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presented at the Riken-BNL spin meeting
1/12/99

W Charge Asymmetry at the Fermilab Tevatron

Publication/Reference List

- Publications:
  - CDF (Run 1a, 1992-1993)
    PRL 74, 850 (1995); Fnal-Pub-94/313-E
  - CDF (Run 1a + 1b, 1992-1995)
    PRL 81, 5754 (1998) ; Fnal-Pub-98/256-E
- Conf. Proceedings:
  - W. Sakumoto (CDF), proc. of ICHEP'98 (7/98)
    Fnal-Conf-98/298-E
  - G.Guglielmo (D0), proc. of PIC'97 (6/97)
    Fnal-Conf-97/235-E
- Transparencies:
  on WWW: Fnal - D0 - results - Electroweak - QCD with W/Z
  - G. Guglielmo - presented at PIC'97
  - D0 W asymmetry plot shown at DPF'96

Introduction to Measurement

$p(900 \text{ GeV}) \longrightarrow \qquad \longleftarrow \bar{\text{p}}(900 \text{ GeV})$

Primary W production at Tevatron:

$$W^+ : \quad u\bar{d} \rightarrow W^+ \rightarrow l^+\nu$$

$$W^- : \quad d\bar{u} \rightarrow W^- \rightarrow l^-\nu$$

with $l = e, \mu$. Of course, contribution from sea too.

Since u quark carries larger fraction of p momentum than d
Then on average:
W^+ boosted (i.e. preferentially produced) in p direction
W^- boosted in $\bar{p}$ direction

Therefore, W production charge asymmetry as function of rapidity, y, is related to difference in u and d quark momentum distribution.

$$A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}$$

Introduction to Measurement - cont.

$$A_W(y) \propto \frac{d/u(x_1) - d/u(x_2)}{d/u(x_1) + d/u(x_2)}$$

where x_1 is fraction of momentum carried by the q in the p and x_2 is fraction of momentum carried by the q in the $\bar{p}$

This asymmetry provides sensitive measure of relative shape of u and d quark momentum distribution.

W asymmetry data provides stronger constraints on d/u ratio than $F^{\mu n}/F^{\mu p}$ which is limited by uncertainties in corrections. $F^{\mu n}/F^{\mu p}$ is sensitive to the magnitude of d/u and to $\bar{u} - \bar{d}$.

Figure 1

from "QCD & Collider Physics", Ellis, Stirling & Webber, 1996
Cambridge Univ. Press

Theory Prediction

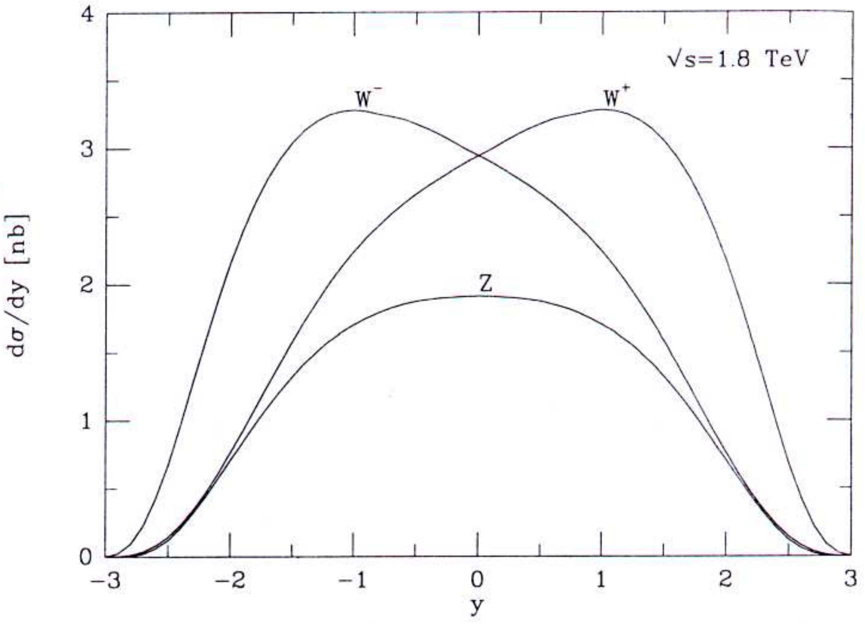


Fig. 9.7. W^+, W^- and Z rapidity distributions in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV.

Introduction to Measurement - cont.

However...

