From W to Z: Electroweak and QCD Results from DØ

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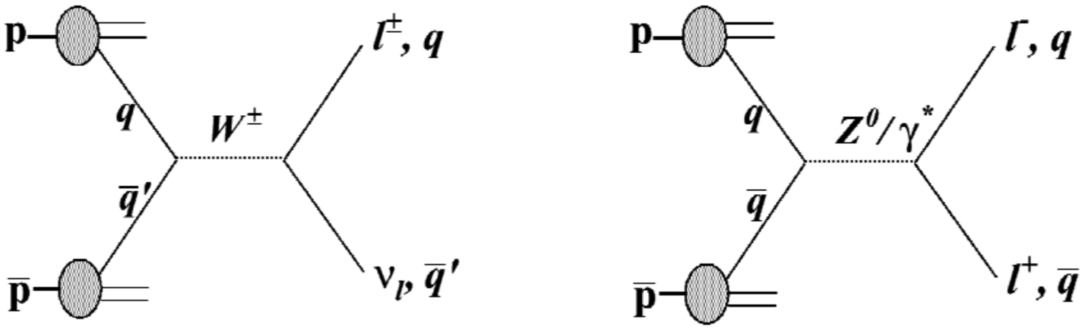
Outline

- Introduction
- Forward-backward asymmetry (A_{FB}) measurement and extraction of $\sin^2\theta_W^{eff}$ ($Z/\gamma^* \rightarrow ee$)
- Electron charge asymmetry ($W \rightarrow e\nu$)
- Z + jet measurement ($Z \rightarrow \mu\mu$)
- Conclusions

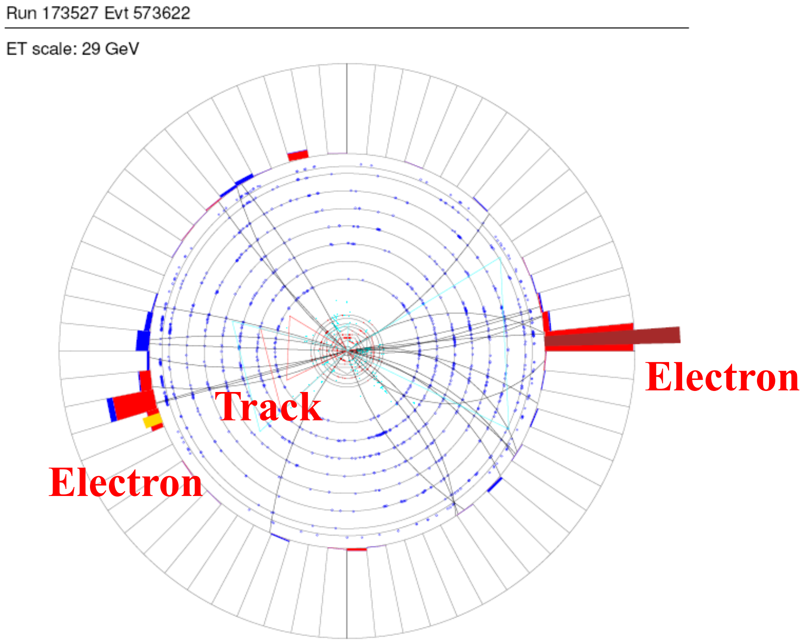
Introduction

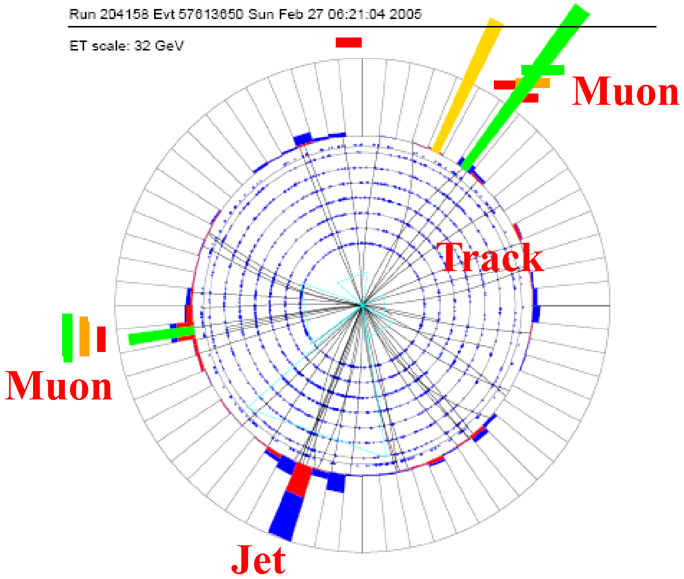
- W and Z boson production at Tevatron



- Constrain parton distribution functions (PDFs)
  - Electron charge asymmetry from W
- Test higher-order QED and QCD corrections
  - Z boson A_{FB} measurement
  - Z+jet measurement
- Make precision measurements of electroweak parameters
  - Extraction of $\sin^2\theta_W^{eff}$
- Search for physics beyond the SM
  - A_{FB} measurement at high mass region

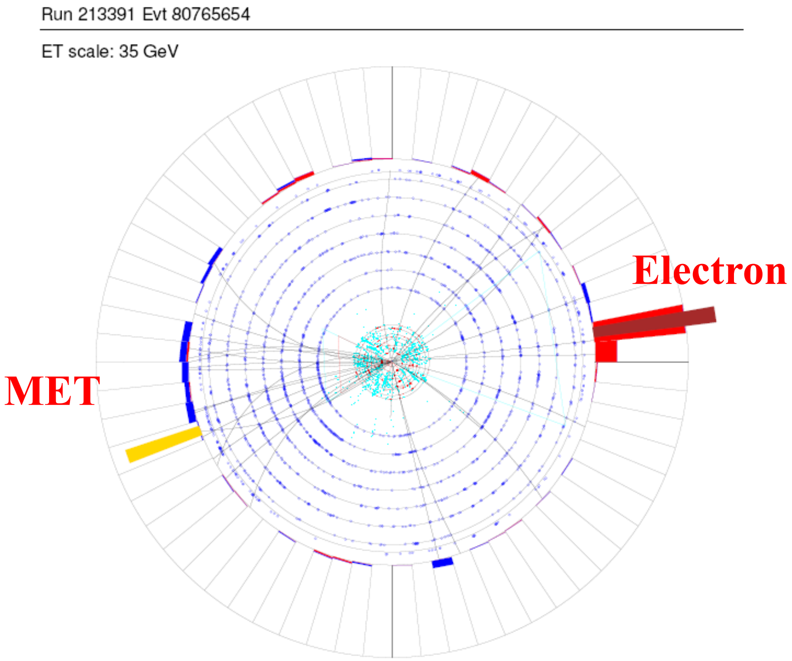
Z event

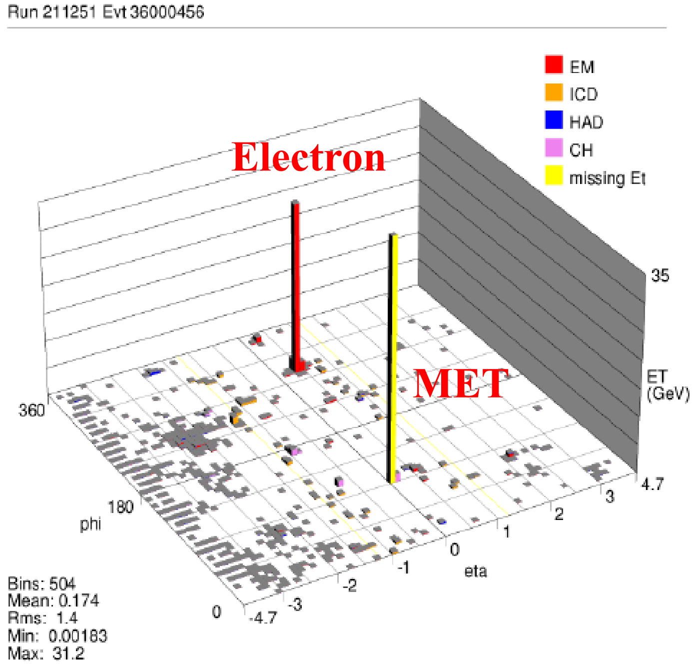




- Two high p_T charged leptons (ee or $\mu\mu$)
- Both charged leptons are detected and their momenta measured
- Electrons: tracker, EM calorimeter
- Muons: tracker, muon detector
- Jets: Hadronic calorimeter

W event





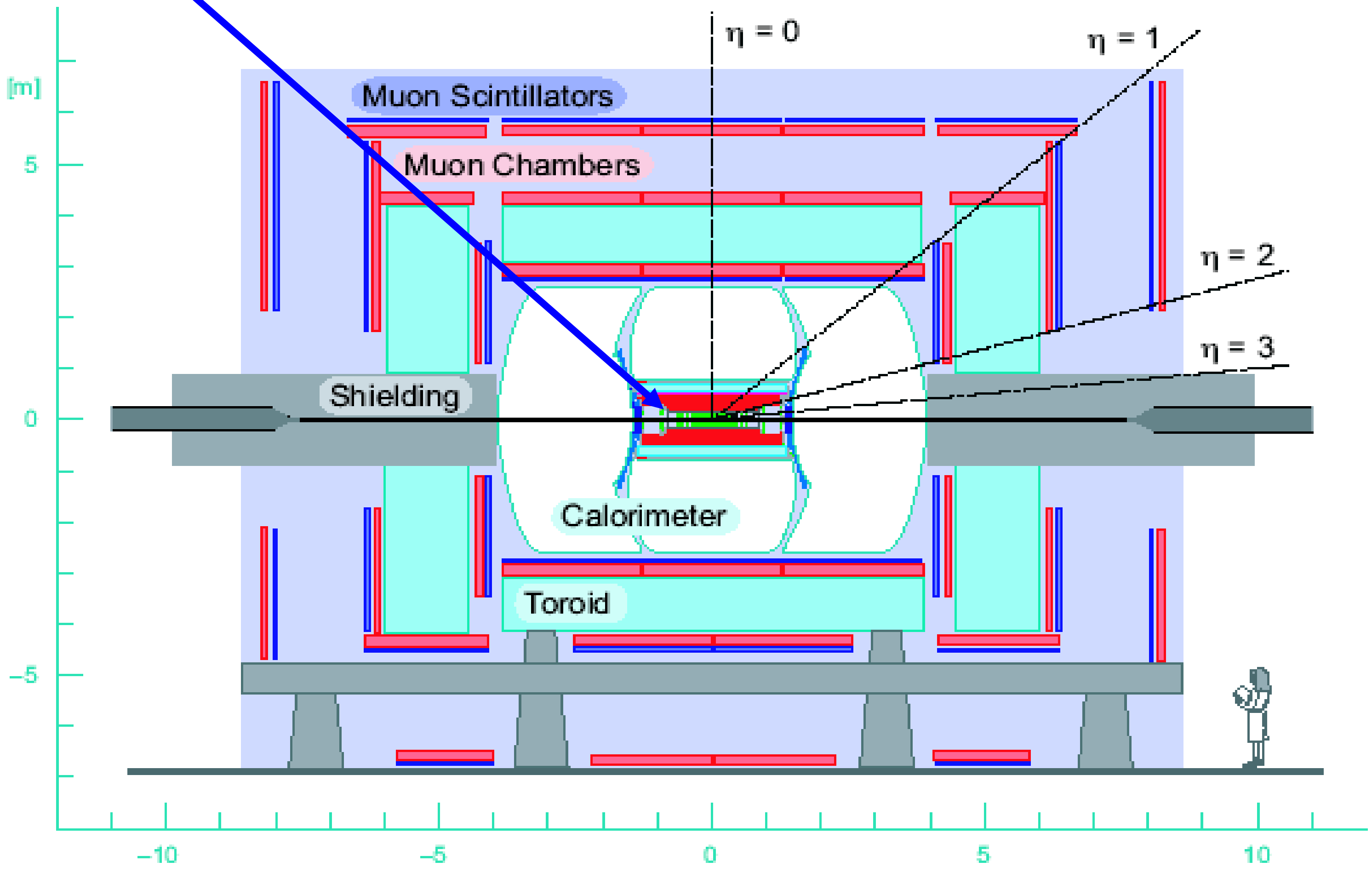
- One high p_T charged lepton, one high p_T neutrino ($e\nu$ or $\mu\nu$)
- Charged lepton is detected and momentum measured
- Neutrino cannot be detected
- $p_T(\nu)$ is inferred by the "missing E_T (MET)" in the detector

DØ Detector

Silicon Microstrip Tracker (SMT)

Central Fiber Tracker (CFT)

2 T magnetic field



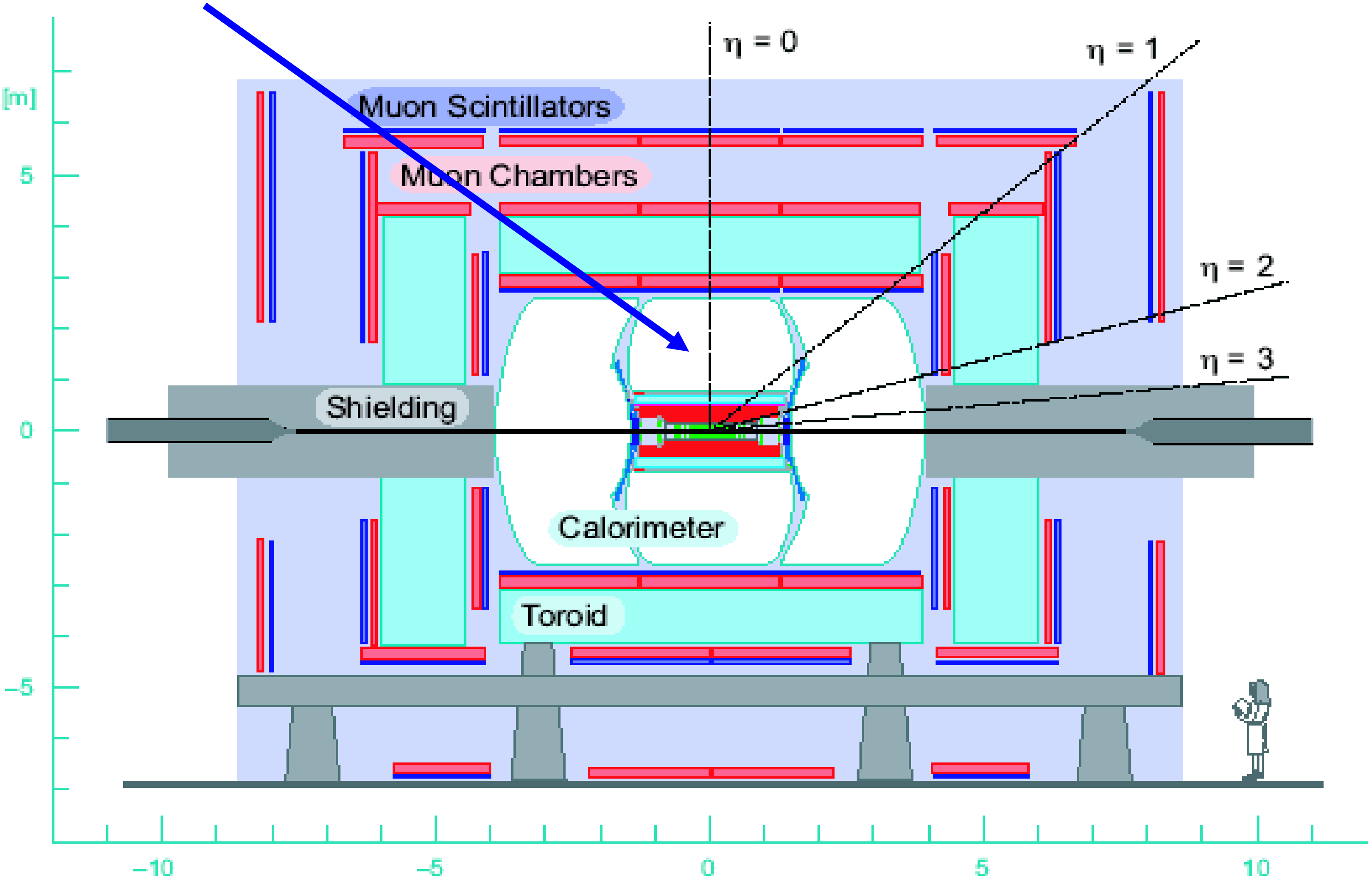
DØ Detector

Liquid-argon sampling calorimeters

Central (CC) and Endcap (EC)

