W/Z Properties (including M_W) from Tevatron

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on behalf of the CDF and DØ Collaborations

HCP2009, Evian, France, November 16, 2009

W/Z Properties Recently Studied at the Tevatron

Active and rich research program on W/Z properties at Tevatron in RunII
⇒28 publications and 12 preliminary results

Presented in this talk:

CDF $W \rightarrow \pi\gamma$ 4.3 fb-1 Preliminary (2009)
CDF W Mass 1.0 fb^{-1} PRL 99, 151801 (2007); PRD 77, 112001 (2008)
CDF W Width 1.0 fb^{-1} PRL 100 071801 (2008)
CDF Afb 4.1 fb^{-1} Preliminary (2009)
CDF Z rapidity 4.1 fb^{-1} hep-ex/0908.3914 (2009)
CDF $W(\rightarrow e\nu)$ charge asymmetry 1.0 fb-1 PRL 102, 181801 (2009)
DØ W Mass, 1.0 fb^{-1} , PRL 103, 141801 (2009)
DØ W Boson Width, 1.0 fb^{-1}, arXiv.org:0909.4814, submitted to PRL (2009)
DØ Electron Charge Asymmetry , 0.70 fb-1 , PRL 101, 211801 (2008)
DØ Muon Charge Asymmetry, 4.9 fb^{-1}, Preliminary (2009)
CDF and DØ W Mass Combination, up to 1.0 fb^{-1}, arXiv:/0908.1374 (hep-ex) (2009)

diboson production: next talk of this session by Sasha Pranko

Outline

- W Mass — **Electroweak Symmetry Breaking**

- W Width — **Standard Model**

- Charge Asymmetry
- Boson Rapidity

Constraining PDFs

- Forward-Backward Asymmetry
- Rare decays

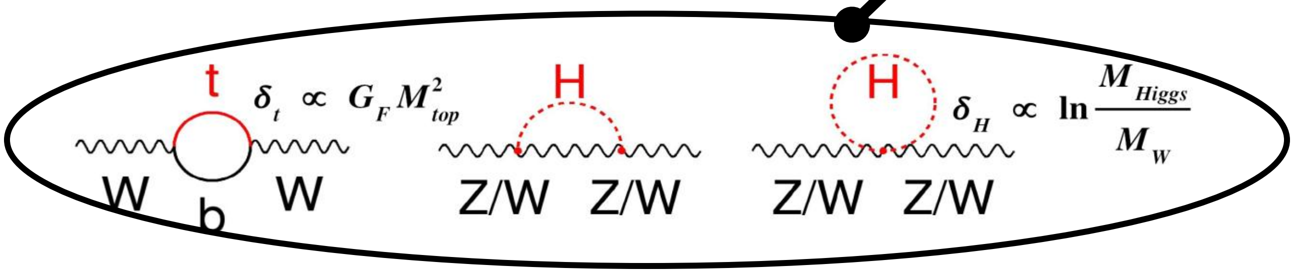
New Physics

M(W) Motivation

- W mass is an important Standard Model parameter related to $\mathbf{G_F}$, $\boldsymbol{\alpha}$, and $\mathbf{M_Z}$ via

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

$$\cos\theta_W = \frac{M_W}{M_Z}$$



- Δr term represents (large!) contribution to M_W from radiative corrections

α	*electron g-2*	0.68 pp10^9
G_F	*muon life-time*	9 pp10^6
M_Z	*LEP 1 lineshape*	23 pp10^6
m_W	*combination*	290 pp10^6

tree level: $\mathbf{m_W = 79.964 \pm 0.005}$ **GeV**

measurement: $\mathbf{m_W = 80.399 \pm 0.023}$ **GeV**

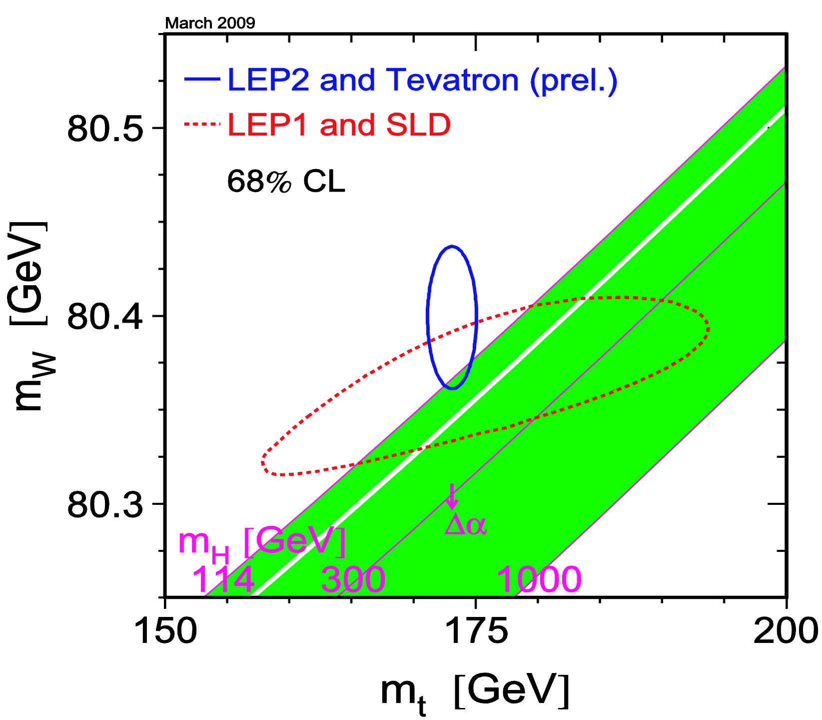
19 σ discrepancy !

- Precise measurements of M_W are used in constraining the Standard Model

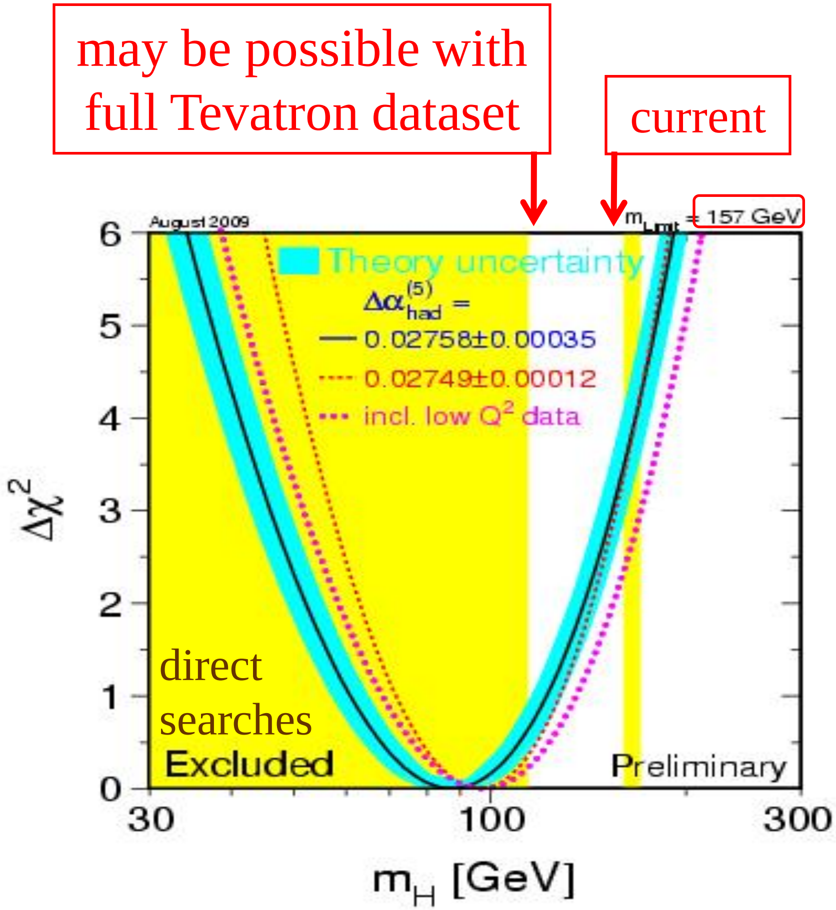
Constraining Standard Model

- Precision measurements provide sensitivity to new physics at much higher energy scales than the mass of the particles on which the measurements are performed

