Measurement of the $W$ Boson Production Charge Asymmetry in $p\bar{p}$ Collisions

by

Bo-Young Han

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Requirements for the Degree
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Supervised by
Professor Kevin McFarland
Department of Physics and Astronomy
The College
Arts and Sciences

University of Rochester
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(1) Discussion of the smearing. Even if you are not unfolding, you still have to provide information from the response matrix to show how events smear so that the charge asymmetry can be interpreted.

(2) At the ends of sections 3.3 and 3.4, I would have expected plots of the reconstructed quantities with, for example, all but one cut applied. You don't need all of them, but I know you have plots from a reasonable set of them. Please add to your thesis.
Curriculum Vitae

The author was born in Seoul, Republic of Korea in September 1972. He graduated from Korea University at Seoul, Republic of Korea with a Master of Science degree in 2001. He came to the University of Rochester in the fall of 2002 to continue his studies in the field of elementary particle physics. He joined the CDF experiment at Fermi National Accelerator Laboratory, where he first worked on the development and validation of filtering code for Level3 Trigger group, and then he conducted the research for his Ph.D. thesis on the $W$ boson production charge asymmetry under the supervision of Prof. Kevin McFarland.
He
Acknowledgments

Bo-Young
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Abstract

We present a measurement of the $W$ boson production charge asymmetry using the $W \rightarrow e\nu$ decay channel. We use data collected the Collider Detector at Fermilab (CDF) from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The data were collected up to February 2006 (Run II) and represent an integrated luminosity of $1 \text{ fb}^{-1}$. The experimental measurement of $W$ production charge asymmetry is compared to higher order QCD predictions generated using MRST2006 and CTEQ6 parton distribution functions (PDF). The asymmetry provides new input on the momentum fraction dependence of the $u$ and $d$ quark parton distribution functions (PDF) within the proton over the fraction of proton’s momentum range from $-3.0 < y_W < 3.0$ at $Q^2 \approx M_W^2$. 
rapidity is not the fraction of the proton's momentum. Rewrite to give both the rapidity range (perhaps in sentence above), and then give the range of x probed by your measurement -- something like 0.002<0.8
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Chapter 1

Introduction

In 1911, Ernest Rutherford and his associates bombarded thin gold foils with $\alpha$-particles and found that some of them were deflected by huge angles, indicating the presence of a small yet massive kernel inside the atom. He thus suggested that the hydrogen nucleus was an elementary particle. The nucleus of the lightest atom (hydrogen) was given the name proton (Greek $\pi\rho\dot{\omega}\tau\omicron = \text{first}$) by Rutherford. In 1914, Niels Bohr proposed a model for hydrogen consisting of a single electron circling the proton held in orbit by the mutual attraction of opposite charges, and in 1932 Chadwick found the neutron, which is an electrically neutral twin to the proton. Physicists realized that every element in the periodic table could be constructed of a single atomic nucleus with a distinct number of protons and neutrons, surrounded by a cloud of electrons.

The notion that protons and neutrons are fundamental particles was shattered in the late 1950’s and 1960’s by a population explosion of newly observed particles. With the construction of large particle accelerators, experiments produced hundreds of ''elementary'' particles, called hadrons, with properties very similar to the nucleons. In 1963, Murray Gell-Mann and George Zweig independently proposed a scheme in which hadrons are composed of smaller particles, dubbed quarks. The quarks interact with
add a citation
each other via the strong force. Some hadrons, like the proton($uud$) and neutron($udd$), consist of three quarks. These are the baryons. Others, called mesons, are comprised of quark-antiquark pairs. Experimental evidence for the proton’s substructure was eventually established in 1968 by a team at the Stanford Linear Accelerator Center (SLAC). In an experiment not so different from Rutherford’s, a high energy beam of electrons was aimed at a small vat of liquid hydrogen. The resulting scattering pattern revealed that the proton was actually a composite system. The mediators of the strong force, called gluons, were proposed as elementary particles that cause quarks to interact, and are transmitted between quarks to bind them into composite particles: the hadrons. The first direct experimental evidence of gluons was found in 1979 when three-jet events were observed at the Positron-Electron Tandem Ring Accelerator (PETRA) at DESY in Hamburg. The interactions between quarks and gluons are explained by Quantum Chromodynamics (QCD).

### 1.1 Quantum Chromodynamics (QCD)

Quantum chromodynamics, a part of the Standard Model of particle physics, is a typical non-Abelian gauge theory based on a local (gauge) symmetry group called SU(3). All the particles in this theory interact with each other through the strong force. The strength of the interaction is parametrized by the "strong coupling constant". This strength is, as usual, modified by the gauge "color charge" of the particle. This really refers to a group theoretical property whose meaning explained non-color charge and has nothing to do with color itself. Quarks and gluons are the only fundamental particles which carry non-vanishing color charge, and hence participate in the strong interactions. The color charge of a quark has three possible values: red, blue, or green. Antiquarks carry anticolor. The gluons are postulated to belong to an octet (8) representation of SU(3). The color singlet does not contribute to strong interactions since it does
which has the opposite color charge of quarks so that, for example, a red quark and an anti-red anti-quark together carry no net color charge
Chapter 1. Introduction

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One combination of color and anti-color, known as $t$,
which means, in effect, that a gluon carries both a color and an anti-color charge.
not carry color and is unable to mediate forces between color charges\footnote{in QCD, since the gluon is a massless boson}, the favored QCD potential is

\[
V_{\text{QCD}} = -\frac{4}{3} \alpha_s r + kr \tag{1.1}
\]

The separation between the two color charged particles is given by \( r \) and \( \alpha_s \) is the strong coupling constant. At small \( r \) (\( \leq 0.1 \text{ fm} \)), the interaction is assumed to be of the Coulomb type, in analogy with electromagnetism (QED), while at large \( r \) (\( \geq 0.1 \text{ fm} \)), the potential must increase indefinitely, so as to confine the quarks inside a hadron. When two quarks become separated by a large enough distance, it is energetically more favorable that a quark-antiquark pair be produced from the vacuum. These newly produced quarks will then form colorless hadrons with the original quark pair. This quark confinement offers an explanation of why no free quarks or gluons have ever been observed in nature.

For most of experiments that involve hadrons in the initial state, the internal structure of the proton must be considered to be able to theoretically calculate the cross section of all physical processes. This requires modeling the kinematics of elementary particles within the proton. These elementary particles are referred to as partons, and the parton distribution function (PDF) for the proton are discussed in the next section.

### 1.2 Parton Distribution Functions (PDF)

Experimentally, high energy electrons serve as a natural probe of the proton’s internal structure, since they interact with quarks via the electromagnetic force. In electron-proton collisions, only about half of the proton’s momentum is carried by quarks, while the other half consists of electrically-neutral objects that do not interact with electrons. This discovery led to a more complete picture of the proton’s substructure and the fact
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maybe a better way to say this is: "a good model for the"

where

is this a note for you? i'm not sure this belongs in the text.

than to maintain the strong interaction field between them
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e.g., its quarks and gluons

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Author: Kevin McFarland  
Subject: Cross-Out  
Date: 4/12/2008 11:44:00 AM

involving the proton

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Author: Kevin McFarland  
Subject: Inserted Text  
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quarks and gluons inside a proton are also referred to as

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Author: Kevin McFarland  
Subject: Cross-Out  
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approximately

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Author: Kevin McFarland  
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it is observed that

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such as gluons,
that various types of partons made up the proton. The partons can each carry a different fraction \( x \) of the parent proton’s momentum and energy. They are the valence quarks, gluons and sea quarks. The valence quarks are the bound-state quarks that define the quantum numbers of the proton, while sea quarks are virtual quark-antiquark pairs produced from the splitting of a gluon. As shown in Figure 1.1, the proton is described as three-valence quarks \( u_v u_v d_v \) accompanied by many quark-antiquark pairs \( u_s \bar{u}_s, d_s \bar{d}_s, s_s \bar{s}_s \), and so on.

![Figure 1.1: A proton made up of valence quarks, gluons, and quark-antiquark pairs.](image)

In the parton model, the structure of the proton is specified by a set of “parton distribution functions” (PDFs) that give the probability for a particular parton to carry a fraction \( x \) of the proton’s total momentum. By summing over all contributing partons,
The partons are often categorized as ...

A model of a
Chapter 1. Introduction

the quantum numbers of the proton must be recovered.

\[
\int_0^1 [u_v(x) + u_s(x) - \bar{u}_s(x)]dx = 2 \\
\int_0^1 [d_v(x) + d_s(x) - \bar{d}_s(x)]dx = 1 \\
\int_0^1 [s_s(x) - \bar{s}_s(x)]dx = 0
\]  

(1.2)

where the subscripts \( v \) and \( s \) denote valence and sea quarks, respectively. The momentum density functions, given by \( xu(x) \), \( xd(x) \), and \( xs(x) \), can be integrated over the possible values of \( x \) to find the overall fraction of the proton momentum carried by each of the quark flavors. Experimental measurements find that the fraction of the proton’s momentum of the valence and sea quarks is about 45%. This implies that the remaining fraction of the momentum is carried by gluons. The structure of the proton is dependent on the energy regime \( (Q^2) \) of the probe. In the low energy regime \( (< 1\text{GeV}) \), the proton interacts predominantly as a single particle. At medium energy \( (< 100\text{GeV}) \), the composite nature of the proton is apparent, and the valence quarks make the largest contribution to the interaction probed. At higher energy, the probability distribution function is dominated by gluons and sea quarks. The electroweak interactions measured in this thesis require a momentum transfer near the \( W \) mass \( (\approx 80\text{ GeV}/c^2) \) and will be dominated by contributions from valence quarks. The proton PDF is shown in Figure 1.2.

PDFs have been extracted from the measurements of the structure function for deep-inelastic scattering data collected at lepton-proton colliders, and the measurement of the asymmetry in Drell-Yan production in hadron-hadron collisions. Since any particular experiment covers a limited range of \( x \) and \( Q^2 \), fixed by the center of mass energy, measurements from a variety of experiments are combined into “global QCD analyses” that attempt to extract the distributions for all partons in a particular hadron simultaneously.
significant momentum be carried by each of the interacting partons in order to create the massive W boson (~80 GeV/c^2), and therefore will usually involve at least one valence quark.

since your adviser has done this in lepton-proton collisions not at a collider, it's probably worth being more general! :-)

in
Figure 1.2: The parton distribution for the proton. The contribution from valence and sea quarks are shown along with the gluon contribution. For $x$ values above $\approx 0.15$, valence quarks dominate the distribution and are the largest contribution to hard interactions involving the proton.
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In this thesis, experimental measurements are compared to recent parton distribution functions from both CTEQ and MRST which perform global fits to world data.

1.3 \( W \) Events at Tevatron

\( W \) bosons in \( p\bar{p} \) collider are produced by hard scatters between the quarks which are inside the protons and anti-protons. Protons and anti-protons are bound states of constituent partons, which are quarks and gluons as discussed in previous section. A schematic diagram of the \( W \) production process is shown in Figure 1.3. In the diagram, the constituent partons of the protons and anti-protons are shown as the horizontal lines, and the ovals that surround the lines represent protons and anti-protons. A hard scatter between a quark from proton and an anti-quark from the anti-proton is shown. These two quarks form a \( W \), and the \( W \) is shown subsequently decaying into a lepton and a neutrino. The other partons in the proton and anti-proton are spectators to the event, and they form the "underlying event." The protons and anti-protons travel in opposite directions, although this is not indicated in the diagram.

![Figure 1.3: Schematic diagram of \( W \) production at \( p\bar{p} \) collisions.](image-url)
In our experiment, t
Chapter 1. Introduction

The inclusive rapidity distribution for production of a $W^+$ boson in $p\bar{p}$ collisions is expressed as

$$
\frac{d\sigma}{dy_{W}}(W^+) = K(y_{W}) \frac{2\pi G_F}{3\sqrt{2}} x_1 x_2 \left\{ \cos^2 \theta_c (u_p(x_1)\bar{d}_p(x_2) + \bar{d}_p(x_1)u_p(x_2)) \\
+ \sin^2 \theta_c (u_p(x_1)\bar{s}_p(x_2) + \bar{s}_p(x_1)u_p(x_2)) \right\},
$$

(1.3)

where $y_W$ is the rapidity of the $W$, $y_W = \ln \frac{E + P_z}{E - P_z}$, $\theta_c$ is the Cabibbo mixing angle, $G_F$ is the weak coupling constant, and the partons from the proton(anti-proton) carry momentum fraction $x_1(x_2)$. In Eqn. 1.3 the $u(x)$, $d(x)$ and $s(x)$ PDF’s are all evaluated at $Q^2 = M_W^2$. $M_W$ is the $W$ boson mass, and the factor $K(y_{W})$ contains higher-order QCD radiative corrections which are discussed in Section 5.2. Furthermore, we can derive the $x$ value related to the rapidity of the $W$ boson from momentum and energy conservation in Eqn. 1.4. The relationship is shown in Figure 1.4.

$$
x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W},
$$

(1.4)

Figure 1.4: The $x$ values of the quark for $W$ production at the Tevatron.
where are

This plot would be better on a semi-log scale (log x)
In a $p\bar{p}$ collider at Tevatron energy, $W$ bosons are reconstructed primarily from $W \to \mu\nu$ or $e\nu$ leptonic decays. The $W \to q\bar{q}$ hadronic decay is usually buried inside a large QCD background ($p\bar{p} \to \text{jets}$), as are the $\tau$'s from the $W \to \tau\nu$ process. In approximately 10% of the $W$ events, the $W$ decays into an electron* and a neutrino. These are the events which we use in this thesis to measure the $W$ production charge asymmetry.

The neutrino is not detected, and passes through the detector without interacting. The electron, on the other hand, leaves a track in the tracking chamber, and also deposits its energy in the calorimeters that surround the interaction region. Furthermore, the leading order $W$ boson production mechanism results in the $W$ boson being polarized in the $\bar{p}$ direction by means of the $V-A$ structure of the weak interaction as shown in Figure 1.5.

![Figure 1.5: The momenta (arrows) and helicities (large outlines of arrows) in $p\bar{p} \to W^\pm$ production and $W^\pm$ leptonic decay in leading order.](image)

The $V-A$ structure means that the weak current couples only to left-handed $u$ and $d$ quarks (or to right-handed $\bar{u}$ and $\bar{d}$ quarks). For ultra-relativistic quarks, where helicity and chirality are approximately equivalent, this results in full polarization of the produced $W$ bosons in the direction of the beam. The $W$ leptonic decay process also couples only to left-handed $e^-$ and right-handed $\bar{\nu}$ (or right-handed $e^+$ and left-handed $\nu$).

*we will use the word electron to refer both the electron and its anti-particle, the positron.
is is done because

e new paragraph

define helicity

(handedness)
generically
	often
ν). The conservation of angular momentum favors a decay with the final state lepton (neutrino or electron) at a small angle with respect to the initial state quark direction (and a similar small angle between the initial state anti-quark and final anti-lepton). The systematic shift in lepton pseudo-rapidity with respect to $y_W$ depending on the charge of the final state lepton is illustrated in Fig. 1.6, which shows the lepton pseudo-rapidity vs. $W$ rapidity for the different charges.

![Figure 1.6: (a) The positively charged W boson and lepton rapidity distribution. (b) The negatively charged W boson and lepton rapidity distribution.](image)

1.4 $W$ Charge Asymmetries

$W^+(W^-)$ bosons are produced in $p\bar{p}$ collisions primarily by the annihilation of $u(d)$ quarks in the proton and $\bar{d}(\bar{u})$ quarks in the anti-proton. Since $u(x_1) = \bar{u}(x_2)$ and $d(x_1) = \bar{d}(x_2)$ by CPT symmetry, the differential cross sections for $W^\pm$ are approxi-
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mately

\[ \frac{d\sigma^+}{dy_W} \approx \frac{2\pi G_F}{3\sqrt{2}} \left[ u(x_1)\bar{d}(x_2) \right], \quad (1.5) \]

\[ \frac{d\sigma^-}{dy_W} \approx \frac{2\pi G_F}{3\sqrt{2}} \left[ d(x_1)\bar{u}(x_2) \right]. \quad (1.6) \]

Since the \( u \) quark tends to carry a larger fraction of the proton’s momentum than the \( d \) quark on average, the \( W^+(W^-) \) is boosted in the proton (anti-proton) direction as shown in Fig. 1.7(a). The \( W \) production charge asymmetry, \( A(y_W) \), in the leading-order parton model is therefore

\[
A(y_W) = \frac{\frac{d\sigma^+}{dy_W} - \frac{d\sigma^-}{dy_W}}{\frac{d\sigma^+}{dy_W} + \frac{d\sigma^-}{dy_W}} = \frac{u(x_p)d(x_p) - d(x_p)u(x_p)}{u(x_p)d(x_p) + d(x_p)u(x_p)} = \frac{R_{du}(x_p) - R_{du}(\bar{x}_p)}{R_{du}(x_p) + R_{du}(\bar{x}_p)},
\]

(1.7)

where we use Eq. 1.5 and Eq. 1.6 and introduce the ratio \( R_{du} = \frac{d(x)}{u(x)} \). As we see in Eq. 1.7, there is a direct correlation between the \( W \) production charge asymmetry and the \( d/u \) ratio. A precise measurement of the \( W \) production charge asymmetry serves as a valuable constraint on the \( u \) and \( d \) quark momentum distributions [1].

Since the \( W \) leptonic decay involves a neutrino whose longitudinal momentum is experimentally undetermined, the charge asymmetry previously has been constrained by the measured charge asymmetry of the decay leptons as a function of the lepton pseudo-rapidity. The lepton charge asymmetry is defined as:

\[
A(y_l) = \frac{\frac{d\sigma^+}{dy_l} - \frac{d\sigma^-}{dy_l}}{\frac{d\sigma^+}{dy_l} + \frac{d\sigma^-}{dy_l}},
\]

(1.8)

Previous measurements [2, 3, 4] are described in the end of this section.
these equations are incorrect... should not have the "bar" indicating anti-quarks. Also for consistency below, x1 should be xproton and x2 should be xpbar.

therefore

citations to Run I and Run II CDF and D0 papers
Chapter 1. Introduction

However, as shown in Fig. 1.7(b), there is a “turn-over” in the lepton charge asymmetry due to a convolution of the \( W \) production charge asymmetry and the \( W V \to A \) decay. This “turn-over” depends on the lepton kinematics, while the \( W \) production charge asymmetry is free from this effect. This convolution means leptons from a single pseudorapidity come from a range of \( W \) rapidity and thus a range of parton \( x \) values. Thus, the measured lepton asymmetry is more complicated to interpret in terms of quark distributions, and we expect the measurement of the asymmetry of the \( W^\pm \) rapidity distribution to be a more sensitive probe of the ratio of \( d(x) \) and \( u(x) \).

Figure 1.7: (a) The \( W \) boson and lepton rapidity distributions in \( p\bar{p} \) collisions. (b) The charge asymmetry for \( W \) production and the decay lepton.

The \( d(x)/u(x) \) ratio constraint

Experimental information on \( d(x)/u(x) \) has usually come from measurements of the \( F_2^n/F_2^p \) structure function ratio, with the neutron structure function \( F_2^n \) extracted from \( F_2^p \) and the deuteron \( F_2^D \) structure functions [5, 6, 7], and the deuterium data are sensitive to nuclear corrections. Consequently, the determination of the \( d(x) \) valence quark
direct

Measurements of t
distribution depends on the modeling of nuclear effects in the deuteron [8, 9]. Another possibility of pinning down the $d(x)/u(x)$ ratio came from the lepton charge asymmetry in $W$ boson decays in $p\bar{p}$ collisions. The $W$ charge asymmetry data in $p\bar{p}$ collisions are free from the kind of theoretical uncertainties that affect the DIS data. The results at Tevatron provided a valuable constraint on the $u$ and $d$ quark distribution in global PDF fits and are shown in Figure 1.8(a), Figure 1.8(b), and Figure 1.8(c).

![Figure 1.8(a)](image1)
- CDF Run I data (110 pb$^{-1}$)

![Figure 1.8(b)](image2)
- CDF Run II data (170 pb$^{-1}$)

![Figure 1.8(c)](image3)
- DØ Run II data (300 pb$^{-1}$)

Figure 1.8: The charge asymmetry for $W$ decay lepton in $p\bar{p}$ collisions.
Previous constraints on the 
also come 

has an advantage over the determination from proton and deutron structure functions as it is 
mentioned above 

in nuclear effects 

repeat the previous citations here as well
1.5 Thesis Outline

The Tevatron accelerator complex and the detectors used to collect the collision data are described in Chapter 2. In Chapter 3 the datasets used in the analyses presented here, the trigger and reconstruction requirements to identify the electron and to select our $W \rightarrow e\nu$ events are shown. Chapter 4 discusses the measurement of backgrounds. Our analysis technique for the $W$ production charge asymmetry is introduced in Chapter 5. The corrections required to remove any bias are described in Chapter 6. Finally, the measurement of $W$ production charge asymmetry and the uncertainties of this measurement are presented and discussed in Chapter 7.
Chapter 2

Experimental Apparatus

The experimental apparatus is located at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois. The detector used in this analysis is the Collider Detector at Fermilab (CDF), a multi-purpose experiment that records proton-antiproton collisions in the Tevatron accelerator. In this chapter we describe the accelerator and CDF detector, with emphasis on the components which are used in the $W$ charge asymmetry measurement with electrons. The trigger systems are discussed in Section 2.3.

2.1 The Fermilab Tevatron

The accelerator complex [10] is shown schematically in Figure 2.1. We can use this diagram to follow the protons and antiprotons from their production to their final collision in the center of the CDF detector.

The Pre-Accelerator, Linac and Booster

Everything starts at a Cockroft-Walton pre-accelerator that generates $H^-$ ions with 750 keV of kinetic energy. These ions are fed into the linear accelerator (Linac) in bunches...
I

with an

k
Figure 2.1: The Fermilab accelerator complex.
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at a rate of 201.24 MHz.

The Linac accelerates the $H^-$ ions to 400 MeV using the electric field in RF cavities that extend for 150 m. These bunches of accelerated $H^-$ ions are then injected into the Booster.

The Booster is a circular synchrotron 151 m in diameter. At injection, the $H^-$ ions are stripped of their electrons by passing them through a thin carbon foil. The protons are then accelerated to 8 GeV and passed to the Main Injector.

The Main Injector is also a circular synchrotron with a diameter of 1 km, where protons from the Booster are accelerated from 8 GeV to 150 GeV. Antiprotons, produced by 120 GeV protons at the Antiproton Source (see below) are focused, re-tuned and accelerated from 8 GeV to 150 GeV in the Main Injector. (The Main Injector provides the 120 GeV protons to the Antiproton Source, which is used to produce and collect 8 GeV antiprotons.)

**The Antiproton Source**

The 120 GeV protons from the Main Injector impact a nickel target at the Antiproton Source. The produced particles include antiprotons, with an efficiency of one antiproton of 8 GeV per $\approx 50,000$ incident protons (after focusing and filtering). To provide good bunches for collisions in the Tevatron, the antiproton beam has to be reduced in its transverse-momentum phase space. This process is called stochastic “cooling”, after which bunches of well focused antiprotons are transferred to the Main Injector to be accelerated to 150 GeV.

**Tevatron**

The Tevatron is the final stage of acceleration. This synchrotron accelerator ring has a diameter of $\approx 2$ km, and uses superconducting magnets of up to $\approx 4$ Tesla to bend and
radio frequency

remaining

by multiple passes around the ring through electromagnetic fields in cavities

also

in a process

this,
contain the beam. The 150 GeV protons and antiprotons are accelerated to 980 GeV in opposite directions, leading to 1.96 TeV collision energy in the center of mass. A total of 36 bunches of protons and 36 bunches of antiprotons share the same pipe and travel in opposite directions. Each proton bunch carries roughly $3 \times 10^{11}$ protons, and the antiproton bunches carry $\approx 3 \times 10^{10}$ antiprotons. These bunches collide at two points of the ring (DØ and CDF) with a design frequency of one collision every 396 ns.

2.2 The Collider Detector at Fermilab (CDF)

The Collider Detector at Fermilab (CDF II) is a general purpose detector designed to study the physics of $p\bar{p}$ collisions at the Tevatron accelerator at Fermilab. Like most detectors used in high energy collision experiments it has a cylindrical geometry with axial and forward-backward symmetry. The innermost part of the detector contains an integrated tracking system with a silicon detector, and an open cell drift chamber immersed in a 1.4 T solenoidal magnetic field. The integrated tracking system is surrounded by calorimeters. Outside of the calorimeters is a muon system. A more detailed elevation view labeling the different components is shown in Figure 2.2.

