# Precision Electroweak Physics at Hadron Colliders

Eric James
Fermi National Accelerator Lab

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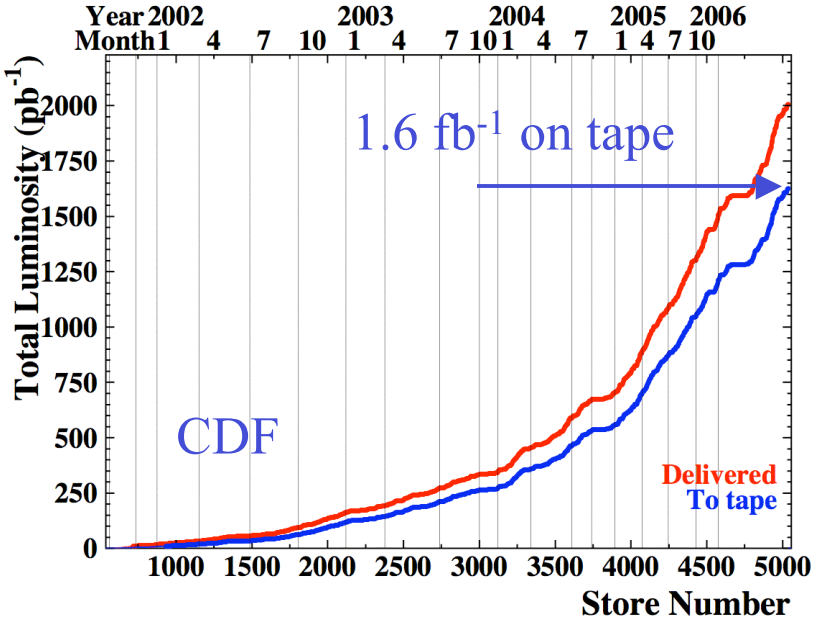
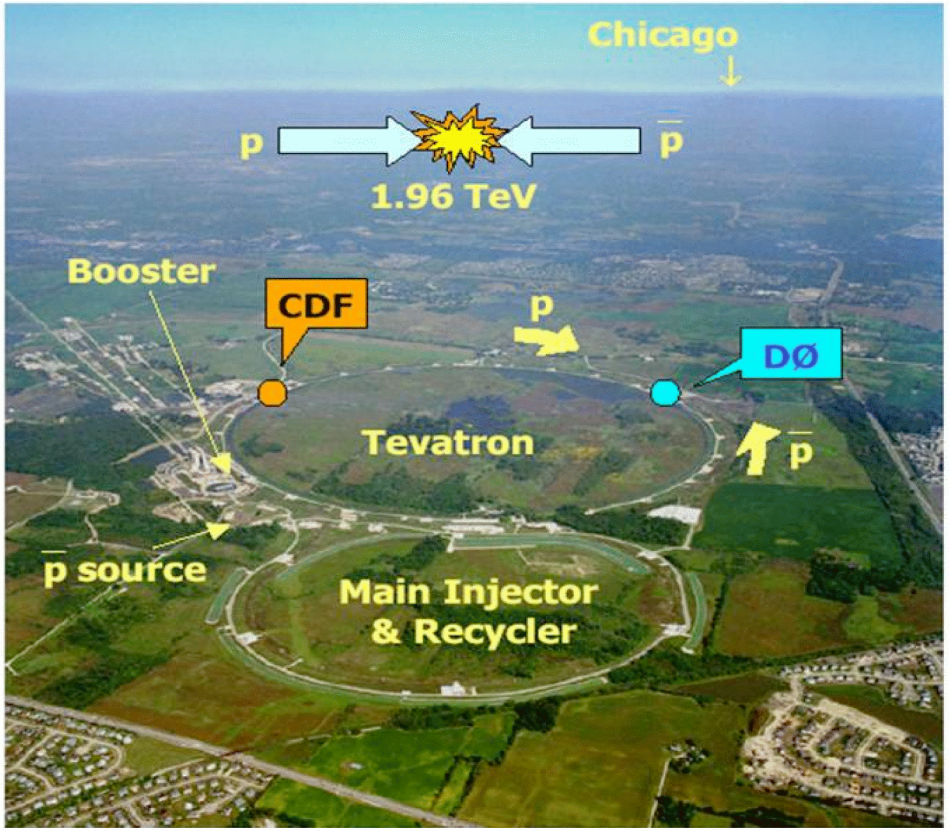
# Outline

- The substantial samples of W and Z bosons collected by the CDF and D∅ experiments at the Tevatron $p\bar{p}$ collider accommodate a wide variety of precision electroweak measurements.
  - Precision measurement of electroweak parameters.
  - Precision tests of QCD production mechanisms

# Tevatron

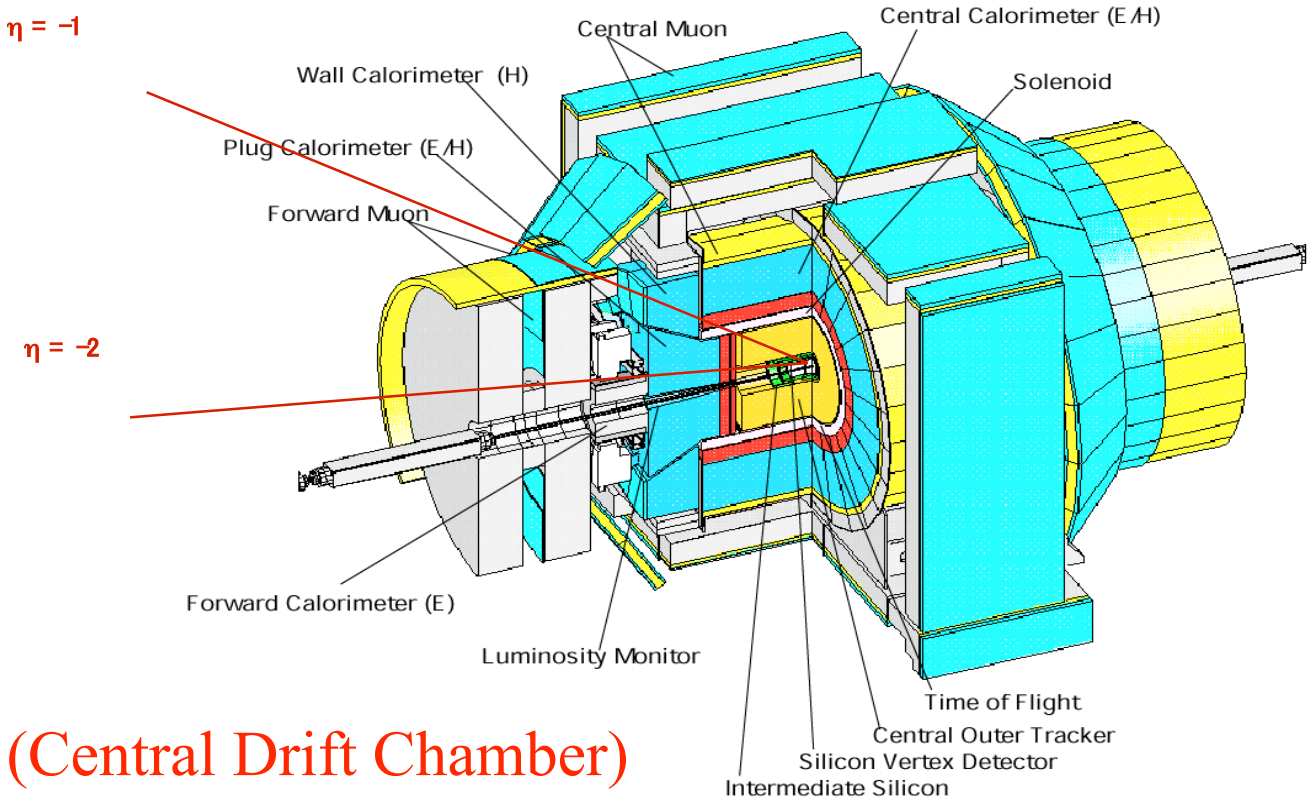



| Mode | Events/Week/Exp. (before trigger & cuts) |
|---|---|
| W→eν | ~50,000 |
| Z→ee | ~5,000 |




- Tevatron is a W & Z factory

# CDF Experiment

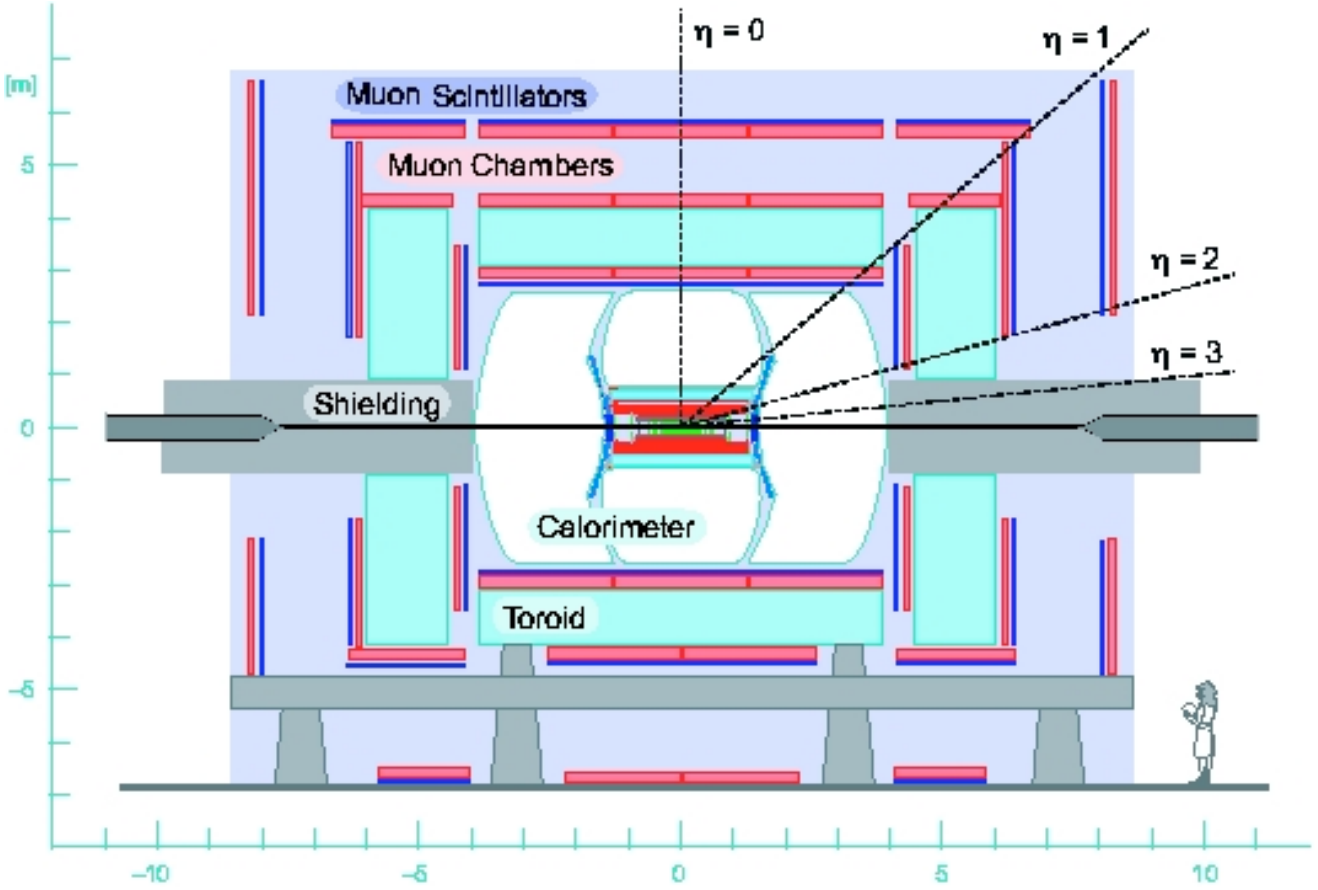



- Tracking (Central Drift Chamber)
  - $\delta p_T/p_T = 0.0005 \times p_T$ [GeV]
- EM Calorimeter
  - $\delta E_T/E_T \sim 13.5\% / \sqrt{E_T} \oplus 1.5\%$ [GeV, $|\eta| < 1.1$]

Leptons from W/Z decays

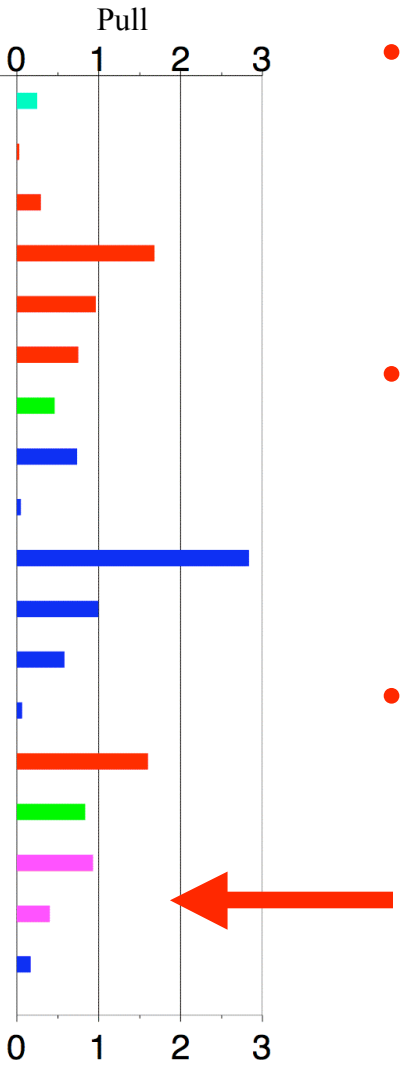
# DØ Experiment

- Fiber Tracker
  - Tracking out to $|\eta| < 1.8$
- Calorimeter
  - Coverage out to $|\eta| < 4$
- Muon System
  - Coverage out to $|\eta| < 2$



