Measurement of the Properties of Electroweak Bosons with the DØ detector

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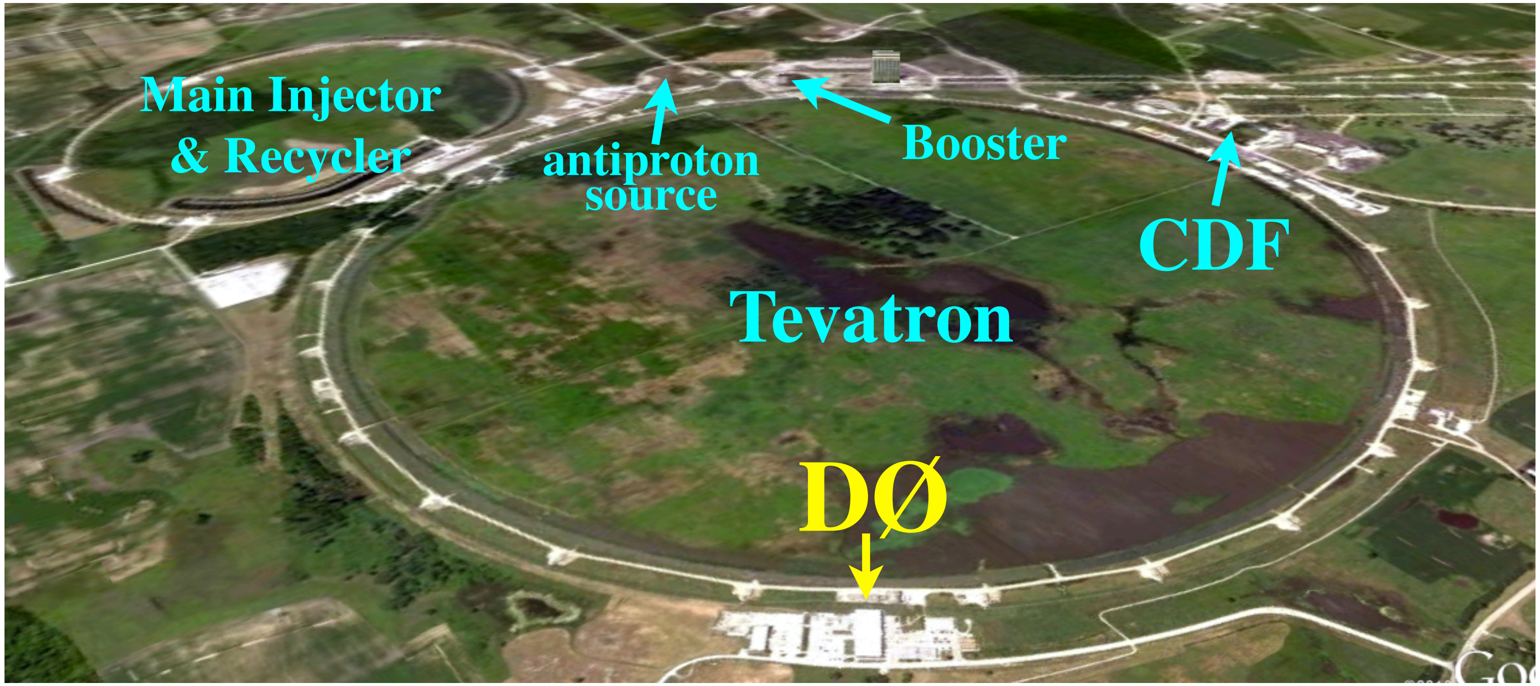
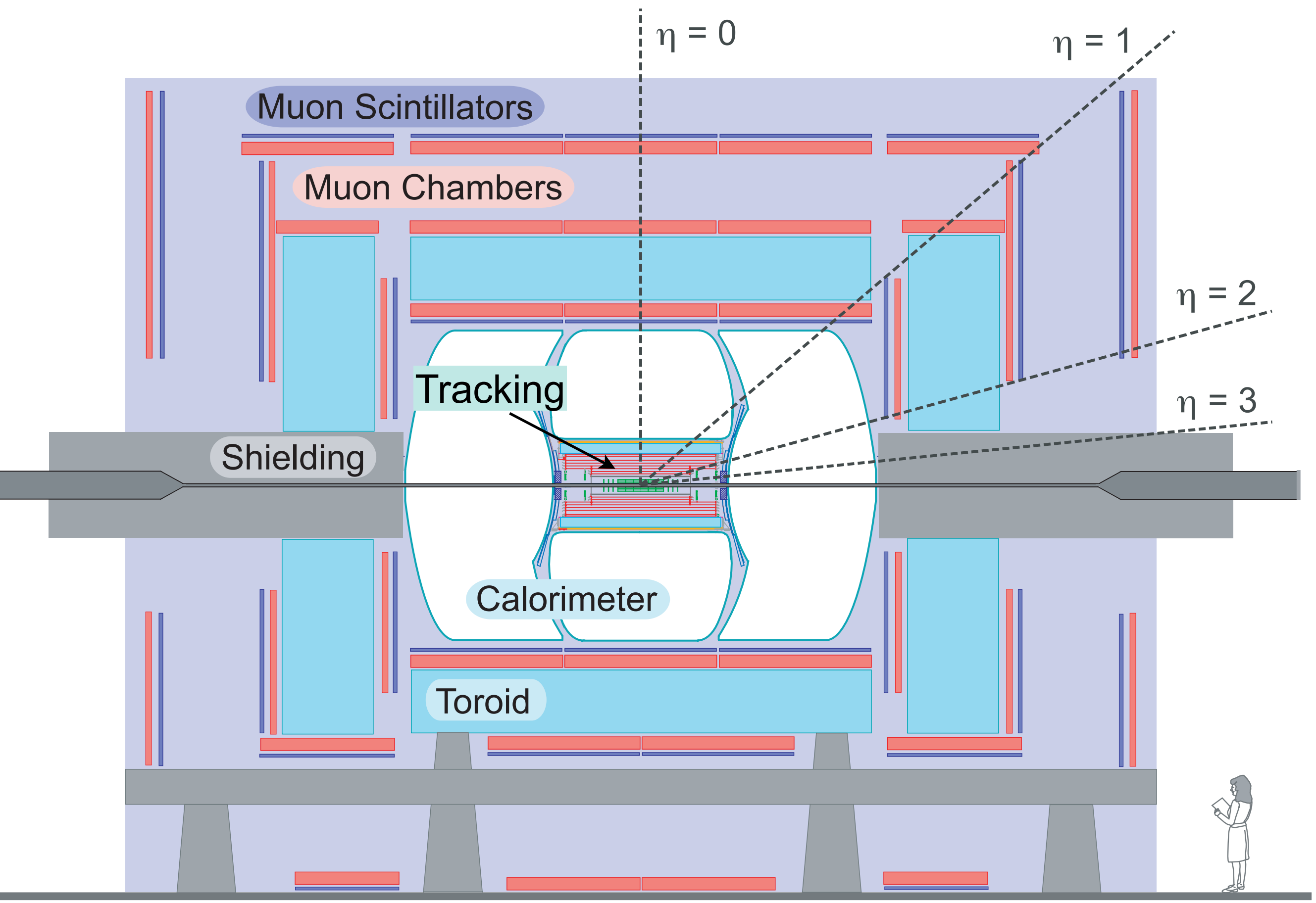
The Tevatron



