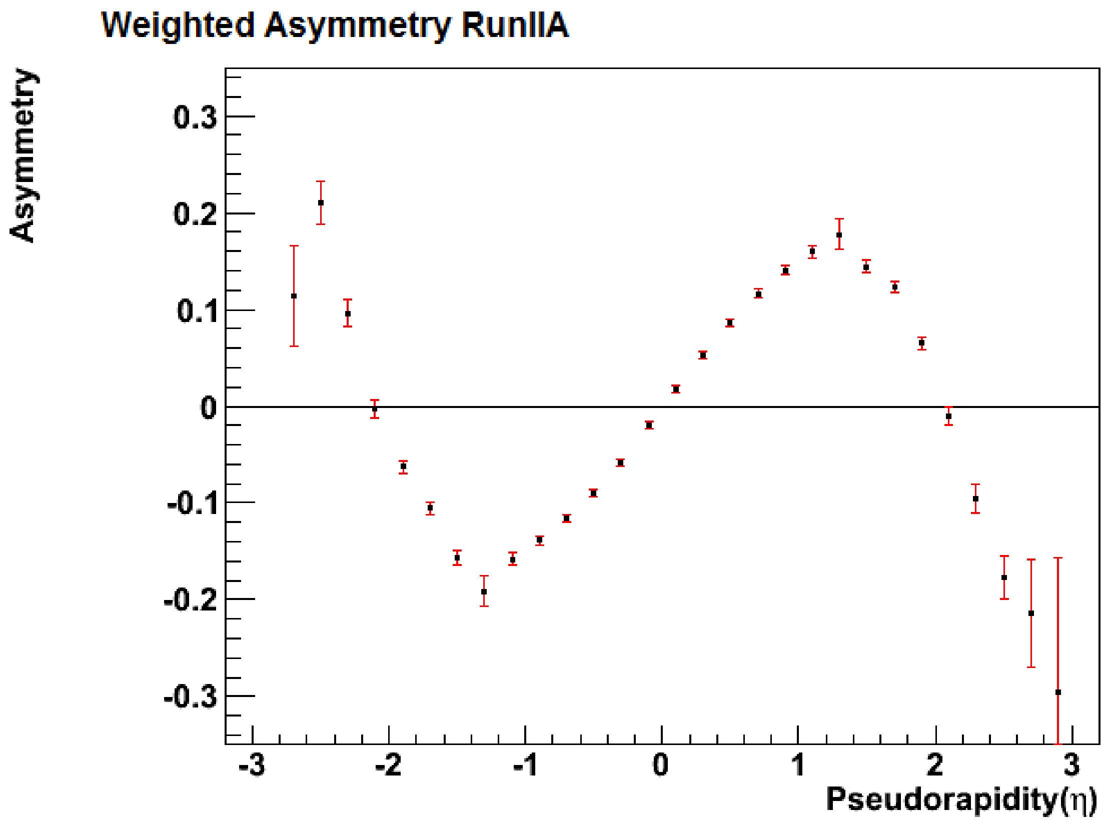

Figure 7: Weighted Average Asymmetry of the W boson.

This method is used because we have to treat the asymmetry values differently depending on how large their uncertainties are. For example: Say there are two types in a bin. One type has a very small uncertainty associated with it while the other type has a very large uncertainty associated with it. Since the uncertainty on the first type is so small, it contributes a greater portion to the full asymmetry plot than the type that has the large uncertainty. For this reason, we must use weighting to assure we are accurately representing each type in the full asymmetry plot.

E. Z boson and Charge Correction

The *Z* boson will decay into either a quark-antiquark pair or a lepton-antilepton pair. In this study, we focus on *Z* bosons that decay as [1][4]:

$$Z \rightarrow e^- e^+$$

To do this we must find events where the number of electrons is greater than one. Once we single out these events, we reconstruct the invariant mass of the *Z* boson by using [1][4]:

$${M_Z^i}^2 = 2E_1E_2 - 2(\vec{p}_1 \cdot \vec{p}_2)$$

Figure 8 is a plot representing the reconstruction of the invariant mass of the *Z* boson.

