A new analysis technique to measure the $W$ Production Charge Asymmetry at the Tevatron

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(Dated: May 28, 2008)

The charge asymmetry of $W$ bosons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV is sensitive to the ratio of $d$ and $u$ quark distributions in the range of $x > 0.002$ at $Q^2 \approx M_W^2$. We propose an analysis technique to directly measure $W$ production charge asymmetry from $W \rightarrow e\nu$ events at the Tevatron and show the feasibility for this method using Monte Carlo simulations.

I. INTRODUCTION

The differential cross section for $W$ boson production in $p\bar{p}$ as a function of $W$ rapidity is

$$\frac{d\sigma^\pm}{dy_W} = \frac{2\pi G_F}{3\sqrt{2}} \sum_q |V_{qq}|^2 \left[ q(x_p)\bar{q}(x_{\bar{p}}) + \bar{q}(x_p)q(x_{\bar{p}}) \right],$$

(1)

where $x_p$ ($x_{\bar{p}}$) is the fraction of the proton (anti-proton) momentum carried by the struck quark, $q$ and $\bar{q}$ are the quark and anti-quark parton distribution functions, and $y_W$ is the rapidity of the $W$ boson. The $x$ values of the quark in the proton and antiquark in the antiproton are related to the rapidity, $y$, of the $W$ boson via the equation $x_{p,\bar{p}} = M_W/\sqrt{s}e^{\pm y_W}$ as shown in Fig. 1. Here $\sqrt{s}$ is the center of mass energy and $M_W$ is the mass of the $W$ boson.

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

$$\frac{d\sigma^+}{dy_W} \approx \frac{2\pi G_F}{3\sqrt{2}} u(x_p)d(x_p),$$

(2)

$$\frac{d\sigma^-}{dy_W} \approx \frac{2\pi G_F}{3\sqrt{2}} d(x_p)\bar{u}(x_{\bar{p}}),$$

(3)

where we use Eq. 2 and Eq. 3 and introduce the ratio $R_{du} = d(x_p)/u(x_p)$. As we see in Eq. 4 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.

$W$ production at hadron colliders is identified through the process $p + \bar{p} \rightarrow W^\pm; W^\pm \rightarrow \ell^\pm + \nu$. Since the $W$ 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 and as a function of the lepton pseudo-rapidity $\eta$. However, as shown in Fig. 2(b) there is a
“turn-over” in the lepton charge asymmetry due to a convolution of the $W$ production charge asymmetry and the $WV$ decay. This convolution means leptons from a single pseudo-rapidity come from a range of $W$ rapidities 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 direct measurement of the asymmetry of the $W_{\pm}$ rapidity distribution to be a more sensitive probe of the differences between $u$ and $d$ quarks.

In this paper, 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. We describe the details of our new analysis technique and outline the sources of systematic uncertainty of this measurement. Our studies are performed in the $W_{\pm} \rightarrow e_{\pm} \nu$ channel produced in $p\bar{p}$ collisions at the Tevatron. We use a realistic Monte Carlo simulation (MC@NLO) and include the effects of higher-order QCD corrections [5].

II. ANALYSIS TECHNIQUE

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 which results in a two-fold ambiguity. This ambiguity can be partially 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 from the $W^+$ and $W^-$ production cross-sections as a function of $W$ rapidity, $d\sigma_{\pm}/dy_{W}$. The $W$ mass constraint is

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

where the $W$ mass, $M_W$, is constrained to its experimentally measured value [6, 7]. 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, $E_T$ [8]. 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 leading order $W$ boson production mechanism in $p\bar{p}$ collisions results in the $W$ boson being polarized in the $\bar{p}$ direction by means of the $V - A$ structure of the weak interaction. 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 $\nu$). 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. 2(a) and 2(b), which shows the lepton pseudo-rapidity vs. $W$ rapidity for the different charges. This effect also explains the discrepancy at high rapidity between the lepton charge asymmetry and the $W$ charge asymmetry as illustrated in Fig. 2(b). The $V - A$ bias in the $W$ decay angle causes leptons at high rapidity to originate primarily from $W^+$ bosons produced in the opposite hemisphere.

$W_{\pm}$ bosons at the Tevatron are primarily produced from the valence quarks in the proton and the anti-quarks simply because $W$ production requires at least one moderately high rapidity, $y_{W}$, where it can 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 since $W$ production by sea anti-quarks will result in the opposite $W$ polarization from valence quark production.