2.2.1 CDF Coordinate System

CDF uses a spherical system of coordinates, with the $z-$axis oriented along the beam direction, where positive $z$ is defined as the direction in which the protons are traveling. The origin is at the center of the detector. The polar angle $\theta$ is the angle measured from the positive $z-$axis. The angle $\phi$ is the angle measured from the vector lying in the plane of the accelerator pointing away from the center (shown in Figure 2.3). Since in hadron colliders the center of mass frame can be boosted along the $z$ axis, it is useful to define quantities that are perpendicular to the $z$ axis. The transverse (or $r-$plane) is
bunch crossing at the interaction regions

der

do not cross-out

may

of the interacting partons

phi
defined as the plane perpendicular to the \( z \) axis. Transverse quantities (such as \( E_T, p_T \), etc) are the components of those quantities in the transverse plane. The pseudorapidity \( \eta \), indicated in Figure 2.4 is defined as

\[
\eta = - \ln \tan \frac{\theta}{2}.
\]

(2.1)

The pseudorapidity is an approximation to rapidity \( y = \frac{1}{2} \ln \left( \frac{E+p_z}{E-p_z} \right) \), and corresponds to \( y \) when particle masses can be neglected. Two forms of pseudorapidity are used. The detector pseudorapidity, \( \eta_d \), measures the pseudorapidity from the nominal interaction point at the center of the detector. It is frequently used to specify the physical segmentation of the detector. The event pseudorapidity, \( \eta \), measures the pseudorapidity of particles from a \( p\bar{p} \) interaction with respect to the interaction vertex.
Because the interaction region at CDF is long along the z direction, approximately 120cm, there is often a significant difference between the two quantities.
The instantaneous luminosity, $\mathcal{L}$, is defined by

$$\mathcal{L} = f \frac{n_p n_{\bar{p}}}{4 \pi \sigma_p \sigma_{\bar{p}}}.$$  \hspace{1cm} (2.2)

Here, $f$ is the frequency of crossing for bunches containing $n_p$ protons and $n_{\bar{p}}$ anti-protons, and the Gaussian transverse beam profiles are given by $\sigma_p$ and $\sigma_{\bar{p}}$. The conventional unit for luminosity is $cm^{-2}s^{-1}$. However, the factors in Eqn 2.2 cannot be measured with sufficient precision. Since measuring the integrated luminosity is necessary to predict event yields and monitoring the instantaneous luminosity critical to detector operation, a custom detector must be used to determine the luminosity. For Run II, CDF uses a Cherenkov Luminosity Counter (CLC) to measure the instantaneous luminosity [11]. The CLC has two modules, each located in the small $3^\circ$ conical hole in the high $\eta$ region of the forward calorimeter. The luminosity monitor is constructed of...
before this

new paragraph

At the Tevatron

to predict the collision luminosity

from the production of particles in the collisions themselves
an array of segmented counters, with each counter being 2 m long and several cm in diameter. The counters are constructed of aluminized mylar and filled with isobutane gas. A fast PhotoMultiplier Tube (PMT) at the end of each counter collects the Cherenkov light from charged particles radiating in the gas, and gives a timing resolution of better than 100 ps. This resolution is needed for coincidence measurement between the two CLC modules. The projective design of the counters means that they have reduced sensitivity to secondary particles produced in the detector or from beam pipe interactions. The CLC is also not sensitive to beam halo particles since they hit the CLC from behind generating Cherenkov light going away from the PMTs. Measuring the number of hits in the CLC allows calculation of the instantaneous $L$ as defined by Eqn. 2.3.

$$L = \frac{f_{BC} < N_H >_a}{\sigma_{in} \epsilon_a < N_H^1 >_a}.$$  \hspace{1cm} (2.3)

Here $f_{BC}$ is the bunch crossing frequency, and $\sigma_{in}$ the inelastic $p\bar{p}$ cross section. Given the selection criteria $\epsilon_a$ is the CLC efficiency, $< N_H >_a$ the number of hits in the CLC for the bunch crossing, and $< N_H^1 >_a$ the number of hits in the CLC for a single $p\bar{p}$ collision. The measured error on the acceptance of the CLC is 4\%, and along with the error on the measured inelastic $p\bar{p}$ cross section of 4\%, gives an integrated luminosity error of 6\% for Run II data collection.

### 2.2.3 Tracker

The "integrated tracking system" at CDF, shown in Figure 2.4, involves a new open cell drift chamber, the Central Outer Tracker (COT), and the "silicon inner tracker" system, which consists of 3 independent structures: the Layer00 detector (L00), the Silicon Vertex Detector (SVX), and the Intermediate Silicon Layer (ISL). Both the SVX and ISL employ double sided silicon, where one side makes measurements in the transverse
\noindent here (this comes up a lot... when you don't mean to start a new paragraph after an equation, use "\noindent")
an array of segmented counters, with each counter being 2 m long and several cm in diameter. The counters are constructed of aluminized mylar and filled with isobutane gas. A fast PhotoMultiplier Tube (PMT) at the end of each counter collects the Cherenkov light from charged particles radiating in the gas, and gives a timing resolution of better than 100 ps. This resolution is needed for coincidence measurement between the two CLC modules. The projective design of the counters means that they have reduced sensitivity to secondary particles produced in the detector or from beam pipe interactions. The CLC is also not sensitive to beam halo particles since they hit the CLC from behind generating Cherenkov light going away from the PMTs. Measuring the number of hits in the CLC allows calculation of the instantaneous $\mathcal{L}$ as defined by Eqn. 2.3.

$$\mathcal{L} = \frac{f_{BC} < N_H >_\alpha}{\sigma_{in} \epsilon_\alpha < N_1^H >_\alpha}.$$  \hspace{1cm} (2.3)

Here $f_{BC}$ is the bunch crossing frequency, and $\sigma_{in}$ the inelastic $p\bar{p}$ cross section. Given the selection criteria $\alpha$, $\epsilon_\alpha$ is the CLC efficiency, $< N_H >_\alpha$ the number of hits in the CLC for the bunch crossing, and $< N_1^H >_\alpha$ the number of hits in the CLC for a single $p\bar{p}$ collision. The measured error on the acceptance of the CLC is 4%, and along with the error on the measured inelastic $p\bar{p}$ cross section of 4%, gives an integrated luminosity error of 6% for Run II data collection.

### 2.2.3 Tracker

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this

Sequence number: 12
Author: Kevin McFarland
Subject: Replacement Text
Date: 4/12/2008 12:31:08 PM

uncertainty

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Author: Kevin McFarland
Subject: Cross-Out
Date: 4/12/2008 12:31:29 PM


Sequence number: 14
Author: Kevin McFarland
Subject: Inserted Text
Date: 4/12/2008 12:31:30 PM

T
plane, and the other side is used to make measurements in the z direction.

**Silicon detectors** (SVX, L00, ISL)

The silicon inner tracker consists of three concentric silicon detectors located at the very center of CDF.

The innermost one, L00, is a single-sided, radiation-hard silicon layer attached to the outside of the beam pipe at a diameter of 2.2 cm and a detailed view of the L00 mounting is shown in Figure 2.5. This provides complete φ coverage, and z coverage extending ±78.4 mm from z = 0.

The Silicon Vertex Detector (SVX) consists of 5 layers of silicon with an inner radius of 2.4 cm and outer radius of 10.7 cm. It is composed of three barrels, each 29 cm
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Subject: Comment on Text
Date: 4/12/2008 12:31:59 PM

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Author: Kevin McFarland
Subject: Inserted Text
Date: 4/12/2008 12:31:51 PM

Sequence number: 3
Author: Kevin McFarland
Subject: Comment on Text
Date: 4/12/2008 12:32:14 PM

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Figure 2.5: Detail of the Layer 00 Silicon along with the two innermost layers of the SVX Silicon.
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long, as shown in Figure 2.5; all together they extend about 45 cm in the \( z \) direction on each side of the interaction point covering 2.5\( \sigma \) of the luminous region. Each barrel is divided in 12 wedges in \( \phi \), where each wedge supports the five layers double-sided silicon micro-strip detectors. The double sided design provides information about \( r - \phi \) and \( z \) position while occupying the small footprint of a single sensor. The stereo side of layers 0,1, and 3 are perpendicular to the \( z \) axis, while the stereo angle of layers 2, and 4 are –1.2\(^\circ\) and +1.2\(^\circ\) respectively. Using the \( z \) position information, a 3D helix for each track can be reconstructed.

The Intermediate Silicon Layer (ISL) consists of three silicon layers placed at radii of 20, 22 and 28 cm respectively from the proton-antiproton beam. The layer at 22 cm covers the central region \( |\eta| < 1 \), while the two outer layer cover the forward region corresponding to \( 1 < |\eta| < 2 \), where the coverage from the COT falls off. The ”inner silicon tracker” when combined with the COT is designed to greatly improve the impact parameter resolution and also improve the momentum resolution.

The side view shown in Figure 2.6 is a cross-section of one half of the silicon tracker, using a compressed \( z \) scale.

Central Outer Tracker

Tracking in the central region is provided by the Central Outer Tracker, an open cell drift chamber which consists of eight superlayers (Figure 2.7) of cells placed between the radii of 40 and 132 cm from the beam pipe. The tracking volume is divided into 8 super layers (SL), 4 axial layers (for \( r - \phi \) measurement) and 4 stereo layers (for \( z \) measurement) with the structure shown in Figure 2.7. The superlayers alternate between stereo and axial, with the innermost superlayer being stereo. The design of three cells from SL2 can be seen in Figure 2.7. Ar-Ethane gas (60:40 mixture) fills the active chamber volume and both provides a source of ionized electrons and defines the drift
axis

to illustrate coverage in \( \eta \)
Chapter 2. Experimental Apparatus

Figure 2.6: A side view of half of the CDF Run II silicon system.
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velocity of the gas. The tracking resolution is given by

$$\frac{\Delta \theta}{\theta} = 0.15\%.$$  \hspace{1cm} (2.4)

where the momentum is in units of GeV/c. The tracking system is a crucial element in the identification of the electrons in the central region, as electron candidates are formed by energy clusters in the electromagnetic calorimeter which match a track in the COT. The electron identification algorithms use the curvature information and the direction of the track.
approximately

\[ \sigma_p/p^2 \]

momentum

this must be wrong (units). Also, put this in-line, not as a separated equation
2.2.4 Calorimeters

Surrounding the tracking volume and solenoid, the CDF calorimeter modules measure not only the energy of particles but also a coarse position. All of the calorimeters in CDF are based upon sandwiching scintillating material between layers of heavy material. As charged particles progress through the calorimeters they interact and develop characteristic 'showers'. Whereas electrons and photons shower quickly and are largely contained in the electromagnetic calorimeter, hadron jets pass through and leave significant energy in the hadronic calorimeters. Specific showering materials allow sensitivity to either electromagnetic (high \(Z\) material) or hadronic (high \(A\) material) particles. In the CDF detector, the electromagnetic calorimeters are immediately followed by hadronic calorimeters. The calorimeter is divided into a central calorimeter covering \(|\eta| < 1.1\), and a forward calorimeter providing coverage out to \(|\eta| < 3.6\). A summary of the sub systems is given in Table 2.1.

Table 2.1: Summary of the CDF calorimeters.

<table>
<thead>
<tr>
<th>Sub Detector</th>
<th>CEM</th>
<th>CHA</th>
<th>WHA</th>
<th>PEM</th>
<th>PHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>(</td>
<td>\eta</td>
<td>&lt; 1.1)</td>
<td>(</td>
<td>\eta</td>
</tr>
<tr>
<td>Modules</td>
<td>48</td>
<td>48</td>
<td>48</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>(\eta) towers per module</td>
<td>10</td>
<td>8</td>
<td>6</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Layers</td>
<td>31</td>
<td>32</td>
<td>15</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Material</td>
<td>Lead</td>
<td>Steel</td>
<td>Steel</td>
<td>Lead</td>
<td>Iron</td>
</tr>
<tr>
<td>Radiation</td>
<td>(18\chi_0)</td>
<td>(4.7\lambda_0)</td>
<td>(4.5\lambda_0)</td>
<td>(21\chi_0)</td>
<td>(7\lambda_0)</td>
</tr>
<tr>
<td>Length</td>
<td>(1.7% + \frac{13.5%}{\sqrt{E}})</td>
<td>(80%)</td>
<td>(80%)</td>
<td>(1% + \frac{16%}{\sqrt{E}})</td>
<td>(5% + \frac{20%}{\sqrt{E}})</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>(\frac{\sqrt{E}}{E})</td>
<td>(\frac{\sqrt{E}}{E})</td>
<td>(\frac{\sqrt{E}}{E})</td>
<td>(\frac{\sqrt{E}}{E})</td>
<td>(\frac{\sqrt{E}}{E})</td>
</tr>
</tbody>
</table>
you don’t give the phi segmentation, but you do give it in eta

Absorber m

Depth
Central Electromagnetic Calorimeter (CEM, CES, CPR)

The central electromagnetic calorimeter (CEM) is constructed in $15^\circ$ wedges placed outside the solenoid and consists of 31 layers of polystyrene scintillator interleaved with layers of lead clad in aluminum. The sheets are stacked in a projective tower geometry, as shown in Figure 2.8(a), where each tower subtends $15^\circ$ in $\phi$ and 0.1 in $\eta$. It can be seen that in each wedge ‘tower 9’ is truncated; this will be important later in defining electron fiduciality. At higher $z$ some of the lead is replaced by plastic in order that the effective radiation depth be approximately independent of angle. Light is fed through waveshifts and collected in phototubes as indicated in Figure 2.8(a). After the eighth layer of lead, corresponding to the depth at which showers typically reach their maximum transverse extent, is the central shower-maximum (CES) detector. This consists of proportional chambers as shown in Figure 2.8(b) that give good position resolution.

A further component of the central calorimeters is the central pre-radiator (CPR), a set of proportional chambers between the CEM and the magnet designed to help separate electrons and pions.

Central and Wall Hadronic Calorimeters (CHA, WHA)

The central hadronic calorimeter (CHA) is immediately on top of the CEM and consists of steel layers sampled each 2.5 cm by scintillator. Filling a space between the CHA and the forward plug hadronic calorimeter (PHA) is the wall hadronic calorimeter (WHA), which continues the tower structure of the CHA but with reduced sampling each 5.0 cm. Like the electromagnetic calorimeters, the hadronic calorimeters are read out using waveshifting lightguides and phototubes.
or do you mean lightguides? i actually forget which it is... waveshifters leading to lightguides, maybe?

this makes it sound like the CPR actually is deeper than the CES

by identifying energy at the very start of the shower

surrounds
Figure 2.8: (a) A wedge of the central calorimeter, showing the projective tower geometry. (b) A central shower-max chamber shown schematically.
This page contains no comments
Chapter 2. Experimental Apparatus

Plug Electromagnetic Calorimeter (PEM, PES, PPR)

The plug electromagnetic calorimeter (PEM) was newly built for CDF Run II. Like the CEM, the PEM consists of a stack of lead and scintillator sheets read out by phototubes. At lower values of $\eta$ the tower segmentation is $7.5^\circ$ in $\phi$, doubling to $15^\circ$ at higher $\eta$ as shown in Figure 2.9, which also gives the $\eta$ segmentation. A 30 GeV electron shower will be largely contained in four of the towers at lower $\eta$. Approximately 6 radiation lengths into the PEM is a shower-maximum detector, the PES, designed to provide good position measurement. It consists of two layers of scintillator strips at $45^\circ$ to each other, assembled in $45^\circ$ sectors.

Finally, the first layer of the PEM is read out separately and referred to as the plug pre-radiator (PPR). The PPR can help to distinguish between electrons/photons and hadrons by indicating the extent to which the particle shower has already developed at the face of the calorimeter.

Plug Hadronic Calorimeter (PHA)

The plug hadronic calorimeter (PHA) consists of layers of iron and scintillator, extending back from maintaining the same segmentation as the PEM.

2.2.5 Muon System

Outside of all other sub detectors is the CDF muon system. As can be seen from the generalized detector response, a high $p_T$ muon will leave a track in the tracking volume but very little energy deposition in the calorimeter. This is due to the $1/M^2$ suppression of EM Bremsstrahlung and the weak interaction of the muon. In order to distinguish muon tracks from electrons and pions that escaped the detector through cracks, drift chambers and scintillators are constructed behind the calorimeter. Short track segments are reconstructed from the hits in these detectors and then matched to tracks in the
I'm not sure what you mean by this.

you don't really mean "weak interactions" here.

in the calorimeters
Figure 2.9: Forward detector segmentation.
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tracking chamber. The muon systems are not used in these analyses.

2.3 Data Acquisition and Trigger Systems

CDF has a trigger system to select scientifically interesting events from all of the events that take place during $p\bar{p}$ collisions and to not exceed the current data acquisitions limitations. The CDF trigger system consists of three levels. Each level is successively more sophisticated and takes a longer time to reach a decision. If all three trigger levels are passed, the event is written out to tape. Each of the levels consists of a logical OR of a number of triggers which are designed to find many types of events. The trigger allows for the event storage rate to be reduced from the bunch crossing rate of $2.5 MHz$, to a rate within the limits of the DAQ system, $100 Hz$. The structure of the trigger is shown in Figure 2.10 and the details of each level of the trigger will be discussed next.

Level 1

The goal of the Level-1 (L1) trigger is to process information on every beam crossing $(2.5 MHz)$, and reduce the rate to less than $30 kHz$. There are three parallel processing streams finding calorimeter objects, muons and tracks respectively, which may be combined with AND and OR to give 64 triggers. At L1, calorimeter objects consist of single tower energies, tracks are 2-dimensional as found by the eXtremely Fast Tracker (XFT) which compares COT hits to look-up tables; and muons consist of a 'stub' in the muon chambers matched to a track within $2.5^\circ$ in $\phi$.

Level 2

The goal of the Level-2 (L2) trigger is to reduce the rate from L1 ($< 30 kHz$) to $300 Hz$. Events accepted by L1 are processed by the second level of trigger, which is com-
 shouldn't be typeset in math mode. This occurs twice in this sentence and over and over again below. They should all be fixed.
Figure 2.10: The three level deadtime-less trigger used to control the DAQ of the CDF detector.
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posed by several asynchronous subsystems. L2 collects the information available at L1 and does some further reconstruction. It identifies displaced vertices seeded by the L1 tracks, collects nearby towers with energy depositions into calorimeter clusters, and measures the amount of energy deposited in the CES detector in each wedge. All of this information is sent to the programmable L2 processors in the Global Level-2 crate, which evaluate if any of the L2 triggers are satisfied.

**Level 3**

The Level-3 (L3) trigger consists of two components, the event builder and the L3 processing farm. The event builder consists of custom built hardware used to assemble and package all of the information from a single event. The L3 farm runs a version of the full offline reconstruction code. This means that for example fully reconstructed 3-dimensional tracks are available to the trigger decision. The L3 output rate is $\sim 75\,Hz$ and accepted events are written to tape in eight separate 'streams', sorted by trigger, by the Consumer-Server Logger (CSL).

All events passing a L3 trigger are collected from the detector and processed with the CDF Offline reconstruction. The details of the analysis and selection of $W \to e\nu$ events are described in the Chapter 3.
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Chapter 3

Data Reduction and Signal Extraction

This analysis focuses on the electron decay of the $W$, and uses a high transverse momentum ($p_T$) electron trigger that selects events containing electron candidates. $W$ candidate events are selected from reconstructed events with one high $p_T$ electron in the central or forward calorimeters and an imbalance of calorimeter energy due to the undetected neutrino. In this chapter, the details of the trigger, event reconstruction and the event selection are discussed and the requirements of the $W \rightarrow e\nu$ sample and the $Z \rightarrow e^+e^-$ sample are presented.

3.1 Data Samples

3.1.1 CDF data

Three data samples are employed in this analysis. These are obtained from the inclusive high-$p_T$ electron data sample.

- The $W \rightarrow e\nu$ sample: Two samples of $W \rightarrow e\nu$ candidates, where electrons are in the central or forward region, are used to measure $W$ charge asymmetry and to study the boson recoil energy scale.
This page contains no comments
• The $Z \rightarrow e^+e^-$ sample: A sample of dielectron candidates is used to calibrate the energy scale and resolution of the EM calorimeter, to study the efficiency of electron identification, and to check charge biases in measuring electrons.

• The dijet sample: A sample of dijet events (events with at least one jet with $E_T > 15\text{GeV}$) is used to measure the rate at which a jet fakes an electron signature and to estimate the dijet background.

3.1.2 Monte Carlo generation and simulation

The Monte Carlo (MC) generation and simulation are used to estimate the acceptance for the $W \rightarrow e\nu$ process, to determine the characteristics and amount of background in the data sample, and to understand the systematic uncertainties on the $W$ charge asymmetry. PYTHIA [13] generator with the CTEQ5L PDFs [14] is used for all samples. PYTHIA generates processes at the leading order (LO) and incorporates initial and final state QCD and QED radiation via its parton shower algorithms. The sample is tuned so that the underlying event and $p_T$ spectrum of $Z$ bosons agree with the CDF data [16]. The detector simulation models the decay of generated particles and their interactions with the various elements of the CDF detector. The calorimeter energy scale and resolution in the simulation are tuned so that the mass distribution of the $Z \rightarrow e^+e^-$ event in the simulation match with those from the data (see Section 6.1). These are three Monte Carlo samples used in this analysis, which are briefly described below.

• The $W \rightarrow e\nu$ sample: A sample of 20M events generated with PYTHIA is used to calculate the correction due to acceptance and recoil energy scale and to estimate the systematic uncertainties on the $W$ charge asymmetry.

• The $Z \rightarrow e^+e^-$ sample: A sample of 10M events generated with PYTHIA is used to calculate the corrections due to electron energy scale and resolution, elec-
tron identification, and charge mis-identification and estimate the background.

- **The $W \rightarrow \tau \nu (\tau \rightarrow e \nu)$ sample**: A sample of 16 M events generated with PYTHIA is used to calculate the correction due to acceptance. The $W \rightarrow e \nu$ signature can be reproduced by $W \rightarrow \tau \nu$ events in which the $\tau$ lepton subsequently decays into an electron and it is included in the acceptance.

For each sample, we use two different simulated samples, GEN5 and GEN6, according to CDF software offline version. GEN5 MC corresponds to the collected data up to February 2004 and GEN6 MC corresponds to the data from December 2004 to February 2006.

### 3.2 Trigger

The $W \rightarrow e \nu$ event is based upon the high energy electron or positron. The identification of electrons begins with the online trigger system, which selects events with electron characteristics. The charged lepton produces a signal in both the calorimeter and the tracker that can be matched in coincidence. For electrons in the central calorimeter, events are selected using only this single object selection. For $W$ decays with electrons in the forward calorimeter, the tracking coverage does not allow for coincidence between the calorimeter and tracking information. To overcome this, a trigger decision based on both the electron calorimeter information and missing transverse energy is used to select events. Using these two triggers, the data events were selected for analysis as $W$ candidates. The detailed requirements of each trigger path are described in the next sections.
I think you meant to add "background from Z events to the W asymmetry sample". Yes?

signal

when calculating

This sample is part of the signal itself, since it has the same underlying charge asymmetry,
3.2.1 Central Electron Trigger: ELECTRON_CENTRAL_18 path

The central electron trigger selects electron candidates with a high-$E_T$ electron in the central region ($|\eta| < 1.1$). In order to have understood trigger efficiencies, for an event to be considered at L2, it must have passed the prerequisite L1 trigger. Similarly at L3, the event must have passed the prerequisite L2 trigger. The trigger efficiency is then the simple product of the individual trigger efficiencies. The following paragraphs describe the selection requirements at each of the three trigger levels.

- **Level 1: L1_CEM8_PT8** This requires a central electromagnetic (EM) cluster with $E_T^{EM} > 8$GeV and $E^{EM}/E^{EM} < 0.125$ for clusters with energy less than 14 GeV. An XFT track with $p_T > 8$GeV/c must be matched to the trigger tower containing the EM cluster.

- **Level 2: L2_CEM16_PT8** This requires a central EM cluster with $E_T^{EM} > 16$GeV and the ratio $E^{HAD}/E^{EM} < 0.125$ for all clusters. An XFT track with $p_T > 8$GeV/c must be matched to the L2 cluster.

- **Level 3: L3_CENTRAL_ELETRON_18** This requires a central EM cluster with $E_T^{EM} > 18$GeV and $E^{HAD}/E^{EM} < 0.125$. A fully reconstructed 3D track with $p_T > 9$GeV/c must be matched to the seed tower of the EM cluster.

When the trigger requirements of all three levels are combined, the efficiency for identifying a central electron with $E_T > 25$GeV from $W \rightarrow e\nu$ decay is $\sim 98\%$. A detailed description of the trigger efficiencies is supplied in Appendix A.1.

3.2.2 Plug Electron Trigger: MET_PEM path

The plug electron trigger selects events with both a high-$E_T$ electron candidate and missing transverse energy, $E_T$. The three trigger levels are described in the following paragraphs.
calculable

reconstructable
Chapter 3. Data Reduction and Signal Extraction

- **Level 1: L1_EM8_MET15** This requires an EM cluster with $E_T^{EM} > 8 \text{ GeV}$ and $E^{HAD}/E^{EM} < 0.125$ for clusters with energy less than 14 GeV. The $E_T$ must be greater than 15 GeV with the $z$ coordinate of the interaction assumed to be zero.

- **Level 2: L2_PEM20_MET15** This requires an plug EM (PEM) cluster with $E_T^{EM} > 20 \text{ GeV}$ and the ratio $E^{HAD}/E^{EM} < 0.125$ for all clusters. There is an implicit cut on the $E_T$ since only events passing the L1_EM8_MET15 trigger are considered for L2.

- **Level 3: L3_PEM20_MET15** This requires an plug EM (PEM) cluster with $E_T^{EM} > 20 \text{ GeV}$ and $E^{HAD}/E^{EM} < 0.125$. The $E_T$, which is offline $E_T$ calculated at $z = 0$, must be greater than 15 GeV.

The efficiency for identifying a plug electron with $E_T > 25 \text{ GeV}$ and $E_T > 25 \text{ GeV}$ from $W \rightarrow e\nu$ decay is $\sim 96\%$. A detailed description of the trigger efficiencies is also supplied in Appendix A.2.

### 3.3 Electrons

The tracking and calorimetry of the CDF detector allow us to identify electrons and measure their energies with high precision. Using information from several detector subsystems, the trajectories of electrons from $p\bar{p}$ collisions can be traced from the interaction region, through the tracking subsystems, and into the electromagnetic calorimeters.

#### 3.3.1 Calorimeter Clustering

Using the objects selected by the high-$p_T$ central and forward trigger, the offline selection of electron candidates begins with the formation of EM clusters in the calorimeters. The initial step in the clustering is to apply tower-to-tower calibrations and to sort the
reconstructable
towers by $E_T$ considering only towers with greater than 100 MeV of energy. At this stage the event vertex is assumed to be located at $z = 0$ for all transverse calculations. Starting with the highest $E_T$ tower, a tower is considered for addition to the cluster. The neighboring towers are now considered for addition to the cluster. Since the geometry of the detectors is different, the clustering strategy varies between the two detectors and the candidate neighboring towers are different in the CEM and PEM.

In the CEM, only towers that neighbor the seed tower in $\eta$ are considered for the cluster. Therefore a CEM cluster will be completely contained within a single wedge. If the neighbor tower has an $E_T$ greater than 100 MeV it is added to the cluster. After considering all neighbor towers, a CEM cluster will have 1, 2, or 3 towers contained in the cluster.

In the PEM, all towers sharing a border or corner with the seed tower are considered as neighbor towers. There are then 8 possible neighboring towers that can be added to the seed tower. These 8 towers are sorted by EM $E_T$. If it has an $E_T$ greater than 100 MeV, the highest $E_T$ tower is selected as the seed tower’s daughter. The clustering now searches for a pair of towers to combine with the seed and daughter towers to make a $2 \times 2$ tower cluster. It considers all $2 \times 2$ combinations, and selects the one with highest $E_T$. If the additional pair of towers has an $E_T$ greater than 100 MeV, then the towers are added to the cluster. This algorithm most commonly produces 4 towers clusters in a $2 \times 2$ configuration.