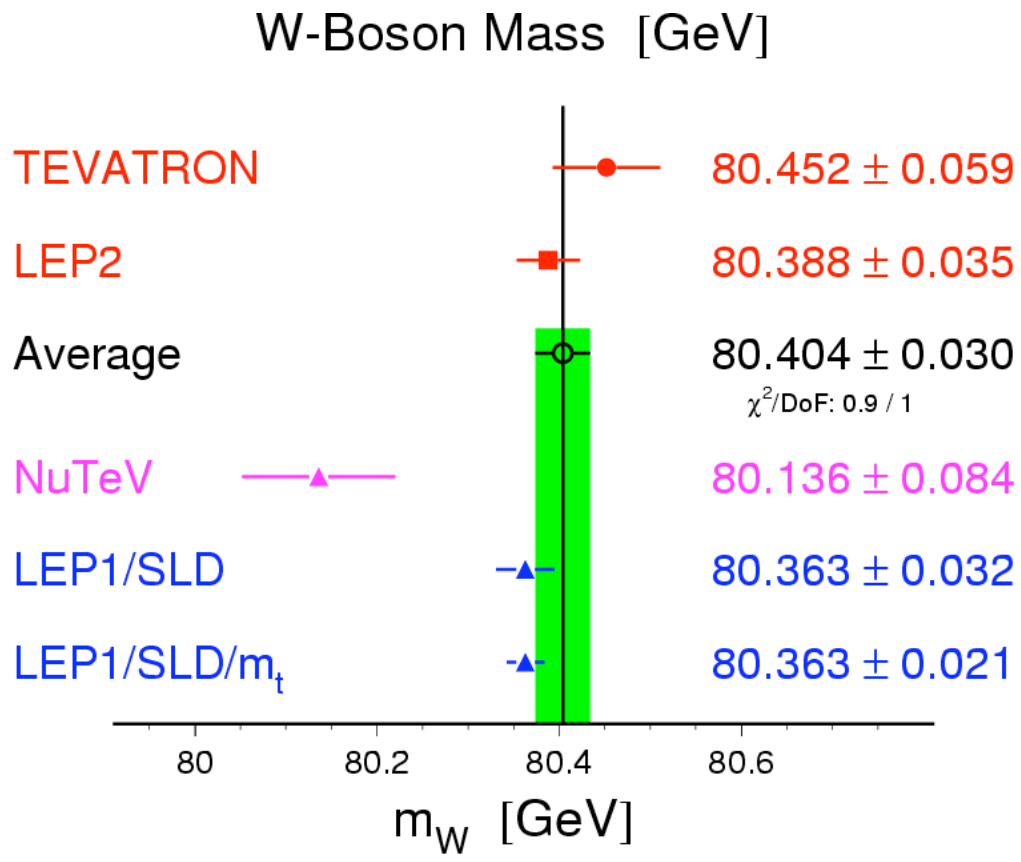
# Precision EWK Measurements

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | 0.02758 ± 0.00035 | 0.02767 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma^0_{had}$ [nb] | 41.540 ± 0.037 | 41.478 |
| $R_l$ | 20.767 ± 0.025 | 20.743 |
| $A^{0,l}_{fb}$ | 0.01714 ± 0.00095 | 0.01643 |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1480 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21581 |
| $R_c$ | 0.1721 ± 0.0030 | 0.1722 |
| $A^{0,b}_{fb}$ | 0.0992 ± 0.0016 | 0.1037 |
| $A^{0,c}_{fb}$ | 0.0707 ± 0.0035 | 0.0742 |
| $A_b$ | 0.923 ± 0.020 | 0.935 |
| $A_c$ | 0.670 ± 0.027 | 0.668 |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1480 |
| $\sin^2\theta^{lept}_{eff}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W$ [GeV] | 80.404 ± 0.030 | 80.376 |
| $\Gamma_W$ [GeV] | 2.115 ± 0.058 | 2.092 |
| $m_t$ [GeV] | 172.5 ± 2.3 | 172.9 |




- Many high precision measurements of EWK observables from LEP and SLD
- A total of roughly 17 million Z events were collected by the four LEP experiments
- In 8 $fb^{-1}$ of running the two Tevatron experiments will collect a similar number of W events

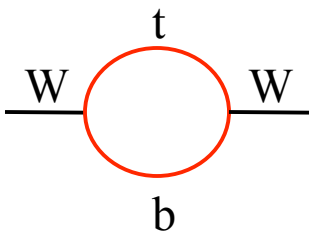
# Current W Mass Results



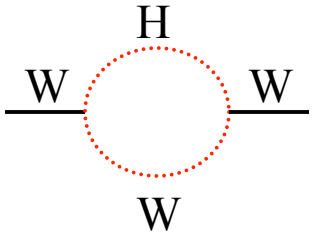

- Current level of precision ~ 0.04%
- This uncertainty is more than an order of magnitude higher than that for the Z boson mass

$M_Z = 91.1876 \pm 0.0021$

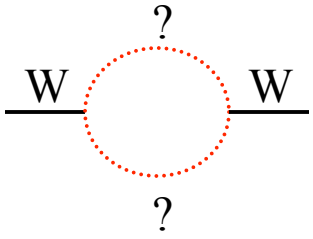
# W Boson Mass




$\Delta M_W \propto M^2_{top}$




$\Delta M_W \propto \ln M_H$

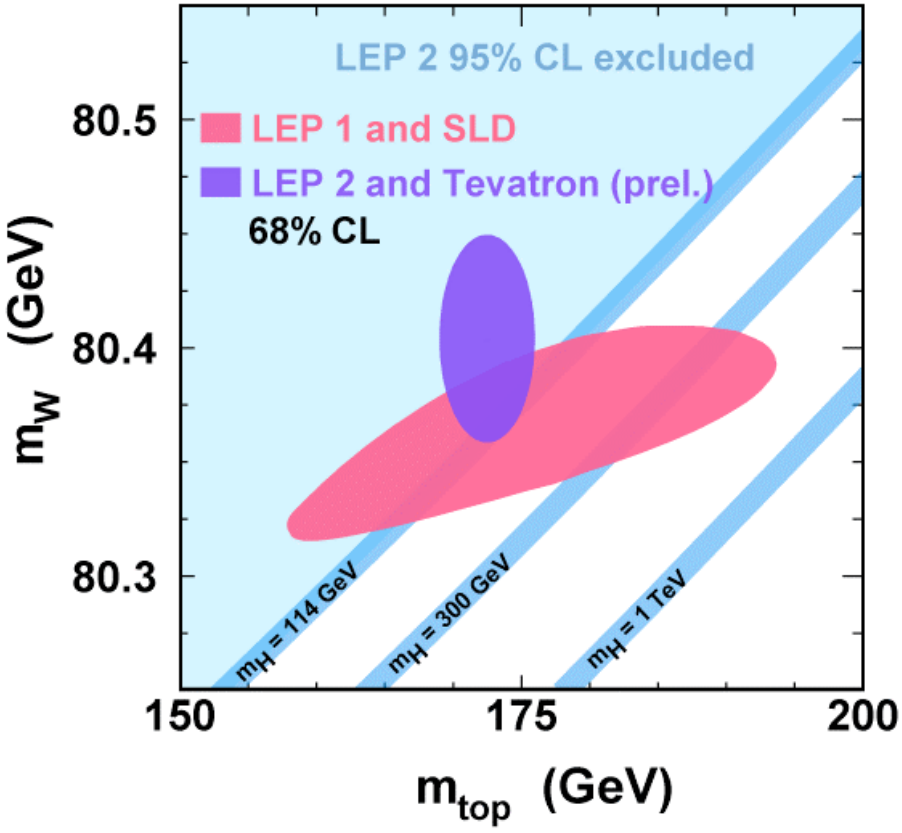



New Physics

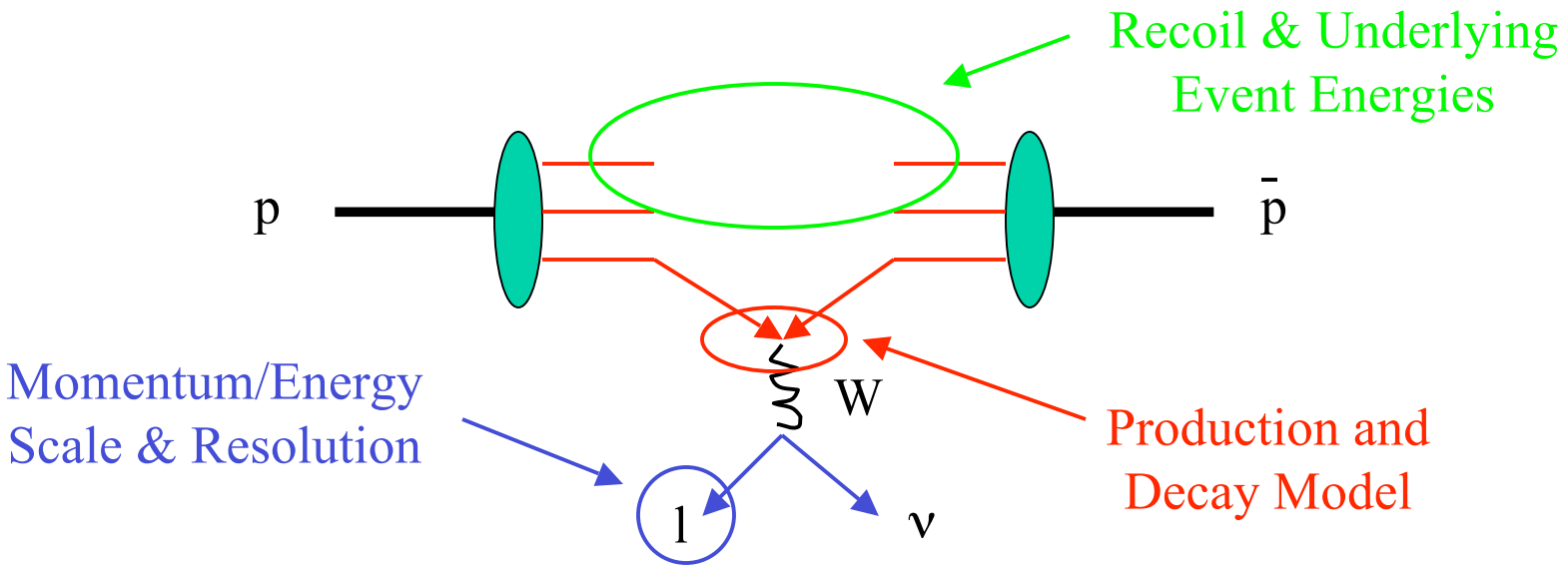
- Self-energy corrections to the W mass depend on the mass of the top quark and Higgs boson.

# Constraints on Higgs Mass

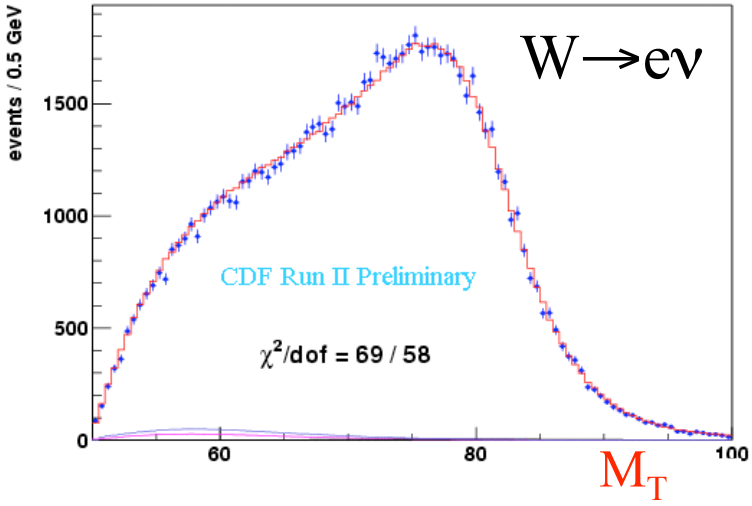
- To obtain equivalent constraint on $M_H$
  - $\Delta M_{top} \sim 1.5$ GeV/$c^2$, $\sim 1\%$ on $M_{top}$
  - $\Delta M_W \sim 10$ MeV/$c^2$, $\sim 0.01\%$ on $M_W$



# W Mass Measurement




- Requires a detailed understanding (~10 MeV) of all aspects of W boson production and detection

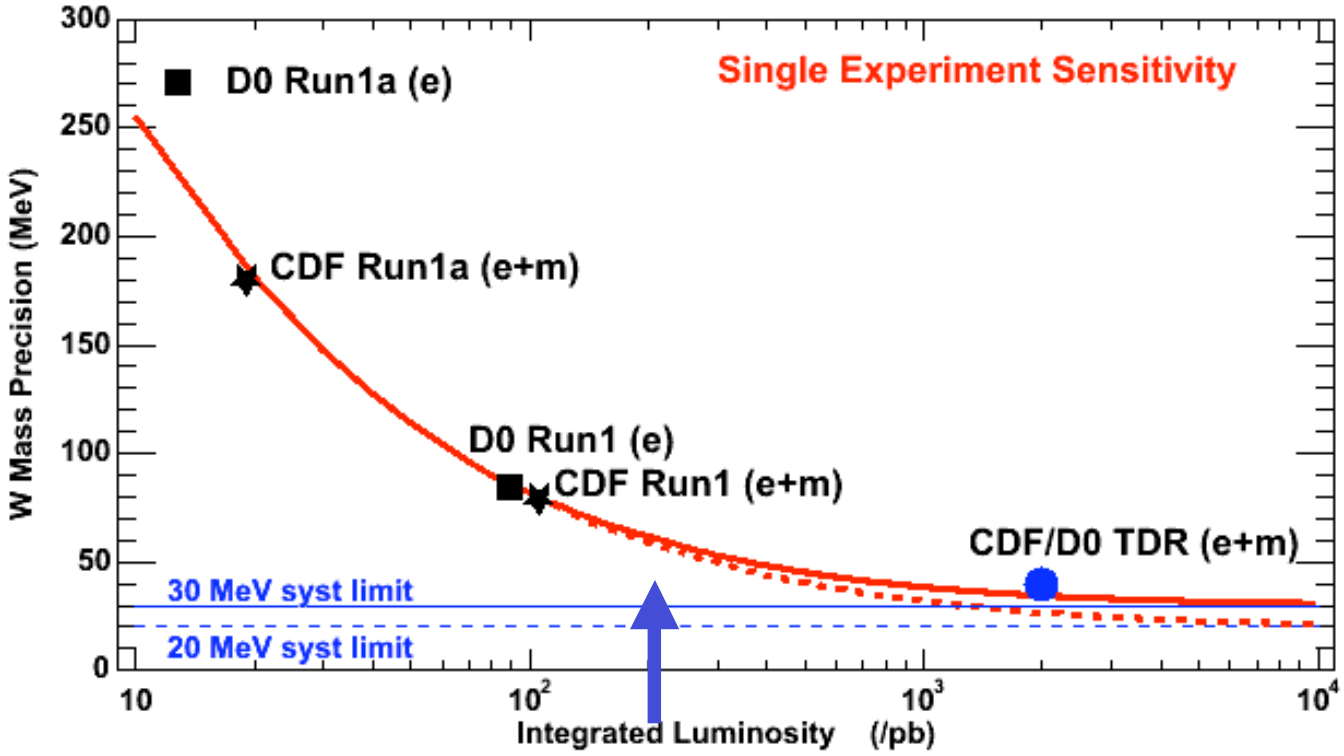


# W Mass Uncertainties

- CDF preliminary systematic uncertainties for 200 $pb^{-1}$
- Currently, estimate a combined 48 MeV uncertainty
- Finalizing analysis and completing exhaustive cross checks

| Systematic [MeV] | Electrons | Muons | Common |
|---|---|---|---|
| Lepton Energy Scale and Resolution | 27 | 17 | 17 |
| Recoil Scale and Resolution | 14 | 12 | 12 |
| Backgrounds | 7 | 9 | |
| Production and Decay Model | 16 | 17 | 16 |
| Statistics | 48 | 53 | |
| Total | 60 | 60 | 26 |

