

# W and Z Production at the Tevatron

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## Abstract

In this paper, recent experimental results on W and Z boson production at the Tevatron are described. These results not only provide tests of the standard model, but are also sensitive to proton parton distribution functions.

## 1 Introduction

The Fermilab Tevatron is a  $p\bar{p}$  collider, operating at a centre-of-mass energy  $\sqrt{s} = 1.96$  TeV. During Run II (in Run I, the Tevatron operated at  $\sqrt{s} = 1.8$  TeV), the two large, general purpose experiments CDF and DØ have collected an integrated luminosity of approximately  $1.5 \text{ fb}^{-1}$  per experiment, at the time of writing. The results presented here have been obtained with integrated luminosities of up to  $350 \text{ pb}^{-1}$ .

In the following, results on inclusive W and Z boson production cross sections, the W boson charge asymmetry and the Z boson rapidity distribution will be given. The experimental results will be compared with predictions from the standard model, in particular Quantum Chromodynamics (QCD), at next-to-leading-order (NLO) and at next-to-next-to-leading-order (NNLO).

## 2 W and Z Boson Production

In  $p\bar{p}$  collisions at the Tevatron energy, W and Z bosons are predominantly produced through the annihilation of a valence quark from the proton and a valence anti-quark from the anti-proton. The probability for such a  $q\bar{q}$  annihilation to happen (*i.e.*, the cross section) is perturbatively calculable from the standard model. Corrections due to gluon exchange in the  $q\bar{q}$  pair or gluon emission from the (anti-) quark are known from QCD. The probability to find a quark of a certain momentum inside the proton is known from experimentally determined parton distribution functions (PDF's). A measurement of inclusive or differential W and Z boson production cross sections therefore provides tests of both QCD and PDF's.

In addition, many other physics processes of interest, such as top-quark decays, involve electroweak bosons. A precise experimental understanding of these bosons is thus a benchmark for other analyses. Also, since theoretical predictions for W and Z boson production are quite accurate, a measurement of the production rate can serve as a tool to determine the integrated luminosity. This will be especially useful at the Large Hadron Collider.

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## 2.1 Experimental Signatures and Backgrounds

The electroweak bosons are detected in their leptonic decay modes<sup>2</sup>. In case of the W boson, the experimental signature is events with a single high  $p_T$  lepton (electron or muon) and a large missing transverse energy ( $\cancel{E}_T$ ) due to the undetected neutrino. With cuts on  $p_T$  and  $\cancel{E}_T$  typically set at 20 to 25 GeV, about 1 million candidates are selected per inverse femtobarn of integrated luminosity. Background in this sample is small, and is composed of so-called QCD background<sup>3</sup> and electroweak boson background. QCD background in the muon channel is dominated by semi-leptonic decays of charm and bottom hadrons, and amounts to approximately 1% of the W boson candidate sample. In the electron channel, jets with an electron signature form the QCD background ( $\sim 1\%$ ). The electroweak boson backgrounds are due to leptonic decays of Z bosons where one of the leptons is not identified ( $\sim 5\%$  in the muon channel,  $\sim 0.5\%$  in the electron channel), and  $W \rightarrow \tau\nu$  decays ( $\sim 2\%$  in both channels).

Z boson decays are selected as events with two high  $p_T$  leptons ( $p_T > 15 - 25$  GeV). For each inverse femtobarn of integrated luminosity, this gives a sample of about  $10^5$  candidates. Backgrounds are very small. QCD background is  $\sim 0.5\%$  in the muon channel and  $\sim 1\%$  in the electron channel. The only other significant source of background is from  $Z \rightarrow \tau\tau$  decays ( $< 0.5\%$ ).

## 2.2 Cross Section Measurements

The W or Z boson production cross section (times the branching fraction) can be determined as follows:

$$\sigma(p\bar{p} \rightarrow W/Z) \times B(W \rightarrow l\nu/Z \rightarrow ll) = \frac{N_{\text{candidates}} - N_{\text{background}}}{\epsilon A \int \mathcal{L} dt}, \quad (1)$$

where the number of candidates is given by  $N_{\text{candidates}}$ . The backgrounds (given by  $N_{\text{background}}$ ), as described in the previous section, are estimated from the data itself (for the QCD backgrounds) or from Monte Carlo simulations of standard model predictions (for the electroweak boson backgrounds). The efficiency  $\epsilon$  to correctly identify and select a W or Z boson is typically determined from the data, with an uncertainty of 1 – 2%. The experimental acceptance  $A$  is calculated from Monte Carlo simulations of W or Z boson production. The uncertainty on the acceptance is  $\sim 1.5\%$ , and is dominated by uncertainties in the PDF's. Finally, the integrated luminosity ( $\int \mathcal{L} dt$ ) is measured by independent luminosity systems.

