Vol. 38 (2007) *ACTA PHYSICA POLONICA B* No 2

W BOSON MEASUREMENTS AT THE TEVATRON*

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(Received November 15, 2006)

I present recent Tevatron Run II results from CDF and DØ on the production and decay properties of the W boson.

PACS numbers: 12.15.Hh, 12.15.Ji, 13.85.Qk, 14.70.Fm

1. Introduction

The W and Z bosons contain key information about the electroweak force. W and Z boson masses and couplings provide many parameters of the standard model (SM), ranging from the CKM matrix to the Higgs vacuum energy. The Z boson parameters have been measured to high precision (*e.g.* the mass to 2 parts in 10^5 [1]) by the large electron–positron collider (LEP) at CERN in Geneva, Switzerland. The W boson parameters are less precisely known (*e.g.* the mass to 4 parts in 10^4 [1]), but measurements at the Tevatron promise to significantly improve this precision. The large W boson sample expected at the Tevatron will rival the 17 million Z boson candidates measured at LEP.

To date, the Tevatron has produced more than 10% of its total expected Run II W boson yield. With this large data sample, the CDF and DØ Collaborations have developed a detailed understanding of W boson production and decay, performed the world's most precise indirect measurement of the W boson width [2], and laid the groundwork for the world's most precise measurements of other W boson parameters.

The successful W boson measurement program at the Tevatron will prove an invaluable guide to data analysis at the LHC, which will produce a W boson sample several orders of magnitude larger than the Tevatron's.

* Presented at the "Physics at LHC" Conference, Kraków, Poland, July 3–8, 2006.

2. Tevatron production

The dominant W^+ (W^-) boson production mechanism in the $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions of the Tevatron is through $u\bar{d}$ ($\bar{u}d$) annihilation (Fig. 1). The total W production cross section can be written as:

$$\sigma = \sum_{a,b} \int dQ\delta(Q - 2E_p\sqrt{x_p x_{\bar{p}}}) \int dx_p f_a(x_p, Q) \int dx_{\bar{p}} f_b(x_{\bar{p}}, Q)\hat{\sigma}(Q)\,, \quad (1)$$

where a and b are summed over the valence u and d quarks, the gluon, the sea quarks; x_p and $x_{\bar{p}}$ are the fractions of energy of the proton and anti-proton, respectively; $f(x, Q)$ is the distribution function describing the momentum fraction of a parton within a proton; and $\hat{\sigma}(Q)$ is the perturbatively-calculable cross section of the hard process $ab \to W$ at a center of mass Q.

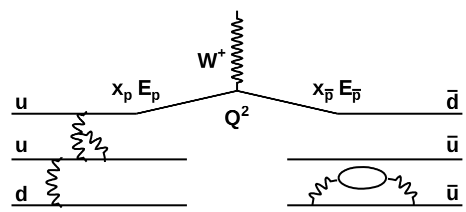

Fig. 1. The typical mechanism for W^+ production in $p\bar{p}$ collisions: u annihilation with a $\bar{d}$ at a squared center of mass $s = Q^2$. In this diagram, the u and $\bar{d}$ have energies $x_p E_p$ and $x_{\bar{p}} E_{\bar{p}}$, respectively.

The parton distribution functions (PDFs) arise from non-perturbative QCD interactions, and thus are not calculable. They are instead parametrized and fit to data from deep inelastic scattering experiments. The two available parametrizations come from the CTEQ [3] and MRST [4] groups. For most of the distribution functions, CTEQ uses the following functional form:

$$xf_a(x, Q_0) = A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1 + A_4 x)^{A_5}\,. \quad (2)$$

This form allows more functional variation than is currently necessary, so a number of the parameters are held fixed in the fits. To facilitate uncertainty calculations, eigenvectors are found for the 20 floating parameters, and $\pm 1\sigma$ variations determined using a prescription of $\delta\chi^2 = 100$ for $\pm 1\sigma$.