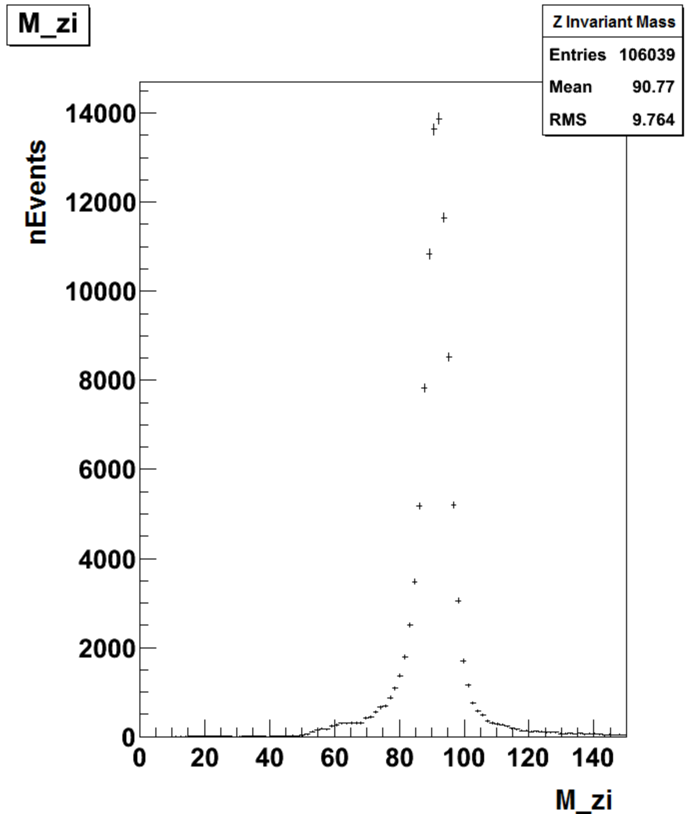

Figure 8: Plot of the invariant mass of the Z boson. The recorded mass of the Z boson is 91 GeV

After we are certain we are dealing with Z boson events, we study the charge mis-identification. In other words, we look to see how often we call an electron an electron when it is really a positron. To do this, we check the charge of the resulting leptons of the Z boson events. If the charges of the leptons are not equal then we correctly identified their charge. If the charges of the leptons are equal, we know the charge of one electron was identified incorrectly. We then count up all the correct identifications and the incorrect identifications. The probability of mis-identification in our detector as seen in Figure 9 is then [1][4]:

$$P_{mid} = \frac{\#\ of\ events\ with\ same\ sign\ particles}{total\ \#\ of\ events}$$

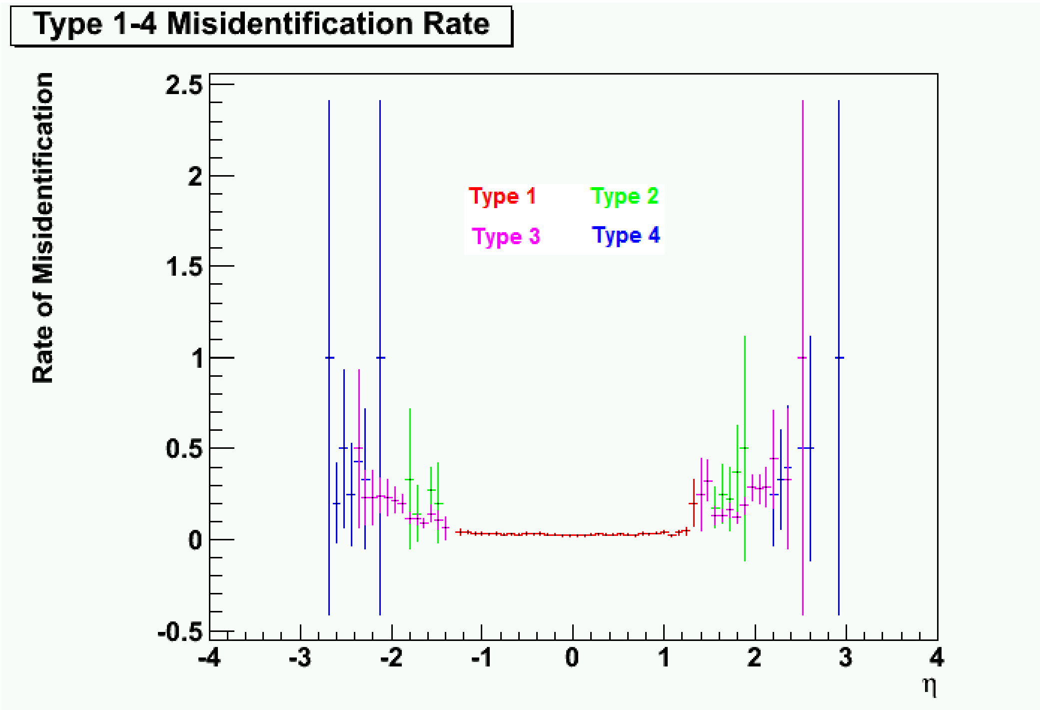

Figure 9: Probability of charge mis-identification for each type of electron. As the readings from the electrons get worse, the rate of charge mis-identification increases.