Current results on W and Z boson cross section measurements at the Tevatron are shown in Figure 1. The largest systematic uncertainty on these measurements ( $\sim 6\%$ ) is due to the measurement of the integrated luminosity ( $\int \mathcal{L} dt = 72 - 350 \text{ pb}^{-1}$  for the Run II points). The solid line in these figures represents an NNLO QCD prediction[1]. There is good agreement between the experimental points and the prediction. Note that cross sections in the  $\tau$  decay channel have also been measured. These are important benchmarks for Higgs and new physics searches.

## 2.3 Cross Section with Forward Electrons

Typically, PDF's are parameterized as a function of  $x$ , the fraction of the proton momentum carried by the quark, and  $Q^2$ , the momentum transfer between the quark and anti-quark. At leading order,

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<sup>2</sup>Hadronic decays are very hard to select, due to the large multi-jet background from QCD processes.

<sup>3</sup>“QCD” here refers to the production of jets in the final state. Of course, the initial state in electroweak boson production is also governed by QCD.

the rapidity of a W boson ( $y_W$ ) is related to  $x$  via  $x = \frac{m_W}{\sqrt{s}} e^{(\pm)y_W}$ . A measurement of the W boson production cross section at large  $y_W$  is therefore sensitive to PDF's at small and large  $x$ . In its turn, the pseudorapidity  $\eta$  of the lepton from a W boson decay is correlated with the rapidity of the W boson. This implies that leptons at large  $\eta$  (*i.e.*, in the forward detectors) come from W bosons with a large rapidity on average, whereas leptons at small  $\eta$  (in the central detectors) are due to W bosons with small rapidity.

The CDF collaboration has exploited this in a measurement of the W boson production cross section using electrons in the forward calorimeters ( $1.2 < |\eta| < 2.8$ ). After a full correction for the limited acceptance of the forward calorimeters, the resulting cross section times branching fraction is:

$$\sigma(p\bar{p} \rightarrow W) \times B(W \rightarrow e\nu) = 2796 \pm 13(\text{stat})_{-90}^{+95}(\text{sys}) \pm 162(\text{lum}) \text{ pb.} \quad (2)$$

This number is in good agreement with the cross section from electrons in the central detector ( $|\eta| < 1.0$ ) and with the predicted cross section. Note that this measurement is also shown in Figure 1 (“CDF (e pl)”).

A first-order test of PDF's is obtained by taking the ratio of the visible cross section (defined as  $\sigma_{\text{vis}} = \sigma_W \times A$ ) in the central and forward detectors. The cross section uncertainty due to the PDF's cancels in this ratio, and the uncertainty due to the integrated luminosity is reduced. This cross section ratio is equivalent to the ratio of W boson acceptances for forward and central electrons. The CDF result is:

$$\sigma_{\text{vis}}^{\text{cent}} / \sigma_{\text{vis}}^{\text{forw}} = 0.925 \pm 0.033, \quad (3)$$

$$A^{\text{cent}} / A^{\text{forw}} = 0.924_{-0.030}^{+0.023} \quad (\text{CTEQ}), \quad (4)$$

$$A^{\text{cent}} / A^{\text{forw}} = 0.941_{-0.015}^{+0.011} \quad (\text{MRST}). \quad (5)$$

The uncertainties on the expected ratios are dominated by the PDF uncertainty. It can be seen that the measured ratio (Eq. 3) is in excellent agreement with the predictions using the CTEQ PDF's (Eq. 4) and in good agreement with the MRST prediction (Eq. 5). It is clear that just this  $\sigma_W(\eta_1)$  measurement is already sensitive to the PDF's.