Uncertainties from PDFs are typically significant in W boson measurements. They can, however, be reduced through measurements of the W boson cross section and the W production charge asymmetry at the Tevatron.

2.1. Cross section

The CDF Collaboration has measured the W boson production cross section separately using electrons in the central [2] ($|\eta_e^{\rm det}| < 1.1$, where $\eta_e^{\rm det} = \eta_e(z_0 = 0)$) and forward regions ($1.2 < |\eta_e^{\rm det}| < 2.8$). These cross section measurements probe different ranges of W boson rapidity (Fig. 2), thus constraining PDFs (since $y_W = \frac{1}{2}\log(x_p/x_{\bar{p}})$).

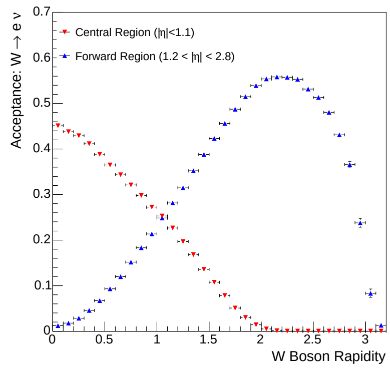

Fig. 2. The W rapidity acceptance distributions for events selected with central (inverted triangles) and forward (triangles) electrons. The $|\eta|$ ranges listed are for electrons originating at the center of the detector.

The measured W boson cross sections from CDF using central or forward electrons are:

$$\sigma\left(|\eta_e^{\rm det}| < 1.1\right) = 2771 \pm 14 \text{ (stat) } {}^{+62}_{-56} \text{ (sys) } \pm 166 \text{ (lum) pb}, \quad (3)$$

$$\sigma\left(1.2 < |\eta_e^{\rm det}| < 2.8\right) = 2796 \pm 13 \text{ (stat) } {}^{+95}_{-90} \text{ (sys) } \pm 162 \text{ (lum) pb}. \quad (4)$$

Both measurements are consistent with the next-to-next-to-leading order (NNLO) calculation of $\sigma(p\bar{p} \to W) = 2684 \pm 54$ pb. The systematic uncertainties (Table I) are dominated by the luminosity, PDF, and electron identification uncertainties. The ratio of the measurements effectively cancels the luminosity uncertainty, leaving roughly equal uncertainties from theory and experiment. To separate these uncertainties, CDF uses the ratio of visible cross sections $\sigma_{\rm vis} = \sigma(p\bar{p} \to W) \times A$, where A is the acceptance, and compares the experimental result to the CTEQ and MRST predictions:

$$\frac{\sigma_{\rm vis}^{\rm cen}}{\sigma_{\rm vis}^{\rm for}} = \left\{ \begin{array}{l} 0.925 \pm 0.033 \text{ (exp)} \\ 0.924^{+0.023}_{-0.030} \text{ (CTEQ)} \\ 0.941^{+0.011}_{-0.015} \text{(MRST)} \end{array} \right\}. \quad (5)$$

TABLE I

The dominant systematic uncertainties on the CDF W boson cross section measurements using central and forward electrons.

Uncertainty	$\delta\sigma/\sigma(\|\eta_e\| < 1)$	$\delta\sigma/\sigma(1.2 < \|\eta_e\| < 2.8)$
Luminosity	$\pm 6.0\%$	$\pm 5.8\%$
PDF	$+1.2\%, -1.5\%$	$+1.7\%, -1.3\%$
Electron identification	$\pm 0.9\%$	$\pm 2.2\%$
Background	$\pm 0.8\%$	$\pm 0.9\%$
Track reconstruction	$\pm 0.4\%$	$\pm 1.1\%$

The largest uncertainty on the ratio for a given CTEQ eigenvector comes from one of the first few eigenvectors (Fig. 3), corresponding roughly to the valence u and d quarks. As expected, the W boson rapidity distribution is most sensitive to the these PDFs.