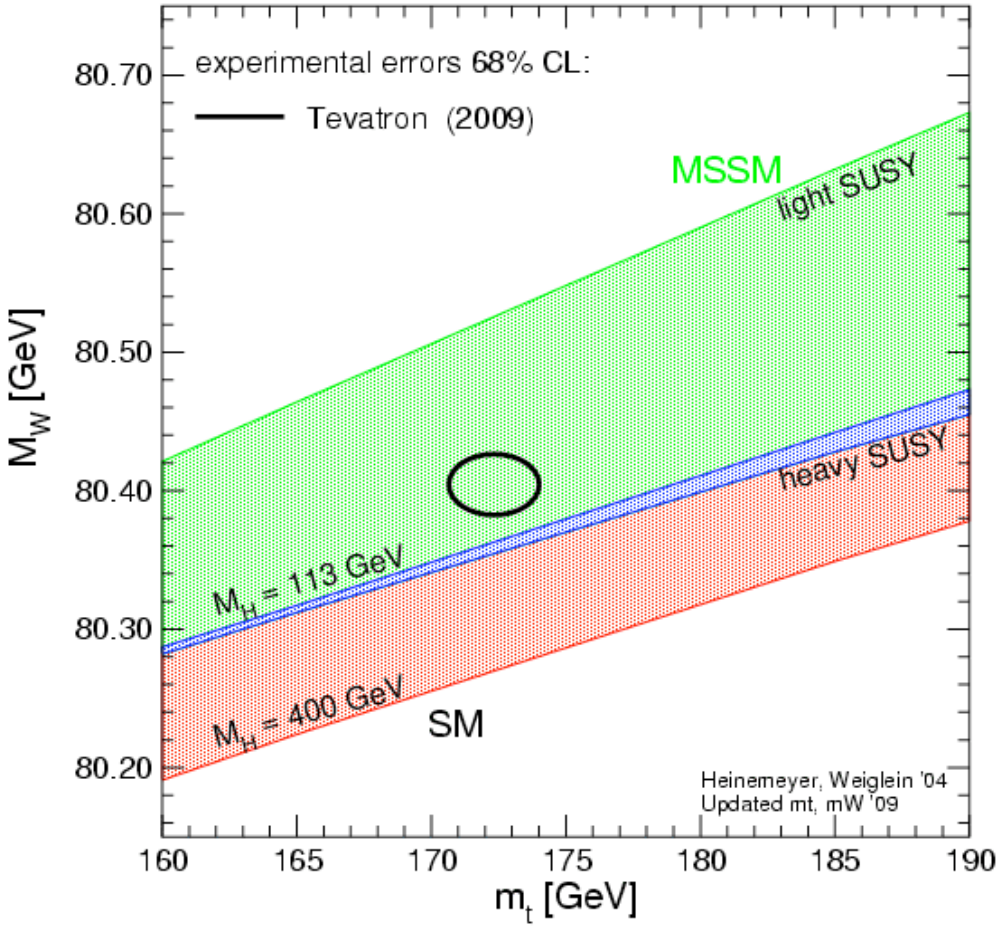
# W Mass Measurement Projections




- Beyond 2 $fb^{-1}$ overall uncertainty does not improve significantly without better understanding of systematics

# Ultimate Tevatron Constraints

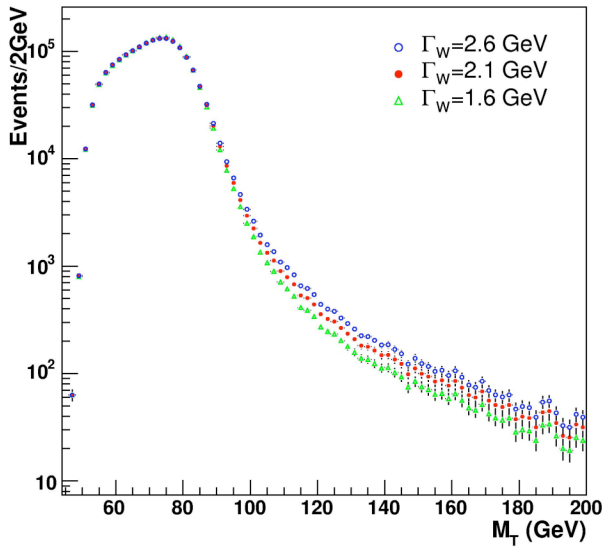
- Potential constraints on $M_H$ based on 8 $fb^{-1}$ of data per experiment
- Use to differentiate between a SM or SUSY-like Higgs
- Provides a test of the theories if a Higgs boson is discovered in the interim

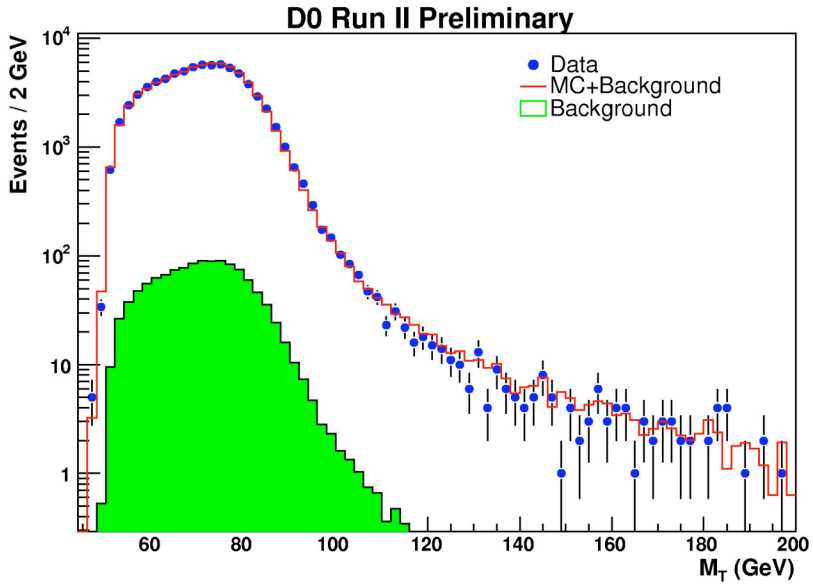


# W Boson Width

- The W boson width plays a less important role in the overall EWK fits than the W boson mass, but a precision measurement still serves as a useful test of the Standard Model
- Direct measurement is sensitive to any deviations from the Standard Model for $M(W^*) > M_W$
- Indirect measurement can be made very precisely and provides CKM matrix constraints.

# Direct Width Measurement




- $\Gamma_W$ is extracted from shape of high $M_T$ tail in W→eν events
- Production effects and detector resolution distort the lineshape
- Use peak region to normalize background and signal contributions

$$\Gamma_W = 2.011 \pm 0.093 \text{ (stat)} \pm 0.107 \text{ (syst) GeV}$$

# Indirect Width Measurement

SM Calculation

Precision LEP Measurements

$$R = \frac{\sigma_W}{\sigma_Z} \times \frac{\Gamma(W \to l\nu)}{\Gamma(W)} \times \frac{\Gamma(Z)}{\Gamma(Z \to ll)}$$

NNLO Calculation

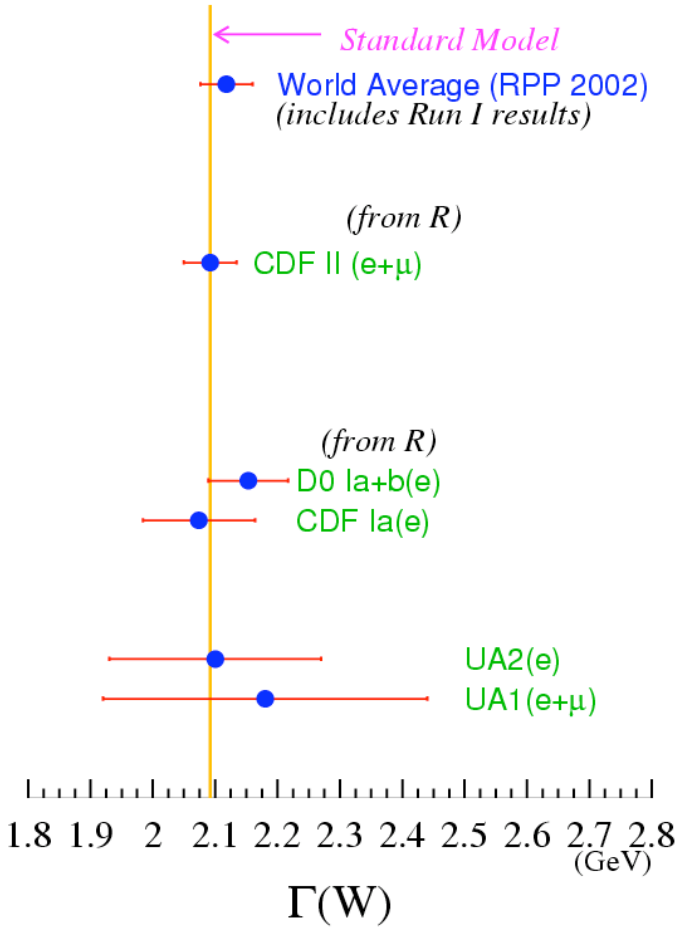
$$R_{exp} = \frac{\sigma \cdot BR\,(W \to l\nu)}{\sigma \cdot BR\,(Z \to ll)}$$

# Using Standard Cross Sections

- R measured in electron and muon decay channels using standard CDF lepton and boson selection criteria
- Combination of channels gave a result for R with an overall precision of 1.9%

$R = 10.84 \pm 0.15(stat) \pm 0.14\ (sys)$

$\Gamma(W) = 2092 \pm 42$ MeV



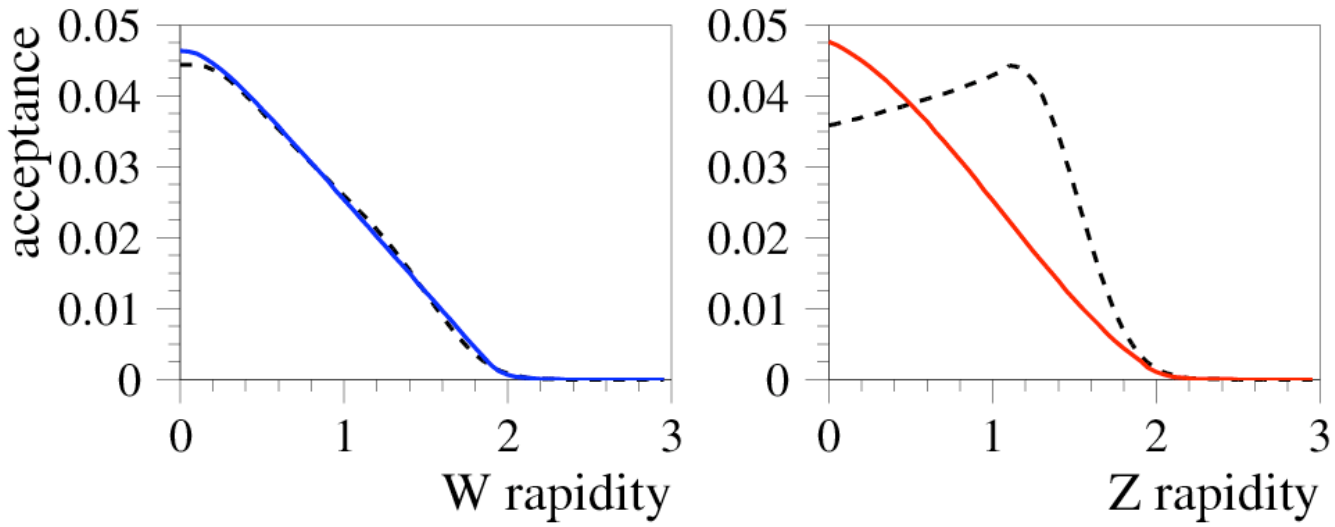
# Indirect Width Uncertainties

| Category | Electron | Muon | Correlation |
|---|---|---|---|
| Stat error | 0.1753 | 0.2705 | 0.0 |
| Acceptance stat error | 0.0294 | 0.0480 | 0.0 |
| Boson $p_T$ | 0.0019 | 0.0044 | 1.0 |
| PDF | 0.0704 | 0.0851 | 1.0 |
| $P_T$ scale/resolution | 0.0012 | 0.0170 | 1.0 |
| $E_T$ scale/resolution | 0.0185 | 0.0000 | 0.0 |
| Material | 0.0319 | 0.0000 | 0.0 |
| Recoil calibration | 0.0267 | 0.0384 | 1.0 |
| Uncorrelated efficiency error | 0.1203 | 0.1015 | 0.0 |
| Track reconstruction efficiency | 0.0170 | 0.0445 | 1.0 |
| QCD background | 0.0435 | 0.0397 | 1.0 |
| Uncorrelated EWK background | 0.0089 | 0.0112 | 0.0 |
| Correlated EWK background | 0.0042 | 0.0290 | 1.0 |
| Cosmic ray background | 0.0000 | 0.0702 | 0.0 |
| $\gamma^*$ correction factor | 0.0109 | 0.0112 | 1.0 |

