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Pawel de Barbaro
For the CDF and D0 Collaborations

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

University of Rochester
New York, New York 14627

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Tests of Proton Structure Functions using Leptons at CDF and D0: W Charge Asymmetry and Drell-Yan Production

Presented by Pawel de Barbaro
The University of Rochester, New York, NY 14627
For the CDF and D0 Collaborations

Abstract

High statistics W charge asymmetry measurements at the Tevatron $\overline{p}p$ collider significantly constrain the u and d quark distributions, and specifically the slope of the $d(x)/u(x)$ in the x range 0.007 to 0.27.

We present measurements of lepton charge asymmetry as a function of lepton rapidity, $A(y_l)$ at $\sqrt{s} = 1.8$ TeV for $|y_l| < 2.0$, for the W decays to electrons and muons recorded by the CDF detector during the 1992-93 run ($\approx 20\ pb^{-1}$), and the first $\approx 50\ pb^{-1}$ of data from the 1994-95 run. These precise data make possible further discrimination between sets of modern parton distributions. In particular it is found that the most recent parton distributions, which included the CDF 1992-93 W asymmetry data in their fits (MRSA, CTEQ3M and GRV94) are still in good agreement with the more precise data from the 1994-95 run.

W charge asymmetry results from D0 based on $\approx$ 6.5 pb^{-1} data from 1992-1993 run and $\approx$ 29.7 pb^{-1} data from 1994-1995 run, using the W decays to muons, are also presented and are found to be consistent with CDF results.

In addition, we present preliminary measurement of the Drell-Yan cross-section by CDF using a dielectron sample collected during the 1993-94 run ($\approx 20\ pb^{-1}$) and a high mass dimuon sample from the combined 1993-94 and 1994-95 runs ($\approx 70\ pb^{-1}$). The measurement is in good agreement with predictions using the most recent PDFs in a dilepton mass range between 11 and 350 GeV/c^2.

Parton Density Constraints from $\overline{p}p$ Collider Data

At Tevatron energies, W bosons are primarily produced via quark anti-quark annihilations. In leading order the W production cross section is proportional to the product of parton density functions:

$$\sigma_W \sim u(x)d(x), \tag{1}$$

at $x = \frac{M_W}{\sqrt{s}}e^{\pm y}$ and $Q^2 = M_W^2$.

The understanding of parton distribution functions (PDF's) in the proton is important in many aspects of collider physics. Uncertainties in PDF's contribute to systematic errors in the predictions of W and Z boson cross sections, in W mass determination and in the prediction for the top quark cross-section. In addition, PDF uncertainties contribute to systematic uncertainties in setting limits on the production of exotic particles, such as Z' bosons and SUSY particles.

Typically PDF's are extracted from deep inelastic scattering (DIS) cross-sections for eN, μN and νN as a function of x and Q^2. In particular, the ratio of d and u quark distributions is extracted from data on ratio of μ (or e) scattering from neutrons and protons. However, such data suffer from uncertainties in neutron binding corrections [3] and higher twist and nonperturbative contributions [4] at low Q^2.

High statistics W charge asymmetry measurements at the Tevatron $\overline{p}p$ collider provide [1,2] new information that significantly constrains u and d quark distributions, and specifically the slope of the $d(x)/u(x)$ ratio in the x range 0.007 to 0.27.

On average, u quark carries more momentum than d quark. Thus, W^+'s are boosted in the proton direction and W^-'s are boosted in the anti-proton direction. This results in a W production charge asymmetry, defined as:

$$A(y_W) \equiv \frac{d\sigma_W^+(y)/dy_W - d\sigma_W^-(y)/dy_W}{d\sigma_W^+(y)/dy_W + d\sigma_W^-(y)/dy_W} \simeq \frac{u_1 d_2 - u_2 d_1}{u_1 d_2 + u_2 d_1} = \frac{d_2/u_2 - d_1/u_1}{d_2/u_2 + d_1/u_1} \tag{2}$$

Thus, $A(y_W)$ is related to the difference in d/u between x_1 of the parton from the proton and x_2 of the parton from the anti-proton:

$$x_{1,2} = \frac{M_W}{\sqrt{s}}e^{\pm y} \tag{3}$$

Since the W decay involves a neutrino, whose longitudinal momentum is undetermined, collider experiments can only the measure the decay lepton charge asymmetry, which includes the added contribution from $V - A$ decay of W.

