Direct measurement of the *W* boson production charge asymmetry at CDF

Eva Halkiadakis
Rutgers University

For the CDF collaboration

Joint Experimental-Theoretical Physics Seminar
Fermilab

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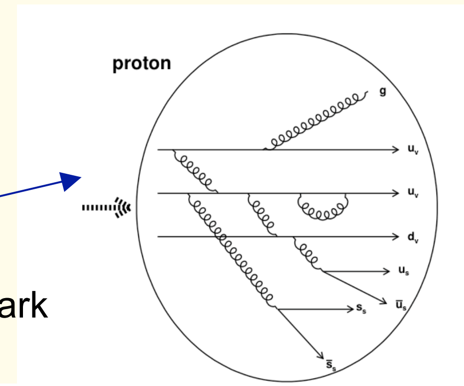
Outline

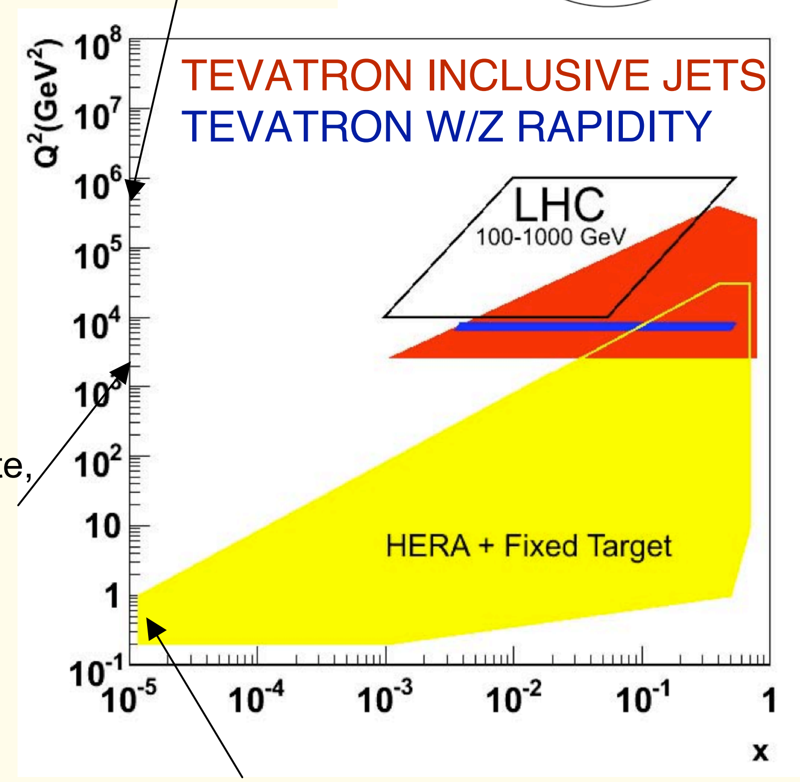
- Introduction
- New Analysis Technique
- Signal, Background and Corrections
- Uncertainties
- Results
- Comparison to latest results from DØ and status of PDF fits

Physics Motivation (I)

- 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.
- Tevatron data provide 10% of the data-points in the PDF fits
- Complement HERA and fixed-target data providing constraints at high-Q^2
- PDF fitting groups: CTEQ and MRST (now MSTW)



Gluon and sea quark PDFs dominate

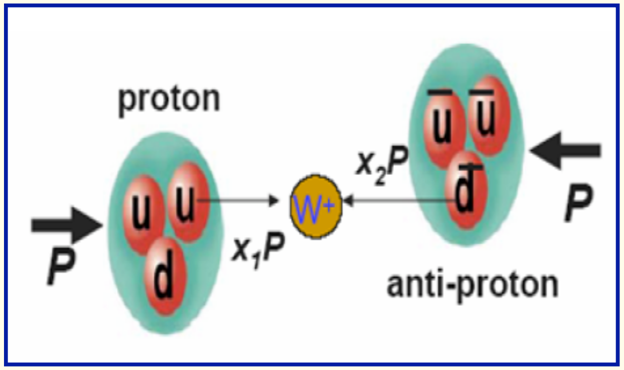


Proton composite, valence quarks dominate

Proton interacts as a single particle

Physics Motivation (II)

- A measurement of the **W charge asymmetry** at the Tevatron provides information on d(x)/u(x) of the proton
  - truly clean measurement



- **Example:** Improvement in PDF uncertainties will reduce total error on W mass

CDF 200pb^{-1}

CDF II preliminary L = 200 pb^{-1}

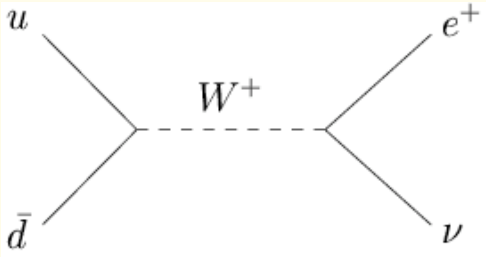
m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\parallel}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

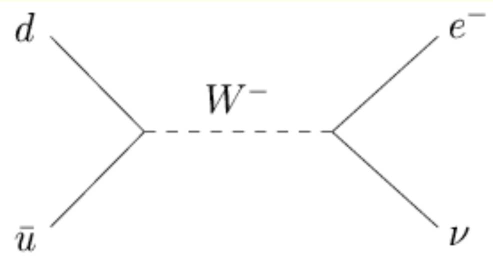
DØ 1 fb^{-1}

Source	$\sigma(m_W)$ MeV m_T	$\sigma(m_W)$ MeV p_T^e	$\sigma(m_W)$ MeV $\not{E}_T$
Experimental			
Electron Energy Scale	34	34	34
Electron Energy Resolution Model	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences	4	4	4
Recoil Model	6	12	20
Electron Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Total	35	37	41
W production and decay model			
PDF	9	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	12	14	17
Total	37	40	44

W Charge Asymmetry at the Tevatron

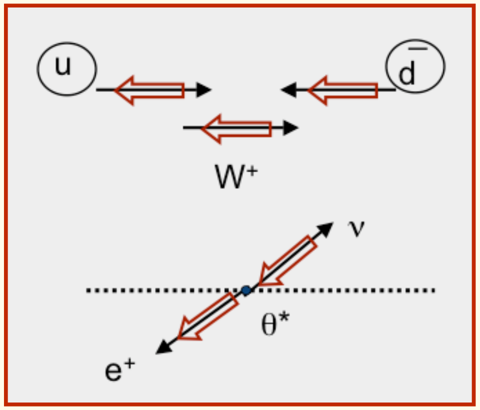
At the Tevatron, $W^{\pm}$ are produced primarily by:

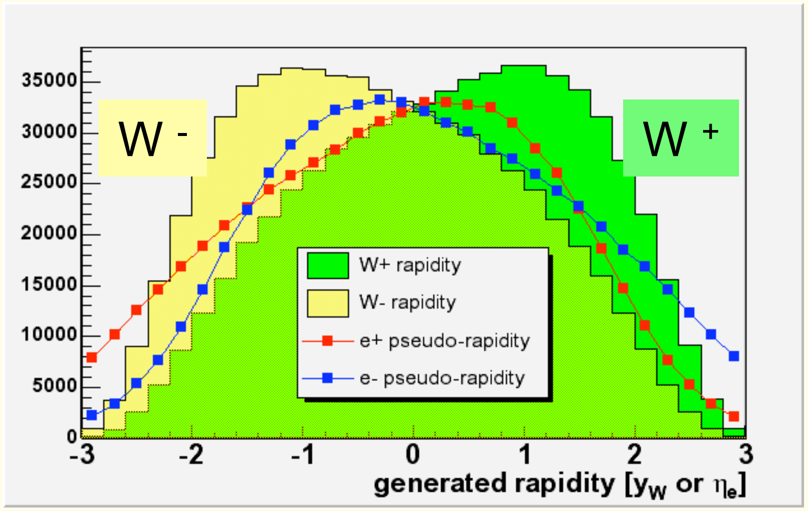




u quark carries higher fraction of proton momentum!

W+ boosted in proton direction and
W- boosted in anti proton direction.



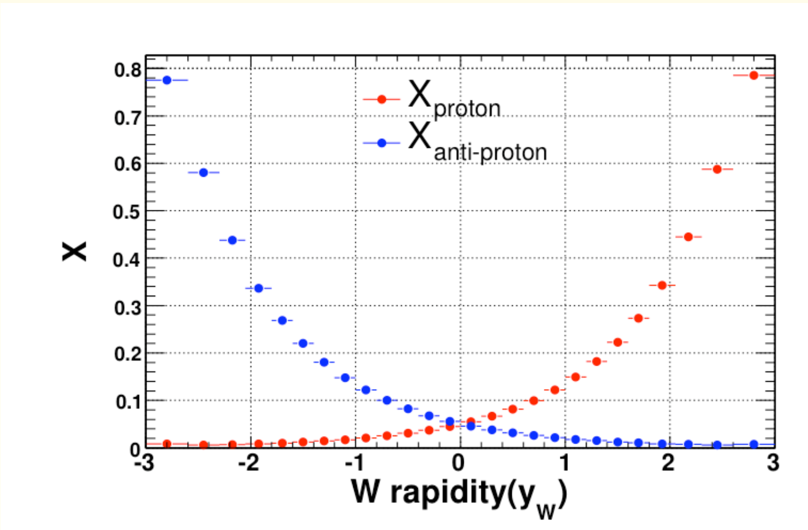


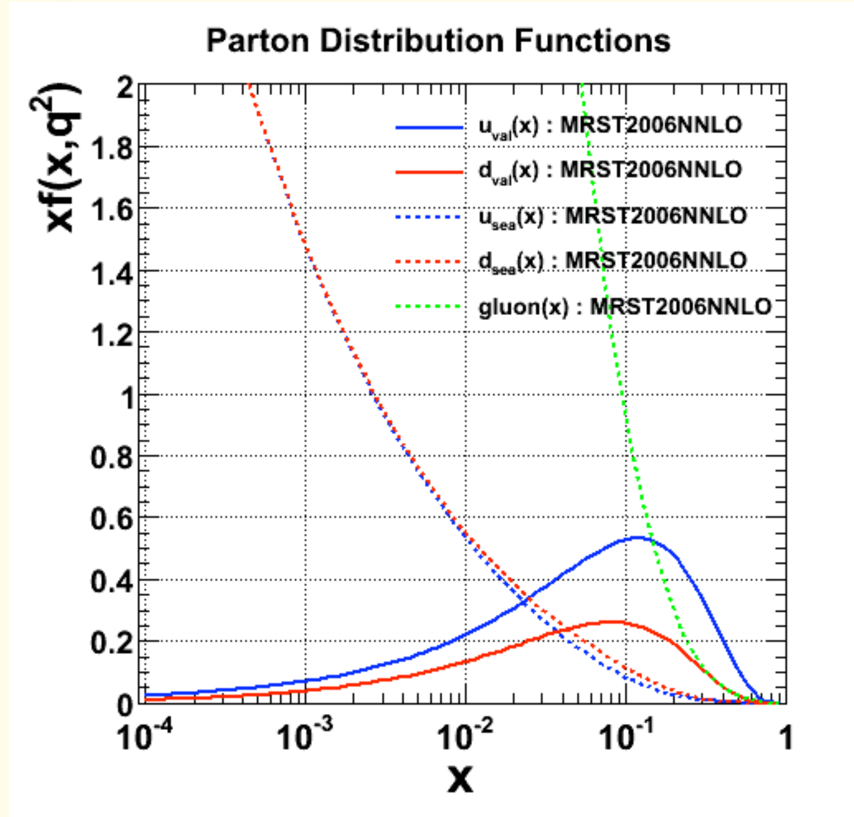
←anti-proton direction proton direction→

W Charge Asymmetry at the Tevatron

W's produced mainly from valence quarks.

W production requires at least one high x parton in the collision.