$W \to e\nu, \mu\nu$
- can't measure $p_z(\nu)$ and therefore can't measure y_W

Therefore, you first determine it's a W and then measure the decay-lepton charge asymmetry instead.

$$A_l(y) = \frac{d\sigma(l^+)/dy - d\sigma(l^-)/dy}{d\sigma(l^+)/dy + d\sigma(l^-)/dy}$$

- $A_l(y)$ is a convolution of W production charge asymmetry & V-A asymmetry from the W decay
- The V-A asym. is well-measured by $\mu-$decay experiments and is already in PDFs
- The V-A interaction causes the $e^-(e^+)$ from the decay of the $W^-(W^+)$ to be emitted preferentially along the incoming $q(\bar{q})$ direction
- This is opposite the direction of the W production and therefore this washes out the asymmetry somewhat.

If acceptance, efficiency and luminosity for l^+, l^- are equal, then:

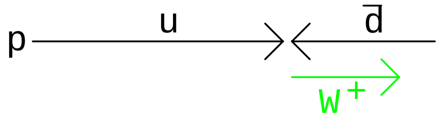
$$A_l(y) = \frac{N^+/dy_l - N^-/dy_l}{N^+/dy_l - N^-/dy_l}$$

From CP invariance, we have:

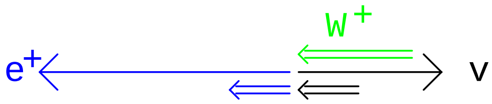
$$A(+y) = -A(-y)$$

Figure 2 - lepton vs W asymmetry

W production is asymmetric:



V-A decay: opposite asymmetry



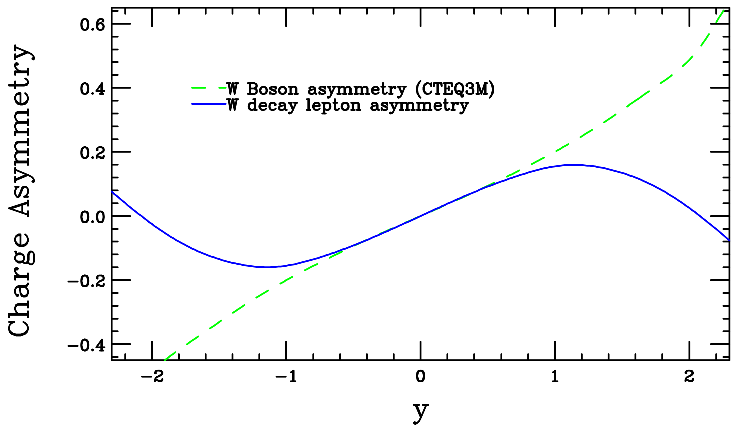


Figure 3 - Table I, from Fnal-Pub-98/256-E

TABLES

TABLE I. The mean x values of the d and u parton distributions probed by the CDF asymmetry data for the W^+ boson as a function of the lepton rapidity. The $\frac{d}{u}$ ratios from the CTEQ-3M parameterization are shown for these x values. The mean x values for the W^- at positive y_l are the same as those for the W^+ at the same negative y_l.

$\langle y_l \rangle$	$\langle x_u \rangle$	$\langle x_d \rangle$	$\frac{d}{u}(x_u)$	$\frac{d}{u}(x_d)$
−2.20	0.009	0.219	0.911	0.412
−1.54	0.016	0.129	0.864	0.542
−1.10	0.021	0.088	0.837	0.625
−0.49	0.038	0.051	0.765	0.722
0.00	0.044	0.044	0.744	0.744
0.49	0.099	0.021	0.601	0.837
1.10	0.165	0.012	0.483	0.889
1.54	0.225	0.009	0.405	0.911
2.20	0.335	0.006	0.306	0.936

TABLE II. Backgrounds (%) in the $W \to e\nu$ and $W \to \mu\nu$ charge asymmetry event samples.