The lepton charge asymmetry $A(y_l)$, is defined as:

$$A(y_l) = \frac{dN_+(y_l)/dy_l - dN_-(y_l)/dy_l}{dN_+(y_l)/dy_l + dN_-(y_l)/dy_l}, \tag{4}$$

where $N_\pm$ are observed numbers of leptons as a function of lepton rapidity. Thus the slope of d/u ratio down to small x at $Q^2{=}M_W^2$ is related to the lepton charge asymmetry from W decays modified by the well understood $V - A$ decay of W bosons to leptons. A comparison between the of W charge asymmetry and W decay lepton charge asymmetry as a function of rapidity y is shown on Figure 1.

In order to measure the lepton charge asymmetry, both good momentum resolution and lepton charge determination are required. In the case of the D0 detector [9] only the $W \to \mu\nu$ decay channel can be used. In CDF [8] several channels are used including the muon decay

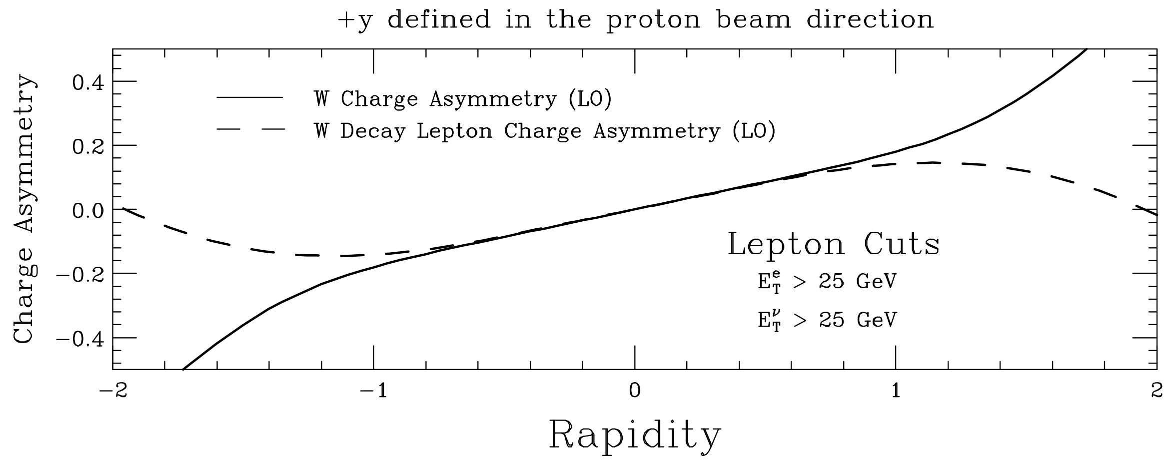

Figure 1: Comparison of W charge asymmetry and W decay lepton charge asymmetry as a function of rapidity y. The W asymmetry is a function of only y and $\sqrt{s}$. The lepton asymmetry is additionally a function of the kinematic cuts and used to select the events.

channel (in the central region, $|\eta| \leq 1.0$) [16] and the electron decay channel in both central and plug regions, ($|\eta| \leq 1.1$ and $1.1 \leq |\eta| \leq 2.4$ respectively).