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

$$y_W = \frac{1}{2}\ln\left(\frac{E-P_z}{E+P_z}\right)$$

$$x_{1,2} = x_0 e^{\pm y_W}$$

$$x_0 = M_W/\sqrt{s}$$

$$A(y_W) = \frac{d\sigma_+/dy_W - d\sigma_-/dy_W}{d\sigma_+/dy_W + d\sigma_-/dy_W} \approx \frac{u(x1)d(x2) - d(x1)u(x2)}{u(x1)d(x2) + d(x1)u(x2)}$$

sensitive to d(x)/u(x) ratio

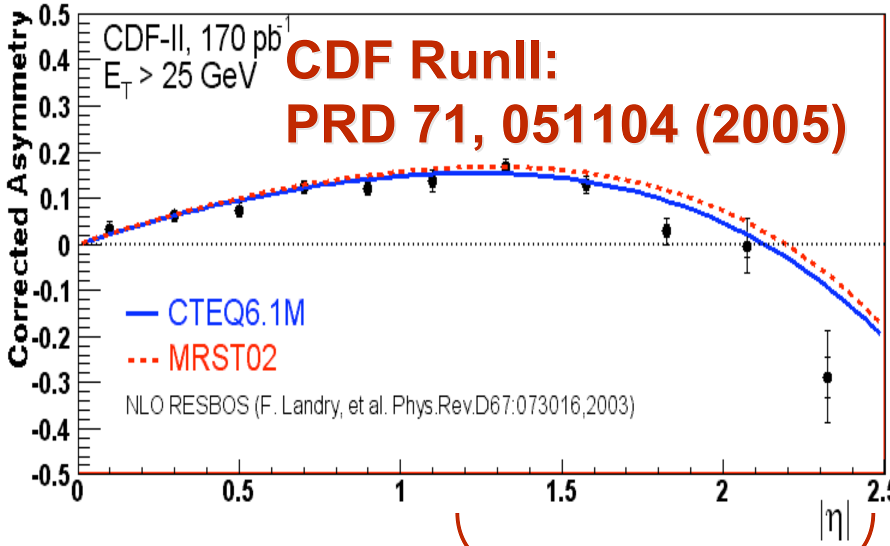
Measurement of the W charge asymmetry constrains PDF's of the proton.

Lepton Charge Asymmetry

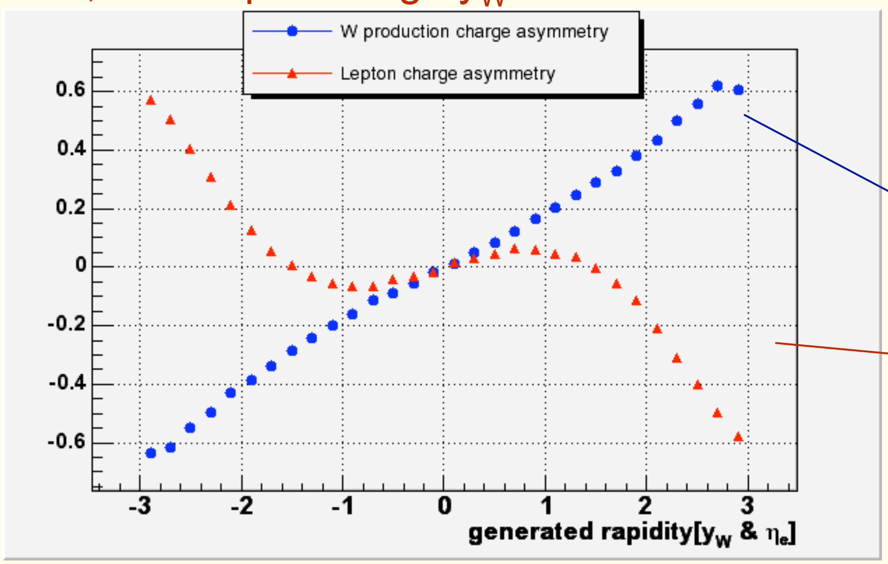
Traditionally we measure lepton charge asymmetry

- leptonic W decay involves ν
  → P_z^{ν} is unmeasured
- lepton charge asymmetry is a convolution of both the *W* charge asymmetry and V-A *W* decay structure
- Results in "turn over" at high |η|
- W^+'s produced boosted in proton direction and polarized in the antiproton direction

W charge asymmetry does not have this effect, so we probe high y_W



CDF RunII: PRD 71, 051104 (2005)



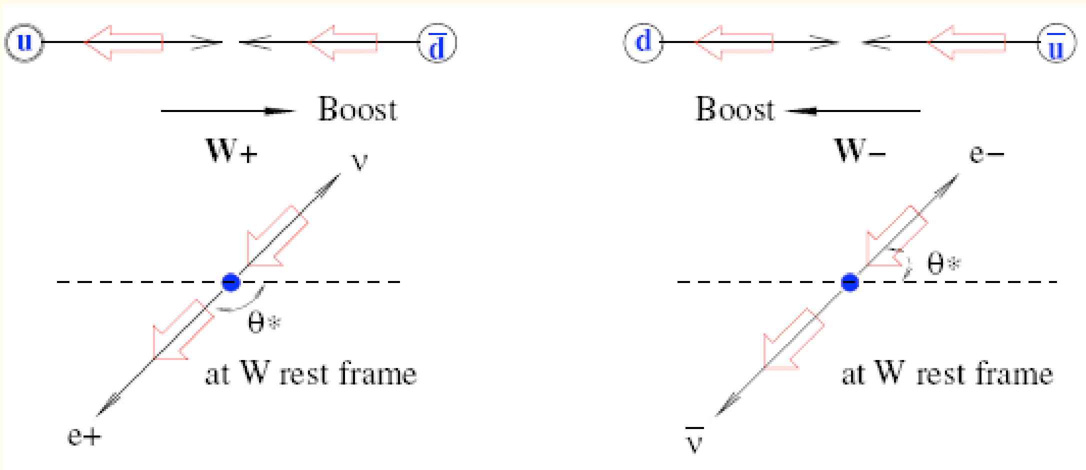
Least constrained at high η!

$$A(y_W) = \frac{d\sigma_+/dy_W - d\sigma_-/dy_W}{d\sigma_+/dy_W + d\sigma_-/dy_W}$$

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

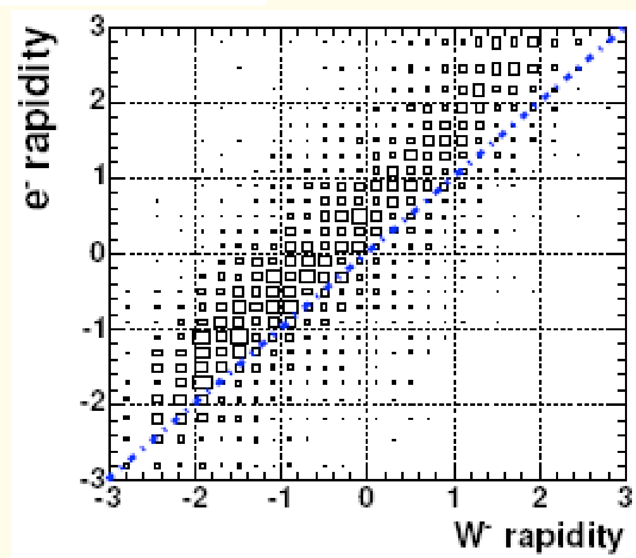
More on the lepton asymmetry later…

Lepton and W rapidity



$$\frac{d\Gamma(W \to e^{\pm}\nu)}{d\theta^{*}} \propto \left(1 \mp \cos\theta^{*}\right)^{2}$$

Lepton prefers to decay against boost



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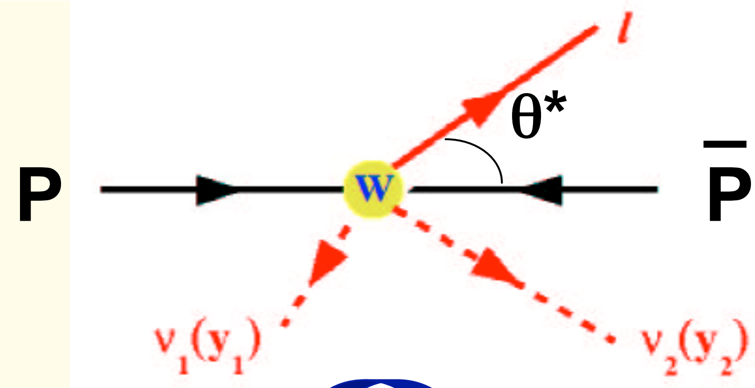
Analysis Technique (I): New Approach



Q: How to reconstruct y_W?

- Measure $W^{\pm}$ rapidity → $$y_W = \frac{1}{2}\ln\left(\frac{E - P_z}{E + P_z}\right)$$ $\overrightarrow{P_z^W} = \overrightarrow{P_z^l} + \overrightarrow{P_z^\nu}$ ← can't measure !!!

- Use ***W*** mass constraint

  solve eqn. $$M_W^2 = (E_l + E_\nu)^2 - (\vec{P_l} + \vec{P_\nu})^2$$ answer : $P_{z1}^\nu,\ P_{z2}^\nu$

- Develop the weight factor → **Probability of angular distribution**

$$w_{1,2}^{\pm} = \frac{P_{\pm}(\cos\theta_{1,2}^*, y_{1,2}, p_T{}^W)\sigma_{\pm}(y_{1,2})}{P_{\pm}(\cos\theta_1^*, y_1, p_T{}^W)\sigma_{\pm}(y_1) + P_{\pm}(\cos\theta_2^*, y_2, p_T{}^W)\sigma_{\pm}(y_2)}$$

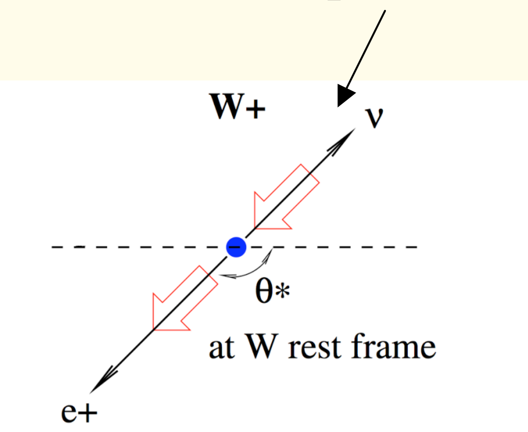
→ **Differential *W* cross section**

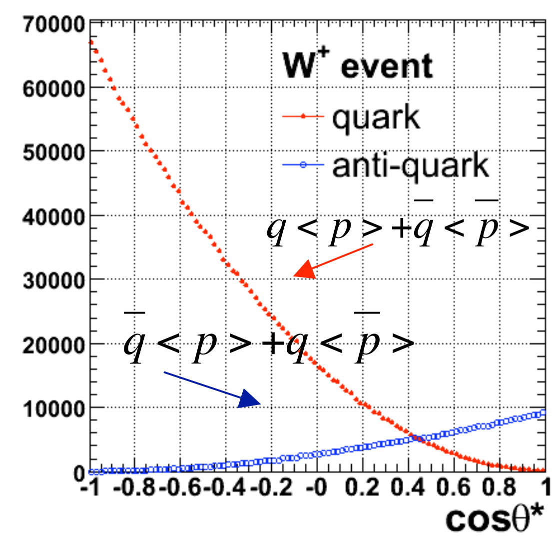
- Iterate the method to remove input bias
  - *shown it does not depend on assumed charge asymmetry*

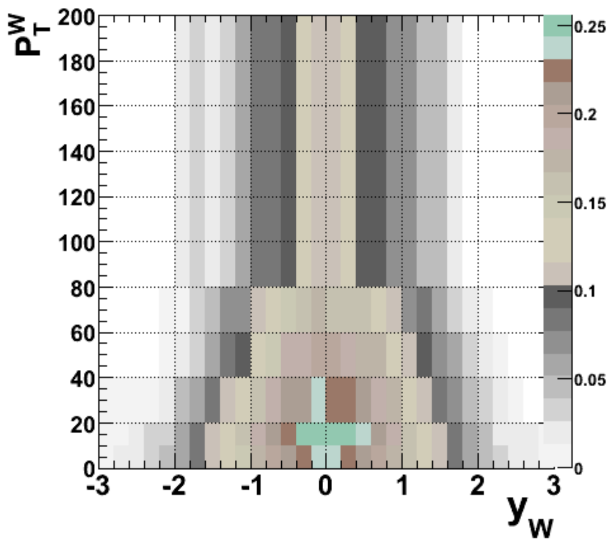
Analysis Technique (II):
W production from the sea