Coverage: $|\eta| < 4.2$

Important for MET measurement

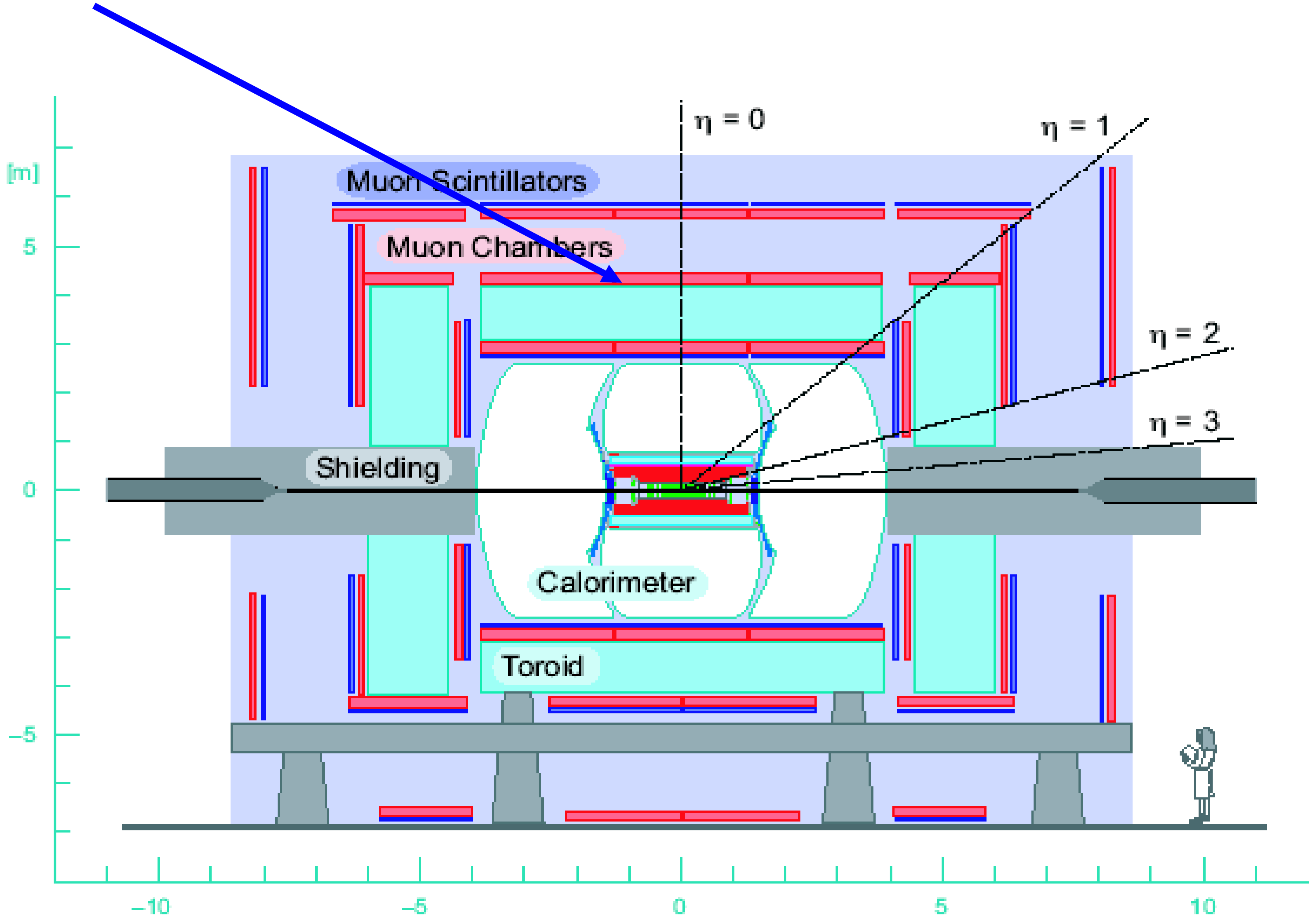


DØ Detector

Muon system

Drift chambers and scintillator counters

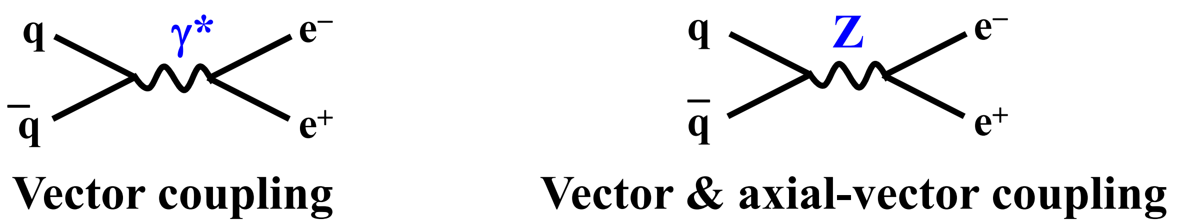
1.8 T toroids

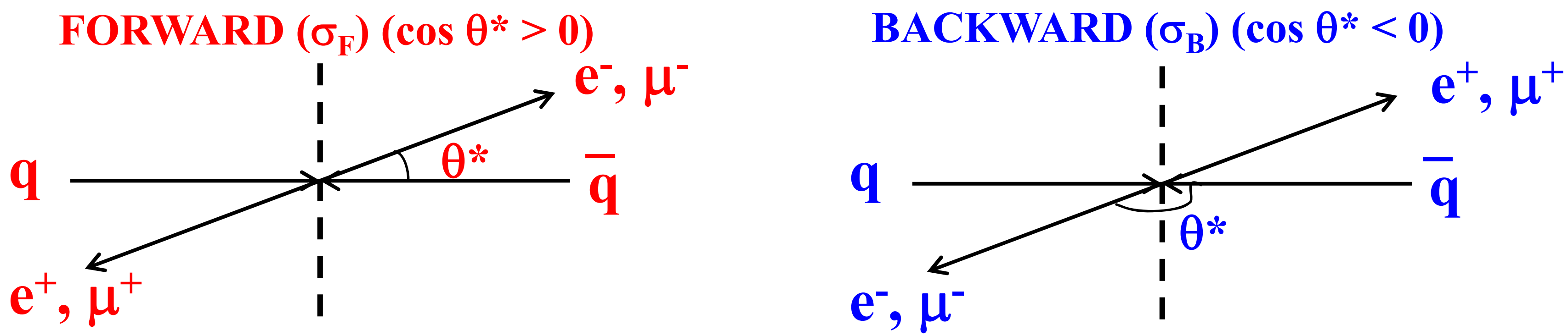


A_{FB} measurement and extraction of $\sin^2\theta_W^{eff}$ $(Z/\gamma^* \rightarrow ee)$

Z/γ* Forward-backward asymmetry

◆ $p\bar{p} \to l^+l^-$: mediated by γ*, Z, Z/γ*





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

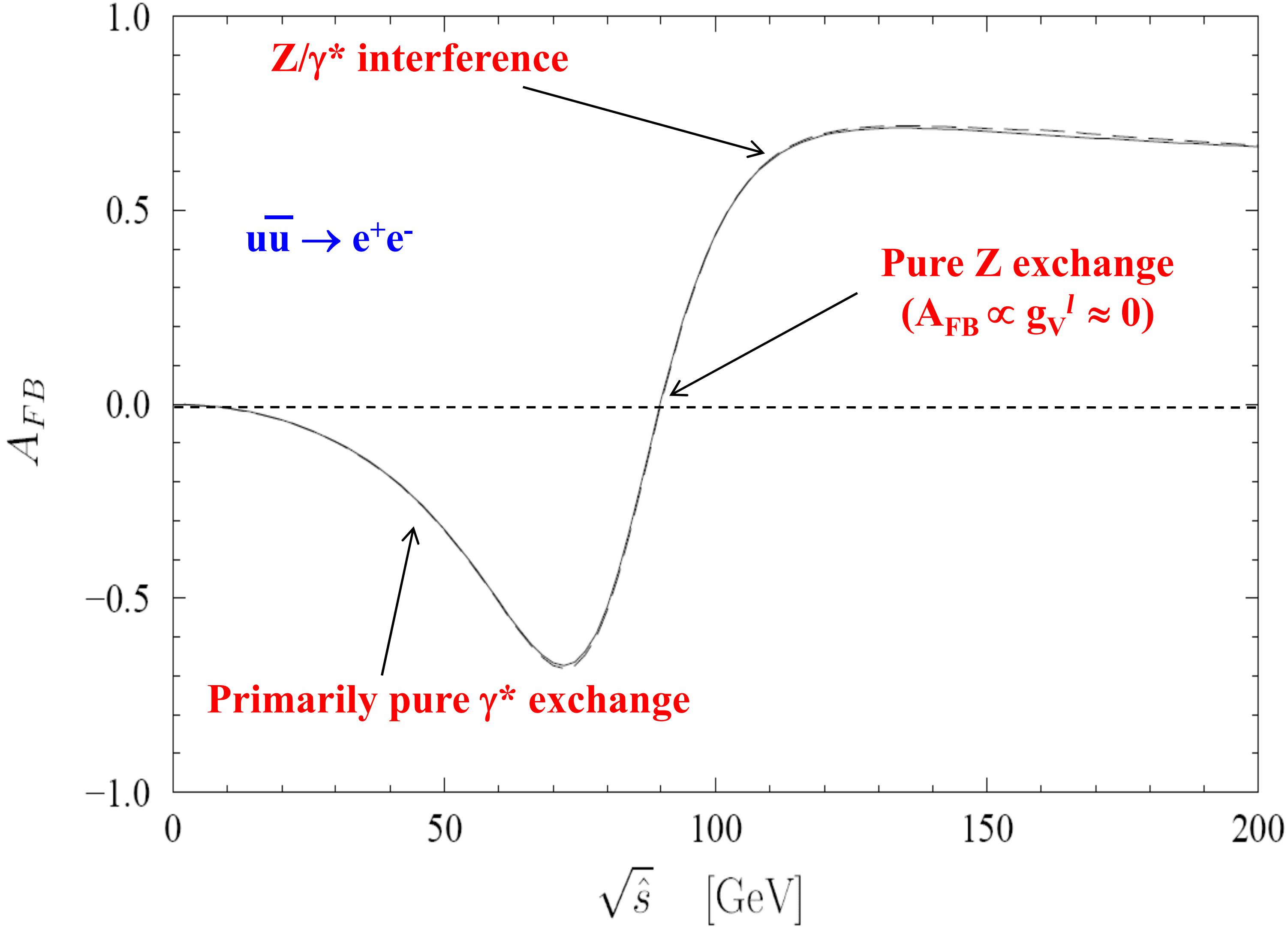
◆ θ*-dependent differential cross section:

$1 + \cos^2\theta^*$ (pure γ*) $1 + \cos^2\theta^*$ and $\cos\theta^*$ (both pure Z and Z/γ* interference)

$$d\sigma/\cos\theta^* = A \times (1 + \cos^2\theta^*) + B \times \cos\theta^*$$

$$A_{FB} = (\sigma_F - \sigma_B) / (\sigma_F + \sigma_B) = (N_F - N_B) / (N_F + N_B)$$

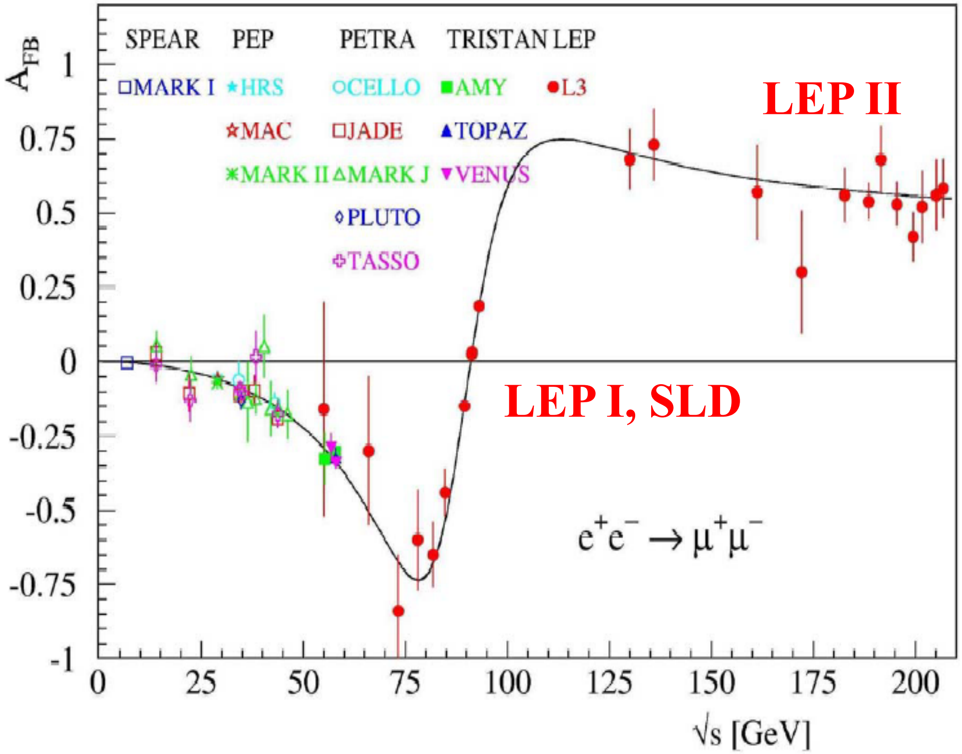
A_{FB} Distribution

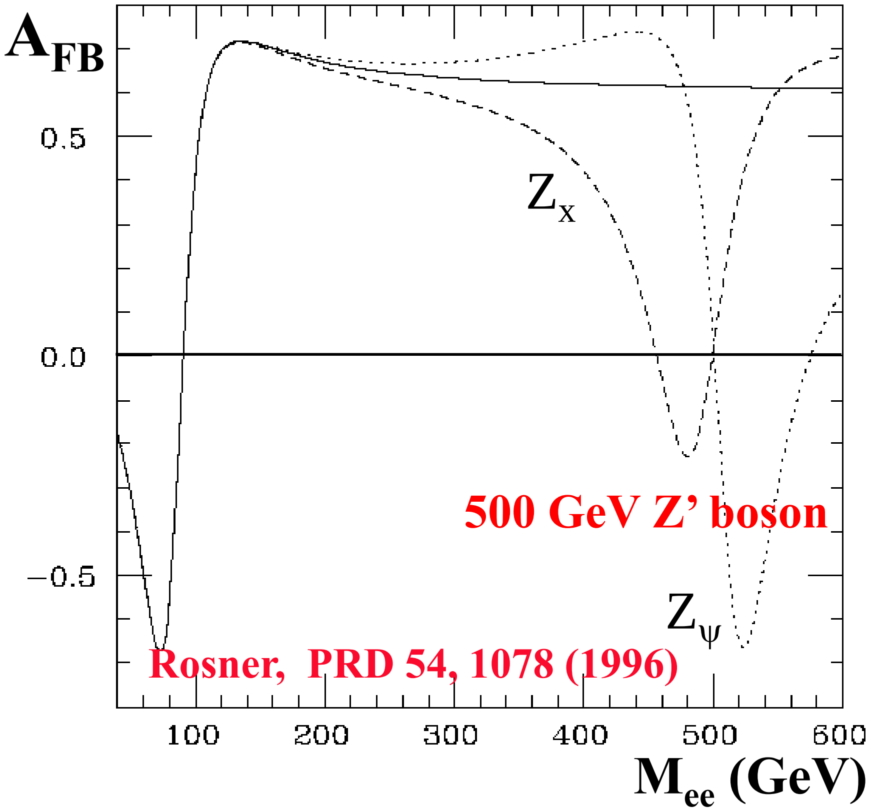


A_{FB} at e^+e^- collider and hadron collider

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

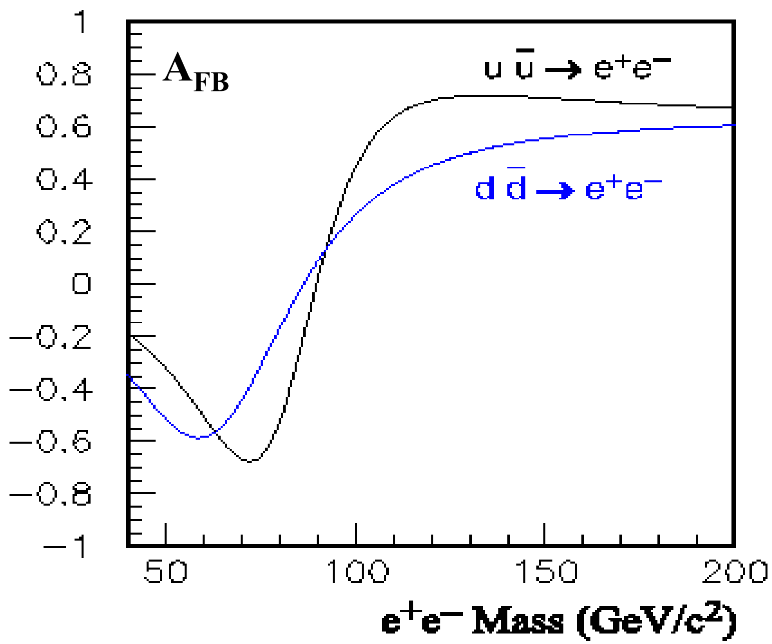
- New resonance (Z', LED etc) can interfere with Z and γ^*
- A_{FB} measurement complementary to bump search





