W/Z boson asymmetry measurements at DØ

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September 22, 2008
Outline

◆ Introduction

◆ Electron charge asymmetry ($W \rightarrow e\nu$)

◆ Forward-backward charge asymmetry ($A_{FB}$) and extraction of weak mixing angle ($\sin^2\theta_W$) ($Z/\gamma^* \rightarrow ee$)

◆ Conclusions
DØ Detector

**Silicon Microstrip Tracker (SMT)**

**Central Fiber Tracker (CFT)**

2 T magnetic field

**Coverage:** $|\eta| < 3.0$

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Uranium Liquid Argon calorimeters
Central (CC) and Endcap (EC)
Coverage: $|\eta| < 4.2$
Drift chambers and scintillator counters

1.8 T toroids

Coverage: $|\eta| < 2.0$
The DØ Collaboration

Institutions: 82 total, 38 US, 44 non-US

Collaborators:
554 physicists from 18 countries

Physics:
B, EW, QCD, Top, Higgs, New Phenomena

September 2007

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Introduction

- Electroweak group → WZ group
- W and Z boson production at Tevatron

\[ l = e, \mu, \tau \]
\[ q = u, d, s, c, b \]

- Z (→ee, μμ) events are often used for detector calibration
- W/Z are backgrounds for many measurements and searches
- Make precision measurements of electroweak parameters
- Test high-order QED and QCD corrections
- Constrain parton distribution functions (PDFs)
- Search for physics beyond the SM
Z boson: Two high $p_T$ electrons
   - Both electrons are detected and their energies measured

W boson: One high $p_T$ electron, one high $p_T$ neutrino
   - Electron is detected and energy measured
   - Neutrino cannot be detected
   - $p_T(\nu)$ is inferred by the “missing $E_T$ (MET)” in the detector
Electron Charge Asymmetry
($W \rightarrow e\nu$)
PDFs describe the momentum distribution of parton in the proton

- $x$: momentum fraction of parton, $Q^2$: square of momentum transfer
- Cannot be calculated from first principles, extracted from experiments
- Parameterized at a fixed scale $Q_0$ with smooth functions with many parameters
- Apply assumptions and constraints from theory and experimental results
- Extrapolate from $Q_0$ to different $Q^2$

At least two major collaborations: CTEQ and MSTW (originally MRST)

Well constrained PDFs are essential for all studies at hadron colliders

- Expect Tevatron Run II $\Delta M_W < 15$ MeV, currently 15 MeV due to PDFs
**W Charge Asymmetry**

- **u quarks** carry on average more momentum than **d quarks** in the proton

\[
A(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}
\]

- **A(y)** sensitive to \( u(x)/d(x) \) in the proton

\[W \rightarrow e\nu \implies A(y) \text{ difficult to measure}\]

- **W asymmetry** \( \rightarrow \) **Lepton asymmetry**

\[
A(\eta) = \frac{d\sigma(l^+)/d\eta - d\sigma(l^-)/d\eta}{d\sigma(l^+)/d\eta + d\sigma(l^-)/d\eta}
\]

- \( y \approx \eta \) for leptons

- **Lepton asymmetry**: \( A(y) \otimes (V-A) \)

- The V-A structure of the \( W^{+(-)} \) decay favors a backward (forward) lepton

- Most systematics reduced due to the ratio

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x-Q^2 reach

- **W asymmetry measurement:**
  \[ Q^2 \approx M_W^2, \quad x = \frac{M_W}{\sqrt{s}} e^{\pm y_W} \]

- This measurement:
  \[ |y_W| < 3.2 \Rightarrow 0.002 < x < 1.0 \]

- Previous measurements:
  \[ |y_W| < 2.5 \Rightarrow 0.003 < x < 0.5 \]

- Complementary to central and forward jet measurements at D0 and CDF

- LHC will explore very different x-Q^2 region (low x and high Q^2)

\[ x = \text{momentum fraction of parton} \]
\[ Q^2 = \text{square of momentum transfer} \]
Electron Types

- Important to determine electron charge correctly
- High rapidity bins suffer from low statistics and higher charge mis-identification rate
- Splitting data into 4 electron types depending on the position of EM cluster, incident angle and the primary vertex
- Different track quality cuts applied for different electron types
Charge Mis-identification

