Measurement of the $W$ boson production charge asymmetry at CDF

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Physics Motivation

• Parton distribution functions (PDFs) describe *quark* and *gluon* content of the proton.
• PDFs are essential input to perturbative calculations of signal and background processes at hadron colliders.
• How can we gain insights into proton PDFs at the Tevatron?
  – **Measure W charge asymmetry!**
  – The measurement provides information on $d(x)/u(x)$ of the proton
W Charge Asymmetry at the Tevatron

u quark carries higher fraction of proton momentum!
PDFs of the proton

\[ A(y_W) = \frac{d\sigma_+ / dy_W - d\sigma_- / dy_W}{d\sigma_+ / dy_W + d\sigma_- / dy_W} \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)} \]

Measurement of the W charge asymmetry constrains PDF’s of the proton.

[http://durpdg.dur.ac.uk/hepdata/pdf3.html]
Lepton Charge Asymmetry

Traditionally we measure lepton charge asymmetry:
- leptonic $W$ decay involves $\nu$ \( \rightarrow P_{z\nu} \) is unmeasured
- lepton charge asymmetry is a convolution of both the $W$ charge asymmetry and V-A $W$ decay structure (“turn over” at high $|\eta|$)
- $W$ charge asymmetry does not have this effect, so we probe high $y_W$

\[
A(y_w) = \frac{d\sigma_+ / dy_w - d\sigma_- / dy_w}{d\sigma_+ / dy_w + d\sigma_- / dy_w}
\]

\[
A_l(\eta) = \frac{d\sigma(l^+) / d\eta - d\sigma(l^-) / d\eta}{d\sigma(l^+) / d\eta + d\sigma(l^-) / d\eta}
\]
**W \rightarrow e\nu event selection**

- **Electron selection**
  - Isolated EM calorimeter energy
  - Transverse Energy
    \[ E_T > 25 \ (20) \text{ GeV} \text{ in central (forward) detector} \]

- **Neutrino selection**
  - Determined from missing transverse energy
  \[ \text{missing } E_T > 25 \text{ GeV} \]

\(~538\text{K events in central and } \sim 177\text{K in forward}\)
Analysis Technique I

• Measure $W^\pm$ rapidity
  $$y_W = \frac{1}{2} \ln \left( \frac{E - P_z^W}{E + P_z^W} \right)$$
  $$P_z^W = P_z^l + P_z^\nu$$

• Use $W$ mass constraint
  $$M_W^2 = (E_l + E_\nu)^2 - (P_l + P_\nu)^2$$
  answer:
  $$P_{z1}^\nu, P_{z2}^\nu$$

• Develop the weight factor
  $$F_{1,2}^{\pm} = \frac{P_+ (\cos \theta_{1,2}^*, y_{1,2}, p_T^W) \sigma_\pm (y_{1,2})}{P_\pm (\cos \theta_1^*, y_1, p_T^W) \sigma_\pm (y_1) + P_\pm (\cos \theta_2^*, y_2, p_T^W) \sigma_\pm (y_2)}$$

• Iterate the method to remove input bias

Probability of angular distribution

Differential $W$ cross section
Analysis Technique II

The W production probability from angular distribution
[cosθ* : in Collins-Soper frame (W rest frame)]

\[ P_{\pm}(\cos\theta^*, y_W, p_T^W) = (1 \mp \cos\theta^*)^2 + Q(y_W, p_T^W) (1 \pm \cos\theta^*)^2 \]

ratio of two angular distributions at each rapidity

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Electron Charge Identification

- Charge identification is crucial for this measurement.
- Measure charge fake rate using $Z \to e^+ e^-$ data sample.

$$f_{mis} = \frac{N_{\text{same sign}}}{N_{\text{opposite sign}} + N_{\text{same sign}}}$$
Backgrounds

- Measure jet backgrounds directly in data
  - use extra energy "isolation" around electron to separate, and fit shape to background fraction
  - use jet sample to predict measured $y_W$ from this background