A_{FB} in $Z/\gamma^*\to ee$ at Tevatron

- $u\bar{u}$ $(d\bar{d}) \to Z/\gamma^* \to e^+e^-$
- SM couplings of fermions to Z boson:
  - Axial-vector coupling: $g_A = I_f^3$
  - Vector coupling: $g_V = I_f^3 - 2Q_f \sin^2\theta_W$
  - 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

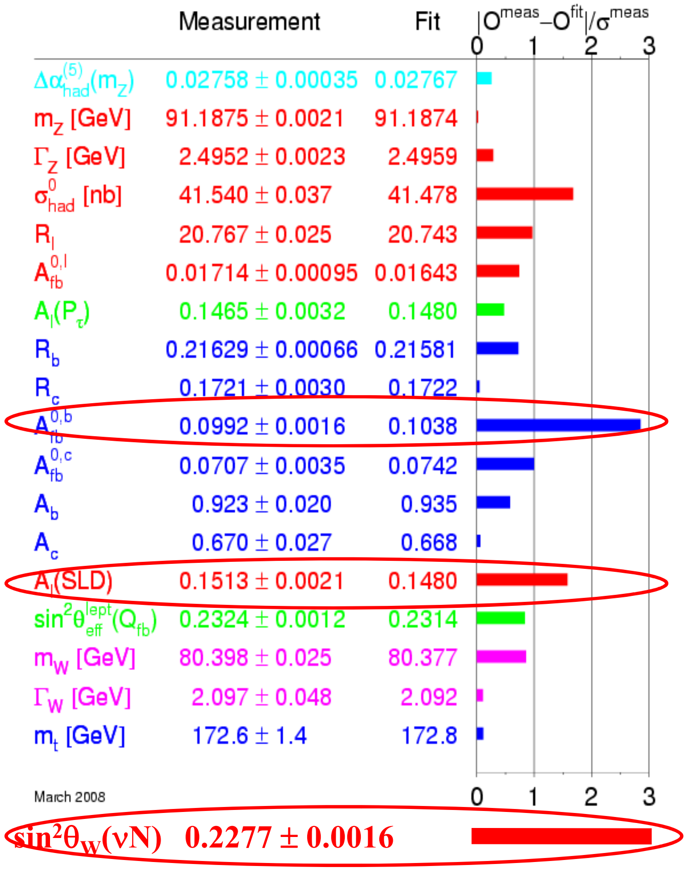


- Probe the relative strengths of Z-q couplings
- Sensitive to the light quarks
- Constrain PDFs

Weak mixing angle $\sin^2\theta_W$

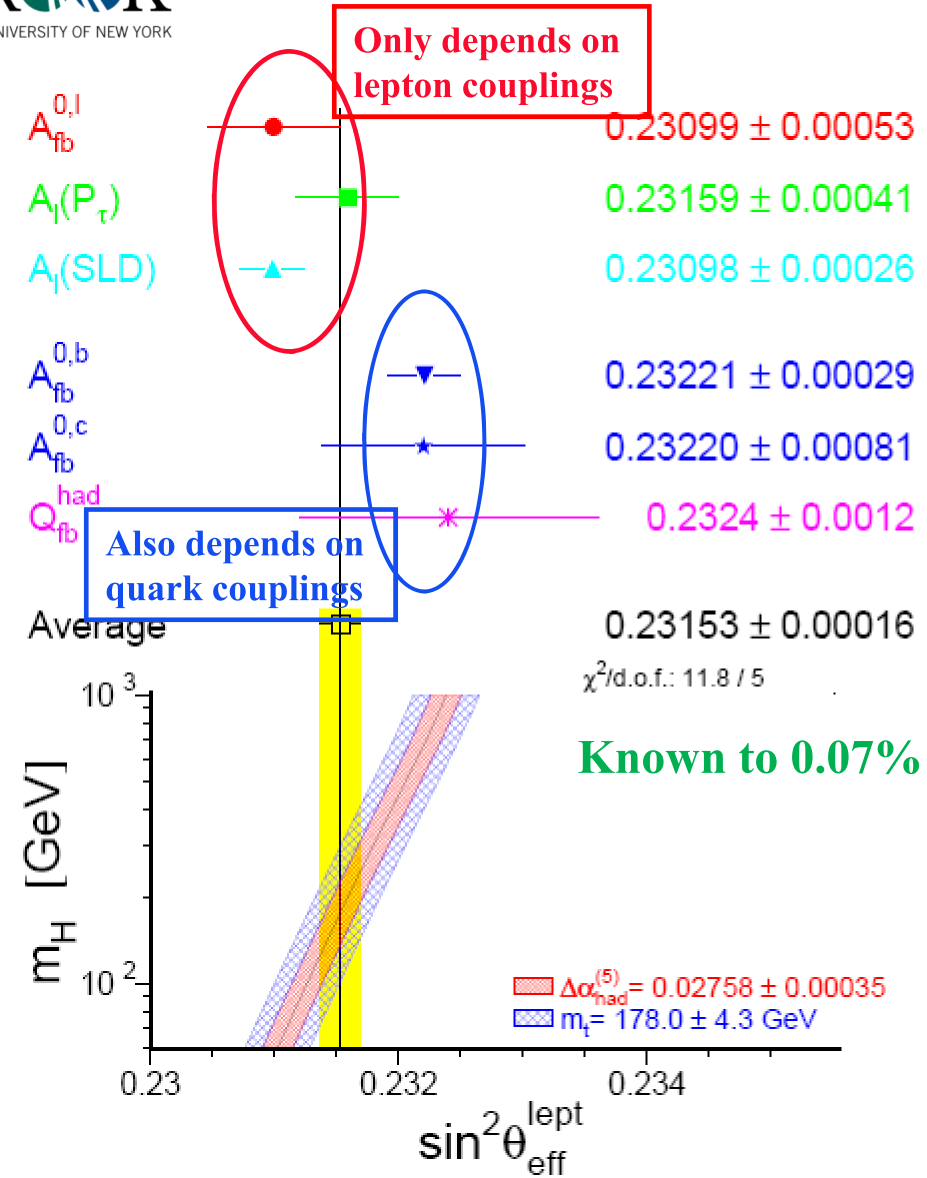
- A_{FB} is sensitive to $\sin^2\theta_W$ ($\sin^2\theta_W^{eff}$ includes higher order corrections)
- LEP A_{FB}^b and SLD A_{LR}: off by 3σ in opposite direction
- NuTeV $\sin^2\theta_W$ result: 3σ away from the global EW fit

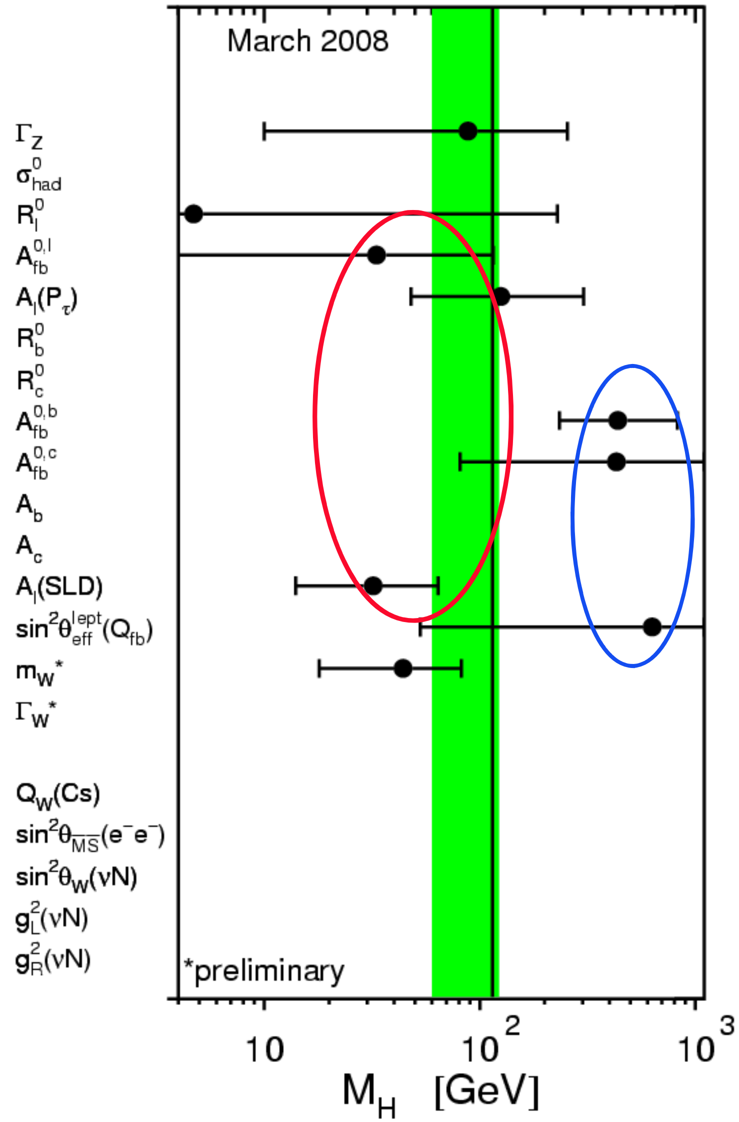
LEP EWWG, Phys. Rep. 427, 257 (2006)



G.P. Zeller *et al.*, PRL 88, 091802 (2002)

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



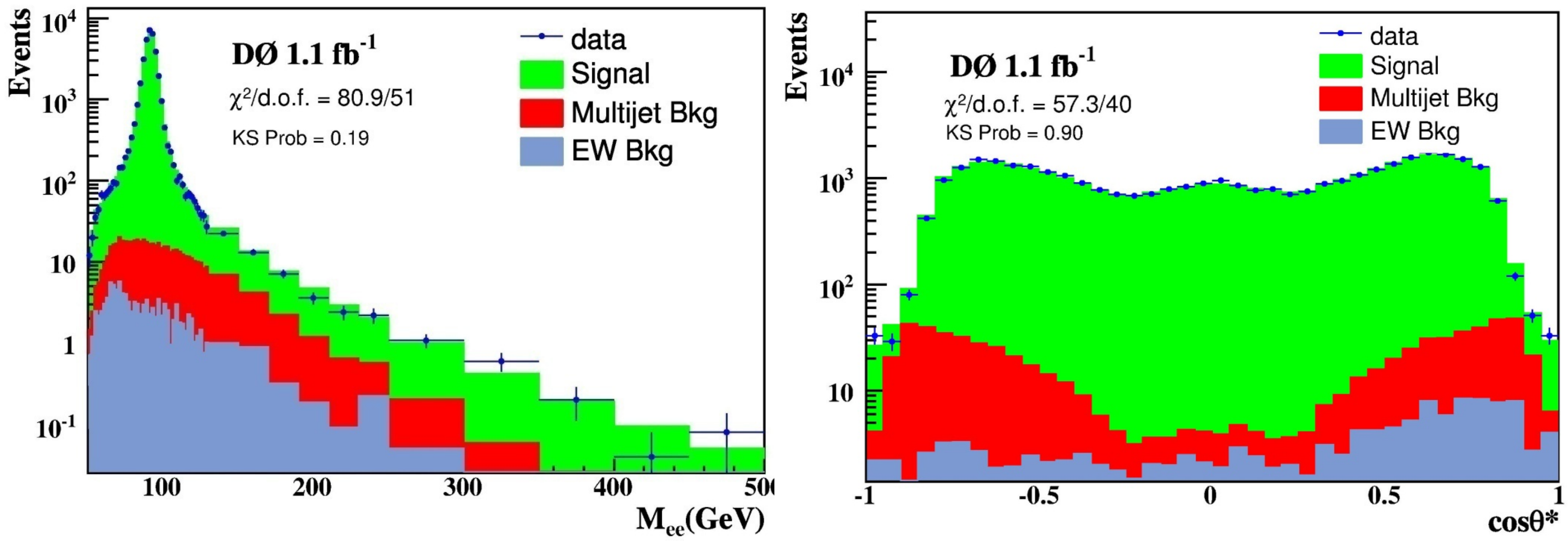


Event selection

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

Mass range (GeV)	CC		CE	
	Forward	Backward	Forward	Backward
50 – 60	69	78	15	16
60 – 70	104	158	51	91
70 – 75	96	117	64	93
75 – 81	191	235	172	293
81 – 86.5	749	763	843	970
86.5 – 89.5	1388	1357	1860	1694
89.5 – 92	2013	1918	2543	2214
92 – 97	2914	2764	3132	2582
97 – 105	686	549	867	470
105 – 115	153	97	243	88
115 – 130	101	39	167	61
130 – 180	91	33	202	69
180 – 250	31	13	53	16
250 – 500	14	15	17	4