Multiplying the asymmetry equation by this mis-identification rate produces an asymmetry plot that has been corrected for charge mis-identification. The new equation for the asymmetry is [1][4]:

$$A(\eta) = \frac{1}{1 - 2P_{mid}} \frac{N_{+}(\eta) - N_{-}(\eta)}{N_{+}(\eta) + N_{-}(\eta)}$$

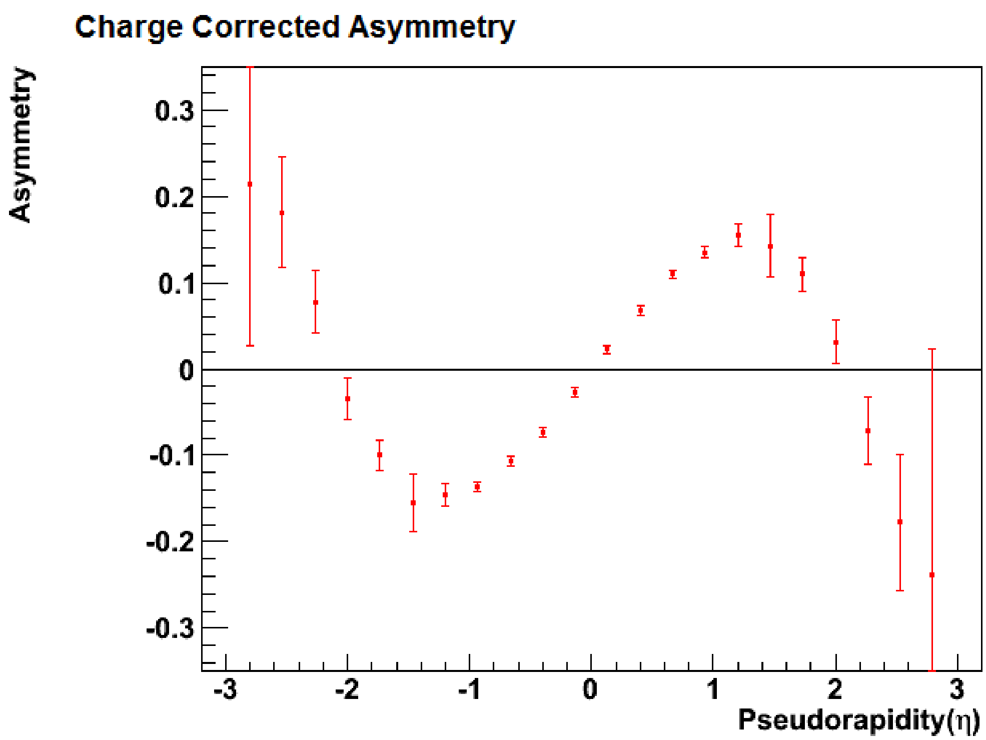

Figure 10: Charge corrected asymmetry.

F. Efficiencies

The efficiency of the detector to identify electrons is found using the tag and probe method and Z boson decays. The signal efficiency is defined as the probability of an electron or positron passing both the loose and tight cuts. In this case, we define one electron as the tag electron and another electron as the probe electron. The tag electron is the electron that passes the tight cuts and the probe electron is the electron that passes the loose cuts. We then check to see if the event has two electrons that pass the tight conditions, meaning that the event has two tag electrons. We then take the number of electrons that pass the tight conditions and the number of electrons that only pass the loose conditions and determine the signal efficiency as [1][4]:

$$\varepsilon = \frac{N_{pass}}{N_{pass} + N_{fail}}$$

Where ε is the signal efficiency, N_{pass} is the number of electrons that pass the tight cuts, and N_{fail} is the number of electrons that pass the loose conditions but do not pass the tight conditions. The result of this analysis is shown in Figure 11.