Raw uncertainties on R

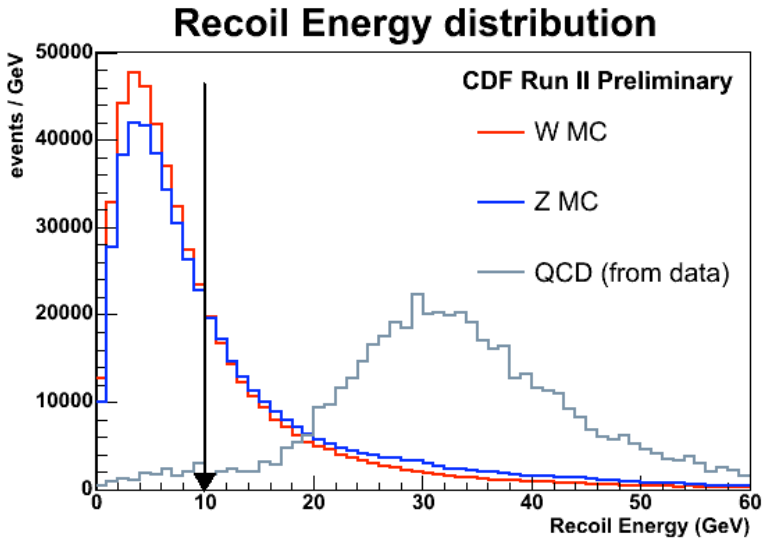
# Improved Method

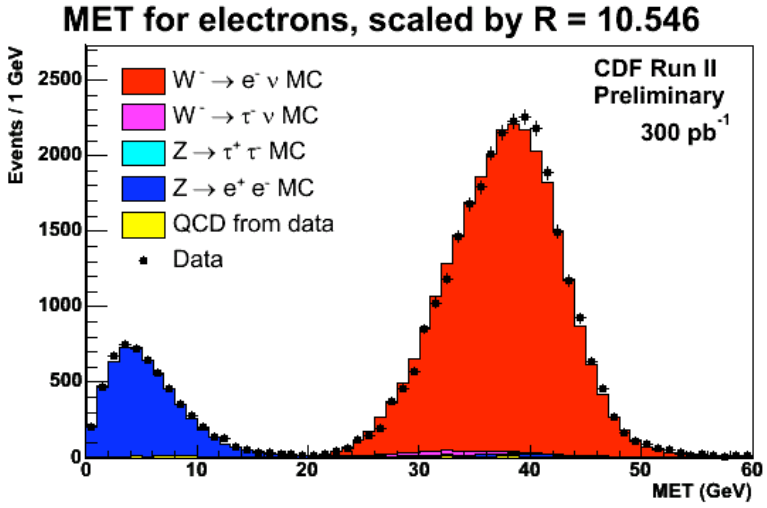
- Use a common set of selection criteria for both W and Z events by requiring a single high-quality lepton (fit +/- charges separately)
  - No efficiency or trigger uncertainties
  - Large reduction in PDF uncertainties



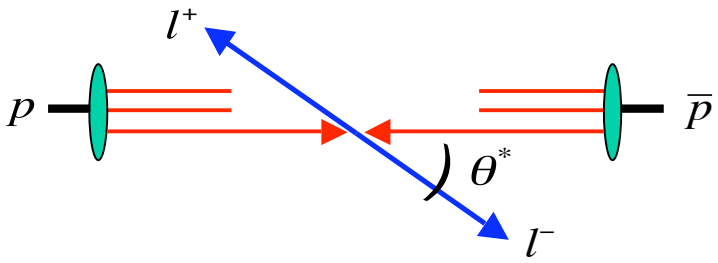
# Precision R Measurement

- Cut on hadronic recoil |U| < 10 GeV to minimize QCD background
- Use maximum likelihood fit to extract W and Z contributions to common candidate sample



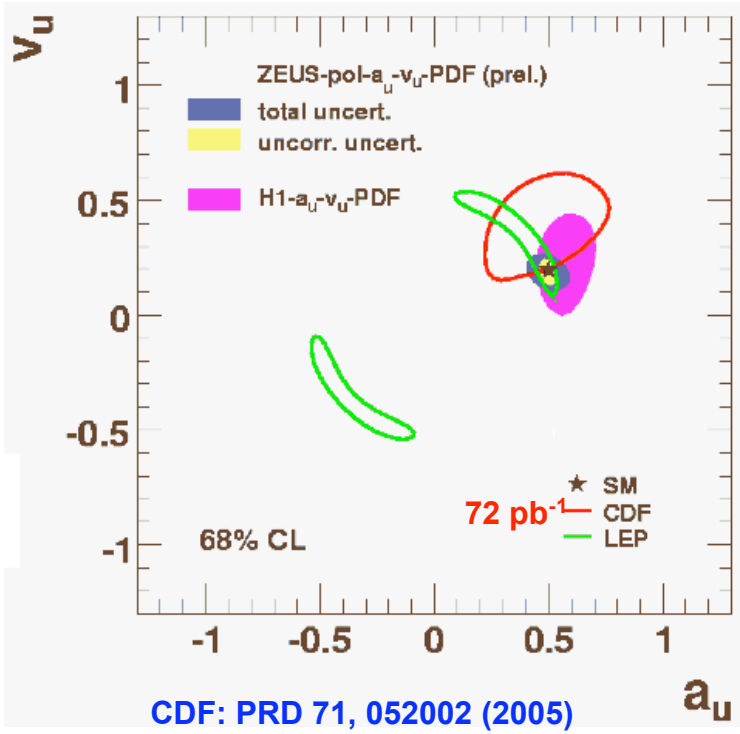
# $A_{FB}$




$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

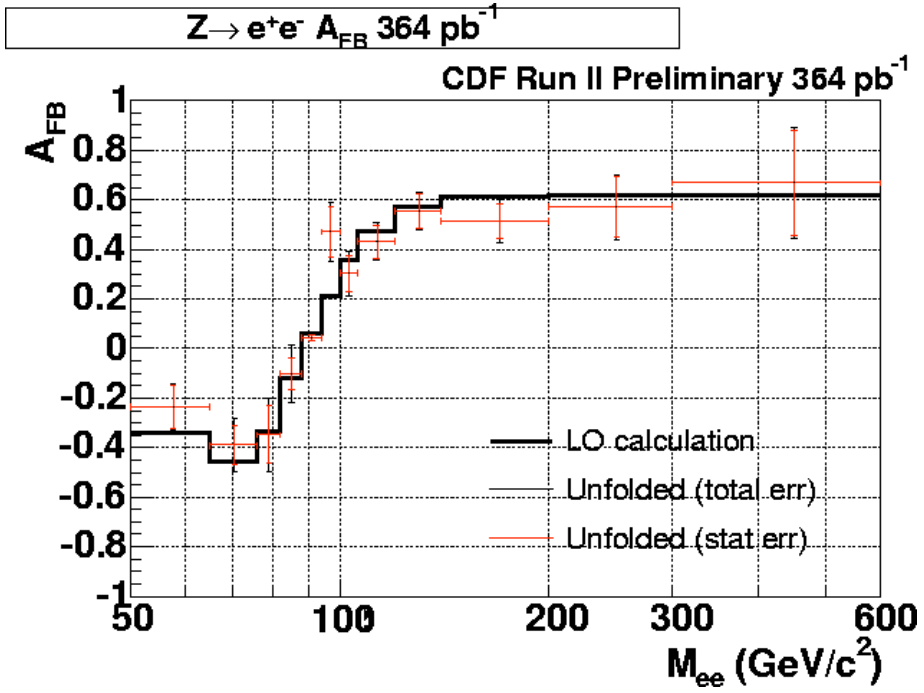
Function of quark & lepton axial and vector neutral current couplings

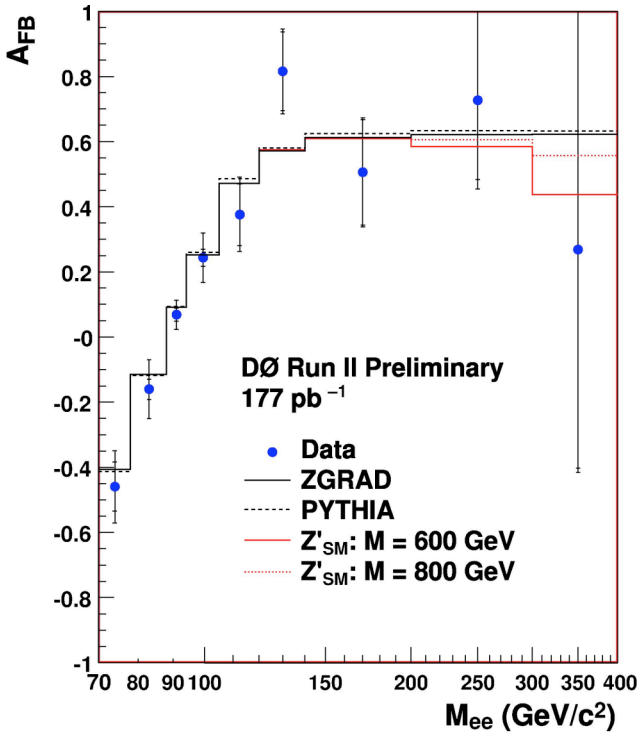
- The relative strengths of the axial and vector couplings of quarks to the Z boson can be extracted from measurement of forward-backward charge asymmetry ($A_{FB}$)
- At Tevatron can measure $A_{FB}$ at the Z-pole as well as above and below




CDF: PRD 71, 052002 (2005)
Wichmann, HCP 2006

# $A_{FB}$ Results

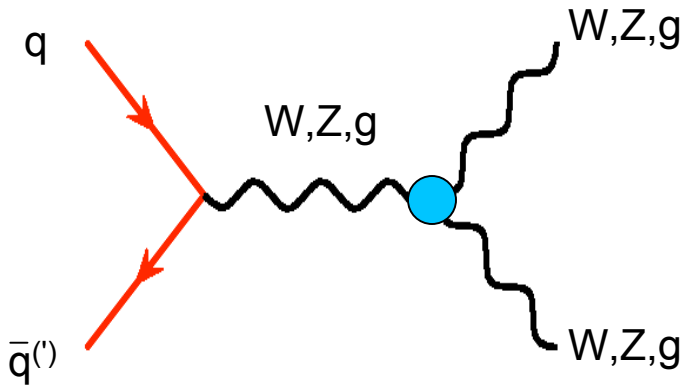



- Current measurements are statistics limited
- The high mass region is of particular interest since this is where new physics can interfere with Standard Model to produce deviations

# Dibosons

- Probe non-Abelian nature of $SU(2)_L \otimes U(1)_Y$ via gauge boson self-interactions (triple, quartic)
- The Tevatron ($p\bar{p}$) is sensitive to different combinations of tri-linear gauge couplings than LEP ($e^+e^-$) and explores higher $\hat{s}$




$q\bar{q}' \rightarrow W^* \rightarrow W\gamma$ : $WW\gamma$ only

$q\bar{q}' \rightarrow W^* \rightarrow WZ$ : $WWZ$ only

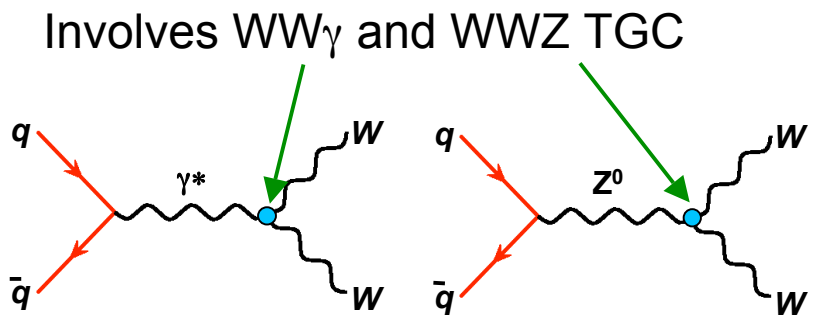
$q\bar{q} \rightarrow Z/\gamma^* \rightarrow WW$ : $WW\gamma$ , $WWZ$

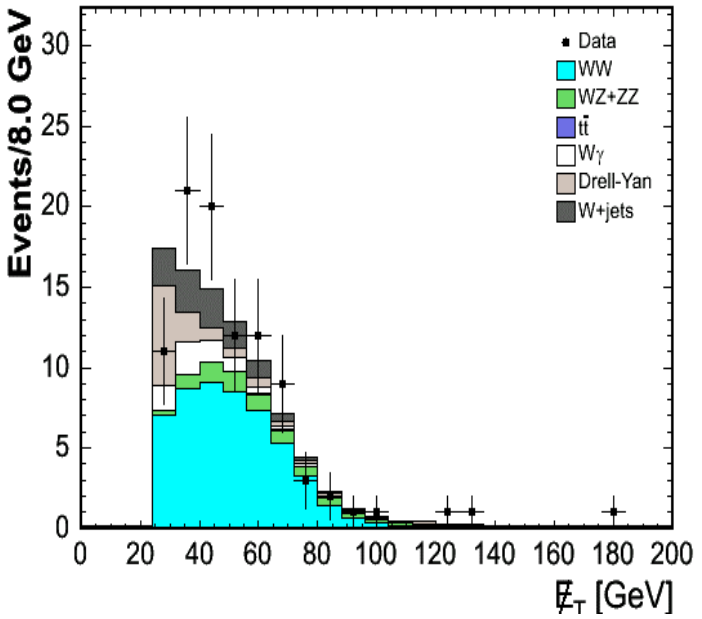
$q\bar{q} \rightarrow Z/\gamma^* \rightarrow Z\gamma$ : $ZZ\gamma$ , $Z\gamma\gamma$

$q\bar{q} \rightarrow Z/\gamma^* \rightarrow ZZ$ : $ZZ\gamma$ , $ZZZ$

Absent in SM

# WW Production




- New CDF cross section measurement (825 $pb^{-1}$)
- Require two opposite sign leptons and large missing $E_T$
- Expect 38 ± 5 background and 52 ± 4 signal events
- Observe 95 events

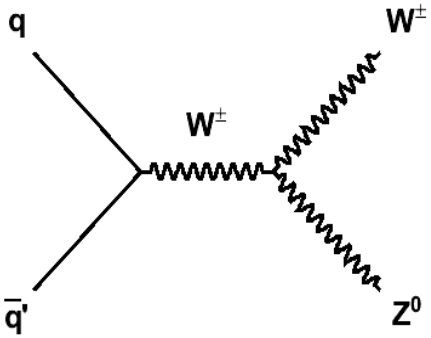
$\sigma(p\bar{p} \rightarrow WW) = 13.6 \pm 2.3(stat)$
$\pm 1.6(syst) \pm 1.2(lum)$ pb