M_{ee} and cosθ* distributions

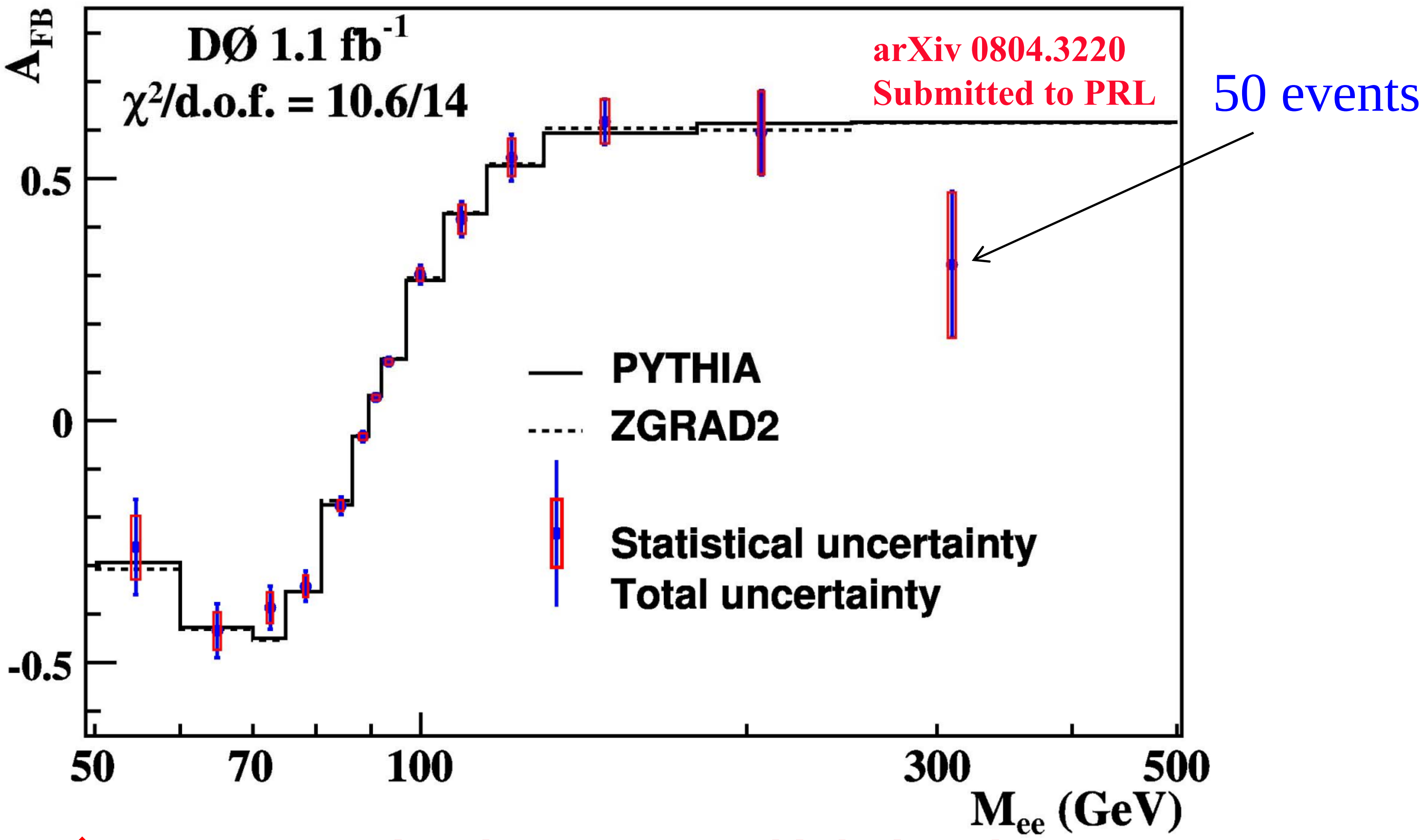


- ◆Electroweak backgrounds estimated using Geant MC simulation:
  - ➢$Z/\gamma^* \rightarrow \tau\tau$, W+X, WW, WZ, ttbar
- ◆QCD multijet background estimated using collider data (0.9%)

A_{FB} Unfolding

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

Unfolded A_{FB}



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

$\sin^2\theta_W^{eff}$ Result

- Extraction of $\sin^2\theta_W^{eff}$ using PYTHIA:
  - Obtained from backgrounds-subtracted A_{FB} distribution
  - Compared with A_{FB} templates according to different values of $\sin^2\theta_W^{eff}$ generated with PYTHIA and GEANT-based MC simulation
- Higher-order QCD and EW corrections: using ResBos and ZGRAD2
- Fitted results (for $50<M_{ee}<500$ GeV):

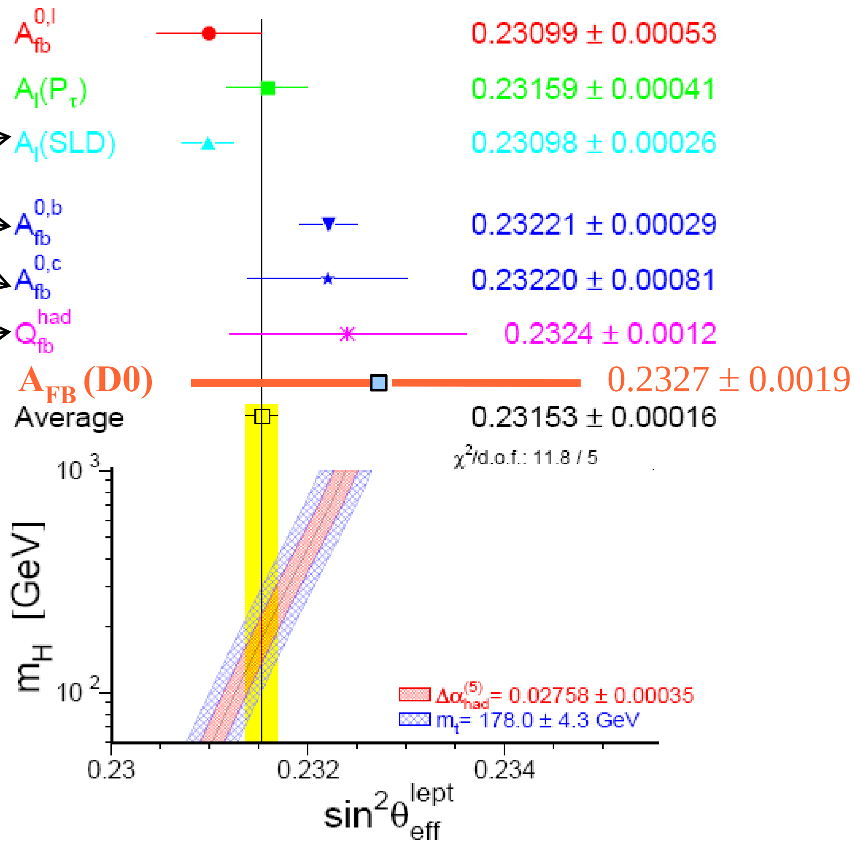
$$\sin^2\theta_W^{eff} = 0.2327 \pm 0.0018 \text{ (stat.)} \pm 0.0006 \text{ (syst.)}$$

  - Systematic uncertainties:
    - PDFs (0.0005)
    - EM energy scale/resolution (0.0003)
  - Similar results for $70 < M_{ee} < 110$ GeV

Difficult to tag light quarks in final state

Relies on MC to determine relative fraction of different quark species

Probe Z-light quark couplings



- Our $\sin^2\theta_W^{eff}$ result agrees with the global EW fit
- Uncertainty comparable with the uncertainties from
  - Combined Q^{had}_{FB} from four LEP experiments (0.0012)
  - NuTeV measurement (0.0016)
- Will approach world average uncertainty (~ 8 fb^{-1}, e + μ, with CDF)
- Will fit for Z-electron, Z-u and Z-d quark couplings, search for new resonances

Electron Charge Asymmetry
($W \rightarrow e\nu$)

W Charge Asymmetry

- u quarks carry on average more momentum than d quarks in the proton
- Use W's to probe proton structure

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

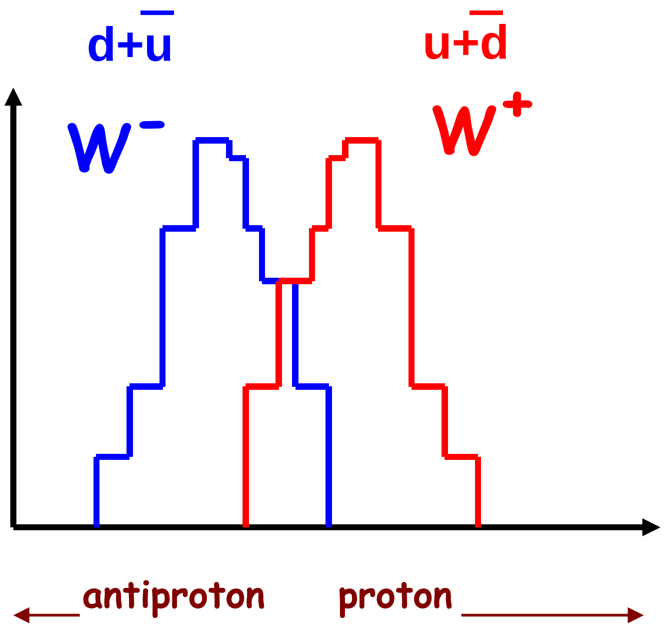
- A(y) sensitive to u(x)/d(x) and anti-quark distribution - PDFs

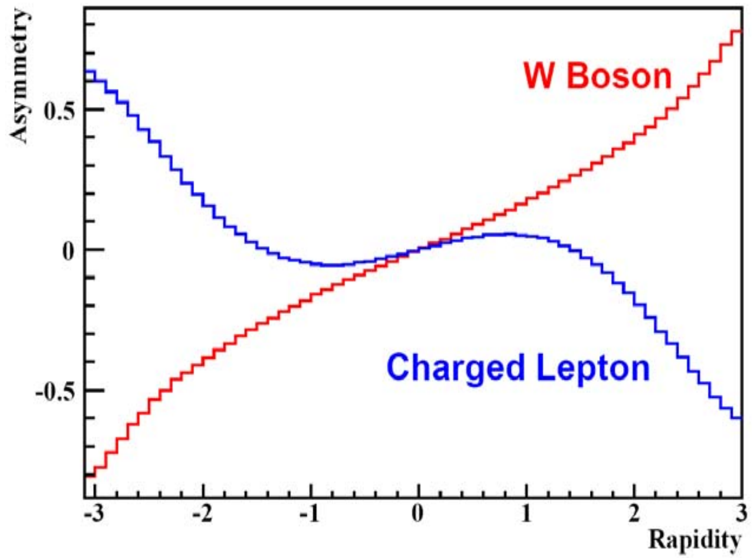
$W \rightarrow e\nu \quad \Rightarrow$ A(y) difficult to measure

- W asymmetry $\rightarrow$ Lepton asymmetry

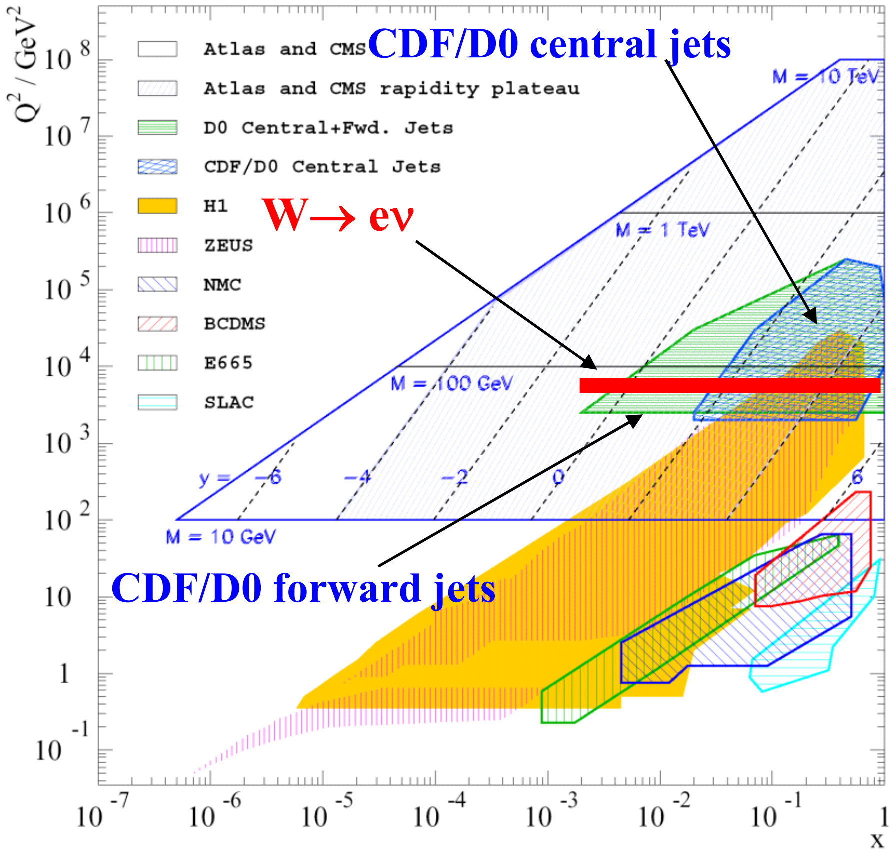
$$A(\eta_l) = \frac{d\sigma(l^+)/d\eta - d\sigma(l^-)/d\eta}{d\sigma(l^+)/d\eta + d\sigma(l^-)/d\eta}$$

- Lepton asymmetry: A(y) $\otimes$ (V-A)
- The V-A structure of the $W^{+(-)}$ decay favors a backward (forward) lepton





Q^2, x reach



x = momentum fraction of parton

Q^2 = square of momentum transfer

- Traditionally, PDFs are measured in deep inelastic scattering – high energy electron-nucleon interactions
- W asymmetry measurement:

$$Q^2 \approx M_W^2, \;\; x = \frac{M_W}{\sqrt{s}} e^{\pm y_W}$$

- This measurement:

$$|y_W| < 3.2 \Rightarrow \;\; 0.002 < x < 1.0$$

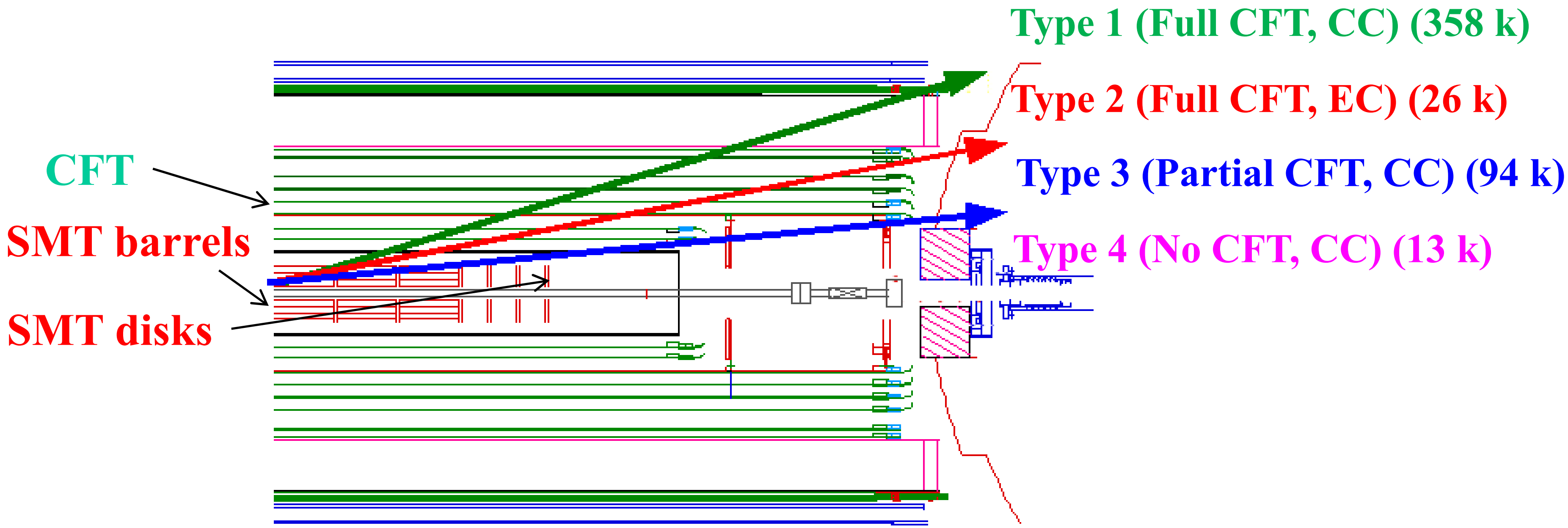
- Previous measurements:

$$|y_W| < 2.5 \Rightarrow 0.003 < x < 0.5$$

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

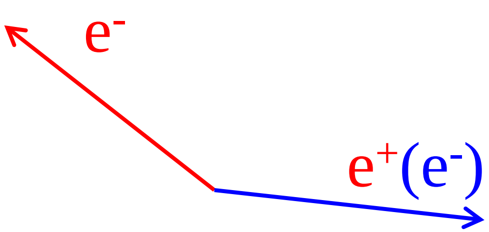
Electron Types

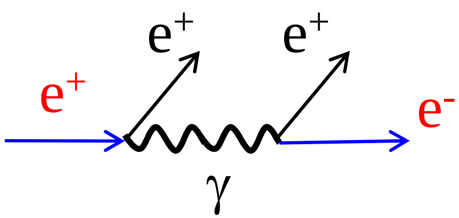
- Important to determine electron charge correctly
- High rapidity bins suffer from low statistics and higher charge mis-identification rate
- Splitting data into 4 electron types depending on the position of EM cluster, incident angle and the primary vertex
- Different track quality cuts applied for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