### 3.3.2 Track Reconstruction

Tracks are a key component in the identification of particles. Having efficient and precise reconstruction is crucial for this analysis. Two tracking algorithms are used to identify charged particles traversing the detector in the offline reconstruction. For particles that cross the calorimeter in $|\eta| < 1.6$ and COT, a hit-based tracking reconstruction is
I can't make sense of this. I think you mean that they have detector eta (which you introduced in the introduction) is <1.6 and that it crosses the COT.
used. But for particles that enter the forward calorimeter outside of $|\eta| = 1.6$, a silicon standalone tracking in the only SVX detector (SISA) is used because of the COT range. The details of the two algorithms are now discussed.

COT tracking

The central track reconstruction algorithm uses several difference strategies to form 3-dimensional charged-particle tracks [17]. The resulting 3D tracks have a transverse momentum resolution of $\sigma(p_T) = 0.15\% p_T^2$ with unit of GeV/c. The reconstruction begins with individual hits of the COT channels. After timing calibration, the initial segment-finding algorithm groups hits in the axial super layers (SLs) into segments based upon both the hit location within the cell and the timing of the hits. During the initial segment-building processing, hits in a SL may be shared by two different segments. But after the processing is finished within the SL, only the segment with the greater total hits retains the shared hit. After completing the construction of the axial segments, a histogramming algorithm is run to create additional segments that the initial segment finder may have missed. The second set of segments is then merged together into the initial segment link. Once segments have been formed in all of the axial SLs, these segments are linked together to form 2D tracks in the $r-\phi$ plane. The segment-finding algorithm is then repeated in the stereo layers. These additional segments are now considered for addition to the 2D tracks in order to provide $z$ information. If a 2D track does not have any stereo hits after the stereo segment linking, the individual hits in the stereo layers are considered for addition to the track. If enough stereo hits are successfully matched to the track, the hits are retained for track $z$ information. After the addition of the stereo segment, the tracks now have full $p_T$ and 3D orientation information. The efficiency of the COT tracking reconstruction was measured using central electron $W$ events triggered without any track requirement. It was found to be 99.3% [18] for these high-$p_T$ isolated tracks.
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Date: 4/12/2008 1:45:15 PM

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Subject: Inserted Text
Date: 4/12/2008 1:45:30 PM

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Subject: Comment on Text
Date: 4/12/2008 1:47:32 PM

I think it's better to write this as 0.15%p_T^2/(1 GeV/c) or p_T^2/(600 GeV)

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Date: 4/12/2008 1:52:07 PM

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Author: Kevin McFarland
Subject: Inserted Text
Date: 4/12/2008 1:52:26 PM
SISA tracking

The standard SVX II tracking at CDF starts with a COT track and searches for SVX II hits by extrapolating the COT track into the SVX II geometrical region. However, the silicon standalone tracking (SISA) in forward region is a track finding procedure for electrons (or positrons) using only SVX II hits. The SISA tracker starts by collecting \( r \phi \) hit combinations from 5 axial layers [19]. Track candidates with 4 or 5 hits are fitted with a curve to obtain the axial track parameters. Once an \( r \phi \) fit is done, the corresponding \( r z \) hits are searched. SVX II has three 90° layers and two small-angle stereo (SAS) layers. The \( r \phi \) hits and SAS hits, are used to reconstruct a silicon 3-D hits, and then a seed line of SISA track is reconstructed using 3-D hits and the primary vertex information. After making the seed line, the hits in the 90° layers are searched. Finally the candidate tracks are tested with a minimum \( \chi^2 \) from all combinations. All tracks from the standalone program are refitted using a CDF refit program which takes into account the energy loss and material effect.

3.3.3 Identification Variables

The following electron identification variables are applied to the electron candidates to reject backgrounds and enhance the fraction of true electrons. Because the sub detectors are constructed differently, the identification variables are different for central and forward electrons.

Central Electron

- \( E_T \): The transverse energy of the electron candidate is \( E \times \sin \theta_e \). \( E \) is the energy of the two most energetic towers in the calorimeter cluster, and \( \theta_e \) is the angle at the beam spot of the COT track matched to the seed tower of the CEM cluster.
multiple scattering in the tracker
• **Had/Em**: The ratio of the total hadronic to total electromagnetic energy in the calorimeter cluster. For this quantity, all three towers in the CEM cluster are used to calculate the ratio.

• **$E_{iso}^{T}$**: The electron isolation is sum of the total energy in a cone of 0.4 centered on the CEM cluster, with the three towers in the CEM cluster excluded from the sum.

• **$P_T$**: The transverse momentum of the electron comes from the COT, beam constrained track that is matched to the CEM cluster.

• **$E/P$**: The ratio of the cluster energy to the track momentum. The tower energy and the COT, beam constrained track quantities are used to calculate the ratio.

• **$L_{shr}$**: A comparison between the lateral profile of the calorimeter cluster and that expected from testbeam. The energies in towers adjacent to the cluster seed tower are summed in the following way:

$$L_{shr} = 0.14 \sum_{adjacent\ towers\ i} \frac{E_i - E_{i}^{expected}}{\sqrt{(0.14 \sqrt{E_i})^2 + (\Delta E_{i}^{expected})^2}},$$

where $E_{i}^{expected}$ is parameterized from the testbeam data and $\Delta E_{i}^{expected}$ is its error, and $0.14 \sqrt{E_i}$ is the uncertainty on the energy measurement [20].

• **Track Quality Cuts**: The requirements are applied on the number of segments used to construct the track. This ensures that the track has well constructed 3D information and accurate momentum resolution.

• **CES Strip $\chi^2$**: The CES shower profile is compared with testbeam templates for the CES cluster matched to the CEM cluster. The shower profile is only compared
needs more explanation?
in the $z$ direction since bremsstrahlung commonly distorts the $\phi$ profile. The $\chi^2$ is scaled with an energy dependent factor since the shower profile is known to change with electron $E_T(\text{GeV})$ while the template is based upon single 50 GeV electrons.

- $\mathbf{q}\Delta x$ and $\Delta z$: The separation between the track and cluster at CES. The CES has good position resolution and can be used to determine how well a track points towards its associated cluster. The track is extrapolated to the plane of the CES and the separation between it and the CES cluster found in the $r-z$ plane, $\Delta z$, and in the $r-\phi$ plane, $\Delta x$. The magnetic field in the $r-\phi$ plane gives an asymmetry in bremsstrahlung for electrons and positrons, so an asymmetric cut is made on $q\Delta x$ rather than just on $\Delta x$.

- **Fiduciality**: In order to assure that the particle traverses an active and instrumented region of the detector, fiduciality requirements are applied. The $\phi$ location of the CES cluster must be within 21 cm of the center of the wedge, and the $|z|$ location must be between 9 and 230 cm. As well the seed tower of the cluster must not be located in the highest $\eta$ tower or in the region containing the solenoid cooling access.

**Forward Electron**

- $E_T$: The transverse energy of the electron candidate is $E \times \sin\theta_e$. $E$ is the energy of the $2 \times 2$ tower cluster in the calorimeter.

- $\text{Had}/\text{Em}$: The ratio of the total hadronic to total electromagnetic energy in the $2 \times 2$ PEM cluster.

- $E^{\text{iso}}_T$: The electron isolation is sum of the total energy in a cone of 0.4 centered on the PEM cluster, with the four towers in the PEM cluster excluded from the
(in the direction that charged particles bend in the solenoid)

you don't say what the cuts are. maybe you should give those numbers?
• PEM $3 \times 3 \chi^2$ Fit: To ensure that the PEM cluster is consistent with an electron, the energy deposition in the 9 towers centered on the PEM cluster seed tower is fit to electron testbeam data. The $\chi^2$ of this fit is used to measure the agreement. The fit is also required to contain at least 1 tower to avoid possible fit divergence and failures.

• PES $5 \times 9$ Ratio: The ratio of the energy measured in the central 5 channels to the energy in the full 9 channels of the PES cluster associated with the PEM cluster. For an electron, the energy should be deposited in the center of the PES cluster, and this removes the multi-particle final states.

• Track Quality Cuts: The PEM cluster is required to have a matched track that has been reconstructed from the COT hits or only SVX II hits. The good quality of the matched track is required to reduce the charge mis-identification of track. The quality includes $E/P$, the number of hits on the track, the residual between PES cluster and the extrapolated track position, and track $\chi^2$.

3.4 The Missing Transverse Energy ($\not{E}_T$)

Unlike the electrons, neutrinos pass through the detector without leaving any measurable signal. Although neutrinos can not be detected directly, their presence in $W$ events can be inferred from an imbalance of transverse energy in the calorimeter. This imbalance is termed the missing transverse energy and is denoted by "$\not{E}_T$." The $\not{E}_T$ for an event is calculated from all of the calorimeter towers within the region $|\eta| < 3.6$, both central and forward calorimeters. The towers are required to have greater than 100 MeV of energy to contribute to the calculation. Both the hadronic and electromagnetic energies
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are used in calculating $\vec{E}_T$. As with the other basic clustering algorithms, the event vertex is initially assumed to be at $z = 0$ in the trigger and offline, and is later corrected for the measured event vertex from the electron or muon from the $W$ decay. For events containing reconstructed muons, the calorimeter response from the muon is removed, and the $\vec{E}_T$ corrected with the $p_T$ of muon track. The last correction to the $\vec{E}_T$ is applied after correcting the measured energy of jets in the event. For example, the missing transverse energy in $W \to e\nu$ events is calculated from the energy deposited by the electron, the jets, and the unclustered energy using the Eqn. 3.2:

$$\vec{E}_T = - \left( \vec{E}_e + \sum \vec{E}_{jet} + \vec{E}_{unc} \right),$$  \hspace{1cm} (3.2)

For an event with a single electromagnetic cluster, $\vec{E}_T$ is simply the vector $E_T$ associated with the cluster as described in Section 3.3.1. However, in order to provide a useful definition of $\vec{E}_T$ for events with more than one electron (such as $Z \to e^+e^-$), we identify all electromagnetic clusters and use the vector sum of their transverse energies. The $\vec{E}_{jet}$ component includes the transverse energy of all jets with $E_T > 10$ GeV and any energy in the calorimeters that is not included in the categories above is termed ”unclustered energy.” We define the unclustered energy $\vec{E}_{unc}$ by computing the vector sum of all calorimeter towers with a minimum $E_T$ of 100 MeV. The definition of $\vec{E}_T$ for this analysis is often called the corrected $\vec{E}_T$ because it is calculated using the corrected $E_T$ of electrons and jets.

### 3.5 $W \to e\nu$ Selection Requirements

In the previous sections of this chapter, we described the electrons and the missing transverse energy of our $W$ event sample. Using the objects selected by the high-$E_T$ central and forward trigger, an electron candidate is selected within either the central
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calorimeter or the forward calorimeter, along with being matched to a reconstructed charged particle track. The detailed requirements and cuts used to identify electron candidates are in the CEM listed in Table 3.1. The corresponding requirements and cuts for electron candidates in the PEM are listed in Table 3.2.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Central Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial</td>
<td>TRUE</td>
</tr>
<tr>
<td>$E_T$</td>
<td>$\geq 25$ GeV</td>
</tr>
<tr>
<td>Track $</td>
<td>Z_0</td>
</tr>
<tr>
<td>Track $p_T$</td>
<td>$\geq 10$ GeV/$c$</td>
</tr>
<tr>
<td>COT Ax. Seg.</td>
<td>$\geq 3$</td>
</tr>
<tr>
<td>COT St. Seg.</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>Conversion</td>
<td>$\neq 1$</td>
</tr>
<tr>
<td>Had/Em</td>
<td>$\leq (0.055 + (0.00045 \times E))$</td>
</tr>
<tr>
<td>Isolation</td>
<td>$\leq 4$ GeV</td>
</tr>
<tr>
<td>LshrTrk</td>
<td>$\leq 0.2$</td>
</tr>
<tr>
<td>$E/P$</td>
<td>$\leq 2.0$ unless $p_T \geq 50$ GeV/$c$</td>
</tr>
<tr>
<td>CES $\Delta Z$</td>
<td>$\leq 3.0$ cm</td>
</tr>
<tr>
<td>Signed CES $\Delta X$</td>
<td>$-3.0 \leq q \times \Delta X \leq 1.5$</td>
</tr>
<tr>
<td>CES Strip $\chi^2$</td>
<td>$\leq 10.0$</td>
</tr>
</tbody>
</table>

Table 3.1: Central electron selection cuts.

The forward electrons are required to have a "good" matching CDF default track (DefTrk) to identify the charge of the electron. We refer to forward electrons with COT tracks ($1.2 < |\eta| < 1.6$) and with SISA tracks ($1.6 < |\eta| < 2.8$) as shown in the following cuts.

- **DefMatch**: The highest $P_T$ track should be within a cone size
  \[ \Delta R = \sqrt{(\Delta X)^2 + (\Delta Y)^2} < \sqrt{2}. \]

- **COT track**: COT Ax. and St. hits $\geq 5$, Silicon hits $\geq 3$, $\chi^2/dof < 10$ and $0.2 < E/P < 4.0$. 
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Table 3.2: Forward electron selection cuts.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Forward Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region</td>
<td>$1.2 \leq</td>
</tr>
<tr>
<td>$E_T$</td>
<td>$\geq 20 \text{ GeV}$</td>
</tr>
<tr>
<td>Had/Em</td>
<td>$\leq 0.05$</td>
</tr>
<tr>
<td>Pem3x3FitTow</td>
<td>$\neq 0$</td>
</tr>
<tr>
<td>Pem3x3Chisq</td>
<td>$\leq 10$</td>
</tr>
<tr>
<td>Pes5by9U</td>
<td>$\geq 0.65$</td>
</tr>
<tr>
<td>Pes5by9V</td>
<td>$\geq 0.65$</td>
</tr>
<tr>
<td>Isolation</td>
<td>$\leq 4 \text{ GeV}$</td>
</tr>
<tr>
<td>$\Delta R_{PemPem}$</td>
<td>$\leq 3.0 \text{ cm}$</td>
</tr>
<tr>
<td>DefMatch*</td>
<td>TRUE</td>
</tr>
<tr>
<td>COT track**</td>
<td>TRUE</td>
</tr>
<tr>
<td>otherwise SISA track***</td>
<td>TRUE</td>
</tr>
</tbody>
</table>

- SISA track***: $|\eta| > 1.6$, Silicon hits $\geq 5$, $\chi^2/dof < 5$, $|\Delta X|, |\Delta Y| < 0.4$ and $0.65 < E/P < 4.0$.

In order to optimize the requirements used to select the default tracks for the forward region, each of the cuts is optimized with $Z \rightarrow e^+e^-$ events in both the Run II data and Monte Carlo simulation, for both COT and silicon tracks. Using maximum value of $\epsilon D^2$, where $\epsilon$ is the tracking efficiency and $D$ is dilution factor, $D = 2(1 - \rho_{charge \ faclrate}) - 1$, the requirements of good matching track are optimized so as to minimize the charge mis-identification rate and to maximize the electron acceptance. The distributions of the track variables are shown in Figure 3.1 (GEN5) and in Figure 3.2 (GEN6) and demonstrate the quality of these tracks. We find that GEN6 MC has better agreement with data than GEN5 MC. In particular, the residuals ($\Delta X$ and $\Delta Y$) on PES show a discrepancy between GEN5 MC and data. This affects the electron track efficiency scale factor (shown later in Section 6.6).

Additionally, to select $W \rightarrow e\nu$ events, we reject the low missing energy events, $E_T < 25 \text{ GeV}$.
I think this sentence belongs in the previous section.
Figure 3.1: Good matching track variables from $Z \to e^+e^-$ events in the forward region. Points and histograms are Run II data and Monte Carlo simulation (GEN5), respectively. COT tracks ($1.2 < |\eta| < 1.6$) and SISA tracks ($1.6 < |\eta| < 2.8$).
This page contains no comments
Figure 3.2: Good matching track variables from $Z \to e^+e^-$ events in the forward region. Points and histograms are Run II data and Monte Carlo simulation (GEN6), respectively. COT tracks ($1.2 < |\eta| < 1.6$) and SISA tracks ($1.6 < |\eta| < 2.8$).
3.6 $Z \rightarrow e^+e^-$ Selection Requirements

The $Z \rightarrow e^+e^-$ sample is used to set the calorimeter energy scale, to determine the electron charge fake rate, to determine the signal template for QCD background estimate, and to measure the electron identification efficiencies. Most of the $Z$ selection requirements are identical to the description in Section 3.5. For forward electron we have an additional electron tracking type to increase the acceptance. We call the track as Phoenix electron track (PHX). The requirements are shown in Table 3.3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>PHX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region</td>
<td>== plug</td>
</tr>
<tr>
<td>$E_T$</td>
<td>$\geq 25$ GeV</td>
</tr>
<tr>
<td>Pes2dEta</td>
<td>$1.2 \leq</td>
</tr>
<tr>
<td>Had/Em</td>
<td>$\leq 0.05$</td>
</tr>
<tr>
<td>Pem3x3FitTow</td>
<td>$\neq 0$</td>
</tr>
<tr>
<td>Pem3x3Chisq</td>
<td>$\leq 10$</td>
</tr>
<tr>
<td>Pes5by9U</td>
<td>$\geq 0.65$</td>
</tr>
<tr>
<td>Pes5by9V</td>
<td>$\geq 0.65$</td>
</tr>
<tr>
<td>Isolation</td>
<td>$\leq 4$ GeV</td>
</tr>
<tr>
<td>$\Delta R_{PemPem}$</td>
<td>$\leq 3$ cm</td>
</tr>
<tr>
<td>PHXMatch</td>
<td>TRUE</td>
</tr>
<tr>
<td>$N_{h_b}^{Siicon}$</td>
<td>$\geq 3$</td>
</tr>
<tr>
<td>$</td>
<td>z_{PHX}</td>
</tr>
</tbody>
</table>

Table 3.3: Phoenix electron selection cuts.

The geometric requirements on selected events are that two electron candidates are identified in either the central ($|\eta| < 1$) or forward regions of the detector. Events in which both electrons are reconstructed in the central region of the detector are referred to as central-central (CC), events with one central and one forward electron are referred to as central-forward (CF), and events in which both electrons are forward are referred to as forward-forward (FF).
the Phoenix electron track (PHX),
Chapter 4

Backgrounds Determination

As described in Chapter 3, we selected $W \rightarrow e\nu$ candidates by identifying high-$p_T$ electrons in events with a large missing transverse energy. Although the $W \rightarrow e\nu$ selection is designed to reject events other than direct $W$ production, a few other physics processes with identical final-state signatures also pass the selection cuts. We separate the background sources into two main categories: The significant $W \rightarrow e\nu$ background is the direct QCD production of multi jets. In some QCD multi jet events, a jet mimics the signature of an electron, and mismeasured transverse energy results in a large $\not{E}_T$. Other physics processes that contribute to our $W$ event sample are $W \rightarrow \tau\nu$ and $Z \rightarrow e^+e^-$. The production cross section for $W \rightarrow \tau\nu$ is identical to that of $W \rightarrow e\nu$, and the $\tau$ lepton decays to an electron with a branching fraction of 18%. In $Z \rightarrow e^+e^-$ events, a large $E_T$ can be observed if an electron is mismeasured or escapes through an uninstrumented part of the detector. In this chapter we describe the techniques used to estimate the contributions to our candidate $W \rightarrow e\nu$ sample from each background source and are to be used in the measurement of the $W$ production charge asymmetry analysis.
QCD backgrounds to electrons, and events containing real electrons.

apparent

tau->enuunu,
4.1 Electroweak Backgrounds

The backgrounds to $W \rightarrow e\nu$ include other electroweak processes that yield an electron and $E_T$ in the final state. The two principal boson backgrounds from $W \rightarrow \tau\nu$ and $Z \rightarrow e^+e^-$.

4.1.1 $W \rightarrow \tau\nu$ Background

The $W \rightarrow e\nu$ signature can also be reproduced by $W \rightarrow \tau\nu$ events in which the $\tau$ lepton subsequently decays into an electron via $\tau \rightarrow e\nu\bar{\nu}$. $W \rightarrow \tau\nu$ accounts for one third of all leptonic $W$ decays, and the $\tau$ has a significant branching fraction (18%) to electrons. The experimental signatures of both $W \rightarrow e\nu$ and $W \rightarrow \tau\nu$ consist of a true electron and $E_T$. The electron from $\tau$ decay is generally softer than that of direct $W \rightarrow e\nu$ decay because the momentum of the $\tau$ is shared among three decay products. Many $W \rightarrow \tau\nu$ events are therefore rejected by the electron $E_T$ cut. To study this process, samples of $p\bar{p} \rightarrow W \rightarrow \tau\nu$ are generated as described in Section 3.1.2.

4.1.2 $Z \rightarrow e^+e^-$ Background

The second type of boson background is from $Z \rightarrow e^+e^-$ production. Although the cross section times branching ratio for $Z \rightarrow e^+e^-$ is a factor of 10 smaller than that of $W \rightarrow e\nu$, the presence of a high $E_T$ electron, together with a large $E_T$, can produce an experimental signature identical to that of $W \rightarrow e\nu$. Whereas the electron $E_T$ spectra for $Z \rightarrow e^+e^-$ and $W \rightarrow e\nu$ are similar, the large $E_T$ in $Z \rightarrow e^+e^-$ events results from mismeasured jets or a second electron that passes through an uninstrumented region of the detector. We measure the $Z \rightarrow e^+e^-$ background by generating $Z \rightarrow e^+e^-$ events using PYTHIA as described in Section 3.1.2.

We apply the $W \rightarrow e\nu$ selection cuts to these events to obtain the fraction of events
in this category
that pass the cuts. Then, based on Standard Model predictions for the relative production rates of our signal process and the two background processes, we use the estimated acceptances from Monte Carlo to obtain the relative contributions of each process to our candidate sample. The results are summarized in Table 4.1.

In Figure 4.1, the rapidity distribution and the systematic uncertainty on the charge asymmetry are shown. However, we do not consider the $W \rightarrow \tau \nu$ ($\tau \rightarrow e \nu$) decay channel as a background in the $W$ charge asymmetry analysis since it has the same decay structure to $W \rightarrow e \nu$. Instead we add $W \rightarrow \tau \nu$ to our total acceptance of $W \rightarrow e \nu$ events and it is taken into account as a smearing effect since the electron comes from a $\tau$ decay. Thus it is considered in the end as part of the total acceptance.

Figure 4.1: The rapidity distribution of $Z \rightarrow e^+e^-$ and $W \rightarrow \tau \nu$ that pass the $W \rightarrow e \nu$ selection cuts. The right plot shows systematic uncertainty on asymmetry measurement when these other electroweak processes are considered in the data.
and I don't think you want to say this. your plot is the charge asymmetry with and without correcting for the background, just to set the scale of the effect.

the same charge asymmetry as

the different in reconstructed rapidity since the electron comes from the tau decay instead of the W decay directly

signal sample

events which pass our analysis cuts

signal
Chapter 4. Backgrounds Determination

Source Contribution to $W \rightarrow e\nu$

<table>
<thead>
<tr>
<th>Region</th>
<th>Central</th>
<th>Plug</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow e^+ e^-$</td>
<td>$0.593 \pm 0.018%$</td>
<td>$0.542 \pm 0.025%$</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu^*$</td>
<td>$2.295 \pm 0.036%$</td>
<td>$2.044 \pm 0.050%$</td>
</tr>
</tbody>
</table>

Table 4.1: Estimates of $Z \rightarrow e^+ e^-$ and $W \rightarrow \tau\nu^*$ contributions to $W \rightarrow e\nu$. Note: $W \rightarrow \tau\nu^*$ ($\tau \rightarrow e\nu$) is not considered a background but is included in the signal acceptance for the $W$ charge asymmetry analysis.

4.2 QCD Background

Extracting the contribution of events to the $W \rightarrow e\nu$ candidate samples in which real or fake leptons from hadronic jets are reconstructed in the detector is challenging. Real leptons are produced both in the semileptonic decay of hadrons and by photon conversions in the detector material. Some events also contain other particles in hadronic jets which are misidentified and reconstructed as leptons. Typically, these types of events will not be accepted into our $W \rightarrow e\nu$ candidate sample because we require large event $E_T$. In a small fraction of these events, however, a significant energy mis-measurement does reproduce the $E_T$ signature. Because of the large total cross section for hadronic jets, even this small fraction results in a substantial number of background events in our $W \rightarrow e\nu$ signal region.

In this section, we present a technique for estimating the QCD background in $W \rightarrow e\nu$ events by fitting the isolation distribution of the electrons [21]. The principal idea behind the method is to exploit the differences in the shapes of the isolation distribution for jets compared to electrons. We obtain a template shape for electrons (signal) from $Z \rightarrow e^+ e^-$ events and a template shape for jets (background) from a dijet enriched sample to be described below. This is done separately for central electrons and for forward (plug) electrons and the isolation shapes are fitted.
that

the

sample.

to be

anywhere in the calorimeter

of such events passing our selections

that of

Comments from page 74 continued on next page
Source Contribution to $W \rightarrow e\nu$ region central plug

<table>
<thead>
<tr>
<th>Source</th>
<th>Contribution to $W \rightarrow e\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow e^+e^-$</td>
<td>$0.593 \pm 0.018%$ $0.542 \pm 0.025%$</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu^*$</td>
<td>$2.295 \pm 0.036%$ $2.044 \pm 0.050%$</td>
</tr>
</tbody>
</table>

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4.2 QCD Background

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in each detector to extract a background measurement from the data itself.
4.2.1 Electron Signal Template

To obtain the electron template for the isolation distribution for electrons we use $Z \rightarrow e^+e^-$ data samples.

Central electron

We select central-central electrons where one electron passes the central electron cuts in Table 3.1 (fitting leg) except for the isolation cut and the other leg passes a tighter electron selection which requires tighter cuts of isolation ratio ($E_{\text{iso}}/E_T < 0.05$ and $L_{\text{shr}} < 0.1$). We also use central-forward events where one electron passes the central cuts (fitting leg) except for the isolation cut and the other passes the tight phoenix cuts in Table 3.3 including a cut on isolation ratio < 0.05. We also require $81 \text{ GeV} < M_{ee} < 101 \text{ GeV}$. Here, the background fraction of central-central $Z \rightarrow e^+e^-$ is pretty small and can be ignored but the one of central-forward(PHX) $Z \rightarrow e^+e^-$ should be subtracted from this electron template.