The W production probability from angular distribution

[cosθ* : in Collins-Soper frame (W rest frame)]







$$P_{\pm}(\cos\theta^*, y_W, p_T^W) = \underbrace{(1 \mp \cos\theta^*)^2}_{q<p>+\bar{q}<\bar{p}>} + Q(y_W, p_T^W)\underbrace{(1 \pm \cos\theta^*)^2}_{\bar{q}<p>+q<\bar{p}>}$$

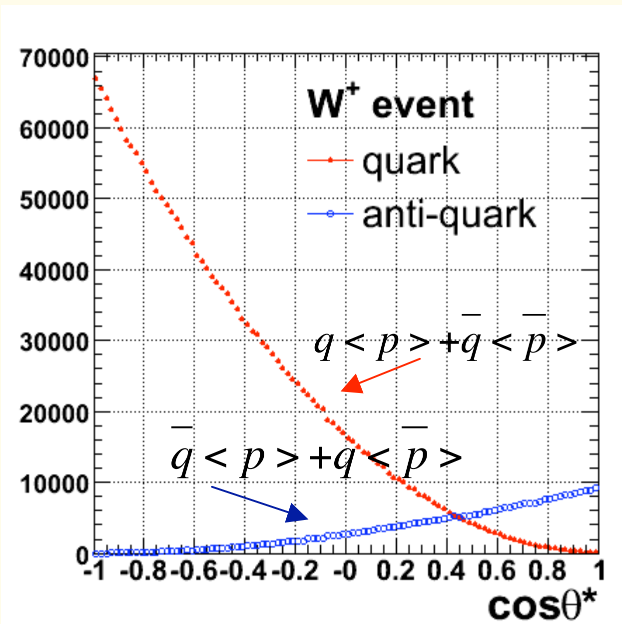
ratio of two angular distributions at each rapidity

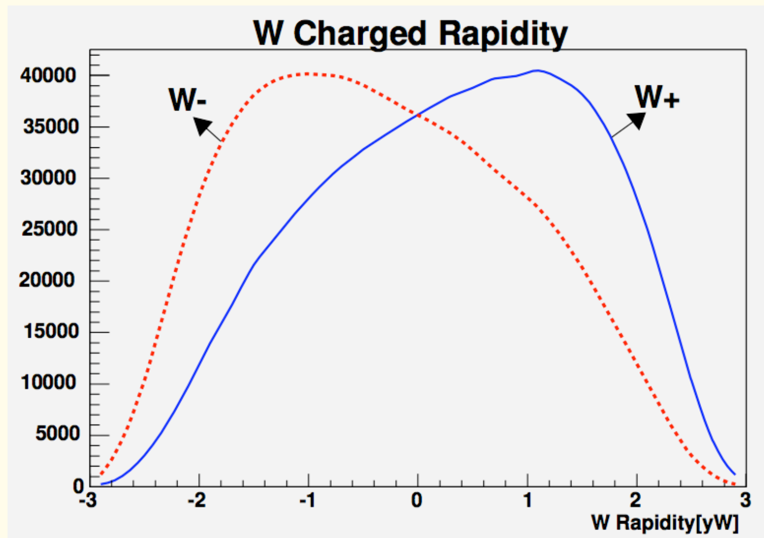
Sign of V-A angular bias flips when $W^{\pm}$ is produced from anti-quarks

→ take this fraction as an input

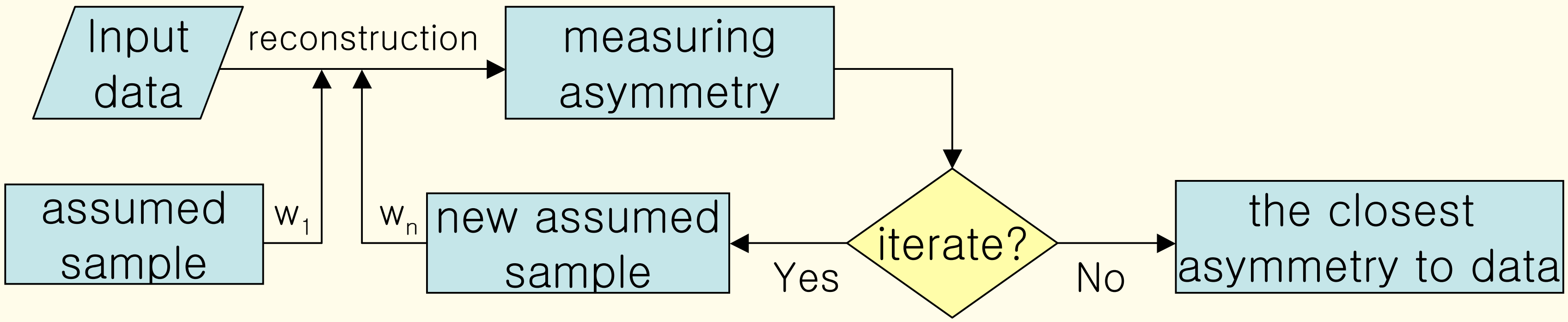
What is input?
What is measured?

- Inputs from theory:
  - $\frac{\bar{u}+\bar{d}}{u+d}$ and $\frac{d\sigma(p\bar{p}\to W^{+}X)}{dy_W} + \frac{d\sigma(p\bar{p}\to W^{-}X)}{dy_W}$





What is input?
What is measured?



- Output from iteration:

$$A\left(y_W\right)=\frac{\frac{d\sigma(p\bar{p}\to W^+X)}{dy_W}-\frac{d\sigma(p\bar{p}\to W^-X)}{dy_W}}{\frac{d\sigma(p\bar{p}\to W^+X)}{dy_W}+\frac{d\sigma(p\bar{p}\to W^-X)}{dy_W}}$$

Method documented in:

Thesis student

A. Bodek, Y. Chung, E. Halkiadakis, B. Han, K. McFarland, Phys. Rev. D 79, 031101(R) (2009).

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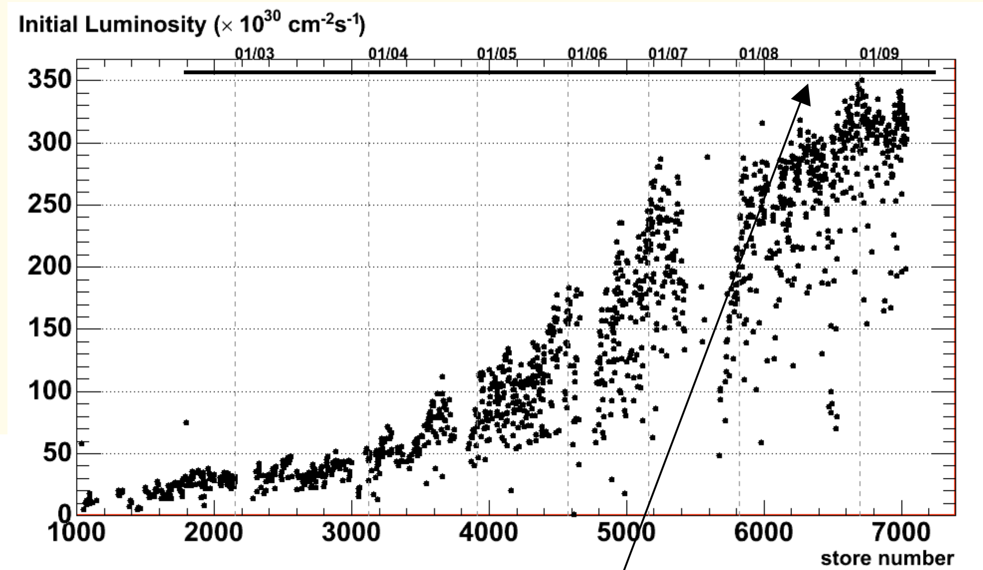
Tevatron & CDF Performance

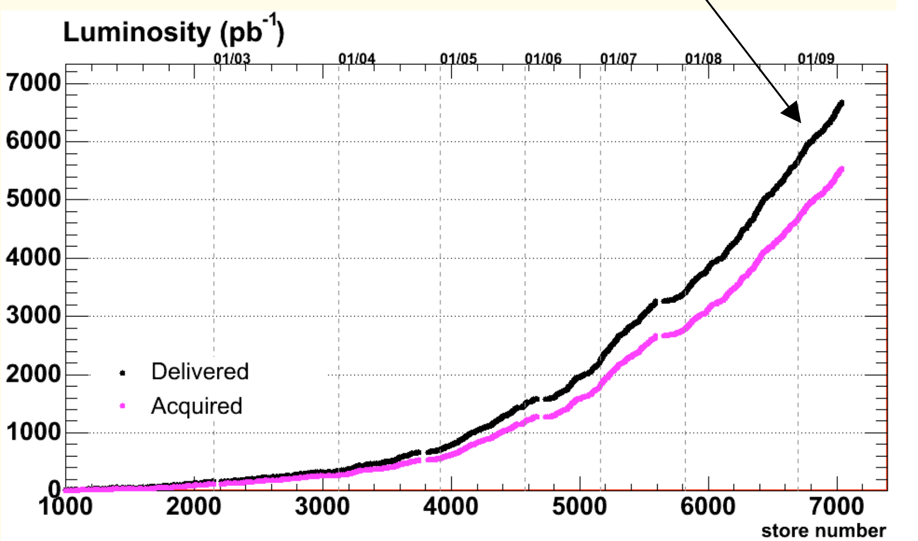
Integrated $\mathcal{L}$

Total delivered: ~6.6 fb^{-1} /expt

(as of May 1st)

Total recorded: >5 fb^{-1} /expt



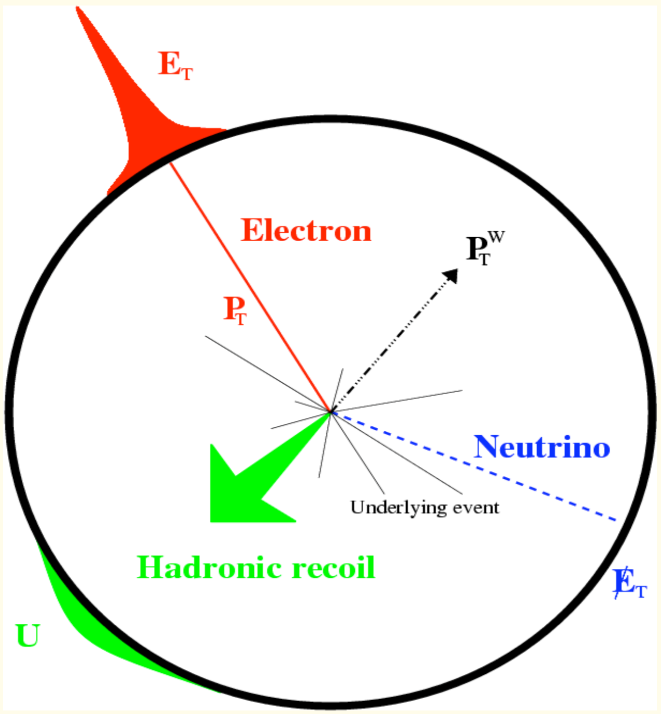


Record peak $\mathcal{L}$ ~3.5×10^{32} $cm^{-2}s^{-1}$

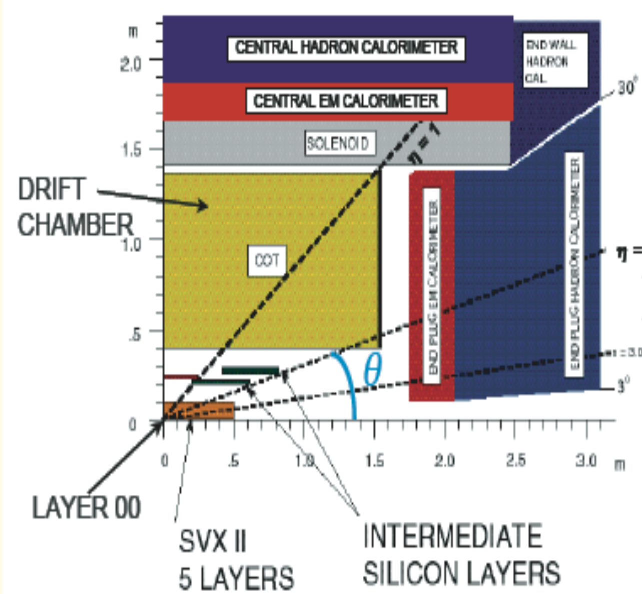
This analysis: 1fb^{-1}

W →eν event selection

- Electron selection
  - Isolated EM calorimeter energy
  - Transverse Energy
    E_T > 25 (20) GeV in central (forward) detector