- The Tevatron is a Proton-Antiproton Collider at 1.96 TeV
  - CP symmetric initial states
- A factory of W and Z bosons
  - DØ has >10 fb^{-1} on tape ~ 5 M reconstructed $W \rightarrow e\nu$ events
- W and Z bosons are produced mainly by valence quarks (compared to LHC)
  - Low PDF uncertainties
  - Ideal for asymmetry measurements

The DØ Detector



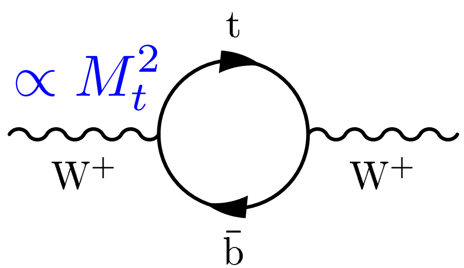
- Tracking
  - 2 T magnet
  - $\delta P_T/P_T \sim 10\%$ @ 45 GeV
  - $\delta\eta \sim 1.5\times10^{-3}$
  - $\delta\phi \sim 4\times10^{-4}$
- Calorimeter
  - η coverage up to 4.2
  - $\delta E/E \sim 4\%$ @ 45 GeV
  - Thickness ~ 20 X_0
  - Granularity $\phi\times\eta \sim 0.1\times0.1$
- Muon System
  - η coverage up to 2

Motivation: **Currently, the W boson mass uncertainty is the limiting factor to tighten the constraint on the Higgs boson mass.**

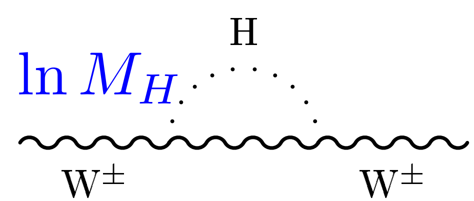
- **W mass is a key parameter in the Standard Model (SM)**
- **Relation between W mass and other experimental observables:**

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{G_F\sqrt{2}}\frac{1}{(1-\Delta r)}$$

Radiative corrections Δr: $\Delta r \propto M_t^2$



$\Delta r \propto \ln M_H$



- **Precise measurements of W mass and Top mass constrain Higgs mass**
- **However, for equal constraint:** $\boldsymbol{\delta M_W \sim 0.006\ \delta M_t}$

I. e. Current World average:

accuracy of Mt : $\delta M_t = 1.1$ GeV needs $\delta M_W = 7$ MeV

accuracy of M_W : $\delta M_W = 23$ MeV

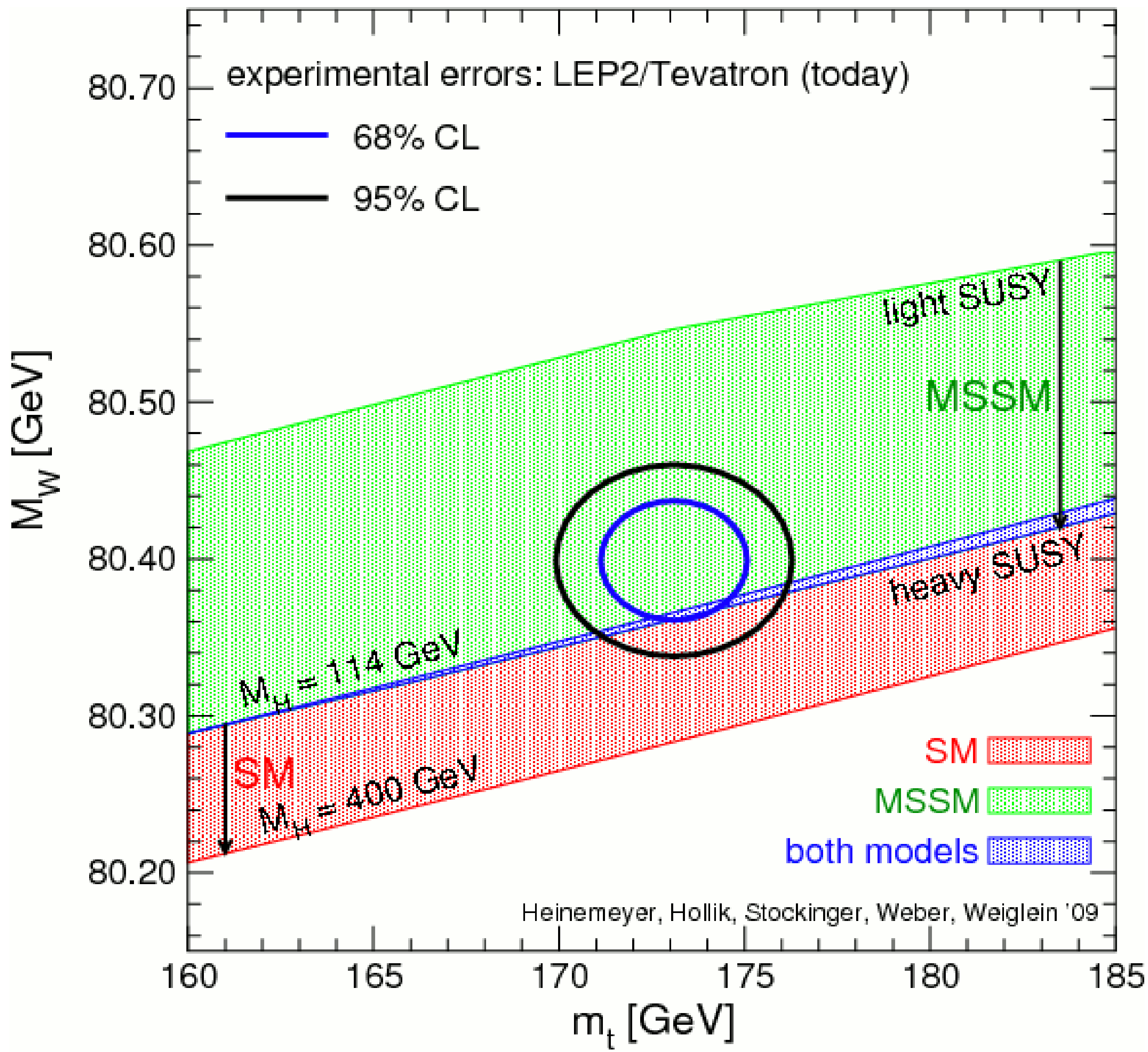
The limiting factor on the M_H prediction is δM_W

W Mass

Current world average central value of W mass (80.399 GeV) prefers a non-SM Higgs. (Knowing that SM M_H>114GeV bound has been set by LEP)