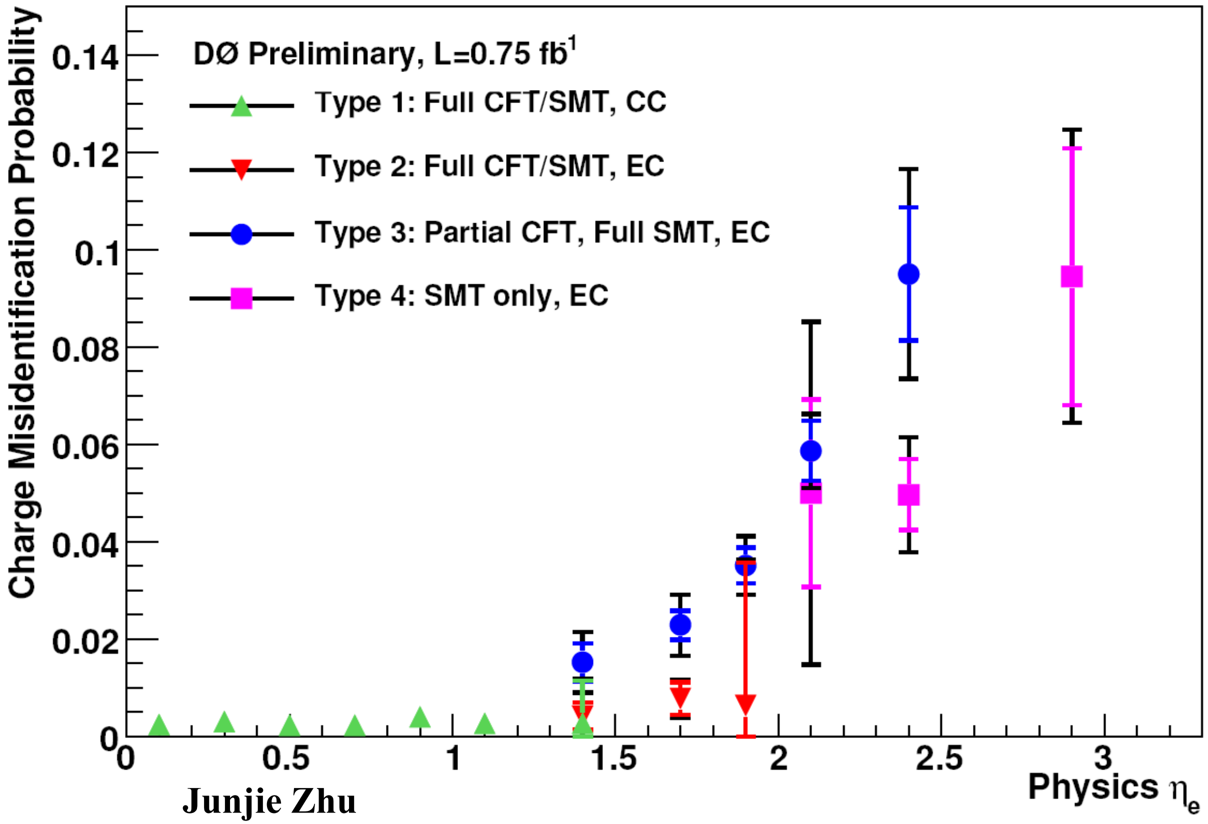


Charge Mis-identification

- Charge mis-identification dilutes the asymmetry
- Rate measured using Z→ ee events: tight selection requirements on one electron, and check the charge of the other electron
- ~ 0.3% for |η| < 1, ~ 9% for 2.8 < |η| < 3.2
- Charge mis-identification: electron bremsstrahlung



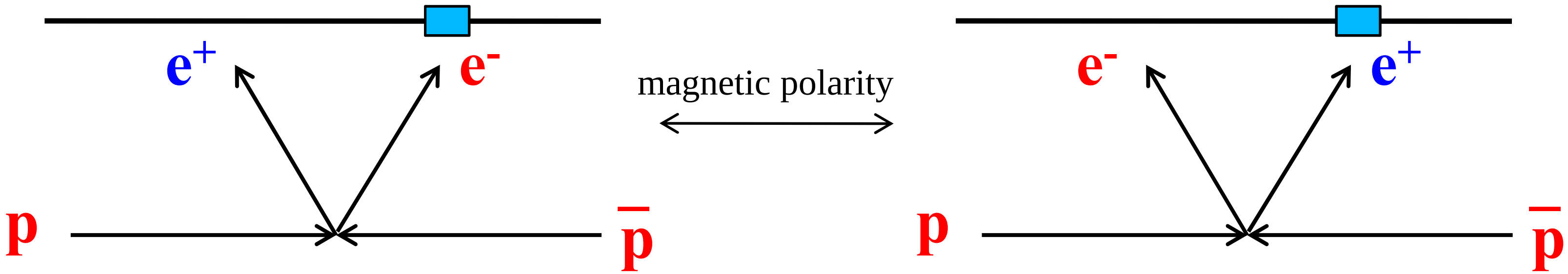




Charge Bias

- ◆ Bias due to detector and selection efficiencies
  - ➢ Detector bias: flip the magnetic field direction frequently

    46% - forward polarity   54% - backward polarity



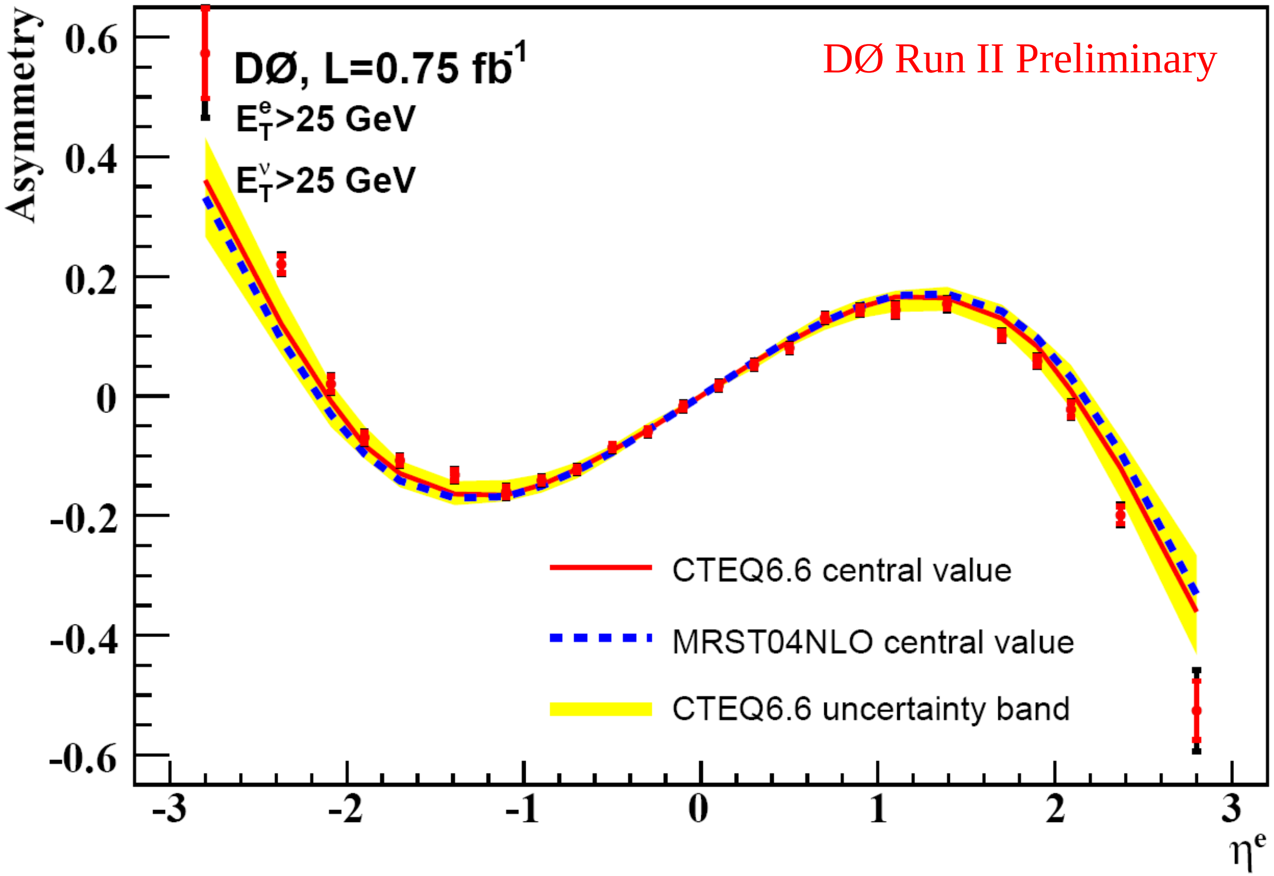
No differences observed on A(η) for different polarities

  - ➢ Efficiencies: check ratio of efficiencies for electrons and positrons

$$A(\eta_e) = \frac{\dfrac{N(e^+)}{A(e^+)\times\varepsilon(e^+)} - \dfrac{N(e^-)}{A(e^-)\times\varepsilon(e^-)}}{\dfrac{N(e^+)}{A(e^+)\times\varepsilon(e^+)} + \dfrac{N(e^-)}{A(e^-)\times\varepsilon(e^-)}} = \frac{N(e^+) - kN(e^-)}{N(e^+) + kN(e^-)}$$

$$k = \frac{A(e^+)\times\varepsilon(e^+)}{A(e^-)\times\varepsilon(e^-)}$$ **consistent with 1**

Electron charge asymmetry for E_T>25 GeV

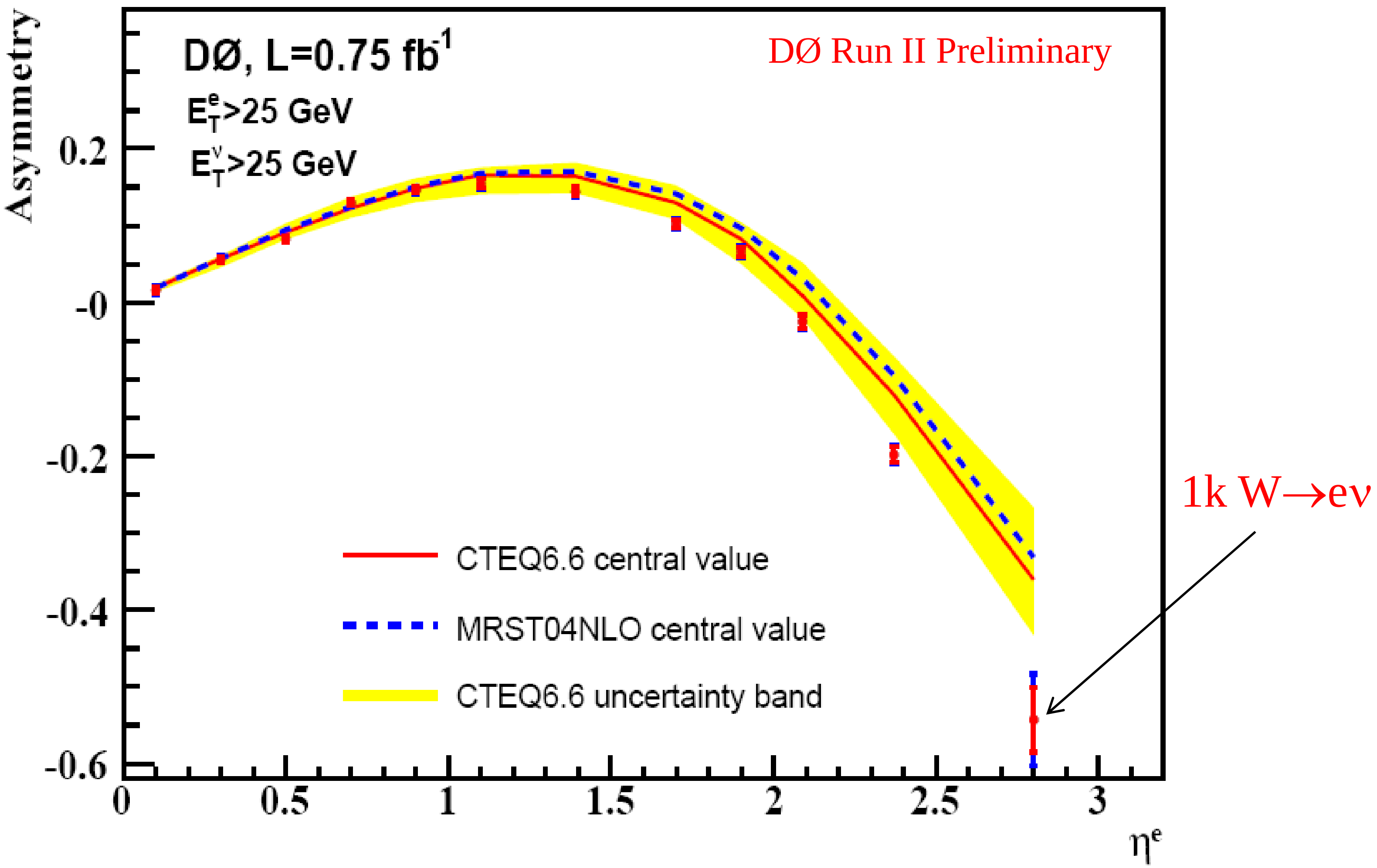


- ResBos + PHOTOS
- Latest CTEQ6.6 NLO PDFs with 44 uncertainty PDF sets (P. Nadolsky *et al.*, arXiv: 0802.0007v3, W&C talk June 6, 2008)
- PDF uncertainties:

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

- CP invariance: $A(-\eta) = -A(\eta)$
- Fold data to increase the available statistics