- Neutrino selection
  - Determined from missing transverse energy
    missing E_T > 25 GeV



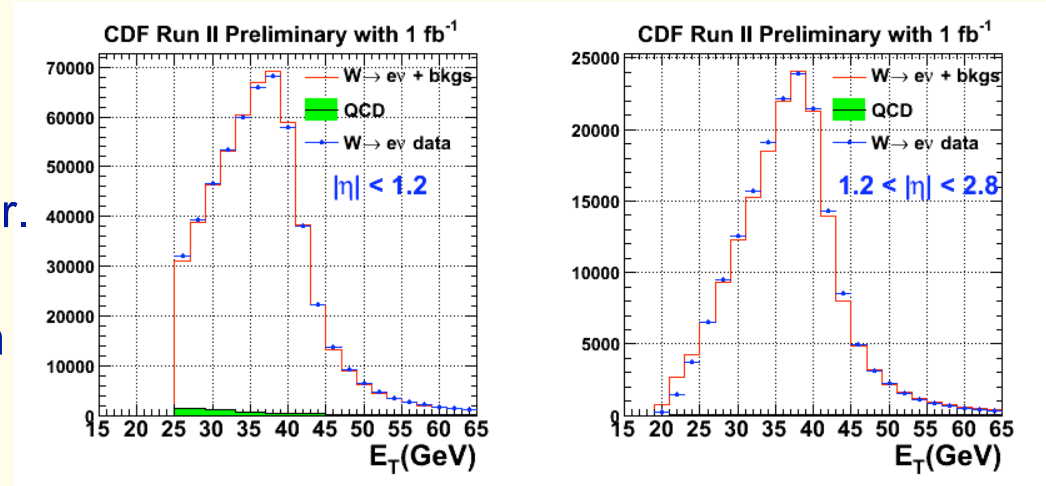
Forward: out to $|\eta|$<2.8

~538K events in central and ~177K in forward

Electrons and Missing Energy

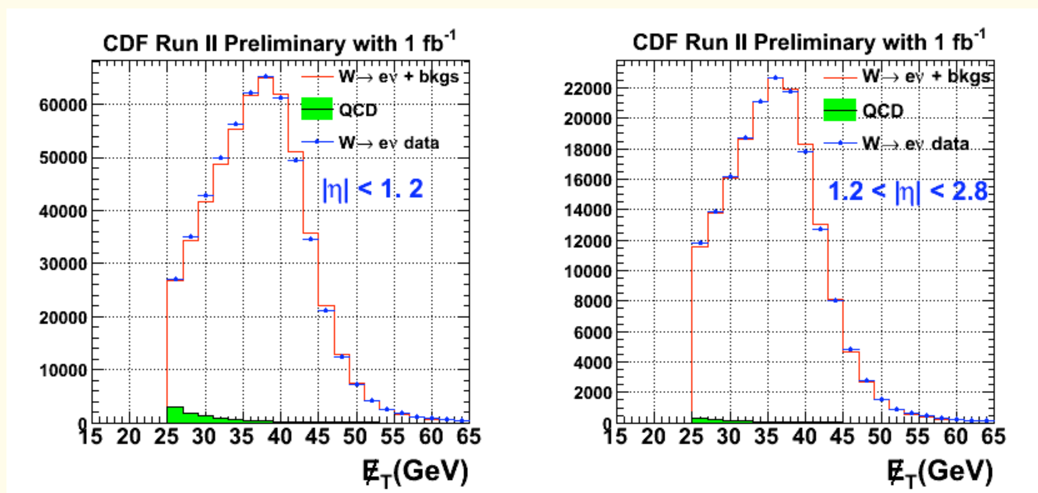
Electrons :

- Have charged particle track.
- Leave almost all of their energy in the electromagnetic calorimeter.
- Ask for no other nearby tracks
  - We do not want leptons from (heavy flavor) jets.



Missing E_T :

- Measure "Missing Transverse Energy" with transverse energy balance.
- EM and hadronic components measured in calorimeters
- Corrected for jets



Scale and resolution tuned on $Z \to ee$ data.

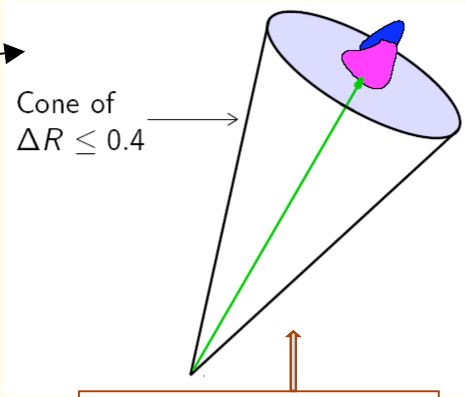
W recoil energy also tuned on data.

Backgrounds (I)

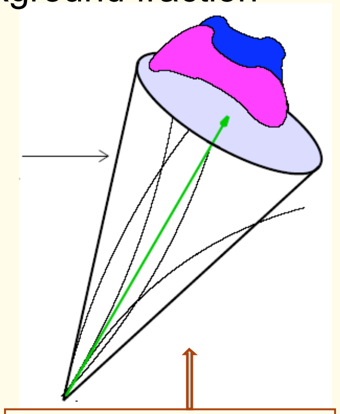
- Measure jet backgrounds directly in data
  - use extra energy "isolation" around electron to separate, and fit shape to background fraction
- Illustrative fit (one of many) below
  - use jet sample to predict measured "y_W" and charge from this sample
  - uncertainty is ~0.15% of total sample

Technique :

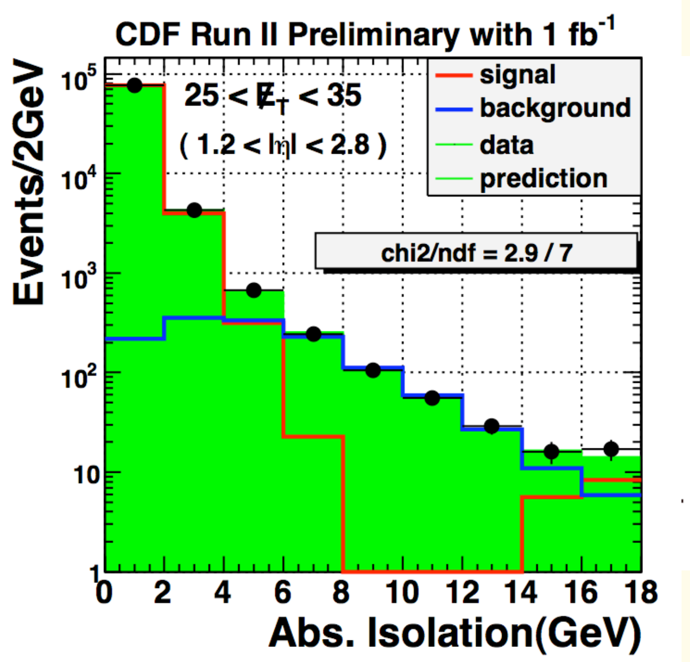
use extra energy "isolation" around electron to separate, and fit shape to background fraction

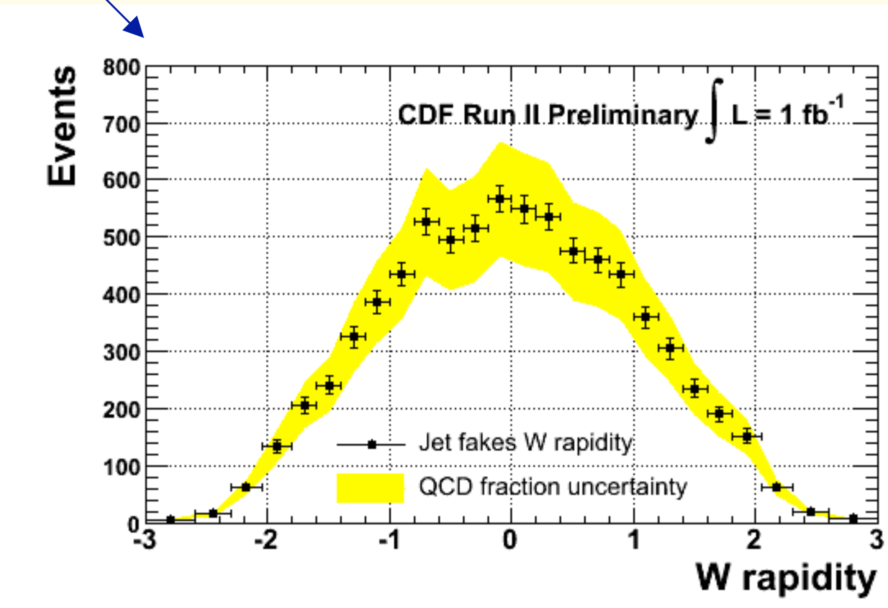


Real electrons from Boson decay are isolated.



Fake or real electrons in jets are non-isolated.





Backgrounds (II)

A number of additional minor backgrounds from MC simulation:

- **$Z \rightarrow e^+e^-$, $Z \rightarrow \tau^+\tau^-$**
- Standard model top pair production→ very small cross-section (< 10 pb)
  - Negligible
- Dibosons: WW and WZ diboson production → very small cross-sections (≤10 pb)
  - Negligible
- $W \rightarrow \tau\upsilon \rightarrow e\upsilon\upsilon$: Not background - included in acceptance (signal!)

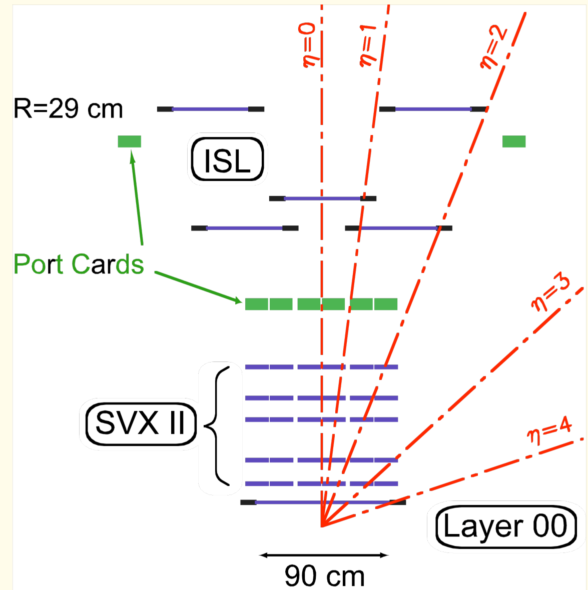
Backgrounds	**central**	**plug**
$Z \rightarrow e^+e^-$	0.59 ± 0.02 %	0.54 ± 0.03 %
$Z \rightarrow \tau^+\tau^-$	0.09 ± 0.00 %	0.10 ± 0.01 %
QCD	1.21 ± 0.14 %	0.67 ± 0.12 %
(Signal) $W \rightarrow \tau^+\upsilon$	2.30 ± 0.04 %	2.04 ± 0.05 %

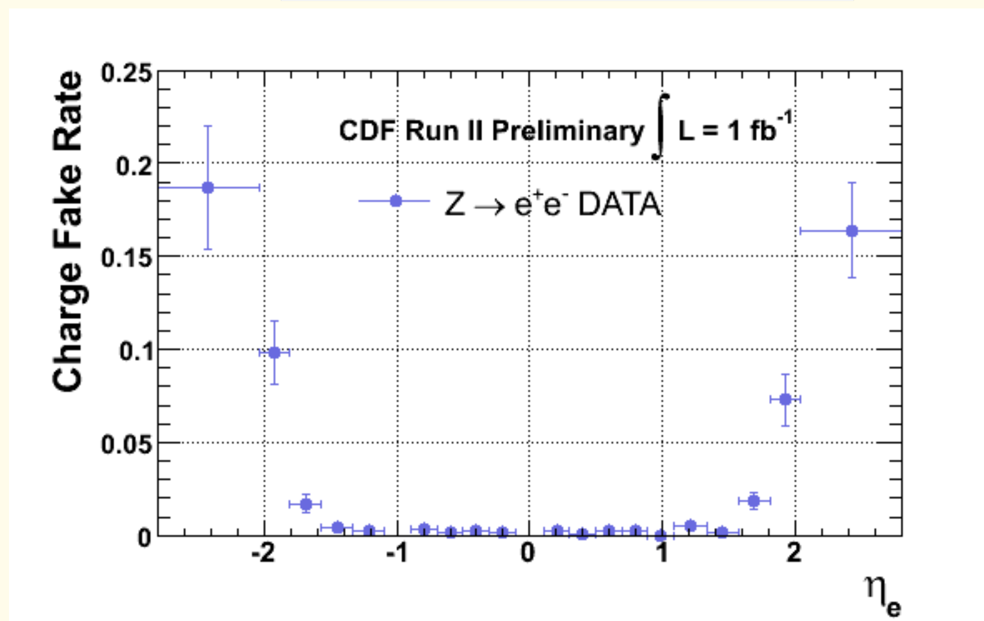
Electron Charge Identification

- Charge identification is crucial for this measurement.
- Forward tracking has fewer points at shorter lever arm
- Measure charge fake rate using $Z \rightarrow e^+e^-$ data sample (background subtracted)

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

- And then determine the charge fake rate as a function of the reconstructed charge and the weight factors.