Sample	QCD dijets	$Z \to e^+e^-$ or $\mu^+\mu^-$
Central e	0.7 ± 0.2	< 0.2
Central μ	0.6 ± 0.2	4.7 ± 0.7
Plug-SVX e	1.6 ± 0.3	< 0.2
Plug-CTC e	2.4 ± 0.6	< 0.2
Forward μ	4 ± 2	6.5 ± 0.6

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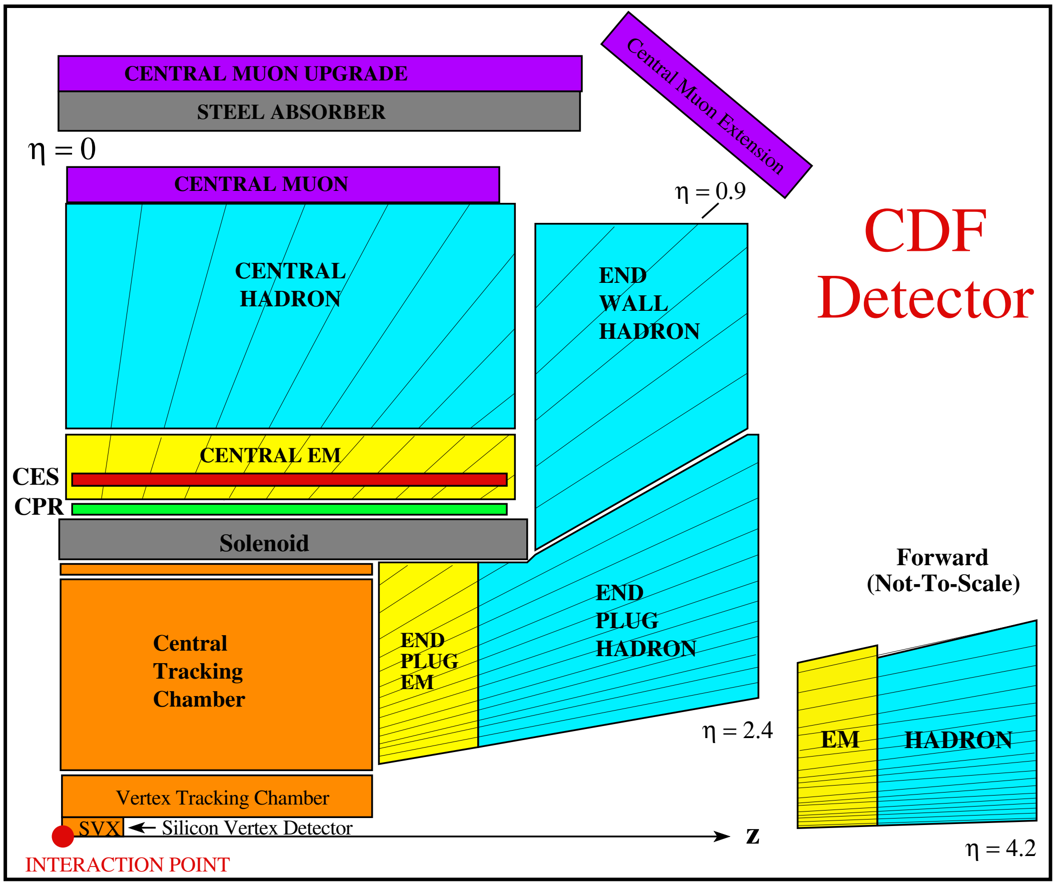
Figure 4 - CDF detector, Run 1



CDF Detectors

These detectors used in Run 1a & 1b measurements:

- central calorimeter, $|y| < 1.1$
  - used to measure electron energy & mip (μ)
- plug calorimeter, $1.1 < |y| < 2.4$
  - used to measure electron energy & mip (μ)
- VTX: vertex time projection chamber
  - used to get z of primary vertex
- CTC: central tracking chamber, $|y| < 1.8$
  - used to measure curvature of e & μ
- SVX: silicon vertex detector, used at $1.2 < |y| < 2.3$
  - used to complement CTC measurement at high y
- CMU,CMX: central μ chambers, $|y| < 1.0$
- FMU: forward μ detector, $1.9 < |y| < 3.5$
  - two toriods between 3 drift chambers

Event Selection

To measure the lepton asymmetry from W production, the events are first identified as being from $W \to l\nu$.

" Reliable charge determination and good energy measurement of the lepton is essential for this analysis".