- Measurements of the M_W and M_{top} constrain the mass of the Higgs boson



Higgs limit from EW fits



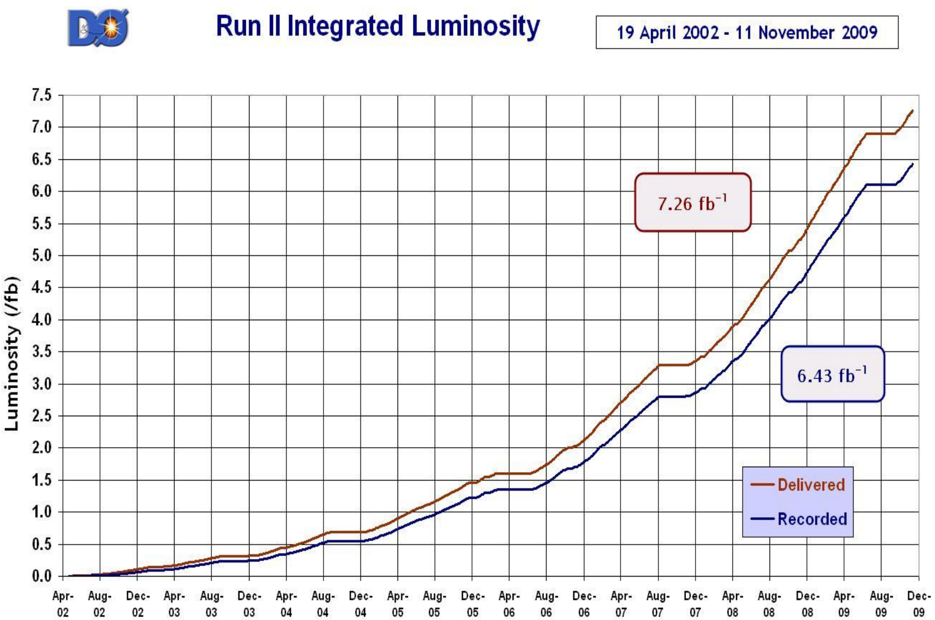
fb^{-1}

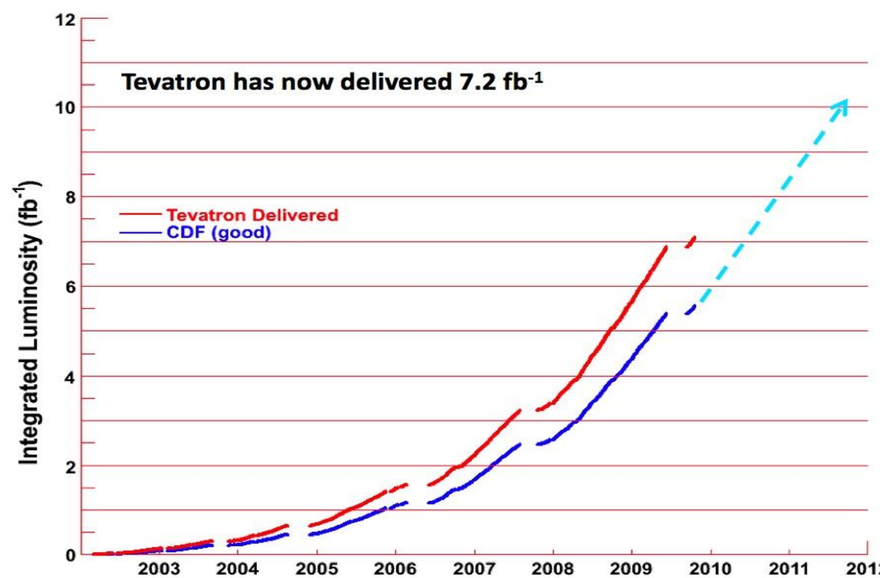
Luminosity

Run II Integrated Luminosity from 19 April 2002 to mid November 2009

luminosity delivered up to now: 7.2 fb^{-1} (5.6 - 6.4 fb^{-1} recorded)
running in 2011 approved

⇒will result in analyses with about 10 fb^{-1} (doubling current dataset)

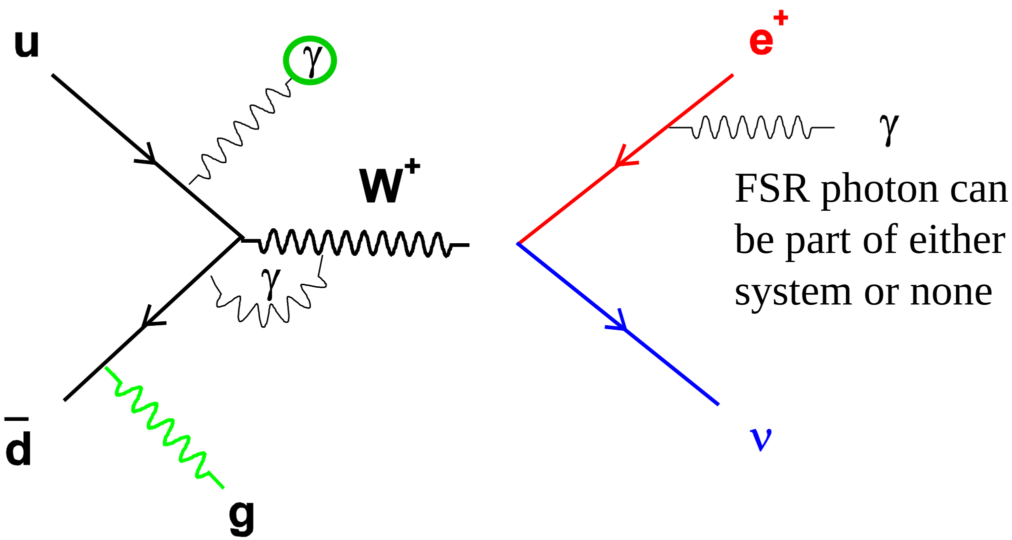




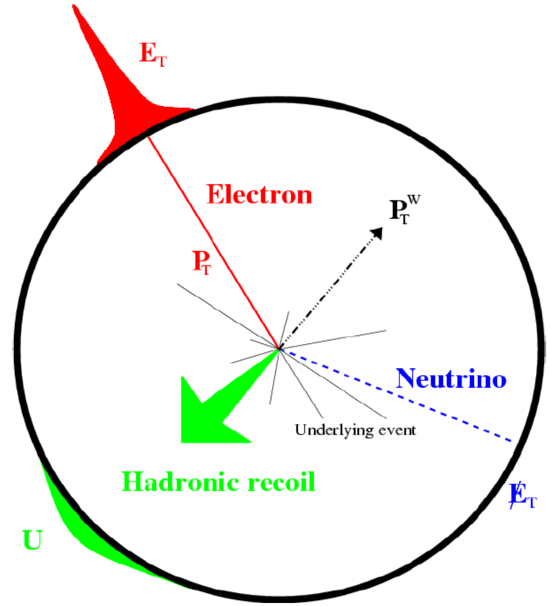
a great thanks to FNAL and Accelerator Division !

