Precision Electroweak Physics at Hadron Colliders

Eric James
Fermi National Accelerator Lab

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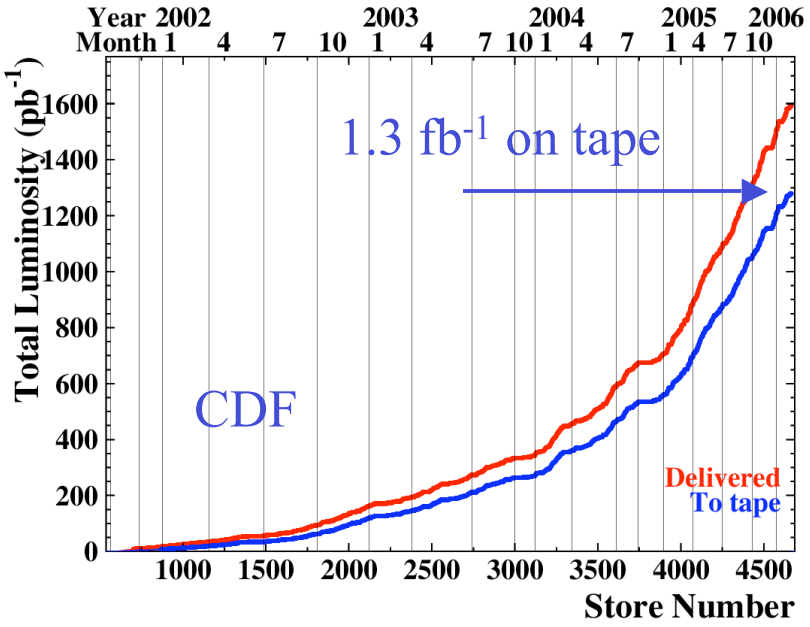
XXVI Physics in Collision

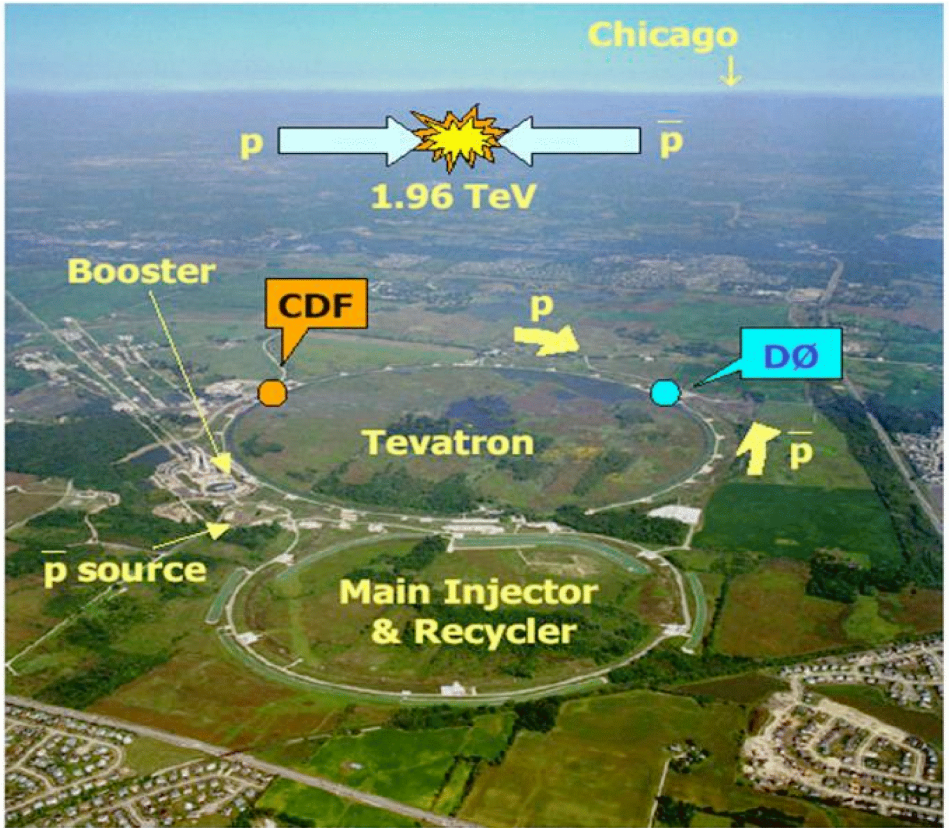
Outline

- 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

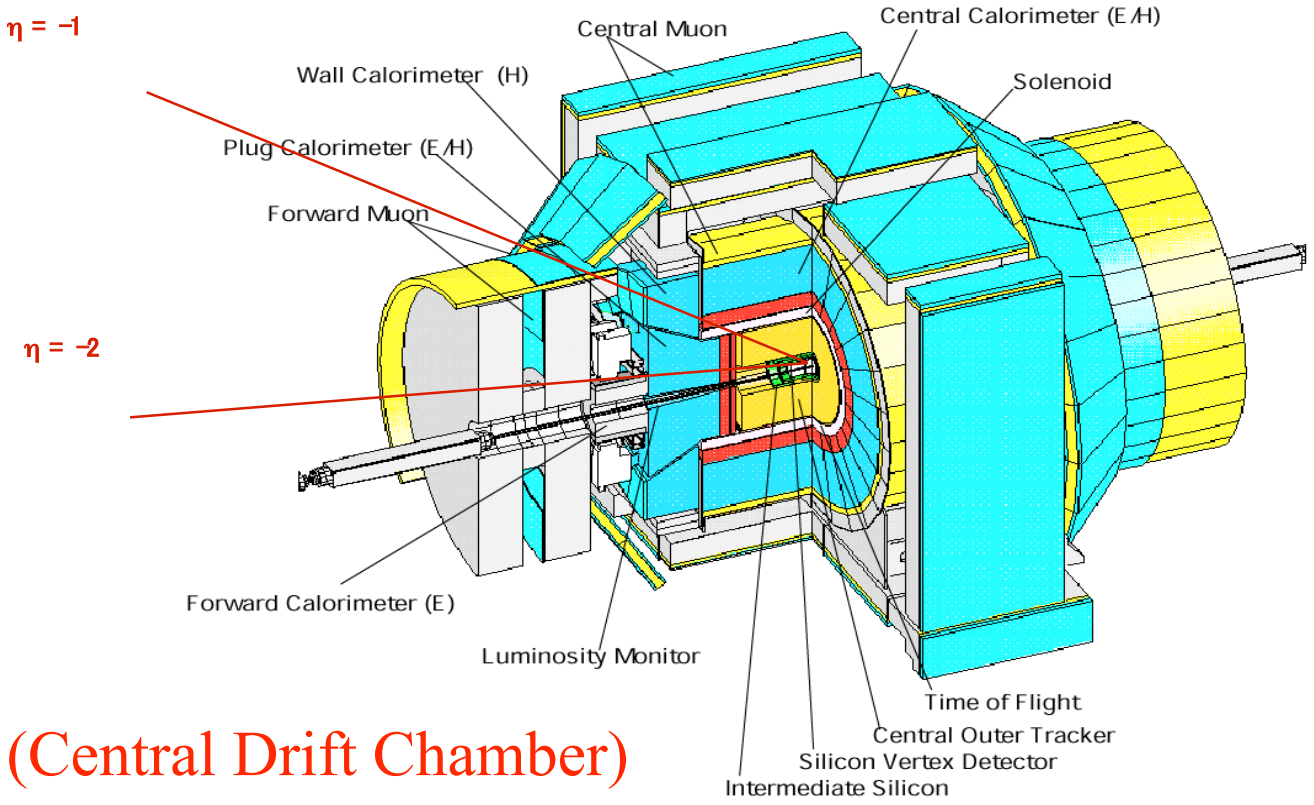


Mode	Events/Week/Exp. (before trigger & cuts)
W→eν	~50,000
Z→ee	~5,000



- Tevatron is a W & Z factory

CDF Experiment

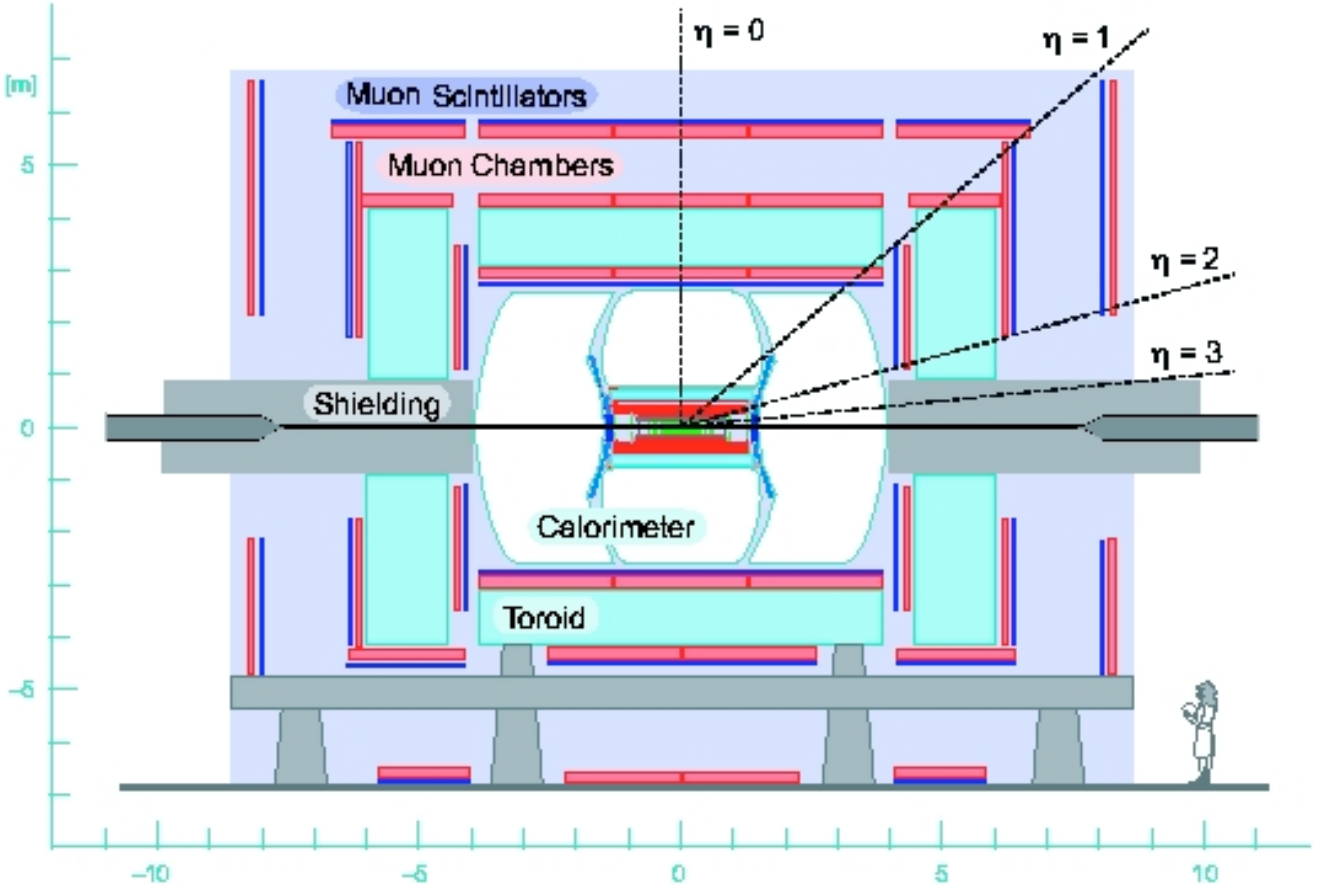


- Tracking (Central Drift Chamber)
  - $\delta p_T/p_T = 0.0005 \times p_T$ [GeV]
- EM Calorimeter
  - $\delta E_T/E_T \sim 13.5\% / \sqrt{E_T} \oplus 1.5\%$ [GeV, $|\eta| < 1.1$]

