Constraints on PDFs from W and Z rapidity distributions at CDF

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The rapidity distributions of W and Z bosons produced in proton anti-proton collisions at CDF are presented. The rapidity distribution of Z bosons, measured for the first time over the entire kinematic range, is better described by NLO QCD (and also by QCD with gluon resummation) than by leading order QCD. The W charge asymmetry data as a function of rapidity strongly constrain the ratio of d and u quark momentum distributions in the proton over the x range of 0.006 to 0.34. The W data are used to rule out recently proposed models for charge and flavor symmetry violation of the sea quark distributions in the nucleon.

In high energy proton-antiproton collisions W and Z bosons are produced via quark-antiquark annihilation. In CDF, both W and Z rapidity distributions are used to study both the high x valence quark distribution as well as the low x antiquark distribution. The x values of the quark in the proton and antiquark in the antiproton are related to the rapidity, y, of the W or Z boson via the equation $x_{1,2} = (M/\sqrt{s})e^{\pm y}$. Here s is the center of mass energy and M is the mass of the W or Z boson.

Electrons and positrons from the decay of Z bosons are detected by tracking detectors and electromagnetic calorimeters at CDF. In this analysis, the central (C), plug (P) and Forward (F) calorimeters are all used. The non-electron background is greatly reduced by requiring a track at the vertex to point at the position of the electromagnetic cluster in the calorimeters. In a previous analysis, one electron was required to be in the central region and the other electron (or positron) to be in either the central (C-C), the plug (C-P), or forward (C-F) calorimeters. In the new analysis, events with one electron in the plug and the other in either plug (P-P) or forward (P-F) calorimeters are also included. The inclusion of these events increases the event sample by about 20% and allows for measurement of Z bosons with y up to 2.5, which is close to the kinematic limit.

Figure 1 shows the y distributions of Z bosons including all C-C, C-P, C-F, P-P and P-F events. The y distribution has been measured over the entire kinematic range. The predictions from the various models have been normalized to the data. As can be seen in the figure, the prediction using a leading order QCD model with leading order PDFs (CTEQ4L) does not describe the data as well as the predictions using either a NLO model, or a NLO model including gluon resummation (VBP), using next to leading order PDFs (CTEQ4M). Because Z bosons can be produced via the annihilations of any of u,d,s and c quarks in the proton with the corresponding antiquarks in the antiproton, the y distribution of Z bosons is not as sensitive to the details of the PDF of each quark individually. However, it is sensitive to the overall order of the QCD calculation, and indicates that both NLO QCD and gluon resummation calculations give an excellent description of the data, up to the kinematic limit. Therefore, these two calculations give a reliable description of the acceptance of the detector for other measurements of the total cross section of W and Z production (for which the acceptance is limited to the central region, i.e. y less than 1.0).

At Tevatron energies, W^+ (W^-) bosons are produced in $p\overline{p}$ collisions primarily by the annihilation of u (d) quarks in the proton and $\overline{d}$ ($\overline{u}$) quarks from the antiproton. Because u quarks carry on average more momentum than d quarks, the W^+'s tend to follow the direction of the incoming proton and the W^-'s that of the antiproton. The charge asymmetry in the production of W's as a function of rapidity (y_W) is therefore related to the difference in the u and d quark distributions, and is roughly proportional to the ratio of the difference and the sum of the quan-

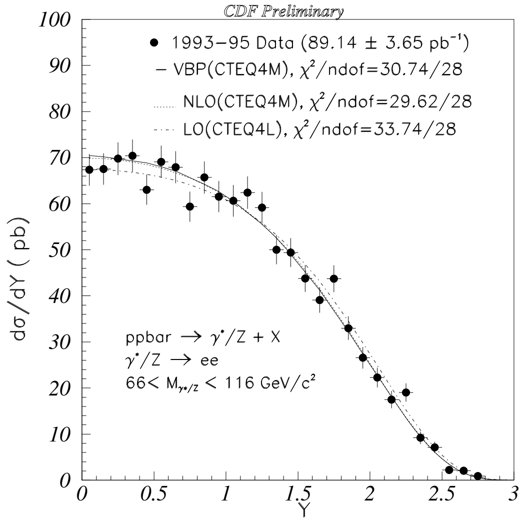

Figure 1. The rapidity distribution of Z bosons, compared to QCD calculation, in leading order (LO), next to leading order (NLO) and including gluon resummation (VBP).

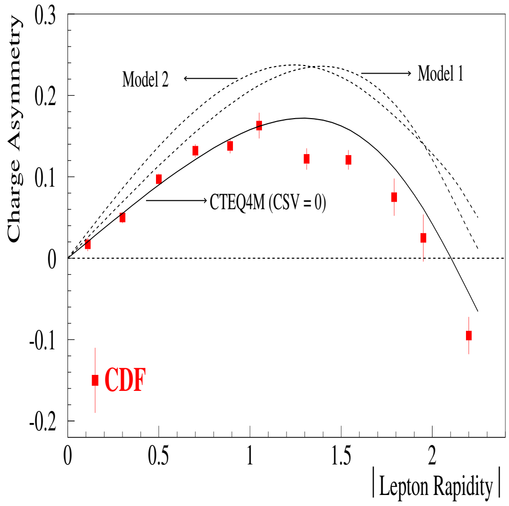

Figure 2. The CDF W Asymmetry data. The solid line is the predictions from the standard CTEQ4M PDFs. The dashed and dotted lines are predictions from the CTEQ4M PDFs modified to include the charge symmetry violation in the quark sea as described in the text. All theoretical predictions are calculated in NLO QCD using the DYRAD program.

tities $d/u(x_1)$ and $d/u(x_2)$, where x_1 and x_2 are the fraction of proton momentum carried by the u and d quarks, respectively. The W data have been used to place constraints on the ratio of d and u quark distributions in the proton in all standard PDF parametrizations.