In Figure 4.2 (top) we check the $E_T$ dependence of the isolation distribution for data (black points). Since we use the isolation distribution from electrons from $Z \rightarrow e^+e^-$ events as a template for electrons from $W \rightarrow e\nu$ events we also compare the $E_T$ dependence to $Z \rightarrow e^+e^-$ MC (red) as well as $W \rightarrow e\nu$ MC (blue) and find that they both agree well with the data. We also check the dependence of the isolation shape on $E_T$ for $W \rightarrow e\nu$ MC events and separately for different $E_T$ ranges; this is shown in Figure 4.2 (bottom). We observe that for $E_T < 35$ GeV there is no dependence of the isolation shape on $E_T$ but find a dependence on $E_T$ for events with $E_T$ above 35 GeV (as well as an $E_T$ dependence). Therefore, we have two signal templates for the isolation distribution, one for $25 \text{ GeV} < E_T < 35 \text{ GeV}$ and the other for $E_T > 35 \text{ GeV}$. In Figure 4.3 we compare the shape of the isolation distributions of electrons from $W$ and $Z$ decay by looking at the ratio of the distributions in bins of isolation.
The selections for central and plug electrons are different because of the differences in the detectors.

I think this parenthetical comment (which I keep editing), really belongs after the "one electron" in all four cases. Also, I've suggested removing "fitting leg" with something less jargony, but since you keep using it later, another thing to do is to define the fitting leg the first time, and then say 'or "fitting leg" of the dielectron event'...

The electrons whose isolation distribution will be used in the template
4.2.1 Electron(Signal) Template

To obtain the electron template for the isolation distribution for electrons we use $Z \rightarrow e^+e^-$ data samples.

Central electron

We select central-central electrons where one electron passes the central electron cuts in Table 3.1 (fitting leg) except for the isolation cut and the other leg passes a tighter electron selection which requires tighter cuts of isolation ratio ($E_{T}^{iso}/E_{T}$) $< 0.05$ and $L_{shr} < 0.1$. We also use central-forward events where one electron passes the central cuts (fitting leg) except for the isolation cut and the other passes the tight phoenix cuts in Table 3.3 including a cut on isolation ratio $< 0.05$. We also require 81 GeV $< M_{ee} < 101$ GeV. Here, the background fraction of central-central $Z \rightarrow e^+e^-$ is pretty small and can be ignored but the one of central-forward(PHX) $Z \rightarrow e^+e^-$ should be subtracted from this electron template.

In Figure 4.2 (top) we check the $E_{T}$ dependence of the isolation distribution for data (black points). Since we use the isolation distribution from electrons from $Z \rightarrow e^+e^-$ events as a template for electrons from $W \rightarrow e\nu$ events we also compare the $E_{T}$ dependence to $Z \rightarrow e^+e^-$ MC (red) as well as $W \rightarrow e\nu$ MC (blue) and find that they both agree well with the data. We also check the dependence of the isolation shape on $E_{T}$ for $W \rightarrow e\nu$ MC events and separately for different $E_{T}$ ranges; this is shown in Figure 4.2 (bottom). We observe that for $E_{T} < 35$ GeV there is no dependence of the isolation shape on $E_{T}$ but find a dependence on $E_{T}$ for events with $E_{T}$ above 35 GeV (as well as an $E_{T}$ dependence). Therefore, we have two signal templates for the isolation distribution, one for 25 GeV $< E_{T} < 35$ GeV and the other for $E_{T} > 35$ GeV. In Figure 4.3 we compare the shape of the isolation distributions of electrons from $W$ and $Z$ decay by looking at the ratio of the distributions in bins of isolation.
Comments from page 75 continued on next page
4.2.1 Electron(Signal) Template

To obtain the electron template for the isolation distribution for electrons we use $Z \rightarrow e^+e^-$ data samples.

Central electron

We select central-central electrons where one electron passes the central electron cuts in Table 3.1 (fitting leg) except for the isolation cut and the other leg passes a tighter electron selection which requires tighter cuts of isolation ratio ($E_{T}^{iso}/E_{T} < 0.05$) and $L_{shr} < 0.1$. We also use central-forward events where one electron passes the central cuts (fitting leg) except for the isolation cut and the other passes the tight phoenix cuts in Table 3.3 including a cut on isolation ratio $< 0.05$. We also require $81 \text{ GeV} < M_{ee} < 101 \text{ GeV}$. Here, the background fraction of central-central $Z \rightarrow e^+e^-$ is pretty small and can be ignored but the one of central-forward (PHX) $Z \rightarrow e^+e^-$ should be subtracted from this electron template.

In Figure 4.2 (top) we check the $E_{T}$ dependence of the isolation distribution for data (black points). Since we use the isolation distribution from electrons from $Z \rightarrow e^+e^-$ events as a template for electrons from $W \rightarrow e\nu$ events, we also compare the $E_{T}$ dependence to $Z \rightarrow e^+e^-$ MC (red) as well as $W \rightarrow e\nu$ MC (blue) and find that they both agree well with the data. We also check the dependence of the isolation shape on $E_{T}$ for $W \rightarrow e\nu$ MC events and separately for different $E_{T}$ ranges; this is shown in Figure 4.2 (bottom). We observe that for $E_{T} < 35 \text{ GeV}$ there is no dependence of the isolation shape on $E_{T}$ but find a dependence on $E_{T}$ for events with $E_{T}$ above 35 GeV (as well as an $E_{T}$ dependence). Therefore, we have two signal templates for the isolation distribution, one for $25 \text{ GeV} < E_{T} < 35 \text{ GeV}$ and the other for $E_{T} > 35 \text{ GeV}$. In Figure 4.3 we compare the shape of the isolation distributions of electrons from $W$ and $Z$ decay by looking at the ratio of the distributions in bins of isolation.
background in the

Sequence number: 23
Author: Kevin McFarland
Subject: Inserted Text
Date: 4/15/2008 6:54:09 PM

Sequence number: 24
Author: Kevin McFarland
Subject: Replacement Text
Date: 4/15/2008 6:54:32 PM

Sequence number: 25
Author: Kevin McFarland
Subject: Inserted Text
Date: 4/15/2008 6:54:44 PM
Chapter 4. Backgrounds Determination

Figure 4.2: Profile plot of the isolation distribution for central electrons vs. $E_T$ (top) and vs. $\not{E}_T$ (bottom).
This page contains no comments
Figure 4.3: Shape comparisons of the isolation distribution. We show the ratio of the isolation distributions in bins of isolation for central electrons for $Z$ data/$Z$ MC (black), $W$ MC/$Z$ MC (red), $W$ MC/$Z$ MC for $25\text{ GeV} < \vec{E}_T < 35\text{ GeV}$ (blue) and $W$ MC/$Z$ MC for $35\text{ GeV} < \vec{E}_T < 200\text{ GeV}$ (green).
Shown are
Forward electron

Similar to what was done for central electrons, we use $Z \rightarrow e^+e^-$ events to obtain the electron template for the isolation distribution for forward electrons. Here, we select central-forward electrons where one electron passes the forward electron cuts and default track requirements in Table 3.2 (fitting leg) except for the isolation cut and the other leg passes a tighter central electron selection which requires tighter cuts of isolation ratio $< 0.05$ and $L_{shr} < 0.1$. We also use forward-forward events where one electron passes the DefTrack cuts (fitting leg) except for the isolation cut and the other passes the PHX cuts and in addition we apply a cut on isolation ratio $< 0.05$. We also require $81 \text{ GeV} < M_{ee} < 101 \text{ GeV}$. We use two signal templates for the forward isolation distribution, one for $25 \text{ GeV} < \not{E}_{T} < 35 \text{ GeV}$ and one for $\not{E}_{T} > 35 \text{ GeV}$, as was done in the central electron case.

Background contamination for electron templates

We consider the background contamination for central-forward and forward-forward $Z$s in the signal template. Since the background contamination for central-forward and forward-forward $Z$s to be non-negligible, the signal template needs to be corrected. First, we estimate the amount of background by selecting central-forward and forward-forward events as described above, except that the fitting leg is forced to have Isolation $> 2 \text{ GeV}$ for the electron and then fit the dielectron invariant mass distribution to a Gaussian plus a 3rd order polynomial; see Figure 4.4.

We subsequently subtract this fraction of background events from the signal shape using the background isolation shape described in section 4.2.2. The background fraction for electron templates are summarized in Table 4.2 and the signal shapes after eliminating the background contamination are shown in Figure 4.5.
Chapter 4. Backgrounds Determination

Forward electron

Similar to what was done for central electrons, we use $Z \rightarrow e^+e^-$ events to obtain the electron template for the isolation distribution for forward electrons. Here, we select central-forward electrons where one electron passes the forward electron cuts and default track requirements in Table 3.2 (fitting leg) except for the isolation cut and the other leg passes a tighter central electron selection which requires tighter cuts of isolation ratio $< 0.05$ and $L_{shr} < 0.1$. We also use forward-forward events where one electron passes the DefTrack cuts (fitting leg) except for the isolation cut and the other passes the PHX cuts and in addition we apply a cut on isolation ratio $< 0.05$. We also require $81 \text{ GeV} < M_{ee} < 101 \text{ GeV}$, we use two signal templates for the forward isolation distribution, one for $25 \text{ GeV} < \not{E}_T < 35 \text{ GeV}$ and one for $\not{E}_T > 35 \text{ GeV}$, as was done in the central electron case.

Background contamination for electron templates

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We subsequently subtract this fraction of background events from the signal shape using the background isolation shape described in section 4.2.2. The background fraction for electron templates are summarized in Table 4.2 and the signal shapes after eliminating the background contamination are shown in Figure 4.5.
one thing you don't discuss in this section is that the background subtracted templates are a bit negative in the high isolation region. You should at least say how you handle that and maybe comment on how significant it is.

for these backgrounds...

The polynomial is used to interpolate the background shape under the largely Gaussian signal region, and therefore can be used to estimate the background events contributing to the templates with Isolation>2 GeV.

Comments from page 78 continued on next page
Chapter 4. Backgrounds Determination

Forward electron

Similar to what was done for central electrons, we use $Z \to e^+e^-$ events to obtain the electron template for the isolation distribution for forward electrons. Here, we select central-forward electrons where one electron passes the forward electron cuts and default track requirements in Table 3.2 (fitting leg) except for the isolation cut and the other leg passes a tighter central electron selection which requires tighter cuts of isolation ratio $< 0.05$ and $L_{shr} < 0.1$. We also use forward-forward events where one electron passes the DefTrack cuts (fitting leg) except for the isolation cut and the other passes the PHX cuts and in addition we apply a cut on isolation ratio $< 0.05$. We also require $81 \text{ GeV} < M_{ee} < 101 \text{ GeV}$. We use two signal templates for the forward isolation distribution, one for $25 \text{ GeV} < \not{E}_T < 35 \text{ GeV}$ and one for $\not{E}_T > 35 \text{ GeV}$, as was done in the central electron case.

Background contamination for electron templates

We consider the background contamination for central-forward and forward-forward $Z$s in the signal template. Since the background contamination for central-forward and forward-forward $Z$s to be non-negligible, the signal template needs to be corrected. First, we estimate the amount of background by selecting central-forward and forward-forward events as described above, except that the fitting leg is forced to have Isolation $> 2 \text{ GeV}$ for the electron and then fit the dielectron invariant mass distribution to a Gaussian plus a 3rd order polynomial; see Figure 4.4.

We subsequently subtract this fraction of background events from the signal shape using the background isolation shape described in section 4.2.2. The background fraction for electron templates are summarized in Table 4.2 and the signal shapes after eliminating the background contamination are shown in Figure 4.5.
**Figure 4.4:** Invariant mass distribution reconstructed from central-forward and forward-forward electrons as described in the text. We require that the fitting leg has non-isolated energy, Isolation > 2 GeV. We fit the distribution to a Gaussian plus a 3rd order polynomial to get an estimate of the background contamination in the signal region of 81 GeV < $M_{ee}$ < 101 GeV.

<table>
<thead>
<tr>
<th>$80 \text{ GeV}/c^2 &lt; M_{ee} &lt; 100 \text{ GeV}/c^2$</th>
<th>Background Fraction(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow e^+e^-$ CF(PEM)</td>
<td>0.677 ± 0.020 %</td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^-$ CF(PHX)</td>
<td>0.691 ± 0.024 %</td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^-$ CF(Def)</td>
<td>0.479 ± 0.030 %</td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^-$ CF(PHX+Def)</td>
<td>0.326 ± 0.023 %</td>
</tr>
</tbody>
</table>

Table 4.2: The summary of background estimates for electron template in $Z \rightarrow e^+e^-$ events.
again... needs to be defined before or replace the jargon
Chapter 4. Backgrounds Determination

(a) $Z$(CF) is applied by PEM cuts

(b) $Z$(CF) is applied by PHX cuts

(c) $Z$(CF) is applied by PEM+DefTrk cuts and $Z$(FF) is applied by PHX and DefTrack for each electron

Figure 4.5: The signal isolation distribution. Black point is the signal shape, red is $Z \rightarrow e^+e^-$ data before removing background and blue is the background shape.
This page contains no comments
4.2.2 Jet(Background) Template

We obtain the jet background template for the isolation distribution for QCD jets faking electrons from the inclusive high-$p_T$ electron data.

Central jet

We select dijet events where one jet behaves like an central electron and passes anti-electron cuts in Table 4.3 (fitting leg) and the other passes the jet cuts in Table 4.3. Although these cuts select many dijet candidates, electron signal events still remain in this sample. To remove dielectron events we require no more than one EM energy with $E_{T}^{\text{Em}} > 15 \text{ GeV}$ and to remove $W +$ jet events we require $E_{T} < 10 \text{ GeV}$ and that the opening angle between the jets is back-to-back. The opening angle distribution is shown in Figure 4.6 for the dijet sample and for $W \to e\nu$ MC. We also show this distribution in three ranges of the $p_T$ of the dijets with the blue dashed line indicating cut for the different $p_T$ values. These cuts are summarized in Table 4.3.

Forward jet

As was done for central electrons, we select dijet events where one jet behaves like an forward electron and passes anti-electron cuts in Table 4.4 (fitting leg) and the other passes the jet cuts in Table 4.4.

In Figure 4.7 (top) we show the $E_{T}$ distribution of the dijet events in the data (black points), $W \to e\nu$, $W \to \tau\nu$ and $Z \to e^+e^-$ MC. We use the MC for these electroweak processes to subtract the remaining contributions from real electron events to obtain the final jet background templates in the central and forward region, respectively. In Figure 4.7 (bottom) we show the isolation distributions for dijet events for $0 \text{ GeV} < E_{T} < 10 \text{ GeV}$ and $10 \text{ GeV} < E_{T} < 20 \text{ GeV}$ and we do use the differences in the shapes of these distributions as a measurement of the systematic uncertainty in the background
Again, because of differences in the calorimeters, the central and forward regions are treated differently.

should explain exactly which cuts you mean here

eutra

but

et

where

some

primarily

transverse

Comments from page 81 continued on next page
4.2.2 Jet(Background) Template

We obtain the jet background template for the isolation distribution for QCD jets faking electrons from the inclusive high-$p_T$ electron data.

Central jet

We select dijet events where one jet behaves like a central electron and passes anti-electron cuts in Table 4.3 (fitting leg) and the other passes the jet cuts in Table 4.3. Although these cuts select many dijet candidates, electron signal events still remain in this sample. To remove dielectron events we require no more than one EM energy with $E_{\text{EM}} > 15$ GeV and to remove $W +$ jet events we require $E_T < 10$ GeV and that the opening angle between the jets is back-to-back. The opening angle distribution is shown in Figure 4.6 for the dijet sample and for $W \to e\nu$ MC. We also show this distribution in three ranges of the $p_T$ of the dijets with the blue dashed line indicating cut for the different $p_T$ values. These cuts are summarized in Table 4.3.

Forward jet

As was done for central electrons, we select dijet events where one jet behaves like an forward electron and passes anti-electron cuts in Table 4.4 (fitting leg) and the other passes the jet cuts in Table 4.4.

In Figure 4.7 (top) we show the $E_T$ distribution of the dijet events in the data (black points), $W \to e\nu$, $W \to \tau\nu$ and $Z \to e^+e^-$ MC. We use the MC for these electroweak processes to subtract the remaining contributions from real electron events to obtain the final jet background templates in the central and forward region, respectively. In Figure 4.7 (bottom) we show the isolation distributions for dijet events for $0 \text{ GeV} < E_T < 10$ GeV and $10$ GeV $< E_T < 20$ GeV and use the differences in the shapes of these distributions as a measurement of the systematic uncertainty in the background
Because these are significantly different,
### Table 4.3: Dijet event selection criteria for QCD background estimate for central electrons.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Anti-CEM</th>
<th>variable</th>
<th>JET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region</td>
<td>== central</td>
<td>Region</td>
<td>== central or forward</td>
</tr>
<tr>
<td>Fiducial</td>
<td>1</td>
<td>JetCluster</td>
<td>0.4</td>
</tr>
<tr>
<td>$E_T$</td>
<td>$\geq 25$ GeV</td>
<td>Jet $E_T$</td>
<td>$\geq 25$ GeV</td>
</tr>
<tr>
<td>Track $Z_0$</td>
<td>$\leq 60$ cm</td>
<td>Had/Em</td>
<td>$\geq 0.125$</td>
</tr>
<tr>
<td>Track $p_T$</td>
<td>$\geq 10$ GeV/$c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Had/Em</td>
<td>$\geq (0.055 + (0.00045 \times E))$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LshrTrk</td>
<td>$\leq 0.2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E/P$</td>
<td>$\leq 2.0$ (unless $p_T \geq 50$ GeV/$c$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CES $\Delta Z$</td>
<td>$\leq 5.0$ cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Singed CES $\Delta X$</td>
<td>$-3.0 \leq q \times \Delta X \leq 1.5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CES StripChi2</td>
<td>$\leq 10.0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi_{jj}</td>
<td>$</td>
<td>if $15 &lt; P_T &lt; 25$, $</td>
</tr>
<tr>
<td></td>
<td>else $</td>
<td>\Delta \phi_{jj}</td>
<td>\geq 2.6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_T$</td>
<td>$\leq 10$ GeV</td>
</tr>
</tbody>
</table>

### Table 4.4: Dijet event selection criteria for QCD background estimate for forward electrons.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Anti-PEM</th>
<th>variable</th>
<th>JET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region</td>
<td>== forward</td>
<td>Region</td>
<td>== central or forward</td>
</tr>
<tr>
<td>Pes2dEta</td>
<td>$1.2 \leq</td>
<td>\eta</td>
<td>\leq 2.8$</td>
</tr>
<tr>
<td>$E_T$</td>
<td>$\geq 20$ GeV</td>
<td>Jet $E_T$</td>
<td>$\geq 25$ GeV</td>
</tr>
<tr>
<td>Had/Em</td>
<td>$\geq 0.05$</td>
<td>Had/Em</td>
<td>$\geq 0.125$</td>
</tr>
<tr>
<td>Pem3x3FitTow</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R_{Pem,Pem}$</td>
<td>$\leq 3.0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DefTrk</td>
<td>TRUE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta \phi_{jj}</td>
<td>$</td>
<td>if $15 &lt; P_T &lt; 25$, $</td>
</tr>
<tr>
<td></td>
<td>else $</td>
<td>\Delta \phi_{jj}</td>
<td>\geq 2.6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E_T$</td>
<td>$\leq 10$ GeV</td>
</tr>
</tbody>
</table>

Table 4.3: Dijet event selection criteria for QCD background estimate for central electrons.

Table 4.4: Dijet event selection criteria for QCD background estimate for forward electrons.
This page contains no comments
Figure 4.6: The opening angle (in the $x - y$ plane), $\Delta \phi$, distribution between the jet-like central electron (non-isolated and $Had/Em > 0.05$) and the leading jet in high $p_T$ electron data (black). We compare this with the $W$ plus jet events from MC (red) as a function of the $p_T$ of the dijets. The blue dashed line represents the dijet event selection cut for the different $p_T$ as summarized in Table 4.3.
This page contains no comments
shape as shown in Section 4.2.4.

4.2.3 Isolation Fit Results

As discussed previously, electrons from the selected \( W \rightarrow e\nu \) candidate data are composed of signal and background contributions. Thus, the isolation distribution for the electron candidates is fitted with the signal shape as described in section 4.2.1 and background shape as described in section 4.2.2 by using a binned maximum likelihood method. The fit results for central and forward electron are shown in Figure 4.8. We estimate the QCD background fraction in the total central and forward \( W \rightarrow e\nu \) candidate sample to be \( (1.210 \pm 0.144_{\text{stat}})\% \) and \( (0.668 \pm 0.117_{\text{stat}})\% \), respectively.

4.2.4 Systematic Uncertainty in QCD Background Estimate

We consider several possible sources of systematics uncertainty in the QCD background estimate:

A Limitations in the electron subtraction of jet templates.

B Jet isolation shape differences for different \( \not{E}_T \) regions as in Figures 4.7.

C Limitations in the background subtraction of the forward electron template.

We subtract the electrons from the jet template. Using a ±1σ statistical variation, we estimate the systematic uncertainty of the electron subtraction, and in a similar way, the \( \not{E}_T \) cut dependence on jet template. For forward electrons, the background subtraction is necessary for obtaining the electron template since the \( Z \) data including forward electrons is contaminated by jet events. Thus, we consider the fit errors from the \( Z \) mass distributions as a systematic uncertainty. The systematic uncertainties on the QCD background estimates for \( W \rightarrow e\nu \) candidates in the central and in the forward are summarized in Table 4.5.
The fit itself uses a way too many digits... remove at least one

Comments from page 84 continued on next page
shape as shown in section 4.2.4.

### 4.2.3 Isolation Fit Results

As discussed previously, electrons from the selected $W \rightarrow e\nu$ candidate data are composed of signal and background contributions. Thus, the isolation distribution for the electron candidates is fitted with the signal shape as described in section 4.2.1 and background shape as described in section 4.2.2 by using a binned maximum likelihood method. The fit results for central and forward electron are shown in Figure 4.8. We estimate the QCD background fraction in the total central and forward $W \rightarrow e\nu$ candidate sample to be $(1.210 \pm 0.144_{\text{stat}}) \%$ and $(0.668 \pm 0.117_{\text{stat}}) \%$, respectively.

### 4.2.4 Systematic Uncertainty in QCD Background Estimate

We consider several possible sources of systematics uncertainty in the QCD background estimate:

- A. Limitations in the electron subtraction of jet templates.
- B. Jet isolation shape differences for different $\not{E}_T$ regions as in Figures 4.7.
- C. Limitations in the background subtraction of the forward electron template.

We subtract the electrons from the jet template. Using a $\pm 1\sigma$ statistical variation, we estimate the systematic uncertainty of the electron subtraction, and in a similar way the $\not{E}_T$ cut dependence on jet template. For forward electrons, the background subtraction is necessary for obtaining the electron template since the $Z$ data including forward electrons is contaminated by jet events. Thus, we consider the fit errors from the $Z$ mass distributions as a systematic uncertainty. The systematic uncertainties on the QCD background estimates for $W \rightarrow e\nu$ candidates in the central and in the forward are summarized in Table 4.5.
To evaluate the uncertainty in the electron subtraction from the jet templates, we consider a

and uncertainties

on the electron content of the jet template and re-extract the background with these varied templates.
shape as shown in the Section 4.2.4.

### 4.2.3 Isolation Fit Results

As discussed previously, electrons from the selected $W \rightarrow e\nu$ candidate data are composed of signal and background contributions. Thus, the isolation distribution for the electron candidates is fitted with the signal shape as described in section 4.2.1 and background shape as described in section 4.2.2 by using a binned maximum likelihood method. The fit results for central and forward electron are shown in Figure 4.8. We estimate the QCD background fraction in the total central and forward $W \rightarrow e\nu$ candidate sample to be $(1.210 \pm 0.144_{\text{stat}})\%$ and $(0.668 \pm 0.117_{\text{stat}})\%$, respectively.

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A. Limitations in the electron subtraction of jet templates.

B. Jet isolation shape differences for different $E_T$ regions as in Figures 4.7.

C. Limitations in the background subtraction of the forward electron template.

We subtract the electrons from the jet template. Using a $\pm 1\sigma$ statistical variation, we estimate the systematic uncertainty of the electron subtraction, and in a similar way the $E_T$ cut dependence on jet template. For forward electrons, the background subtraction is necessary for obtaining the electron template since the $Z$ data including forward electrons is contaminated by jet events. Thus, we consider the fit errors from the $Z$ mass distributions as a systematic uncertainty. The systematic uncertainties on the QCD background estimates for $W \rightarrow e\nu$ candidates in the central and in the forward are summarized in Table 4.5.
s in forming the

we re-extract the background fraction we find if we use different

propagate

through to the evaluation of the final background.
Figure 4.7: Top: $\not{E}_T$ distribution of the dijet events in data (black points) and for $W \rightarrow e\nu$, $W \rightarrow \tau\nu$, and $Z \rightarrow e^+e^-$ MC. We correct the dijet data for these electroweak processes. Bottom: The isolation distribution for dijet events for $0$ GeV < $\not{E}_T$ < $10$ GeV (red) and $10$ GeV < $\not{E}_T$ < $20$ GeV (blue). The isolation distribution for $0$ GeV < $\not{E}_T$ < $10$ GeV is used as the background template for electrons.
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Figure 4.8: Isolation fit distributions for the $W \rightarrow e\nu$ data (black dots), signal template (red), background template (blue) and the prediction from the fit (green). The results for two different $E_T$ regions are presented: $25 \text{GeV} < E_T < 35 \text{GeV}$ (left) and $E_T > 35 \text{GeV}$ (right). (a) for central electrons. (b) for forward electrons.
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4.3 Summary

We have introduced the background sources to the $W \rightarrow e\nu$ sample to be used for the $W$ charge asymmetry analysis. The background contributions are estimated for two categories, the electroweak processes and hadronic jets. For the hadronic jet background we have used an method by fitting the isolation shape of electron candidates from $W \rightarrow e\nu$ data. Table 4.6, 4.7 summarize the total background estimates for central and forward $W \rightarrow e\nu$ candidates.
of Backgrounds to the W->enu Sample
### Table 4.5: Systematic uncertainties in QCD background estimate.