Leptons from W/Z decays

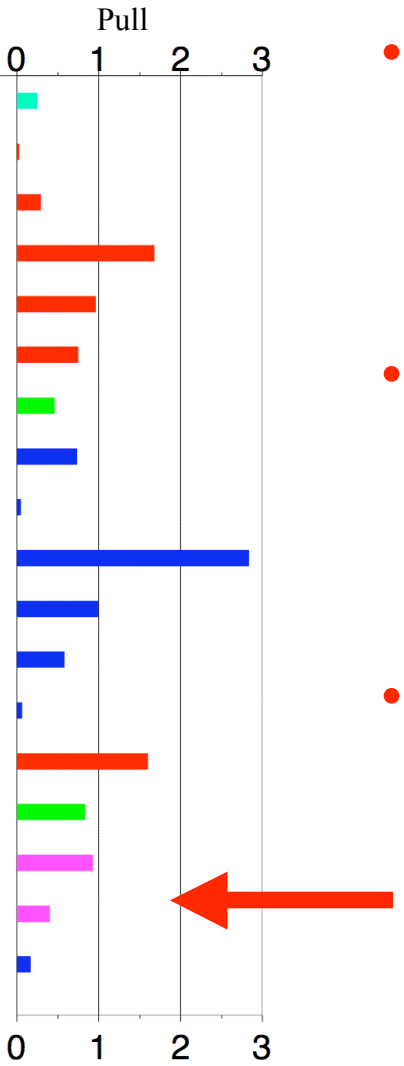
DØ Experiment

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



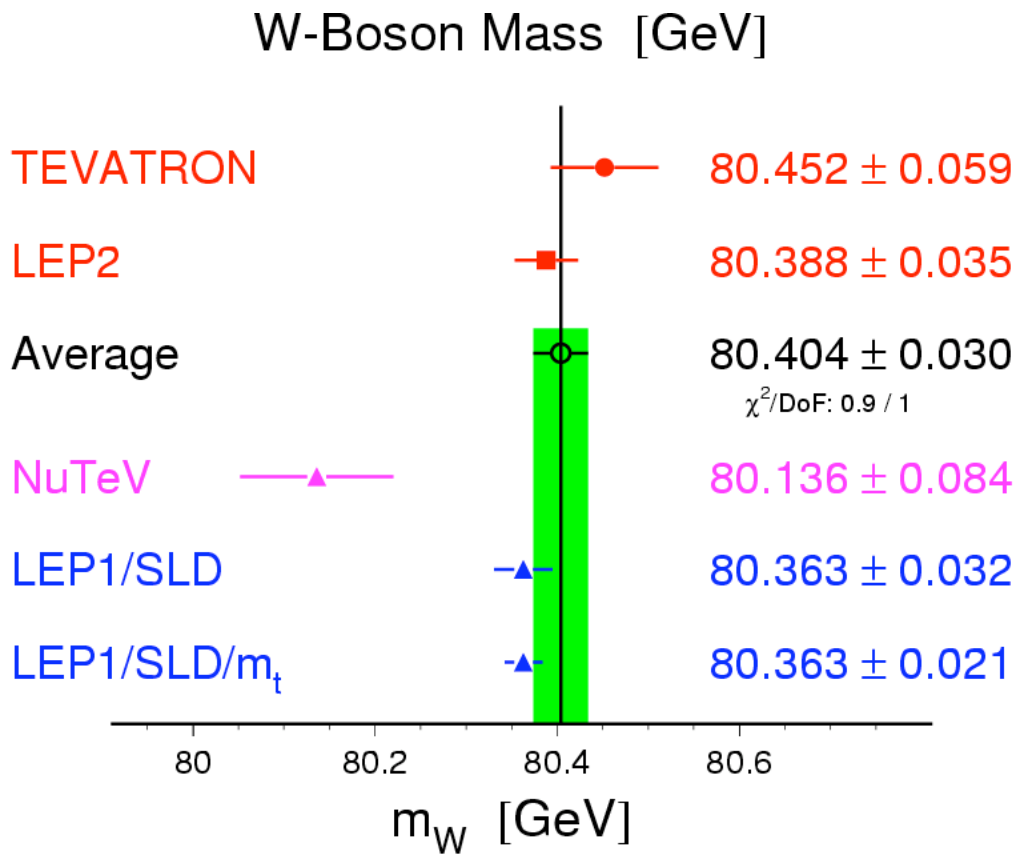
Precision EWK Measurements

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^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
Γ_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

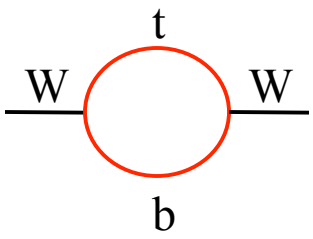
Current W Mass Results



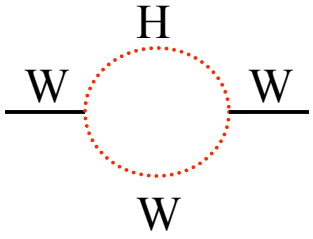
- Current level of precision ~ 0.04%
- This uncertainty is more than an order of magnitude higher than that for the Z boson mass

$M_Z = 91.1876 \pm 0.0021$

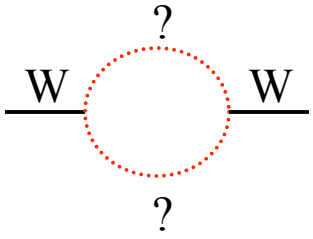
W Boson Mass



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



$\Delta M_W \propto \ln M_H$

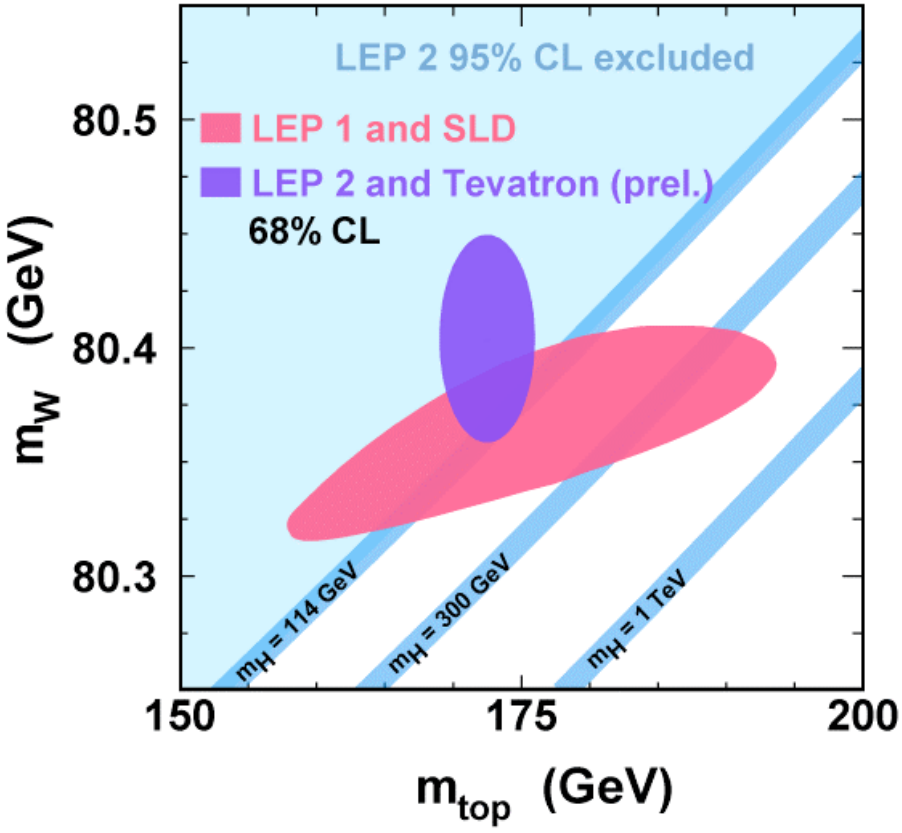


New Physics

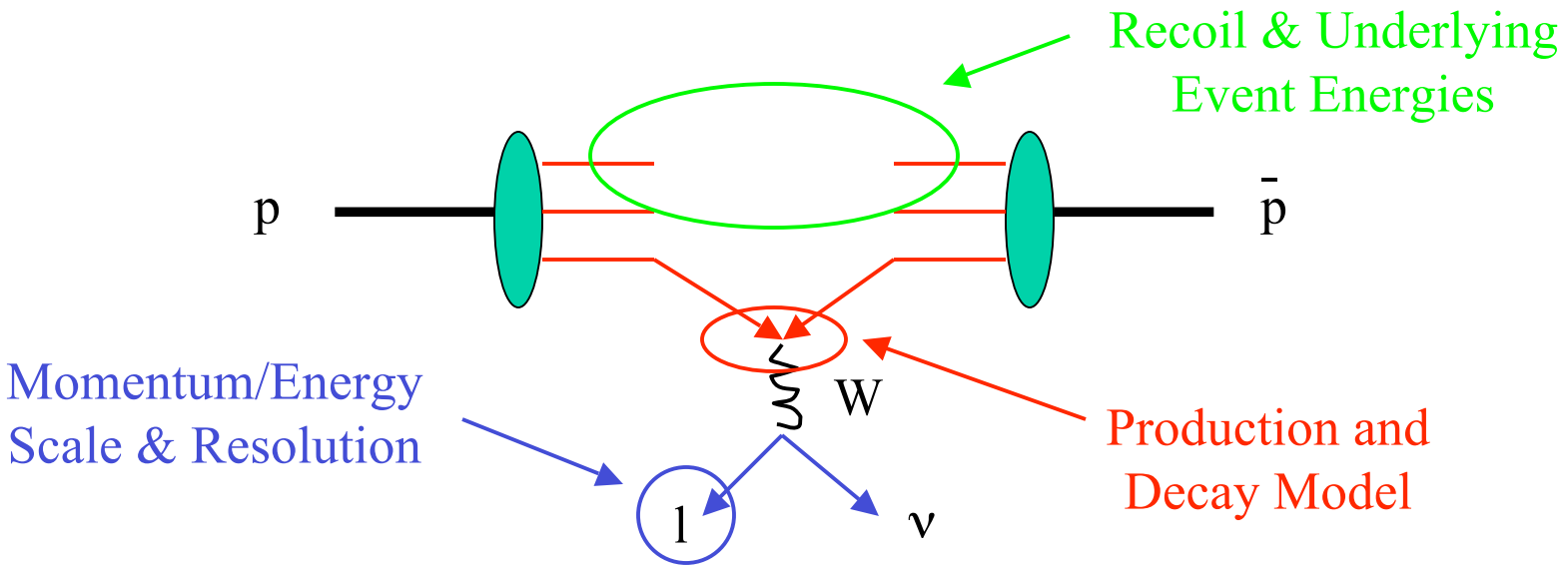
- Self-energy corrections to the W mass depend on the mass of the top quark and Higgs boson.

Constraints on Higgs Mass

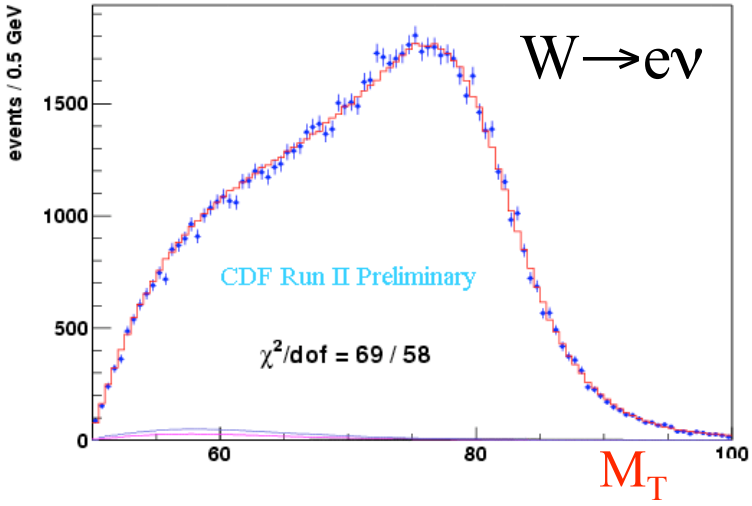
- To obtain equivalent constraint on M_H
  - $\Delta M_{top} \sim 1.5$ GeV/c^2, $\sim 1\%$ on M_{top}
  - $\Delta M_W \sim 10$ MeV/c^2, $\sim 0.01\%$ on M_W