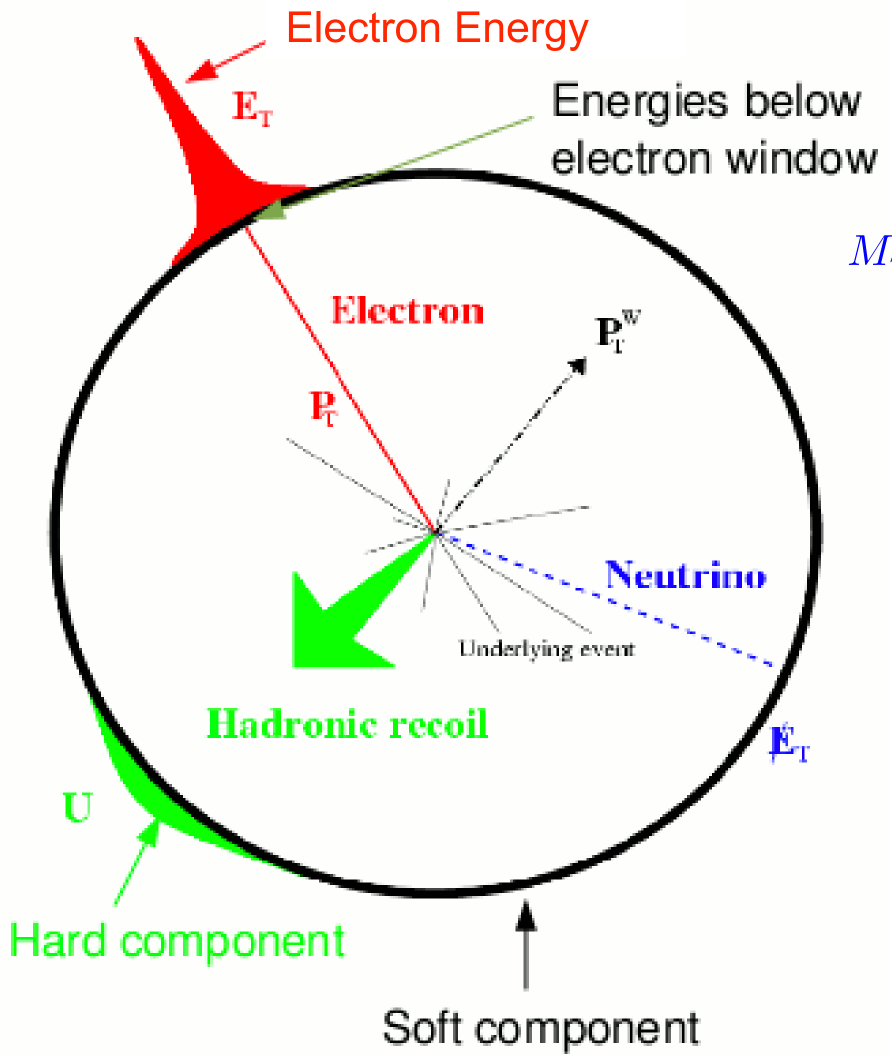
If the central value of M_W does not change in the future, a 15 MeV precision will exclude SM Higgs at 95% CL.

(P. Renton, ICHEP 2008)



Analysis Strategy

A Typical W→eν Event



Reconstruct three observables:

$$M_T^W \qquad P_T^e \qquad \not{E}_T$$

$$M_T^W = \sqrt{2P_T^e \not{E}_T (1 - \cos\Delta\phi)}$$

Using Z->ee events for detector calibration

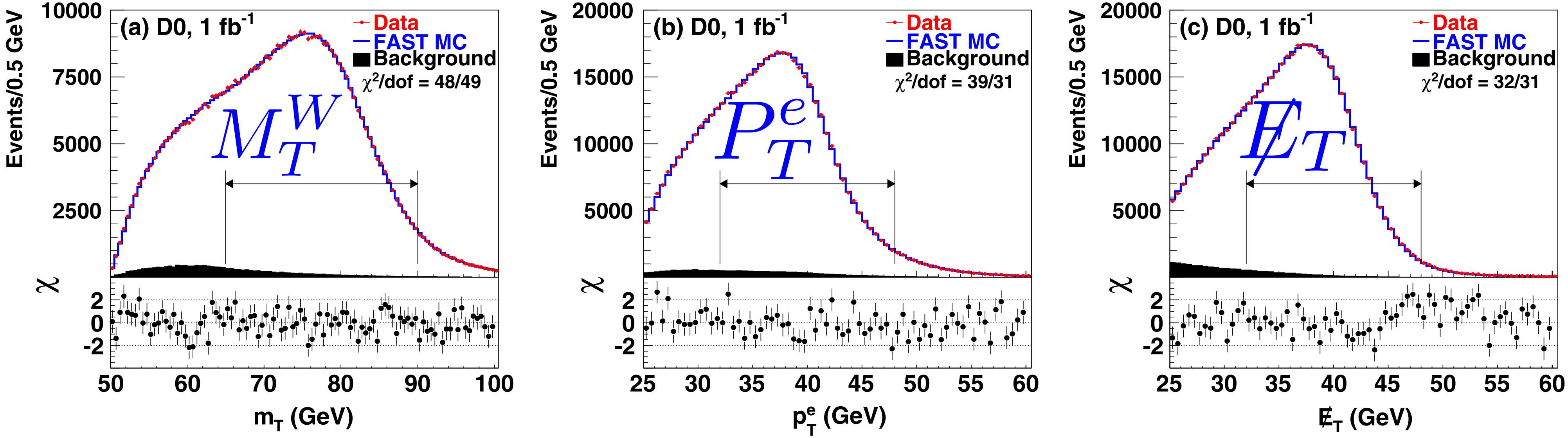
A Fast MC model **to generate templates of the 3 observables with different W mass hypotheses. Fit the templates to the Data to extract W mass.**

The Fast MC model:

- **Event Generator: Resbos(CTEQ6.1)+Photos**
- **Parameterized Detector Model (Essential!!)**

Results

DØ RunIIa 1 fb^{-1}, Center Calorimeter (CC) Electrons



80.401 ± 0.023 (stat.) ± 0.037 (syst.) GeV

80.400 ± 0.027 (stat.) ± 0.040 (syst.) GeV

80.402 ± 0.023 (stat.) ± 0.043 (syst.) GeV

$$\mathrm{M_W} = 80.401 \pm 0.021(stat.) \pm 0.038(syst.)\ \mathrm{GeV}$$
$$= 80.401 \pm 0.043\ \mathrm{GeV}$$

Most precise single experiment measurement

Phys. Rev. Lett. 103, 141801 (2009).

A ~19 MeV precision would be achieved with 10 fb^{-1} full DØ dataset.