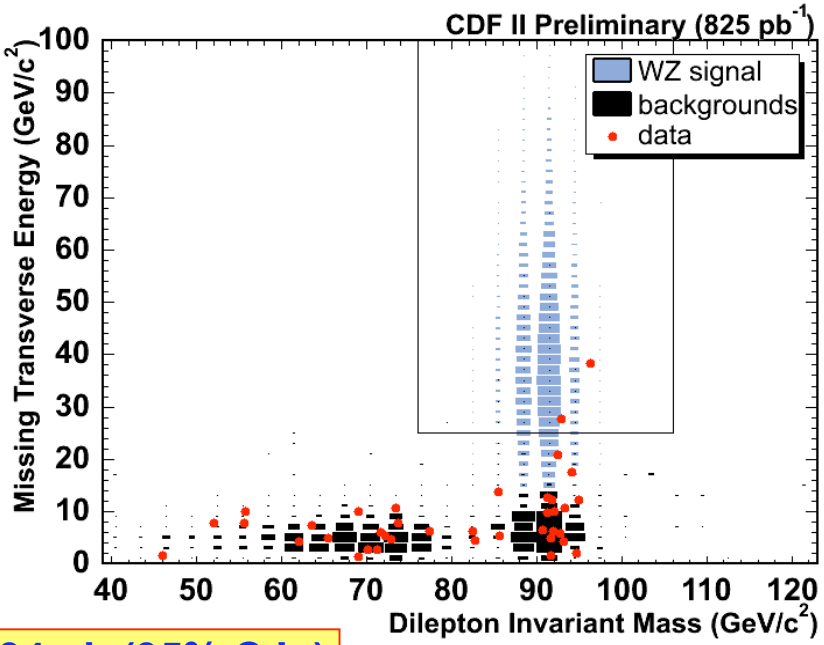
NLO cross section: 12.4 ± 0.8 pb

Campbell,Ellis, Phys.Rev. D60 (1999) 113006

# WZ Production

- Involves a single tri-linear gauge coupling not accessible at LEP
- Measure WWZ coupling independent of WWγ
- CDF search using three lepton plus Missing $E_T$ signature (825 $pb^{-1}$).
- Observe 2 events with an expected background of 0.9 ± 0.2 events and signal of 3.7 ± 0.3 events

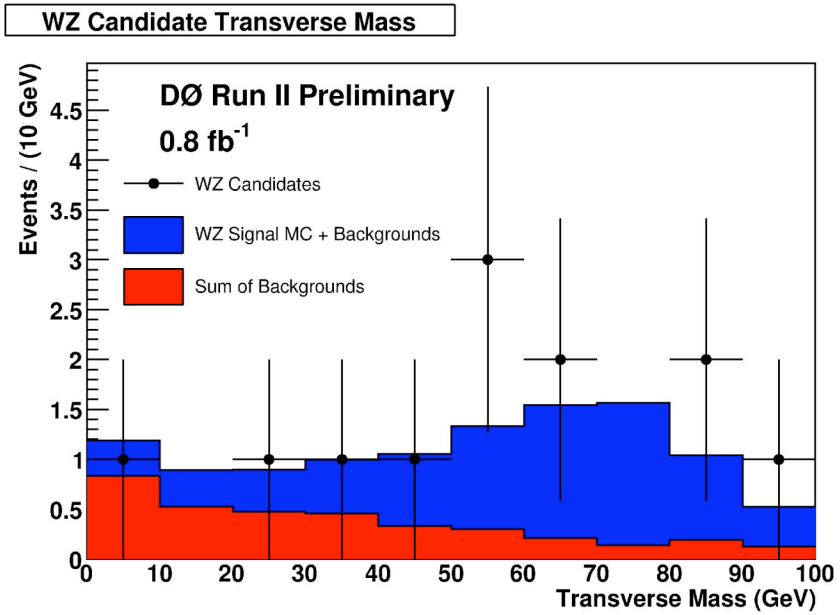



**σ(WZ) < 6.34 pb (95% C.L.)**

# Evidence for WZ Production

- DØ has made a similar analysis on a roughly equivalent-sized data sample
- Takes advantage of the wider acceptance for leptons in DØ detector
- Observe 12 events with an expected background of 3.6 ± 0.2 events and signal of 7.5 ± 1.2 events (3.3σ)

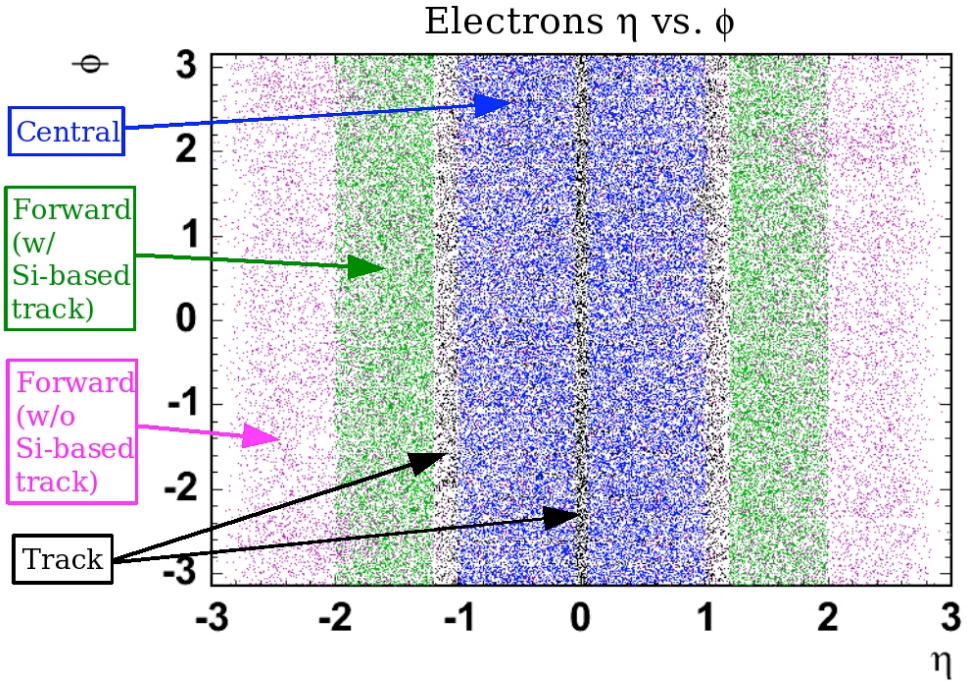


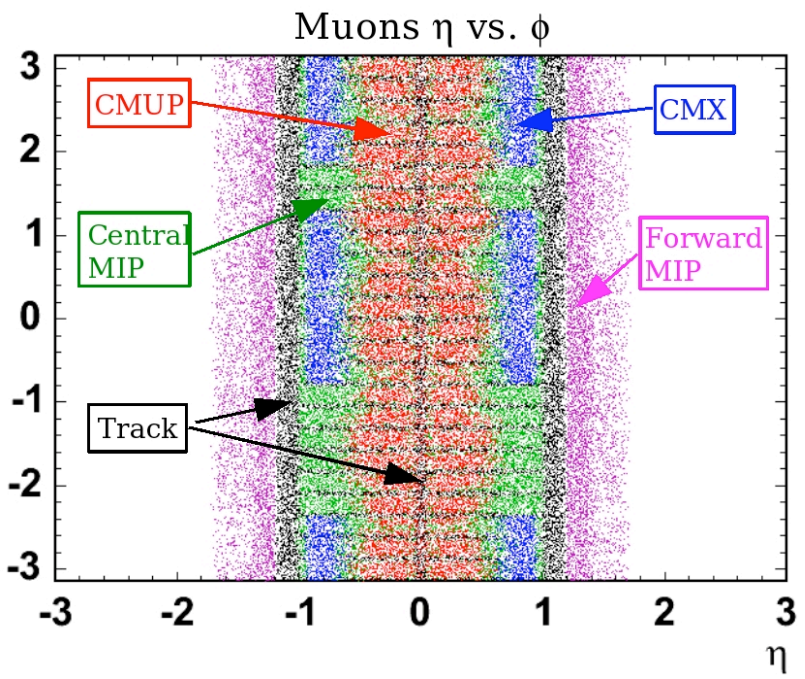

$$\sigma(p\bar{p} \rightarrow WZ) = 3.98^{+1.91}_{-1.53}\ \text{pb}$$

NLO cross section: 3.68 ± 0.25 pb

Campbell,Ellis, Phys.Rev. D60 (1999) 113006

# New CDF Lepton Categories

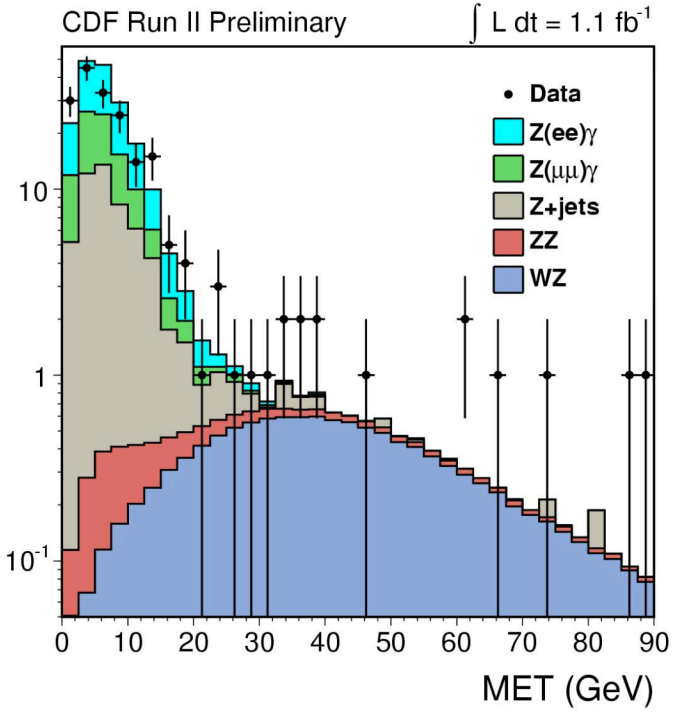



- Add forward electron candidates with no track match
- Add forward muon candidates fiducial to calorimeter
- Add flavor-neutral crack tracks (electron or muon)

# Observation of WZ Production

- Recent CDF analysis that takes advantage of new lepton categories
- Observe 16 events with an expected background of 2.7 ± 0.4 events and signal of 12.5 ± 0.9 events
- Probability of background fluctuation < 1.5 x $10^{-7}$ (5.1σ) and 2-bin MET analysis gives 5.9σ



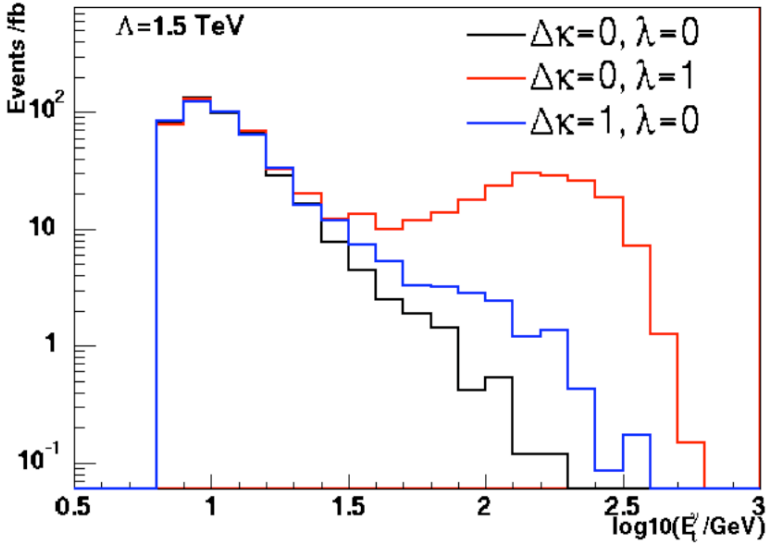

$$\sigma(\bar{p}p \rightarrow WZ) = 5.0^{+1.8}_{-1.6}\,\text{pb}$$

NLO cross section: 3.7 ± 0.3 pb

Campbell,Ellis, Phys.Rev. D60 (1999) 113006

# Anomalous Couplings

- Diboson production is sensitive to potential new physics appearing in the tri-linear gauge couplings
- Impose unitarity by imposing a "new physics" energy scale $\alpha(s) = \alpha_0 / (1 + s / \Lambda^2)^2$. AC increase as new physics scale approaches




$$L_{WWV}/g_{WWV} = ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + i\lambda_V/M_W^2\, W^\dagger_{\lambda\mu}W^\mu{}_\nu V^{\nu\lambda}$$

SM: $g_1^\gamma = g_1^Z = 1$
AC: $\Delta g_1^Z$ ( $= g_1^Z - 1$)

SM: $\kappa_\gamma = \kappa_Z = 1$
AC: $\Delta\kappa_Z$ , $\Delta\kappa_\gamma$( $= \kappa_V - 1$)

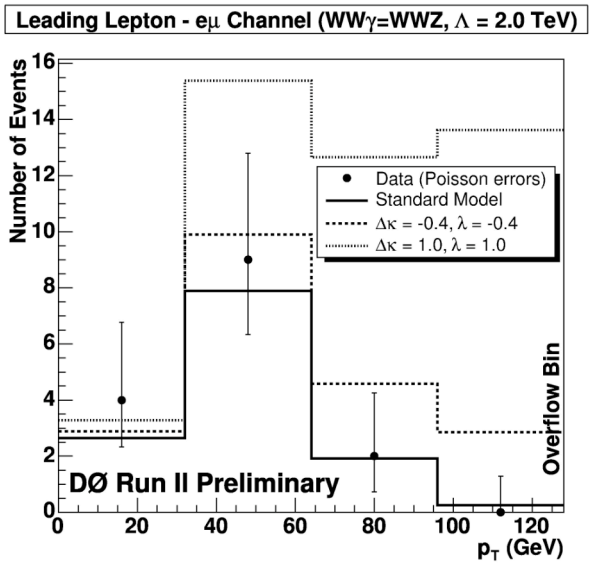
SM: $\lambda_\gamma = \lambda_Z = 0$
AC: $\lambda_Z$ , $\lambda_\gamma$