We use a Monte Carlo simulation with NLO QCD corrections [5] to determine the production probability with sea quarks by identifying initiating quarks as a function of $y_W$. We verify the expected angular distribution of $(1 \pm \cos \theta^*)^2$ from production of $W_{\pm}$ with quarks in the proton and the opposite distribution with anti-quarks in the proton. For example, in Fig. 2(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 an 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 form that fits the data,

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

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

FIG. 3: (a) The positively charged $W$ boson and lepton rapidity distribution. (b) The negatively charged $W$ boson and lepton rapidity distribution.
The parameters \( f(P_T^W) \) and \( g(P_T^W) \) are

\[
\begin{align*}
\mathcal{L}(x, \mu, \sigma) &= 0.2811 \mathcal{L}(P_T^W, \mu = 21.7\text{GeV}, \sigma = 9.458\text{GeV}) \\
&\quad + 0.2185 e^{-0.04433\text{GeV}^{-1} P_T^W}, \\
\mathcal{L}(x, \mu, \sigma) &= 0.2085 + 0.0074 \text{GeV}^{-1} P_T^W \\
&\quad - 5.05 \times 10^{-5} \text{GeV}^{-2} P_T^{W2} \\
&\quad + 1.18 \times 10^{-7} \text{GeV}^{-3} P_T^{W3},
\end{align*}
\]

where \( \mathcal{L}(x, \mu, \sigma) \) is the Landau distribution with most probable value \( \mu \) and the RMS \( \sigma \). The first term of Eq. 6 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. 4(b).

A second relevant factor in the selection 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. For 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.

The information used to select among the two solutions can be represented by a weighting factor for each rapidity solution and charge, \( w_{1,2}^\pm \), which can be expressed as

\[
w_{1,2}^\pm = \frac{P_{z}(\cos\theta^\pm_1, y_1, p_T^W)\sigma^\pm(y_1, 2)}{P_0(\cos\theta^0_1, y_1, p_T^W)\sigma^0(y_1, 2) + P_0(\cos\theta^0_2, y_2, p_T^W)\sigma^0(y_2, 2)},
\]

where the \( \pm \) signs indicate the \( W \) boson charge and indices of 1, 2 are for the two \( W \) rapidity solutions.

In our analysis, we include kinematic cuts for detecting charged leptons. For \( W \rightarrow e\nu \) event selection, we apply

\[
|y_{e}^{ab}| < 2.8, \; E_{T}^{e} > 25\text{GeV}, \; \text{and} \; E_{\nu} > 25\text{GeV}.
\]

We also consider a multiplicative correction factor for the detector acceptance and event migration from smearing effects as shown in Figs. 5(a) and 5(b). In order to study smearing effects, we use the fact that the energy resolutions in the electromagnetic calorimeter of the Collider Detector at Fermilab (CDF) are \( 14\%/\sqrt{E} \) (central calorimeter) and \( 16\%/\sqrt{E} \) (end plug calorimeter) and in the hadronic calorimeter are \( 75\%/\sqrt{E} \) (central) and \( 80\%/\sqrt{E} \) (end plug). We randomly smear the electron and recoil hadronic energies in simulated events with a Gaussian distribution modeling their uncertainties prior to making the selection above. The correction factors are determined using a Monte Carlo program which includes both a model of the process under study as well as a simulation of the measuring apparatus. In Eq. 9 the weighting factor depends primarily on the \( W^+ \) and \( W^- \) cross-sections, but does have some weak dependence on the assumed \( W \) charge asymmetry, and thus the correction factors can be biased by computing the factors with different Monte Carlo models. Therefore, this method requires us to iterate the procedure to eliminate our measurement’s dependence on the input asymmetry. In order to confirm our analysis technique and take into account the bias from physics input variables (such as the charge asymmetry itself, the total differential cross-section and the angular distribution) we have studied the \( W \) charge asymmetry measurement with different Monte Carlo models and evaluated systematic uncertainties, which are described in the next section.

### III. SYSTEMATIC UNCERTAINTIES

We consider potentially significant sources of systematic uncertainty on the \( W \) charge asymmetry measurement from the assumed parton distributions, the detector resolutions and misidentifications and backgrounds. Input PDFs are used to determine the parameters of the weighting factor, and may affect the final result. The detector resolutions affect the \( W \) rapidity reconstruction due to uncertainties in the calorimeter energy scale and its energy resolution, and the missing transverse energy scale also has a significant uncertainty from the \( W \) boson recoil energy scale. Finally, the detector may misidentify the charge, especially from leptons at high \(|y_W| \), and there are backgrounds to \( W \rightarrow e\nu \) at the Tevatron.