- $Z \rightarrow e^+e^-$ background from simulation
Systematic Uncertainties

1. Trigger and electron ID efficiencies
2. Hadronic recoil energy scale
3. Calorimeter energy scale and resolution
4. PDF uncertainty
5. Uncertainties on QCD and \( Z \rightarrow e^+e^- \) background estimates
6. Uncertainty on charge fake rate

| \(|y_W|\) | \(A(y_W)\) | \(\sigma_{sys}\) | \(\sigma_{sys+stat}\) |
|----------|----------|----------------|----------------|
| 0.0 - 0.2 | 0.0199 | ±0.0013 | ±0.0034 |
| 0.2 - 0.4 | 0.0571 | ±0.0027 | ±0.0042 |
| 0.4 - 0.6 | 0.0813 | ±0.0037 | ±0.0049 |
| 0.6 - 0.8 | 0.1168 | ±0.0055 | ±0.0063 |
| 0.8 - 1.0 | 0.1456 | ±0.0072 | ±0.0079 |
| 1.0 - 1.2 | 0.2040 | ±0.0084 | ±0.0092 |
| 1.2 - 1.4 | 0.2354 | ±0.0109 | ±0.0118 |
| 1.4 - 1.6 | 0.2613 | ±0.0143 | ±0.0151 |
| 1.6 - 1.8 | 0.3027 | ±0.0135 | ±0.0144 |
| 1.8 - 2.05 | 0.3553 | ±0.0126 | ±0.0141 |
| 2.05 - 2.3 | 0.4363 | ±0.0134 | ±0.0158 |
| 2.3 - 2.6 | 0.5374 | ±0.0136 | ±0.0178 |
| 2.6 - 3.0 | 0.6415 | ±0.0116 | ±0.0260 |

Systematics <1.5 % for |\(y_W| > 2.0
• Positive and negative $y_W$ agree, so fold
• Compare to NLO Prediction
  – NLO error PDFs (CTEQ)
CDF Preliminary Result (1fb⁻¹)

• Compare to CTEQ6M (NLO) and MRST2006 (NNLO) PDFs and their uncertainties
Conclusions

- First direct measurement of $W$ charge asymmetry
  - despite additional complication of multiple solutions, it works!
  - appears that it will have impact on $d/u$ of proton
- Looking forward to working with PDF fitting groups to incorporate

Backup
### Systematic Uncertainties

| $|y_W| < 0.2$ | PDF  | Et    | Recoil | CFR   | BKG   | Trig   | ID    | Syst.  | Stat.  |
|------------|-------|-------|--------|-------|-------|--------|-------|--------|--------|
| 0          | 0.00027 | 0.00014 | 0.0011 | 0.00017 | 0.00043 | 0.00029 | 0.00016 | 0.0013 | 0.0031 |
| 0.2        | 0.00077 | 0.00038 | 0.0022 | 0.00011 | 0.00091 | 0.0008  | 0.00067 | 0.0027 | 0.0032 |
| 0.4        | 0.0015  | 0.00055 | 0.0022 | 0.00018 | 0.0011  | 0.0013  | 0.0017  | 0.0037 | 0.0033 |
| 0.6        | 0.0022  | 0.00071 | 0.0034 | 0.00025 | 0.0015  | 0.0014  | 0.003   | 0.0055 | 0.0032 |
| 0.8        | 0.0024  | 0.00071 | 0.0042 | 0.00031 | 0.002   | 0.0011  | 0.0047  | 0.0072 | 0.0034 |
| 1          | 0.0027  | 0.00079 | 0.0033 | 0.0004  | 0.0018  | 0.00089 | 0.0069  | 0.0084 | 0.0038 |
| 1.2        | 0.0028  | 0.0015  | 0.0067 | 0.00047 | 0.0018  | 0.00059 | 0.0078  | 0.011  | 0.0043 |
| 1.4        | 0.0028  | 0.0014  | 0.011  | 0.00035 | 0.0014  | 0.0004  | 0.0085  | 0.014  | 0.005  |
| 1.6        | 0.0029  | 0.0026  | 0.0092 | 0.00077 | 0.0012  | 0.00028 | 0.0089  | 0.013  | 0.0055 |
| 1.8        | 0.0034  | 0.0031  | 0.0082 | 0.0022  | 0.0013  | 0.00056 | 0.008   | 0.013  | 0.0062 |
| 2          | 0.0042  | 0.0053  | 0.0059 | 0.0044  | 0.0021  | 0.0017  | 0.0085  | 0.013  | 0.0083 |
| 2.3        | 0.005   | 0.0062  | 0.004  | 0.0045  | 0.0019  | 0.0027  | 0.0086  | 0.014  | 0.011  |
| 2.6        | 0.0053  | 0.006   | 0.0043 | 0.0014  | 0.001   | 0.0028  | 0.0065  | 0.012  | 0.023  |
Acceptance correction