Acceptance

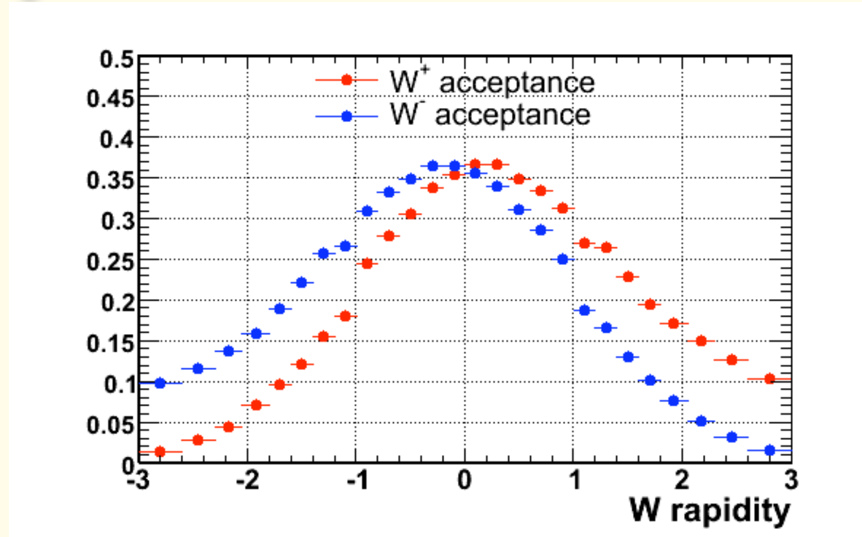
- Correction for the detector acceptance

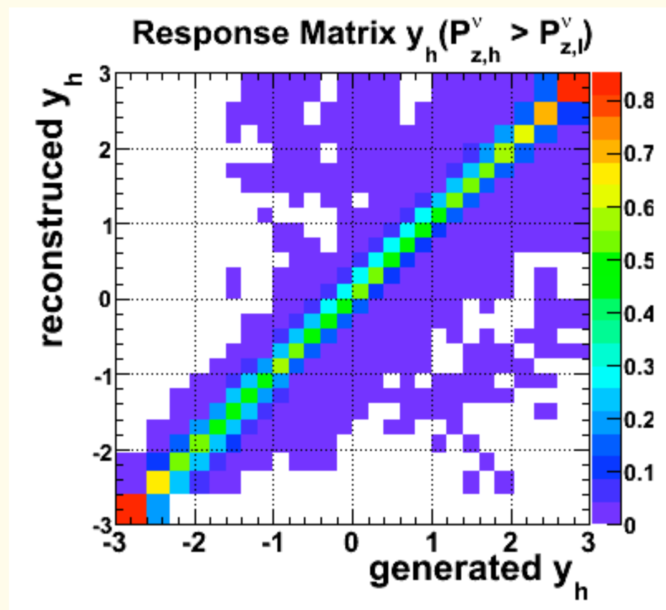
$$a^{\pm}(y_W) = \frac{\sum w^{\pm}(y_W)}{d\sigma^{\pm} / dy_W^{gen}}$$

- Trigger and electron ID efficiencies are also addressed to correct detector acceptance.

- Response Matrix : detector smearing

$$R_{ij}^{\pm} = \frac{P(\text{ observed in bin } i \text{ and true value in bin } j\text{ })}{P(\text{ true value in bin } j\text{ })} = P(\text{ observed in bin } i \mid \text{true value in bin } j\text{ })$$





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Uncertainties

Statistical:

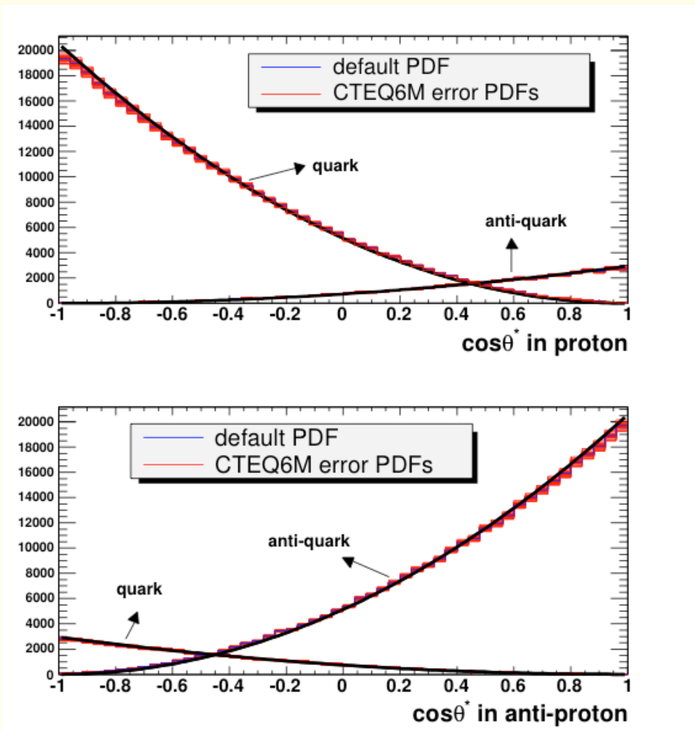
- Unfolding could correlate the statistical errors in nearby bins
- The statistical correlation coefficient between bins is found to be < 0.05.

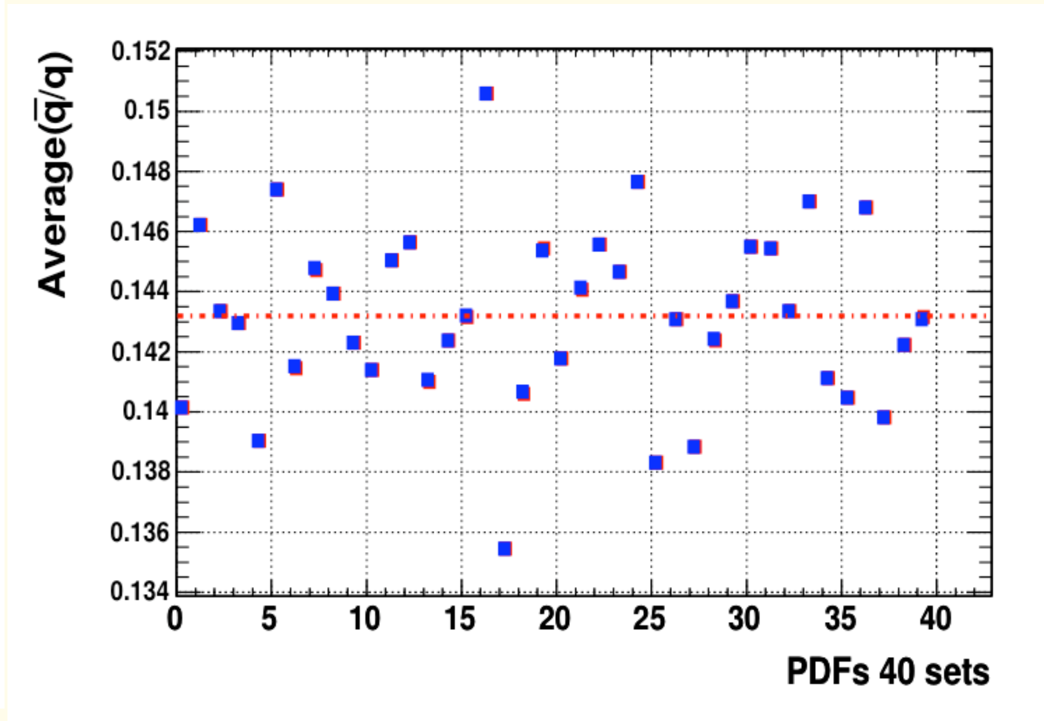
Systematic:

- Detector response
  - energy scale and smearing for electron and recoil
  - efficiency to find electron and pass missing E_T cut
- Reconstruction & Backgrounds
  - Uncertainties on charge fake rate and background estimates
- Inputs
  - PDF uncertainties (CTEQ6 PDF error sets) for total *W* production and quark/anti-quark fractions

Evaluation of Systematics

- Derive result with shifted parameters
- Example: effect of PDF's on Q factor (sea/valence quark ratio)

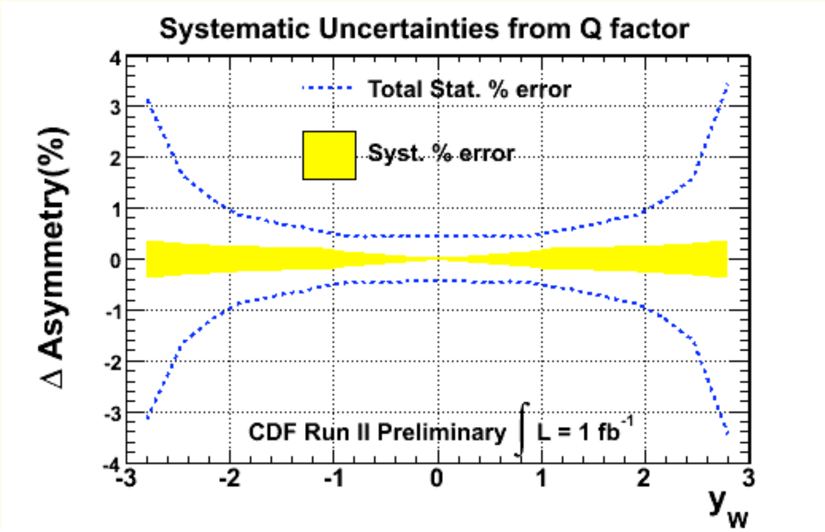


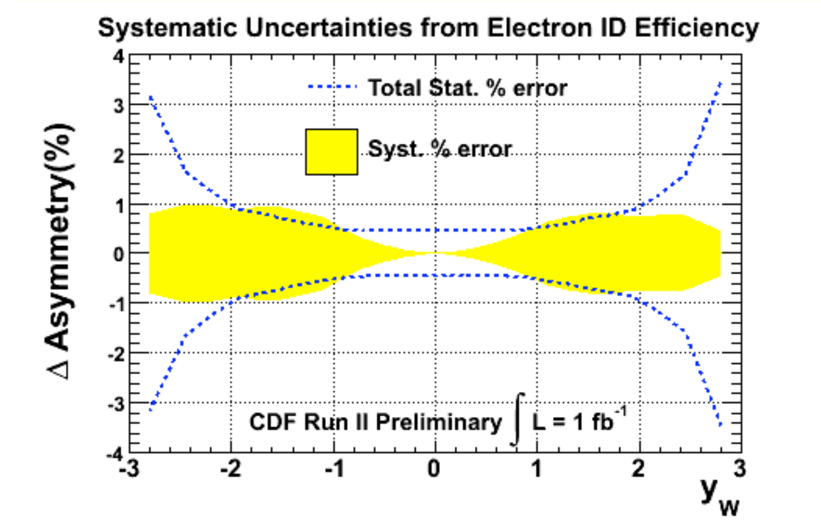


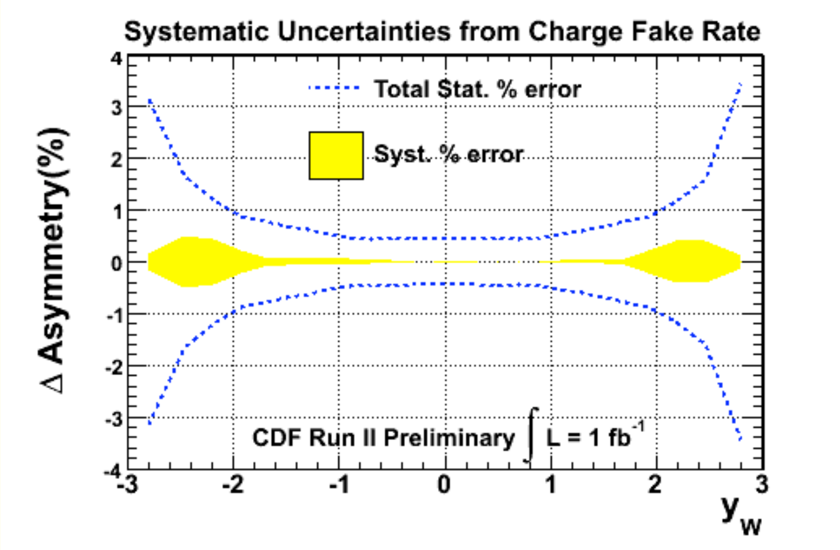
The effect of the 40 error PDFs from CTEQ on the cosθ∗ distributions in the proton (top) and anti-proton (bottom).