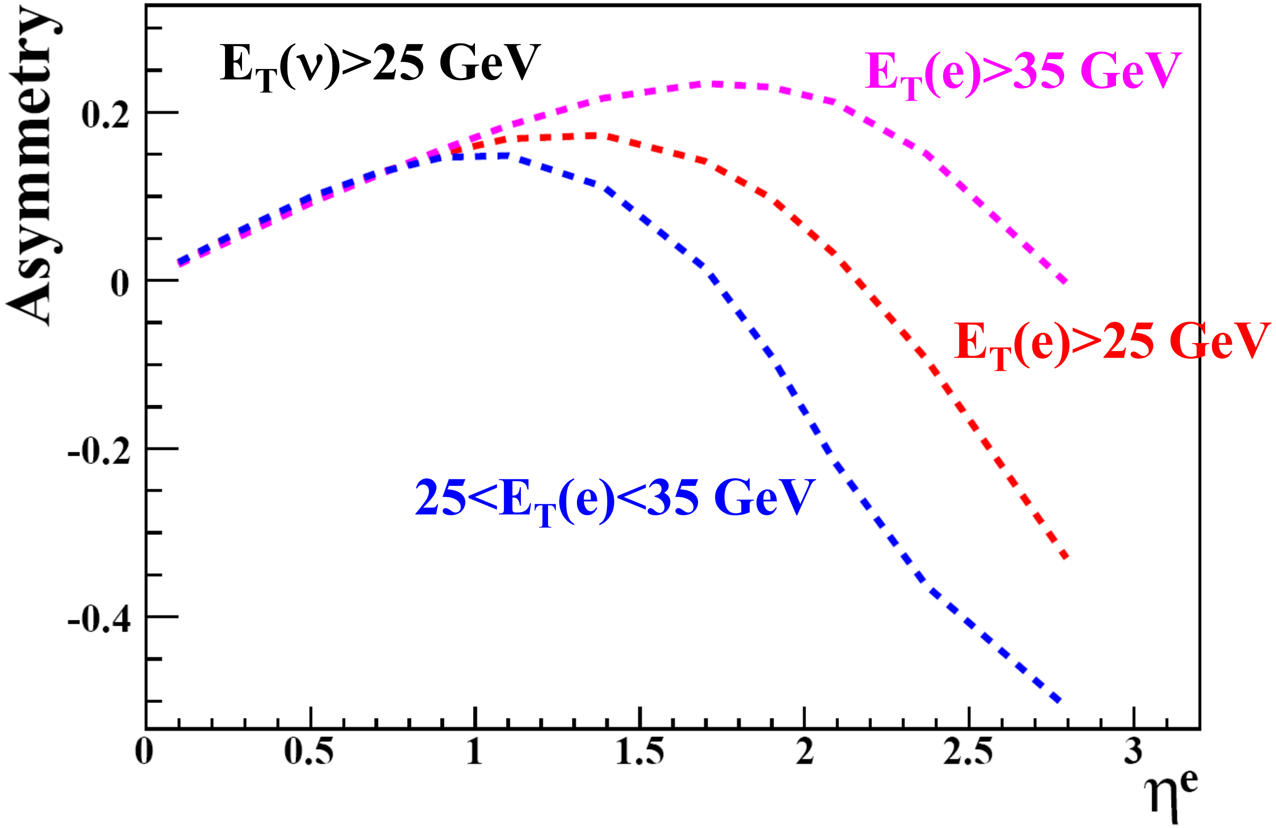
Folded charge asymmetry for E_T>25 GeV



- Experimental uncertainties smaller than theoretical uncertainties for all but the highest rapidity bin

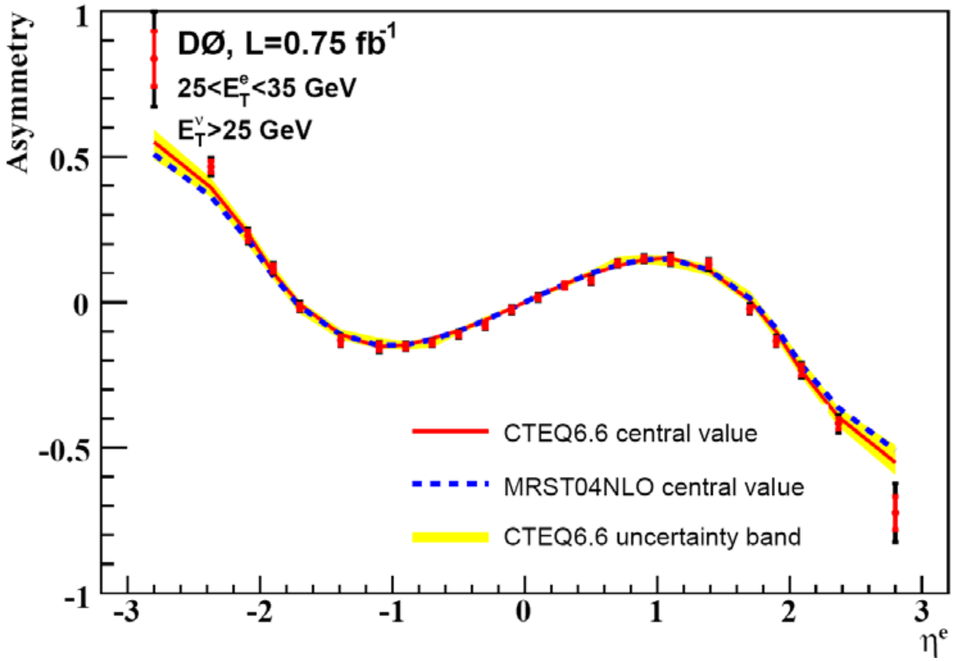
Electron E_T Bins

- For a given η(e), different electron E_T regions 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(η) is larger
- Allows a finer probe of the x dependence

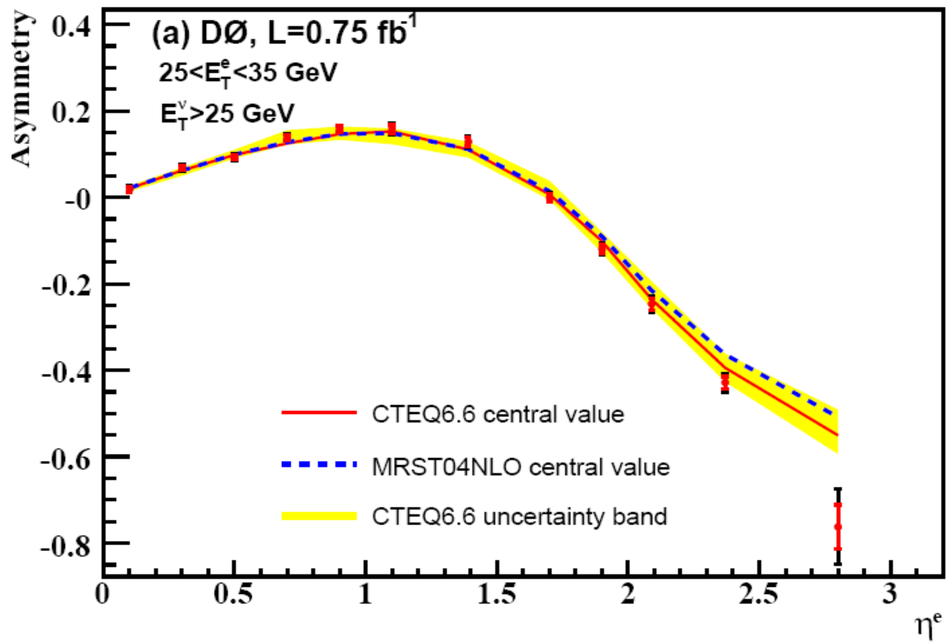


Electron charge asymmetry for $25<E_T<35$ GeV

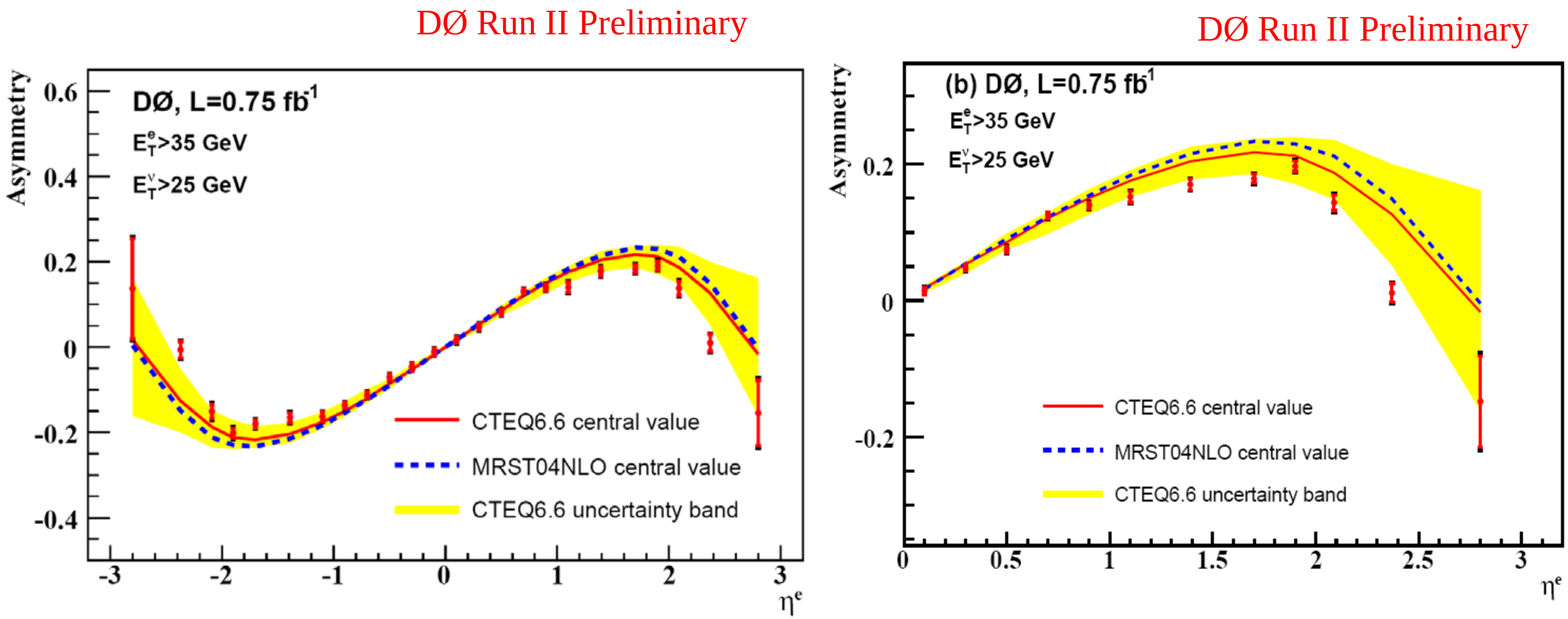
DØ Run II Preliminary



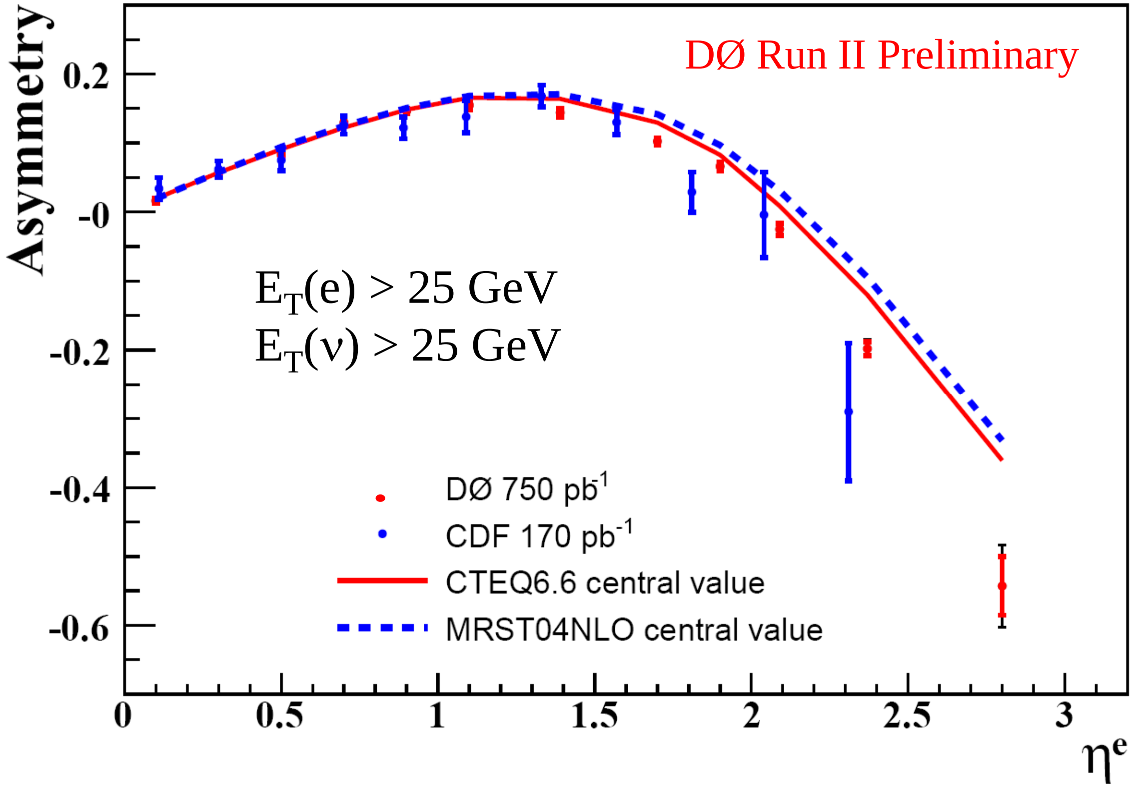
DØ Run II Preliminary



Electron charge asymmetry for E_T>35 GeV



Comparison between DØ and CDF results



- Experimental uncertainties smaller than PDF uncertainties for most of 36 $\eta(e)$ bins
- Can be used to improve the precision and accuracy of next generation PDF sets
- Request from MSTW group for data to be incorporated into global PDF fits
- Analysis with 2 fb^{-1} ongoing (muon channel)

Z + jet Measurement
$(Z/\gamma^* \rightarrow \mu\mu)$

Motivation for Vector Boson + Jet Physics

- Key sample to verify LO and NLO simulation programs:
  - Pythia, Herwig, Alpgen, Sherpa, MCFM, MC@NLO, MadGraph, etc
- Signature for a number of high pT physics processes:
  - Top pair/single top
  - Higgs boson searches
  - Searches for SUSY particles
  - Many signals are overwhelmed by a large QCD production of boson+jets
- Crucial to have a better understanding of SM vector boson+jet processes

Event Selection

- $Z \rightarrow \mu\mu$ selection:
  - Triggered by a set of inclusive single muon triggers
  - 2 muons with loose muon and track quality requirements
  - $p_T > 15$ GeV, $|\eta| < 1.7$
  - $65 < M_{\mu\mu} < 115$ GeV
  - Isolated both in the tracker and the calorimeter
  - $\Delta R(\mu, \text{jet}) > 0.5$
- Jet selection:
  - Jets reconstructed with DØ RunII MidPoint algorithm with R=0.5
  - $p_T > 20$ GeV
  - $|\eta| < 2.8$
- 60k candidates selected before jet requirements
- 10k of them have ≥1 jet with $p_T > 20$ GeV

Cross Section Measurements

- Total cross section:

$$\sigma = \frac{N_{corr}}{A \times \varepsilon \times L}$$

- Four differential cross sections measured:
  - vs leading jet p_T and rapidity
  - vs Z boson p_T and rapidity