In this section, we show how the W asymmetry data can also be used to rule out recently proposed non-standard parametrizations of PDFs. In a recent Physical Review Letter [1], Boros *et al.* proposed a model in which a substantial charge symmetry violation (CSV) for parton distributions in the nucleon accounts for the experimental discrepancy between neutrino (CCFR) and muon (NMC) nucleon structure function data at low x. Charge symmetry is a symmetry which interchanges protons and neutrons, thus simultaneously interchanging up and down quarks, which implies the equivalence between the up (down) quark distribution in the proton and the down (up) quarks in the neutron. Boros *et al.* have proposed [1] that charge symmetry is broken such that the d sea quark distribution in the nucleon is larger than the u sea quark distribution in the region of x less than 0.1. Since both neutrino and muon scattering data have been taken on isoscalar targets, such as iron or deuterium, which have an equal number of neutrons and protons, both a charge symmetry and flavor symmetry violation of the sea quarks in the nucleon is required in order to explain the discrepancy ($10 \sim 15\%$) between neutrino and muon structure function data. Within this model, the authors extract a large CSV from the difference in structure functions as measured in neutrino and muon scattering experiments. Theoretically, such a large charge symmetry violation (of order of 25% to 50%) at small values of x is very unexpected.

There are two possible ways that standard PDFs can be modified to introduce the charge symmetry violations proposed by Boros *et al.*. These two parametrizations are given in a recent paper [2] by Bodek *et al.*. In Model 1, it is assumed that the standard PDF parametrizations are dominated by neutrino data and therefore represent the average of d and u sea quark distributions. Therefore, half of the CSV is introduced into the u sea quark distribution and half of the effect is introduced into the d sea quark distribution such that the average of d and u sea quark distributions is conserved. In Model 2, it is assumed that standard PDFs are dominated by muon scattering data, and therefore are a good representation of the 2/3 charge u quark distribution. In this model, the entire effect is introduced into the d sea quark distribution.

At large rapidity of W bosons produced in proton-antiproton collisions, x_1 is larger than 0.1, which is a region for which there are no proposed CSV violations. On the other hand x_2 is in general less than 0.1, and a 25% to 50% CSV effect would imply a very large effect on the W asymmetry. Since the W charge asymmetry is sensitive to the d/u ratio, it does not matter if the CSV effect at small x is present in either d or u sea quark. Both of these models would result in a similar change in the W asymmetry.

The CDF W asymmetry data shown in Fig. 2 spans the broad range of lepton rapidity ($0.0 < |y_l| < 2.2$), and provide information about the d/u ratio in the proton over the wide x range ($0.006 < x < 0.34$). Also shown in Fig. 2 (solid line) are the predictions for the W asymmetry from QCD calculated to Next-to-Leading-Order (NLO) using the program DYRAD, with the CTEQ4M PDF parametrization for the d and u quark distributions in the proton (we have used CTEQ4 because it is the PDF set that has been used by Boros *et al.* in their paper). As pointed out by Yang and Bodek [3], the small difference between prediction of the CTEQ4M PDF at high rapidity is due to the fact that the d quark distribution is somewhat underestimated at high x in the standard PDF parametrizations. The dashed and dotted lines in Fig. 2 show the predicted W asymmetry for the CTEQ4M PDF with the proposed charge symmetry violation in the sea for Model 1 and Model 2, respectively. The CDF W data clearly rule out these models.

In the direct measurement of the W mass at the Tevatron, the CDF W asymmetry data have been used to limit the error on M_W from PDFs to about 15 MeV. This has been done by calculating the deviation between the error weighted average measured asymmetry over the rapidity range of the data, and the predictions from various PDFs, and only using PDF's which are within two standard deviations of the best PDF. This measured average asymmetry for the data is 0.087 ± 0.003. The predicted average asymmetries (weighted by the same errors as the data) are 0.094, 0.125, and 0.141 for the CTEQ4M PDF, and for Model 1 and Model 2, respectively. If we only accept PDFs which are within two standard deviations of the CTEQ4M PDF, the W asymmetry data rule out CSV effects at the level of more than 10 standard deviations for the two models with CSV effects.

In conclusion, the CDF W asymmetry data strongly constrain the d/u ratio in the nucleon and rule out charge symmetry violation in parton distributions as the source of the difference between neutrino (CCFR) and muon (NMC) deep inelastic scattering data. The rapidity distribution of Z bosons, measured for the first time over the entire kinematic range, is better described by NLO QCD (and also by QCD with gluon resummation) than by leading order QCD.

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