When comparing the experimental measurement with theory, the significant dependence of the lepton charge asymmetry on the lepton E_t cut (and the weaker dependence on missing E_t cut) must be taken into account. In the comparison of data with theory, the CDF collaboration uses the NLO calculations with the "DYRAD" Monte Carlo simulation program. [6] The D0 collaboration uses a LO calculation with input $p_T^W(y)$ spectrum based on the NLO resummation calculation. [7]

D0 Lepton Charge Asymmetry from $W \rightarrow \mu\nu$

The D0 experiment measures the W decay lepton charge asymmetry in the $W \rightarrow \mu\nu$ channel. The data sample consists of 6.5 pb^{-1} taken during 1992/93 run and 29.7 pb^{-1} recorded during 1994/95 run. The charge of the μ is determined by toroidal magnets in the muon detector system. The $W \rightarrow \mu\nu$ event candidates are required to have $P_t^\mu >$20 GeV and missing $E_t >$20 GeV.

In case of the D0 measurement, muon charge mis-identification dilutes the charge asymmetry. This systematic effect is estimated from number of same sign pairs in $Z \rightarrow \mu\mu$ sample. The charge misidentification probability is of $\approx 9\% \pm 5\%$ for the 1992/93 run and $\approx 3\% \pm 1.5\%$ for the 1994/95 run. In addition, the detector acceptance for two charges of muons depends on the polarity of the toroids (forward vs reverse). Therefore for the fraction of data with unbalanced luminosity in forward vs reverse magnet polarization mode ($\approx 20\%$ in the 1992/93 run and 1.5% for the 1994/95 run) the measured charge asymmetry is corrected for this bias.

Figure 2 shows the D0 preliminary W charge asymmetry measurement. The data is compared with the theoretical predictions using leading order calculation with input p_T of W spectrum based on NLO resummation calculation. [7] As the figure indicates, the data are consistent with modern PDFs, but are unable to distinguish between various PDFs.

CDF W Charge Asymmetry Measurement

The CDF asymmetry analysis makes use of both $W \rightarrow e\nu$, and $\mu\nu$ events. These events are selected by requiring the e's and μ's be isolated, identified, and well tracked, and have

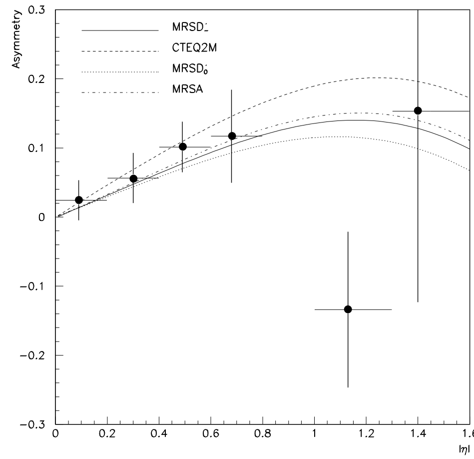

Figure 2: D0 Preliminary W decay lepton charge asymmetry in the $W \rightarrow \mu\nu$ channel. The data sample consists of 6.5 pb^{-1} taken during 1992/93 run and 29.7 pb^{-1} recorded during 1994/95 run. The lines correspond to the theoretical predictions using several modern Parton Distribution Functions.

transverse energy $E_T > 25\ GeV$. The missing transverse energy of the event in the calorimeter and muon system must be $\not{E}_T > 25\ GeV$. In order to suppress QCD backgrounds, events with a jet with $E_T > 20 GeV$ are rejected. In CDF, the acceptance and efficiencies for detecting l^+ and l^- are equal, and the charge asymmetry $A(\eta)$ reduces to the difference in the number of l^+ and l^- over the sum of the two. Since CP invariance implies $A(+\eta) = -A(-\eta)$, the data at $-\eta$ is combined with that at $+\eta$ to increase the statistics in each η bin. In CDF, the systematic errors are negligible relative to statistical errors and corrections to the raw measurement are small (5% or less). Hence, the asymmetry measurement is very robust.