W Mass Measurement



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

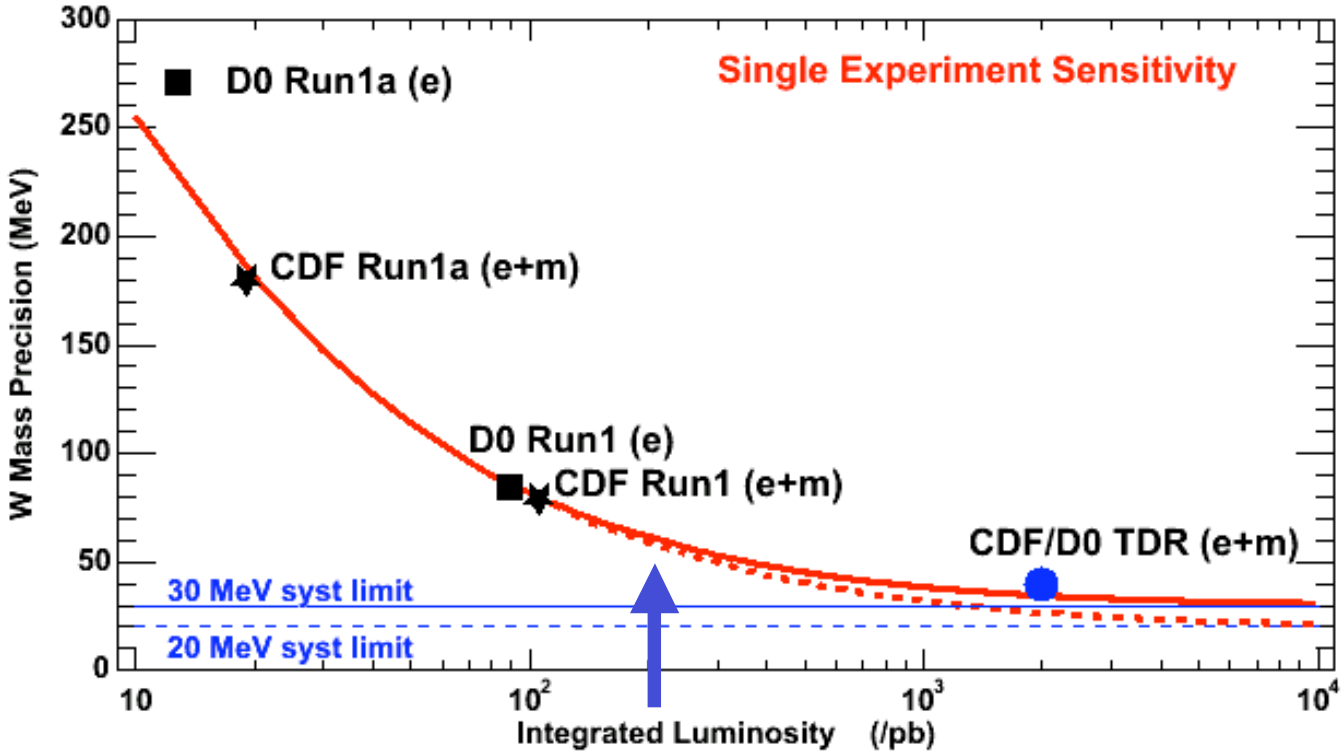


W Mass Uncertainties

- CDF preliminary systematic uncertainties for 200 pb^{-1}
- Currently, estimate a combined 76 MeV uncertainty
- Finalizing analysis and completing exhaustive cross checks

Systematic [MeV]	Electrons	Muons	Common
Lepton Energy Scale and Resolution	70	30	25
Recoil Scale and Resolution	50	50	50
Backgrounds	20	20	
Production and Decay Model	30	30	25
Statistics	45	50	
Total	105	85	60

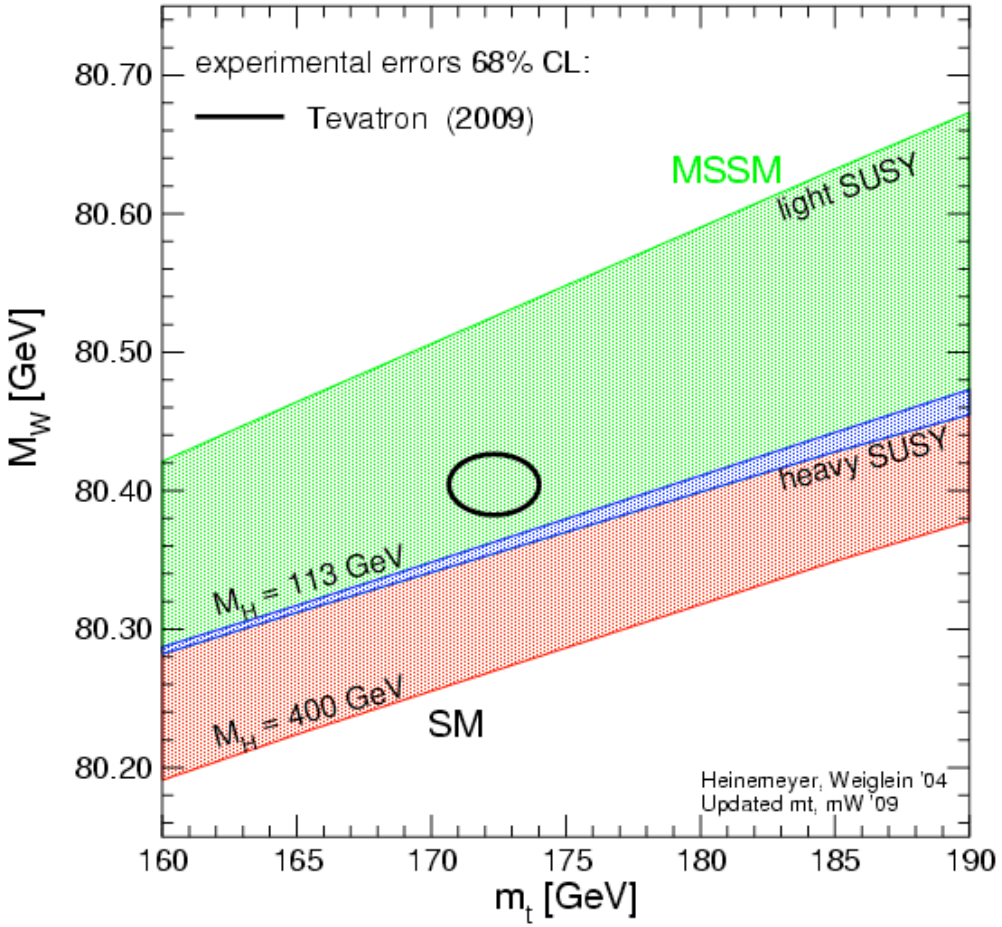
W Mass Measurement Projections



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

Ultimate Tevatron Constraints

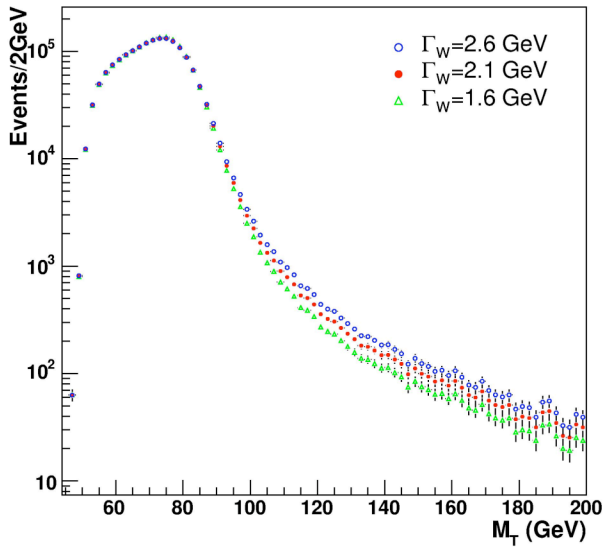
- Potential constraints on M_H based on 8 fb^{-1} of data per experiment
- Use to differentiate between a SM or SUSY-like Higgs
- Provides a test of the theories if a Higgs boson is discovered in the interim

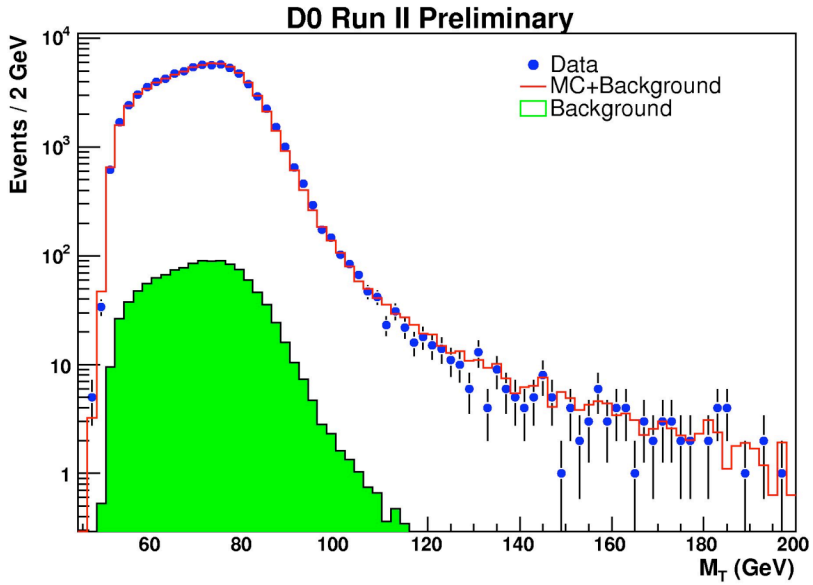


W Boson Width

- 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





- Γ_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

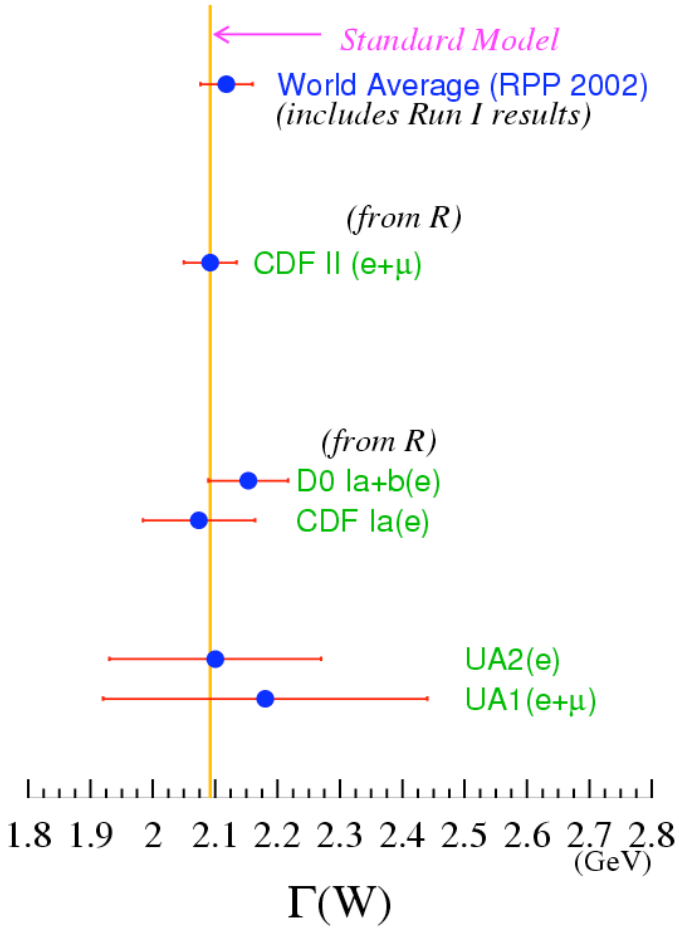
$$R_{exp} = \frac{\sigma \cdot BR\,(W \to l\nu)}{\sigma \cdot BR\,(Z \to ll)}$$