◆ Charge mis-identification dilutes the asymmetry
◆ Rate measured using $Z \rightarrow e^+ e^-$ events: tight selection requirements on one electron, and check the charge of the other electron
◆ ~ 0.3% for $|\eta|<1$, ~ 9% for $2.8<|\eta|<3.2$ (CDF: 18% for $2<|\eta|<2.5$)
Electronic charge asymmetry for $E_T > 25$ GeV

- ResBos + PHOTOS

- Latest CTEQ6.6 NLO PDFs with 44 uncertainty PDF sets (P. Nadolsky et al., PRD 78, 013004 (2008))

- MRST04NLO: (A.D. Martin et al., PLB 604, 61 (2004))

- PDF uncertainties: (D. Stump et al., JHEP 0310, 046 (2003))

\[ \Delta A^\pm = \sqrt{\sum_{i=1}^{n} (A(a_i^\pm) - A_0)^2} \]

- Asymmetry measured for each electron type and then combined together
- CP invariance: $A(-\eta) = -A(\eta)$
- Fold data to increase the available statistics

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Folded charge asymmetry for $E_T > 25$ GeV

Experimental uncertainties smaller than theoretical uncertainties for all bins except the largest rapidity bin.
Electron $E_T$ Bins

- For a given $\eta(e)$, different electron $E_T$ bins probe different ranges of $y_W$
  - Higher $E_T$ bin covers a narrower $y_W$ range
  - At higher electron $E_T$, V-A distribution smaller, $A(\eta)$ is larger
- Allows a finer probe of the u and d quarks with different x

$E_T(\nu)>25$ GeV
$E_T(e)>35$ GeV
$E_T(e)>25$ GeV
$25<E_T(e)<35$ GeV

$2.8 < |\eta(e)| < 3.2$

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Electron charge asymmetry for $25 < E_T < 35$ GeV

\[ \text{Asymmetry} \]

- **DØ, L=0.75 fb}^{-1}
  - $25 < E_T < 35$ GeV
  - $E_T > 25$ GeV

\[ \eta^e \]

- **CTEQ6.6 central value**
- **MRST04NLO central value**
- **CTEQ6.6 uncertainty band**

\[ \eta^\pi \]

- **CTEQ6.6 central value**
- **MRST04NLO central value**
- **CTEQ6.6 uncertainty band**

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Electron charge asymmetry for $E_T > 35$ GeV

(a) DØ, $L = 0.75 \text{ fb}^{-1}$
$E_T^e > 35$ GeV
$E_T^\mu > 25$ GeV

(b) DØ, $L = 0.75 \text{ fb}^{-1}$
$E_T^e > 35$ GeV
$E_T^\mu > 25$ GeV
Comparison between DØ and CDF results

- **DØ (750 pb⁻¹) vs CDF (170 pb⁻¹)** (PRD 71, 051104R (2005))
- Both results agree with each other within uncertainties
- Both results indicate smaller asymmetry at high rapidity than predicted
- Larger η coverage
- Significantly smaller overall uncertainties

- Experimental uncertainties smaller than PDF uncertainties for most η bins (33 out of 36)
- Can improve the precision and accuracy of next generation PDF sets
- Request from MSTW group to use our data for MSTW2008 PDF fits

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$\chi^2$ between data and predictions

25 < $E_T(e)$ < 35 GeV

12 electron $\eta$ bins

$E_T(e)$ > 35 GeV

Prefer set 9, 13 and 15

Disfavor set 10, 14, 16, 43 and 44
Implication of our results on PDFs

$u(x)/d(x)$ at $Q = 80.4$, CTEQ6.6M

- $u(x)/d(x)$ for the PDF sets with best and worst fits to the $p_t(e) > 35$ GeV W asymmetry.
- Dashed lines are highest chisquare (> 160)
- Solid colored lines are lowest chisquare (< 80)
- Thick black line is the central fit (chisquare = 113)
- There are 12 degrees of freedom

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Implication of our results on PDFs

\[ \frac{u(x)}{d(x)} \text{ over } \frac{u(x, \text{set 0})}{d(x, \text{set 0})} \text{ at } Q=80.4 \text{ GeV} \]

\[ \frac{u(x)}{d(x)} \text{ relative to the central PDF sets for the PDF sets with best and worst fits to the } pt(e) > 35 \text{ GeV } W \text{ asymmetry.} \]

Dashed lines are highest chisquare (> 160)

Solid colored lines are lowest chisquare (< 80)

Thick black line is the central fit (chisquare = 113)