<table>
<thead>
<tr>
<th>$E_T$ region</th>
<th>central</th>
<th></th>
<th></th>
<th>forward</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$25 &lt; E_T &lt; 35$</td>
<td>$35 &lt; E_T$</td>
<td>total</td>
<td>$25 &lt; E_T &lt; 35$</td>
<td>$35 &lt; E_T$</td>
<td>total</td>
</tr>
<tr>
<td>A</td>
<td>0.002</td>
<td>0.000</td>
<td>0.002</td>
<td>0.002</td>
<td>0.000</td>
<td>0.002</td>
</tr>
<tr>
<td>B</td>
<td>0.105</td>
<td>0.100</td>
<td>0.145</td>
<td>0.098</td>
<td>0.094</td>
<td>0.136</td>
</tr>
<tr>
<td>C</td>
<td>0.014</td>
<td>0.010</td>
<td>0.017</td>
<td>0.027</td>
<td>0.036</td>
<td>0.045</td>
</tr>
<tr>
<td>total syst. (%)</td>
<td>± 0.146</td>
<td></td>
<td></td>
<td>± 0.143</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.6: The predicted background contribution in events to the experimental signal for central $W \rightarrow e\nu$ signal. The error represents the statistical uncertainty and the systematic uncertainty caused by our isolation fit method (QCD).

<table>
<thead>
<tr>
<th>Central</th>
<th>events</th>
<th>BG/DATA fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA</td>
<td>537858</td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^-$</td>
<td>3173.36</td>
<td>$0.59 \pm 0.02$ (stat.)</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>12370.73</td>
<td>$2.30 \pm 0.04$ (stat.)</td>
</tr>
<tr>
<td>QCD</td>
<td>6508.08</td>
<td>$1.21 \pm 0.14$ (stat.) $\pm 0.15$ (syst.)</td>
</tr>
</tbody>
</table>

### Table 4.7: The predicted background contribution in events to the experimental signal for forward $W \rightarrow e\nu$ signal. The error represents the statistical uncertainty and the systematic uncertainty caused by our isolation fit method (QCD).

<table>
<thead>
<tr>
<th>Forward</th>
<th>events</th>
<th>fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA</td>
<td>176941</td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^-$</td>
<td>955.48</td>
<td>$0.54 \pm 0.03$ (stat.)</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>3609.60</td>
<td>$2.04 \pm 0.05$ (stat.)</td>
</tr>
<tr>
<td>QCD</td>
<td>1185.50</td>
<td>$0.67 \pm 0.12$ (stat.) $\pm 0.14$ (syst.)</td>
</tr>
</tbody>
</table>
Sequence number: 1
Author: Kevin McFarland
Subject: Note
Date: 4/16/2008 7:30:33 AM

I don't think "A", "B", "C" works in this table. Also, the way the table is layed out, it looks like "Met region" refers to "A", "B" and "C" when in fact that is the source of the systematic. If you are out of room, use two tables for central and forward.

Sequence number: 2
Author: Kevin McFarland
Subject: Note
Date: 4/16/2008 7:31:43 AM

I know these are by far your largest backgrounds, but did you really never look at diboson and ttbar fraction in your sample? they will be <10^-3 probably, but at least it would be good to say something about that.
Chapter 5

Analysis Technique

In this chapter, we propose a new analysis technique which resolves the kinematic ambiguity of the longitudinal momentum of the neutrino to directly reconstruct the $W^\pm$ rapidity. The $W$ decay to leptons, in our case $W^\pm \rightarrow e^\pm \nu$, involves a neutrino whose longitudinal momentum cannot be experimentally determined. However, we can determine the longitudinal momentum by constraining the $W$ mass in Eq. 5.1:

$$M_W^2 = (E_l + E_\nu)^2 - (\vec{P}_l + \vec{P}_\nu)^2$$  \hspace{1cm} (5.1)

where the $W$ mass, $M_W$, is constrained to its experimentally measured value [22, 23, 24, 25, 26, 27, 28, 29]. Events which cannot satisfy the $W$ mass constraint (and which get imaginary values of the neutrino longitudinal momentum) are due to a mis-reconstruction of the neutrino (missing) transverse energy, $E_T$. Therefore, in such cases, we re-scale the $E_T$ to the value which makes the imaginary part to be zero. This new $E_T$ is then used to correct the $y_W$ for the event.

The $W$ mass constraint results in a two-fold ambiguity. This ambiguity can be partly resolved on a statistical basis from the known $V - A$ (vector-axial vector) decay distribution using the center-of-mass decay angle between the electron and the proton, $\theta^*$, and
Chapter 5

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$$M_W^2 = (E_l + E_\nu)^2 - (\vec{P}_l + \vec{P}_\nu)^2$$

where the $W$ mass, $M_W$, is constrained to its experimentally measured value [22, 23, 24, 25, 26, 27, 28, 29]. Events which cannot satisfy the $W$ mass constraint (and which get imaginary values of the neutrino $z$-momentum) are due to a mis-reconstruction of the neutrino (missing) transverse energy, $E_T$. Therefore, in such cases, re-scale the $E_T$ to the value which makes the imaginary part to be zero. This new $E_T$ is then used to correct the $y_W$ for the event.

The $W$ mass constraint results in a two-fold ambiguity. This ambiguity can be partly resolved on a statistical basis from the known $V - A$ (vector-axial vector) decay distribution using the center-of-mass decay angle between the electron and the proton, $\theta^*$, and
with real values of the neutrino z-momentum

There are some e
Chapter 5

Analysis Technique

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where the $W$ mass, $M_W$, is constrained to its experimentally measured value [22, 23, 24, 25, 26, 27, 28, 29]. Events which cannot satisfy the $W$ mass constraint (and which get imaginary values of the neutrino $z$-momentum) are due to a mis-reconstruction of the neutrino (missing) transverse energy, $E_T$. Therefore, in such cases, we re-scale the $E_T$ to the value which makes the imaginary part to be zero. This new $E_T$ is then used to correct the $y_W$ for the event.

The $W$ mass constraint results in a two-fold ambiguity. This ambiguity can be partly resolved on a statistical basis from the known $V - A$ (vector-axial vector) decay distribution using the center-of-mass decay angle between the electron and the proton, $\theta^*$, and
what you do is not so obvious given the vector arithmetic above. You should probably explain explicitly how missing Et is related to Enu and pnu and how you do the scaling.

I

in Eqn. 5.1
from the $W^+$ and $W^-$ production cross-sections as a function of $W$ rapidity, $d\sigma^{\pm}/dy_W$. These are discussed in the next sections.

### 5.1 $V - A$ decay distribution

$W^\pm$ bosons at the Tevatron are primarily produced from the valence quarks in the proton and in the anti-proton and rarely from sea quarks because $W$ production requires at least one moderately high $x$ parton to be involved in the collision. At very large forward or backward rapidities where one very high $x$ parton must participate in the production, the production probability from the sea quarks nearly vanishes. Understanding of the sea quark contribution is important to exactly know the decay angle distributions from the $V - A$ structure because $W$ production by sea quarks will result in the opposite $W$ polarization from valence quark production.

We use a Monte Carlo simulation using MC@NLO program with NLO QCD corrections [30] to determine the production probability with sea quarks by identifying initiating quarks as a function of $y_W$. We verify the expected angular distribution \((1 \pm \cos\theta^*)^2\) from production of $W^\pm$ with quarks in the proton and the opposite distribution with anti-quarks in the proton. For example, in Fig. 5.1(a), we show the $\cos\theta^*$ distributions of $e^+$ in the $W^+$ rest frame for the case when a quark from the proton and an anti-quark from the anti-proton form the $W^+$ (labeled “quark”) and the case when a anti-quark from the proton and a quark from the anti-proton form the $W^+$ (labeled “anti-quark”). The ratio of quark (proton) and anti-quark (proton) induced $W$ production therefore determines the angular decay distribution. In the simulation, we measure the fraction of quark and anti-quark contributions, and parameterize the angular distributions for $y_W$ and the $W$ transverse momentum, $p_T^W$. We find an empirical functional
an important distinction: throughout this discussion you sometimes use the phrase "sea quarks" when you specifically mean anti-quarks. The quarks from the quark-antiquark sea give the same angular distribution as the valence quarks, of course. So where you are talking about the angular distribution, it's important to specify "anti-quarks". I've tried to mark this clearly through the section, but maybe I've missed some.

---

As expected, the
from the $W^+$ and $W^-$ production cross-sections as a function of $W$ rapidity, $d\sigma^\pm/dy_W$. These are discussed in the next sections.

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in different regions of

of the W production reaction

partons

the

follows a $(1 \cos)^2$ distribution

flips the sign of the angular term
form that fits the data,

\[ P_{\pm}(\cos \theta^*, y_W, p_T^W) = (1 \mp \cos \theta^*)^2 + Q(y_W, p_T^W) (1 \pm \cos \theta^*)^2, \]  

(5.2)

\[ Q(y_W, p_T^W) = f(p_T^W)e^{-|g(p_T^W) + 0.05|y_W^{+1/2}}, \]  

(5.3)

The parameters \( f(P_T^W) \) and \( g(P_T^W) \) are

\begin{align*}
  f(P_T^W) &= 0.2811 L(P_T^W, \mu = 21.7\, \text{GeV}, \sigma = 9.458\, \text{GeV}) \\
          &+ 0.2185 e^{-0.04333\, \text{GeV}^{-1} P_T^W}, \\
  g(P_T^W) &= 0.2085 + 0.0074\, \text{GeV}^{-1} P_T^W \\
          &- 5.051 \times 10^{-5}\, \text{GeV}^{-2} P_T^W^2 \\
          &+ 1.180 \times 10^{-7}\, \text{GeV}^{-3} P_T^W^3, \\
\end{align*}

(5.4)

where \( L(x, \mu, \sigma) \) is the Landau distribution with most probable value \( \mu \) and the RMS \( \sigma \). The first term of Eq. 5.2 corresponds to the contribution from quarks in the proton and the second term from anti-quarks in the proton. The parameterization, \( Q(y_W, p_T^W) \), the ratio of the two angular distributions as a function of the \( W \) rapidity and \( p_T^W \), is obtained from the fit to the distribution in Fig. 5.1(b). Comparing the NLO QCD prediction with LO prediction. We show the fit as a function of \( y_W \) and \( p_T^W \) in Figure 5.2 and the fit of amplitudes and spreads of functional form in Figure 5.3.

## 5.2 The differential cross section, \( d\sigma^\pm/dy_W \)

A second relevant factor among the two \( W \) rapidity solutions is the \( W \) differential cross-section as a function of \( y_W, d\sigma^\pm/dy_W \). The \( W \) boson production decreases sharply beyond \(|y_W| > 2\) because of the scarcity of high \( x \) quarks as shown in Figure 5.4. For
where the functions

Figures 5.2 and 5.3 compare functions f(...) and g(...)
Chapter 5. Analysis Technique

form that fits the data,

\[ P_{\pm}(cos\theta^*, y_W, p_{T}^W) = (1 \mp cos\theta^*)^2 + Q(y_W, p_{T}^W)(1 \pm cos\theta^*)^2, \]  

\[ Q(y_W, p_{T}^W) = f(p_{T}^W)e^{-g(p_{T}^W)y_W^2 + 0.05|y_W^3|}, \]  

where \( L(x, \mu, \sigma) \) is the Landau distribution with most probable value \( \mu \) and the RMS \( \sigma \). The first term of Eq. 5.2 corresponds to the contribution from quarks in the proton and the second term from anti-quarks in the proton. The parameterization, \( Q(y_W, p_{T}^W) \), the ratio of the two angular distributions as a function of the \( W \) rapidity and \( p_{T}^W \), is obtained from the fit to the distribution in Fig. 5.1(b). Comparing the NLO QCD prediction with LO prediction, we show the fit as a function of \( y_W \) and \( p_{T}^W \) in Figure 5.2 and the fit of amplitudes and spreads of functional form in Figure 5.3.

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for $Q(yw, pt)$

Sequence number: 12
Author: Kevin McFarland
Subject: Replacement Text
Date: 4/17/2008 12:25:10 PM

distinguishing
Figure 5.1: (a) The \( \cos \theta^* \) distributions of \( e^+ \) in the \( W^+ \) rest frame, averaged over all produced \( W^+ \). The curve labeled “quark” shows the case when a quark from the proton and anti-quark from the anti-proton form the \( W^+ \). The curve labeled “anti-quark” shows the opposite case, when an anti-quark from the proton and a quark from the anti-proton form the \( W^+ \). (b) The dependence of the ratio of “anti-quark” \( (\bar{q}) \) and “quark” \( (q) \) contributions to the overall \( W \) decay angle distribution, \( Q(y_W, p_T^W) \), as a function of \( W \) rapidity and \( p_T \) of the \( W \).
This page contains no comments
Figure 5.2: The ratio of anti-quark and quark in $\cos\theta^*$ distribution as a function of $y_W$ and $P_T/W$. 
This page contains no comments
instance, if one of the two possible solutions falls in the central region of rapidity and the other has $|y_W| > 2$, the former should receive more weight as the latter is very unlikely to be produced. As mentioned in Section 1.3, we consider the $K(y_W)$ factor which includes next-to-next-to leading order in QCD to the cross section,

$$K(y_W) = \frac{d\sigma^{NNLO}(y_W)}{d\sigma^{LO}(y_W)}, \quad (5.5)$$

The rapidity distributions of $W$ through NNLO in QCD [15] are shown in Figure 5.4 with the $K(y_W)$.

### 5.3 Event Reconstruction Probability

The information used to select among the two solutions can be represented by a weighting factor for each rapidity solution and charge, $w^{\pm}_{1,2}$, can be represented as

$$w^{\pm}_{1,2} = \frac{P^{\pm}(\cos\theta_1^{\pm}, y_{1,2}, P_{T}^W)\sigma^{\pm}(y_{1,2})}{P^{\pm}(\cos\theta_1^{\pm}, y_1, P_{T}^W)\sigma^{\pm}(y_1) + P^{\pm}(\cos\theta_2^{\pm}, y_2, P_{T}^W)\sigma^{\pm}(y_2)}, \quad (5.6)$$

where the $\pm$ signs indicate the $W$ boson charge and indices of 1, 2 are for the two $W$ rapidity solutions. In Eq 5.6, the weighting factor depends primarily on the $W^+$ and $W^-$ cross-sections, but doesn’t have some weak dependence on the $W$ charge asymmetry itself. Therefore, this method requires us to iterate the procedure to eliminate the dependence of the asymmetry on the weighting factor for our measurement.
use a simulation to leading order (LO) in QCD, but we apply a

i don't know that the dependence is really so weak, actually. certainly not at high rapidity. but the point is that the iteration fo the technique works...

also depends

I think it is very important to explain exactly how you do this since it is so critical to the analysis... in other words there is a predicted sigma+ and simga-, and then what do you do with the charge asymmetry. I assume what you do (based on the way the analysis works) is to hold (sigma+)+(sigma-) fixed and to adjust sigma+ and sigma- individually to reproduce the observed charge asymmetry
Figure 5.3: Fit parameter functions of amplitudes and spreads.

Figure 5.4: The comparison of the $W$ rapidity with NNLO, NLO, and LO QCD predictions (left). The K-factor is determined from the fraction of NNLO and LO predicted distributions (right).
This page contains no comments
Chapter 6. Corrections

In this chapter, we describe corrections to address several experimental effects and to remove the biases which affect our measurement. In order to measure the $W$ charge asymmetry in $W \to e\nu$ decay, any detector acceptances and event selection efficiencies that treat positive and negative events differently must be accounted for. Similarly, any sources contributing to the mismeasurement of electron charge and energy must also be accounted for. These include:

- Correction for electron energy scale and resolution
- Correction for boson recoil energy
- Correction for charge mis-identification in the central and forward tracking
- Correction for the backgrounds
- Correction for the trigger efficiency and electron identification efficiency scale factor
- Correction for the effects of smearing and detector acceptance
(the difference between what is expected from the simulation and what is measured in data is referred to as a "scale factor")
Chapter 6

Corrections

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- Correction for boson recoil energy
- Correction for charge mis-identification in the central and forward tracking
- Correction for the backgrounds
- Correction for the trigger efficiency and electron identification efficiency scale factor
- Correction for the effects of smearing and detector acceptance
in reconstructed rapidity
6.1 Energy Scale Determination

Both energy scale and resolution corrections are applied to the electron energy. Using a control sample of $Z \rightarrow e^+e^-$ events, the energy scale and resolution are determined for both the collected data and the generated Monte Carlo. The absolute calibration of the central and forward calorimeters is used as the energy scale determination. The scale is a factor which multiplies the energy measurement of the calorimeter, and the scale of cluster $E_T$ in the Monte Carlo is tuned to match one in the data. The energy resolution factor is applied to improve resolution by correcting for variations in the energy response of the calorimeter. The formula used to tune the cluster $E_T$ scale and resolution factors is shown in Eq 6.1.

\[
(E_{\text{scale}}') = (K_s \times E_T)
\]
\[
(E_{\text{resol}}') = \text{Gaus}(E_T, \sigma_{E_T})
\]

where $\sigma_{E_T} = R_s \times E_T$ (6.1)

In order to determine the CEM and PEM energy scales, the calorimeter scales are varied in small steps in the simulated data and the resulting $Z$ mass peak monitored. For the CEM scale, the peak obtained from the central-central events, and for the PEM scale, the central-forward events but the scales for four different PEM regions, $-2.8 < \eta < -1.6$, $-1.6 < \eta < -1.2$, $1.2 < \eta < 1.6$, $1.6 < \eta < 2.8$, are considered. At each scaling step a $\chi^2$ is calculated between the rescaled simulated $Z$ mass peak and the data. The fit is made in the small-mass window $80 \text{ GeV}/c^2 < M_{ee} < 100 \text{ GeV}/c^2$ to reduce bias from any mismodeling of the radiative tail in the simulation. The energy resolution is considered in the same way, by introducing extra smearing on top of the best-fitting value in the simulation by generating a random number from a Gaussian distribution with mean equal to $E_T$ and width equal to a chosen $\sigma_{E_T}$ for each lepton candidate in our samples and calculating $\chi^2$ at each step. The mass peaks are shown in
Comments from page 97 continued on next page
Chapter 6. Corrections

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\[
(E_{\text{scale}}) = (K_s \times E_T) \\
(E_{\text{resol}}) = \text{Gaus}(E_T, \sigma_{E_T}) \text{ where } \sigma_{E_T} = R_s \times E_T
\] (6.1)

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An agreement in the width of the invariant mass distribution of Z->ee candidates by adding additional smearing to that already in the simulation.

you need to write this more formally. What you really mean is that you take the E_T measured and add a random number pulled from a Gaussian distribution with width R_S*E_T.
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$$ (E_{\text{scale}}') = (K_s \times E_T) $$

$$ (E_{\text{resol}}') = \text{Gaus}(E_T, \sigma_{ET}) \quad \text{where} \quad \sigma_{ET} = R_s \times E_T $$

(6.1)

In order to determine the CEM and PEM energy scales, the calorimeter scales are varied in small steps in the simulated data and the resulting $Z$ mass peak monitored. For the CEM scale, the peak obtained from the central-central events, and for the PEM scale, the central-forward events but the scales for four different EM regions, $-2.8 < \eta < -1.6$, $-1.6 < \eta < -1.2$, $1.2 < \eta < 1.6$, $1.6 < \eta < 2.8$, are considered. At each scaling step a $\chi^2$ is calculated between the rescaled simulated $Z$ mass peak and the data. The fit is made in the $80 \text{ GeV}/c^2 < M_{ee} < 100 \text{ GeV}/c^2$ mass window to reduce bias from any mismodeling of the radiative tail in the simulation. The energy resolution is considered in the same way, by introducing extra smearing on top of the best-fitting value in the simulation by generating a random number from a Gaussian distribution with mean equal to $E_T$ and width equal to a chosen $\sigma_{ET}$ for each lepton candidate in our samples and calculating $\chi^2$ at each step. The mass peaks are shown in
the sample used were dielectron
dielectron events

In the PEM,

independent energy

you mean eta_det here
6.1 Energy Scale Determination

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$$\left( E_{\text{scale}} \right)^{\prime} = \left( K_s \times E_T \right)$$

$$\left( E_{\text{resol}}^{\prime} \right) = \text{Gaus}(E_T, \sigma_{E_T}) \quad \text{where} \quad \sigma_{E_T} = R_s \times E_T \quad (6.1)$$

In order to determine the CEM and PEM energy scales, the calorimeter scales are varied in small steps in the simulated data and the resulting $Z$ mass peak monitored; for the CEM scale, the peak obtained from the central-central events, and for the PEM scale the central-forward events but the scales for four different PEM regions, $-2.8 < \eta < -1.6$, $-1.6 < \eta < -1.2$, $1.2 < \eta < 1.6$, $1.6 < \eta < 2.8$, are considered. At each scaling step a $\chi^2$ is calculated between the rescaled simulated $Z$ mass peak and the data. The fit is made in the small-mass window $80 \text{ GeV}/c^2 < M_{ee} < 100 \text{ GeV}/c^2$ to reduce bias from any mismodeling of the radiative tail in the simulation. The energy resolution is considered in the same way, by introducing extra smearing on top of the best-fitting value in the simulation by generating a random number from a Gaussian distribution with mean equal to $E_T$ and width equal to a chosen $\sigma_{E_T}$ for each lepton candidate in our samples and calculating $\chi^2$ at each step. The mass peaks are shown in
Figure 6.1, 6.2 and 6.3. The $\chi^2$ are shown in Figure 6.4, 6.5 and 6.6. The cluster $E_T$ scaling and smearing factors in Table 6.1 and 6.2 are applied to the lepton energy in the $W \to e\nu$ Monte Carlo sample used to measure $W$ charge asymmetry. As part of this work, appropriate energy scalings were found for data in different offline versions (run-periods).

![Histograms](image)

(a) GEN5 MC  
(b) GEN6 MC

Figure 6.1: $M_{ee}$ for central-central events: The plots show the scaling and smearing giving the best $\chi^2$ fit between data and simulation.

<table>
<thead>
<tr>
<th>Region</th>
<th>$K_\eta \pm 1\sigma$</th>
<th>$R_\eta \pm 1\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.2$</td>
</tr>
<tr>
<td>$1.2 &lt; \eta &lt; 1.6$</td>
<td>0.9914 ± 0.0022</td>
<td>0.0087 ± 0.0051</td>
</tr>
<tr>
<td>$1.6 &lt; \eta &lt; 2.8$</td>
<td>1.0171 ± 0.0021</td>
<td>0.0132 ± 0.0044</td>
</tr>
<tr>
<td>$-1.6 &lt; \eta &lt; -1.2$</td>
<td>0.9884 ± 0.0020</td>
<td>0.0000 ± 0.0054</td>
</tr>
<tr>
<td>$-2.8 &lt; \eta &lt; -1.6$</td>
<td>1.0280 ± 0.0032</td>
<td>0.0070 ± 0.0085</td>
</tr>
</tbody>
</table>

Table 6.1: The cluster $E_T$ scaling and resolution factors (GEN5).
(GEN5 and GEN6) which correspond to different periods of data taking.
Figure 6.2: central-forward events for GEN5: The comparison of the $Z \rightarrow e^+ e^-$ invariant mass between data and MC.
This page contains no comments
Figure 6.3: central-forward events for GEN6: The comparison of the $Z \rightarrow e^+e^-$ invariant mass between data and MC.
This page contains no comments
Figure 6.4: Central electron: The best $\chi^2$ fit of the $Z \to e^+e^-$ invariant mass comparison between data and MC for the cluster $E_T$ energy scale. The fit formula is $p_0(x + p_1)^2 + p_2$. 

(a) GEN5 MC

(b) GEN6 MC
This page contains no comments
Figure 6.5: Forward electron for GEN5: The best $\chi^2$ fit of the $Z \to e^+e^-$ invariant mass comparison between data and MC for the cluster $E_T$ energy scale. The fit formula is $p_0(x + p_1)^2 + p_2$.

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<tr>
<th>Region</th>
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<th>$R_s \pm 1\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.2$</td>
</tr>
<tr>
<td>1.2 &lt; $\eta$ &lt; 1.6</td>
<td>0.9830 ± 0.0016</td>
<td>0.0079 ± 0.0052</td>
</tr>
<tr>
<td>1.6 &lt; $\eta$ &lt; 2.8</td>
<td>1.0235 ± 0.0022</td>
<td>0.0044 ± 0.0051</td>
</tr>
<tr>
<td>−1.6 &lt; $\eta$ &lt; −1.2</td>
<td>0.9817 ± 0.0015</td>
<td>0.0031 ± 0.0042</td>
</tr>
<tr>
<td>−2.8 &lt; $\eta$ &lt; −1.6</td>
<td>1.0160 ± 0.0023</td>
<td>0.0038 ± 0.0054</td>
</tr>
</tbody>
</table>

Table 6.2: The cluster $E_T$ scaling and resolution factors (GEN6).
This page contains no comments
Figure 6.6: Forward electron for GEN5: The best $\chi^2$ fit of the $Z \rightarrow e^+e^-$ invariant mass comparison between data and MC for the cluster $E_T$ energy scale. The fit formula is $p_0(x + p_1)^2 + p_2$. 
This page contains no comments
Chapter 6. Corrections

6.2 **Boson Recoil Energy Scale Determination**

The modeling of hadronic showering, the boson recoil-energy, and the underlying event energy in the Monte Carlo can be inaccurate to some degree and lead to differences between the Monte Carlo and the data. Since the calorimeter energy measurement plays an important role in determining the $E_T$, the Monte Carlo model for calorimeter deposition in $W \rightarrow e\nu$ events should be tuned to provide the best possible match with data.