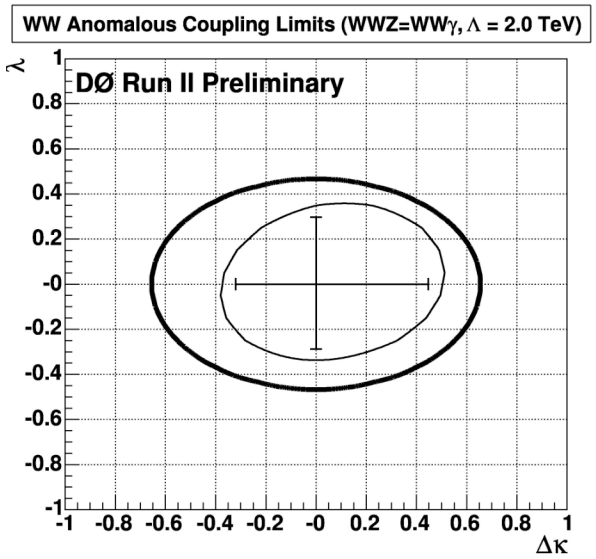
# Anomalous Coupling Limits

- New D0 result based on WW decays to dilepton (e,μ) final states
- Sets limits on anomalous WWγ and WWZ tri-linear gauge couplings under the assumption that the two couplings are equal and $\Lambda = 2$ TeV

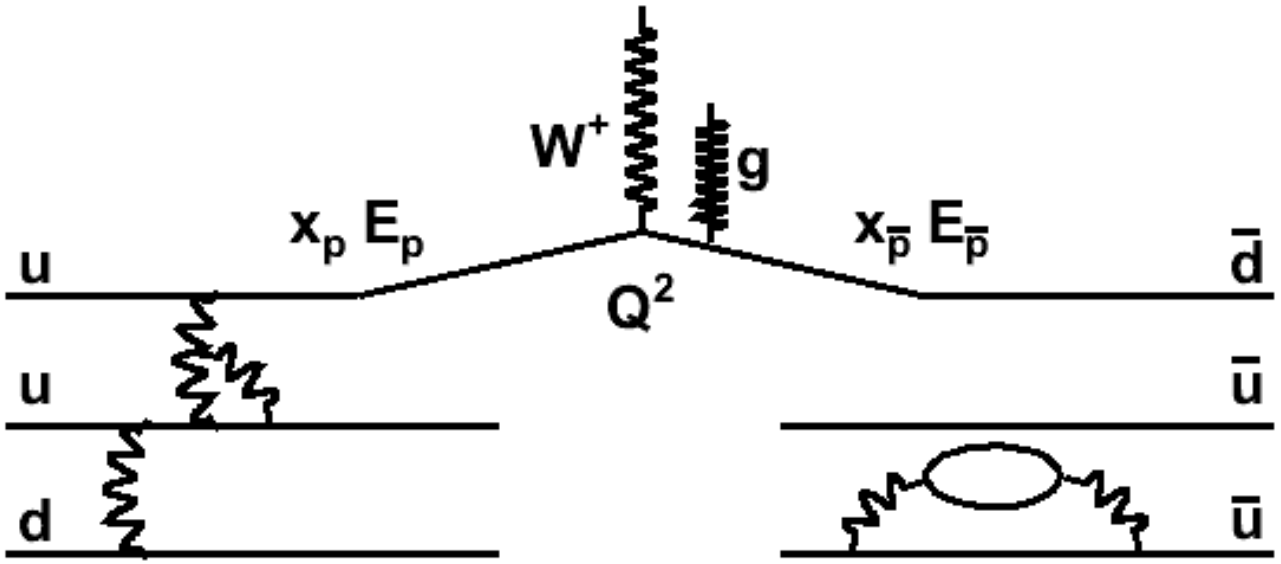
$$-0.32 < \Delta\kappa < 0.45$$

$$-0.29 < \lambda < 0.45$$



# QCD Boson Production




$$\sigma = \sum_{ab} \int dQ\ \delta(Q - 2E_p\sqrt{x_p x_{\bar{p}}}) \int dx_p\ f_a(x_p, Q) \int dx_{\bar{p}}\ f_b(x_{\bar{p}}, Q)\ \hat{\sigma}(Q)$$

Sum over quarks, gluons

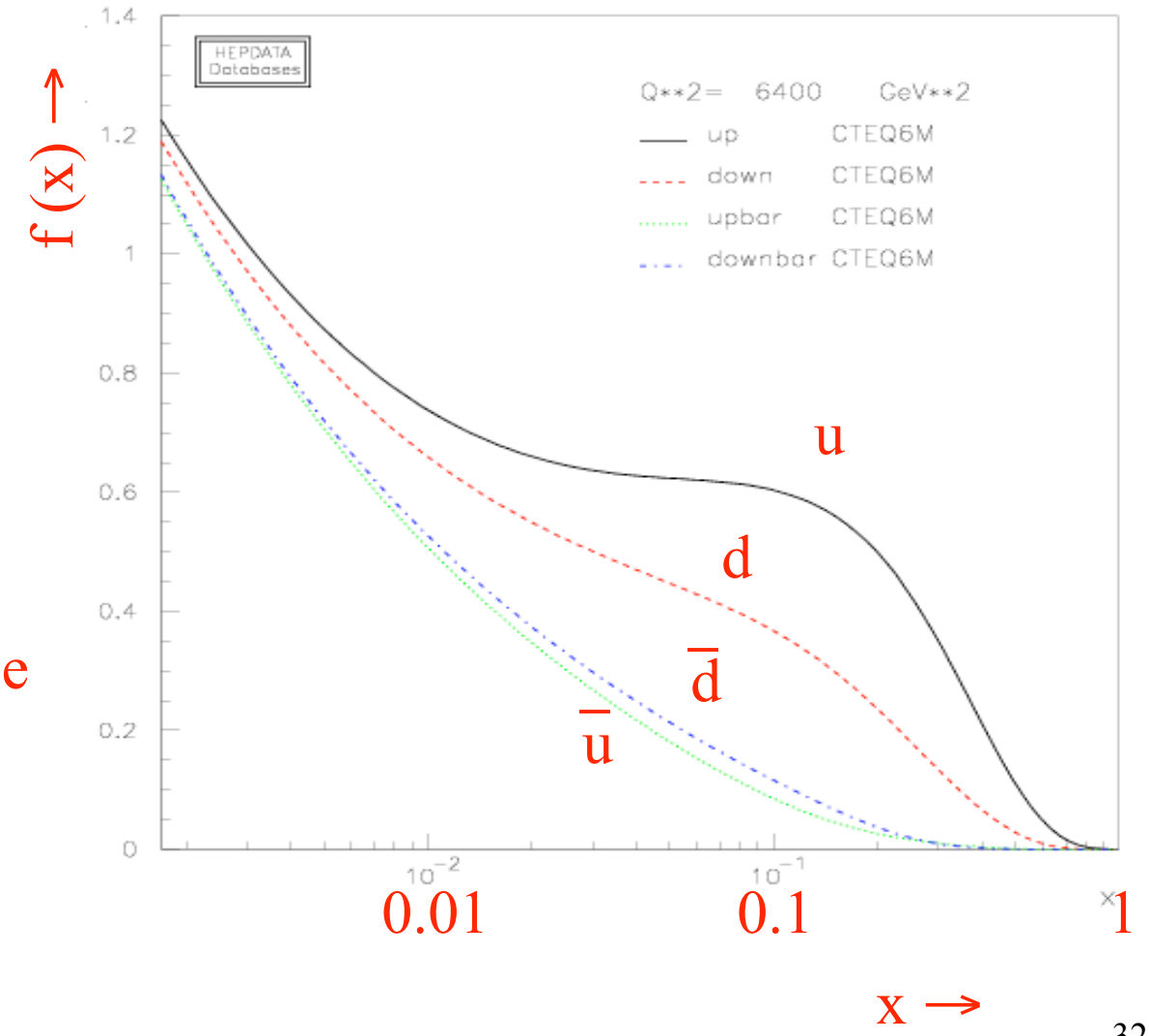
Kinematic constraint

Parton distribution functions

Calculable hard scattering cross section

# Parton Distribution Functions

- Parton momentum fraction within the proton depends on quark type and is different for valence and sea quarks



# PDF Parameterization

$$xf_a(x,Q_0) = A_0\, x^{A1}\, (1-x)^{A2}\, e^{(A3)x}\, (1 + A_4 x)^{A5} \quad \text{(CTEQ)}$$

Separate functions for u,d,g,$\bar{u}$,$\bar{d}$

30 total parameters (10 fixed)

- PDF functions are based on fits to experimental data made by two independent groups (CTEQ & MRST)
- Parameters are determined for $Q_0$ = 1.3 GeV and the Q dependence is modeled by QCD evolution equations
- The $A_i$ parameters are correlated and eigenvectors are determined to facilitate uncertainty calculations

# Example

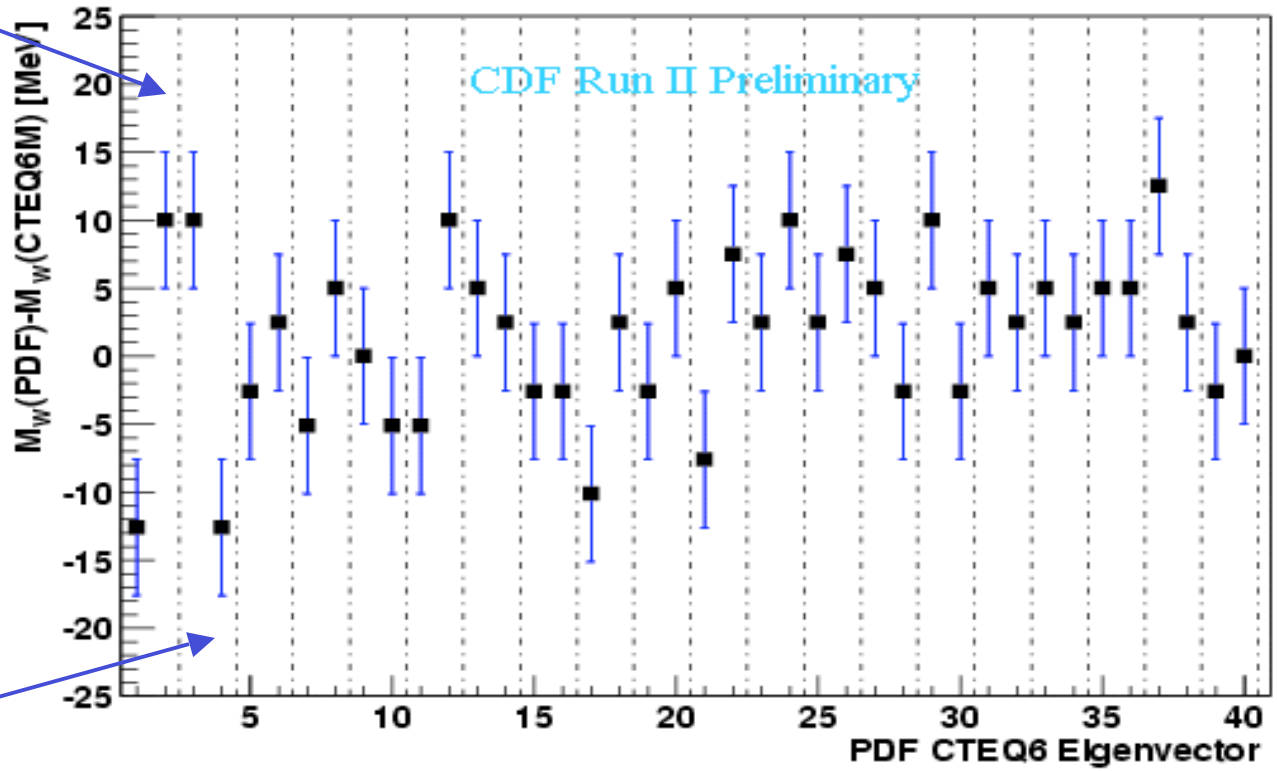
- W boson mass PDF uncertainty

*valence up quark*

*A1: low x*

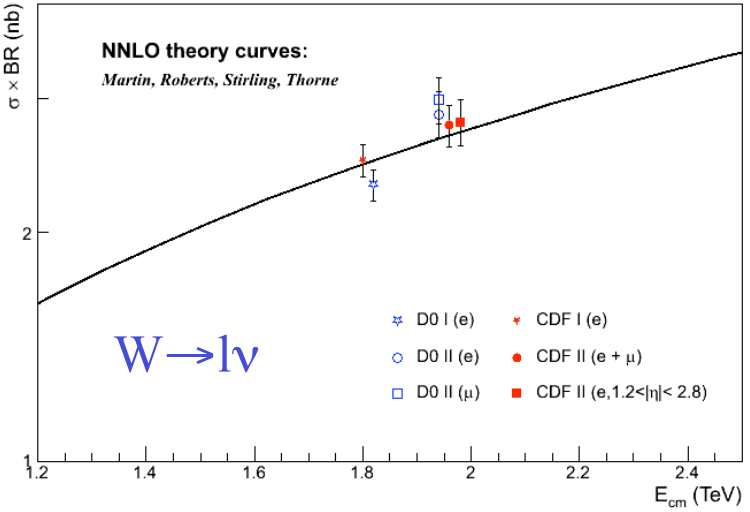
*valence down quark, sea quarks*

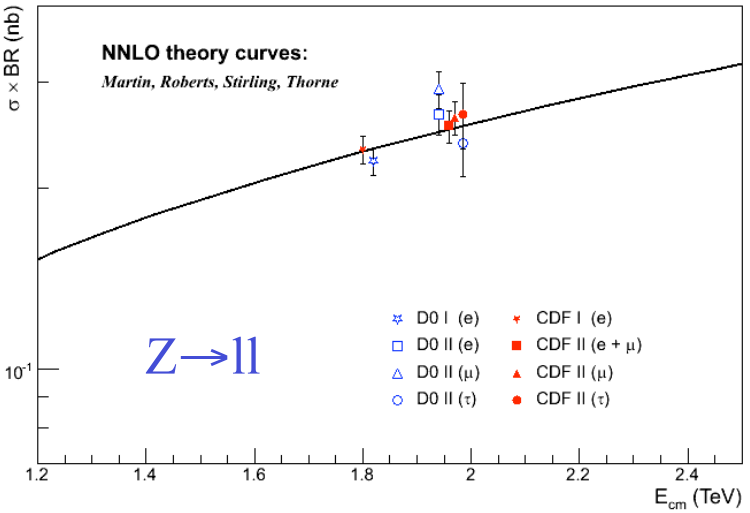
*A1: low x*



# Cross Section Measurements

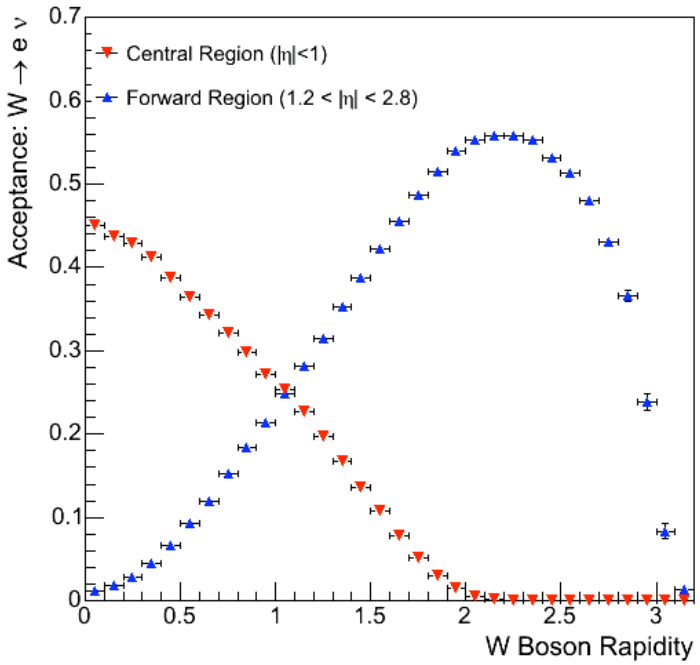
- CDF and D0 measure the inclusive W and Z boson production cross sections in all lepton (e,μ,τ) decay channels
- Largest uncertainty comes from luminosity measurements (~6%)
- Within that uncertainty, agree well with precise NNLO calculations