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



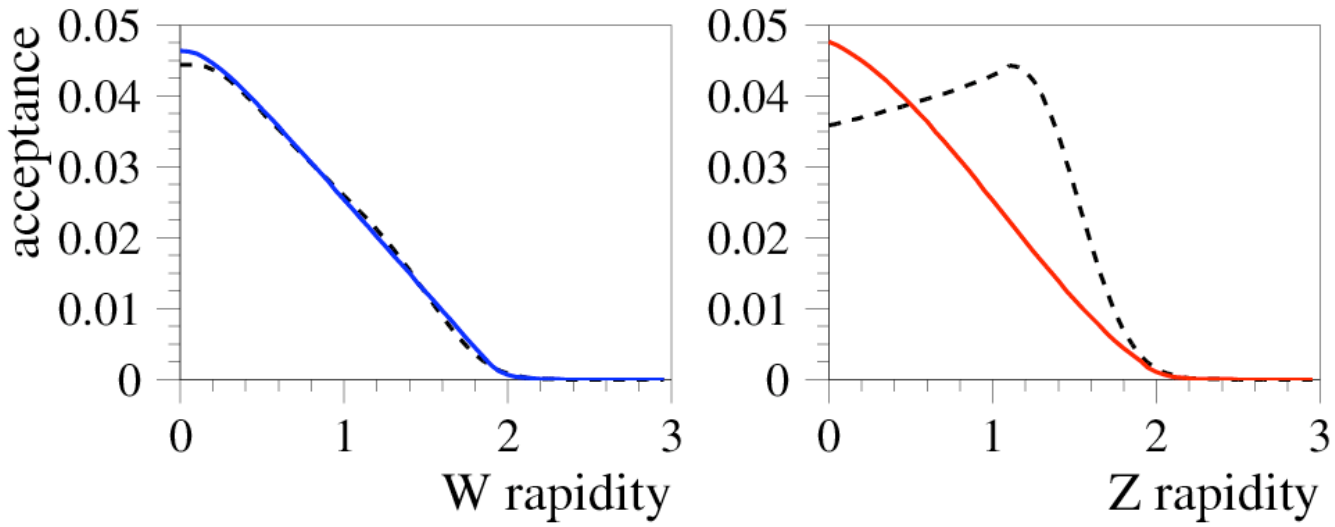
Indirect Width Uncertainties

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
γ^* correction factor	0.0109	0.0112	1.0

Raw uncertainties on R

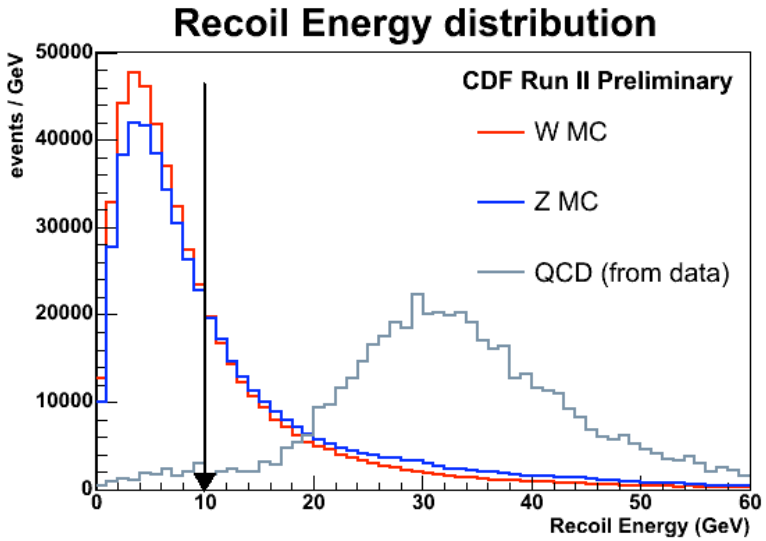
Improved Method

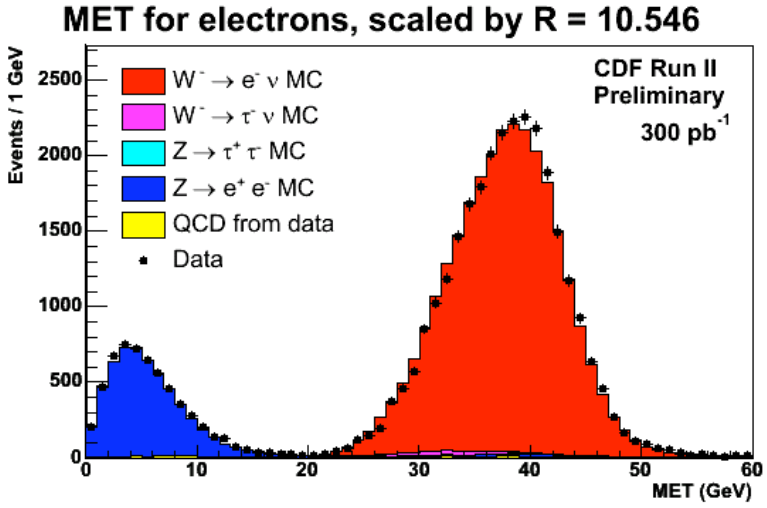
- Use a common set of selection criteria for both W and Z events by requiring a single high-quality lepton (fit +/- charges separately)
  - No efficiency or trigger uncertainties
  - Large reduction in PDF uncertainties



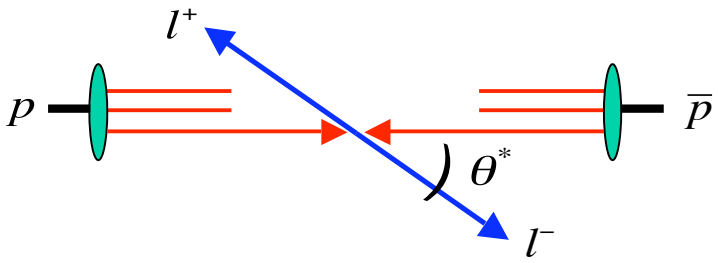
Precision R Measurement

- 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





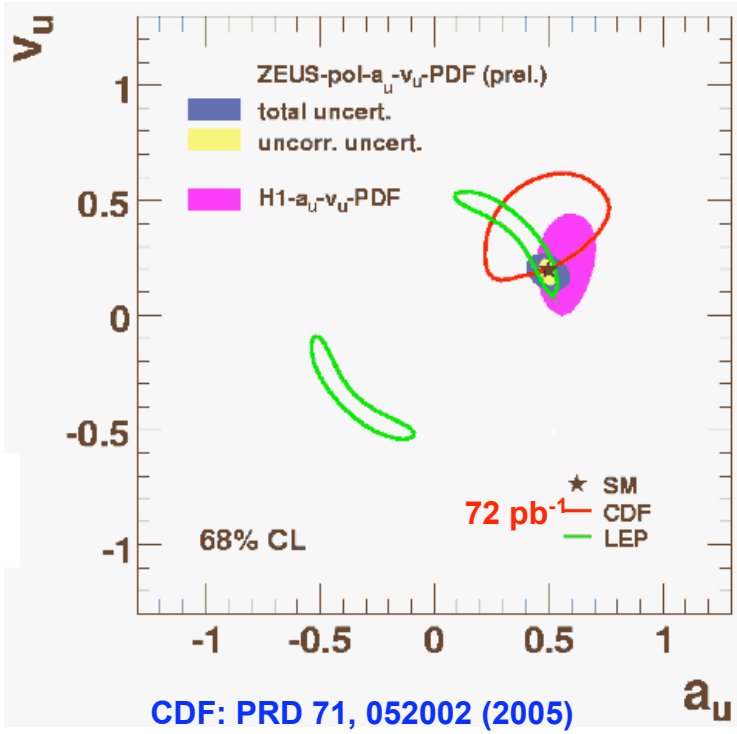
A_{FB}



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

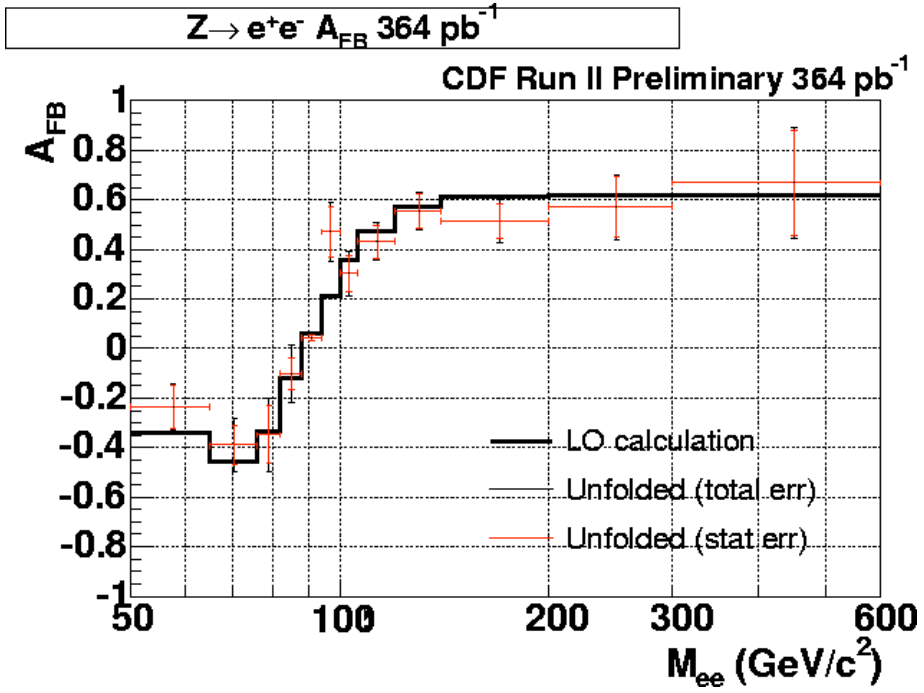
Function of quark & lepton axial and vector neutral current couplings

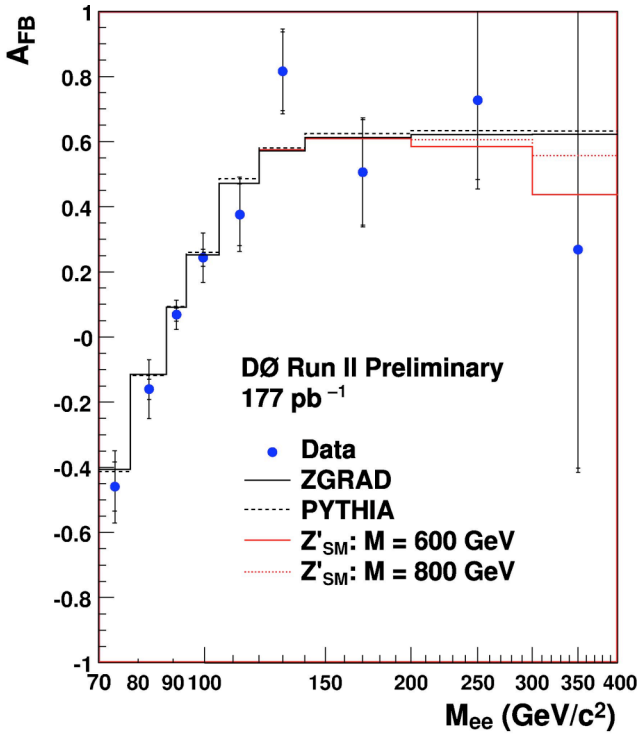
- The relative strengths of the axial and vector couplings of quarks to the Z boson can be extracted from measurement of forward-backward charge asymmetry (A_{FB})
- At Tevatron can measure A_{FB} at the Z-pole as well as above and below



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

A_{FB} Results

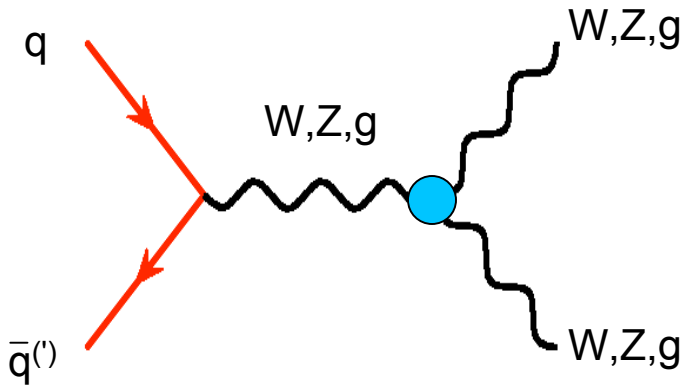




- Current measurements are statistics limited
- The high mass region is of particular interest since this is where new physics can interfere with Standard Model to produce deviations

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

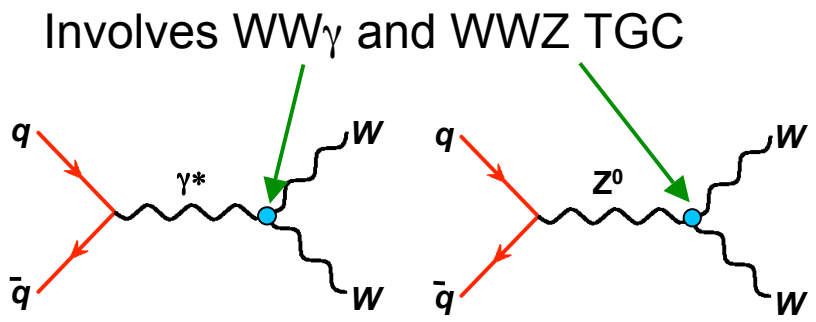
$q\bar{q} \rightarrow Z/\gamma^* \rightarrow WW$: $WW\gamma$, WWZ