The CDF collaboration has previously published a W charge asymmetry study using the 1992-93 data, [5] which was able to distinguish between modern PDFs and place tight constraints on these functions. A comparison of the lepton charge asymmetry measured by CDF with predictions from Parton Distribution Functions available prior to the publication of CDF measurement is shown on Fig. 3. The CDF measurement favored the MRS fits over the CTEQ2 PDF's.

The W charge asymmetry is particularly sensitive to the slope of the d/u ratio versus x, [1,2] whereas the $F_2^{\mu n}/F_2^{\mu p}$ measurements are sensitive to the magnitude of this ratio as well as to the quantity $\overline{u} - \overline{d}$. The NMC collaboration has published measurements of $F_2^{\mu n}/F_2^{\mu p}$ [10] over an x range comparable to that accessible at CDF (although at much lower Q^2). The NMC data [11,3] were used to constrain d/u in the most recent parton distribution fits. For easier comparison of the d/u slopes, Figure 4b shows the d/u ratios shifted by a constant such that they agree with MRS D$'_0$ at $x = 0.2$. The distributions which predict the largest average slope of the d/u ratio over the x range $0.007 - 0.24$, also predict the largest charge asymmetry. One sees that even though the MRS and CTEQ PDFs were both determined by fitting to the same $F_2^{\mu n}/F_2^{\mu p}$ data, the fits result in a different d/u distributions and thus very different charge asymmetry predictions. This is because $F_2^{\mu n}/F_2^{\mu p}$ is also sensitive to the differences in

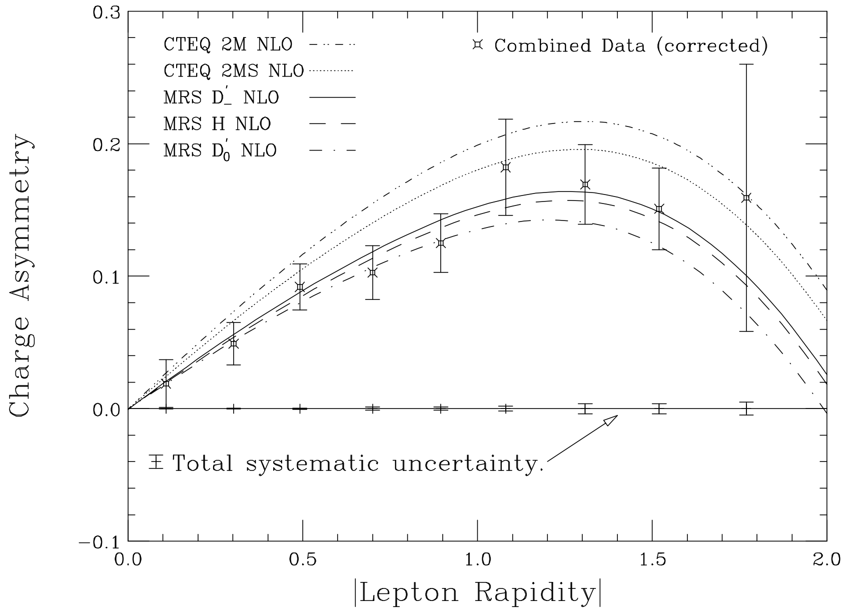

Figure 3: A comparison of the lepton charge asymmetry measured by CDF with predictions using Parton Distribution Functions available prior to the publication of the CDF 1992/93 measurement.

the $\overline{u}$ and $\overline{d}$ distributions, whereas the $A(y_l)$ asymmetry is not as sensitive. The old CTEQ2's parameterization of the $\overline{u}$ and $\overline{d}$ sea distributions compensates for a steep d/u ratio [12] and leads to a prediction for $F_2^{\mu n}/F_2^{\mu p}$ which is consistent with the NMC data but is much less consistent with the $A(y_l)$ measurement.