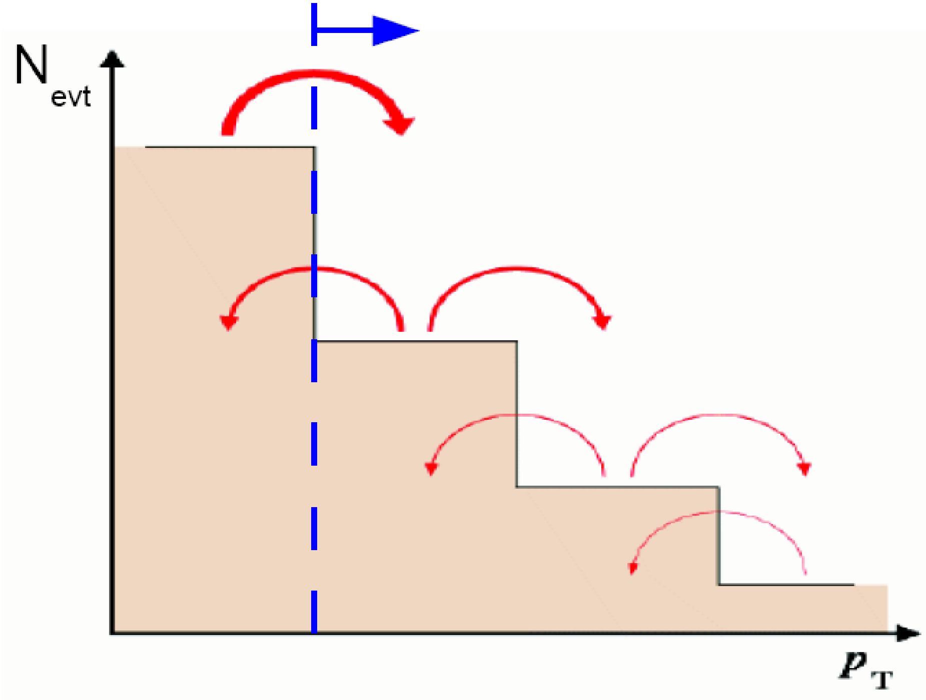
$$\frac{d\sigma}{dK} = \frac{N_{corr}}{A \times \varepsilon \times L \times \Delta K}$$

Unfolding

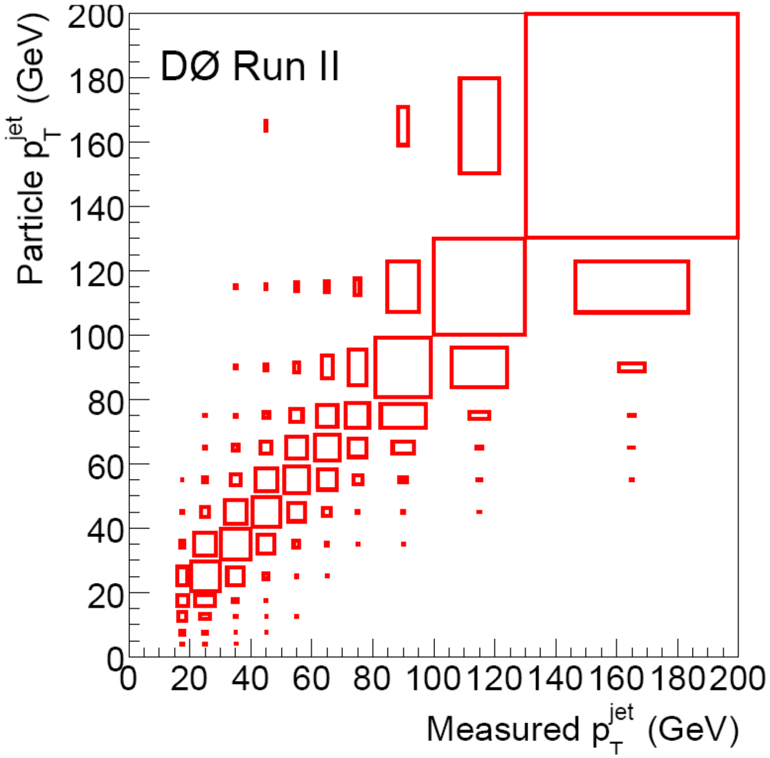
- Exponentially falling distribution, finite detector resolution
  - Suffer significant migrations between bins
  - And across reconstruction threshold

$$R_i = \Sigma\, M_{ij}\, \varepsilon_j T_j$$

- M and ε measured from Pythia+Geant MC simulation
- GURU program used to do regularized unfolding (A. Hocker *et al.*, hep-ph/9509307)



DØ Run II Preliminary

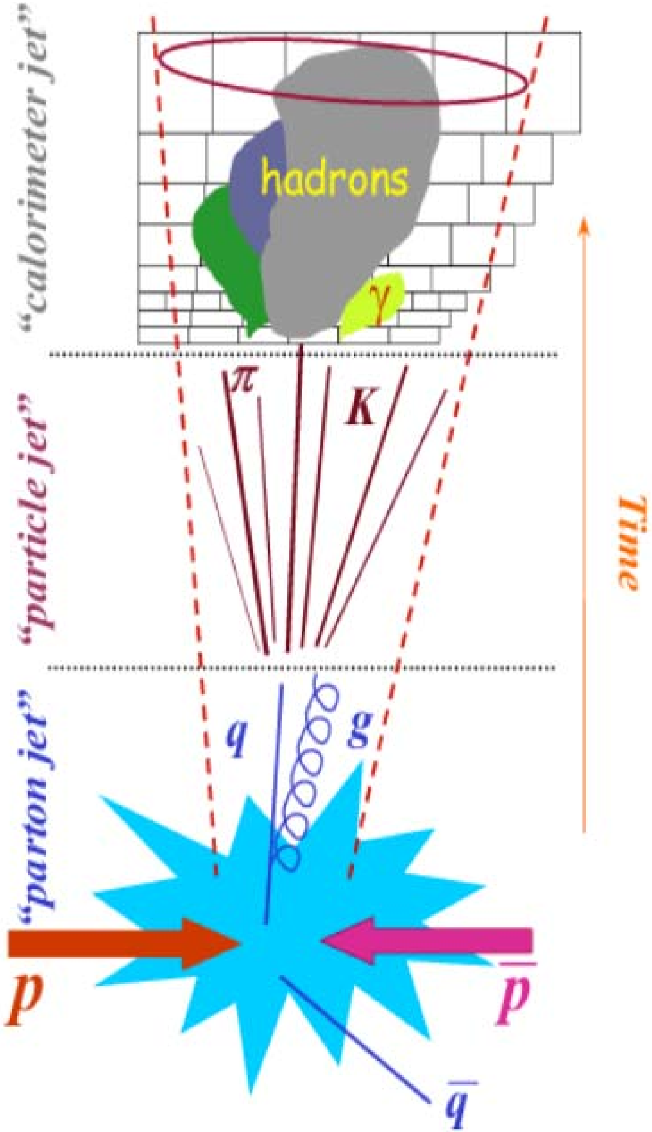


NLO pQCD prediction

- MCFM:
  - NLO predictions up to 2 jets in final state
  - CTEQ6.5M PDF
  - Renormalization and factorization scale:

$$\mu_0 = M_Z$$

  - Jets reconstructed using DØ RunII MidPoint algorithm with cone size R = 0.5
  - Cross section at parton level:
    - Needs correction for underlying event and hadronization effects (non-pert. effect) (~ 3%)
    - Needs correction for FSR (~ 2%)
    - Corrections are made using Pythia MC with tune DW
- Compare with three event generators (LO Matrix Element calculations matched with Parton Shower):
  - Alpgen, Sherpa, Pythia



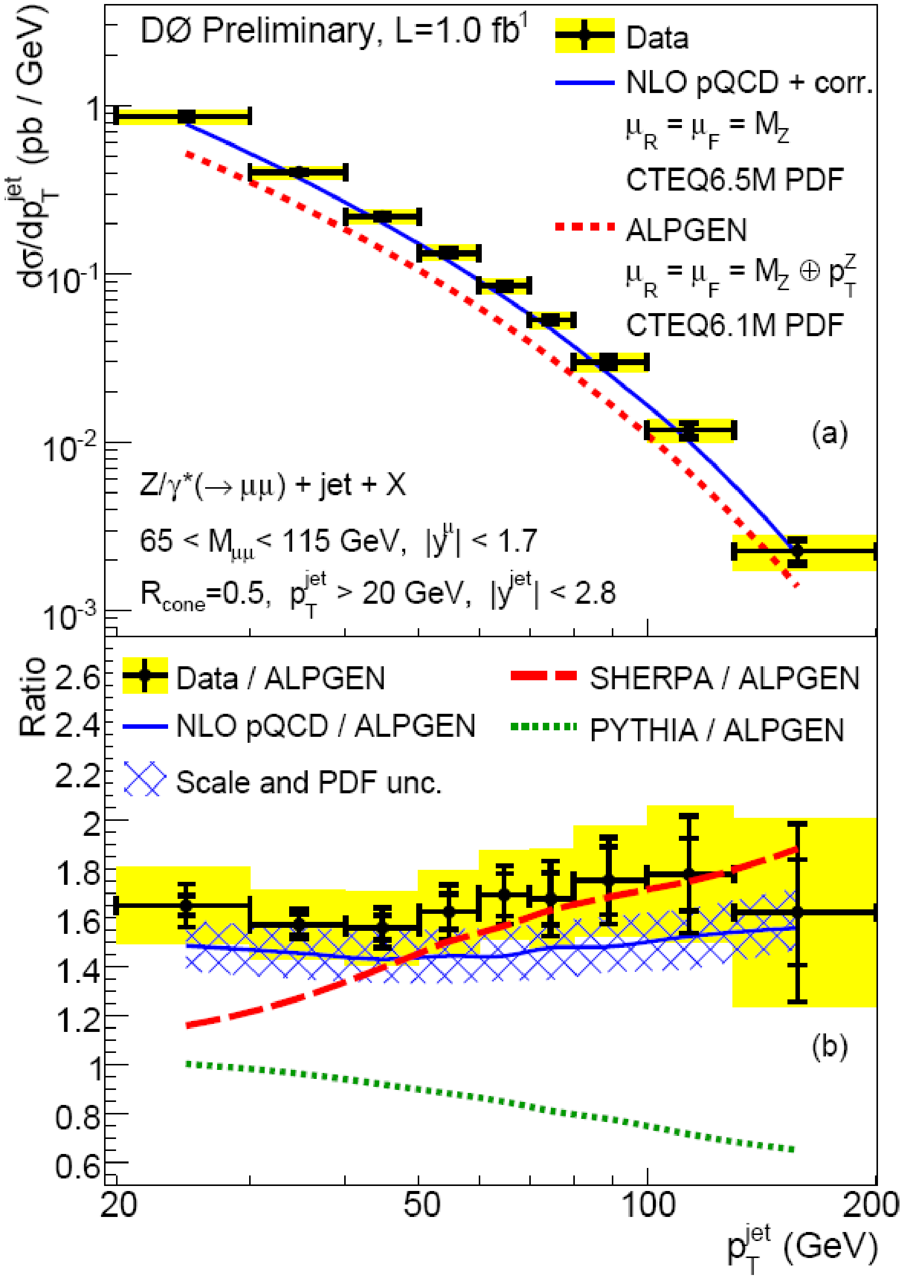
Cross Section For Z + ≥ 1 jet

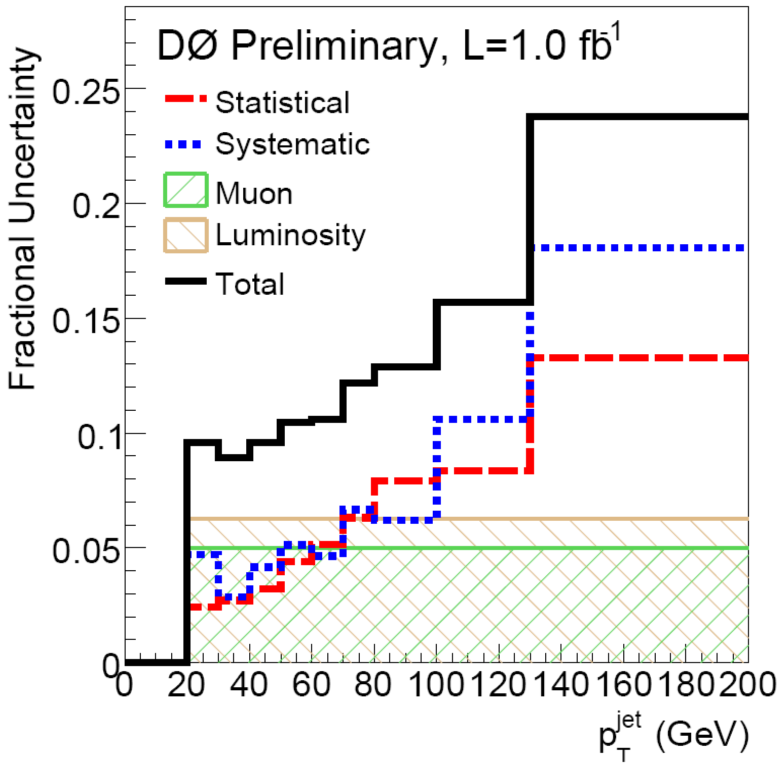
- $Z/\gamma^*(\rightarrow\mu\mu)$ + ≥ 1 jet cross section:

18.7 ± 0.2 (stat.) ± 0.8 (syst.) ± 0.9 (muon) ± 1.1 (lumi) pb

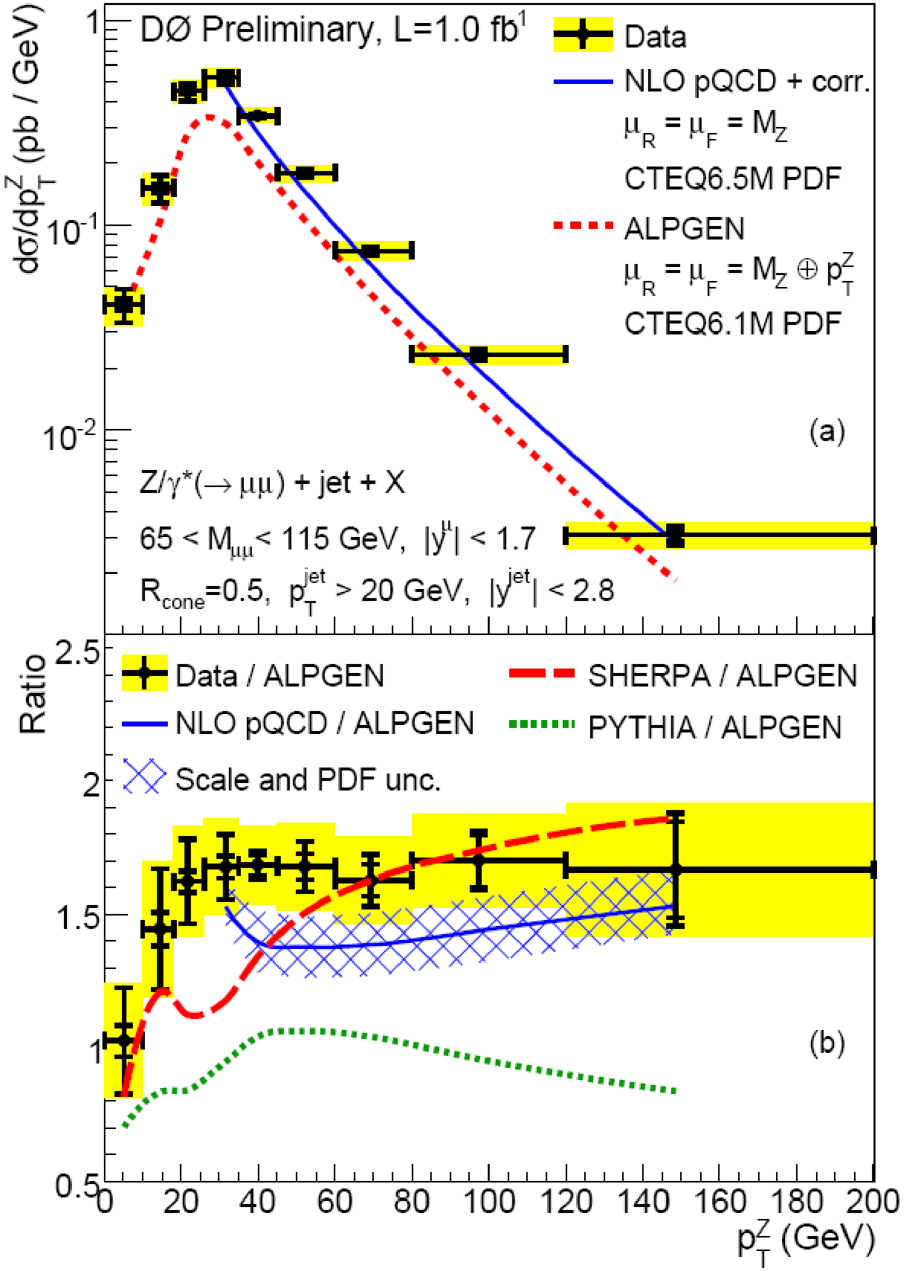
- With the following requirements
  - Muons with $|\eta|<1.7$, $65< M_{\mu\mu}<115$ GeV after QED FSR
  - Particle jets reconstructed with DØ RunII MidPoint algorithm with R=0.5, jet $|y| < 2.8$ and $p_T > 20$ GeV
- Systematic uncertainties measured from ensemble tests:
  - Jet energy scale (~ 4%)
  - Jet resolution and efficiency uncertainties (~ 0.7%)
  - Data/MC reweighting function (~ 0.6%)
  - PDF uncertainties (~ 0.5%)
- Theoretical predictions (CTEQ6.5M):
  - NLO pQCD + corr: 16.9 ± 1.1(scale) ± 0.5(PDF) pb