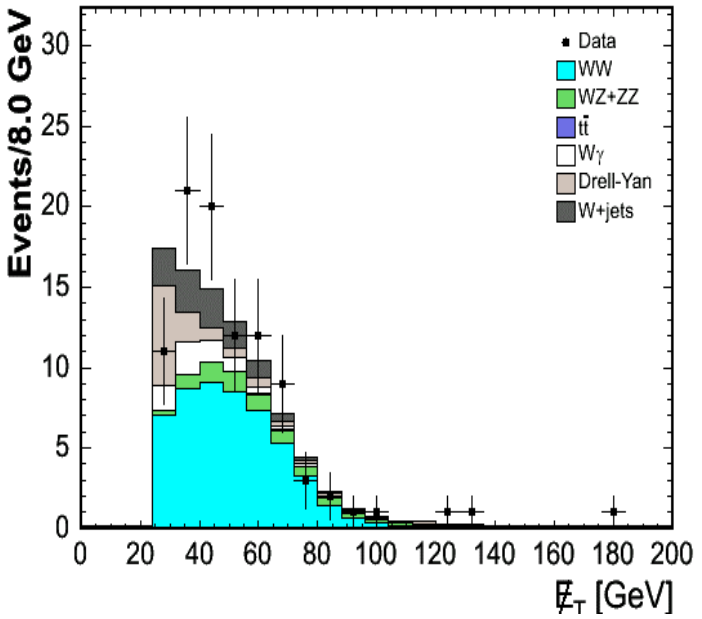
$q\bar{q} \rightarrow Z/\gamma^* \rightarrow Z\gamma$: $ZZ\gamma$, $Z\gamma\gamma$

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

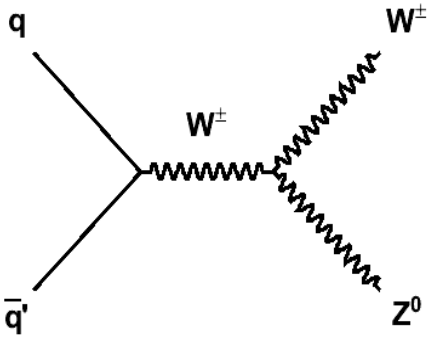
$\sigma(p\bar{p} \rightarrow WW) = 13.6 \pm 2.3(stat)$
$\pm 1.6(syst) \pm 1.2(lum)$ pb

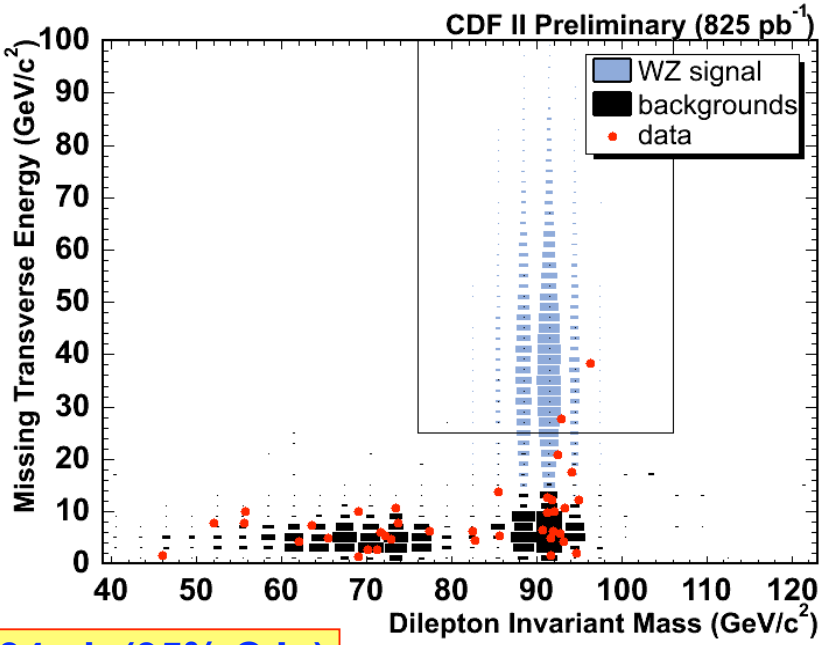
NLO cross section: 12.4 ± 0.8 pb

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

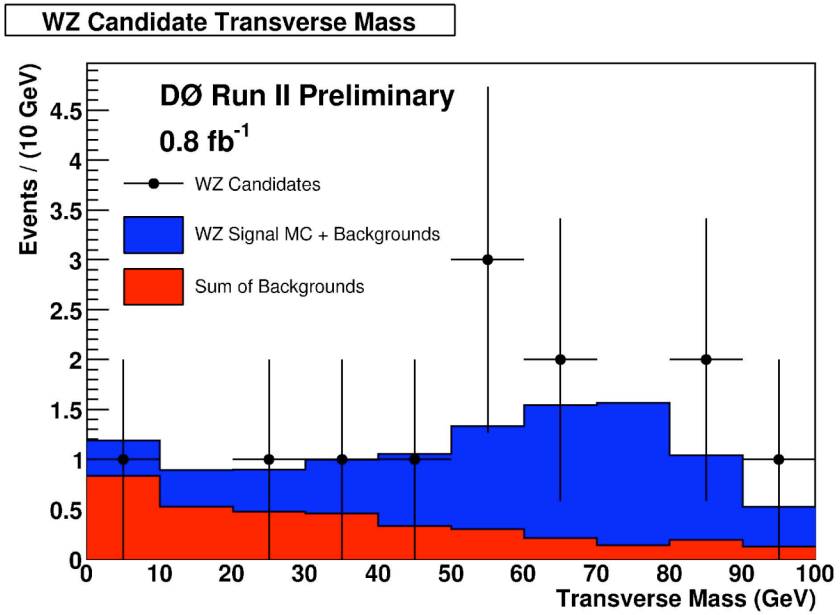




σ(WZ) < 6.34 pb (95% C.L.)

WZ Cross Section

- 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



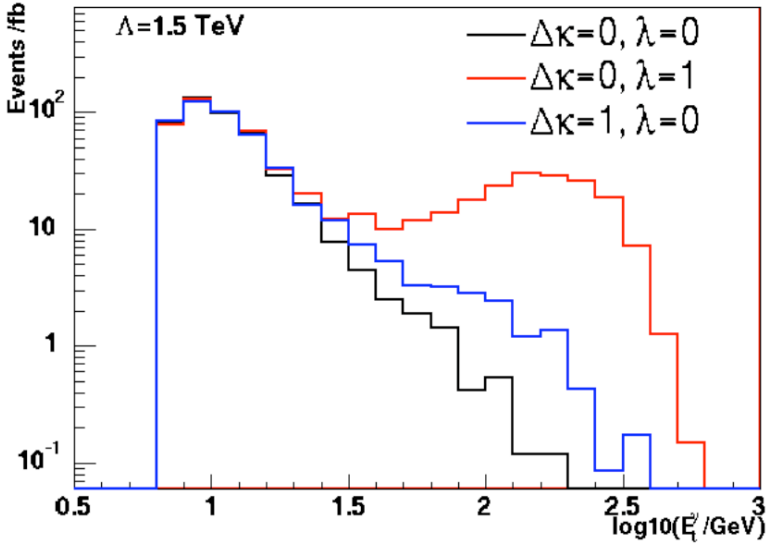
$$\sigma(p\bar{p} \rightarrow WZ) = 3.98^{+1.91}_{-1.53}\ \text{pb}$$

NLO cross section: 3.68 ± 0.25 pb

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

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



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

SM: $g_1^\gamma = g_1^Z = 1$

AC: Δg_1^Z ($= g_1^Z - 1$)