There are 12 degrees of freedom

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$A_{FB}$ measurement and extraction of $\sin^2 \theta_W^{\text{eff}}$

$(Z/\gamma^* \rightarrow ee)$
Z/γ* Forward-backward asymmetry

◆ q¯q → l⁺l⁻: mediated by γ*, Z and Z/γ*

Vector coupling

FORWARD (σ_F) (cos θ* > 0)

BACKWARD (σ_B) (cos θ* < 0)

θ* defined in the Collins-Soper frame (Z/γ* rest frame)

◆ θ*-dependent differential cross section:

1 + cos²θ* (pure γ*)

1 + cos²θ* and cosθ* (both pure Z and Z/γ* interference)

dσ/cos θ* = A × (1 + cos²θ*) + B × cosθ*

\[ A_{FB} = (\sigma_F - \sigma_B) / (\sigma_F + \sigma_B) = (N_F - N_B) / (N_F + N_B) \]
$\cos\theta^*$ distribution using Pythia

50 < $M_{ee}$ < 75 GeV
$N_F < N_B$  $A_{FB} < 0$

80 < $M_{ee}$ < 100 GeV
$N_F \approx N_B$  $A_{FB} \approx 0$

150 < $M_{ee}$ < 500 GeV
$N_F > N_B$  $A_{FB} > 0$
$A_{FB}$ distribution

$Z/\gamma^*$ interference

$\bar{u}u \rightarrow e^+e^-$

Pure Z exchange

$(A_{FB} \propto g_{Ve} \approx 0)$

Primarily pure $\gamma^*$ exchange

$\sqrt{s}$ [GeV]
New resonance ($Z'$, LED etc) can interfere with $Z$ and $\gamma^*$

$A_{FB}$ measurement complementary to bump search

- Precise measurement around $Z$ pole
- Difficult to reach very high energies ($> 200$ GeV)

Rosner, PRD 54, 1078 (1996)
$A_{FB}$ in $Z/\gamma^* \rightarrow e^+e^-$ at Tevatron

- $u \bar{u}$ (dd) $\rightarrow Z/\gamma^* \rightarrow e^+e^-$
- SM couplings of fermions to Z boson:
  - Axial-vector coupling:
    $$ g_A = I^3_f $$
  - Vector coupling:
    $$ g_V = I^3_f - 2Q_f \sin^2 \theta_W $$
- With $\sin^2 \theta_W = 0.232$:
  - $g_A = -0.5, \ g_V = -0.036$ for electron
  - $g_A = 0.5, \ g_V = 0.191$ for u quark
  - $g_A = -0.5, \ g_V = -0.345$ for d quark

- Probe the relative strengths of Z-light quark couplings
- Can be used to make constraints on PDFs
Weak mixing angle $\sin^2 \theta_W$

- $A_{FB}$ is sensitive to $\sin^2 \theta_W$ ($\sin^2 \theta_W^{\text{eff}}$ includes higher order corrections)
- LEP $A_{FB}^b$ and SLD $A_{LR}$: off by $3\sigma$ in opposite direction
- NuTeV $\sin^2 \theta_W$ result: $3\sigma$ away from the global EW fit


<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit $\sigma_{\text{meas}}$</th>
<th>$\sigma_{\text{meas}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha^{(S)}_{\text{had}}(m_Z)$</td>
<td>0.02758 ± 0.00035</td>
<td>0.02767</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1874</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4959</td>
</tr>
<tr>
<td>$\sigma^{\text{had}}_{\text{had}}$ [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.478</td>
</tr>
<tr>
<td>$R_t$</td>
<td>20.767 ± 0.025</td>
<td>20.743</td>
</tr>
<tr>
<td>$A_{b}^{(S)}$</td>
<td>0.01714 ± 0.00095</td>
<td>0.01643</td>
</tr>
<tr>
<td>$A_{(P)}$</td>
<td>0.1465 ± 0.0032</td>
<td>0.1480</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21629 ± 0.00066</td>
<td>0.21581</td>
</tr>
<tr>
<td>$A_{t}^{(S)}$</td>
<td>0.0992 ± 0.0016</td>
<td>0.1038</td>
</tr>
<tr>
<td>$A_{b}^{(T)}$</td>
<td>0.0707 ± 0.0035</td>
<td>0.0742</td>
</tr>
<tr>
<td>$A_{b}$</td>
<td>0.923 ± 0.020</td>
<td>0.935</td>
</tr>
<tr>
<td>$A_{s}$</td>
<td>0.670 ± 0.027</td>
<td>0.668</td>
</tr>
<tr>
<td>$A_{(S, L)}$</td>
<td>0.1513 ± 0.0021</td>
<td>0.1480</td>
</tr>
<tr>
<td>$\sin^2 \theta_W^{(S)}(O_8)$</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.398 ± 0.025</td>
<td>80.32</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.097 ± 0.048</td>
<td>2.092</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>172.6 ± 1.4</td>
<td>172.8</td>
</tr>
</tbody>
</table>

March 2008

Weak mixing angle $\sin^2 \theta_W$ (cont.)