![Figure 6.7: Kinematics of $W$ boson production and decay, as viewed in the transverse plane to the proton-antiproton beams.](image)

In order to do this tuning, we define the recoil energy of an event in the directions parallel and perpendicular to the direction of the high $p_T$ lepton from the $W$ boson decay in the transverse plane of the detector as shown in Figure 6.7. The calculations of these...
A major problem with this section is that you never define what sample you are tuning (it's the Z sample, right?) to or show a data/MC distribution for that sample. The rest of this is fine, but you need to add that.
components of the recoil energy are shown in Eq 6.2.

\[
\begin{align*}
U_x &= -E_T x - (E_{T}^{EM} + E_{T}^{HAD}) \cos(\phi_e) \\
U_y &= -E_T y - (E_{T}^{EM} + E_{T}^{HAD}) \sin(\phi_e) \\
U_\parallel &= U_x \cos(\phi_e) + U_y \sin(\phi_e) \\
U_\perp &= U_x \sin(\phi_e) - U_y \cos(\phi_e) \\
\end{align*}
\] (6.2)

\[
\begin{align*}
(U_\parallel)^2 &= (K_\parallel \times U_\parallel) + C_\parallel \\
(U_\perp)^2 &= (K_\perp \times U_\perp) + C_\perp \\
\end{align*}
\] (6.3)

The appropriate corrections to apply to the MC recoil energy model are an overall scale correction for both the parallel and perpendicular directions and an additional constant term (shift correction). The scaling correction accounts for potential problems in modeling calorimeter response and the effects of multiple interactions, the underlying event model, and accelerator backgrounds which should not be dependent on the lepton direction. The shift correction is designed to account for modeling effects that do have a lepton-direction dependence such as the $W$ boson recoil model and the model for lepton energy deposition in the calorimeter.

Eq. 6.3 shows the formula used to correct the MC recoil energy distributions to match those seen in data. In order to determine the best values for the scaling and shifting constants in these formulas, $\chi^2$ fits between the data recoil energy distributions and corrected MC distributions for a range of scaling and shifting constants are performed. An iterative process is used in which we first determine the best possible shifting constants and then fit for scaling constants based on those values. This process repeats until the $\chi^2$ fits for both the scaling and shifting constants stabilize at set values. The results of the $\chi^2$ fits used to obtain the central values and uncertainties for the tuning parameters defined in Eq. 6.3 are shown in Table 6.4 and as a function of electron $\eta$ in Figure 6.8. The final $\chi^2$ fits for the recoil energy scale corrections and a comparison of
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Subject: Comment on Text
Date: 4/17/2008 1:51:28 PM

this belongs below where it is discussed in the text

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Author: Kevin McFarland
Subject: Replacement Text
Date: 4/17/2008 1:52:14 PM

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Sequence number: 4
Author: Kevin McFarland
Subject: Inserted Text
Date: 4/17/2008 1:52:30 PM

by corrections of the form: (now put Eqn 6.3 in!)
Chapter 6. Corrections

the tuned MC recoil energy distributions with those obtained from the data are shown in Appendix B.

| $|\eta| < 1.2$ | $K_{||} \pm 1\sigma$ | $C_{||} \pm 1\sigma$ |
|----------------|------------------|------------------|
| 1.2 < $\eta$ < 1.6 | 0.9635 ± 0.0096 | -0.8461 ± 0.0405 |
| 1.6 < $\eta$ < 2.8 | 0.9482 ± 0.0120 | -0.3371 ± 0.0557 |
| -1.6 < $\eta$ < -1.2 | 0.9759 ± 0.0100 | -1.0146 ± 0.0426 |
| -2.8 < $\eta$ < -1.6 | 0.9619 ± 0.0126 | 0.0675 ± 0.0613 |

<table>
<thead>
<tr>
<th>$U_{\perp}$</th>
<th>$K_{\perp} \pm 1\sigma$</th>
<th>$C_{\perp} \pm 1\sigma$</th>
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</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.2$</td>
</tr>
<tr>
<td>1.2 &lt; $\eta$ &lt; 1.6</td>
<td>0.9368 ± 0.0098</td>
<td>0.1870 ± 0.0414</td>
</tr>
<tr>
<td>1.6 &lt; $\eta$ &lt; 2.8</td>
<td>0.9335 ± 0.0127</td>
<td>0.1963 ± 0.0563</td>
</tr>
<tr>
<td>-1.6 &lt; $\eta$ &lt; -1.2</td>
<td>0.9424 ± 0.0102</td>
<td>-0.0664 ± 0.0426</td>
</tr>
<tr>
<td>-2.8 &lt; $\eta$ &lt; -1.6</td>
<td>0.9394 ± 0.0142</td>
<td>-0.0575 ± 0.0568</td>
</tr>
</tbody>
</table>

Table 6.3: The recoil energy scaling factors (GEN5).

Figure 6.8: Recoil Energy Scale Factors as a function of $\eta_e$. 

I know it's a lot of plots, but I think it's fine to move this into the main text here. There isn't really any reason for the appendix (unlike the case of the trigger work where it is a lot of details that don't belong in the main text)
Chapter 6. Corrections

### Table 6.4: The recoil energy scaling factors (GEN6).

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<tr>
<th>$U_\parallel$</th>
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<th>$C_\parallel \pm 1\sigma$</th>
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</thead>
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<td>\eta</td>
<td>&lt; 1.2$</td>
</tr>
<tr>
<td>1.2 &lt; $\eta$ &lt; 1.6</td>
<td>0.9587 ± 0.0070</td>
<td>-1.1924 ± 0.0320</td>
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<tr>
<td>1.6 &lt; $\eta$ &lt; 2.8</td>
<td>0.9687 ± 0.0095</td>
<td>-0.1519 ± 0.0450</td>
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<tr>
<td>−1.6 &lt; $\eta$ &lt; −1.2</td>
<td>0.9567 ± 0.0073</td>
<td>-1.0944 ± 0.0336</td>
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<tr>
<td>−2.8 &lt; $\eta$ &lt; −1.6</td>
<td>0.9554 ± 0.0098</td>
<td>-0.2037 ± 0.0477</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>$U_\perp$</th>
<th>$K_\perp \pm 1\sigma$</th>
<th>$C_\perp \pm 1\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.2$</td>
</tr>
<tr>
<td>1.2 &lt; $\eta$ &lt; 1.6</td>
<td>0.9434 ± 0.0077</td>
<td>0.2526 ± 0.0330</td>
</tr>
<tr>
<td>1.6 &lt; $\eta$ &lt; 2.8</td>
<td>0.9448 ± 0.0098</td>
<td>0.2253 ± 0.0443</td>
</tr>
<tr>
<td>−1.6 &lt; $\eta$ &lt; −1.2</td>
<td>0.9309 ± 0.0076</td>
<td>−0.0448 ± 0.0338</td>
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<tr>
<td>−2.8 &lt; $\eta$ &lt; −1.6</td>
<td>0.9380 ± 0.0103</td>
<td>−0.0009 ± 0.0469</td>
</tr>
</tbody>
</table>

### 6.3 Charge Identification

Good charge identification is crucial for the asymmetry measurement because the charge determines the sign of the weight factor, $w^\pm$ (see Eqn. 5.6), which determines the number of $W^\pm$ rapidity events. Therefore, charge misidentification of electrons changes the $W$ charge asymmetry and the charge misidentification rate needs to be properly determined. The charge fake rate of an electron is measured using the $Z \to e^+e^-$ samples and is defined as:

$$f_{\text{mis}}(\eta) = \frac{N_{\text{wrong-sign}}(\eta)}{N_{\text{right-sign}}(\eta) + N_{\text{wrong-sign}}(\eta)},$$  \hspace{1cm} (6.4)

where $N_{\text{wrong-sign}}$ is the number of $Z$ candidates where two electrons have the same sign, and $N_{\text{right-sign}}$ is the number where they have the opposite sign. In order to study this charge misidentification, $Z$ candidates from the high-$p_T$ electron dataset is used, since $Z \to e^+e^-$ data is a clean sample to identify the charge of electron, and then $Z$ data is compared sample to Monte Carlo to determine the charge misidentification in the...
The events have very low backgrounds, the electrons have similar kinematics to the $W \rightarrow e \nu$ events, and the events self-identify as correct or incorrect charge measurements by comparing the same to opposite sign dielectron events.

between the data and any differences in
6.3 Charge Identification

Good charge identification is crucial for the asymmetry measurement because the charge determines the sign of the weight factor, \( w^\pm \) (see Eqn. 5.6), which determines the number of \( W^\pm \) rapidity events. Therefore, charge misidentification of electrons changes the \( W \) charge asymmetry and the charge misidentification rate needs to be properly determined. The charge fake rate of an electron is measured using the \( Z \to e^+e^- \) samples and is defined as:

\[
f_{\text{mis}}(\eta) = \frac{N_{\text{wrong-sign}}(\eta)}{N_{\text{right-sign}}(\eta) + N_{\text{wrong-sign}}(\eta)},
\]

(6.4)

where \( N_{\text{wrong-sign}} \) is the number of \( Z \) candidates where two electrons have the same sign, and \( N_{\text{right-sign}} \) is the number where they have the opposite sign. In order to study this charge misidentification, \( Z \) candidates from the high-\( p_T \) electron dataset is used, since \( Z \to e^+e^- \) data is a clean sample to identify the charge of electron, and the \( Z \) data is compared sample to Monte Carlo to determine the charge misidentification in the
simulation.

For central-central $Z$s, two electrons are required so that one leg pass the tight electron cuts in Table 3.1, but other leg pass extra tight cuts: isolation ratio $< 0.05$ and the lateral shower quality ($L_{shr}$) $< 0.1$. These cuts are applied to the electron used to probe the true charge of the electron. For central-forward $Z$s, the central electron is selected with the same extra tight cuts, and the forward electron must pass the PEM and default track requirements in Table 3.2. For all candidates, the dielectron invariant mass is also required to be between 76 and 106 GeV/$c^2$ for central-central $Z$s and between 81 and 101 GeV/$c^2$ for central-forward $Z$s. The background contribution (0.48%) from jets in $Z$ data is subtracted for the central-forward $Z$s; the background estimate is described in section 4.2.1. The charge fake rate (CFR) from the selected $Z$ candidates is measured as a function of $\eta$. Figure 6.9 shows that the CFRs of two different run-periods data (run 138425 - 186598 : 0d and run 190697 - 212133 : 0h+0i) are consistent but the CFR of GEN6 MC is higher than one of GEN5 MC at $|\eta| > 1.6$. Thus, GEN5 and GEN6 MCs are tuned to the corresponding data, respectively. The CFR of the MC is tuned by scale factors which are determined from the best $\chi^2$ value between data and MC for four the electron $\eta$ regions listed in Table 6.5.

In order to have a charge mis-identification correction for our asymmetry, we need to describe the charge fake rate as a function of $W$ rapidity. Thus, we derive a correc-

<table>
<thead>
<tr>
<th>Region</th>
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<th>GEN6 MC $K_s \pm 1\sigma$</th>
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<tr>
<td>$-2.8 &gt; \eta &gt; -1.6$</td>
<td>1.662 ± 0.192</td>
<td>1.033 ± 0.120</td>
</tr>
<tr>
<td>$1.6 &gt; \eta &gt; -1.1$</td>
<td>0.488 ± 0.195</td>
<td>0.524 ± 0.204</td>
</tr>
<tr>
<td>$1.1 &gt; \eta &gt; 1.6$</td>
<td>0.257 ± 0.134</td>
<td>0.299 ± 0.150</td>
</tr>
<tr>
<td>$1.6 &lt; \eta &lt; 2.8$</td>
<td>1.543 ± 0.168</td>
<td>0.847 ± 0.093</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>GEN5 MC $K_s \pm 1\sigma$</th>
<th>GEN6 MC $K_s \pm 1\sigma$</th>
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<td>0.847 ± 0.093</td>
</tr>
</tbody>
</table>

Table 6.5: The Charge Fake Rate Scale factors.
Comments from page 108 continued on next page
Chapter 6. Corrections

Simulation.

For central-central $Z$s, two electrons are required so that one leg pass the tight electron cuts in Table 3.1, but other leg pass extra tight cuts: isolation ratio $< 0.05$ and the lateral shower quality ($L_{shr}$) $< 0.1$. These cuts are applied to the electron used to probe the true charge of the electron. For central-forward $Z$s, the central electron is selected with the same extra tight cuts, and the forward electron must pass the PEM and default track requirements in Table 3.2. For all candidates, the dielectron invariant mass is also required to be between 76 and 106 GeV/$c^2$ for central-central $Z$s and between 81 and 101 GeV/$c^2$ for central-forward $Z$s. The background contribution ($0.48\%$) from jets in $Z$ data is subtracted for the central-forward $Z$s; the background estimate is described in section 4.2.1. The charge fake rate (CFR) from the selected $Z$ candidates is measured as a function of $\eta$. Figure 6.9 shows that the CFRs of two different run-periods data (run 138425 - 186598 : 0d and run 190697 - 212133 : 0h+0i) are consistent but the CFR of GEN6 MC is higher than one of GEN5 MC at $|\eta| > 1.6$. Thus, GEN5 and GEN6 MCs are tuned to the corresponding data, respectively. The CFR of the MC is tuned by scale factors which are determined from the best $\chi^2$ value between data and MC for four the electron $\eta$ regions listed in Table 6.5.

In order to have a charge mis-identification correction for our asymmetry, we need to describe the charge fake rate as a function of $W$ rapidity. Thus, we derive a correc-

<table>
<thead>
<tr>
<th>Region</th>
<th>GEN5 MC $K_s \pm 1\sigma$</th>
<th>GEN6 MC $K_s \pm 1\sigma$</th>
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<tbody>
<tr>
<td>$-2.8 &gt; \eta &gt; -1.6$</td>
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<td>1.543 ± 0.168</td>
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Table 6.5: The Charge Fake Rate Scale factors.
other

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simulation charge fake rates

det

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Subject: Cross-Out
Date: 4/17/2008 2:13:54 PM

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Subject: Comment on Text
Date: 4/17/2008 2:16:56 PM
at least one too many significant figures everywhere!
(a) The consistency of CFRs for both 0d and 0h+0i dataset

(b) The comparison of CFR between data and MCs

Figure 6.9: The charge fake rate is plotted as a function of electron $\eta$. 
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Figure 6.10: The Charge Fake Rates for data and GEN5 MC (left) and GEN6 MC (right). We applied the scale factors to the MC samples.

We applied the scale factors to the MC samples. The total reconstructed number of positively and negatively charged events and the total number of true charged events are described in Eq. 6.5 and 6.6, respectively.

\[
N_{\text{obs}}^{+}(w^{+}) = N_{+}^{+}(w^{+}) + N_{-}^{-}(w^{+}) \\
N_{\text{obs}}^{-}(w^{-}) = N_{+}^{-}(w^{-}) + N_{-}^{-}(w^{-}) 
\]

\[
N_{\text{true}}^{+} = N_{+}^{+}(w^{+}) + N_{+}^{-}(w^{+}) \\
N_{\text{true}}^{-} = N_{+}^{-}(w^{-}) + N_{+}^{-}(w^{-}) 
\] (6.5)

\(N_{+}^{+}(w^{+})\) is the number of truly positive charge events reconstructed with a negative charge and is a function of the weight factor \((w)\) in that bin of \(W\) rapidity. The number
This page contains no comments
of true charged events is alternatively described with the reconstructed information as

\[
N_{\text{true}}^+ = \left[ N_+^+(w^+) + N_+^-(w^-) \right] \times \frac{N_+^+(w^+)}{[N_+^+(w^+) + N_+^-(w^-)]} \\
+ \left[ N_-^+(w^+) + N_+^-(w^-) \right] \times \frac{N_-^+(w^+)}{[N_-^+(w^+) + N_+^-(w^-)]} \\
= N_{\text{obs}}^+(w^+) \times (1 - \rho^+(w^+)) + N_{\text{obs}}^-(w^-) \times (\rho^+(w^-)) 
\]

(6.7)

\[
N_{\text{true}}^- = \left[ N_-^-(w^-) + N_+^-(w^-) \right] \times \frac{N_-^-(w^-)}{[N_-^-(w^-) + N_+^+(w^-)]} \\
+ \left[ N_+^-(w^-) + N_+^+(w^-) \right] \times \frac{N_+^-(w^-)}{[N_+^-(w^-) + N_+^+(w^-)]} \\
= N_{\text{obs}}^-(w^-) \times (1 - \rho^-(w^-)) + N_{\text{obs}}^+(w^-) \times (\rho^-(w^-)) 
\]

(6.8)

In Eq. 6.9, the four charge fake rates, that are \( \rho^+(w^+), \rho^+(w^-), \rho^-(w^-) \) and \( \rho^-(w^+) \) in Eq. 6.7 and 6.8, are defined as the reconstructed charge and the weight factors of the two \( W \) rapidity solutions.

\[
\rho^+(w^+) = \frac{N_-^+(w^-)}{N_+^+(w^+) + N_+^-(w^-)} \\
\rho^+(w^-) = \frac{N_+^-(w^-)}{N_+^+(w^-) + N_+^-(w^-)} \\
\rho^-(w^-) = \frac{N_+(w^-)}{N_-^-(w^-) + N_-^+(w^-)} \\
\rho^-(w^+) = \frac{N_-^+(w^+)}{N_-^-(w^+) + N_-^+(w^+)} 
\]

(6.9)

### 6.4 Backgrounds

The corrections for two backgrounds are used for this analysis: QCD and \( Z \rightarrow e^+e^- \). Note that we consider the \( W \rightarrow \tau \nu \rightarrow e \nu \) as signal and it is included in the acceptance. The estimates of these backgrounds are described in the Chapter 4. For the \( Z \rightarrow e^+e^- \)
I'm quite confused by this notation. It looks to me like w+ and w- are actually y_W(1) and y_W(2). If that's true, you should label them as such. The w+ and w- look like the refer to electric charge otherwise!

that

since it has the same W production charge asymmetry

Recall
and $W \rightarrow \tau\nu$ contributions, we rely on Monte Carlo simulation and the contributions are shown in Figure 4.1.

### 6.4.1 Jet-like-electron sample

However, in order to estimate the QCD jet contribution in the measured $W$ rapidity, the QCD fake $W$ rapidity should be reconstructed using our analysis technique and it can be done with a jet sample plus require large $E_T$. Since the dijet sample in Section 4.2.2 has been restricted in $E_T < 10$ GeV, An alternative approach is proposed to extract the QCD background in $y_W$ bins for the $W$ charge asymmetry measurement. The approach defines QCD electron-fake sample using the same dataset and trigger path as is used to form the $W$ candidate sample, but the fake electron are selected by requiring an electron cluster which passes all baseline selection cuts in Table 3.1 and 3.2 but fail the $Had/Em$ and isolation cut. An electron which meets this criteria is referred to as an “jet-like-electron”. A jet-like-electron sample excludes any other tight electron and low $E_T$ ($< 25$ GeV) events.

This sample contains some signal contamination, which can be estimated out by fitting the isolation distribution and should be subtracted. As was discussed in Section 4.2, the isolation shape of the jet-like-electron data is fitted to estimate the signal contribution using the electron and jet templates. However, since $Z \rightarrow e^+e^-$ data with the veto cuts has limited statistics and backgrounds, the electron template for this fit is obtained from $W \rightarrow e\nu$ MC instead. The results for the different $E_T$ regions are presented in Figure 6.11. We estimate the electron fraction in the central and non-isolated ($\leq 6$ GeV) jet-like-electron sample to be $(0.54 \pm 1.25_{\text{stat}})\%$ for $25$ GeV $< E_T < 35$ GeV and $(2.96 \pm 1.74_{\text{stat}})\%$ for $E_T$ $> 35$ GeV and in the forward to be $(0.04 \pm 1.82_{\text{stat}})\%$ for $25$ GeV $< E_T < 35$ GeV and $(0.17 \pm 2.18_{\text{stat}})\%$ for $E_T$ $> 35$ GeV.
I'm confused by this. The backgrounds from the \(Z\rightarrow\text{ee}\) sample are really very low. Why does this matter for subtracting the electron content from a jet sample?
and $W \rightarrow \tau \nu$ contributions, we rely on Monte Carlo simulation and the contributions are shown in Figure 4.1.

6.4.1 Jet-like-electron sample

However, in order to estimate the QCD jet contribution in the measured $W$ rapidity, the QCD fake $W$ rapidity should be reconstructed using our analysis technique and it can be done with a jet sample plus require large $\not{E}_T$. Since the dijet sample in Section 4.2.2 has been restricted in $\not{E}_T < 10$ GeV, An alternative approach is proposed to extract the QCD background in $y_W$ bins for the $W$ charge asymmetry measurement. The approach defines QCD electron-fake sample using the same dataset and trigger path as is used to form the $W$ candidate sample, but the fake electron are selected by requiring an electron cluster which passes all baseline selection cuts in Table 3.1 and 3.2 but fail the $H_{\text{ad/Em}}$ and isolation cut. An electron which meets this criteria is referred to as an “jet-like-electron”. A jet-like-electron sample excludes any other tight electron and low $\not{E}_T$ (< 25 GeV) events.

This sample contains some signal contamination, which can be estimated out by fitting the isolation distribution and should be subtracted. As was discussed in Section 4.2, the isolation shape of the jet-like-electron data is fitted to estimate the signal contribution using the electron and jet templates. However, since $Z \rightarrow e^+e^-$ data with the veto cuts have a limited statistics and backgrounds, the electron template for this fit is obtained from $W \rightarrow e\nu$ MC instead. The results for the different $\not{E}_T$ regions are also presented in Figure 6.11. We estimate the electron fraction in the central and non-isolated (< 6 GeV) jet-like-electron sample to be $(0.54 \pm 1.25_{\text{stat}})$% for $25 \text{ GeV} < \not{E}_T < 35$ GeV and $(2.96 \pm 1.74_{\text{stat}})$% for $\not{E}_T > 35$ GeV and in the forward to be $(0.04 \pm 1.82_{\text{stat}})$% for $25 \text{ GeV} < \not{E}_T < 35$ GeV and $(0.17 \pm 2.18_{\text{stat}})$% for $\not{E}_T > 35$ GeV.
again, at least one too many significant figures. Just to make sure, you intent to show that these are all more or less consistent with zero background, right? You should probably add a sentence to say that.
Figure 6.11: Isolation distribution fit of jet-like-electron data.
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6.4.2 QCD contribution on the $W$ rapidity

The QCD fake $W$ rapidity is reconstructed using the jet-like-electron plus $E_T$ sample and then the electron contribution is subtracted with the estimated fraction previously. Figure 6.12 shows the fake $W$ rapidity, which implemented by the weight factors which are determined with the probability of the differential cross section and the decay angular distribution on the $W$ decay structure using the jet kinematics and $E_T$. The QCD $W$ rapidity and the $Z \rightarrow e^+e^-$ rapidity are then subtracted from the $W$ candidate rapidity.

Figure 6.12: QCD Fake $W$ rapidity distribution obtained from the jet-like plus $E_T$ sample.
as just discussed

and reconstruction algorithm applied to the signal sample.

same

with

constructed in this matter

and

backgrounds as a function of rapidity and charge
Chapter 6. Corrections

6.5 Trigger Efficiencies

The trigger efficiency is the probability that a $W \rightarrow e\nu$ signal event meeting the kinematic cuts is accepted by the trigger. The efficiency for an event to pass the trigger requirement is measured in other samples containing the trigger object but not biased by the analysis trigger requirements. Using trigger paths parallel to the analysis path, the trigger response is determined in the offline from high purity objects. The efficiency of each trigger is measured separately for the L1, L2, and L3 efficiencies and then the product of these is taken as the overall efficiency. The measured efficiency is then applied to the simulated signal sample to correct the predicted number of events.

For the central electron trigger efficiency, only the L1 tracking trigger efficiency has an $\eta$ dependence, which is what is relevant for this analysis. For electrons in the forward region, the L2 trigger has a dependence on $\eta$ and $E_T$. The details of each measurement are discussed in Appendix A.

6.6 Electron Identification Efficiencies

A systematic bias in the $W$ charge asymmetry occurs if the electron identification cuts have any $\eta$ dependence and the detector response to electrons differs from that to positrons. Separate from the electron identification selection, the tracking reconstruction efficiency is compared between the data and detector simulation.

6.6.1 Central Electron Identification efficiency

To measure the central electron identification efficiencies [31], the tight electron requirements of Table 3.1 are applied to one leg, geometric and kinematic cuts of $E_T > 25$ GeV, $p_T > 10$ GeV and fiduciality are applied to the second leg, and opposite sign and tight invariant mass cuts are made ($76$ GeV/$c^2 < M_{ee} < 106$ GeV/$c^2$). Figure 6.13
Unlike the measurement of charge asymmetry vs. lepton pseudorapidity from this sample, this direct measurement of the W charge asymmetry is sensitive to acceptance and trigger efficiency as a function of lepton eta and energy. This is because leptons of different charges from the same pseudorapidity and energy are preferentially assigned to different W boson rapidities. Therefore, we must be especially careful to study these efficiencies.
6.5 Trigger Efficiencies

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To improve the purity of the sample with tight cuts on only one electron,

which is the electron where identification efficiency will be tested.

The identification efficiency is then measured by looking at how many of the second leg electrons pass the tight electron cuts of the analysis.

do you want to assert that the remaining background to this sample is minimal and therefore ignored in your efficiency determination?
Chapter 6. Corrections

shows that the central electron identification efficiencies have an $\eta$ dependence and the data/MC scale factor of the ID efficiency has a few percent variation as a function of $\eta$. This correction is applied to $W \rightarrow e\nu$ acceptance in this analysis.

For the central electron tracking, the COT tracking reconstruction is measured using a $W$ no-track sample. The efficiency that a high-$p_T$ track is reconstructed for a central electron with $E_T > 25$ GeV is found to be $100 \pm 0.4\%$ in both the data and the simulation. Therefore, no correction is needed.

6.6.2 Forward Electron Identification efficiency

The forward electron identification efficiency is more straightforward to obtain than the central efficiencies as the selection of the central leg of central-forward events is independent of the forward leg used as the probe. However even more care must be taken over the backgrounds, which are greater. In addition to the forward electron selection, the track quality cuts are required for the forward electrons, as shown in Table 3.2. The efficiency scale factor of the track quality cuts in the forward using $CF Z \rightarrow e^+e^-$ events is measured, where the forward leg has only the PEM selection. To reduce backgrounds, one leg passes extra tight CEM cuts (Iso $< 0.05$ and Lshr $< 0.1$) and the invariant mass should be in the region $81$ GeV $< M_{ee} < 101$ GeV. To measure the efficiency vs. $\eta$ in the data and the MC the track quality cuts on the PEM electron are applied to these events. A correction factor for the simulated data is calculated as the ratio of the two efficiencies.