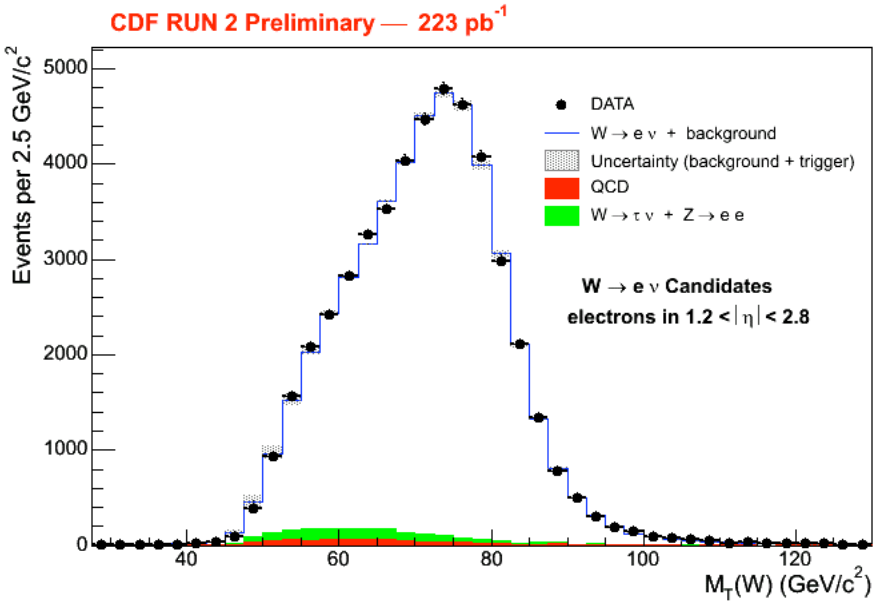


# Forward Cross Section

- CDF has recently completed a measurement of the W→eν in the forward detector region




- The boson acceptance for this measurement is mostly complimentary to that for the standard central measurement

# Cross Section Ratio

- The ratio of the visible cross sections in the central and forward regions of the detector is sensitive to the PDF distributions

$$\sigma_{vis} = \sigma_{tot} \times A$$

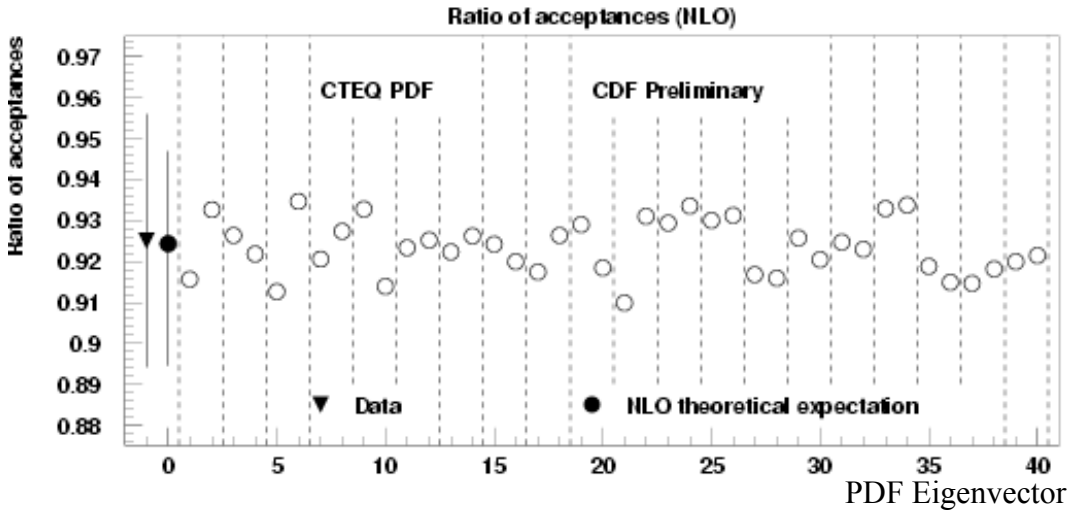
$$R_{exp} = \sigma^{cent}_{vis} / \sigma^{forw}_{vis} = 0.925 \pm 0.033$$

$$R_{th} = A^{cent} / A^{forw} = 0.924 \pm 0.037 \text{ (CTEQ 6.1)}$$

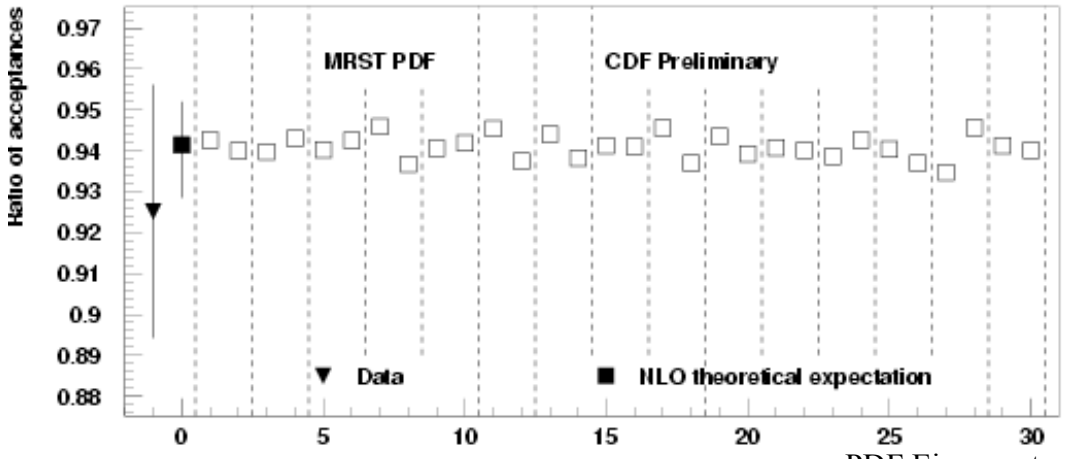
$$= 0.941 \pm 0.012 \text{ (MRST01E)}$$

# PDF Constraints

CTEQ




MRST

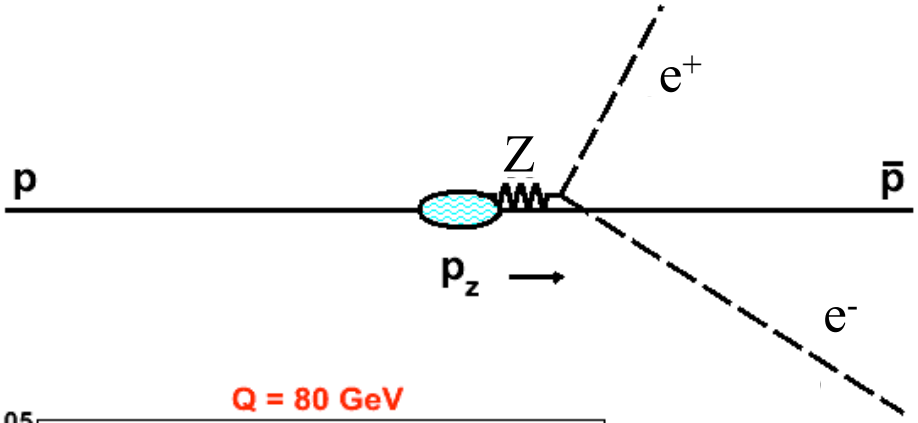


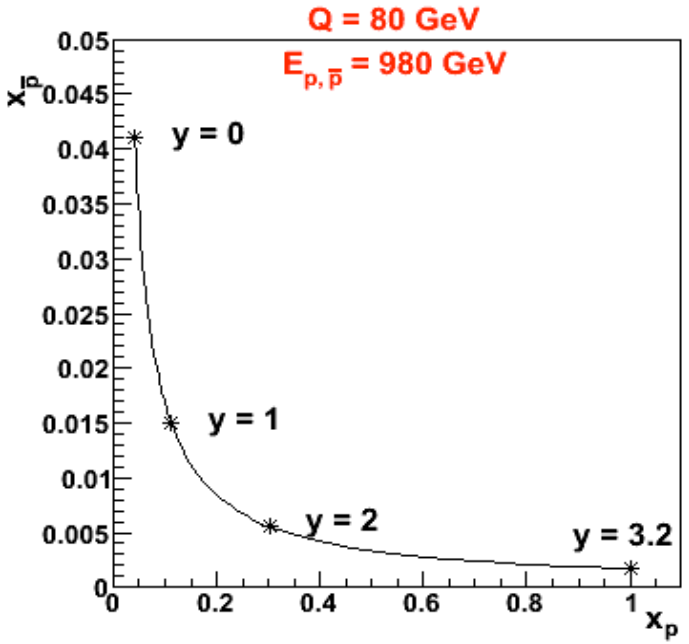
# Differential Cross Sections

$$y = 0.5 \ln \left[ \frac{E + p_z}{E - p_z} \right]$$

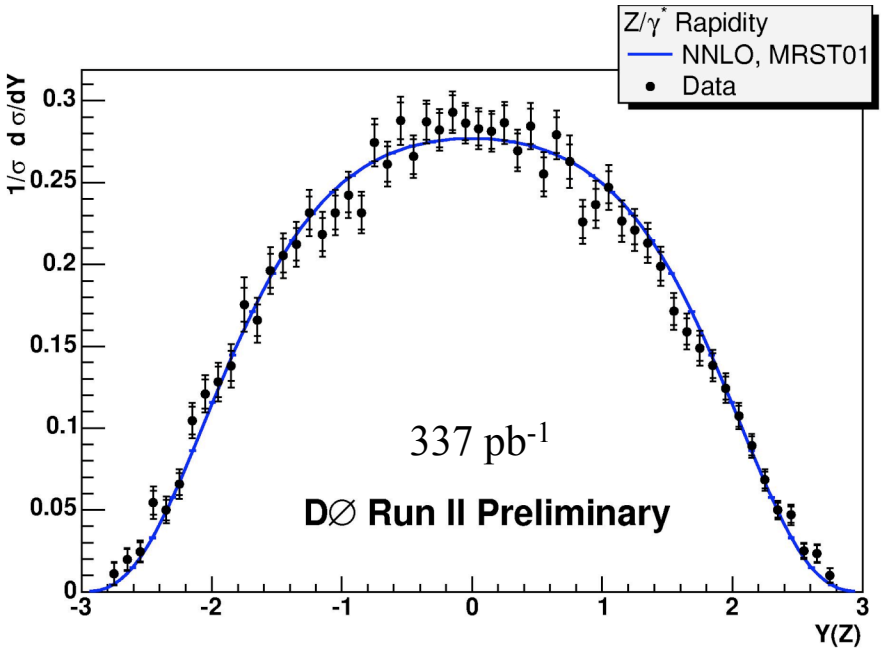
$$y = 0.5 \ln \left[ \frac{x_p}{x_{\bar{p}}} \right]$$

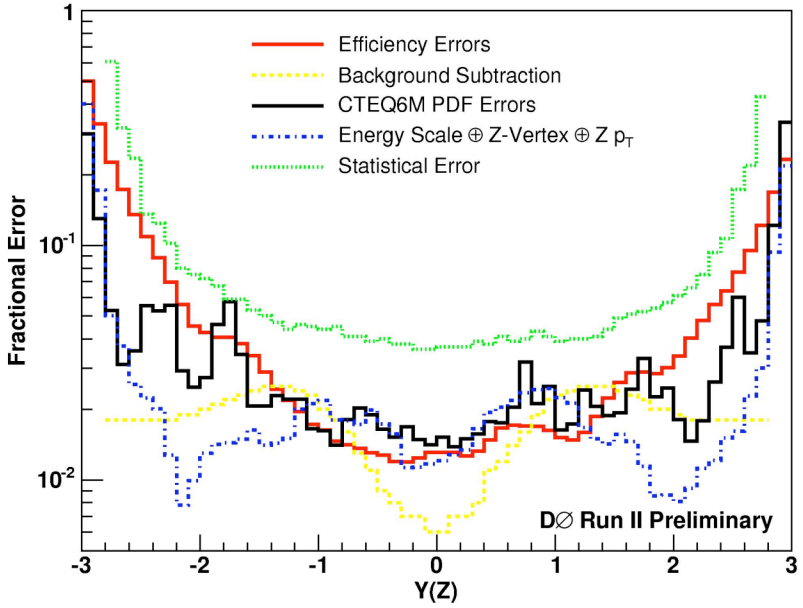
- Relative sizes of $x_p$, $x_{\bar{p}}$ determine the longitudinal momentum of boson