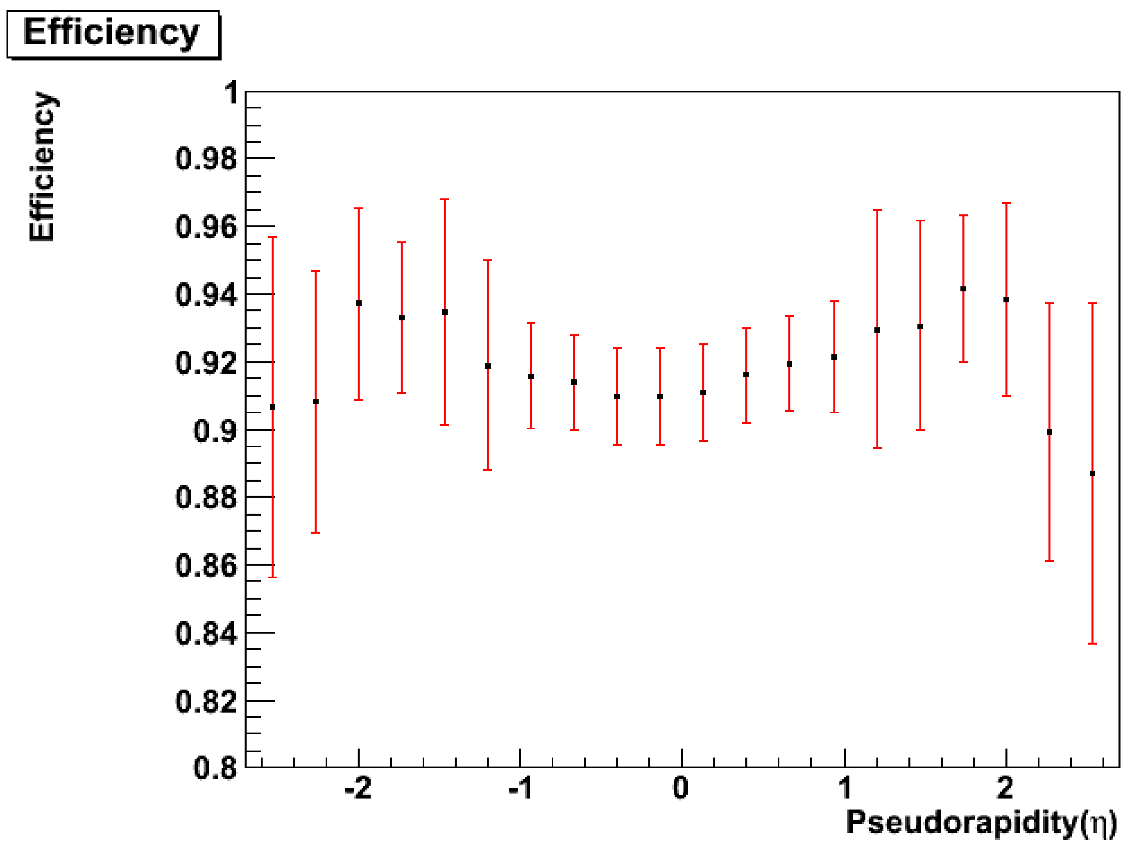

Figure 11: Efficiency for an electron to pass both the tight and loose cuts.

G. EM-like Jet Probability

A jet is an object that results from the hadronization of quarks and gluons. Any free quarks or gluons that result from the collision form jets. This happens due to the strong force and color confinement. Since a quark or gluon cannot exist on its own, a free quark or gluon will spontaneously create its antiparticle out of the vacuum. These particles then come together to form hadrons, or particles that are made up of either two or three quarks. This process of hadronization creates a narrow cone-shaped object that is the jet.

The fake rate is the probability for a jet that results from the collision to pass both the loose and tight electron cuts. We measure the fake rate using both EM and jet events. The fake rate is defined as [1][4]:

$$f = \frac{N_L}{N_T}$$

Where f is the fake rate, N_L is the number of events that passed the loose electron cuts, and N_T is the number of events that passed both the loose and tight electron cuts.

This portion of the analysis has not yet taken place. However, it is the last step in the analysis of the asymmetry using real data. We can now use these corrections to find the final asymmetry equation [1][4].

First we have:

$$N_+ - N_- = \frac{N_{T^+} - N_{T^-}}{\varepsilon(1 - 2P_{mi})}$$

And:

$$N_+ + N_- = \frac{N_{T^+} + N_{T^-} - f(N_{T^+} + N_{T^-} + N_{nt})}{(\varepsilon - f)}$$

Finally:

$$A = \frac{N_+ - N_-}{N_+ + N_-} = \frac{\varepsilon - f}{\varepsilon(1 - 2P_{mi})} \frac{N_{T^+} - N_{T^-}}{(1 - f)(N_{T^+} + N_{T^-}) - fN_{nt}}$$

Where A is the asymmetry, ε is the efficiency, f is the fake rate, P_{mi} is the probability of mis-identification, N_{T^+} is the number of positrons that pass tight cuts, N_{T^-} is the number of electrons that pass tight cuts, and N_{nt} is the number of events that pass the loose cuts and fail the tight cuts. Further explanation of this method can be found in reference [4], the DØ note on this analysis.