SM: $\kappa_\gamma = \kappa_Z = 1$

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

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

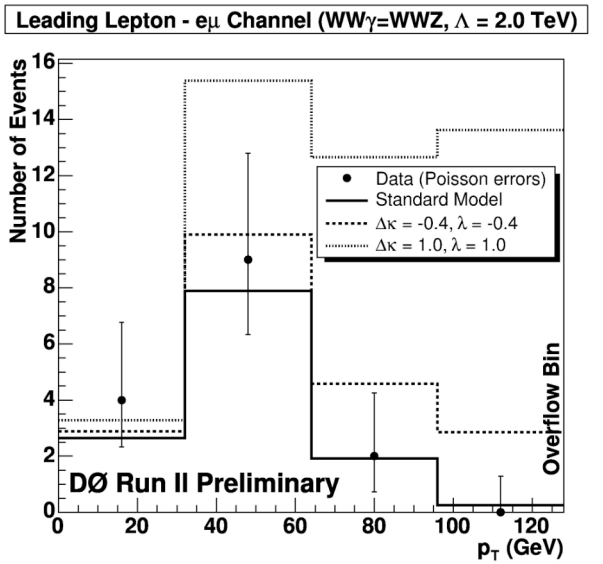
AC: λ_Z , λ_γ

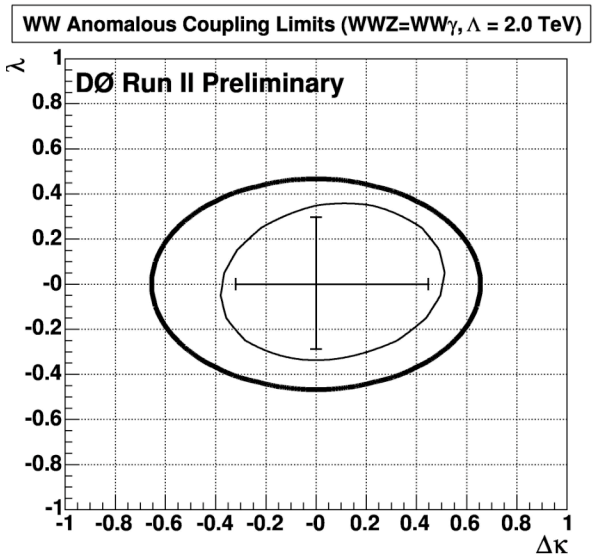
Anomalous Coupling Limits

- 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

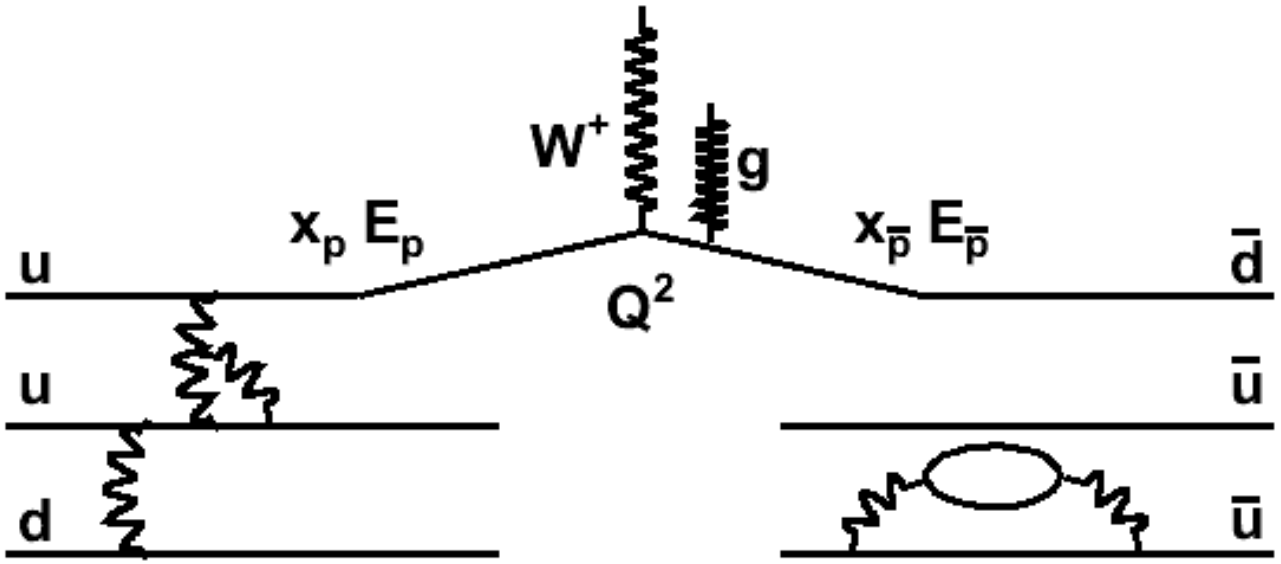
$$-0.32 < \Delta\kappa < 0.45$$

$$-0.29 < \lambda < 0.45$$





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

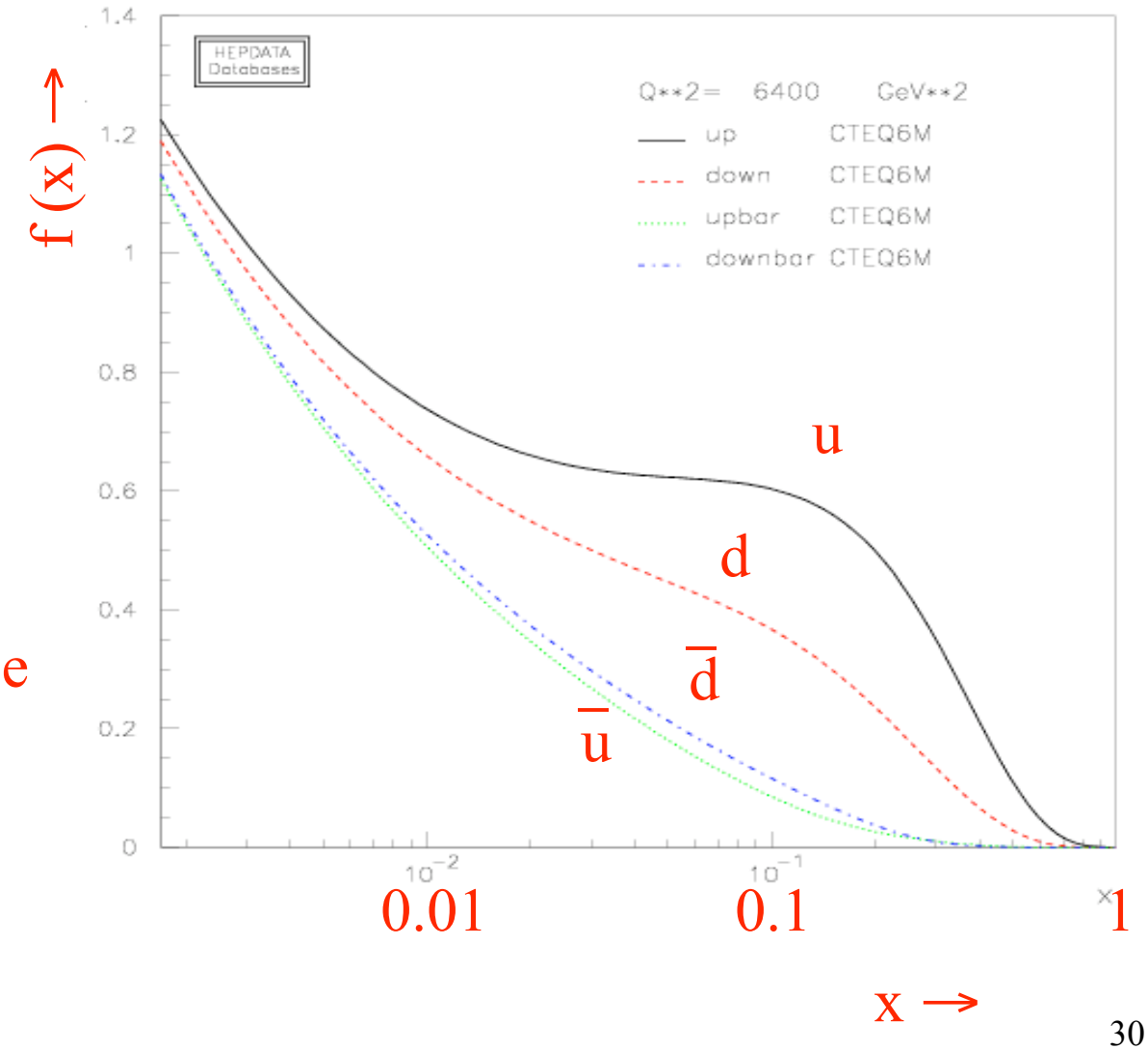
Kinematic constraint

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)

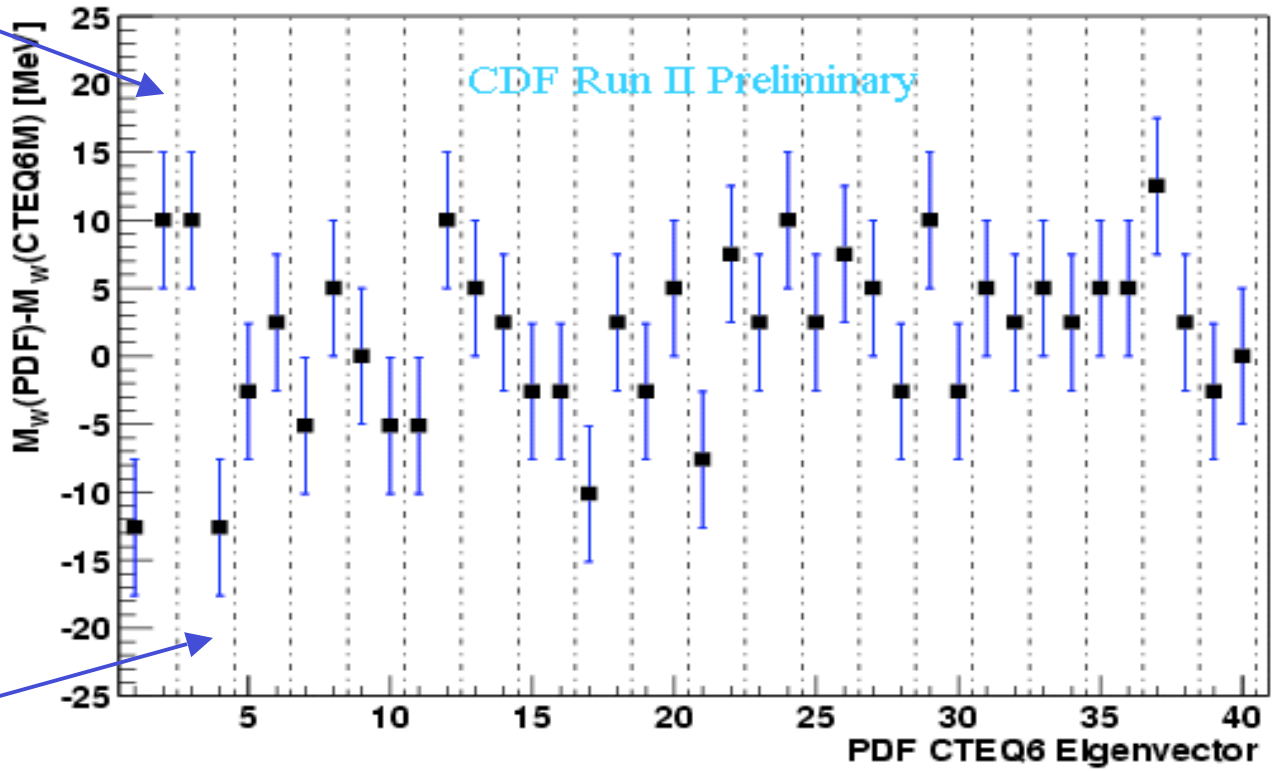
- PDF functions are based on fits to experimental data made by two independent groups (CTEQ & MRST)
- Parameters are determined for Q_0 = 1.3 GeV and the Q dependence is modeled by QCD evolution equations
- The A_i parameters are correlated and eigenvectors are determined to facilitate uncertainty calculations

Example

- W boson mass PDF uncertainty

valence up quark

A1: low x

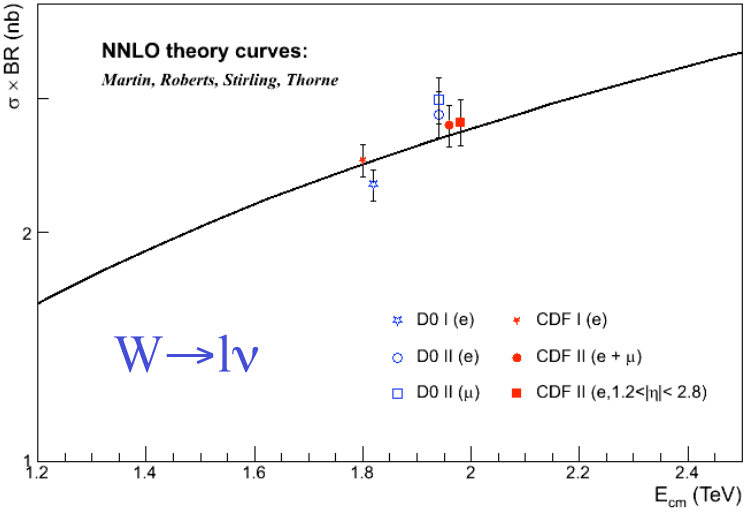


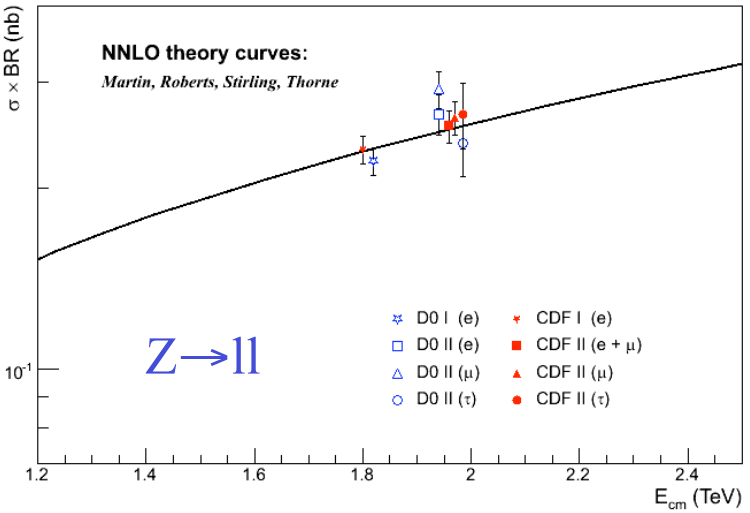
valence down quark, sea quarks

A1: low x

Cross Section Measurements

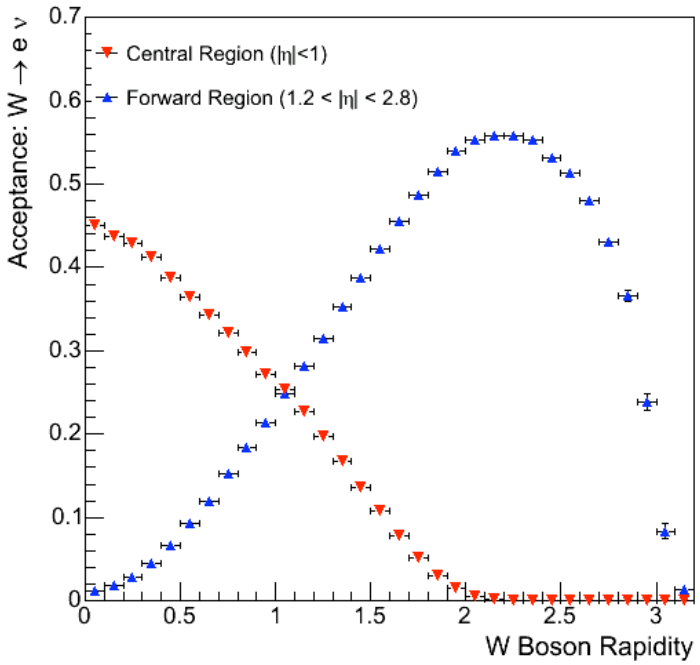
- CDF and D0 measure the inclusive W and Z boson production cross sections in all lepton (e,μ,τ) decay channels
- Largest uncertainty comes from luminosity measurements (~6%)
- Within that uncertainty, agree well with precise NNLO calculations