M(W) Analysis (DØ)

hard component = recoil against W



soft component =
spectator partons +
additional collisions



$$\not{E}_T = \left| \vec{p}_T^{\,e} + \vec{p}_T^{\,recoil} \right|$$

Modelled recoil: $\mathbf{u}_T = \mathbf{u}_T^{Hard} + \mathbf{u}_T^{soft} + \mathbf{u}_T^{Elec} + \mathbf{u}_T^{FSR}$

Analysis: describe W→eν event in terms of **recoil** and **electron** systems

Required precision: **electron** ~ 0.3 pp10^3
hadronic recoil ~ 1%

Measuring M(W)

- Cannot reconstruct M(W) directly (missing neutrino p_z)
- Extract it from observables that are sensitive to M(W)

$$M_T = \sqrt{2 p_T^e \, p_T^\nu (1 - \cos\phi_{e\nu})} \qquad p_T^e \qquad p_T^\nu \left(\not{E}_T = \left| \vec{\boldsymbol{p}}_{\boldsymbol{T}}^{\boldsymbol{e}} + \vec{\boldsymbol{p}}_{\boldsymbol{T}}^{\boldsymbol{recoil}} \right| \right)$$

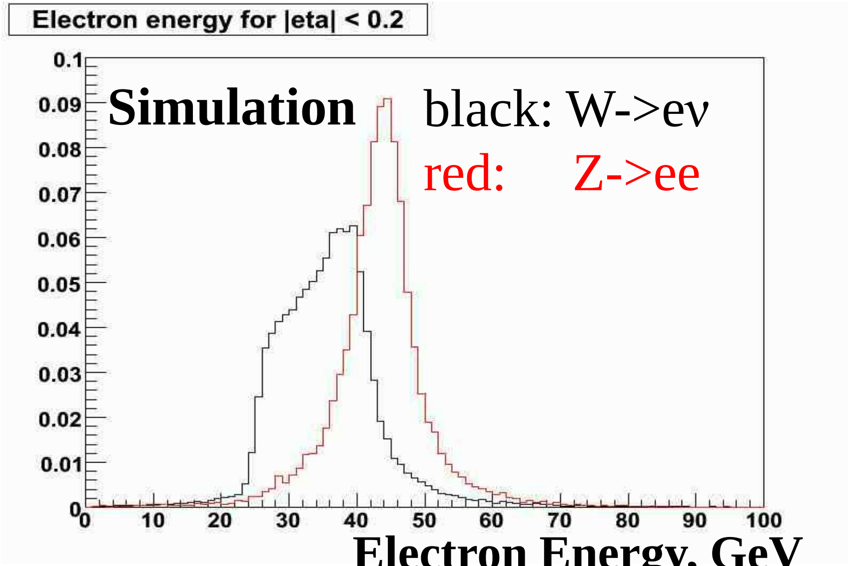
  - due to complicated detector effects analytical computation impossible
  - determine M(W) via template fit (need Fast Monte Carlo model of detector effects)

- The observables are not Lorentz-invariant: sensitive to W boson dynamics
  - need good model of W boson production

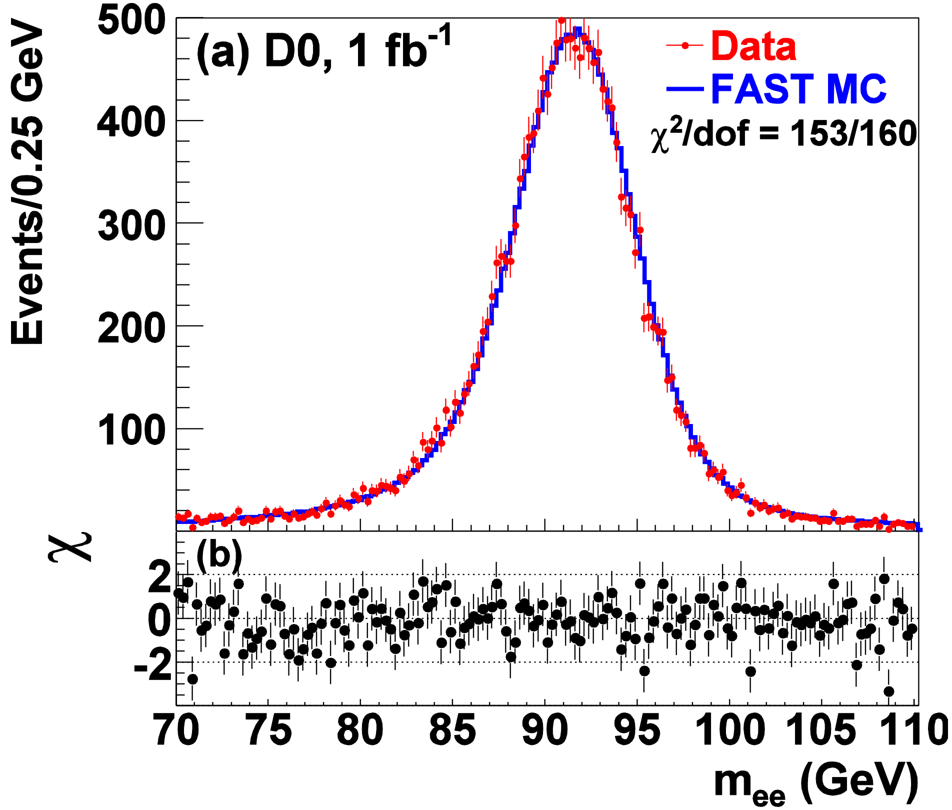
Electron Energy Calibration

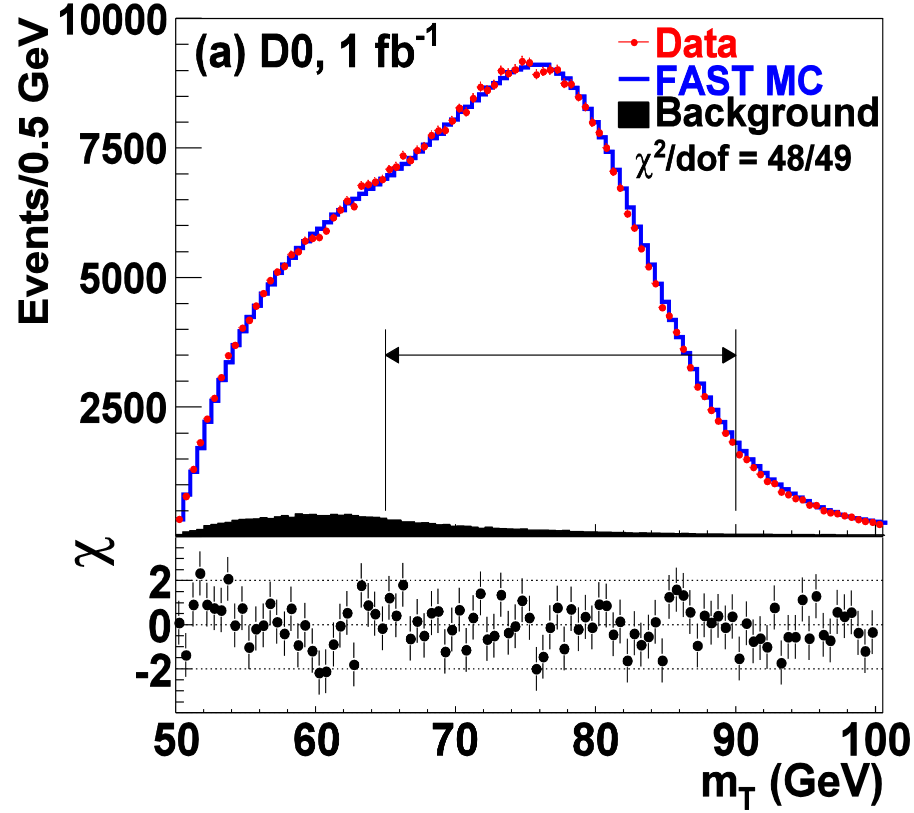
- M(W) precision is controlled by electron energy scale precision
- Understanding electron showers in the calorimeter is very important
- Knowing the amount of un-instrumented material is the key
- Use Z->ee data sample for calibration to precisely measured M(Z) by LEP
- Need proper description of energy dependence as well
- Achieved via
  - detailed GEANT simulation
  - accurate calibration of longitudinal shower profile
  - tuning of material model