H. Solenoid Polarity

In order to reduce the effects of selection charge bias in the detector, the polarity of the solenoid was reversed regularly during data collection. Roughly half of the data was collected with a solenoid polarity of zero while the other half was collected while the solenoid polarity was one [1][4]. Figure 12 shows that there is no difference in the data collected with different solenoid polarities so no correction is needed.

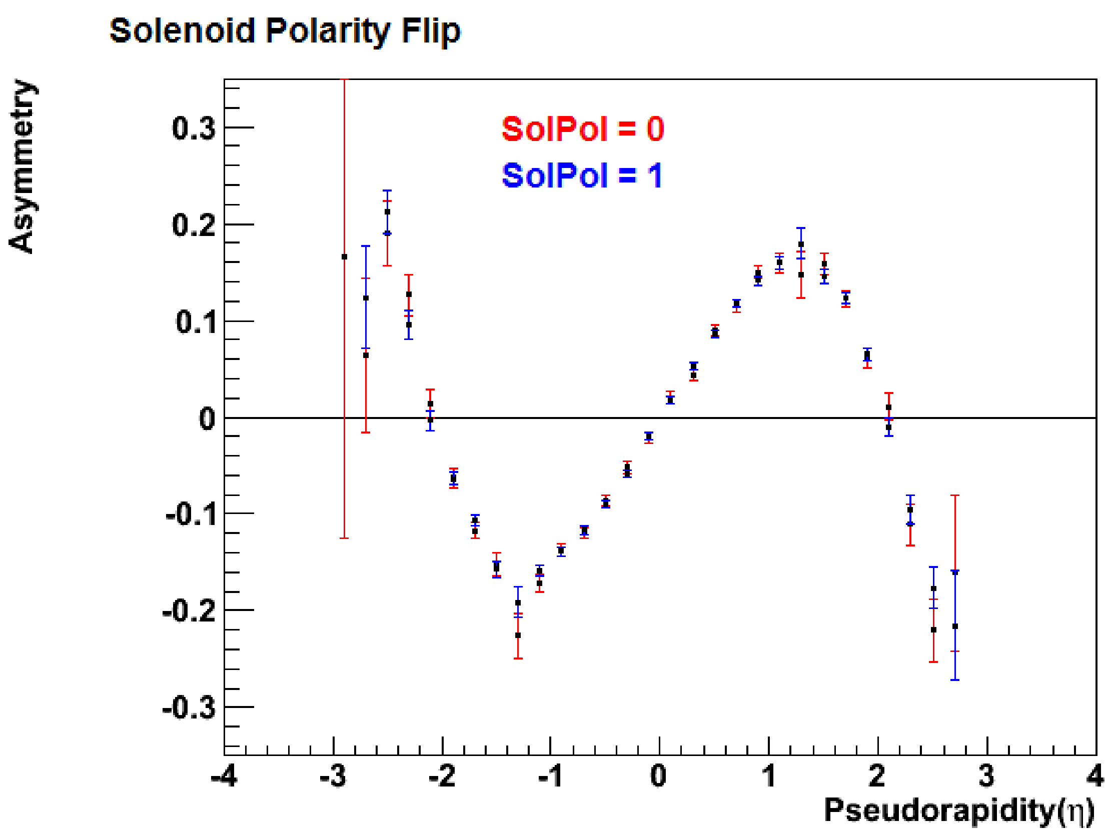

Figure 12: Plot representing the flip in the solenoid polarity. The plot is of the weighted average asymmetry and the uncertainties are statistical.

I. New Data: RunIIB

All of the results discussed above were found using data collected during the Tevatron's RunIIA. During the Fall of 2012, we received new data that was collected during RunIIB at the Tevatron. This dataset is larger than RunIIA by a factor of about sixteen. The data from RunIIB went through the same analysis as the data from RunIIA. The weighted average asymmetry and the charge corrected asymmetry from RunIIB are shown below.