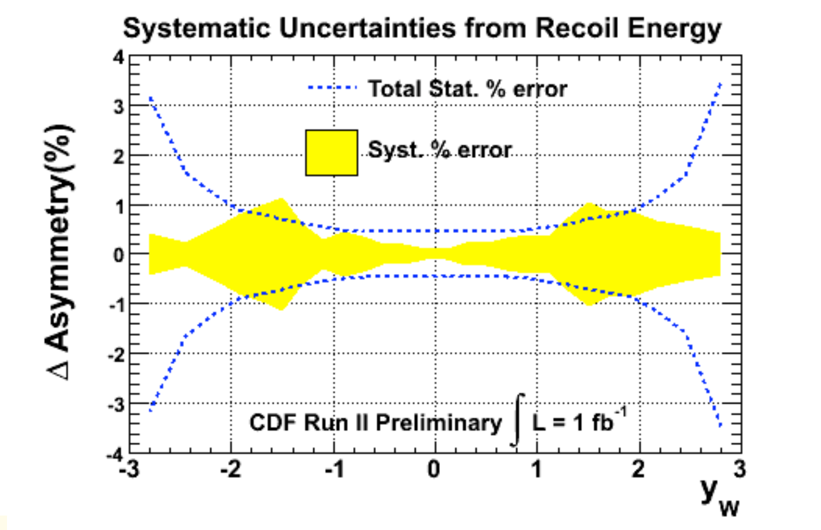
The average ratio of anti-quark to quark for each of the 40 error PDF sets.

Systematic Uncertainties

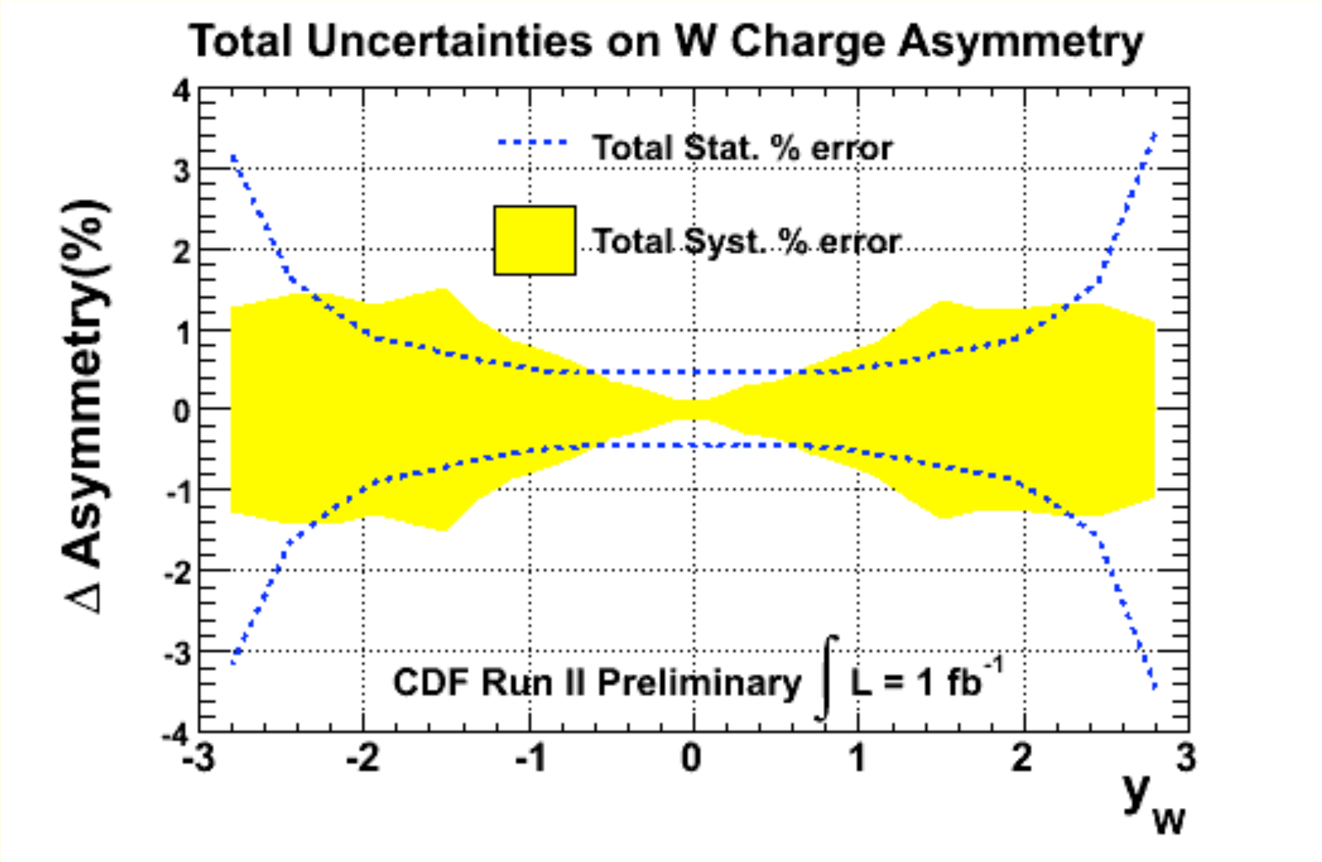








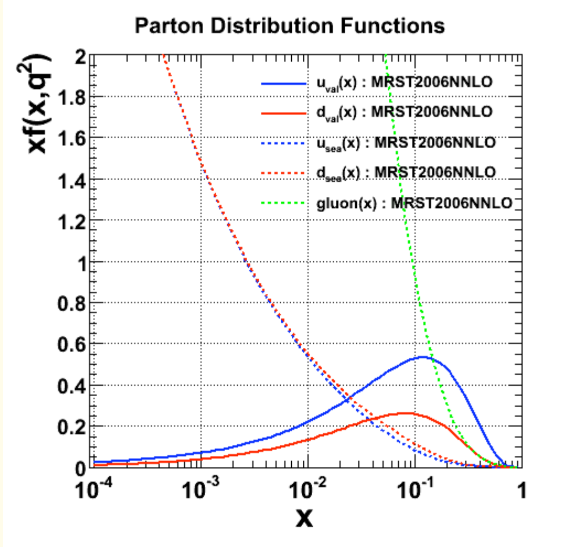
Systematic Uncertainties

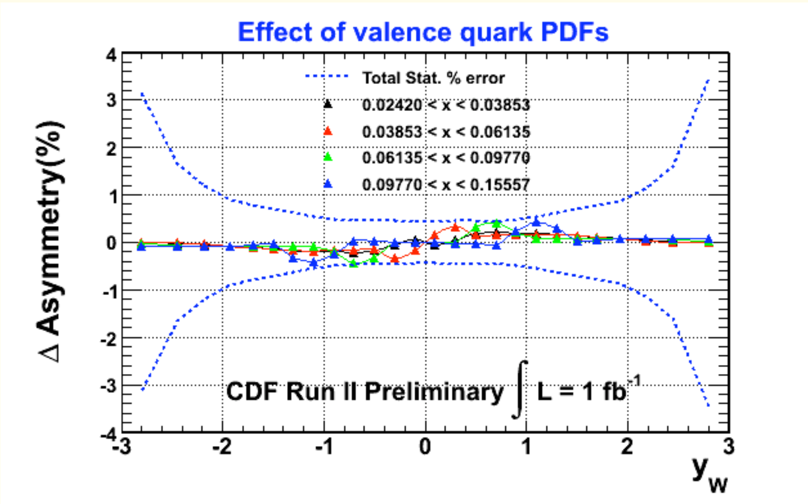


Systematics <1.5 % for $|y_W|$ > 2.0

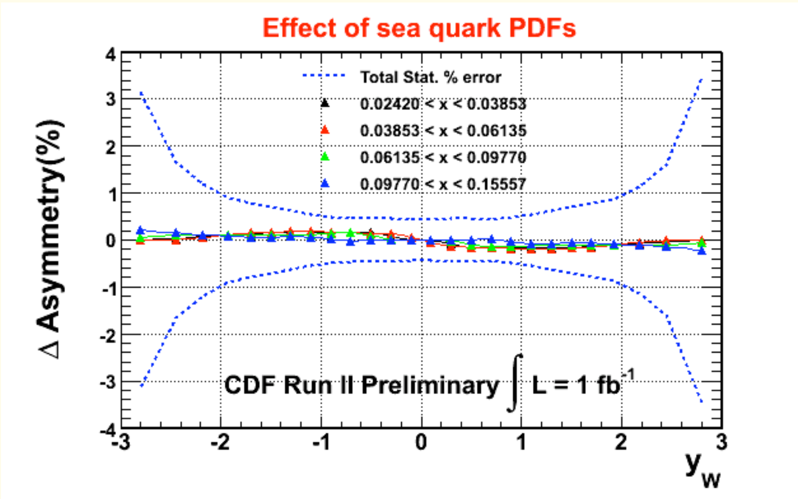
Effect of Input PDFs

- Studied effect of how W charge asymmetry measurement depends on *input* valence quark, sea quark and gluon PDFs
- Below we show the x range for which we find the largest differences in the measured W charge asymmetry
- Note that the effects of even these large changes in the quark and gluon distributions is small (< 0.003) compared with the statistical uncertainty (> 0.004).