Only depends on lepton couplings

Also depends on quark couplings

- $A_{fb}^{0.1} = 0.23099 \pm 0.00053$
- $A_{fb}(P_c) = 0.23159 \pm 0.00041$
- $A_{fb}(SLD) = 0.23098 \pm 0.00026$
- $A_{fb}^{0.0, b} = 0.23221 \pm 0.00029$
- $A_{fb}^{0.0, c} = 0.23220 \pm 0.00081$
- $Q_{fb}^{had} = 0.2324 \pm 0.0012$

Average

$\chi^2$/d.o.f.: 11.8 / 5

Known to 0.07%
Event selection

- Integrated luminosity: $1065 \pm 65 \text{ pb}^{-1}$
- Two electrons satisfy:
  - $p_T > 25 \text{ GeV}$
  - Isolated with large EM fraction
  - Shower shape consistent with that of an electron
- $50 < M_{ee} < 500 \text{ GeV}$
- $A_{FB}$ measured in 14 mass bins
- Bin size chosen by detector resolution and available statistics

<table>
<thead>
<tr>
<th>Mass range (GeV)</th>
<th>CC Forward</th>
<th>Backward</th>
<th>CE Forward</th>
<th>Backward</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 – 60</td>
<td>69</td>
<td>78</td>
<td>15</td>
<td>16</td>
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<tr>
<td>60 – 70</td>
<td>104</td>
<td>158</td>
<td>51</td>
<td>91</td>
</tr>
<tr>
<td>70 – 75</td>
<td>96</td>
<td>117</td>
<td>64</td>
<td>93</td>
</tr>
<tr>
<td>75 – 81</td>
<td>191</td>
<td>235</td>
<td>172</td>
<td>293</td>
</tr>
<tr>
<td>81 – 86.5</td>
<td>749</td>
<td>763</td>
<td>843</td>
<td>970</td>
</tr>
<tr>
<td>86.5 – 89.5</td>
<td>1388</td>
<td>1357</td>
<td>1860</td>
<td>1694</td>
</tr>
<tr>
<td>89.5 – 92</td>
<td>2013</td>
<td>1918</td>
<td>2543</td>
<td>2214</td>
</tr>
<tr>
<td>92 – 97</td>
<td>2914</td>
<td>2764</td>
<td>3132</td>
<td>2582</td>
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<tr>
<td>97 – 105</td>
<td>686</td>
<td>549</td>
<td>867</td>
<td>470</td>
</tr>
<tr>
<td>105 – 115</td>
<td>153</td>
<td>97</td>
<td>243</td>
<td>88</td>
</tr>
<tr>
<td>115 – 130</td>
<td>101</td>
<td>39</td>
<td>167</td>
<td>61</td>
</tr>
<tr>
<td>130 – 180</td>
<td>91</td>
<td>33</td>
<td>202</td>
<td>69</td>
</tr>
<tr>
<td>180 – 250</td>
<td>31</td>
<td>13</td>
<td>53</td>
<td>16</td>
</tr>
<tr>
<td>250 – 500</td>
<td>14</td>
<td>15</td>
<td>17</td>
<td>4</td>
</tr>
</tbody>
</table>
**M_{ee} and \cos{\theta^*} distributions**

- **QCD multijet background** estimated using collider data (0.9%)
- **Electroweak backgrounds** estimated using Geant MC simulation:
  - $Z/\gamma^* \rightarrow \tau\tau, W+X, WW, WZ, \text{ttbar}$