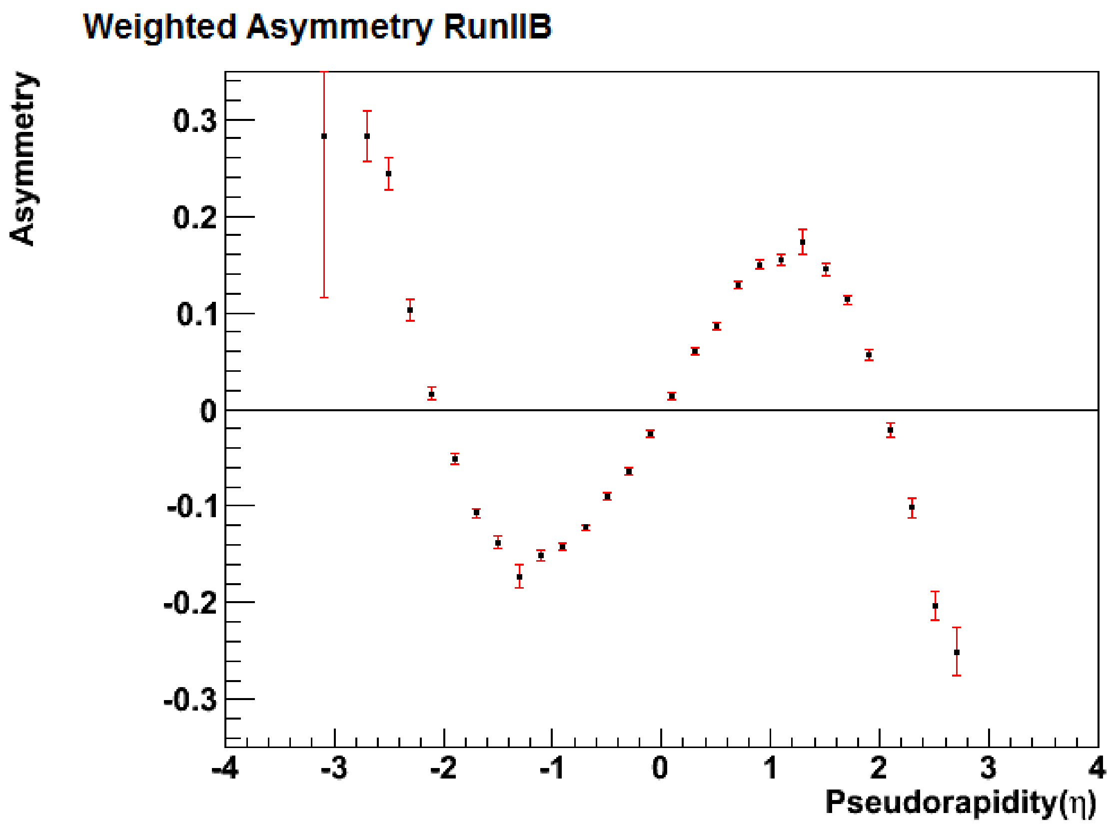

Figure 13: Plot of the weighted average asymmetry using data collected during RunIIB