effect of increasing valence u+d by +5%



effect of increasing sea u+d by +5%

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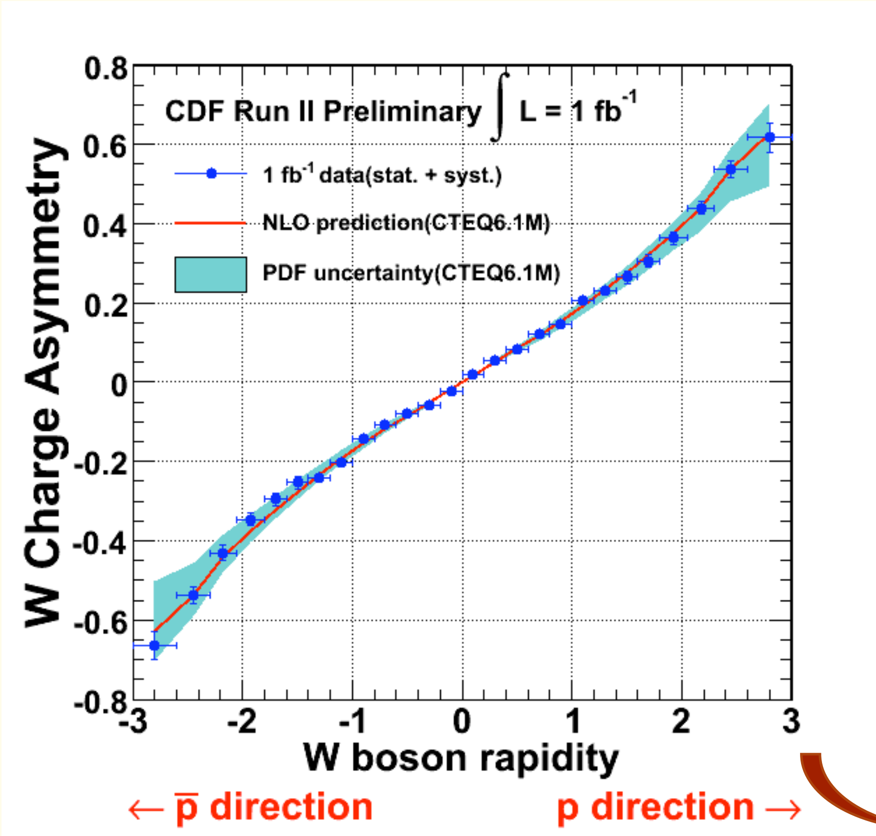
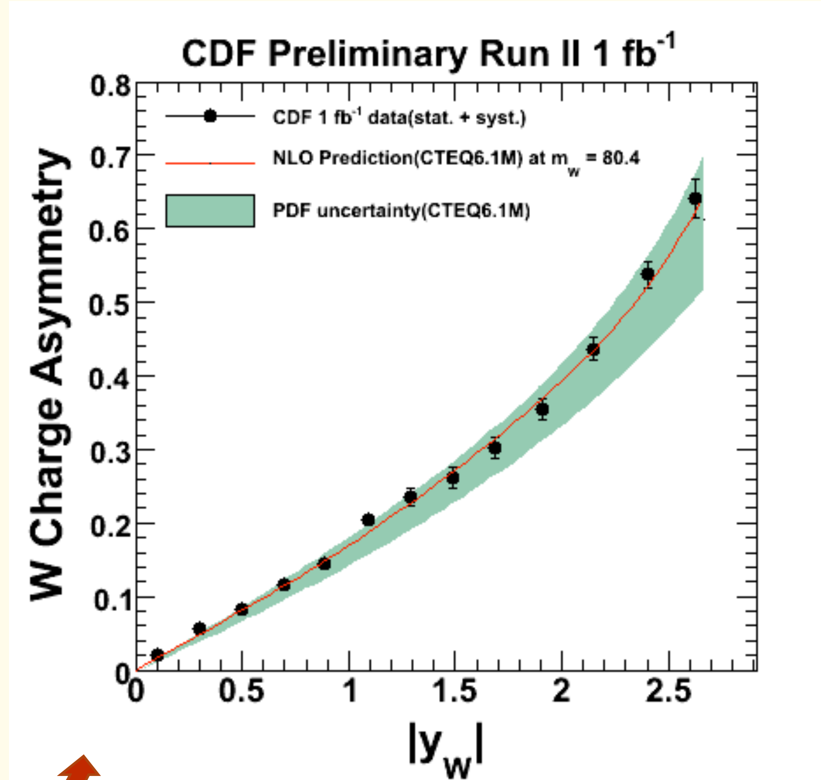
- New Analysis Technique
- Signal, Background and Corrections
- Uncertainties
- Results
- Comparison to latest results from DØ and status of PDF fits

CDF Result ($1fb^{-1}$)



Fold



Precision *much* better than error band!

- Positive and negative y_W agree, so fold
- The combination of the asymmetry accounts for all correlation for both positive and negative bins in y_W.
- Compare to NLO Prediction
  - NLO error PDFs (CTEQ)

CDF Result ($1fb^{-1}$)

Phys. Rev. Lett. 102, 181801 (2009).
Recently published in PRL!

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

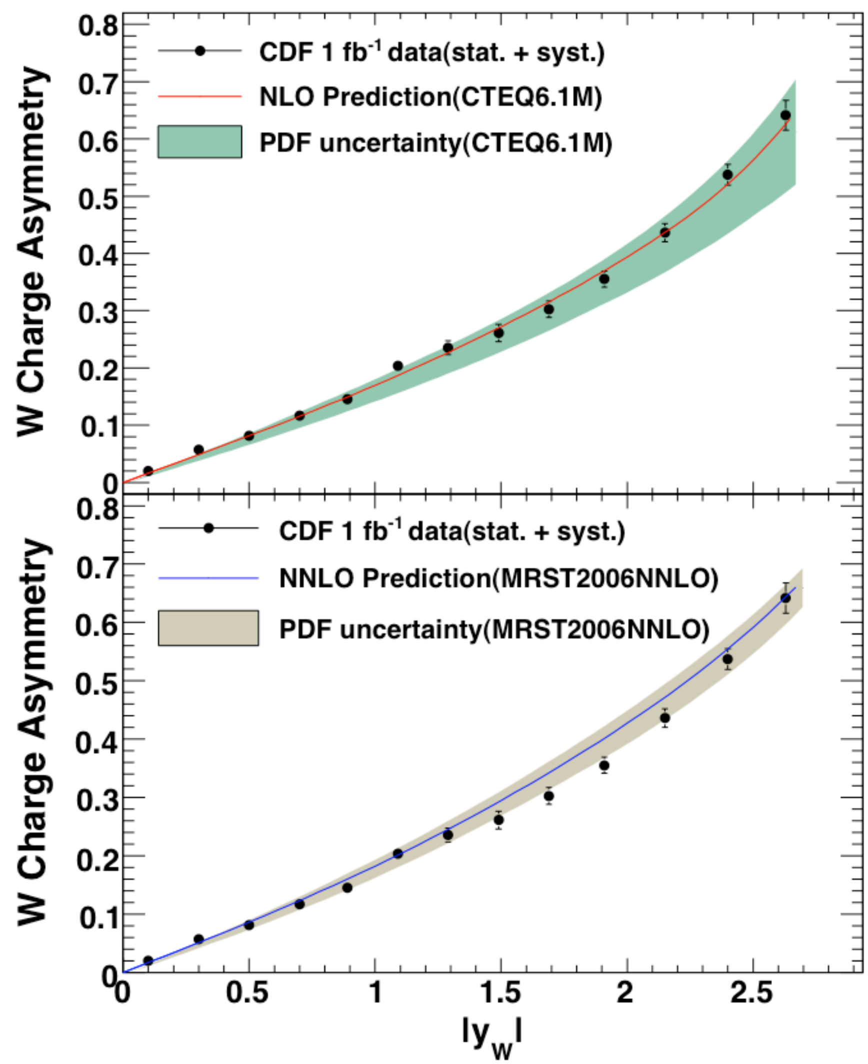
Precision *much* better than error band!

CTEQ6 NLO:P. M. Nadolsky et al., Phys. Rev. D 78, 013004 (2008).

CTEQ6 error PDFs: D. Stump et al., J. High Energy Phys. 10 (2003) 046.

NNLO Prediction: C. Anastasiou et al., Phys. Rev. D69 , 094008 (2004).

MRST 2006 PDFs: A. D. Martin et al., hep-ph/0706.0459, Eur. Phys. J., C28 , 455 (2003).



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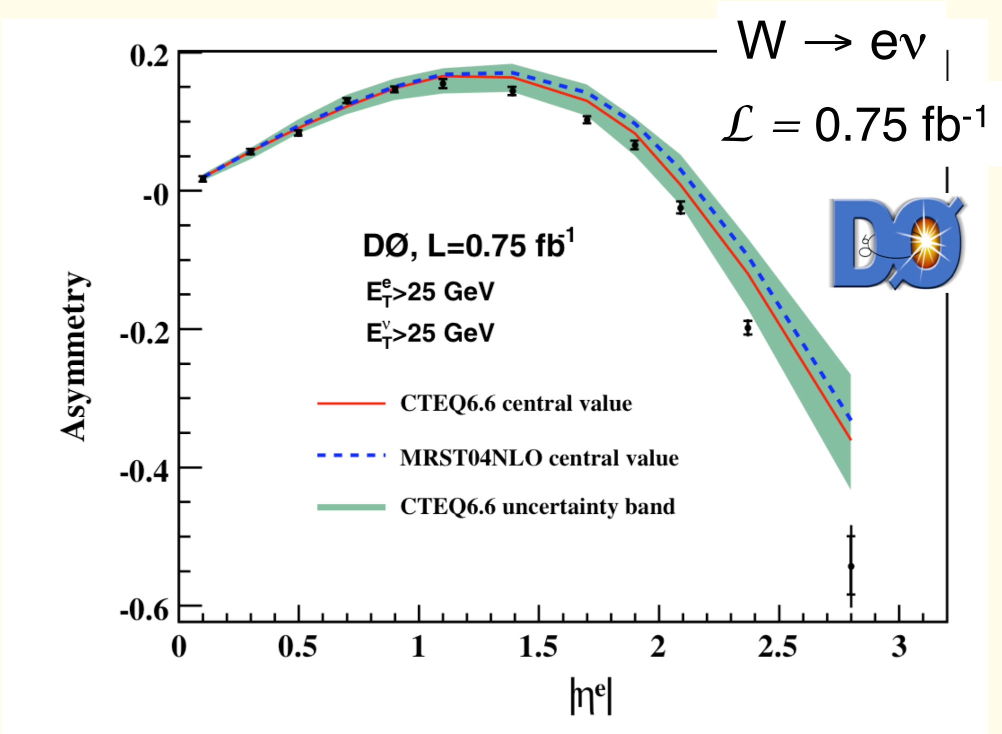
Latest Lepton Charge Asymmetry from DØ

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



PRL 101, 211801 (2008)

The measured charge asymmetry tends to be lower than the theoretical predictions for high $|\eta_e|$.

CTEQ6 NLO:P. M. Nadolsky et al., Phys. Rev. D 78, 013004 (2008).

CTEQ6 error PDFs: D. Stump et al., J. High Energy Phys. 10 (2003) 046.

MRST04NLO: A. D. Martin, R. G. Roberts, W. J. Stirling, and R. S. Thorne, Phys. Lett. B 604, 61 (2004).

Latest Lepton Charge Asymmetry from DØ

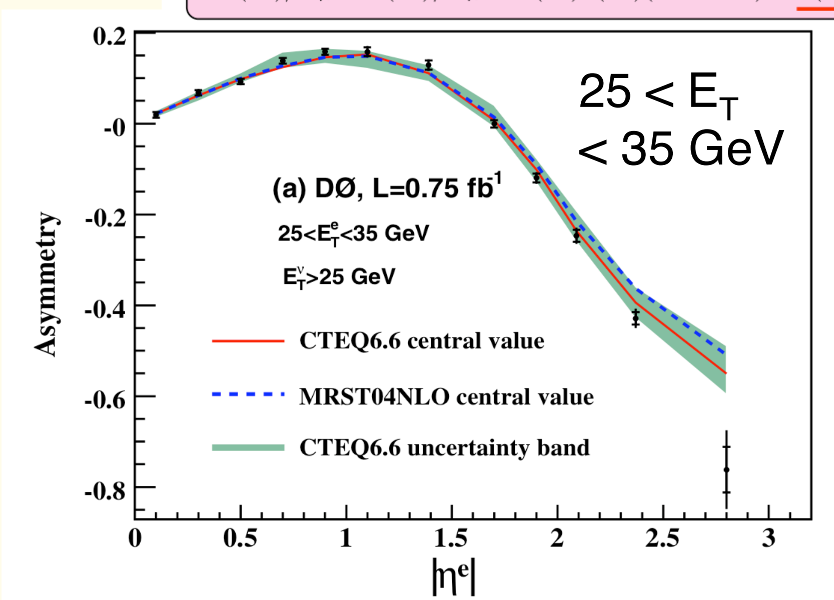
- Also measure the asymmetry in two bins of electron E_T
  - $25 < E_T < 35$ GeV and $E_T > 35$ GeV
- For a given η_e, the two E_T regions probe different ranges of y_W
  - For higher E_T, electron direction closer to W direction
  - Anti-quark term enhanced at low E_T
  - Can provide some distinction between sea & valence
  - Improve sensitivity to the PDFs