DØ measures W/Z mass ratio
⇒ many systematic effects cancel



Mass fits: M(Z), MT(W)



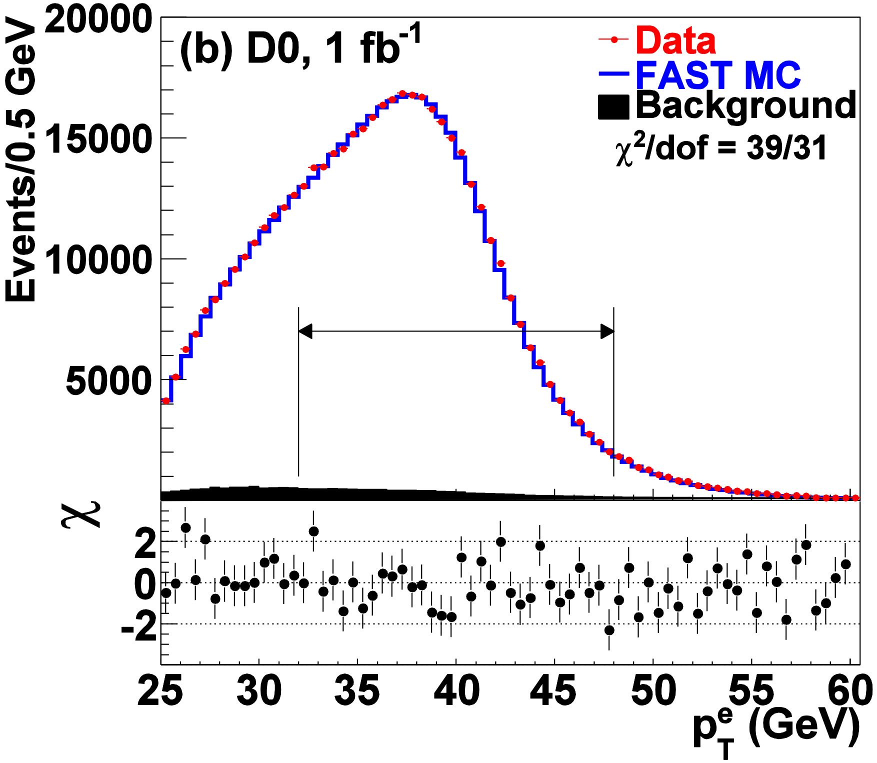


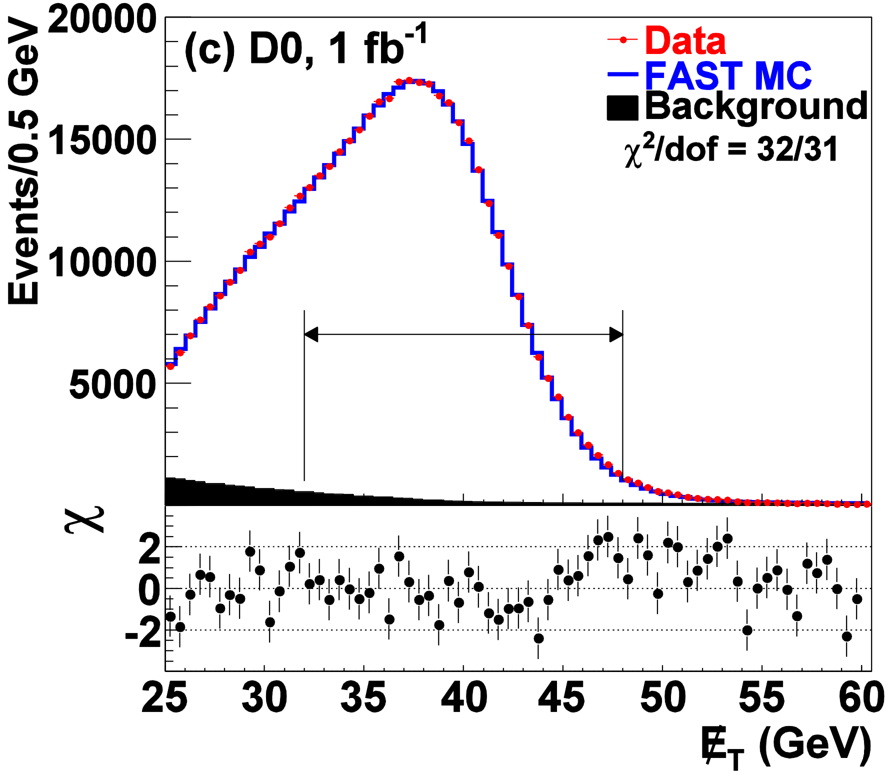
m(Z) = 91.185 ± 0.033 GeV (stat)

m(W) = 80.401 ± 0.023 GeV (stat)

Remember that Z mass value from LEP was input to electron energy scale calibration, PDG: M(Z) = 91.1876 ± 0.0021 GeV

Mass fits: PT(e), MET





m(W) = 80.400 ± 0.027 GeV (stat)