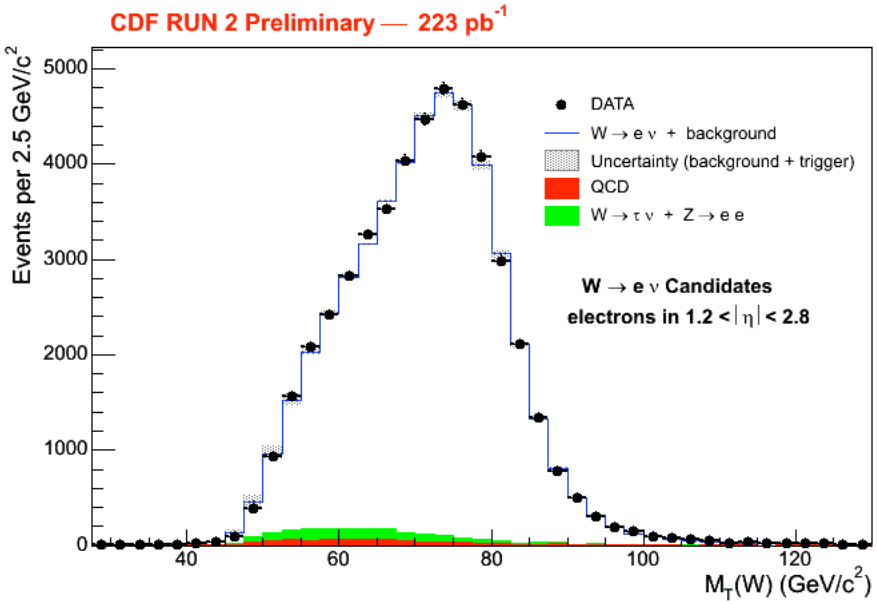




Forward Cross Section

- 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

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

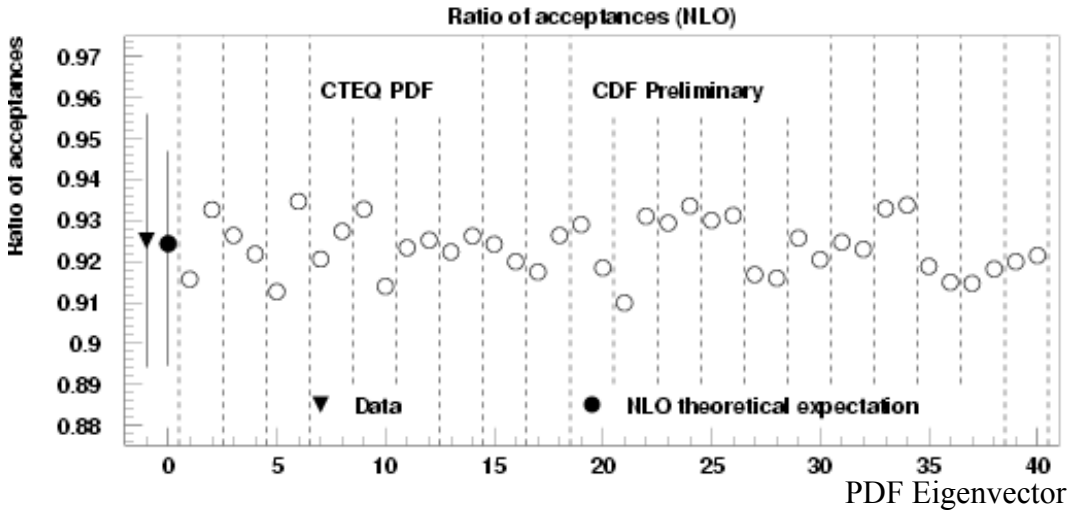
$$R_{exp} = \sigma^{cent}_{vis} / \sigma^{forw}_{vis} = 0.925 \pm 0.033$$

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

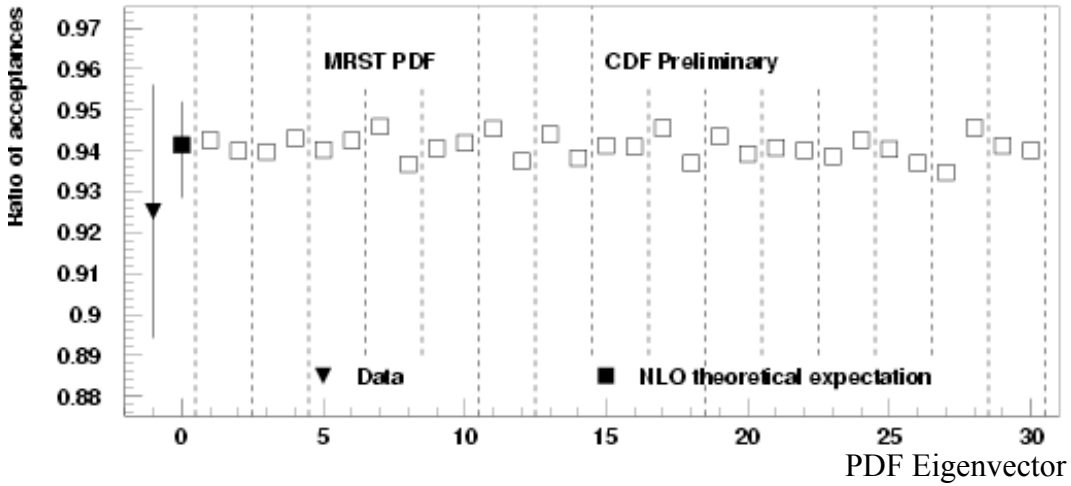
$$= 0.941 \pm 0.012 \text{ (MRST01E)}$$

PDF Constraints

CTEQ



MRST

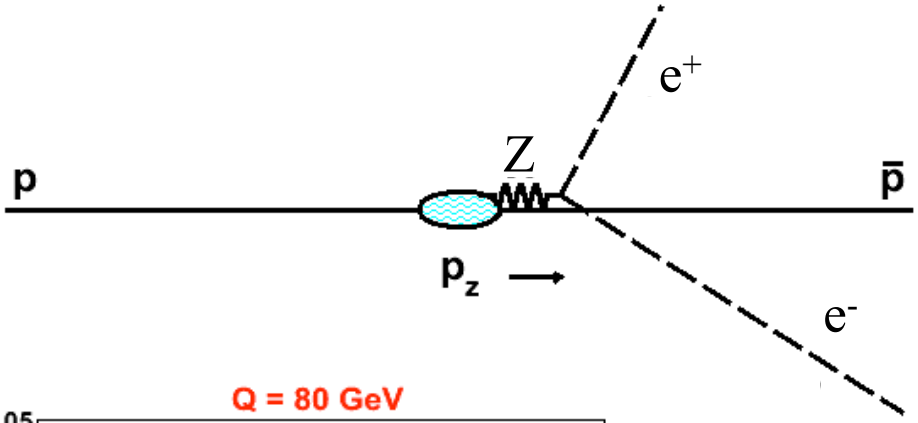


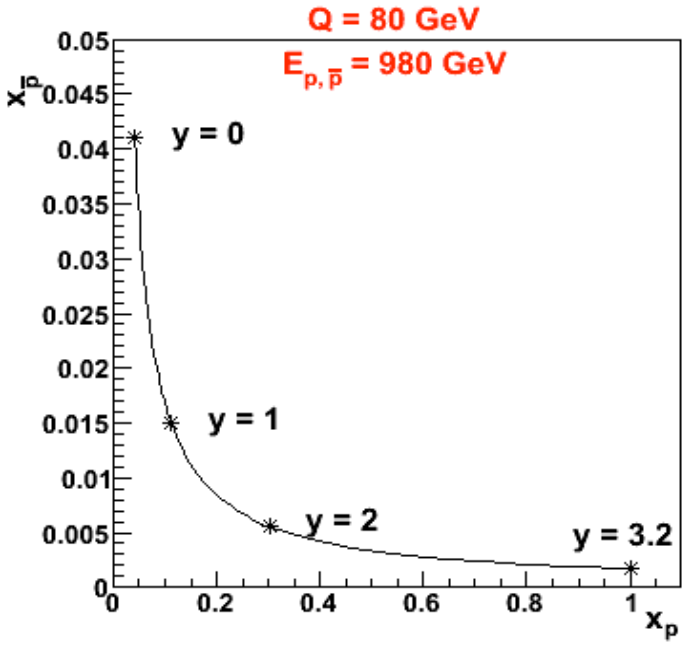
Differential Cross Sections

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

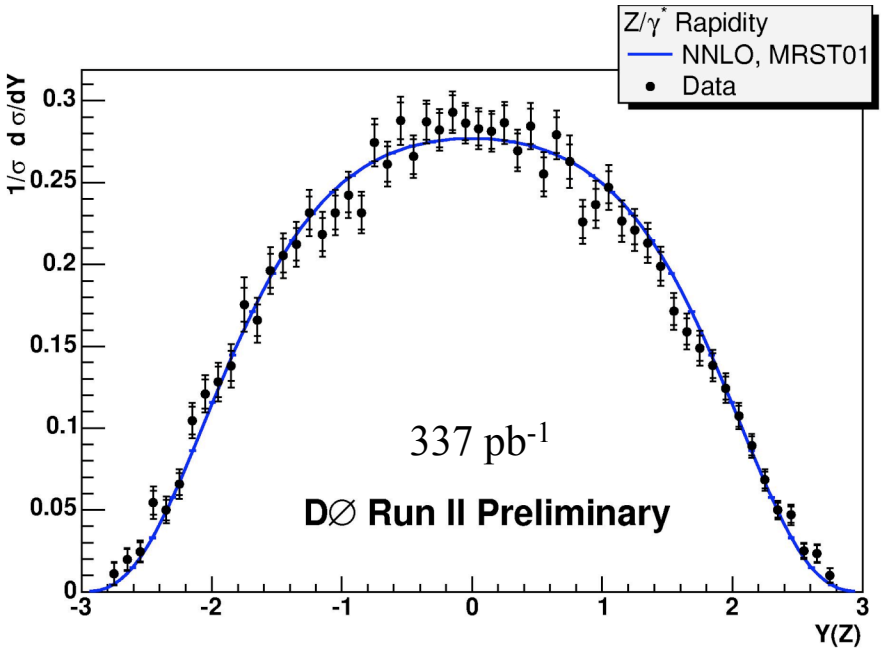
$$y = 0.5 \ln \left[\frac{x_p}{x_{\bar{p}}} \right]$$

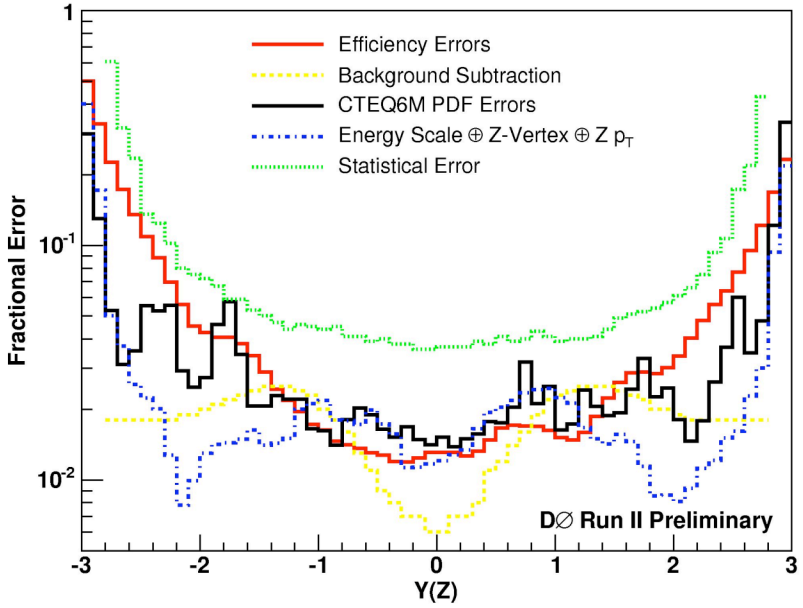
- Relative sizes of x_p, $x_{\bar{p}}$ determine the longitudinal momentum of boson