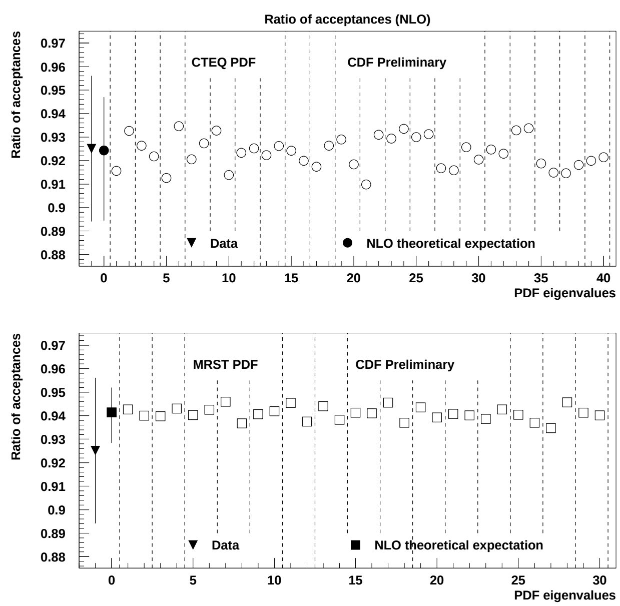

Fig. 3. The predicted (solid square and circle) and observed (solid triangles) ratio of central to forward visible W boson cross sections. Also shown are the individual ratios (open squares and circles) for each CTEQ (top) and MRST (bottom) eigenvector.

These experimental results are consistent with theoretical predictions, and provide the first probe of PDFs to use the unsigned lepton rapidity distribution of W boson decays.

2.2. Production asymmetry

The W boson production asymmetry measurement strongly constrains PDFs. A u quark inside the proton contains on average a higher fraction of the proton's energy than a d quark. Thus, the Tevatron produces W^+ bosons with a net positive rapidity (Fig. 4). Precise measurement of this asymmetry provides information on the relative momentum fraction of the u and d quarks, or $u(x)/d(x)$.

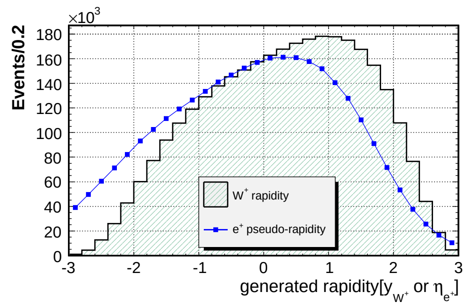

Fig. 4. The W^+ boson rapidity (histogram) and the e^+ pseudorapidity (squares) distributions from the process $p\bar{p} \to W^+ \to e^+\nu$.

The production asymmetry measurement is typically performed using charged leptons from the W boson decays. The V−A structure of the electroweak couplings governs the lepton angular distribution, which is preferentially opposite to the production asymmetry. The CDF and DØ Collaborations have measured the lepton asymmetry, defined as:

$$A_l^+(\eta_l) = A_l^-(\eta_l) = \pm\frac{\sigma_{l^\pm}(\eta_l) - \sigma_{l^\pm}(-\eta_l)}{\sigma_{l^\pm}(\eta_l) + \sigma_{l^\pm}(-\eta_l)}\,. \quad (6)$$

The DØ measurement uses 230 pb^{-1} of $W \to \mu\nu$ data (Fig. 5). The uncertainties are smaller than the CTEQ variations over much of the pseudorapidity spectrum, demonstrating the constraining power of the measurement.

CDF separates its electron asymmetry measurement [5] into two transverse energy (E_{T}) ranges, $25 < E_{\mathrm{T}} < 35$ GeV and $35 < E_{\mathrm{T}} < 45$ GeV. At low E_{T} the production asymmetry is significantly reduced by the lepton decay, with the lepton asymmetry changing sign at high $|\eta|$. At high E_{T} more of the production asymmetry is preserved, and the lepton asymmetry has the same sign as the production asymmetry to high $|\eta|$. Fig. 6 shows the measured CDF electron asymmetry at high E_{T}, along with the CTEQ and MRST PDF predictions.