Trigger & Event selection requirements:

1. charged track pointing at either calorimeter EM energy deposition or hits in μ-chambers – accompanied by large missing-E_T
2. $e \to$ fiducial volume of calorimeter plus shower profile req.
   $\mu \to$ track in μ-chamber and mip signal in calorimeters
3. $E_T(l) > 25$ GeV
4. missing-$E_T > 25$ GeV
5. remove events containing a jet with $E_T(jet) > 30$ GeV to remove background

Data Sample

Run 1a + 1b analysis used 5 data samples:

central e's with CTC track - $|y| < 1.1$

central μ's with CTC track - $|y| < 1.0$

plug e's within SVX with SVX track - $1.1 < |y| < 2.4$ [*,†]

plug e's outside SVX & have CTC track - $1.1 < |y| < 1.8$

forward μ's - $1.9 < |y| < 2.5$ [†]

TOTAL # events = 88047

[*] New charge determination technique used in 1a+1b analysis

[†] Not used in 1a-only analysis

Corrections

$\Longrightarrow$ Trigger Effects

The charge or E_T dependence of each trigger was measured using independent triggers.

- find no charge dependence in electron and central μ data
- forward μ data taken with toroid polarity set for μ^+ and μ^- are averaged to cancel effects of charge bias in trig.
- plug electron efficiency not dependent on charge but falls to 78% at $E_T = 25$ GeV
  $\rightarrow$ apply correction determined using MC calc. and measured efficiency as function of E_T and y_l
  $\rightarrow$ The overall correction to $A_l(y)$ is $< .005$, compared to stat. error of $.015$

Biases

$\Longrightarrow$ Biases in Event Selection
To look for charge bias, select high-E_T leptons from W or Z events with tight kinematic constraints.

- No charge dependent bias in acceptance or efficiencies found
- central μ's charge mis-ID negligible
- forward μ's charge mis-ID $< 1\%$
- electron charge mis-ID determined (central) from rate of same-sign Z electrons
  - rate is 0.2% (central) and 10% (forward - in largest y bin)

Effects of charge mis-ID dilutes asymmetry and are corrected for on bin-by-bin basis.

Backgrounds

$\Longrightarrow$ Backgrounds due to misidentified dijets or Z's, etc.

- average $W \rightarrow \tau\nu = 2.0 \pm 0.2\%$
- cosmic-ray bkgnd in μ sample is $< 0.2\%$
- $Z \rightarrow \tau\tau$ negligible
- $Z \rightarrow ee$ negligible
- plug (forward) electron sample:
  - bkgnd from mis-ID dijets is largest - charge symmetric
- central electron sample:
  - mis-ID $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$ largest

  central μ sample:
  - mis-ID $Z \rightarrow \mu\mu$ largest, where one μ outside acceptance

  $\Rightarrow$ these are not charge symmetric ... corrections are made using asymmetry estimates from MC
- forward μ sample:
  - bkgnd from $\rightarrow \mu\mu = 6.5\%$
  - charge symm. bkgnd is 8% due to dijets and mis-reconstructed lower-p_T muons

$A_l(y)$ values are corrected for backgrounds bin-by-bin

Figure 5 - Table II, from Fnal-Pub-98/256-E

TABLES

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Results - CDF Run 1a (publ. 1995)

- data taken 1992-1993
- luminosity 20 pb^{-1}
- $|y_l| < 1.8 \rightarrow .007 < x < .24$ at $Q^2 \approx M_W^2$
- data sample: central and forward e's and central μ's

$\rightarrow$ Figures show comparisons to NLO theory prediction:
- DYRAD (Giele *et al.*, Nucl Phys. **B** 403 (633) 1993.)

$\rightarrow$ The asymmetry measurements *are not included in PDFs shown*

$\rightarrow$ MRS & CTEQ both used the same data from NMC to fit PDFs

$\rightarrow$ MRS distributions are favored over CTEQ2

Figure 6 - from Fnal-Pub-94/313-E

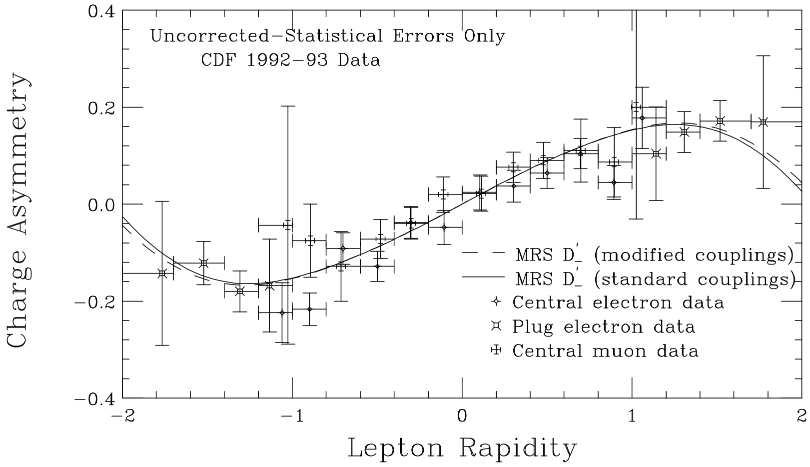

Figure 1: The charge asymmetry before applying any corrections found in each of the detector types (Central EM, Plug EM and Central Muon). Also shown (dashed line) is the effect of allowing the W couplings to go to their 90% C.L. limits.