dσ/dy Measurement



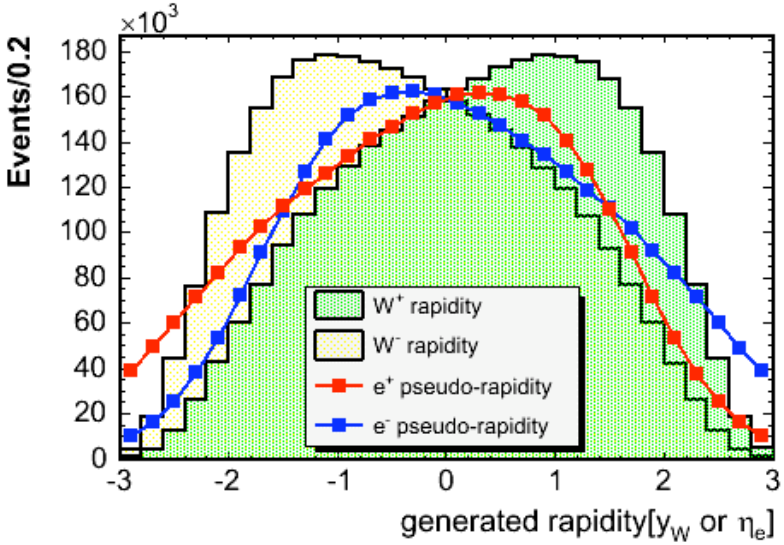


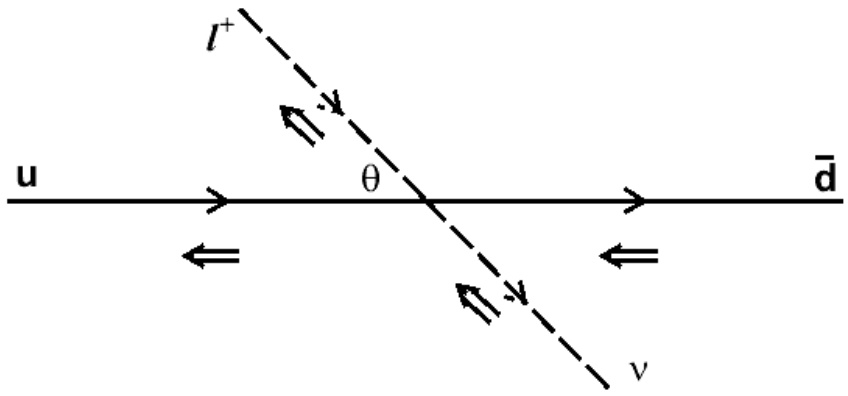
- Measurements are currently statistics limited
- Potential PDF uncertainty with increased statistics, particularly in the tails where the PDF variation is largest

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

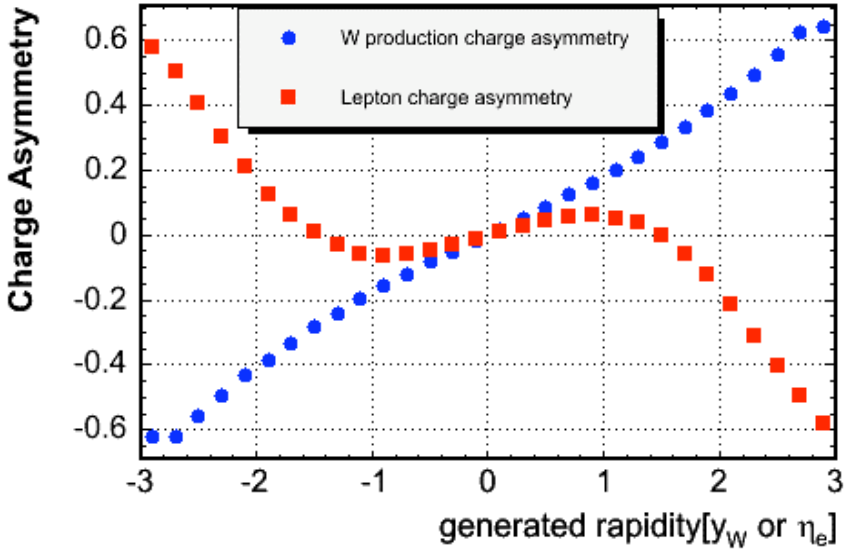
$$d\sigma/d\theta \propto (1 + \cos\theta)^2$$





Charge Asymmetry

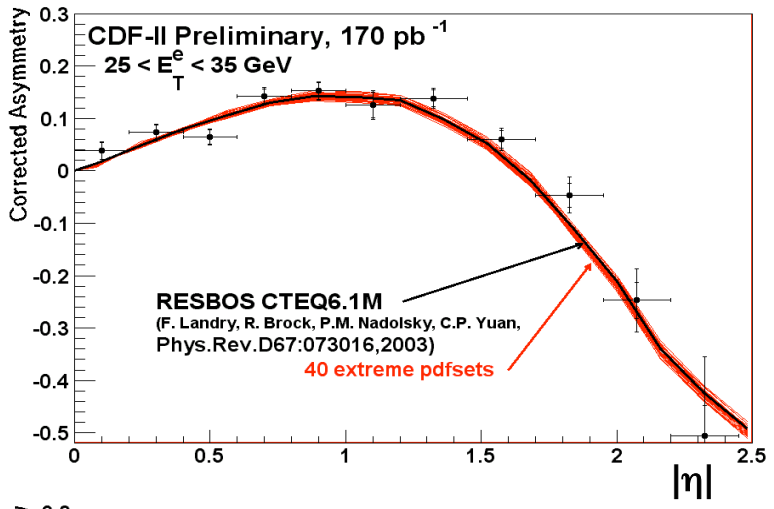
$$A^{\pm}_{W}(y) = \frac{\sigma_{W+}(y) - \sigma_{W-}(y)}{\sigma_{W+}(y) + \sigma_{W-}(y)}$$

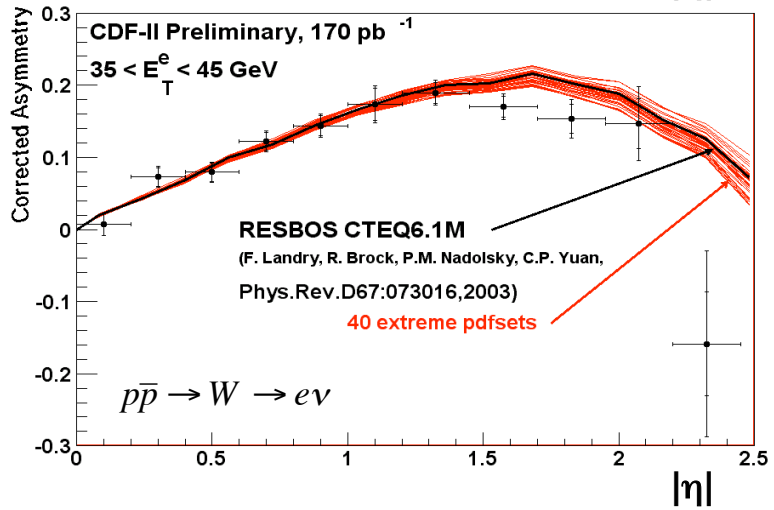


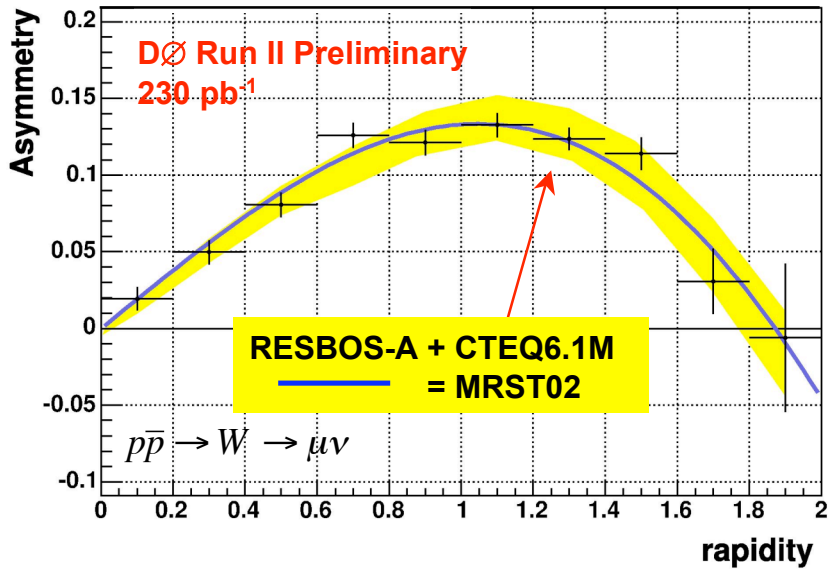
- Equivalent definition for lepton asymmetry

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

Lepton Charge Asymmetry

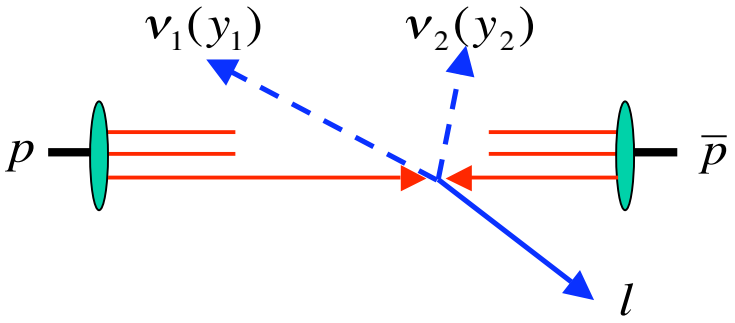




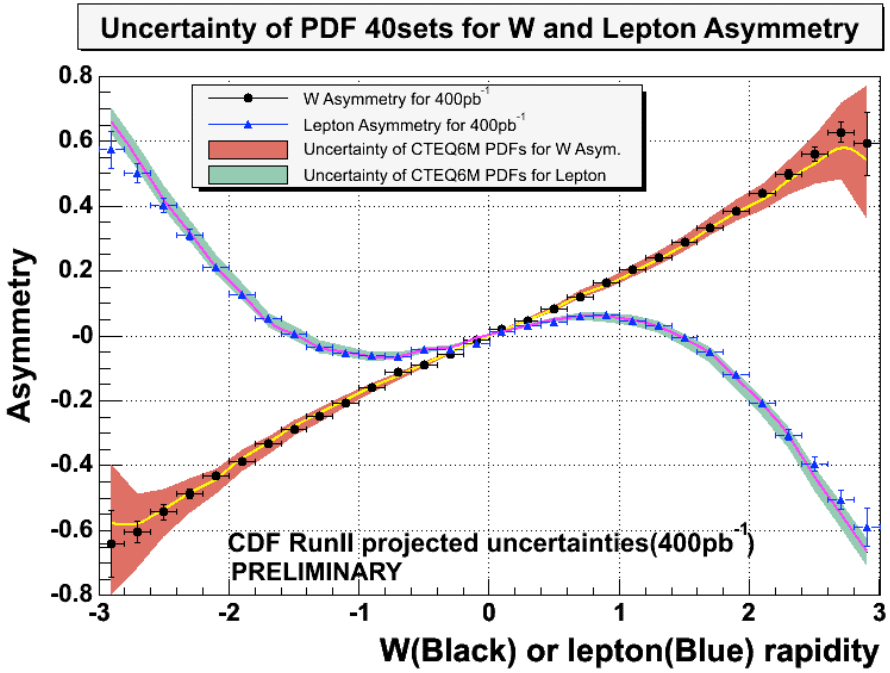


- Current DØ measurement using muons has some sensitivity to PDFs
- CDF measurement breaks data into separate E_T ranges

Future Asymmetry Measurements



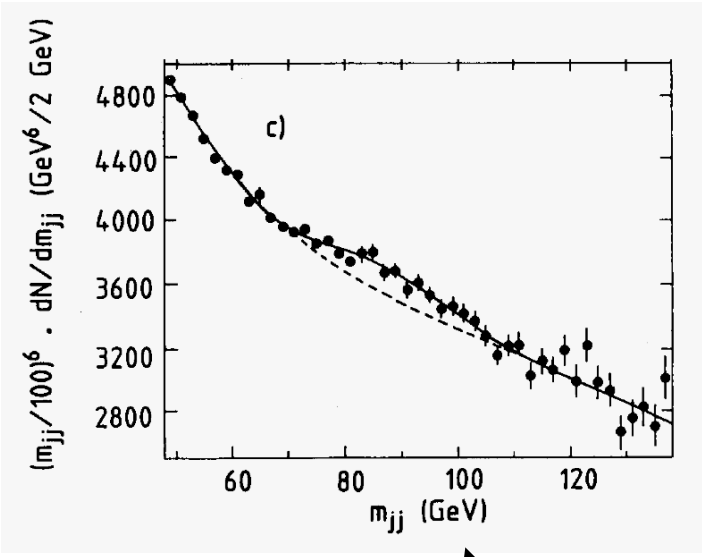
- Reconstruct W production asymmetry $A(y_W)$ directly
- Two kinematic solutions using M_W constraint
- Weight solutions taking into account production & decay
- Resolve dependence on y_W iteratively



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