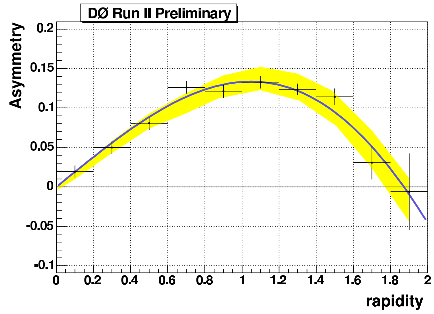

Fig. 5. The muon asymmetry $|\eta|$ dependence from W boson production and decay, as measured by the DØ Collaboration (points) and predicted by the CTEQ PDFs (band).

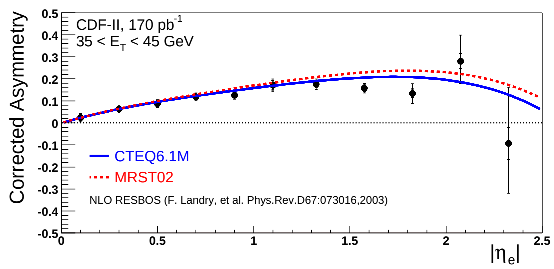

Fig. 6. The high-E_{T} electron asymmetry $|\eta|$ dependence from W boson production and decay, as measured by the CDF Collaboration (circles) and predicted by the CTEQ (solid) and MRST (dashed) PDFs.

The DØ and CDF measurements are currently being incorporated into the CTEQ and MRST PDF fits, and will reduce the uncertainties on the proton $u(x)$ and $d(x)$ distributions.

3. Couplings

The Tevatron's 1.96 TeV center of mass collisions provide access to W boson couplings to heavy particles such as the top quark and electroweak vector bosons. Recent measurements from CDF and DØ probe these couplings and their energy dependence with unprecedented sensitivity.

3.1. Wtb vertex

A W^+ boson produced at a little more than twice its pole mass can decay to $t\bar{b}$. This s-channel single-top production provides a direct probe to the CKM V_{tb} parameter. An additional probe, the t-channel, produces $t\bar{b}q$

when a gluon splits into a $b\bar{b}$ pair and interacts with a quark. The total cross section for single-top production is 2.9 pb for $m_t = 175$ GeV/c^2, sufficiently small that it has not yet been observed.

CDF and DØ have searched for single-top production in 695 pb^{-1} and 370 pb^{-1} of data, respectively. Both experiments use advanced analysis techniques to separate the signal from the W+jets and $t\bar{t}$ backgrounds. The most stringent 95% confidence level (C.L) cross section limits come from CDF (Fig. 7), and are within 50% of the theoretical prediction. With an increase in data to 2 fb^{-1} (4 fb^{-1}), CDF and DØ expect to obtain a 3σ (5σ) signal from single-top production.