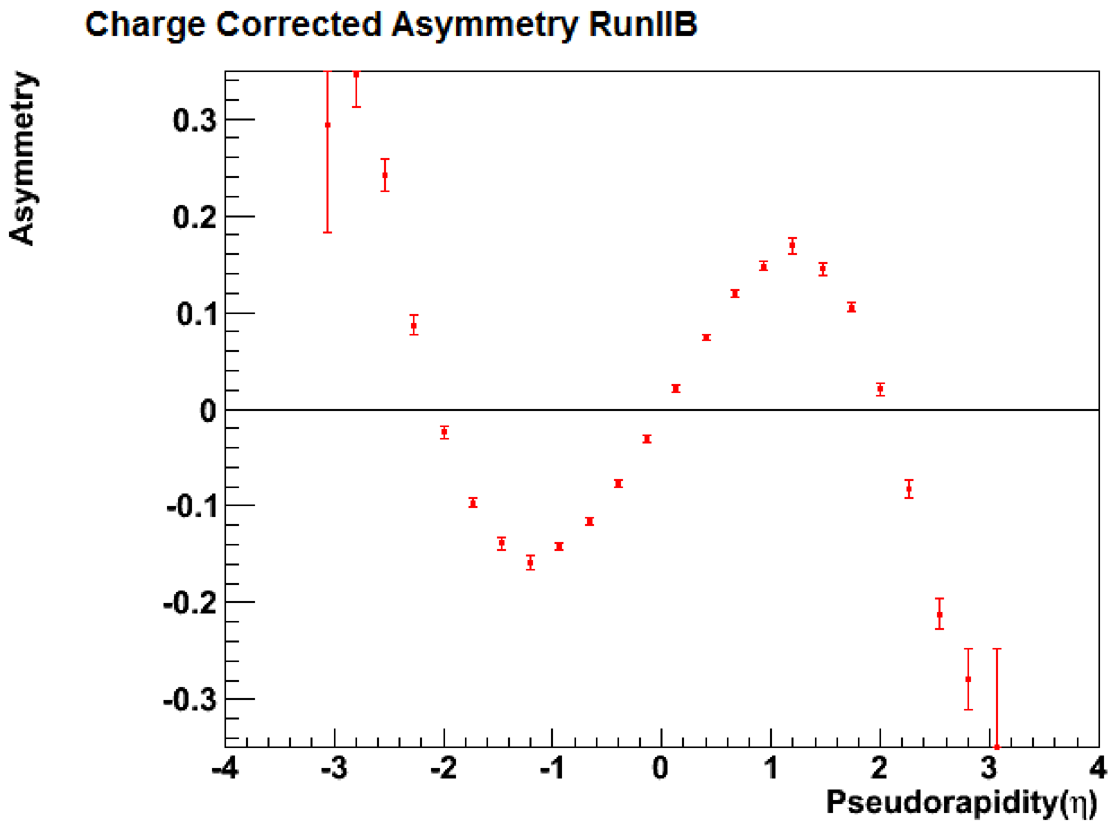

Figure 14: Plot of the weighted average asymmetry with charge correction using data collected during RunIIB.

J. Monte Carlo

The real data needs to be compared to simulations created through Monte Carlos. We use Monte Carlos that simulated the signal event (*W* boson production) to compare with the results we found using real data. The Monte Carlos are based on the theories that govern particle physics and are not subject to detector flaws. Figure 15 uses the Monte Carlo data to produce the weighted average asymmetry and Figure 16 compares this plot to the charge corrected asymmetry found for all of RunII.

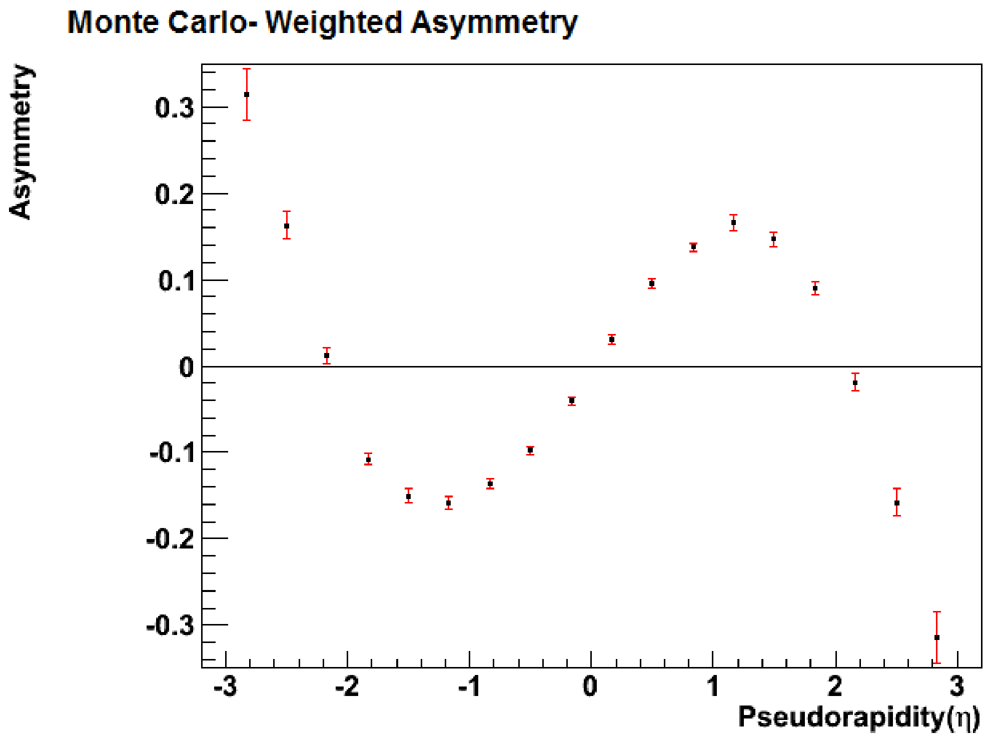

Figure 15: Plot of the weighted average asymmetry using the signal Monte Carlo events