W Mass

Let's take the result from observable M_T, and project to 10 fb^{-1} full data set:

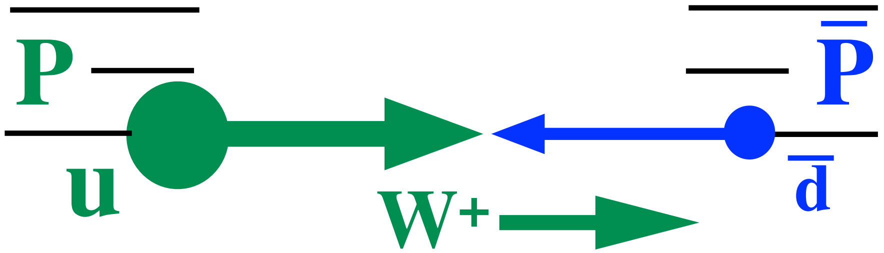
Uncertainties from observable M_T	Statistical	Systematic	
		Experimental (e.g. Energy Response)	Theoretical (e.g. PDF)
RunIIa 1 fb^{-1}	23 MeV	35 MeV	12 MeV
	Decrease	Decrease (Z→ee statistics)	Remain the same (independent of this particular analysis)
RunIIa+RunIIb 10 fb^{-1} (expected)	8 MeV	13 MeV	12 MeV

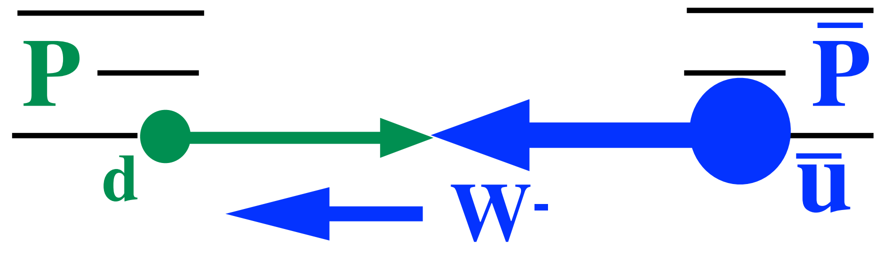
Theoretical uncertainty will be a more important contribution to the precision in future measurements

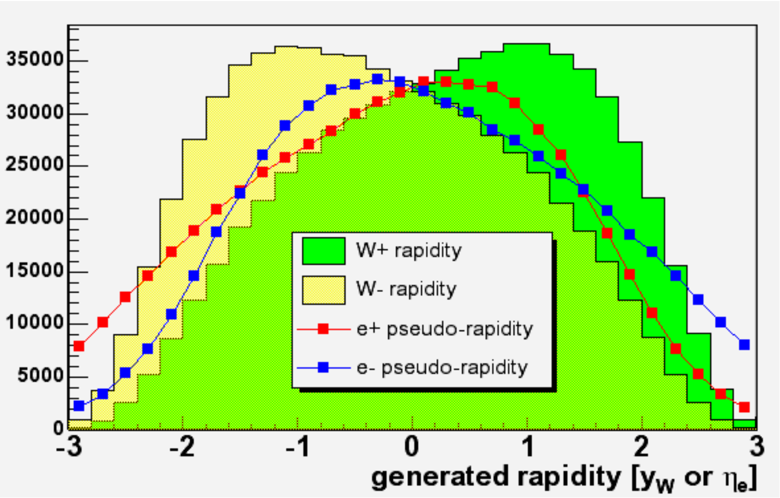
Need to improve our knowledge of PDFs.

W Charge Asymmetry

Motivation: Directly constrain valence quark PDFs





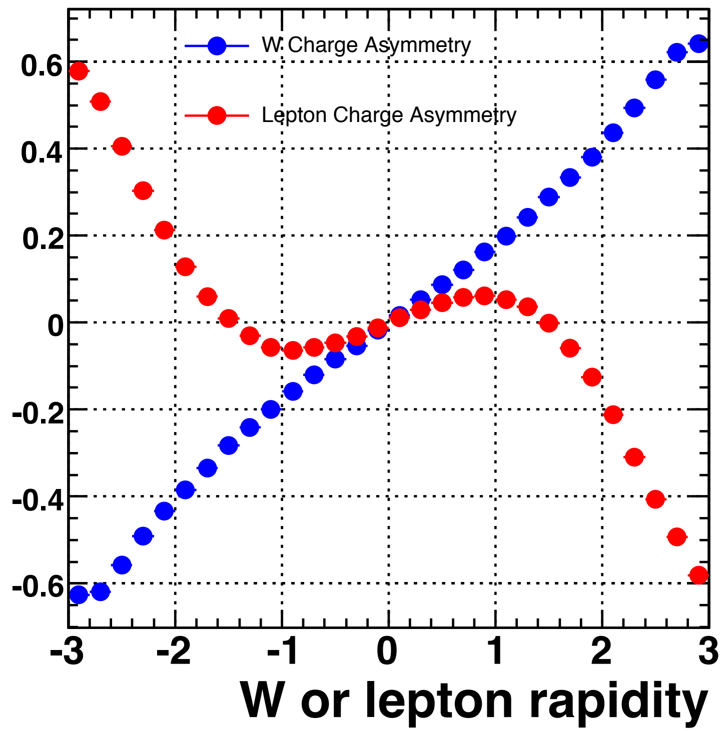


- W Boson is mostly produced by valence quark pairs at Tevatron
- u(ubar) quark carries more momentum than d(dbar) quark
- Thus:
  - W^+ preferentially boosted along proton direction
  - W^- preferentially boosted along anti-proton direction

W Charge Asymmetry:

$$A(y_W) = \frac{\frac{d\sigma(W^+)}{dy_W} - \frac{d\sigma(W^-)}{dy_W}}{\frac{d\sigma(W^+)}{dy_W} + \frac{d\sigma(W^-)}{dy_W}} \simeq \frac{u(x_1)/d(x_1) - u(x_2)/d(x_2)}{u(x_1)/d(x_1) + u(x_2)/d(x_2)}$$

- Where, u(x) and d(x) are the PDFs of the valence u quark and d quark in the proton
- And, x1 and x2 are the momentum fractions in the proton and anti-proton



Directly constrains PDFs, but the 4-momentum of W is not easy to reconstruct, because the neutrino longitudinal momentum (P_z) is not directly measurable at hadron colliders.

Alternative observable is the charge asymmetry of the lepton from the W decay.

One can of cause try to infer the W longitudinal momentum from the W mass constraint within a two fold ambiguity.