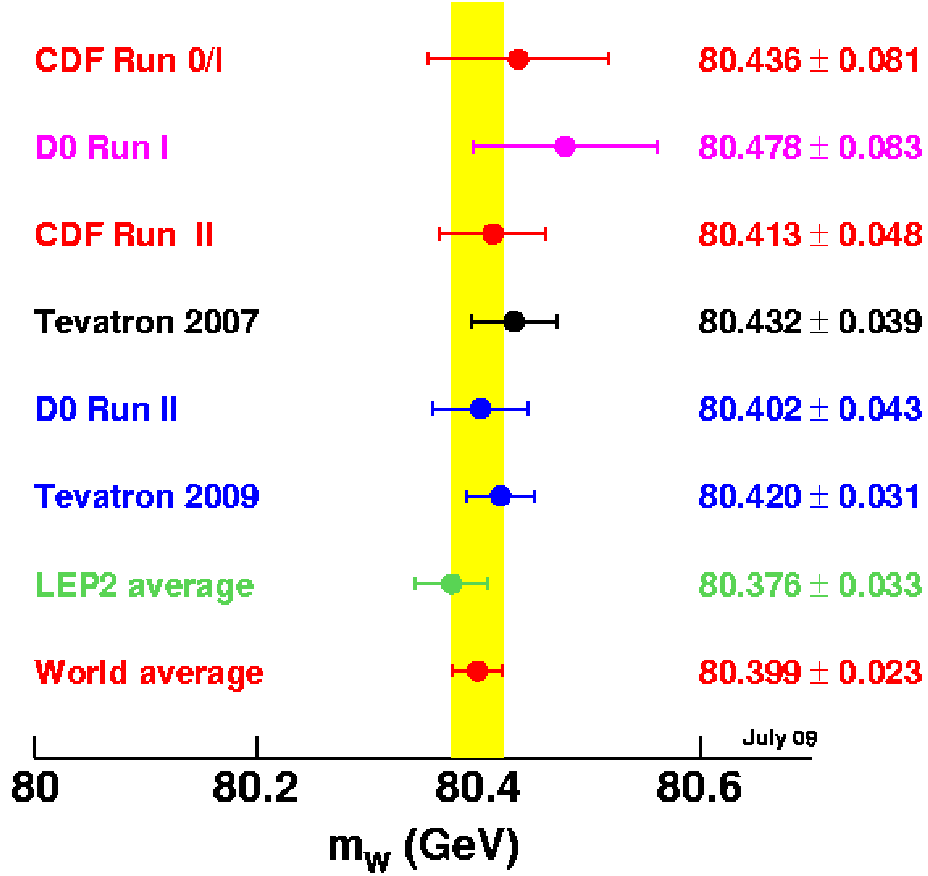
m(W) = 80.402 ± 0.023 GeV (stat)

M(W) Uncertainties, MeV

Source	m_T	p_T^e	E_T
Statistical	**23**	**27**	**23**
Systematic - Experimental			
Electron energy response	34	34	34
Electron energy resolution	2	2	3
Electron energy non-linearity	4	6	7
Electron energy loss differences	4	4	4
Recoil model	6	12	20
Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Subtotal	**35**	**37**	**41**
Systematic – W production and decay model			
PDF	10	11	11
QED	7	7	9
Boson pT	2	5	2
W model subtotal	**12**	**17**	**17**
Systematic -- Total	**37**	**40**	**44**

in the near future expect reduction of experimental errors and increased importance of theoretical errors

M(W) World Average



DØ RunII 1fb^{-1}
80.401 ± 0.021(stat.) ± 0.038(syst.) GeV
80.401 ± 0.043 GeV
this new result is the
single most precise measurement
of the W boson mass to date.

For the first time the total uncertainty of 31 MeV from Tevatron is smaller than that of 33 MeV from LEPII

World average is now:
80.399 ± 0.023 GeV

Tevatron ElectroWeak Working Group
http://tevewwg.fnal.gov
Combination performed with B.L.U.E. method
L. Lyons et al, NIM in Phys. Res. A **500**, 391 (2003)
A. Valassi, NIM in Phys. Res. A **500**, 391 (2003)

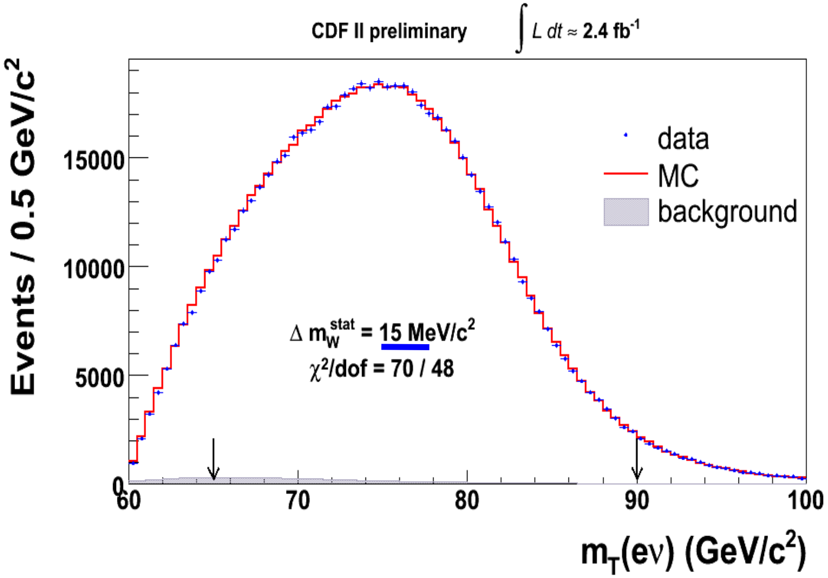
theory errors are highly correlated between DØ and CDF, need help from theory in reducing these errors

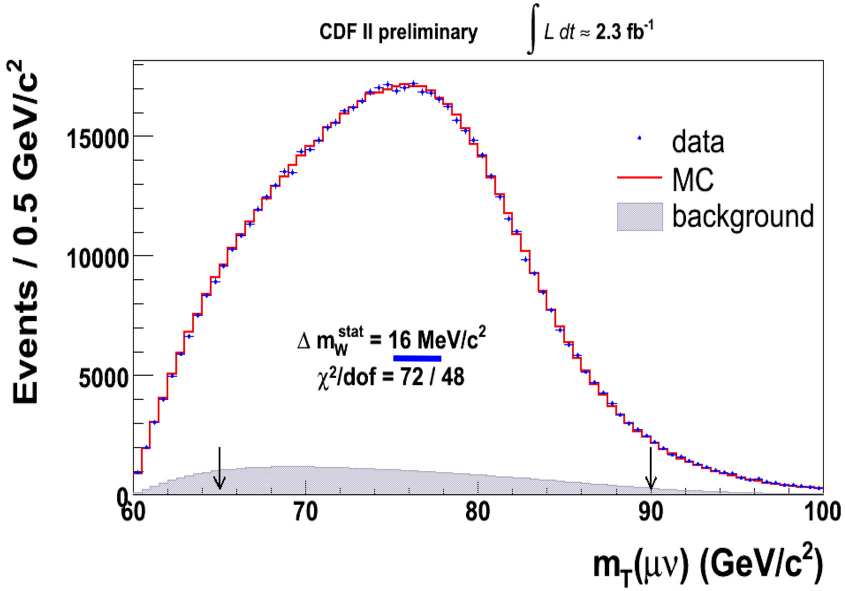
CDF M(W) Analysis

CDF RunII result with 200 pb^{-1} (both electron and muon channel)
electron energy calibration: transfer precise tracker calibration to calorimeter using E/p in W->eν sample

M(W) = 80413 ± 34 (stat.) ± 34 (syst.) MeV = 80413 ± 48 MeV

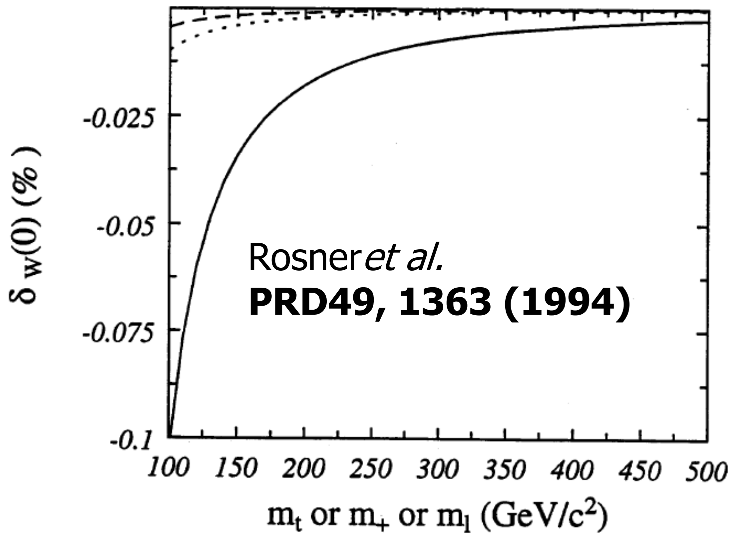
More data are being analyzed in both channels
Significantly reduced statistical errors