In this communication, the W charge asymmetry analysis from the 1992-93 data($\approx$ 20 pb^{-1}), and the first $\approx$ 50 pb^{-1} of data in central detector region($|\eta| < 1.1$) from the 1994-95 run is presented. The larger statistical sample results in a factor of 2.5 reduction in the overall error in the central detector region relative to the previous analysis.

The theoretical predictions for $A(\eta)$ are calculated from the DYRAD [6] program which employs next to leading order (NLO) QCD partonic cross section calculation. NLO parton distribution functions (PDF), and the well-known, purely leptonic V-A decay of the W are used as input. Experimental cuts and detector effects are included in the calculations. Figure 5 shows the recent CDF results compared to the asymmetries predicted by the most recent PDF's from Martin, Roberts and Stirling (MRS) [12] , the CTEQ [13] collaboration and Gluck, Reya and Vogt. [14] These last three PDF's included the 1992-93 published CDF asymmetry data in their global fits. The theoretical curve for GRV94 is taken from Fig. 3 of the paper. [15] It is found that with the much reduced statistical error in this analysis these most recent PDF's are still in good agreement with the 1993-94 CDF data. To quantify the data's discriminating power to the various predictions, Table 1 shows the goodness of fit χ^2 over seven η bins ($0.2 < |\eta| < 1.7$) and the χ^2 test of the error weighted mean difference ($\Delta\overline{A}$) of the seven data points against the predictions from various PDF's.

Figure 6 shows a comparison of lepton charge asymmetry measured by CDF and the D0 experiments, and also the predictions using most recent Parton Distribution Functions.

By restricting the shape of PDF's, the W asymmetry measurement has significantly reduced the systematic uncertainty in the W mass measurement. The dependence of the fitted W mass on the choice of PDF's is strongly correlated with predictions of the PDF's for the

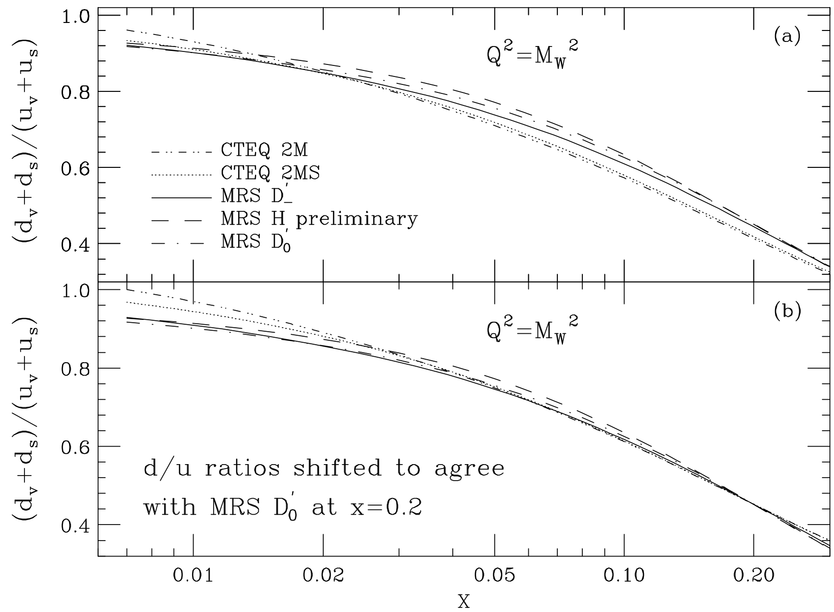

Figure 4: (a) The d/u ratios for various parton distributions.
(b) The d/u ratios of various PDFs after they have been shifted to agree with MRS D_0' at x=0.2; those which have the largest average slope predict the largest asymmetry.