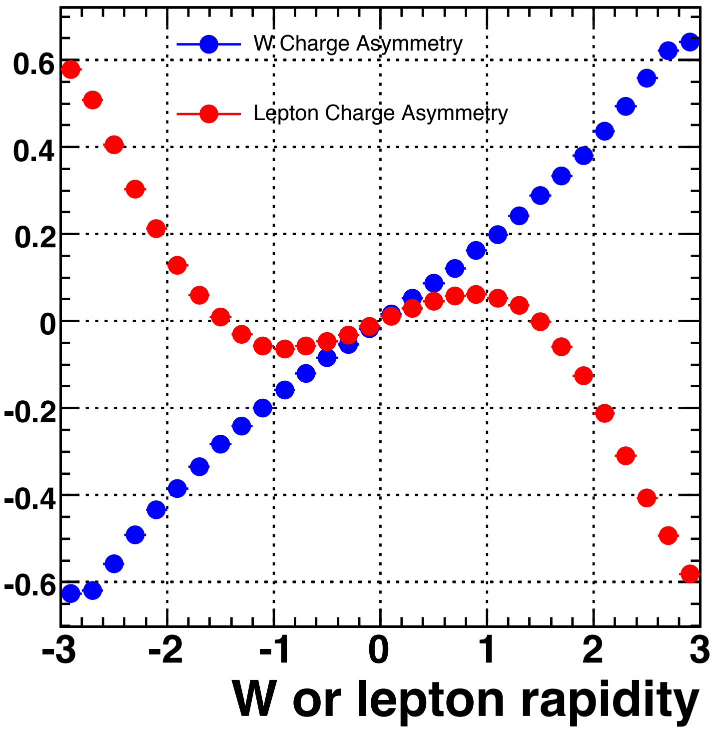
W Charge Asymmetry

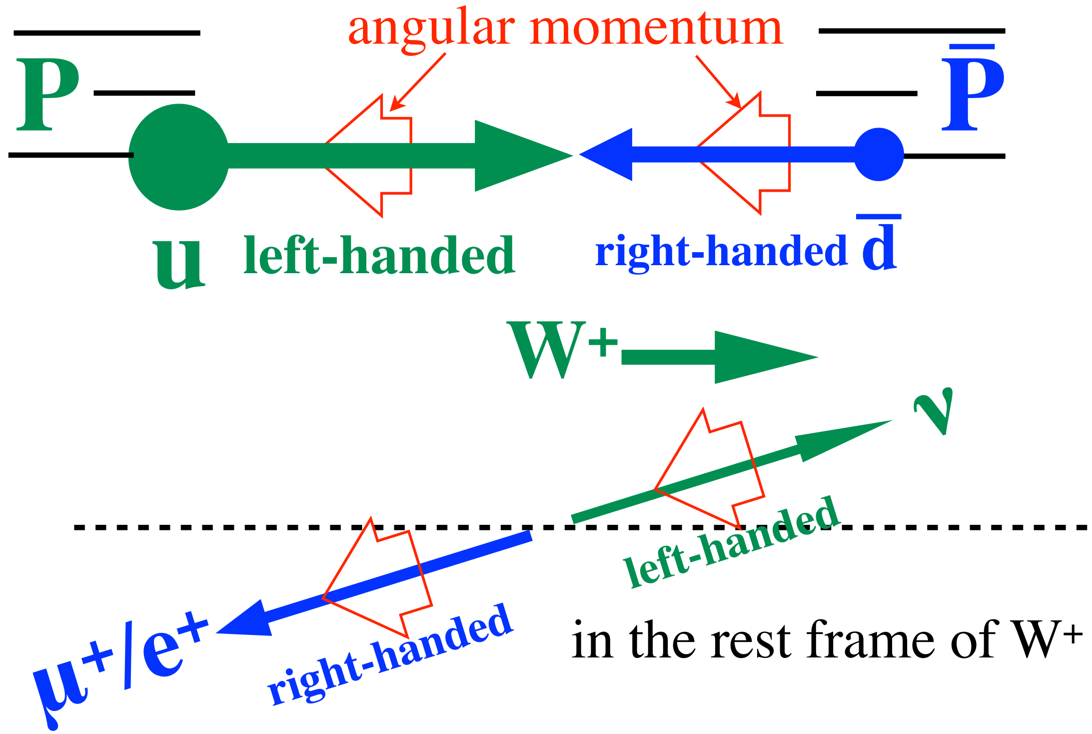
Lepton Charge Asymmetry:

$$A(\eta_\mu) = \frac{\frac{d\sigma(\mu^+)}{d\eta_\mu} - \frac{d\sigma(\mu^-)}{d\eta_\mu}}{\frac{d\sigma(\mu^+)}{d\eta_\mu} + \frac{d\sigma(\mu^-)}{d\eta_\mu}}$$

Directly observable but counterbalances the W charge asymmetry, due to the V-A asymmetry and angular momentum conservation.

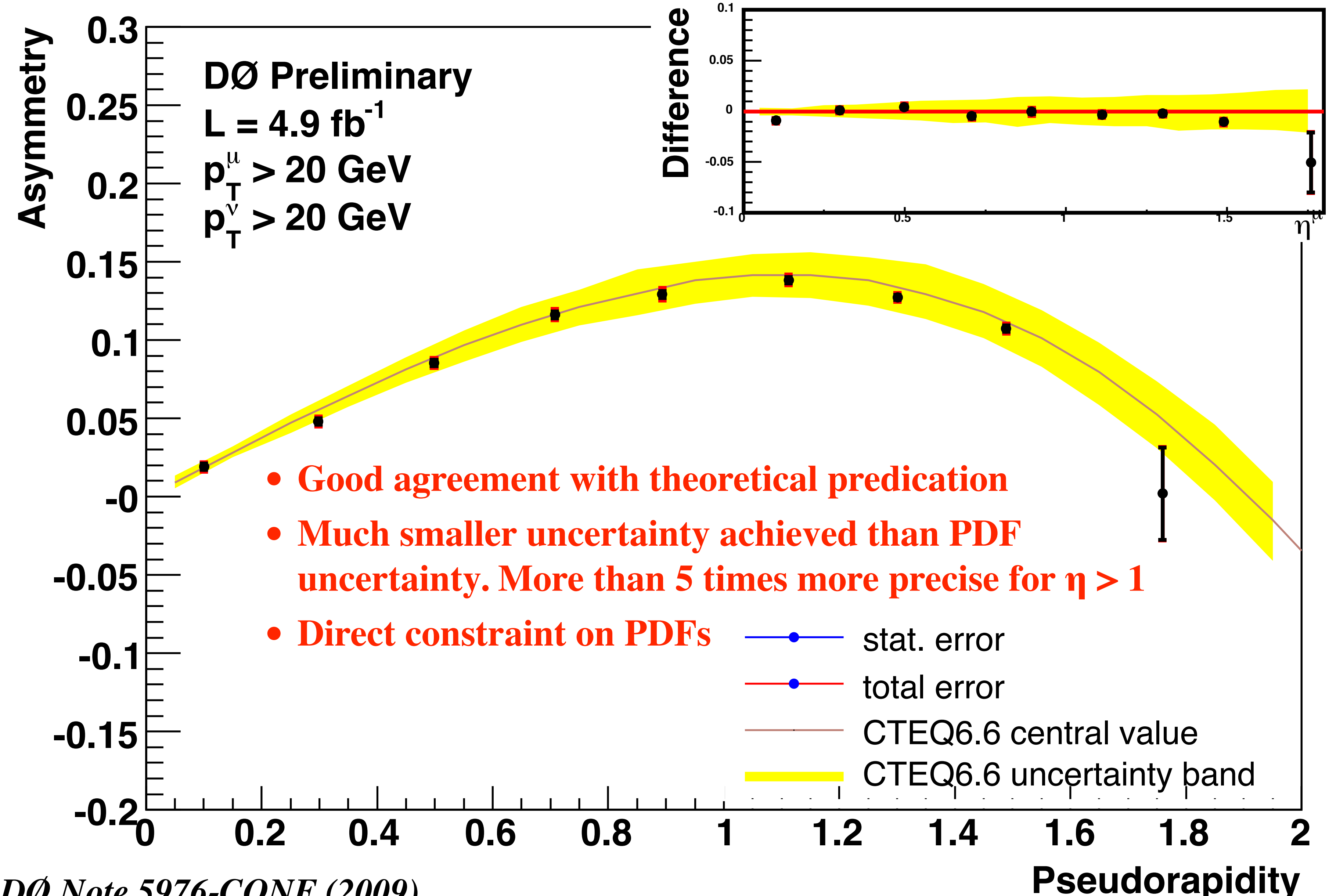
E.g. for W+:





W Charge Asymmetry

Results: Muon charge asymmetry, DØ RunIIb 4.9 fb^{-1}



- **Good agreement with theoretical predication**
- **Much smaller uncertainty achieved than PDF uncertainty. More than 5 times more precise for η > 1**
- **Direct constraint on PDFs**

DØ Note 5976-CONF (2009)

Z/γ* Forward-Backward Asymmetry

- **In the process:** $q\bar{q} \rightarrow Z/\gamma^* \rightarrow e^+e^-$
  - **fermion-γ* coupling contains only vector component**
  - **fermion-Z coupling contains both vector and axial-vector components**

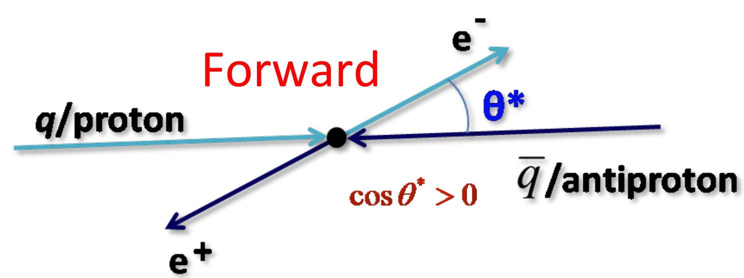
Vector coupling: $g_v^f = I_3^f - 2Q_f \sin^2\theta_W$ **effective weak mixing angle**

Axial-vector coupling: $g_a^f = I_3^f$

- **Give rise to non-zero Forward-Backward Asymmetry (A_{FB}) in the final states**

$$\frac{d\sigma(q\bar{q} \rightarrow e^+e^-)}{d\cos\theta^*} = A(1-\cos^2\theta^*) + B\cos\theta^*$$

functions of vector and axial-vector couplings.



A_{FB} is a direct observable of :

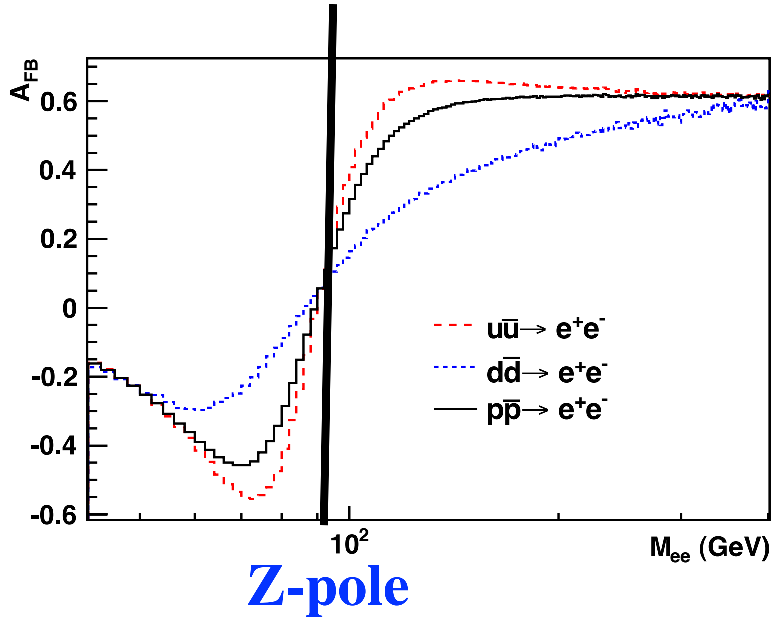
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8} \cdot \frac{B}{A} = f(\boxed{g_v^f, g_a^f, sin^2\theta_w}, \ldots)$$

Forward: $\cos\theta^* > 0$ **Backward:** $\cos\theta^* < 0$

Motivation

- At Tevatron, Z/γ* is mostly produced by light valence quark pair, u-ubar or d-dbar
- From the observable A_{FB}, we can:
  - Precisely measure $\sin^2\theta_W$ based on Z to light quark couplings
  - Directly probe the coupling of Z/γ* to light quarks

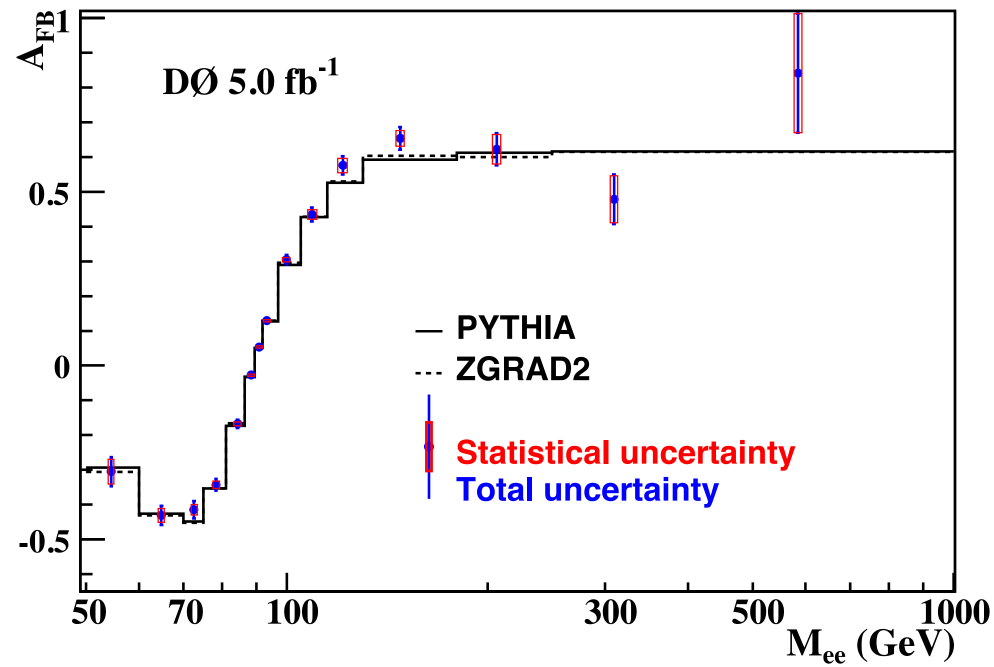
- Investigate possible new phenomena, e.g. new neutral gauge boson Z'
  - Around Z-pole, A_{FB} is dominated by interference of vector and axial-vector couplings of Z to quarks
  - Far away above Z-pole, A_{FB} is dominated by Z/γ* interference, which is sensitive to new physics.