The uncertainties on the weighting factor (Eq. 9) 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 \( d\sigma^\pm/dy_W \) distribution as well as on the ratio of quark and anti-quark in the angular decay distribution. We use the CTEQ6 error PDF sets [10] and re-determine the \( d\sigma^\pm/dy_W \) production cross section and the angular distribution of \( (1 \pm \cos^2\theta) \) for each error PDF set. We evaluate the uncertainty on the \( W \) charge asymmetry by checking the deviation of the asymmetry values based on each calculation from the central value obtained using the best-fitted PDF set.

We also consider several experimental sources of systematic uncertainty. The scale and resolution of the electromag-
netic calorimeter energy and the missing transverse energy where the electromagnetic (EM) calorimeter energy scale and resolution was tuned in the simulation so as to fit to data. The energy uncertainties measured in [11], to be 3σ (scale), 1.5% (resolution) for central electron and 0.6% (scale), 1.1% (resolution) for plug electron. These values correspond to a 3 σ variation. The asymmetry uncertainties are estimated as the changes in the measured asymmetry when the energy scale and resolution are changed between its default and the ±3σ value. The missing transverse energy (E_{miss}) 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, we consider the transverse recoil energy, which is affected by multiple interactions in the event. The uncertainty on the transverse recoil energy scale is 2% (3σ) [11]. The charge misidentification rate and background estimates are crucial for the charge asymmetry measurement since both can directly change the measurement. We estimate these uncertainties using the charge fake rates (CFR) and background fractions (BKG) from the previous W lepton charge asymmetry result from CDF [3]. The charge fake rate is about 0.01 for |\eta| < 1.5 and 0.04 for |\eta| > 2.0. The upper bound on the background fraction is 2% for |\eta| < 1.0 and increases to about 15% for |\eta| > 2.0. We also investigate sources of any charge bias and \eta dependence in the kinematic and geometrical acceptance of the event. An uncorrected acceptance shift of 3% central and forward electrons and 5% far forward electrons (|\eta| > 2.4) based on measurements of Z \rightarrow e^+e^- data [12] are taken to address the effects of systematic on W charge asymmetry measurement.

Table I summarizes the systematic uncertainties on the W boson production charge asymmetry for rapidities |\eta| < 3.0. We compare the expected statistical uncertainty obtained by assuming an analysis using an integrated luminosity of 1 fb^{-1}, where we also extrapolate the expected statistical uncertainty from the number of events from the previous W lepton charge asymmetry result of CDF with 0.2 fb^{-1} [3].

### IV. RESULTS

We compare the expected statistical uncertainties in 1.0 fb^{-1} of data at the Tevatron with the uncertainties coming from parton distribution functions (PDFs) using CTEQ6M in Fig. 6. In particular, we notice that at high rapidities (|\eta| > 1.4) there is a large difference in the precision with which the as yet unmeasured W production asymmetry and the previously measured asymmetry from the decay leptons scaled to 1.0 fb^{-1} of integrated luminosity are known. The total systematic and statistical uncertainties on the W production charge asymmetry measurement is shown in Fig. 7 with the uncertainties coming from parton distribution functions (PDFs) using CTEQ6M. Since the systematic uncertainty estimates, as summarized in Table I are lower than the statistical error, a direct measurement of the W charge asymmetry with this method should significantly improve parameterizations of the PDFs.

In this paper, we present a study of the W boson produc-
We propose a new analysis technique which resolves the ambiguity in the neutrino longitudinal momentum, using a realistic Monte Carlo simulation. We show that the W charge asymmetry can be directly measured at the Tevatron. We conclude that by measuring the W production charge asymmetry with reconstructed W rapidity, the result should be one of the best determinations of the proton d/u momentum ratio, and play an important role in global PDF fits.

FIG. 6: Comparison of statistical uncertainties expected from this analysis in 1.0 fb$^{-1}$ with those from the uncertainties from CTEQ6M PDFs [10].

FIG. 7: Total systematic uncertainty estimate and statistical uncertainty of this method compared with the current uncertainty on the W charge asymmetry from the CTEQ6 PDFs.

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