### 3 W Boson Charge Asymmetry

On average, the u-quark in the proton carries a larger fraction of the proton's momentum than the d-quark. This implies that at production, a  $W^{+(-)}$  boson is typically boosted in the  $p(\bar{p})$  direction. This leads to a charge asymmetry, as a function of  $y_W$ . A measurement of this asymmetry is directly sensitive to the PDF's.

The momentum of the neutrino in a W boson decay is not fully reconstructible, which implies that  $y_W$  is not fully reconstructible. However, some of the original asymmetry is preserved in the pseudorapidity distribution of the decay-lepton.

Both the DØ (muon channel) and CDF (electron channel) collaborations have measured the lepton charge asymmetry, defined as:

$$A(y) = \frac{N^+(y) - N^-(y)}{N^+(y) + N^-(y)}. \quad (6)$$

These measurements probe a region in  $(x, Q^2)$  that is not probed by, e.g., HERA experiments. The main experimental challenge is to keep the lepton-charge misidentification rate low ( $\sim 0.01\%$  for DØ's

muon channel;  $\sim 1\%$  for CDF's electron channel), and to understand possible charge-dependencies of selection efficiencies.

The result of  $D\bar{O}$ 's measurement, based on  $\int \mathcal{L}dt \simeq 230 \text{ pb}^{-1}$ , is given in Figure 2. Even though the uncertainties on the experimental points are dominated by the finite data-sample-size, some sensitivity to PDF's is already obtained (assuming the W boson decays according to the standard model). Thus, with more data, this measurement will constrain the PDF's.

A description of the CDF measurement ( $\int \mathcal{L}dt \simeq 170 \text{ pb}^{-1}$ ) can be found in Ref. [2]. CDF split up the final data sample in two bins ( $25 < E_T(e) < 35 \text{ GeV}$  and  $35 < E_T(e) < 45 \text{ GeV}$ ) to get additional PDF sensitivity.

## 4 Z Boson Production Rapidity

The rapidity of a Z boson ( $y_Z$ ) produced in a  $p\bar{p}$  collision is also sensitive to the u- and d-quark momentum fractions in the proton. As opposed to the W boson rapidity, the rapidity of the Z boson is fully reconstructible. However, u- and d-quark contributions cannot be separated. The result of a measurement by the  $D\bar{O}$  collaboration of  $y_Z$  in the electron channel ( $\int \mathcal{L}dt \simeq 340 \text{ pb}^{-1}$ ) is given in Figure 3. A good agreement with an NNLO prediction[3] is observed, but the data sample is still too small to be sensitive to PDF's.

## 5 Conclusion and Outlook

Precision measurements of inclusive and differential W and Z boson production cross sections at the Tevatron have been performed. The results agree well with standard model predictions. Measurements of lepton charge asymmetries as a function of lepton rapidity are already sensitive to PDF's. In the near future, an order of magnitude more data will be analyzed. This will provide a better determination of PDF's, which in its turn is important for reducing systematic uncertainties on, for example, the W boson mass measurement.

## References

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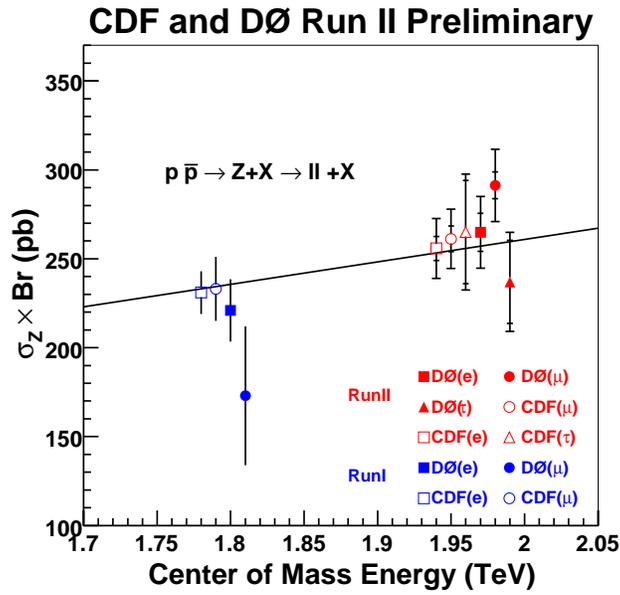
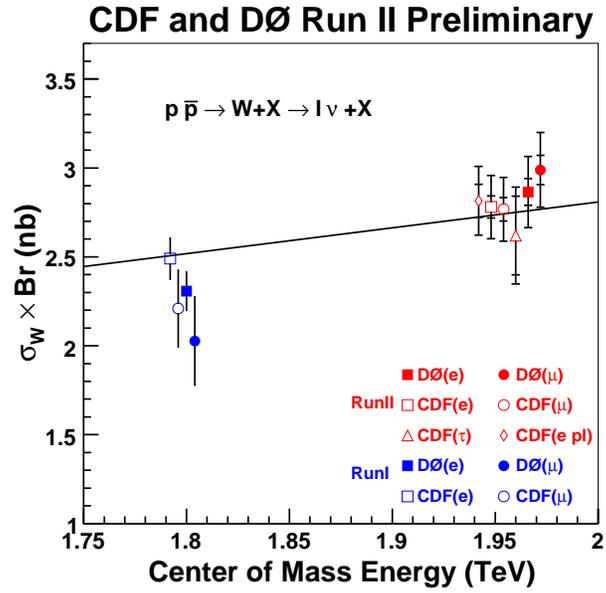