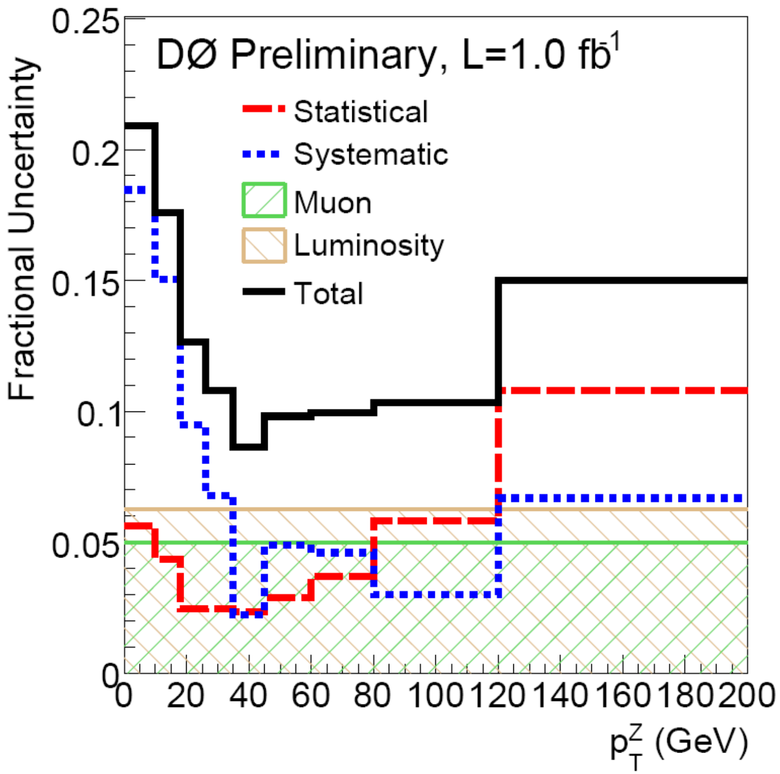
Cross Section vs Leading Jet p_T



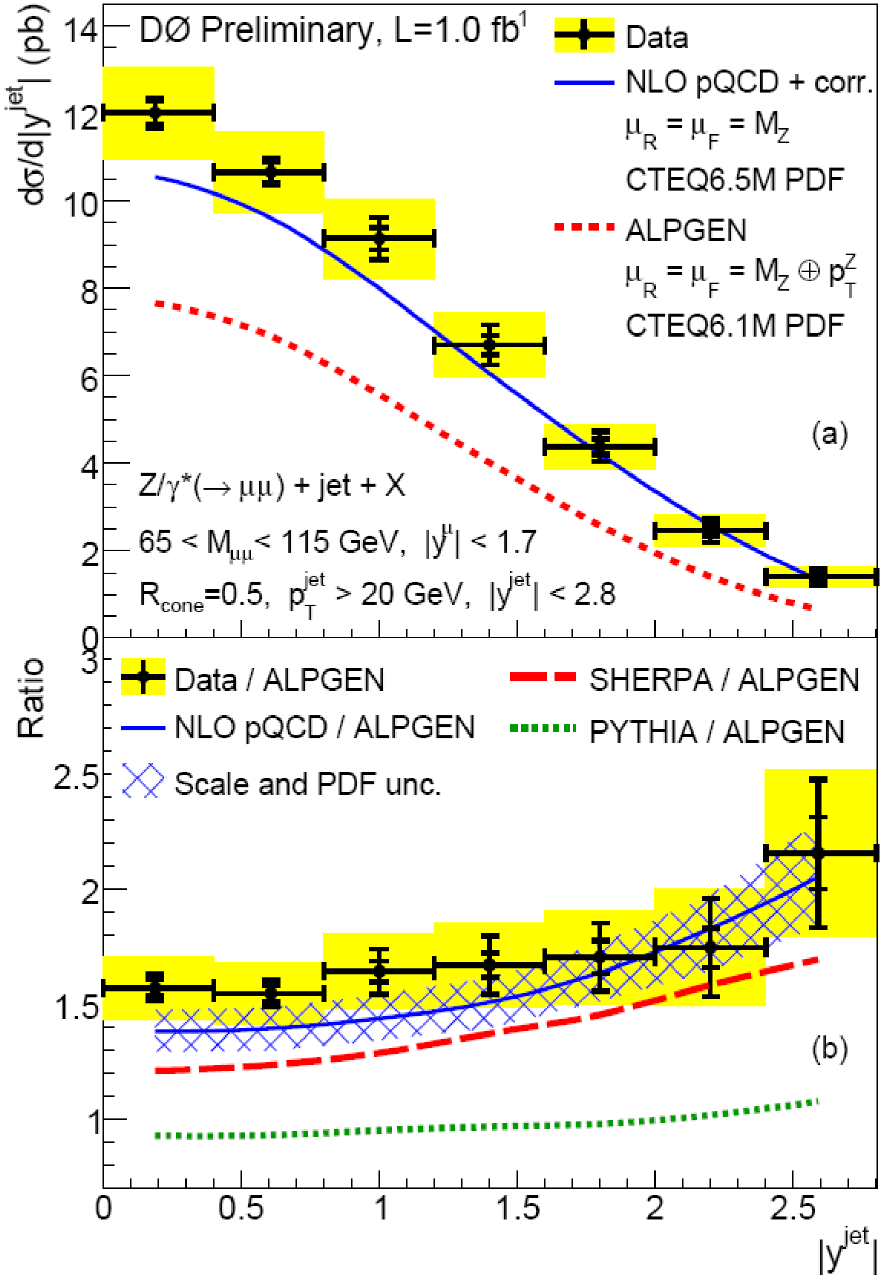


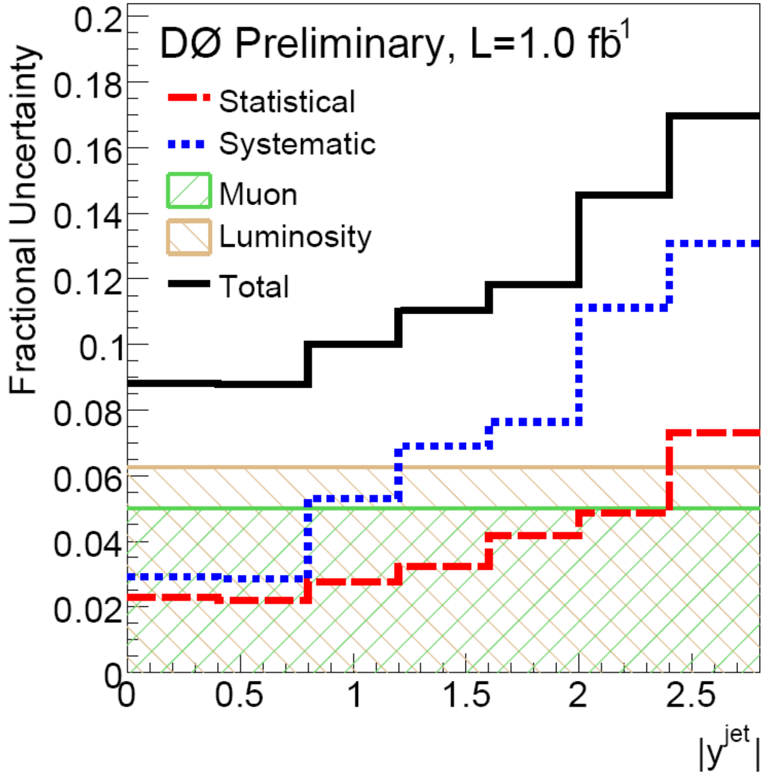
Cross Section vs Z Boson p_T



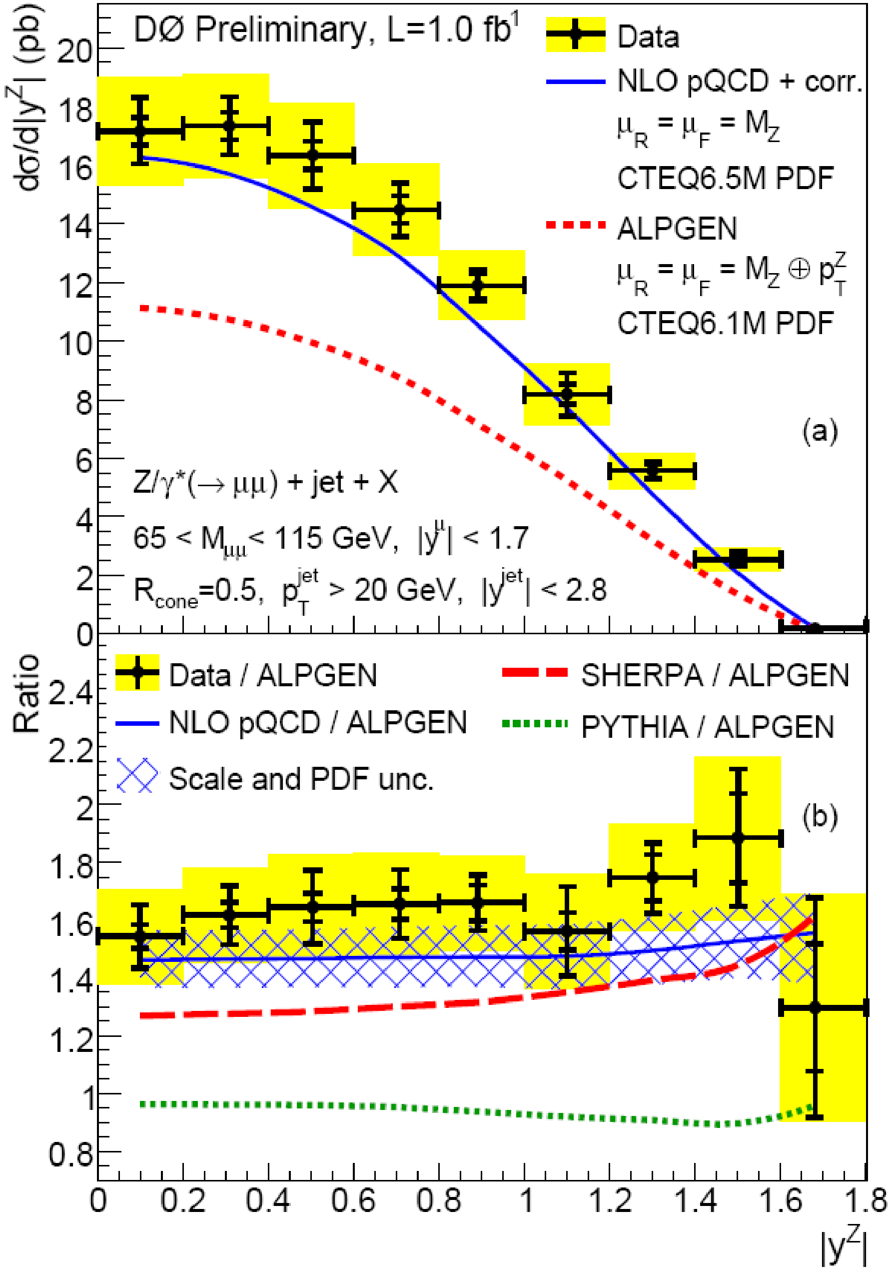


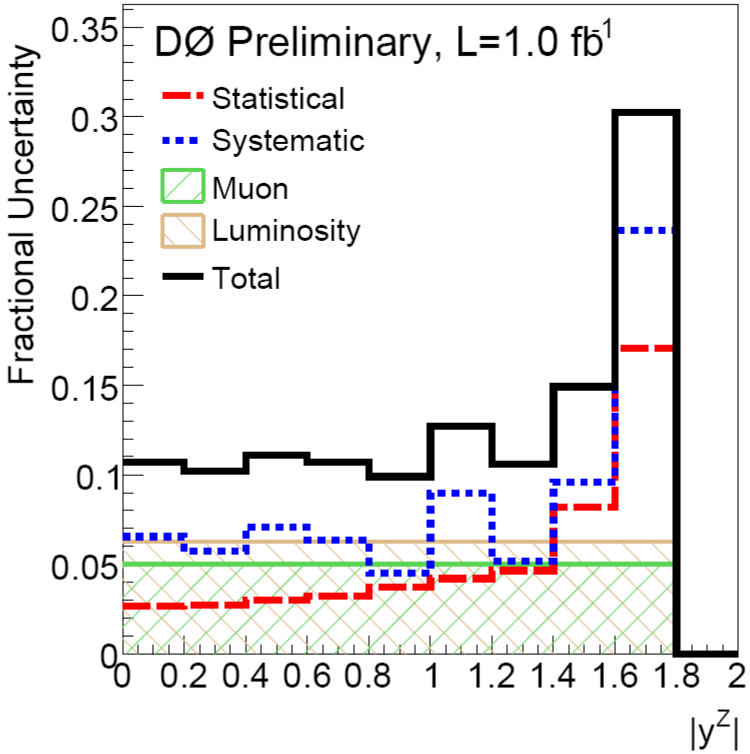
Cross Section vs Leading Jet Rapidity





Cross Section vs Z Boson Rapidity





$Z/\gamma^*(\rightarrow\mu\mu)$+ Jet Measurement

- Predicted Z+jet cross section from NLO pQCD+corr. is 9% lower than measured cross section but within the total uncertainties
- First results for differential cross section vs $p_T(Z)$ and $y(Z)$
- Extended leading jet p_T and y ranges
- Shapes well-described by pQCD except low $p_T(Z)$
- Shapes well-described by Alpgen except low $p_T(Z)$
- Rapidity distribution well-described by pQCD, Sherpa, Pythia
- Leading jet rapidity distribution from Alpgen is narrower

Conclusions

- A_{FB} measurement and extraction of $\sin^2\theta^{eff}_W$ ($Z \rightarrow ee$)
  - Unfolded A_{FB} distribution agrees with SM predictions
  - $\sin^2\theta_W^{eff} = 0.2327 \pm 0.0018$ (stat.) ± 0.0006 (syst.)
- W charge asymmetry ($W \rightarrow e\nu$)
  - Measured in three different electron E_T bins
  - Experimental uncertainties smaller than PDF uncertainties for most $\eta(e)$ bins
- Z+jet measurement ($Z \rightarrow \mu\mu$)
  - Cross section:

    18.7 ± 0.2 (stat) ± 0.8 (syst) ± 0.9 (muon) ± 1.1 (lumi) pb
  - Differential cross section vs leading jet (Z boson) p_T and rapidity
  - Compared with predictions from NLO pQCD and three event generators
- More data collected and more high precision EW and QCD measurements expected, stay tuned!