However, as mentioned in section 3.5 the forward tracking efficiency of GEN5 MC is higher than GEN6 MC and this effect requires us to use two different electron tracking scale factors for both run-periods ($0i$ and $0h+0i$) as show in Figure 6.14. Figure 6.15 shows no charge dependence of the correction for the forward tracking efficiency.
Therefore, we apply a

that the data and Monte Carlo (MC) simulation do not agree precisely in their estimates of the ID efficiency.

which

to

do you need to say anything about how you treat the (common) case where multiple electrons in the event already pass the tight
cuts? You actually already raise that point in the first sentence of section 6.6.2, but you don't say how you handle it here.

Because the identification efficiency determined above already starts from tracks,

new paragraph starting here
shows that the central electron identification efficiencies have an $\eta$ dependence and the data/MC scale factor of the ID efficiency has a few percent variation as a function of $\eta$. This correction is applied to $W \rightarrow e\nu$ acceptance in this analysis.

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The efficiency is measured in simulation and data as a function of electron eta, and a check that there is a requirement to study.

cuts and no requirement is made on tracking.

two electron

must pass
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is required to be between

The efficiency is measured in simulation and data as a function of electron eta, and a check that there is
Figure 6.13: The central electron identification efficiency in $Z \rightarrow e^+e^-$ events as a function of $\eta$ (top) and the scale factor of ratio data/MC (bottom).
This page contains no comments
Figure 6.14: The tracking efficiency of the forward leg in $Z \rightarrow e^+e^-$ events as a function of $\eta$ (top) and the scale factor of ratio data/MC (bottom).
This page contains no comments
6.7 $W \rightarrow e\nu$ Acceptance

The raw $W$ charge asymmetry must be corrected for detector acceptance and smearing effects to obtain the true $W$ asymmetry, which can be compared to theoretical calculations. The acceptance $a^\pm(y_W)$, is simply defined as the fraction of the $W$ events generated that meet the geometric and kinematic requirements of the analysis:

$$a^\pm(y_W) = \frac{\# \text{ of events from MC and simulation which pass cuts}}{\# \text{ of events from MC without cuts at generation level}}, \quad (6.10)$$

where the sign, $\pm$, indicates the charge of $W$ boson. The acceptance depends on the charge of the $W$ boson, and such effects need to be carefully studied and evaluated before being applied blindly in this analysis because of their direct impact on the charge asymmetry. The corrections to the acceptance are the trigger efficiency measured from the data, the electron ID and tracking efficiency scale factors (data/MC) and the charge fake rate also measured in the data. The acceptance correction is shown in Figure 6.16. Note that this acceptance correction must also be iterated since the weighting of the $W$s at reconstruction level depends on the underlying assumed distributions.
you don't really want to typeset this in math mode with such a long expression. Inside the equation, use \textstyle \# of events from MC...}
Figure 6.15: The scale factor of ratio data/MC (bottom) separately for positrons and electrons.

Figure 6.16: The acceptance correction.
This page contains no comments
Chapter 7

Measurement of $W$ Charge Asymmetry

In this chapter, all of the results obtained in the preceding sections are put together in the physics measurements, which are then interpreted and their significance discussed. The $W$ production charge asymmetry is measured using the analysis technique. The statistical and systematic uncertainties associated with this analysis are summarized in the following sections. Furthermore, this result is compared with the predictions from the perturbative QCD calculation and the different PDFs. The systematic effects on our measurement are estimated when the input valence, sea quark and gluon distributions are changed.

7.1 Summary of Statistical Uncertainties

The $W$ production charge asymmetry is measured by the differential cross section of $W^\pm$ which is reconstructed using the weighting factor and followed by the iteration. In Eq. 7.1, the statistical uncertainty on the $W$ charge asymmetry is evaluated from the weighting factor of the two possible solutions. Since our iteration method can cause a statistical fluctuation, we estimate an additional statistical error using 600 pseudo-
to measure the W boson charge asymmetry

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also studied.

might amplify the expected
Chapter 7

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experiments. The pseudo-experiments are randomly made from 20M \( W \rightarrow e\nu \) MC sample so that the total number of events is same to one of \( W \rightarrow e\nu \) candidate. In Figure 7.1, each result from the pseudo-experiments is compared with default charge asymmetry and also the variation of pull ratio distributions in \( y_W \) bins indicates the statistical fluctuation caused by iteration method. In the end, the RMS of pull ratio is multiplied to the calculated statistical error in Eq. 7.1. Table 7.1 summarize the total statistical uncertainty on the \( W \) charge asymmetry measurement.

\[
A_i^{\text{true}}(y_W) = \frac{\mu_i^+ - \mu_i^-}{\mu_i^+ + \mu_i^-}
\]

\[
(\sigma_{A_i})^2 = \frac{4(\mu_i^+ \mu_i^-)^2}{(\mu_i^+ \mu_i^-)^4} \times \left[ \left( \frac{\sigma_{\mu_i^+}}{\mu_i^+} \right)^2 + \left( \frac{\sigma_{\mu_i^-}}{\mu_i^-} \right)^2 \right]
\]

(7.1)

where \( \mu_i = a_i^{-1} \nu_i \),

\[
(\sigma_{\mu_i})^2 = \left[ \left( \frac{\partial \mu_i}{\partial \nu_i} \sigma_{\nu_i} \right)^2 + \left( \frac{\partial \mu_i}{\partial a_i^{-1} \sigma_{a_i^{-1}}} \right)^2 \right]
\]

\[
= \left[ (a_i^{-1} \sigma_{\nu_i})^2 + (\nu_i \sigma_{a_i^{-1}})^2 \right]
\]

where \( a_i \) indicates the acceptance, \( (\sigma_{\nu_i})^2 = \sum w^2 \) and \( w \) is the weighting factor in Eq. 5.6.

### 7.2 Summary of Systematic Uncertainties

As described in previous chapters, the systematic uncertainty on the \( W \) charge asymmetry measurement arises from potentially significant sources: the uncertainties in the total (charge summed) \( W \) production as a function of rapidity and the ratio of quark and anti-quark in the angular decay distribution, the energy scale uncertainty of the electron \( E_T \) and the uncertainty in the measured boson recoil energy scale, the uncertainties on the
Comments from page 122 continued on next page
Chapter 7. Measurement of W Charge Asymmetry

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where $\mu_i = a_i^{-1} \nu_i$

$$\sigma_{\mu_i}^2 = \left[ \left( \frac{\partial \mu_i}{\partial \nu_i} \sigma_{\nu_i} \right)^2 + \left( \frac{\partial \mu_i}{\partial a_i^{-1}} \sigma_{a_i^{-1}} \right)^2 \right]$$

= $\left[ (a_i^{-1} \sigma_{\nu_i})^2 + (\nu_i \sigma_{a_i^{-1}})^2 \right]$

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set to be the number of

in each pseudo-experiment sample

input

each of the

to the simulation.

In the absence of effects from the iteration,
Chapter 7. Measurement of $W$ Charge Asymmetry

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where $\mu_i = a_i^{-1}\nu_i$
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\[ = \left[ (a_i^{-1} \sigma_{\nu_i})^2 + (\nu_i \sigma_{a_i^{-1}})^2 \right] \]

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this was missing a lot of material. i tried to indicate what i think should be added. "pull" is something you need to define!

Figure 7.1 compares the calculated statistical error to the statistical error measured in pseudo-experiments, by defining a "pull" for each pseudo-experiment, pull=(meas-expected)/(calculated uncertainty). As suspected, the statistical error is larger than that calculated in Eqn. 7.1. Table 7.1 summarize the total statistical uncertainty on the W charge asymmetry measurement.

several
Chapter 7. Measurement of W Charge Asymmetry

(a) The W charge asymmetries from 600 pseudo-experiments (top left), the averaged W charge asymmetry and input prediction (top right)

(b) the pull ratio mean (bottom left) and RMS (bottom right) of the pseudo-experiments.

Figure 7.1: The statistical fluctuation caused by our iteration method.
you have to define what "pull ratio" is. By the way, I think this is what people just call "pull" usually. Mean pull and RMS of the Pull of the pseudoexperiments (referring to the definition I suggested of pull in the text) would be OK.
corrections of charge mis-identification and background as well as the trigger efficiency and electron identification scale factor. For each source, the corresponding uncertainty on the $W$ charge asymmetry is evaluated by varying each input quantity by $\pm \sigma$, recalculating $W$ charge asymmetry, and computing the difference between the new charge asymmetry and the nominal value in each $y_W$ bin. The total systematic uncertainty on $W$ charge asymmetry is found by adding in quadrature the uncertainties from the individual sources. The quantities that are varied are listed below. The details are described in the following sections:

- Input PDFs used to determine the parameters of the weighting factor.
- Electron energy uncertainty due to the calorimeter energy scale and resolution.
- Missing transverse energy uncertainty due to the boson recoil energy scale.
- Trigger and electron ID efficiencies.
- Charge misidentification of electron.
- Background contribution.
- $W_{p_T}$ distribution.

### 7.2.1 PDF uncertainty on input asymmetry, $W$ rapidity and $Q(y_W, p_T)$

Since input PDFs are used to determine the parameters of the weighting factor (Eq. 5.6), they may affect the final result and are considered as a source of systematic uncertainty. The uncertainties on the weighting factor arise from uncertainties on the momentum distribution of quarks and gluons in the proton modeled with the PDF sets used. The choice of PDF set has an effect on the shape of the $d\sigma_{\text{jet}}/dy_W$ distribution, on the ratio of quarks and anti-quarks in the angular decay distribution and on the $W$ charge asymmetry itself.
might want to say something about correlations from bin-to-bin in this procedure. One way to handle it would be to say that the
"total systematic uncertainty on the W charge asymmetry in a single y_w bin is found"...

this list is redundant with the list at the start of the section and with your sub-chapter headings, so i think you can just skip it

this section is pretty good. however, it could be clearer (and would make more sense when you talk about input PDFs) if you added
some physics discussion about WHAT pdfs affect this. In particular, the charge-summed production dsigma/dy_w depends (at
leading order) on sums of parton distributions like u+d+ubar+dbar and Q depends on (ubar+dbar)/(u+d). that makes it more clear
what you are doing.

specifically here, it's more clear if you say d(sigma+ + sigma-)/dy_W

Comments from page 124 continued on next page
Chapter 7. Measurement of $W$ Charge Asymmetry

We re-determine the input $W$ charge asymmetry, the $d\sigma/dy_W$ production cross section and the angular distribution of $(1 \pm \cos\theta^*)^2$ using the CTEQ6M error PDF sets [34]. The systematic effects due to the PDF uncertainty are evaluated by checking the deviation of the asymmetry values based on these calculations from the central values. The effects are independently estimated.

First, we measure how the measured asymmetry is affected if the input asymmetry is varied by the error PDFs while keeping the total differential cross section constant. Figure 7.2(a) shows the input asymmetry and the uncertainty obtained from the error PDFs. The uncertainty on the $W$ charge asymmetry is shown in Figure 7.2(b).

![Figure 7.2](a) The $W$ charge asymmetry using the error PDF sets. The band is the uncertainty on the input asymmetry from the error PDFs. (b) The systematic uncertainty on $W$ asymmetry caused by varying the input asymmetry.

Next, the charge summed $d\sigma(W^+ + W^-)/dy_W$ production enters into the weighting factor given in Eq 5.6. Uncertainties in this production in principle could affect the extraction of the charge asymmetry. Thus, the differential cross section, $d\sigma/dy_W$, is derived from each error PDF set and normalized to a fixed value at $y_W = 0$ since this analysis depends on the shape of $d\sigma/dy_W$ and the differential cross-section in small $y_W$ is well known. The uncertainty of the $W$ differential cross section obtained from
Note that a change in the input asymmetry of +/-0.1 at high rapidity results in a change of the output asymmetry of only +/-0.003, which is evidence of the success of the iterative method for extracting the W charge asymmetry. We take this remaining bias from the input asymmetry as a systematic uncertainty.

which

I consider

as shown in

to study how uncertainties in this affect the extract charge asymmetry

then
We re-determine the input $W$ charge asymmetry, the $d\sigma/dy_W$ production cross section and the angular distribution of $(1 \pm \cos\theta^*)^2$ using the CTEQ6M error PDF sets [34]. The systematic effects due to the PDF uncertainty are evaluated by checking the deviation of the asymmetry values based on these calculations from the central values. The effects are independently estimated.

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normalization is appropriate since
Chapter 7. Measurement of W Charge Asymmetry

the error PDF sets is shown in Figure 7.3(a). The systematic uncertainty on the W asymmetry caused by the uncertainty of the differential W cross section is shown in Figure 7.3(b).

![Figure 7.3: (a) The difference of the W differential cross section using the error PDF sets and the band is quadrature sum of the error PDFs. (b) The systematic uncertainty on W asymmetry caused by the uncertainty of the differential W cross section.](image)

In addition, uncertainties in the factor \(Q(y_W, p_T)\) (see Eq. 5.3) are taken into account. To measure the systematic uncertainty, the different \(\cos\theta^*\) distributions are obtained using the error PDFs as shown in Figure 7.5. The average ratio of anti-quark to quark for each of the error PDF sets is shown in Figure 7.4(a). The systematic uncertainty on W asymmetry caused by the ratio of anti-quark and quark in the proton as we vary the PDFs is shown in Figure 7.4(b).

7.2.2 Electron Energy Scale, Resolution, and Recoil Energy Scale Factors

The scale and resolution of the electromagnetic calorimeter energy and the missing transverse energy (\(E_T\)) are directly related with the reconstructed W rapidity and thus the asymmetry measurement. The EM calorimeter energy scale and resolution are tuned
resulting

again as with Figure 7.2, this should be floating in the text, not \begin{figure}[h]

what is this text? i can't make sense of it, even in a printout.

will affect the measured W charge asymmetry

the ratio of production from anti-quarks to that from quarks,

(EM)
Figure 7.4: (a) The average ratio of anti-quark to quark for each of the 40 error PDF sets. (b) The systematic uncertainty on the $W$ asymmetry caused by the ratio of anti-quark and quark in the proton.

Figure 7.5: The effect of the 40 error PDFs on the $\cos \theta^*$ distributions in the proton (top) and anti-proton (bottom).
these two figures should be in the opposite order, I think.
in the simulation, as to fit to the $Z \rightarrow e^+e^-$ data mass peak, which are described in Section 6.1. The uncertainties on the energy scale and resolution for central electrons have been measured to be $\pm 0.05\%$ (scale); for forward electrons they are $\pm 0.3\%$ and $\pm 0.8\%$, respectively. These values correspond to a $\pm 1 \sigma$ variation and contribute to the systematic uncertainty of our measurement as shown in Figure 7.6(a) and 7.6(b).

The missing transverse energy ($E_T$) in our $W \rightarrow e\nu$ sample is determined by the assumption that the vector sum of all transverse energy should be zero. Since hadronic transverse energy is due to the $W$ boson recoil energy, this transverse recoil energy, which is affected by multiple interactions in the event, should be carefully determined. Given the energy scale and resolution calibration, we fit the recoil energy in the simulation to the $W \rightarrow e\nu$ data, including its dependence on $\eta$. The uncertainty on the transverse recoil energy scale is $\pm 0.3\%$ and $\pm 1.4\%$ for central and forward electrons, respectively. Figure 7.6(c) shows the systematic uncertainty on the $W$ charge asymmetry measurement.

### 7.2.3 Trigger and Electron ID efficiencies

We investigate sources of any charge bias and $\eta$ dependence in the kinematic and geometrical acceptance (measured with MC) of the event and efficiencies of the trigger and the electron identification (measured with data). The trigger efficiencies for the central and forward electrons are measured using data from independent triggers. The trigger efficiencies do not depend on charge, but depend on the $\eta$ and $E_T$ of the electron. The average trigger efficiencies for the central and forward electrons are $96.1\pm 1.0\%$ and $92.5\pm 0.3\%$, respectively. Since our MC has no trigger simulation, these efficiencies are applied to the MC to reflect those determined in data in each $\eta$ bin and $E_T$ value of the electron. Electron identification and track matching efficiencies are measured using $Z \rightarrow e^+e^-$ control samples from both data and MC. These efficiencies have uncertain-
as

to match

resolution uncertainty for central electrons? even if you don't have an increase in the smearing, you still have an uncertainty...

neutrino transverse energy

and therefore that [MET symbol] is only due to the undetected neutrino

balances

in the event

must
in the simulation so as to fit to the \( Z \rightarrow e^+e^- \) data mass peak, which are described in Section 6.1. The uncertainties on the energy scale and resolution for central electrons have been measured to be ±0.05% (scale); for forward electrons they are ±0.3% and ±0.8%, respectively. These values correspond to a ±1 \( \sigma \) variation and contribute to the systematic uncertainty of our measurement as shown in Figure 7.6(a) and 7.6(b).

The missing transverse energy (\( E_T \)) in our \( W \rightarrow e\nu \) sample is determined by the assumption that the vector sum of all transverse energy should be zero. Since hadronic transverse energy is due to the \( W \) boson recoil energy, this transverse recoil energy, which is affected by multiple interactions in the event, should be carefully determined. Given the energy scale and resolution calibration, we fit the recoil energy in the simulation to the \( W \rightarrow e\nu \) data, including its dependence on \( \eta \). The uncertainty on the transverse recoil energy scale is ±0.3% and ±1.4% for central and forward electrons, respectively. Figure 7.6(c) shows the systematic uncertainty on the \( W \) charge asymmetry measurement.

### 7.2.3 Trigger and Electron ID efficiencies

We investigate sources of any charge bias and \( \eta \) dependence in the kinematic and geometrical acceptance (measured with MC) of the event and efficiencies of the trigger and the electron identification (measured with data). The trigger efficiencies for the central and forward electrons are measured using data from independent triggers. The trigger efficiencies do not depend on charge, but depend on the \( \eta \) and \( E_T \) of the electron. The average trigger efficiencies for the central and forward electrons are 96.1±1.0% and 92.5±0.3%, respectively. Since our MC has no trigger simulation, these efficiencies are applied to the MC to reflect those determined in data in each \( \eta \) bin and \( E_T \) value of the electron. Electron identification and track matching efficiencies are measured using \( Z \rightarrow e^+e^- \) control samples from both data and MC. These efficiencies have uncertain-
including its dependence on \( \eta \), resulting

However, these determinations cannot be done with perfect precision. Therefore, uncertainties in data/Monte Carlo scale factors or in measurements of efficiencies directly from the data may cause systematic uncertainties in this result. [new paragraph]

the writing in this section is fine. BUT, please add references to previous sections where the determinations are discussed.
Figure 7.6: The effects of electron $E_T$ scale uncertainty (a), energy resolution uncertainty (b) and the recoil energy scale uncertainty (c) on the W charge asymmetry.
This page contains no comments
ties from the data statistics. Additionally, we use the scale factors of the electron ID efficiencies to correct for the differences between MC and data. Figure 7.7 shows both effects on the $W$ charge asymmetry.

Figure 7.7: The effect of the trigger efficiency uncertainty (a) and the scale factor uncertainty of the defTracks efficiency (b) on the $W$ charge asymmetry.

### 7.2.4 Charge Fake Rate and Background Estimate

The charge misidentification rate is determined from the rate of same sign charge $Z \rightarrow e^+e^-$ events as a function of $y$, where a track matched to one lepton is used to identify the charge of the other. Therefore, the statistically limited $Z \rightarrow e^+e^-$ sample yields an uncertainty on estimating the charge misidentification rate. The background contributions in our $W \rightarrow e\nu$ candidates come from QCD events, misidentified jets, and $Z \rightarrow e^+e^-$ events where one of the jets or electrons is not reconstructed and mimics a neutrino. The background contributions on $W$ charge asymmetry are corrected. The background from misidentified jets is estimated by fitting the isolation distribution of electron candidates. The uncertainty of fitting the isolation distribution shapes arises from the variation of electron and jet templates. The effect of the charge fake rate uncertainty and the QCD
I think it's true that the forward electron Id efficiency is the biggest systematic. you might want to add a sentence to say so here.

in the caption, this is labelled as being from tracking efficiency; here's it's the electron ID efficiency. which is it? also, are these in both (a) and (b) central+forward? forward only because central is small? please explain.

As described in Section xxxx, t

As shown in Section xxxx, significant

faking electrons

with
ties from the data statistics. Additionally, we use the scale factors of the electron ID efficiencies to correct for the differences between MC and data. Figure 7.7 shows both effects on the $W$ charge asymmetry.

Figure 7.7: The effect of the trigger efficiency uncertainty (a) and the scale factor uncertainty of the defTracks efficiency (b) on the $W$ charge asymmetry.

### 7.2.4 Charge Fake Rate and Background Estimate

The charge misidentification rate is determined from the rate of same sign charge $Z \rightarrow e^+e^-$ events as a function of $\eta$ where a track matched to one lepton is used to identify the charge of the other. Therefore, the statistically limited $Z \rightarrow e^+e^-$ sample yields an uncertainty on estimating the charge misidentification rate. The background contributions in our $W \rightarrow e\nu$ candidates come from QCD events misidentified jets and $Z \rightarrow e^+e^-$ events where one of the jets or electrons is not reconstructed and mimics a neutrino. The background contributions on $W$ charge asymmetry are corrected. The background from misidentified jets is estimated by fitting the isolation distribution of electron candidates. The uncertainty of fitting the isolation distribution shapes arises from the variation of electron and jet templates. The effect of the charge fake rate uncertainty and the QCD
background on the $W$ charge asymmetry is shown in Figure 7.8(a) and 7.8(b). Additionally, there is a systematic uncertainty due to the $Z \rightarrow e^+ e^-$ background in Figure 7.8(c).

![Figure 7.8](image)

**Figure 7.8:** The effect of the charge fake rate uncertainty (a) and QCD event (b) and $Z \rightarrow e^+ e^-$ event (c) contributions on the $W$ charge asymmetry.

### 7.2.5 $W$ boson $p_T$ distribution

Although the electron $E_T$ and $\not{E}_T$ are corrected with the tuned parameters, we further address the effect of the weighting factor being a function of $p_T^{W_T}$ and some uncertainty associated with the $p_T^{W_T}$, which affects the angular distributions and energies of the decay electrons and hence the acceptance. The corrected $p_T^{W}$ distribution is shown in Figure 7.9(a). The $p_T^{W}$ relatively has a good agreement except for a small discrepancy.
on Z to ee data

parameters

and the transverse boost of the W boson

and the transverse boost of the W boson

of the pT distribution of produced W bosons. These effects include:

I think you should add some text to explain what "corrected" means (i don't believe you discussed this earlier in the thesis)

new paragraph
Chapter 7. Measurement of $W$ Charge Asymmetry

at low $p_T$ energy. We require a small additional smearing in simulation to improve the agreement. A small Gaussian contribution with the zero mean and $0.4 \sigma$ is used for the additional smearing. Even though it makes better agreement at low $p_T$ energy as shown in Figure 7.9(b), the corresponding uncertainty on the $W$ charge asymmetry is less than $10^{-5}$, which is a negligible effect.

Figure 7.9: $W$ boson $p_T$ distribution (top) and the discrepancy between the resulting $p_T$ distributions in simulation and data (bottom).
Because this procedure isn't well motivated by a model, we consider the effect of the addition of this smearing as a systematic uncertainty. However,
Chapter 7. Measurement of $W$ Charge Asymmetry

7.3 Results for $W$ Charge Asymmetry

In this section the measurement of the $W$ production charge asymmetry are presented using an integrated luminosity of $1 \text{ fb}^{-1}$. The $W$ rapidity is directly measured through our analysis method described in Chapter 5 and the analysis corrections are considered to address several experimental effects, which are discussed in Chapter 6. In Figure 7.10(a), the corrected asymmetries with the statistical uncertainty and the total systematic uncertainty are shown for two different run-periods in bins of reconstructed rapidity of the $W$ and as can be seen the agreement is reasonably good. Both asymmetry values are then combined in Figure 7.10(b).

$CP$ invariance requires $A(y_W) = -A(-y_W)$. The full corrected data shown in Figure 7.10(b) have no significant evidence of $CP$ asymmetry as shown in Figure 7.11. The level of agreement is characterized by $\chi^2/dof = 13.1/13$. Thus, the $\pm y_W$ data are folded together to obtain a more precise measure of $A(|y_W|)$.

To fold the asymmetry, the correlations between positive and negative $W$ rapidity bins should be taken into account. Since most of the systematic uncertainties are correlated between both bins, it is fair to assume (and also for simplicity) $100\%$ correlation of all systematic uncertainties in the folding procedure. Additionally, we find the difference of two extreme assumptions, $100\%$ correlation, to be small as shown in Figure 7.12, further supporting our assumption.

The statistical combination of the asymmetry at positive rapidity with the negative of the asymmetry at negative rapidity is performed using the Best Linear Unbiased Estimate (BLUE) method [32] accounting for all correlations for both positive and negative bins in $W$ rapidity. The correlation coefficient for adjacent bins is evaluated using pseudo-experiments and is found to be $< 0.05$. Table 7.1 summarizes the systematic uncertainties on the $W$ boson production charge asymmetry for rapidities $|y_W| < 3.0$.

The measured asymmetry $A(|y_W|)$, combining the positive and negative $y_W$ bins, is
Recall that several effects, such as tracking efficiency and charge fake rate, had some significant changes in the two different running periods considered in this analysis. Before combining the two periods, we first see whether they give the same measured charge asymmetry.
Chapter 7. Measurement of W Charge Asymmetry

7.3 Results for W Charge Asymmetry

In this section the measurement of the W production charge asymmetry are presented using an integrated luminosity of 1 fb$^{-1}$. The W rapidity is directly measured through our analysis method described in Chapter 5 and the analysis corrections are considered to address several experimental effects, which are discussed in Chapter 6. In Figure 7.10(a), the corrected asymmetries with the statistical uncertainty and the total systematic uncertainty are shown for two different run-periods in bins of reconstructed rapidity of the W and as can be seen the agreement is reasonably good. Both asymmetry values are then combined in Figure 7.10(b).

$CP$ invariance requires $A(y_W) = -A(-y_W)$. The full corrected data shown in Figure 7.10(b) have no significant evidence of $CP$ asymmetry as shown in Figure 7.11. The level of agreement is characterized by $\chi^2/dof = 13.1/13$. Thus, the $y_W$ data are folded together to obtain a more precise measure of $A(|y_W|)$.