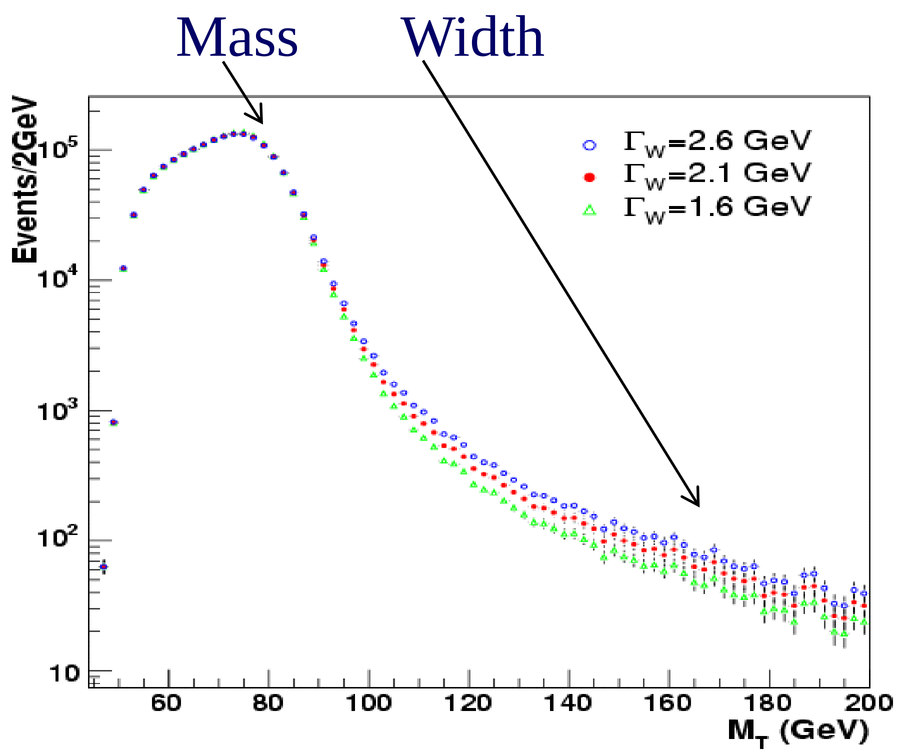


Γ(W) (DØ)

Due to insensitivity to "oblique" corrections, expected to agree with SM prediction almost regardless of new physics.



Exploit high tail of $M_T(W)$ distribution

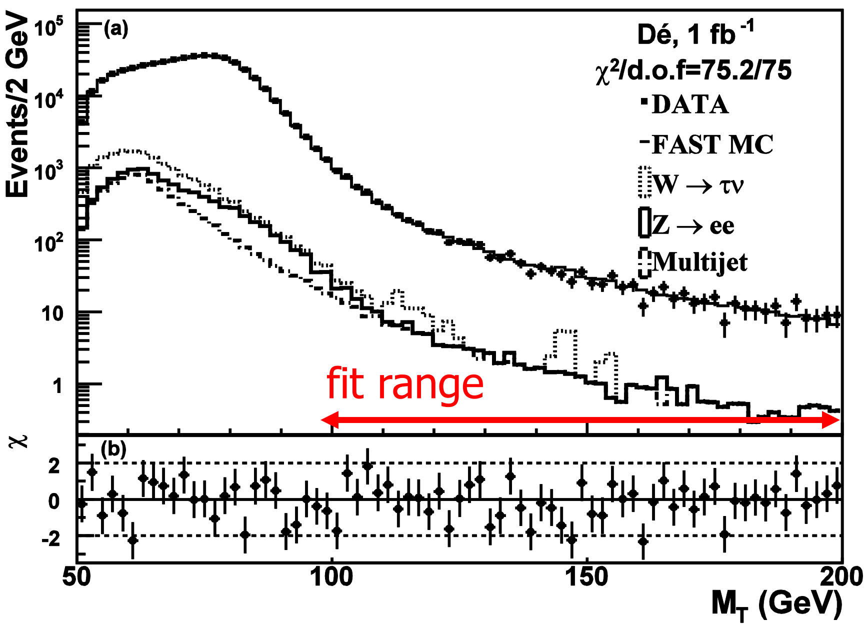


Width, to LO, is proportional to the fraction of events at high M_T

New recoil model for DØ analysis based on the recoil library from Z→ee events…uncertainty dominated by the limited Z statistics NIM 609, 250 (2009)

Γ(W) Results

DØ Γ_W = 2.028 ± 0.038 (stat) ± 0.061 (syst) GeV = 2.028 ± 0.072 GeV



Source	$\Delta\Gamma_W$ (MeV)
Electron energy scale	33
Electron resolution model	10
Recoil model	41
Electron efficiencies	19
Backgrounds	6
PDF	20
Electroweak radiative corrections	7
Boson p_T	1
M_W	5
Total Systematic	61

CDF RunII 350 fb^-1 2.032 ± 0.073 GeV

Tevatron combined value without DØ Run II:
Γ_W = 2.050 ± 0.058 GeV
Expect ~ 10 MeV improvement from including it

Electroweak fit uzing Z-pole data plus Mtop measurement

(SM Γ_W = 2.093 ± 0.002 GeV)
(LEP Γ_W = 2.196 ± 0.083 GeV)

Constraining the PDFs with W and Z

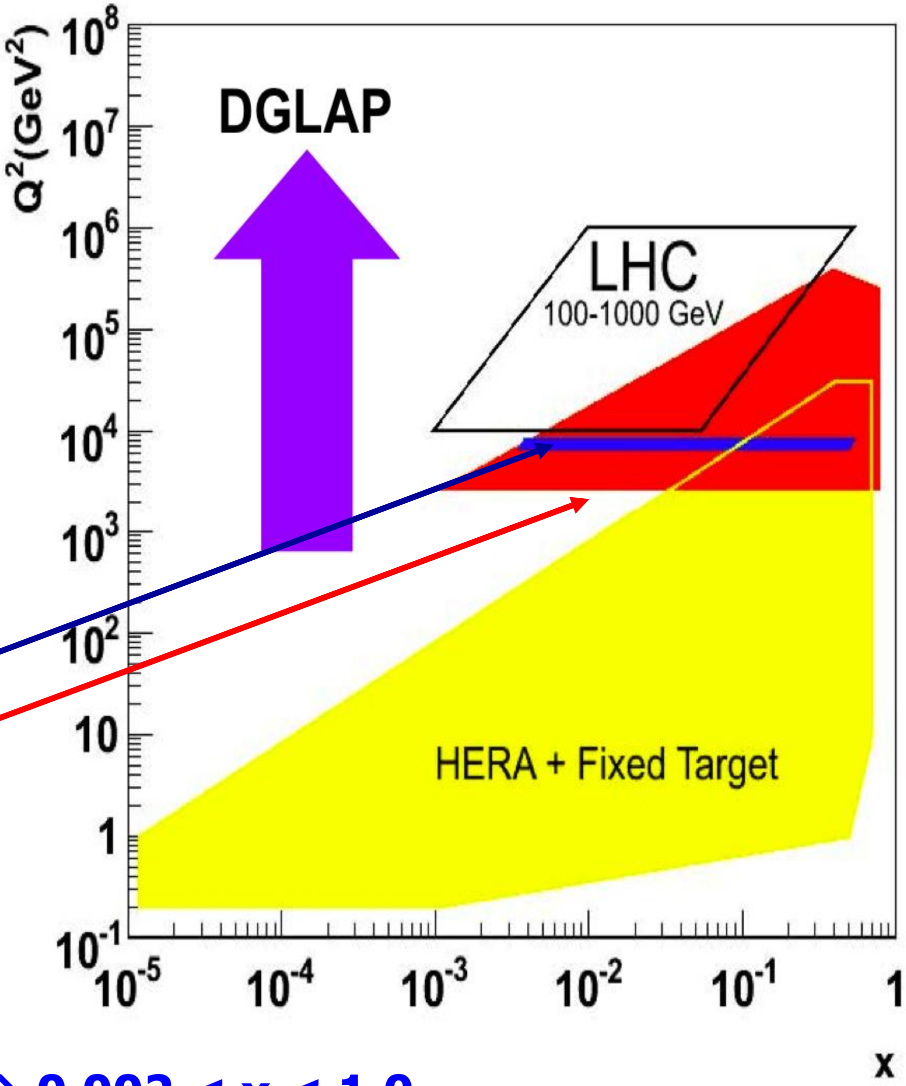
W charge asymmetry and rapidity distributions measured at Tevatron constrain the PDFs at large-x,
⇒essential input to all calculations of processes at present and future hadron colliders (LHC).