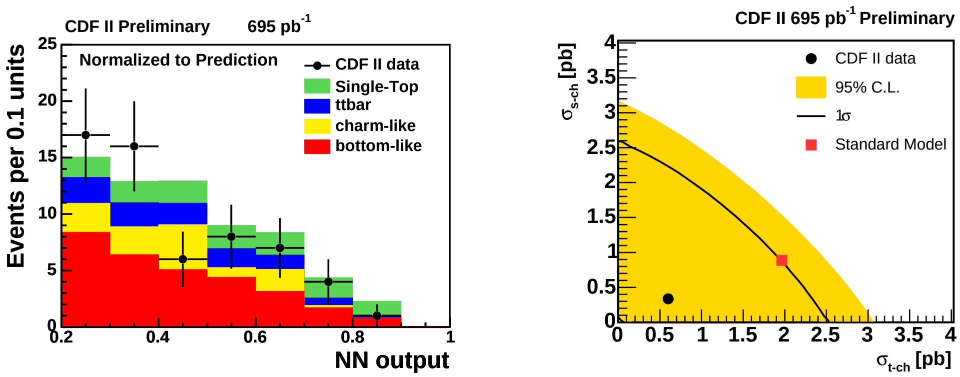

Fig. 7. The distributions of neural network output for data (circles) and standard model prediction (histograms) (left). The prediction (solid square) for the single-top production cross section, in the s–t channel plane (right). Also shown are the CDF best fit (solid circle) and allowed 95% C.L. region (solid).

3.2. *WVV vertices*

W boson couplings to vector bosons test the electroweak SU(2) structure, and are sensitive to new particles coupling to electroweak bosons.

The process $p\bar{p} \to WW \to ll\nu\nu$ was first observed in 200 pb^{-1} of Run II data by the DØ and CDF Collaborations [6]. CDF has updated its measurement using 825 pb^{-1} of data, obtaining a signal with 10σ significance: 95 observed events with 37.8 ± 4.8 expected background. The measured cross section, $\sigma(p\bar{p} \to WW) = 13.6 \pm 2.3$ (stat) ± 1.6 (sys) ± 1.2 (lum) pb, agrees well with the theoretical cross section of 12.4 ± 0.8 pb.

The $p\bar{p} \to WZ \to lll\nu$ process has never been observed. Both CDF and DØ have performed recent searches with an expected 3σ sensitivity using $\approx$800 pb^{-1} of data. CDF observes 2 events with an expected background of $0.92^{+0.17}_{-0.12}$ events, and sets a 95% C.L. cross section limit of $\sigma(WZ) < 6.3$ pb, close to the theoretical cross section of 3.7 ± 0.3 pb. DØ observes a 3.3σ excess over background, and measures a WZ production cross section of $4.0^{+1.9}_{-1.5}$ pb. In the search, two same-flavor leptons are required to have a mass consistent with the Z boson; the transverse mass of the third lepton and the missing transverse momentum is shown in Fig. 8. The majority of events are near 80 GeV, as expected from WZ production.

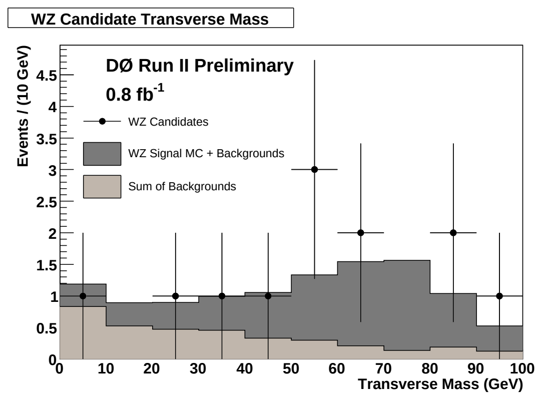

Fig. 8. The transverse mass obtained from the event p_{T} imbalance and the p_{T} of the lepton not attributed to a Z boson decay in the DØ WZ production search.

WW and WZ production have not been observed in the final state $l\nu qq'$. Using this final state in 350 pb^{-1} of data, CDF fits the dijet mass spectrum for $W+Z$ production and observes a 0.9σ excess. With 2 fb^{-1} of data, CDF expects to have better than 3σ sensitivity to these processes.

4. Conclusion

The Tevatron's large W boson samples allow the world's most precise measurements of many W properties. In addition to measurements of the W production cross section and asymmetry, and studies of the Wtb and WVV vertices, the Tevatron collaborations have made the world's highest precision indirect measurement of the W boson width (CDF) [2], performed the first Run II direct measurement of the width (DØ) [7], and determined the uncertainty on the first Run II W mass measurement (CDF) [7]. These measurements will improve the knowledge of SM parameters and test the existence of new processes beyond the SM with unprecedented sensitivity.

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