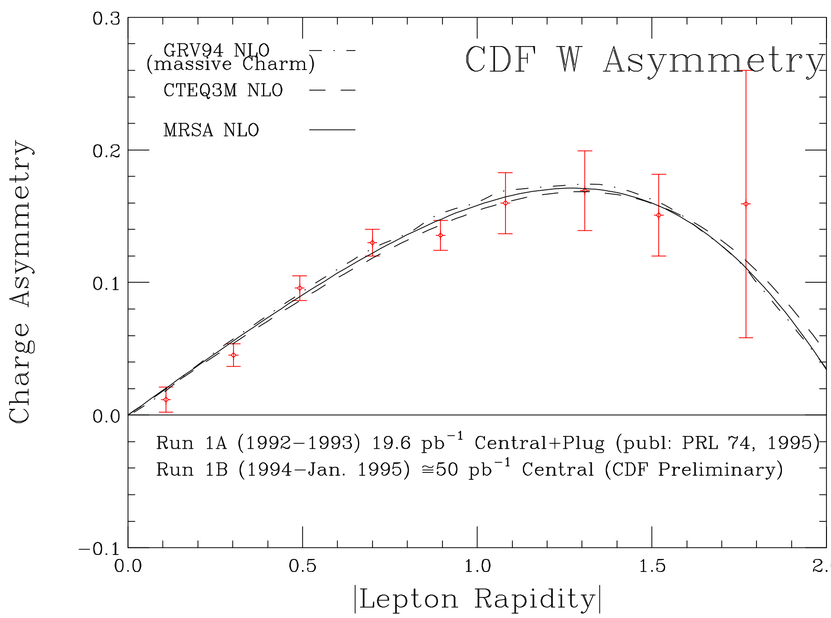

Figure 5: Comparison of lepton charge asymmetry measured by CDF with predictions using Parton Distribution Functions available after the publication of CDF measurement (Phys. Rev. Lett, **74**, 95.)

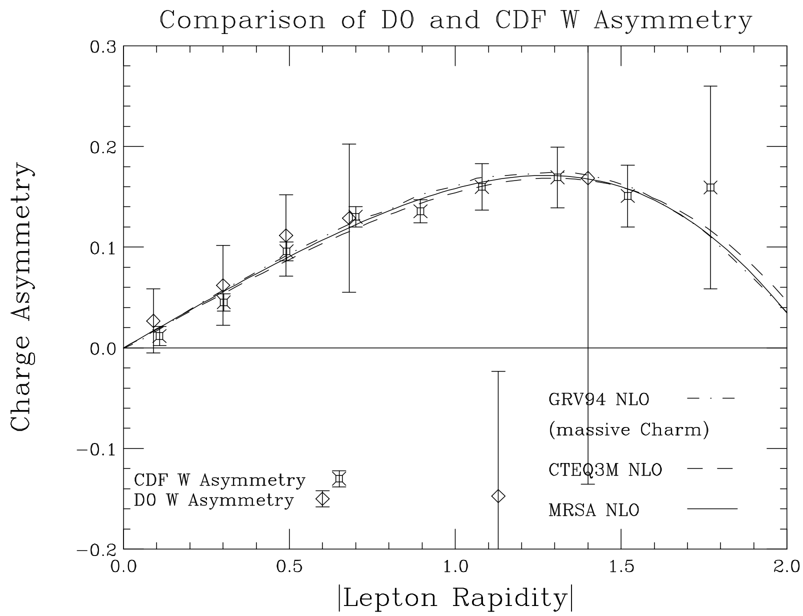

Figure 6: Comparison of lepton charge asymmetry measured by CDF and D0 experiments with predictions using most recent Parton Distribution Functions.

W charge asymmetry. The published 1992-93 CDF results for the W asymmetry from Run 1A have been used as a guide in reducing the the uncertainty from the choice of PDF's used in the W analysis. Fig. 7 shows the correlation between the ΔM_W (in MeV) and $\Delta\sigma_{\overline{A(\eta)}}$, the deviation between average measured asymmetry and the PDF predictions. The 1992-93 asymmetry measurement allowed CDF to reduce systematic uncertainty on M_W due to PDF's from 100 MeV, of only DIS data are used, to 50 MeV (2σ error), when the W asymmetry constraints are included.