Figure 1: Measured and predicted cross section times branching fraction for W (top) and Z (bottom) boson production, as a function of centre-of-mass energy.

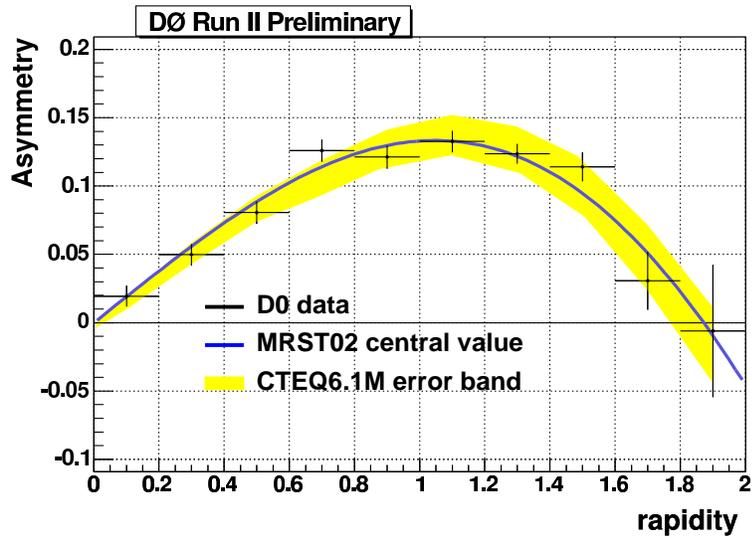


Figure 2: Measured and predicted lepton charge asymmetry, as a function of lepton rapidity. The theoretical curves are based on NLO calculations (RESBOS).

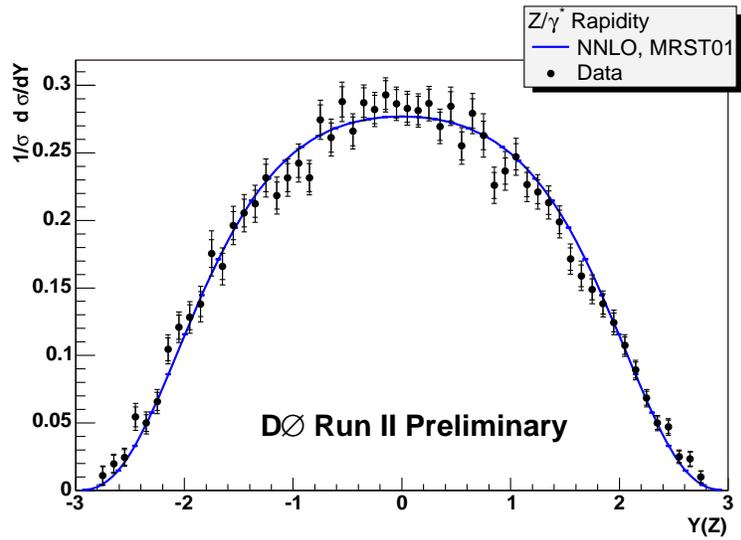


Figure 3: Measured and predicted Z boson rapidity distribution.