M(W) largest theoretical error: PDF (currently ~10 MeV ;
could be ~20 MeV at LHC !)

Complement measurements from HERA and neutrino experiments

W/Z asymmetries at Tevatron

inclusive jets at Tevatron



$$x_1 = M_W e^y / \sqrt{s}, x_2 = M_W e^{-y} / \sqrt{s}.$$

$Q^2 \sim M_W^2$

$y^W < 3.2 \rightarrow 0.002 < x < 1.0$

W Charge Asymmetry. Introduction

The W^+ is boosted along the proton direction because the u quarks carry more momentum than the d quark → asymmetry in W production

W charge asymmetry

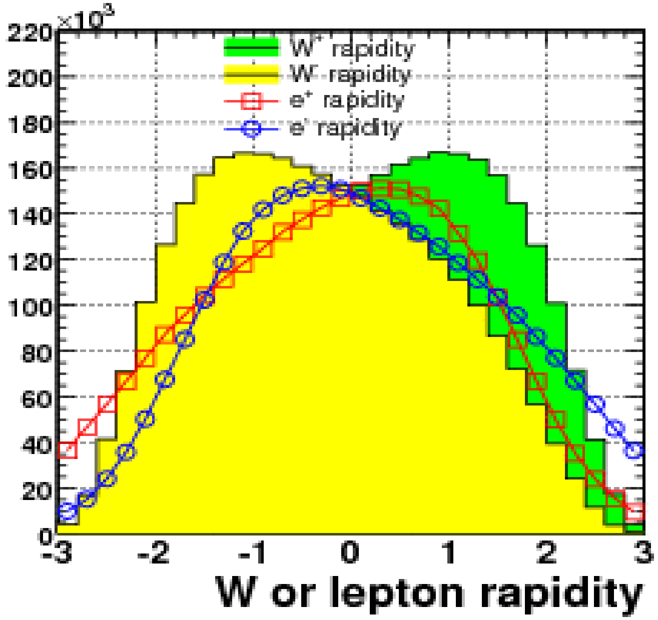
$$A(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W}$$

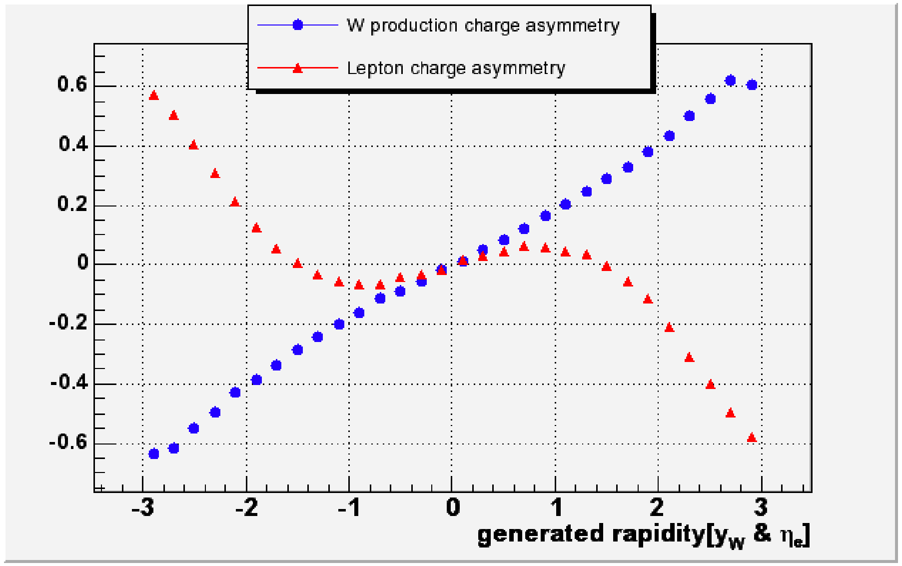
$$y_W = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

lepton charge asymmetry

$$A(\eta_l) = \frac{d\sigma_+/d\eta_l - d\sigma_-/d\eta_l}{d\sigma_+/d\eta_l + d\sigma_-/d\eta_l} \sim \frac{d(x)}{u(x)} = A(y_W) \otimes (V\text{-}A)$$

$$x_{u,d} = \frac{M_W}{\sqrt{s}} e^{\pm y_W}$$

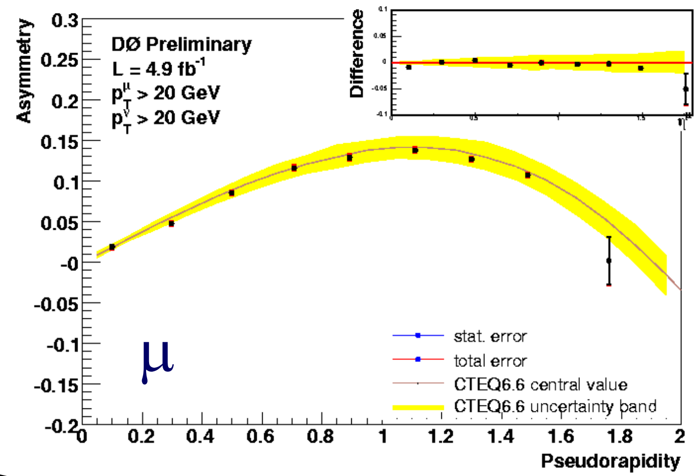




E.L. Berger, F. Halzen, C.S. Kim and S. Willenbrock; Phys. Rev. D40 (1989) 83

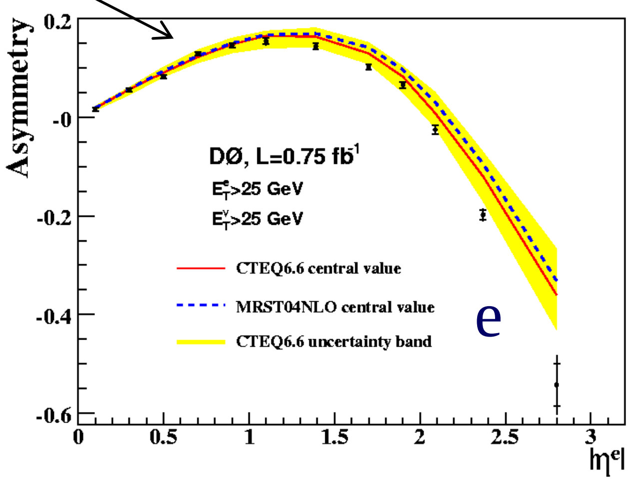
Lepton charge asymmetry (DØ)