CDF Preliminary Measurement of Drell-Yan Production

The Drell-Yan events are easily reconstructed from the measured properties of the decay leptons. The differential Drell-Yan cross section provides information on the magnitude of the quark distributions in the x range 0.006-0.03 over a Q^2 range of 121-3600 GeV^2. The CDF collaboration has published [17)] the differential cross section $d^2\sigma/dMdy_{|y|<1}$, over the mass range $11 < M < 150$ GeV/c^2 using dielectron and dimuon data from 1988-89 collider run (≈ 4 pb^{-1}). The results show $1/M^3$ dependence as is expected from naive Drell-Yan model. The measurement favored those distributions which have the largest quark contribution in the x interval 0.006 to 0.03, in particular the sets which used the most recent DIS data. However, as was the case for the 1988-89 W asymmetry data, the statistics were limited.

Figure 8 presents the CDF preliminary results of the Drell-Yan cross-section measurement using high mass dielectron events collected during 1992/93 run and very high mass dimuon events collected during 1992/93 and 1994/95 runs. The measured cross sections agree well with LO predictions, after correction for higher order diagrams (K factor), for Z+Drell-Yan processes.

Conclusions and Outlook

New preliminary results from CDF using 1994-95 Run, central region data ($|\eta| \leq 1$) are consistent with 1992-93 W asymmetry published results. Preliminary W-asymmetry measurement by the D0 is consistent with modern Parton Density Functions (MRS A, CTEQ 2M),

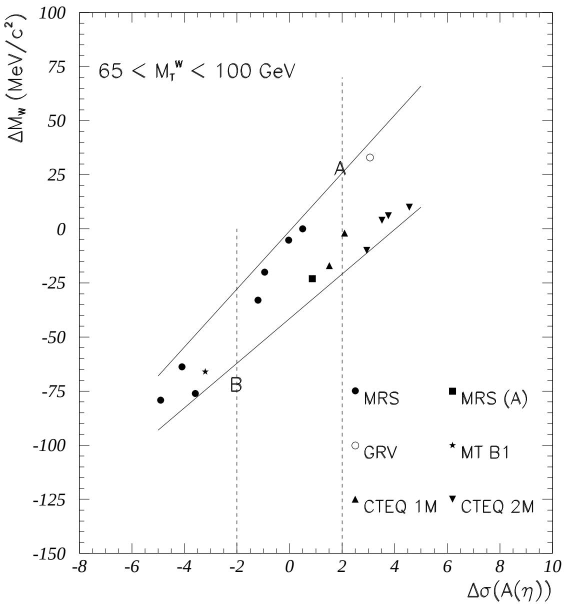

Figure 7: The correlation between the ΔM_W (in MeV) and $\xi = \Delta\sigma_{\overline{A(\eta)}}$, the deviation between average measured asymmetry and the PDF predictions. The M_T^W regions for the W mass fitting is $65 < M_T^W < 100$ GeV. The area between solid lines covers all the points and the dashed lines denote $\pm$ 2 $\Delta\sigma_{\overline{A(\eta)}}$. The W mass measurement uncertainty due to PDF's is taken to be half of the two extreme values in the area within $\pm$ 2 $\Delta\sigma_{\overline{A(\eta)}}$. The figure shows the correlation for $W \to e\nu$ decay channel.