# dσ/dy Measurement



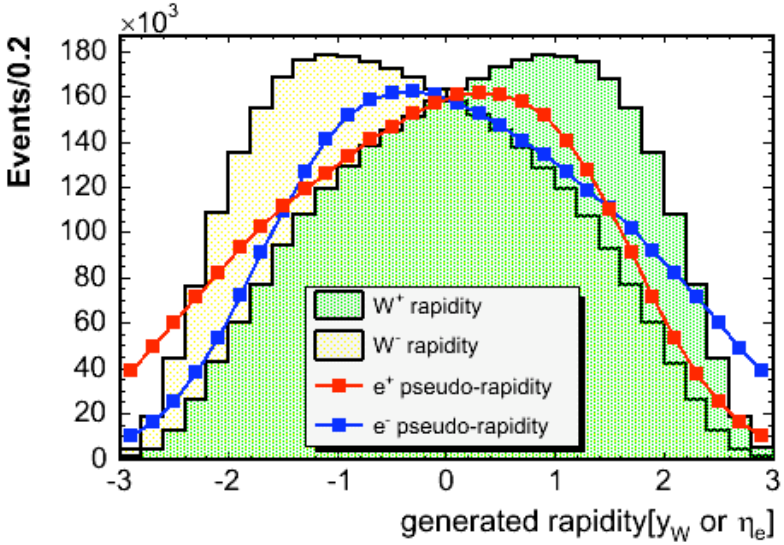



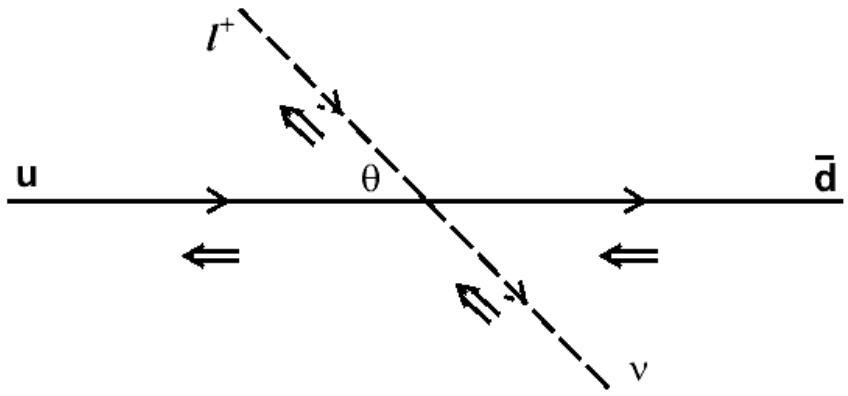

- Measurements are currently statistics limited
- Potential PDF uncertainty with increased statistics, particularly in the tails where the PDF variation is largest

# W Asymmetry

- Asymmetric u,d quark momentum distributions within proton lead to asymmetric $W^+$,$W^-$ rapidity distributions
- V-A decay of W boson reduces the observable asymmetry in the lepton rapidity distributions

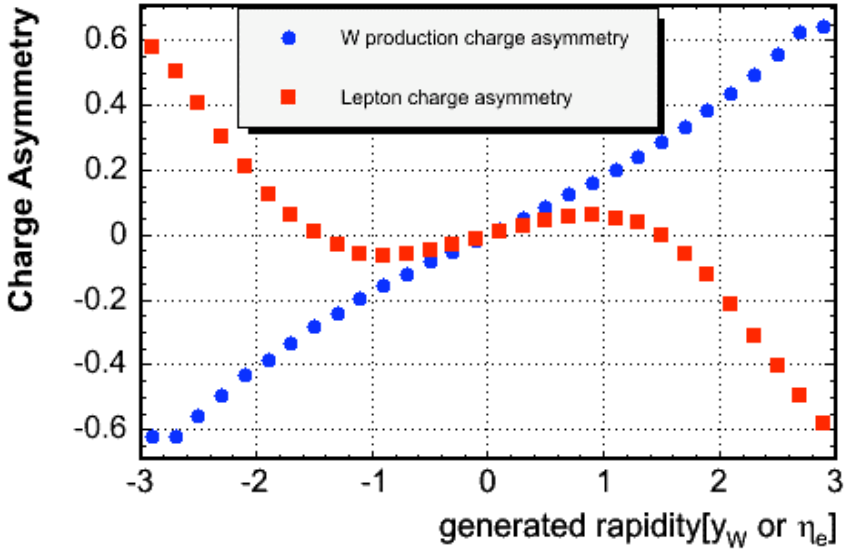
$$d\sigma/d\theta \propto (1 + \cos\theta)^2$$



# Charge Asymmetry

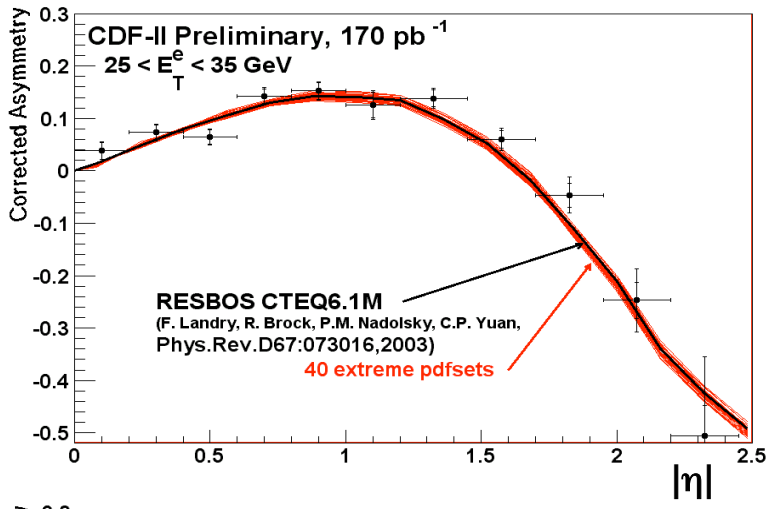
$$A^{\pm}_{W}(y) = \frac{\sigma_{W+}(y) - \sigma_{W-}(y)}{\sigma_{W+}(y) + \sigma_{W-}(y)}$$

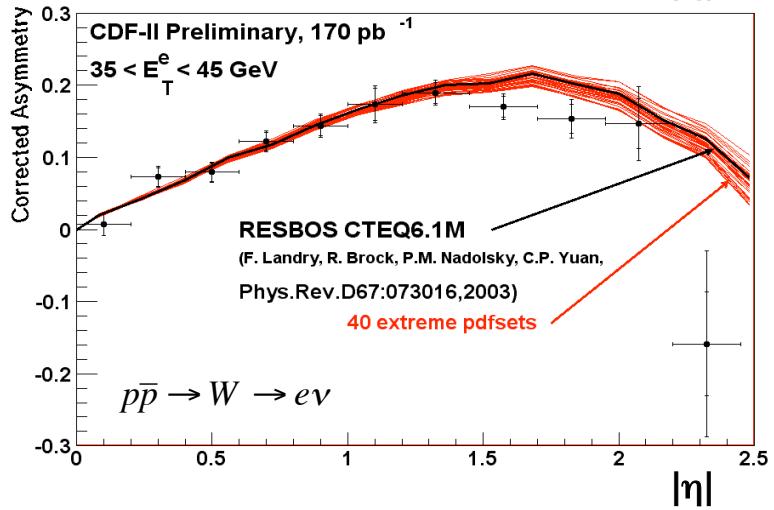


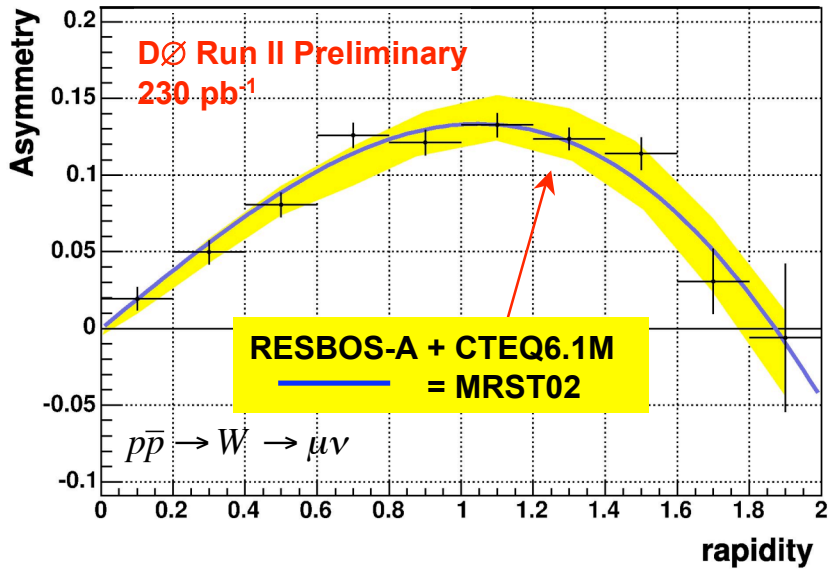

- Equivalent definition for lepton asymmetry

$$A^{\pm}_{W}(y) = \frac{u(x_p)d(x_{\bar{p}}) - d(x_p)u(x_{\bar{p}})}{u(x_p)d(x_{\bar{p}}) + d(x_p)u(x_{\bar{p}})} \approx F\left[(d/u)_{x_p}, (d/u)_{x_{\bar{p}}}\right]$$

# Lepton Charge Asymmetry

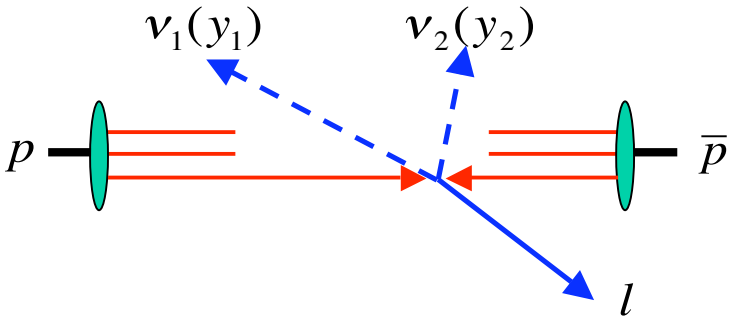


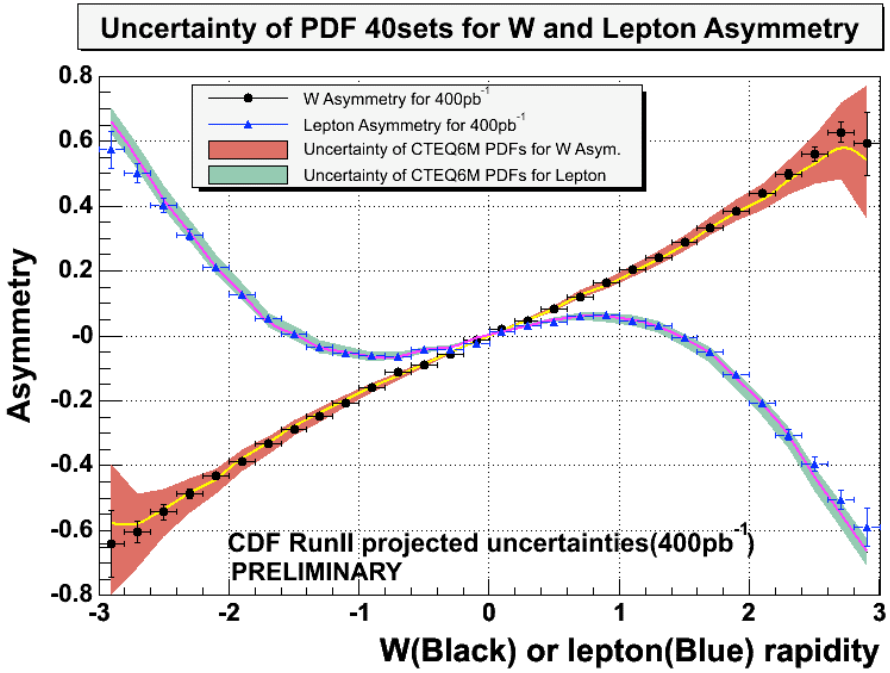




- Current DØ measurement using muons has some sensitivity to PDFs
- CDF measurement breaks data into separate $E_T$ ranges

# Future Asymmetry Measurements



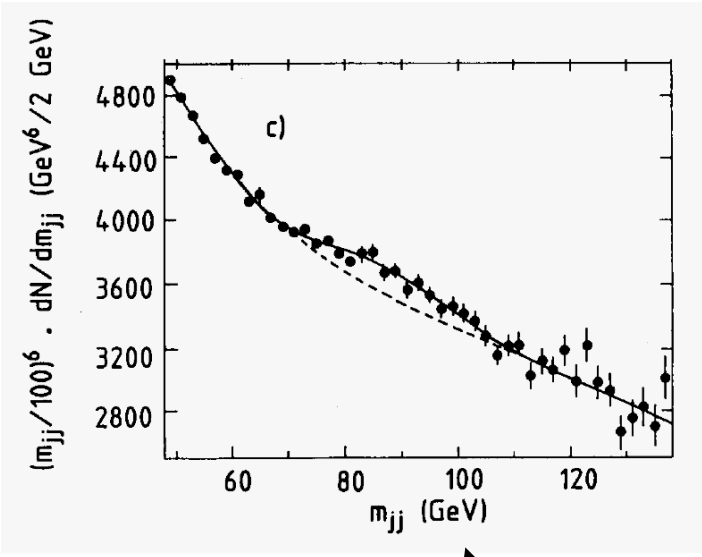

- Reconstruct W production asymmetry $A(y_W)$ directly
- Two kinematic solutions using $M_W$ constraint
- Weight solutions taking into account production & decay
- Resolve dependence on $y_W$ iteratively




Preliminary CDF studies indicate significantly increased sensitivity using this approach

# Conclusions and Outlook

- Large W & Z boson samples collected at the Tevatron accommodate a wide variety of precision electroweak measurements.
- Current analyses typically are based on only a small fraction of the data samples that we hope to eventually collect.
- Obtaining similar precision results from the LHC will be challenging and require input from Tevatron (e.g. PDF constraints)




UA2 W/Z→jj
CDF and DØ
can not even
trigger on
these events