To fold the asymmetry, the correlations between positive and negative W rapidity bins should be taken into account. Since most of the systematic uncertainties are correlated between both bins, it is fair to assume (and also for simplicity) 100% correlation of all systematic uncertainties in the folding procedure. Additionally, we find the difference of two extreme assumptions, 0% and 100% correlation, to be small as shown in Figure 7.12, further supporting our assumption.

The statistical combination of the asymmetry at positive rapidity with the negative of the asymmetry at negative rapidity is performed using the Best Linear Unbiased Estimate (BLUE) method [32] accounting for all correlations for both positive and negative bins in W rapidity. The correlation coefficient for adjacent bins is evaluated using pseudo-experiments and is found to be $< 0.05$. Table 7.1 summarizes the systematic uncertainties on the W boson production charge asymmetry for rapidities $|y_W| < 3.0$.

The measured asymmetry $A(|y_W|)$, combining the positive and negative $y_W$ bins, is
I think this test is a little silly. I would just say that the 100% assumption is, in any event, always conservative. You can leave the plot in if you want, but I think it's just a "feel good" check.

Bo-Young, I really don't understand this at all. The unfolding, for example, tells you this isn't true. And with systematics, how can this be true? Are you just talking about statistical uncertainties here in the non-unfolded case. If so, I think you have to specify this.
Chapter 7. Measurement of $W$ Charge Asymmetry

Figure 7.10: The corrected $W$ production charge asymmetry.

(a) The result for both run-periods

(b) The result for combined data
This page contains no comments
Figure 7.11: The sum of $A(y_W)$ and $A(-y_W)$ plot. The error shown is only the statistical uncertainty.

| $|y_W|$ | CFR | BKG | EM | Recoil | Trig | ID | PDF | Stat. (1fb$^{-1}$) |
|-------|-----|-----|----|--------|------|----|-----|-----------------|
| 0.0 - 0.2 | 0.02 | 0.04 | 0.01 | 0.11 | 0.03 | 0.02 | 0.03 | 0.31 |
| 0.2 - 0.4 | 0.01 | 0.09 | 0.04 | 0.22 | 0.08 | 0.07 | 0.08 | 0.32 |
| 0.4 - 0.6 | 0.02 | 0.11 | 0.06 | 0.22 | 0.13 | 0.17 | 0.15 | 0.33 |
| 0.6 - 0.8 | 0.03 | 0.15 | 0.07 | 0.34 | 0.14 | 0.30 | 0.22 | 0.32 |
| 0.8 - 1.0 | 0.03 | 0.20 | 0.07 | 0.42 | 0.11 | 0.47 | 0.24 | 0.43 |
| 1.0 - 1.2 | 0.04 | 0.18 | 0.08 | 0.33 | 0.09 | 0.69 | 0.27 | 0.38 |
| 1.2 - 1.4 | 0.05 | 0.18 | 0.15 | 0.67 | 0.06 | 0.78 | 0.28 | 0.43 |
| 1.4 - 1.6 | 0.04 | 0.14 | 0.14 | 1.10 | 0.04 | 0.85 | 0.28 | 0.50 |
| 1.6 - 1.8 | 0.08 | 0.12 | 0.26 | 0.92 | 0.03 | 0.89 | 0.29 | 0.55 |
| 1.8 - 2.05 | 0.22 | 0.13 | 0.31 | 0.82 | 0.06 | 0.80 | 0.34 | 0.62 |
| 2.05 - 2.3 | 0.44 | 0.21 | 0.53 | 0.59 | 0.17 | 0.85 | 0.42 | 0.83 |
| 2.3 - 2.6 | 0.45 | 0.19 | 0.62 | 0.40 | 0.27 | 0.86 | 0.50 | 1.10 |
| 2.6 - 3.0 | 0.14 | 0.10 | 0.60 | 0.43 | 0.28 | 0.65 | 0.53 | 2.30 |

Table 7.1: Systematic uncertainties for the $W$ production charge asymmetry. The values shows the correlated uncertainties for both positive and negative rapidities.
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Figure 7.12: The difference of two extreme assumptions, 0% and 100% correlation of all systematic uncertainties on the folded asymmetry.
This page contains no comments
Chapter 7. Measurement of $W$ Charge Asymmetry

shown in Figure 7.13. Also shown are the predictions of a NNLO QCD calculation using the MRST 2006 NNLO PDF sets [33] and a NLO QCD calculation using the CTEQ6M NLO PDF sets [34]. The results of $\chi^2$ tests between the thirteen data points and the central asymmetry values for the CTEQ6M sets and the MRST2006 sets are 11.8 and 28.8, respectively. The $W$ boson charge asymmetry for each $|y_W|$ with the total systematic uncertainty and the statistical uncertainty obtained in this 1 fb$^{-1}$ measurement is summarized in Table 7.2.

| $|y_W|$ | $A(y_W)$ | $\sigma_{sys}$ | $\sigma_{sys+stat}$ |
|--------|-----------|----------------|---------------------|
| 0.0 - 0.2 | 0.0199 | $\pm 0.0013$ | $\pm 0.0034$ |
| 0.2 - 0.4 | 0.0571 | $\pm 0.0027$ | $\pm 0.0042$ |
| 0.4 - 0.6 | 0.0813 | $\pm 0.0037$ | $\pm 0.0049$ |
| 0.6 - 0.8 | 0.1168 | $\pm 0.0055$ | $\pm 0.0063$ |
| 0.8 - 1.0 | 0.1456 | $\pm 0.0072$ | $\pm 0.0079$ |
| 1.0 - 1.2 | 0.2040 | $\pm 0.0084$ | $\pm 0.0092$ |
| 1.2 - 1.4 | 0.2354 | $\pm 0.0109$ | $\pm 0.0118$ |
| 1.4 - 1.6 | 0.2613 | $\pm 0.0143$ | $\pm 0.0151$ |
| 1.6 - 1.8 | 0.3027 | $\pm 0.0135$ | $\pm 0.0144$ |
| 1.8 - 2.05 | 0.3553 | $\pm 0.0126$ | $\pm 0.0141$ |
| 2.05 - 2.3 | 0.4363 | $\pm 0.0134$ | $\pm 0.0158$ |
| 2.3 - 2.6 | 0.5374 | $\pm 0.0136$ | $\pm 0.0178$ |
| 2.6 - 3.0 | 0.6415 | $\pm 0.0116$ | $\pm 0.0260$ |

Table 7.2: The $W$ production charge asymmetry with total systematic and statistical uncertainties.

7.4 Predictions of Parton Distribution Functions

The goal of this section is to test how the valence quark, sea quark and gluon distributions affect our $W$ charge asymmetry measurement. To do this study Monte Carlo sample is generated by MC@NLO program with NLO QCD calculation and CTEQ6.1M
should also put the numbers in the plots in an appendix. Or maybe this whole section should be an appendix?

Effects of
Figure 7.13: The W production charge asymmetry and predictions from (a) CTEQ6.1 with the associated PDF uncertainty and (b) MRST2006 and its associated PDF uncertainty.
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PDFs to determine the quarks and gluon distributions involving the $W$ boson production. The parton distributions in the range $10^{-4} < x < 1.0$ are shown in Figure 7.14.

As shown in Eq. 1.4 and in Figure 1.4, the momentum fraction, $x$, is directly related to the rapidity of the $W$ boson. The charge asymmetry of $W$ boson can be affected from the variation of parton distribution for some $x$ value. The effects on our measurement are independently estimated for the valence quark, sea quark and gluon distributions. First of all, the valence quark distribution within a fine $x$ bin increases by 5%, where the quark distributions for both proton and antiproton are changed, and then the rapidity of $W$ boson is reconstructed using our analysis method. The result of $W$ charge asymmetry corresponding to the valence quark distribution weighted by +5% is compared with the initial asymmetry not weighted. According as the $x$ range increases, the differences of $W$ charge asymmetry are shown in Figure 7.15 and Figure 7.16. The sea quark distribution is given by the quark and antiquark pairs in proton and antiproton. By varying the sea quark distribution by a factor of +5%, the measured asymmetry is compared to...
and so it might be expected that changes of PDFs in a limited x range will affect a narrow region of rapidity. However, input PDFs are used in many cases to distinguish between two solutions, and therefore, a change in the input PDFs in a particular x range can actually affect a broader ranges of rapidities than one might naively expect. Both types of effects can be seen in the studies below.

---

you need to explain what you mean exactly by valence and sea quark since the PDF distributions return, i believe, quarks and anti-quarks. (Or is it valence and sea?) In either event, when you change valence, you change it so that $q(x) = q(x) + 5\% \cdot (q(x) - \overline{q}(x))$. "Sea" would mean $q(x) = q(x) + 5\% \cdot \overline{q}(x)$ and $\overline{q}$ increased by the same amount? Also, you are doing this for only u and d quarks SYMMETRICALLY so that d/u and d/ubar don't change (right?) and you need to say that. so this needs some more explicit equations before it is done...

---

A similar study varying the weight of up and down sea quarks by +5% is shown...
Chapter 7. Measurement of W Charge Asymmetry

The initial asymmetry as shown in Figure 7.17 and Figure 7.18. For gluon distribution, the effect on our measurement is negligible for all x range as shown in Figure 7.19 and Figure 7.20. Note that the effects of the quarks and gluon distribution is small ($\lesssim 0.003$) comparing the statistical uncertainty ($\gtrsim 0.004$) and this study allows us to estimate the systematic shift on the $W$ asymmetry measurement from the variation of input parton distribution functions.
Sequence number: 1
Author: Kevin McFarland
Subject: Cross-Out
Date: 4/21/2008 9:54:55 AM

Sequence number: 2
Author: Kevin McFarland
Subject: Inserted Text
Date: 4/21/2008 9:55:00 AM

Sequence number: 3
Author: Kevin McFarland
Subject: Replacement Text
Date: 4/21/2008 9:55:25 AM

Sequence number: 4
Author: Kevin McFarland
Subject: Replacement Text
Date: 4/21/2008 9:55:21 AM

Sequence number: 5
Author: Kevin McFarland
Subject: Inserted Text
Date: 4/21/2008 9:55:17 AM
Figure 7.15: The shift on the $W$ charge asymmetry when the valence quark distribution is weighted by $+5\%$ at low $x$ region.
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Figure 7.16: The shift on the $W$ charge asymmetry when the valence quark distribution is weighted by +5% at high $x$ region.
This page contains no comments
Chapter 7. Measurement of $W$ Charge Asymmetry

Figure 7.17: The shift on the $W$ charge asymmetry when the sea quark distribution is weighted by +5% at low $x$ region.
This page contains no comments
Figure 7.18: The shift on the $W$ charge asymmetry when the sea quark distribution is weighted by $+5\%$ at high $x$ region.
This page contains no comments
Figure 7.19: The shift on the $W$ charge asymmetry when the gluon distribution is weighted by $+5\%$ at low $x$ region.
This page contains no comments
Figure 7.20: The shift on the $W$ charge asymmetry when the gluon distribution is weighted by $+5\%$ at high $x$ region.
This page contains no comments
At the Fermilab Tevatron, where $p\bar{p}$ collisions occur at $\sqrt{s} = 1.96$ TeV, the $W^+$ and $W^-$ boson rapidity distributions result in a charge asymmetry since $u$ quarks carry, on average, a higher fraction of the proton’s momentum than $d$ quarks. The parton distribution functions (PDF) describing the internal structure of the proton can be constrained by measuring this charge asymmetry of the production of the $W$ bosons.

Previous measurements of the $W$ asymmetry at the Tevatron were conducted by measuring the pseudorapidity ($\eta$) distribution of leptons from decays of $W$ bosons since the $W$ decay involves a neutrino whose longitudinal momentum is experimentally undetermined. However, the lepton charge asymmetry is a convolution of the $W$ production charge asymmetry and the $V - A$ asymmetry from $W$ decay; the two asymmetries tend to cancel at large values ($|\eta| \gtrsim 2.0$). As a result, it is more complicated to interpret the correlation between the proton PDFs and the lepton charge asymmetry. In this thesis, this complication is resolved in a direct measurement of the $W$ production charge asymmetry as a function of the $W^{\pm}$ rapidity.

The analysis is based on the ability to efficiently identify the leptonic decay products of the $W$. The events are triggered using the decay lepton from the $W$ in the central
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region, and using both the electron and missing transverse energy in the forward region. A $W$ candidate is then reconstructed from tightly selected electron with good track and corrected missing transverse energy. The data sample is taken from approximately 1 fb$^{-1}$ of proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV produced at the Fermilab Tevatron and recorded with the Collider Detector Facility. Analysis technique was developed to determine the neutrino longitudinal momentum, within a two-fold ambiguity, by constraining the $W$ mass. The ambiguity was resolved on a statistical basis from the known $V - A$ decay distribution and from the differential cross-sections, $d\sigma^\pm / dy_W$. The background from QCD events is estimated using the isolated energy distribution for a jet to be detected as an electron. Additionally, other electroweak processes are studied for contribution to the $W$ candidates. Using these techniques, the $W$ production charge asymmetry is measured from the selected candidates and compared to the predictions given by both CTEQ and MRST PDF group.

In conclusion, this analysis significantly improves the precision on the proton $d/u$ momentum ratio over previous lepton charge asymmetry measurements at the Tevatron through the analysis technique. Therefore, the result will provide one of the best determinations of this ratio in global PDF fits.
region, and using both the electron and missing transverse energy in the forward region. A $W$ candidate is then reconstructed from tightly selected electron with good track and corrected missing transverse energy. The data sample is taken from approximately $1 \text{fb}^{-1}$ of proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV produced at the Fermilab Tevatron and recorded with the Collider Detector Facility. Analysis technique was developed to determine the neutrino longitudinal momentum, within a two-fold ambiguity, by constraining the $W$ mass. The ambiguity was resolved on a statistical basis from the known $V - A$ decay distribution and from the differential cross-sections, $d\sigma^{\pm}/dy_W$. The background from QCD events is estimated using the isolated energy distribution for a jet to be detected as an electron. Additionally, other electroweak processes are studied for contribution to the $W$ candidates. Using these techniques, the $W$ production charge asymmetry is measured from the selected candidates and compared to the predictions given by both CTEQ and MRST PDF group.

In conclusion, this analysis significantly improves the precision on the proton $d/u$ momentum ratio over previous lepton charge asymmetry measurements at the Tevatron through the analysis technique. Therefore, the result will provide one of the best determinations of this ratio in global PDF fits.
Appendix A

Trigger Efficiencies

A.1 Central Electron trigger Efficiency

As the central electron trigger is the basis of a large number of analyses, the trigger efficiency was performed by several groups within the CDF collaboration. A summary of the results is given here, with more complete details in [35]. The central electron trigger is based upon both calorimeter and tracking quantities, and so the measurement of the efficiency is split between these two systems. The tracking efficiency is measured using a $W$ trigger with no tracking requirements, $W$ _NOTRACK_. While the calorimeter efficiencies are measured using data samples collected from muon triggers or prescaled auto-accept triggers. The tracking and calorimeter efficiencies are multiplied together for a total central electron trigger efficiency.

A.1.1 XFT Efficiency

At L1, the central electron trigger requires an XFT track of 8 $\text{GeV}/c$. The trigger efficiency is measured by applying the central event selection, listed in Table 3.1, to the $W$ _NOTRACK_ trigger sample. After selecting a $W$ candidate event, the $L1\_XFT\_PT8$
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trigger bit is checked, and the efficiency calculated with Equation A.1.

\[ \epsilon(L1_{XFT_{PT8}}) = \frac{W_{NOTRACK \& L1_{CEM8_{PT8}}}}{W_{NOTRACK}} \] (A.1)

Except for a small dependence upon the \( \eta \) distribution of the electron as shown in Figure A.1, the efficiency is independent of kinematic variables, and the integrated L1_{XFT_{PT8}} efficiency 96.3%.

![Figure A.1: L1 tracking trigger efficiency as a function of detector \( \eta \).](image)

No additional requirement is made on the tracking at L2, but the efficiency was checked to certify that no errors occurred within the trigger hardware. No such problems were found, and the L2_{XFT_{PT8}} is 100%.

The L3 central electron trigger requires that a 3D track with \( p_T \) greater than 9 GeV/c be reconstructed in the COT. Selecting \( W \) candidates dataset triggered from the
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W_NOTRACK trigger, the events are also required to have the passed the L1_CEM_PT8 and L2_CEM16_PT8 triggers to isolate the efficiency at L3 from effects upstream in the trigger. The formula for the L3 tracking efficiency is then given in Equation A.2.

\[ \epsilon(L3_{PT9}) = \frac{W_{NOTRACK} & L1_{CEM8_{PT8}} & L2_{CEM16_{PT8}} & L3_{CEM18_{PT9}}}{W_{NOTRACK} & L1_{CEM8_{PT8}} & L2_{CEM16_{PT8}}} \] (A.2)

No dependence on any kinematic variable is found, and the integrated L3_{PT9} trigger efficiency is measured to be 99.6%.

A.1.2 Calorimeter Trigger Efficiency

At L1, the central electron trigger requires a tower with EM \( E_T > 8 \text{GeV} \), L1_CEM8. Unfortunately, there was no trigger used during the data taking process that used the L1_CEM8 without it being coupled to some other trigger requirement (e.g. track, \( \not E_T \), etc.). The L1_EM8 trigger bit is decoupled from other trigger requirements though, and so by requiring minimal activity in the forward calorimeter, the trigger response in the central calorimeter is measured. The control sample was collected using muon triggered events, and the activity in the calorimeter is considered. The energy in the calorimeter towers is combined into the trigger geometry (two physical towers per trigger tower). If an event has a trigger tower with energy greater than 8 GeV, the L1_EM8 trigger bit is checked. The efficiency is found to be 100% for towers with energy greater than 14 GeV, a threshold much lower than the central electron cut of 25 GeV.

The L2 calorimeter trigger requires EM \( E_T > 16 \text{GeV} \), and its efficiency is measured with a prescaled, auto-accept L2 trigger, L2_PS50_L1_CEM8_PT8. This trigger has the identical path as the central electron trigger with the exception of L2, where no calorimeter requirements are applied. After selecting central \( W \) candidates, the effi-
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The trigger is measured to be 100% efficient within statistical errors for all $E_T$ above 25 GeV.

The L3 central electron trigger efficiency is measured using a sample of lower-$E_T$, inclusive electron trigger events, ELECTRON\_CENTRAL\_8. By requiring that the events in the sample have passed the L1 and L2 central electron trigger path, only the effect of the L3 trigger is measured. After selecting central $W$ events, the efficiency is calculated from Equation A.4.

$$
\epsilon(L3\_CEM18) = \frac{EL\_CENT\_8\_NO\_L2 & L2\_CEM16 & L3\_CEM18}{EL\_CENT\_8\_NO\_L2 & L2\_CEM16}
$$

(A.4)

Since the full calorimeter reconstruction is performed at L3, the only difference between offline and trigger quantities is the offline calibrations which are no larger than 10%. The efficiency is therefore expected to be near 100%, and the measured efficiency is found to reach 100% at 23 GeV as suspected.

All of the calorimeter trigger efficiencies are calculated to be 100% for an electron selection with $E_T$ greater than 25 GeV.

## A.2 Forward $W$ Trigger Efficiency

The forward $W$ trigger is based solely on calorimeter quantities, and the control samples collected from prescaled, lower $E_T$ threshold triggers as shown in Table A.1.
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Table A.1: List of trigger paths considered to measure the forward $W$ trigger efficiency.

<table>
<thead>
<tr>
<th>level</th>
<th>MET_PEM</th>
<th>PLUG_ELECTRON_20</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>L1_EM8_MET15</td>
<td>L1_EM8</td>
</tr>
<tr>
<td>L2</td>
<td>L2_PEM20_L1_EM8_MET15</td>
<td>L2_PEM20_PS10</td>
</tr>
<tr>
<td>L3</td>
<td>L3_PEM20_MET15</td>
<td>L3_PEM20</td>
</tr>
</tbody>
</table>

A.2.1 $L1\_MET15\_L3\_MET15$

The efficiency of the combined $L1\_MET15\_L3\_MET15$ trigger is measured using $W \to e\nu$ candidates selected using the requirements described in Section 3.5. From Table A.1 we find that the $PLUG\_ELECTRON\_20$ and $MET\_PEM$ triggers differ only in the requirement of $E_T$ at L1 and L3 (and a prescale factor). Therefore, to measure the efficiency of the $L1\_MET15\_L3\_MET15$ trigger we check how often $W \to e\nu$ events passing the $PLUG\_ELECTRON\_20$ trigger also pass the $MET\_PEM$:

$$\epsilon(L1\_MET15\_L3\_MET15) = \frac{PLUG\_ELECTRON\_20 && MET\_PEM}{PLUG\_ELECTRON\_20} \quad (A.5)$$

Figure A.2 shows the efficiency of the $L1\_MET15\_L3\_MET15$ trigger as a function of raw $E_T$ (offline $E_T$ calculated at $z = 0$ and used in the trigger), offline $E_T$ (calculated at $z$ of the highest sum $p_T$ vertex and used in analysis) and $\eta_{det}$ of the electron. We fit the turn-on curve vs. $E_T$ with Eqn. A.6

$$\epsilon(x) = \frac{1}{1 + e^{-\beta(x-\alpha)}} \quad (A.6)$$
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A.2.2 L2\_PEM20

The efficiency of the L2\_PEM20 trigger was measured using the $Z \rightarrow e^+e^-$ (CP) sample because it provides a higher statistics sample of unbiased electrons. The $Z \rightarrow e^+e^-$ (CP) events are collected with the central electron trigger, ELECTRON\_CENTRAL\_18, which belongs to the HIGH\_PT\_ELECTRON\_1 data stream. We require a CEM and a PEM electron where the selection criteria are shown in Table ??, 3.2. We have measured the L2 PEM20 trigger efficiency using "No Prescale Bit" for prescale trigger.

$$\epsilon(L2\_PEM20) = \frac{Z \rightarrow e^+e^-(CP) \& \& L2\_PEM20\_NoPS}{Z \rightarrow e^+e^-(CP)}.$$  \hspace{1cm} (A.7)

Since the L2\_PEM20 trigger efficiency decreases as it goes to high $|\eta|$, we measure $E_T$ turn-on curve in different $\eta$ ranges. These are shown in Figure A.3.

A.2.3 L3\_PEM20

The $Z \rightarrow e^+e^-$ (CP) events are also used to evaluate the L3\_PEM20 trigger efficiency. We define it as:

$$\epsilon(L3\_PEM20) = \frac{Z \rightarrow e^+e^-(CP) \& \& L2\_PEM20\_NoPS \& \& L3\_PEM20}{Z \rightarrow e^+e^-(CP) \& \& L2\_PEM20\_NoPS}.$$  \hspace{1cm} (A.8)

This L3\_PEM20 trigger requires that an event has EM transverse energy greater than 20 GeV and Had/Em less than 0.125. We can get Level3 trigger variables by accessing the L3SummaryObject. Figure A.4 shows the turn-on curve vs. raw and offline $E_T$ and $\eta$. 
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Figure A.2: Efficiency of the L1\_MET15\_L3\_MET15 trigger as a function of raw or offline $E_T$ and $\eta_{\text{det}}$ of the electron. The turn-on curve vs. $E_T$ is fitted with the function in equation A.6.
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Figure A.3: The L2_PEM20 trigger efficiency as a function of raw and offline $E_T$ and the $\eta_{\text{det}}$ dependence.
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Figure A.4: Efficiency of the L3_PEM20 trigger as a function of raw and offline $E_T$ and $\eta_{det}$ of the electron,
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Appendix B

Boson Recoil Energy Tune

B.1 The best $\chi^2$ fits of the recoil energy

Figure B.1 - B.6 show the results of the final $\chi^2$ fits for the recoil energy corrections in the parallel and perpendicular directions.

B.2 $W$ boson recoil energy distributions

A comparison of the tuned Monte Carlo recoil energy distributions with those obtained from the data are shown in Figure B.7 - B.11.
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Figure B.1: Central electron fiducial region (GEN5): The best $\chi^2$ fit of the recoil energy comparison between data and MC for central electrons. The fit formula is $p0(x + p1)^2 + p2$. 
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Figure B.2: Central electron fiducial region (GEN6): The best $\chi^2$ fit of the recoil energy comparison between data and MC for central electrons. The fit formula is $p0(x + p1)^2 + p2$. 
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Figure B.3: GEN5 MC foward electron region: The best $\chi^2$ fit of the recoil energy comparison between data and MC for foward electrons with COT tracks. The fit formula is $p0(x + p1)^2 + p2$.
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Figure B.4: GEN5 MC foward electron region: The best \( \chi^2 \) fit of the recoil energy comparison between data and MC for forward electrons with SISA tracks. The fit formula is \( p_0(x + p1)^2 + p2 \)
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Figure B.5: GEN6 MC foward electron region: The best $\chi^2$ fit of the recoil energy comparison between data and MC for foward electrons with COT tracks. The fit formula is $p0(x + p1)^2 + p2$. 

(a) $1.2 < \eta < 1.6$

(b) $-1.6 < \eta < -1.2$
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Figure B.6: GEN6 MC foward electron region: The best $\chi^2$ fit of the recoil energy comparison between data and MC for forward electrons with SISA tracks. The fit formula is $p0(x + p1)^2 + p2$. 
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Figure B.7: Central electron fiducial region: The recoil energy distributions after the MC is tuned.
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Figure B.8: GEN5 MC forward electron region ($\eta > 1.2$): The comparison of recoil energy between data and MC. We applied the cluster $E_T$ scale, resolution and recoil energy scale factors to MC sample.
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Figure B.9: GEN5 MC forward electron region ($\eta < -1.2$): The comparison of recoil energy between data and MC. We applied the cluster $E_T$ scale, resolution and recoil energy scale factors to MC sample.
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Figure B.10: GEN6 MC forward electron region ($\eta > 1.2$): The comparison of recoil energy between data and MC. We applied the cluster $E_T$ scale, resolution and recoil energy scale factors to MC sample.
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Figure B.11: GEN6 MC forward electron region ($\eta < -1.2$): The comparison of recoil energy between data and MC. We applied the cluster $E_T$ scale, resolution and recoil energy scale factors to MC sample.
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