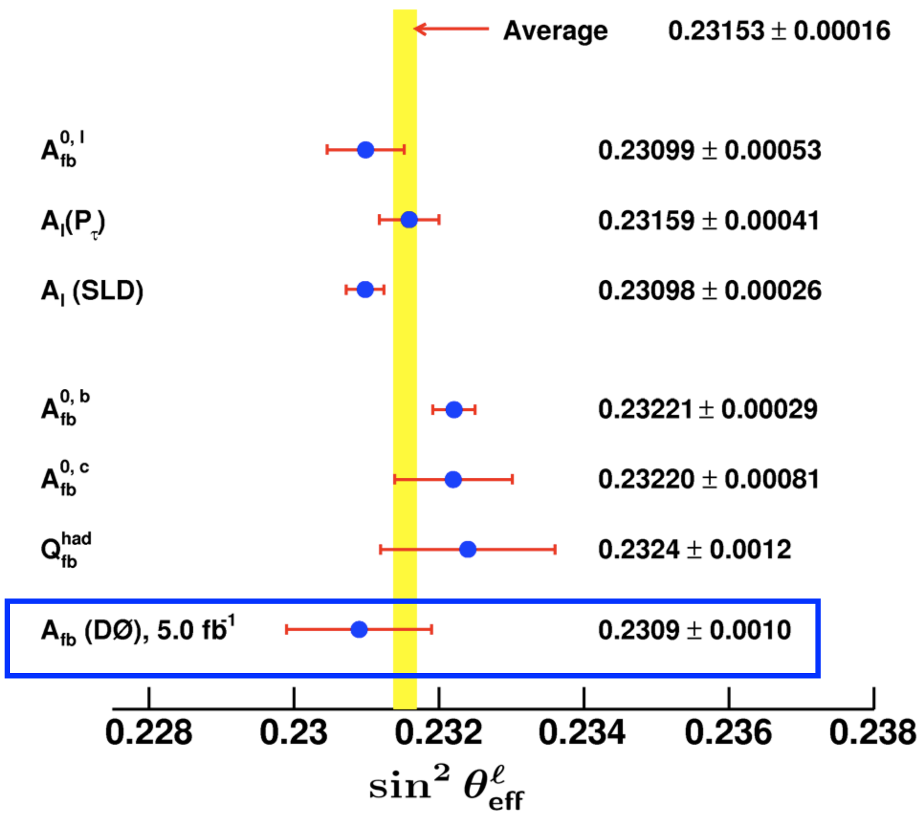


Z/γ* Forward-Backward Asymmetry

- **Unfolded AFB agrees well with theoretical prediction**
  - **No evidence for new physics at high mass**
- **Extracted $\sin^2\theta^l_{eff}$**

= 0.2309 ± 0.0008 (stat.) ± 0.0006 (syst.)

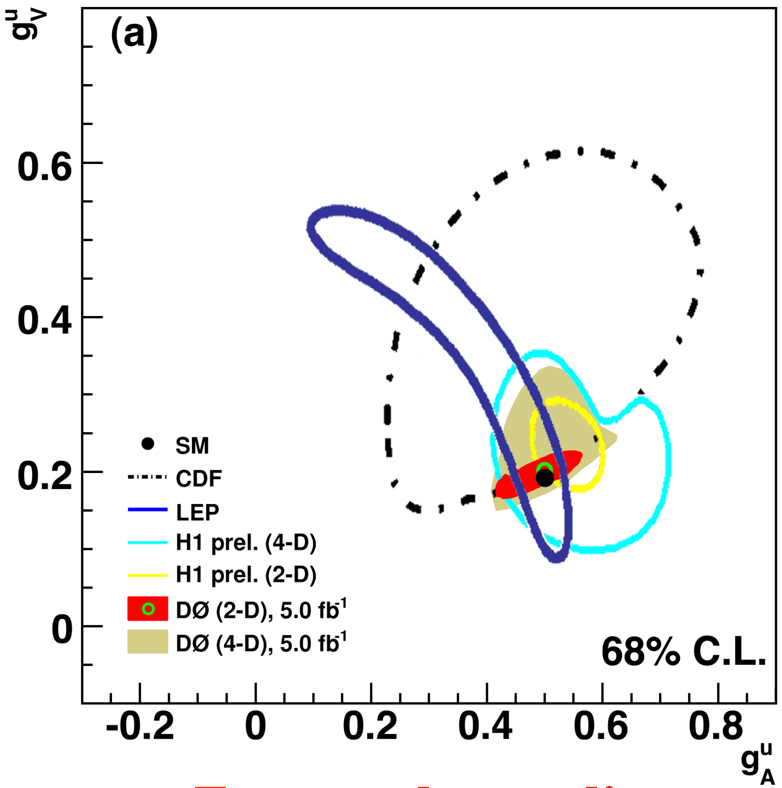




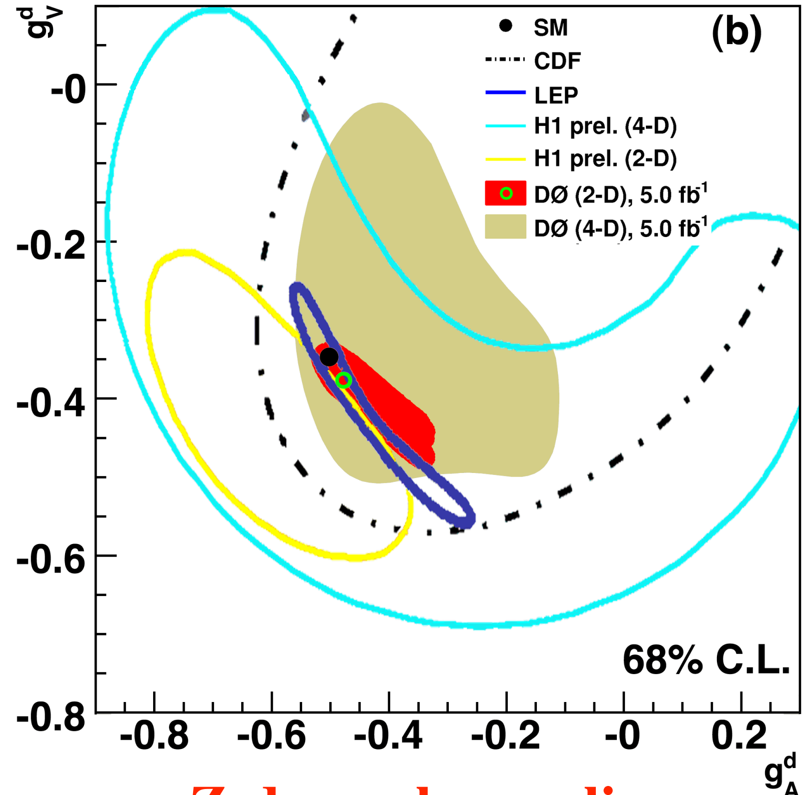
- **Statistical uncertainty is still dominant**
- **PDF uncertainty (0.00048) is dominant in systematic uncertainty**
- **Most precise measurement based on Z to light quark couplings**

Accepted 6/29/11: Phys. Rev.D, arXiv:1104.4590

Z/γ* Forward-Backward Asymmetry



Z-u quark couplings



Z-d quark couplings

Most precise direct measurement of couplings of Z to light quarks u and d.