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Figure 7 - from Fnal-Pub-94/313-E

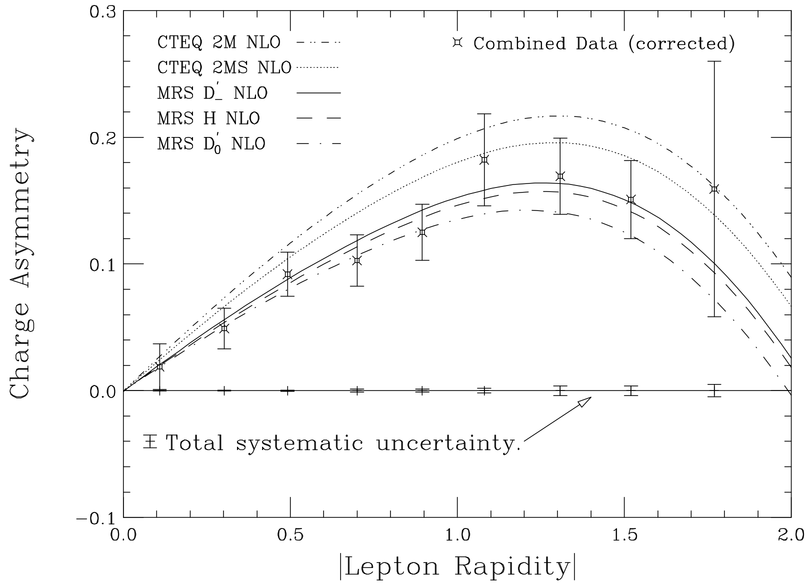

Figure 2: The fully corrected charge asymmetry after the data from the various detectors are combined and folded about $y = 0$. The error bars along the x-axis show the total systematic errors associated with each bin.

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Figure 8 - from Fnal-Pub-94/313-E

Table III: The χ^2 comparisons between the predicted asymmetries (calculated at NLO) for several NLO PDFs including the most recent MRS and CTEQ distributions. The comparison of the weighted means, $\overline{A}(y_l)$ indicates the MRS H distributions fit the asymmetry data best. The very recent PDFs (CTEQ3 and MRS A) are not included in the comparison, since the CDF asymmetry data was included in these fits.

	$0.2 < \lvert y_l \rvert < 1.7$		$\overline{A}(y_l)$	
PDF Set	χ^2 (7 dof)	$\mathcal{P}(\chi^2)$	$\Delta\sigma$	$\mathcal{P}(\sigma^2)$
CTEQ 2M	24.	< 0.01	4.6	< 0.01
CTEQ 2MS	11.	0.15	2.9	< 0.01
CTEQ 2MF	17.	0.02	3.8	< 0.01
CTEQ 2ML	15.	0.04	3.5	< 0.01
CTEQ 1M	6.1	0.52	2.1	0.04
CTEQ 1MS	3.9	0.79	1.5	0.13
MT B1	17.	0.02	-3.2	< 0.01
MRS H	1.8	0.97	-0.1	0.96
MRS D'_-	1.9	0.97	0.5	0.61
MRS D'_0	3.6	0.83	-0.9	0.35
HMRS B	4.2	0.75	-1.2	0.23
KMRS B_0	19.	0.01	-3.6	< 0.01
MRS E'	30.	< 0.01	-4.9	< 0.01
MRS B'	24.	< 0.01	-4.1	< 0.01
GRV NLO	12.	0.12	3.0	< 0.01