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\textbf{AFB Unfolding}

\begin{itemize}
  \item \textbf{Raw A\textsubscript{FB} → Unfolded A\textsubscript{FB}}
    \begin{itemize}
      \item Detector resolution:
      \begin{itemize}
        \item Events migrate from one mass bin to the other
        \item Especially important for mass bins near Z pole
      \end{itemize}
      \item Acceptance and efficiencies
    \end{itemize}
  \item \textbf{Iterative matrix inversion method}
    \begin{itemize}
      \item Migration matrix measured using Geant MC simulation
      \item Procedure tested by comparing the truth and unfolded spectrum generated using pseudo-experiments
    \end{itemize}
  \item \textbf{Systematic uncertainties on the unfolded A\textsubscript{FB}}
    \begin{itemize}
      \item Unfolding bias
      \item Electron energy scale and resolution
      \item Backgrounds
    \end{itemize}
\end{itemize}
Unfolded $A_{FB}$

$D\bar{O}$ $1.1\ fb^{-1}$

$\chi^2$/d.o.f. = 10.6/14

10 times more data than previous published results
Unfolded $A_{FB}$ distribution agrees with SM predictions

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\( \sin^2 \theta_W^{\text{eff}} \) Result

◆ Extraction of \( \sin^2 \theta_W^{\text{eff}} \) using PYTHIA:
  ◆ Obtained from backgrounds-subtracted \( A_{FB} \) distribution
  ◆ Compared with \( A_{FB} \) templates according to different values of \( \sin^2 \theta_W^{\text{eff}} \) generated with PYTHIA and GEANT-based MC simulation

◆ Fitted results (for \( 70 < M_{ee} < 110 \) GeV):

\[
\sin^2 \theta_W^{\text{eff}} = 0.2326 \pm 0.0018 \text{ (stat.)} \pm 0.0006 \text{ (syst.)}
\]

◆ Mainly dominated by statistical uncertainty
◆ Systematic uncertainties:
  ◆ PDFs (0.0005)
  ◆ EM energy scale/resolution (0.0003)
Our $\sin^2 \theta_W^{\text{eff}}$ result agrees with the global EW fit

Uncertainty comparable with the uncertainties from

- Combined $Q^{\text{had}}_{\text{FB}}$ from four LEP experiments (0.0012) (better than OPAL/DELPHI results, close to L3 result, worse than ALEPH result)
- NuTeV measurement (0.0016)

Approach world average uncertainty (0.0003 for 8 fb$^{-1}$, $e + \mu$, with CDF)

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Difficult to tag light quarks in final state

Relies on MC to determine relative fraction of different quark species (with b, c contributions removed)

\[ A_{FB}, A_{LR} \text{ (SLD)} \]

\[ A_{FB}^{\theta, b} \]

\[ A_{FB}^{\theta, c} \]

\[ Q_{fb}^{\text{had}} \]

\[ A_{\ell\ell} (D\O) \]

\[ \sin^2 \theta_{\text{eff}} \]

0.23153 ± 0.00016

0.23099 ± 0.00053

0.23159 ± 0.00041

0.23098 ± 0.00026

0.23221 ± 0.00029

0.23200 ± 0.00081

0.2324 ± 0.0012

0.2326 ± 0.0019

\[ \text{NuTeV} \]

This measurement

\[ \text{e}^+, \ell, q \]

\[ \text{e}^-, \bar{\ell}, \bar{q} \]

\[ \text{e}^+, \text{Z}/\gamma^* \]

\[ \text{Z}/\gamma^* \]

\[ \text{b, c} \]

\[ \text{b, c} \]

\[ \text{Z} \]

\[ \text{u, d} \]

\[ \text{u, d} \]

\[ \text{Z}/\gamma^* \]

\[ \text{e}^+, \text{e}^- \]
Conclusions

◆ **Electron charge asymmetry (W→ev)**
  - Measured in three different electron $E_T$ bins
  - Experimental uncertainties smaller than PDF uncertainties for most $\eta(e)$ bins
  - Useful for future global PDF fits
  - Best lepton charge asymmetry measurement to date

◆ $A_{FB}$ measurement and extraction of $\sin^2\theta_{W}^{\text{eff}}$ (Z→ee)
  - Unfolded $A_{FB}$ distribution agrees with SM predictions
  - $\sin^2\theta_{W}^{\text{eff}} = 0.2326 \pm 0.0018$ (stat.) $\pm 0.0006$ (syst.)
  - Sensitive to Z-u and Z-d couplings
  - Most precise $A_{FB}$ and $\sin^2\theta_{W}^{\text{eff}}$ measurements at the Tevatron

◆ More data (> 4 fb$^{-1}$ so far) collected, better understanding of the detector, more high precision electroweak measurements expected!