Accepted 6/29/11: Phys. Rev.D, arXiv:1104.4590

Conclusions

- **W Boson Mass: constraint on the SM Higgs boson mass**
- **W charge asymmetry: direct constraint on the valence quark PDFs**
- **A_{FB}: precise measurement of $\sin^2\theta_W$ and direct probe the Z-light quark couplings**
- **All the three analysis could not be easily challenged by LHC:**
  - **Tevatron is a Proton-Antiproton collider**

Backups

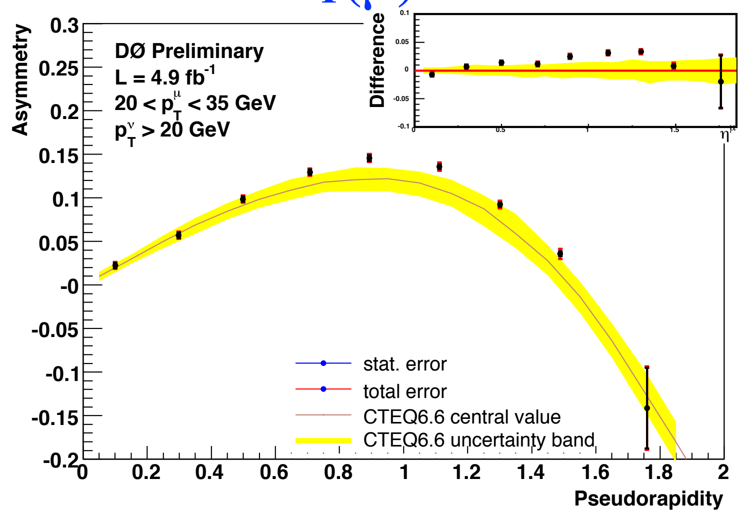
TABLE II. Systematic uncertainties of the M_W measurement.

Source	ΔM_W (MeV) m_T	p_T^e	$\not{E}_T$
Electron energy calibration	34	34	34
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	6	12	20
Electron efficiencies	5	6	5
Backgrounds	2	5	4
Experimental subtotal	35	37	41
PDF	10	11	11
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	12	14	14
Total	37	40	43

W Charge Asymmetry

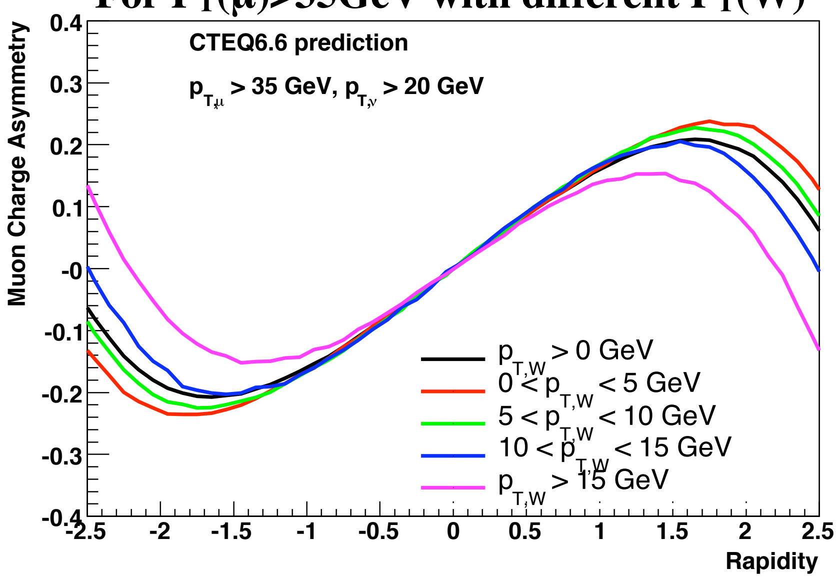
- However, disagreement if split sample according to $P_T(\mu)$
- Need better understanding of $P_T(W)$ before drawing definite conclusions

$20<P_T(\mu)<35$ GeV

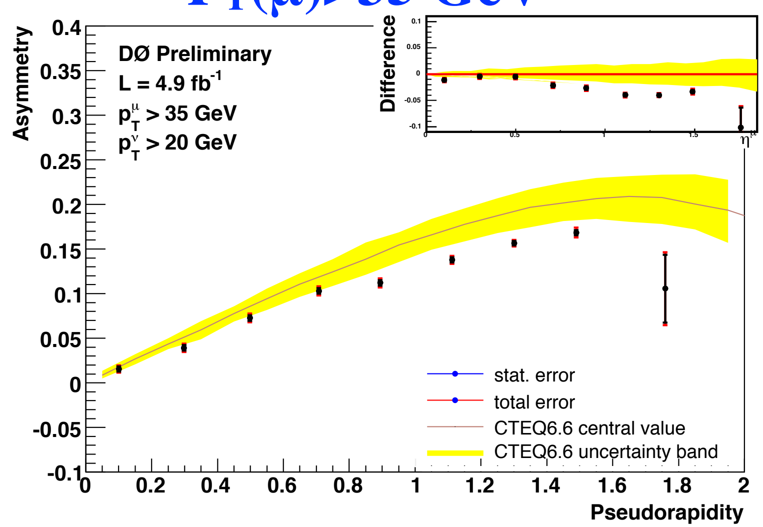


Resbos+CTEQ6.6 predicted

For $P_T(\mu)$>35GeV with different $P_T(W)$



$P_T(\mu)>35$ GeV



DØ Note 5976-CONF (2009)

AFB

Source		$\Delta\sin^2\theta_{eff}^{lept}$
Statistical		0.00080
Systematics		0.00061
	PDFs	0.00048
	EM scale/reso	0.00029
	MC stat.	0.00020
	EMID	0.00008
	Bkg. Modeling	0.00008
	Charge misID	0.00004
	Higher order	0.00008
Total		0.00102

	g_A^u	g_V^u	g_A^d	g_V^d
SM	0.500	0.196	-0.500	-0.346
DØ	0.543 ± 0.045	0.216 ± 0.016	-0.335 ± 0.047	-0.491 ± 0.025

TABLE VII: Measured Z to light quark couplings compared with SM values.

Outline

- The Tevatron and DØ Detector
- W Mass and Width Precision Measurement
- W (muon) Charge Asymmetry using $W \rightarrow \mu\nu$ events
- Forward-Backward Charge Asymmetry using $Z/\gamma^{*} \rightarrow e^{+}e^{-}$ events