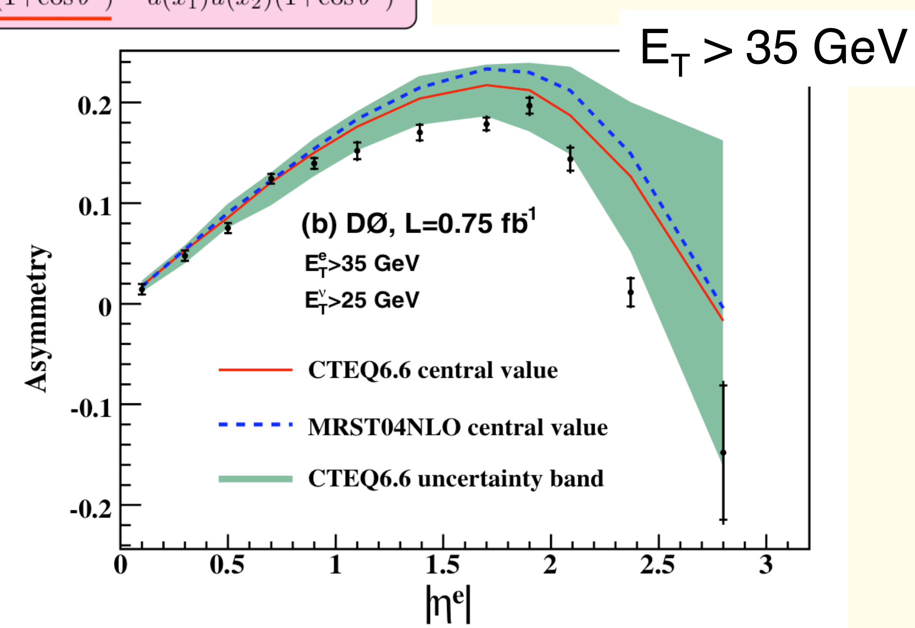
$$\cos\theta^* = \sqrt{1 - 4E_T^2/M_W^2}$$

Angle between lepton and proton in W rest frame

$$y_l = y_W \pm \frac{1}{2}\ln\left(\frac{1+\cos\theta^*}{1-\cos\theta^*}\right)$$

$$d\sigma(l^+)/d\eta_l - d\sigma(l^-)/d\eta_l \approx u(x_1)d(x_2)(1-\cos\theta^*)^2 + \underline{\bar{d}(x_1)\bar{u}(x_2)}(1+\cos\theta^*)^2 - d(x_1)u(x_2)(1+\cos\theta^*)^2$$



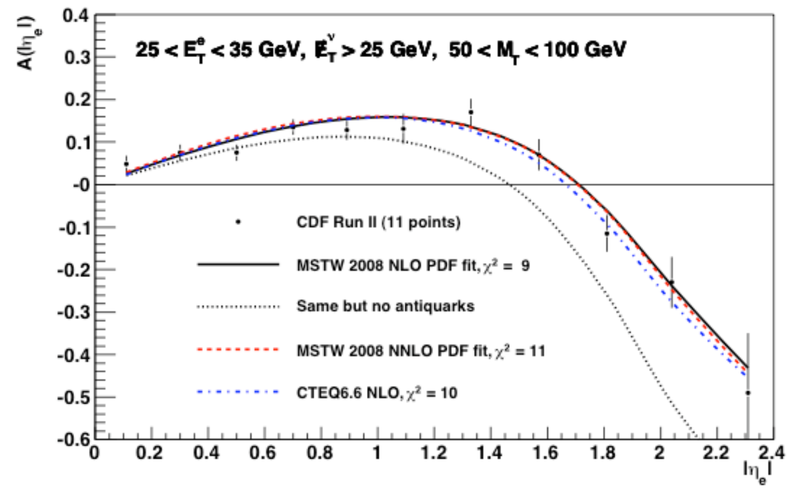


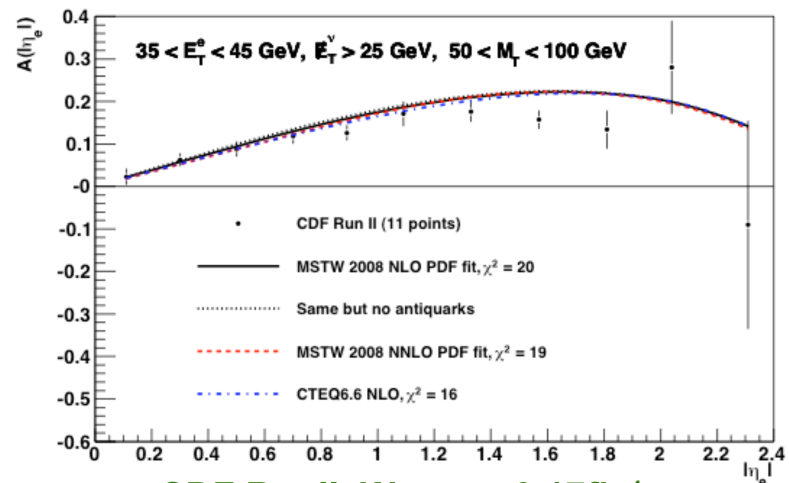
Latest fits from MSTW

- Latest fits from MSTW *do not* use the latest Tevatron results just shown. They use:
  - DØ Run II, $W \to \mu\nu$, 0.3 fb^{-1}
  - CDF Run II, $W \to e\nu$, 0.17fb^{-1}
- Show anti-quark discriminating power at low E_T

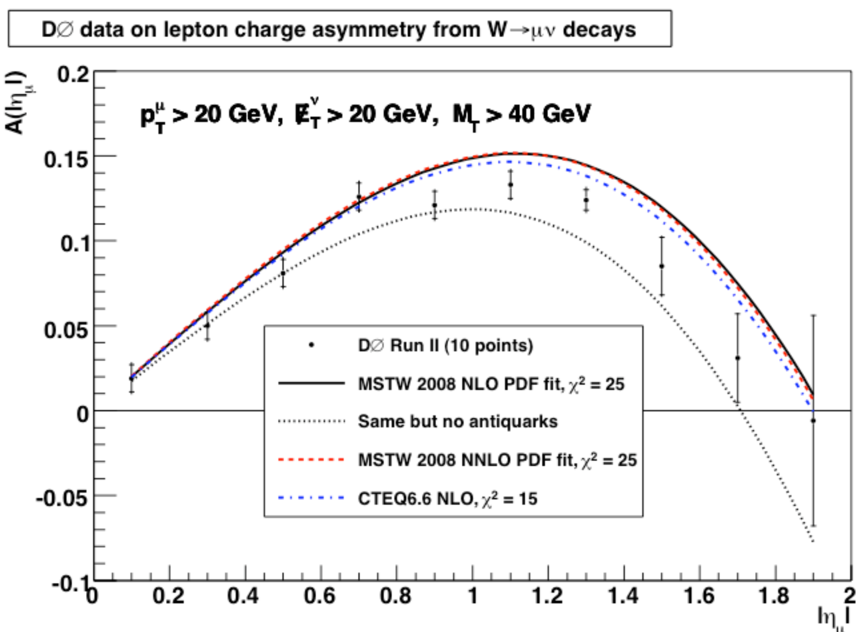
A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt: arXiv:0901.0002v1 [hep-ph]

CDF data on lepton charge asymmetry from W→eν decays





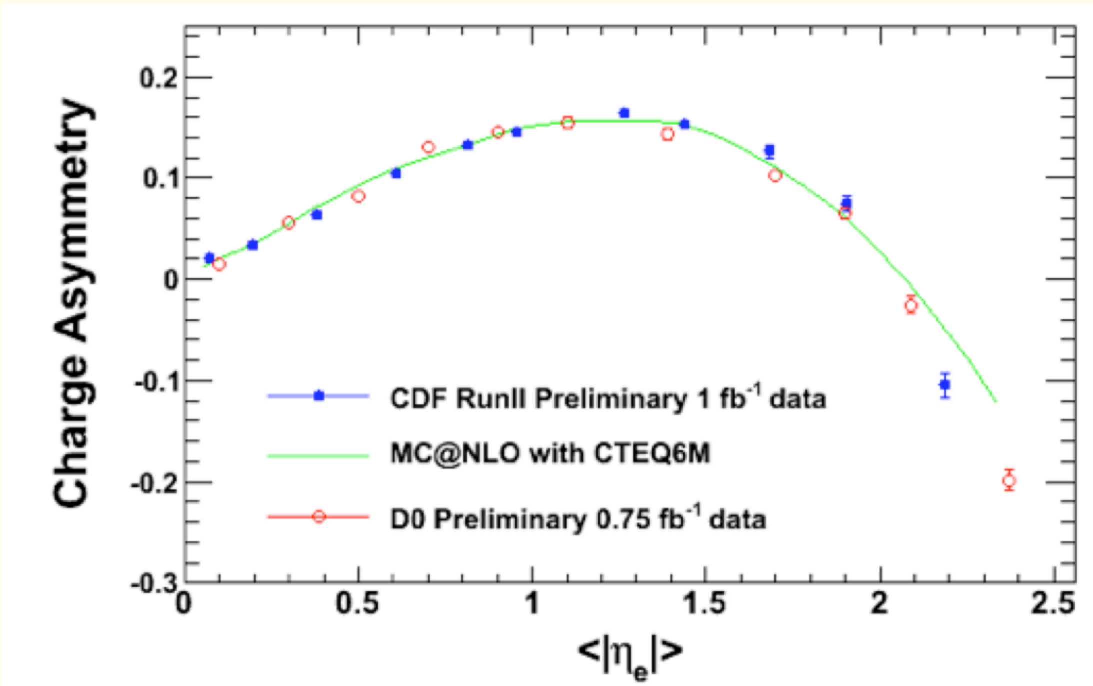
CDF RunII, $W \to e\nu$, 0.17fb^{-1}
PRD 71, 051104 (2005)



DØ RunII, $W \to \mu\nu$, 0.3 fb^{-1}
PRD 77, 011106 (2008)

Comparison of latest CDF & DØ measurements

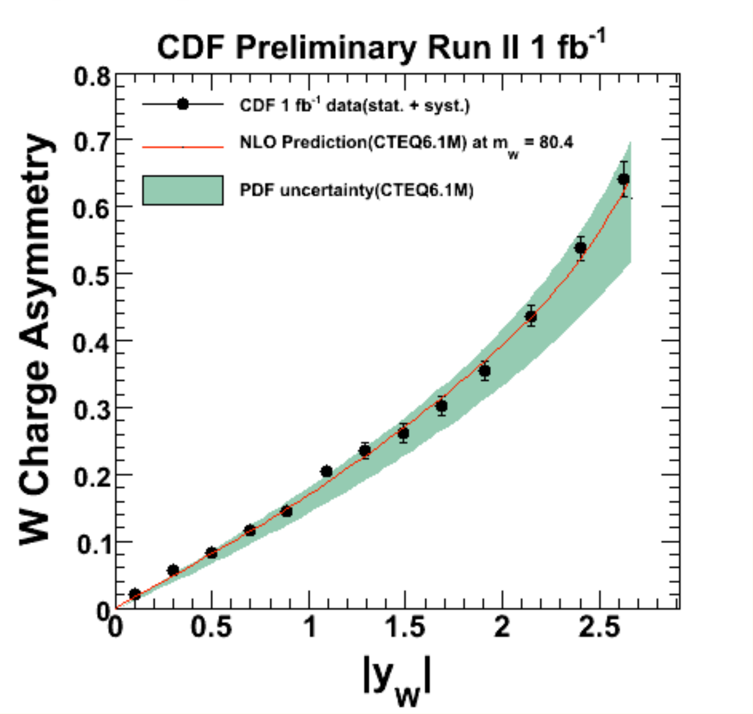
- Both latest CDF/DØ data should be providing improved d/u constraints but life is never that simple...



- Note:
  - CDF provides stat. only η_l data above for $1 fb^{-1}$
  - Distributions not broken down in E_T bins
- For $0.8 < \eta_l < 2.0$: DØ data below CDF
- Investigation ongoing …

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



- **Both experiments working with PDF fitting groups to incorporate results and understand differences**

Measurement: Phys. Rev. Lett. 102, 181801 (2009).

Thesis of B. Han: FERMILAB-THESIS-2008-15

Method: Phys. Rev. D 79, 031101(R) (2009).