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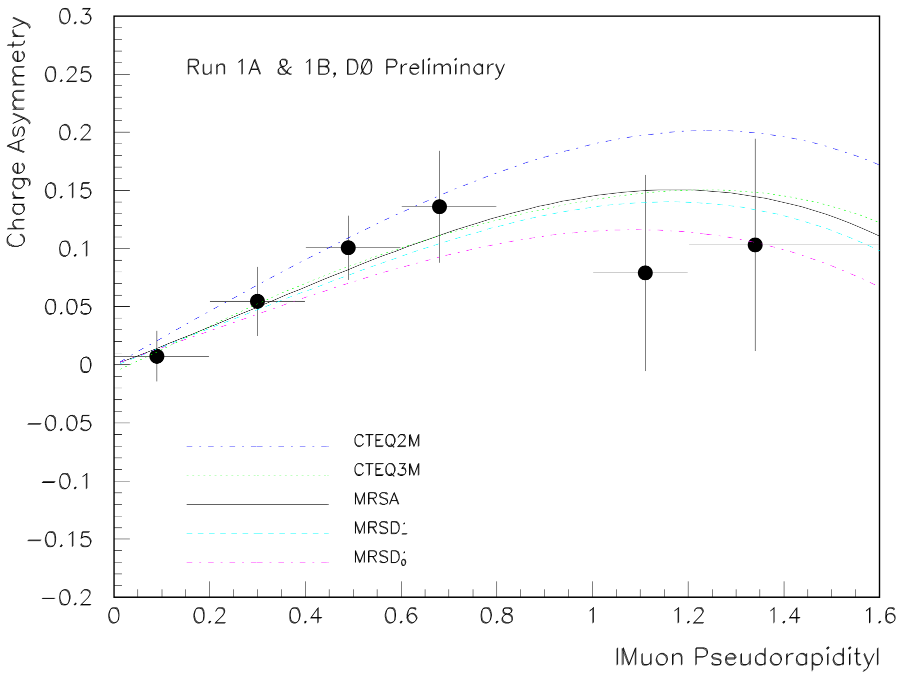
After Run 1a Results:

New PDF distributions calculated using W production charge asymmetry measurements:

CTEQ3M, MRSA, MRS-R2

Figure 9 - DØ W Asymmetry



Results - CDF Run 1a+1b (submitted to PRL, 10/98)

- data taken 1992-1995 (supersedes previous result)
- luminosity $110 \pm 7\ \mathrm{pb}^{-1}$
- $|y_l| < 2.4 \rightarrow .006 < x < .34$ at $Q^2 \approx M_W^2$
- data sample: central and forward e's and μ's

Preliminary Results (7/97 figures):

$\rightarrow$ show comparisons to NLO theory prediction - DYRAD

$\rightarrow$ CTEQ3M, MRSA, MRS-R2 include the previous measurements and agree with new results out to $|y_l| < 1$

Figure 10a - page 2, from Fnal-Conf-97/235-E

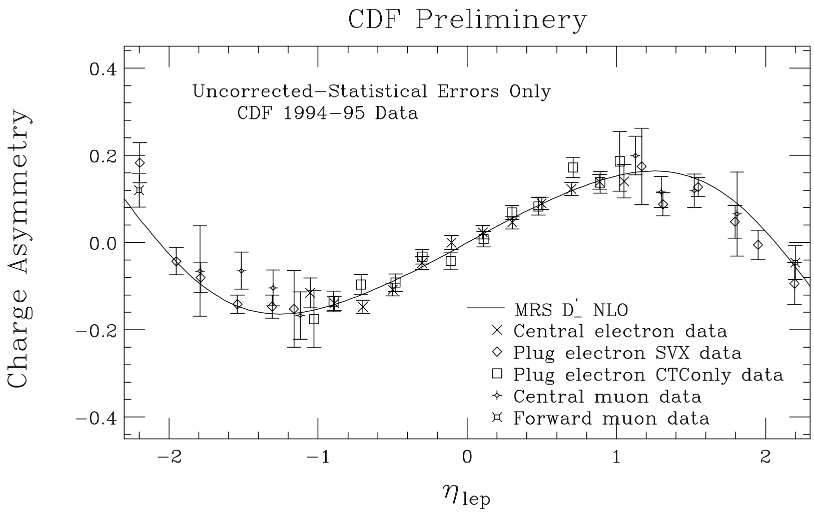


Figure 1: The CDF W charge asymmetry measurement as a function of rapidity before corrections were applied.

where $dN_{l^+}/dy_l(dN_{l^-}/dy_l)$ is the number of leptons $l^+(l^-)$ at a given lepton rapidity; the acceptance, efficiencies, and luminosity cancel. In addition, CP invariance requires that the asymmetry at y_l be equal and opposite to the the asymmetry at $y_l' = -y_l$. Therefore the asymmetries at equal but opposite y_l can be combined to reduce the effects of any differences in efficiencies for detecting the oppositely charge leptons.