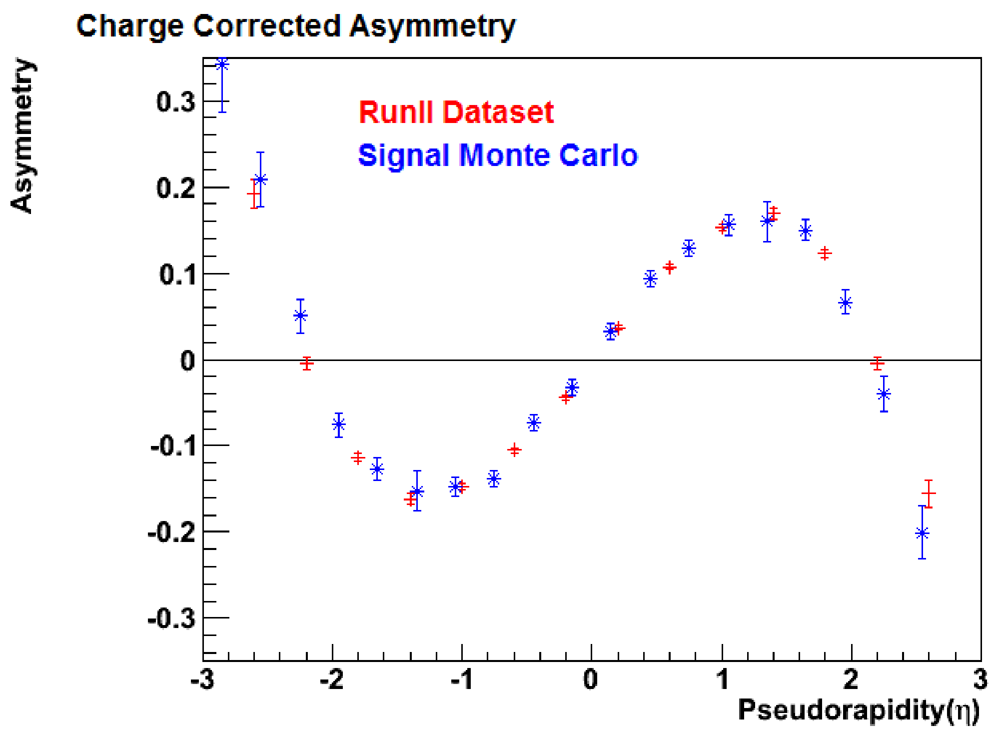

Figure 16: Plot of the charge corrected asymmetry for all of RunII compared to the signal Monte Carlo. The bins are offset due to a computational error.

The final step of this analysis is to study the Monte Carlo backgrounds. The backgrounds come from [1][4]:

$$Z \to ee$$

$$Z \to \tau\tau \to e\overline{\nu}_e\nu_e$$

$$W \to \tau\nu$$

We expect the background from these samples to be small but we still need to account for them. The background from Z production is small because the cross section (likelihood of interaction) for Z bosons is small. These events become background events when one of the leptons is deposited outside the fiducial region of the detector (outside the calorimeter). This means that we do not get a reading from it and record it as a neutrino instead of an electron or tau. Recording a neutrino causes us to include this interaction in our study since it looks like a W boson event. Other scenarios where the electron is not identified correctly are also possible.

The background from $W \to \tau\nu$ production is small because although tau leptons may decay into electrons, it is with a fairly small probability. Since the same W boson production asymmetry exists in the tau channel, the data must be corrected for this small effect. An asymmetry is created in the decay of the tau lepton to the electron however, this is not the same asymmetry that we are studying therefore it can interfere with our results.

III. Conclusion

We have measured the electron charge asymmetry through $W \to e\nu_e$ decays with the DØ detector. We were able to measure the asymmetry of the W boson charge production by first dividing the resulting electrons into four types. We then found the raw asymmetry of each type of electron. With these raw asymmetries we were able to find the total asymmetry of W boson charge production by combining these separate asymmetries using weighted averaging. The results found in this analysis can be used by theorists to constrain the fits to PDFs leading to improved predictions for new physics in the future.

IV. References

[1] D. Khatidze. *The Charge Asymmetry in W Bosons Production in* $p\bar{p}$ *Collisions at the* $\sqrt{s}$ = *1.96 TeV Using the D0 Detector at the Fermilab Tevatron.* Thesis. Columbia University, 2009

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[5] http://www.fnal.gov/pub/now/live_events/explain_det_dzero.html

[6] Lyons, Louis. *Statistics for Nuclear and Particle Physicists*. Cambridge, 1986. Print.