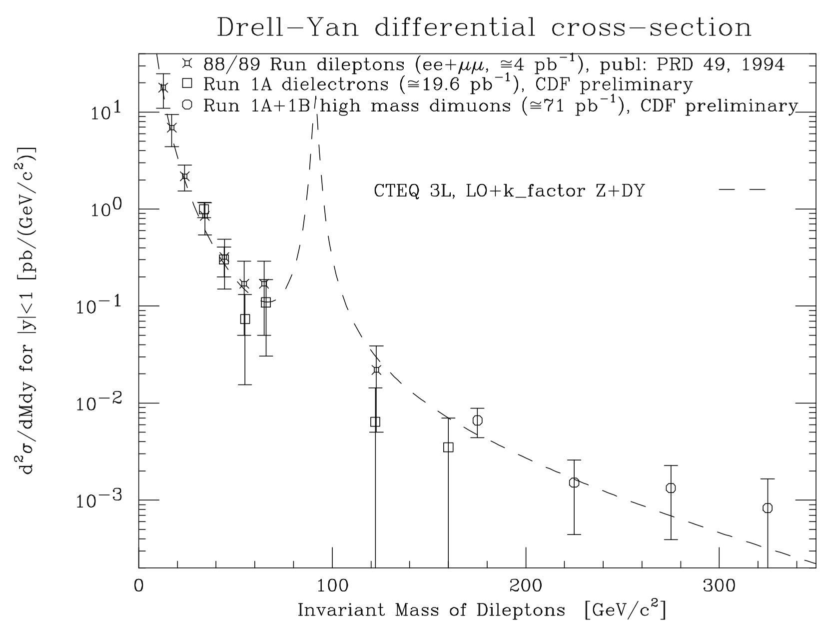

Figure 8: Drell-Yan dilepton pair production cross section for the 1988-89 (4 pb^{-1}) data (star symbols) and preliminary CDF results from 1992/93 run (square symbols), corresponding to 20 pb^{-1}) of data and high mass dimuon data for 1994/95 run (circle symbols), corresponding to 70 pb^{-1} of data.

but as yet can not select PDF's unambiguously. By restricting the shape of PDF's, the W asymmetry measurement has significantly reduced the systematic uncertainty in the W mass measurement.

By the end of 1995, Both CDF and D0 will have a much larger data sample. CDF in particular should have accumulated $\approx 100\ pb^{-1}$ data. W lepton charge asymmetry measurement at CDF is dominated by statistical error and will be further improved and provides tight contraint on parton density functions. In the future it is clear that the charge asymmetry will be able to play an even more significant role in the determination of the proton's structure.

The preliminary Drell-Yan cross-section measurement is in good agreement with most recent PDFs over dilepton mass range between 11 and 350 GeV/c^2. More quantitative tests are underway for 1992/93 and 1994/95 Drell-Yan data sets, including binning data in y in addition to mass bins.

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16. The pseudorapidity, $\eta = -\ln\tan(\theta/2)$, is the rapidity for a massless particle.
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Table 1: CDF data includes 1992/93 and 1994/95 central data sets. The results of χ^2 and the weighted means ($\overline{A}(y)$) comparisons for various recent PDFs. The weighted means are sensitive to the different systematic shifts which are predicted by each PDF. The MRSA , CTEQ3M and GRV94 (*) included the CDF 1992-1993 data in their global fits.

	$0.2 < \|y\| < 1.7$ ($7\ dof$)		$\overline{A}(y)$ $0.2 < \|y\| < 1.7$	
PDF Set	χ^2	$\mathcal{P}(\chi^2)$	$\Delta\sigma$	$\mathcal{P}(\sigma^2)$
CTEQ 3M*	4.0	0.781	-0.16	0.875
CTEQ 2M	53.1	<0.001	6.7	<0.001
CTEQ 2MS	21.5	0.003	4.0	<0.001
CTEQ 2MF	35.6	<0.001	5.5	<0.001
CTEQ 2ML	31.2	<0.001	5.1	<0.001
MRS A*	3.9	0.789	0.5	0.621
MRS H	6.5	0.480	-0.9	0.352
MRS D'_{-}	5.1	0.650	-0.01	0.990
MRS D'_{0}	12.5	0.085	-2.3	0.024
GRV94*	5.5	0.605	1.3	0.187
GRV92	9.9	0.193	2.5	0.012