The CDF data comes from 20pb^{-1} and 91pb^{-1} from the 1992-1993 and 1994-1995 collider runs respectively for both the electron and muon channels. The latter run greatly increases the data at forward rapidity and extends the rapidity range [2] over the earlier published results [1].

The direction of curvature of charged tracks in the CDF detector due to the magnetic field allows for the determination of the charge of the particle which made the track. The transverse energy of the lepton (E_T^l), and the missing transverse energy ($\not\!\!E_T$) of the event are both required to be greater than 25 GeV. The electrons are required to have $|\, y_e \,| < 1.1$ or $1.1 < |\, y_e \,| < 2.4$. The muons were required to be in the muon tracking system ($|\, y \,| < 1.0$), which was extended to $1.9 < |\, y_\mu \,| < 2.5$ in the forward region for the 1994-1995 run. Additionally, a requirement of no jets with ${E_T}^{Jet} > 30$ GeV was imposed to reduce the dijet background. Other quality cuts were also imposed.[1].

The new CDF preliminary results for the W charge asymmetry are shown (see Figure 1) compared to next-to-leading order (NLO) theory, calculated with

Figure 10b - page 3, from Fnal-Conf-97/235-E

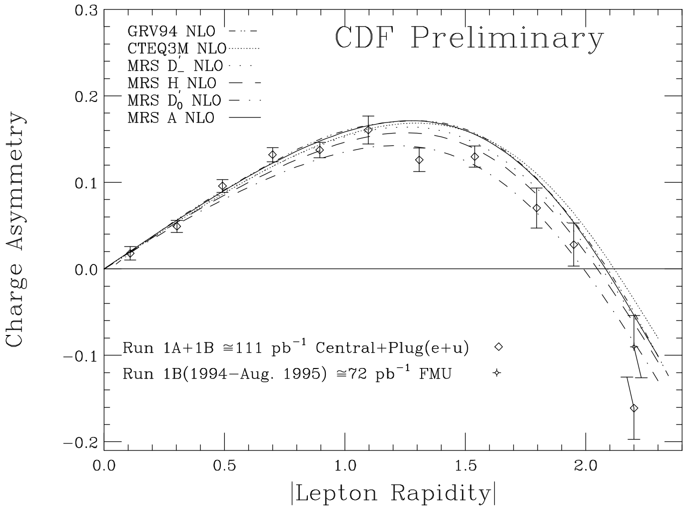


Figure 2: The corrected CDF W charge asymmetry as a function of rapidity folded about a rapidity of zero ($y = 0$). The total systematic errors for each bin are plotted on the x-axis.

the DYRAD [3] Monte Carlo, using various parton distribution functions (pdfs) from both the CTEQ[4] and MRS[5] families, unfolded in rapidity. Figure 2 shows the W charge asymmetry with asymmetries at equal and opposite rapidities combined. The differences between theory and data in the forward rapidity region indicates that the d/u quark ratio embodied in the pdfs may need to be adjusted. Constraints on the W charge asymmetry from the CDF data are already reducing the systematic error on measurements of the W mass due to pdfs.

2 Color Coherence in $W+$ Jets

Color coherence is the interference of color connected partons on soft gluon radiation. In jet events produced by a hard scatter, this interference can produce an angular distribution of particles which can be described using antennae patterns between the color connected partons involved.[6] Color coherence can take place in perturbative processes, where analytical calculations can be used to predict the effect, and in nonperturbative processes where phenomenological techniques must be used. In $p\overline{p} \rightarrow W+$ Jets interactions, the high Q^2 initial hard scatter can be analyzed with perturbative methods, while the low Q^2 fragmentation is in the nonperturbative regime and must rely upon phenomenology to describe the behavior.

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Results - CDF Run 1a+1b (submitted to PRL, 10/98)

Final Results:

$\rightarrow$ MRS-R2 - corrected for re-analysis of NMC data

$\rightarrow$ MRST - incorporated new CDF measurement

Note: W asymmetry mostly sensitive to d/u ratio. However, at large y, also affected by W production p_T spectrum.

Comparisons to Theory:

- DYRAD - NLO calculation
  - doesn't reproduce $p_T(W)$ distribution at low p_T
- REBOS - NLO calculation plus resummation of soft gluon emission to all orders
  - Balazs *et al.*, Phys. Lett. **B355**, 548 (1995)
  - reproduces $p_T(Z)$ spectrum at $p_T < 30$ GeV

Both DYRAD & REBOS yield identical results of $y(W)$ but different for $p_T(W)$

Figure 11 - from Fnal-Pub-98/256-E

FIGURES

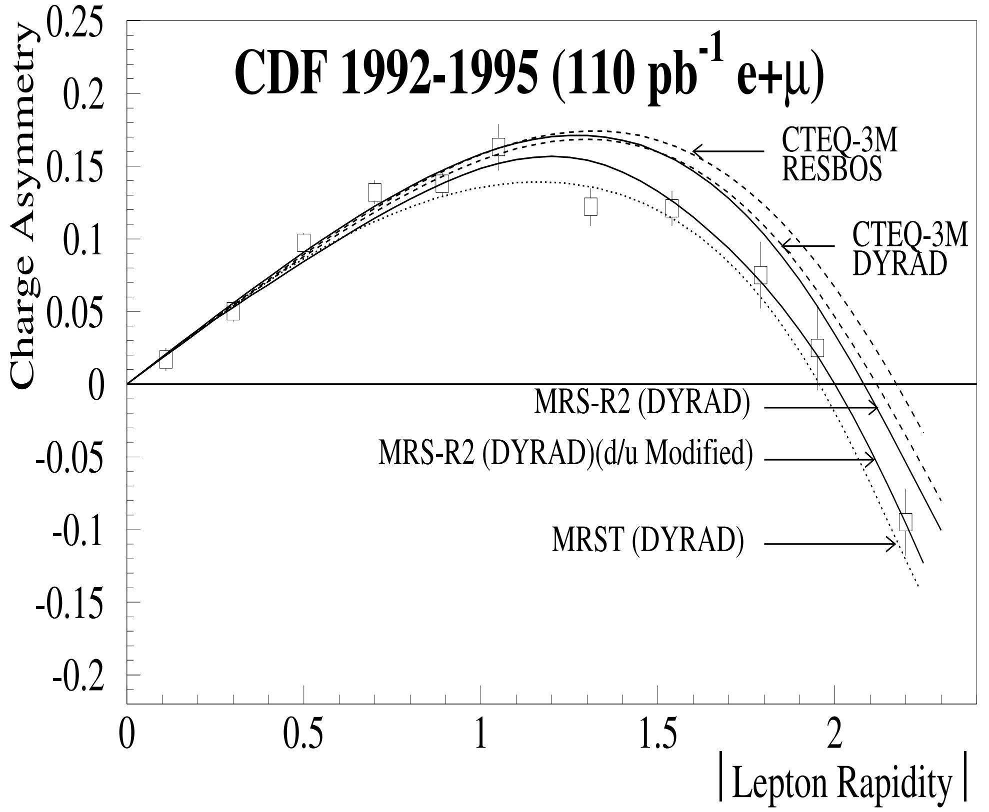

FIG. 1. The fully corrected charge asymmetry. Data from all the detectors for positive and negative y_l are combined. The statistical and systematic errors are added in quadrature.

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Figure 12 - Table III, from Fnal-Pub-98/256-E

TABLE III. The charge asymmetries (after all corrections) and statistical and systematic uncertainties in the combined e and μ channels.

$\langle \lvert y_l \rvert \rangle$	$A(y_l)$	σ_{sys}	$\sigma_{\mathrm{stat+sys}}$
0.11	0.017	±0.000	±0.008
0.30	0.050	±0.000	±0.007
0.50	0.097	±0.000	±0.007
0.70	0.132	±0.001	±0.008
0.89	0.138	±0.001	±0.009
1.05	0.163	±0.002	±0.016
1.31	0.122	±0.002	±0.013
1.54	0.121	±0.003	±0.012
1.79	0.075	±0.005	±0.023
1.95	0.025	±0.010	±0.029
2.20	−0.095	±0.015	±0.023

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Conclusions

Further modifications needed in d/u ratio of PDFs constrained by this data.

PDFs used as input to hadronic cross-sections, top quark cross-sections, W mass measurements, etc.

From CDF W asymmetry measurements:

- W mass error due to PDF uncertainty reduced from 75 to 50 MeV
- expect these data to take this error down to 20 MeV $\rightarrow$ provide tighter constraints on Higgs mass