- Splitting analysis in Et bins allow finer probing of PDFs
- Uncertainties smaller than PDF uncertainties
- Inclusion of these results will further constrain future PDF fits and improve predictions

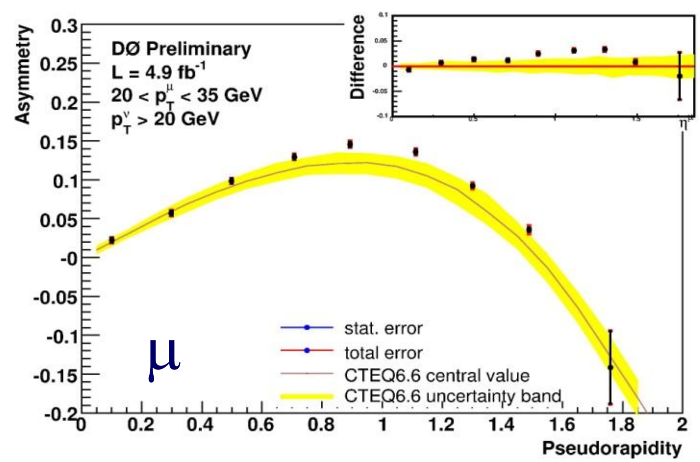


Electrons: wide acceptance

Muons: high statistics



Asymmetry folded due to CP invariance $A(y) = -A(-y)$

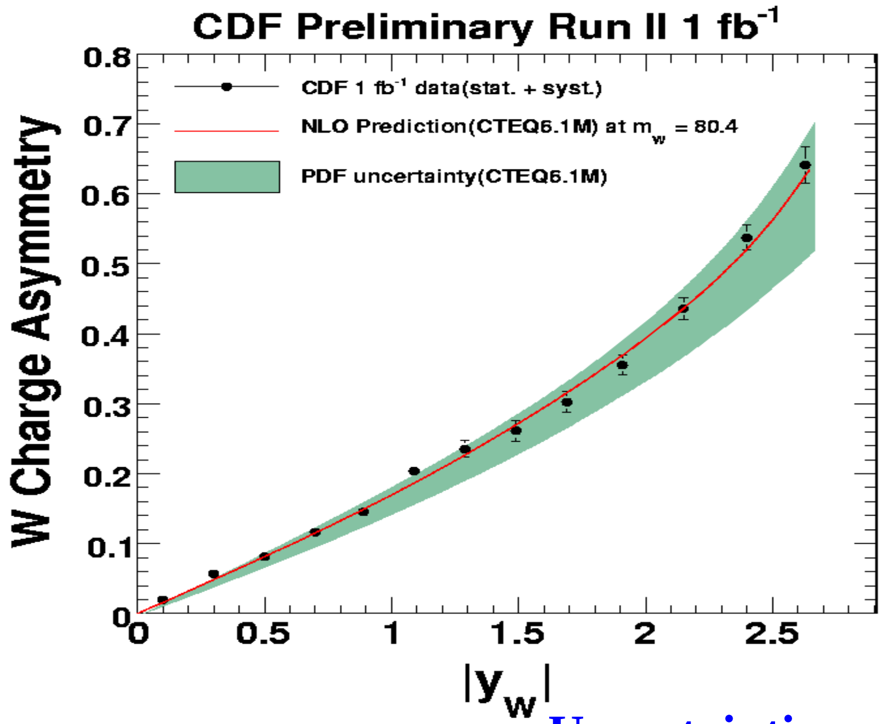


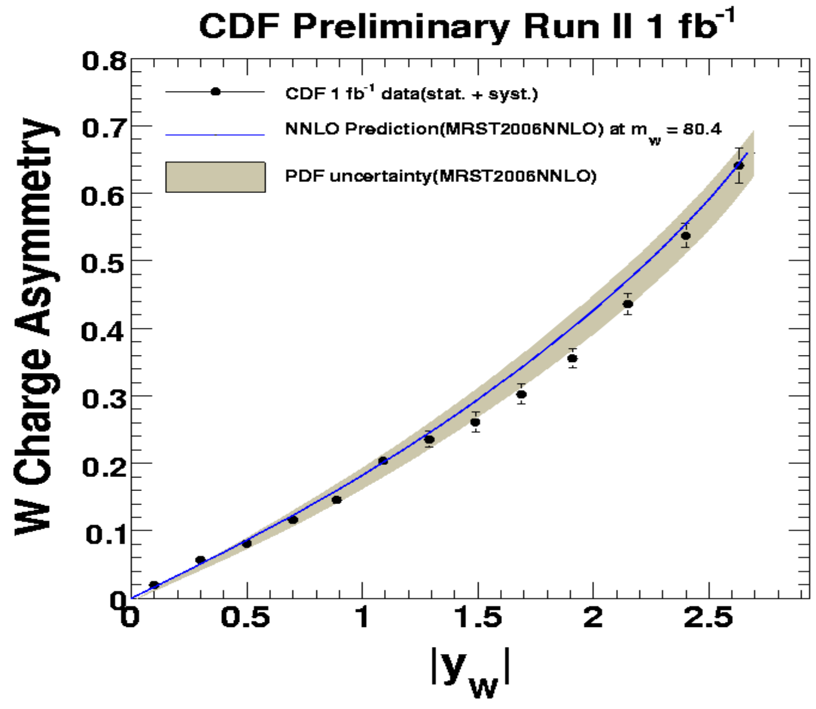
CTEQ 6.6 NLO P.M.Nadolsky et al. Phys. Rev. D78 013004 (2008)
MRST2004 A.D. Martin et al. Phys. Lett. B604, 61 (2004)

W charge asymmetry (CDF)

CDF: direct determination of y_W

W mass constraint → neutrino momentum with weight probability assigned (decay structure; $d\sigma_W/dy$)





Uncertainties smaller than PDF one. <u>Still statistics driven</u>

Compare NLO (better) and NNLO PRL 102, 181801 (2009)

working with theorists to quantify the degree of compatibility between CDF, DØ data and theory

Z Boson Rapidity (CDF)

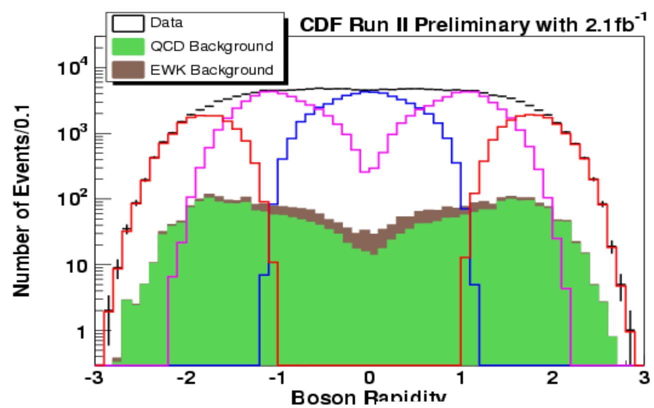
Can also constrain the PDFs with Z boson rapidity

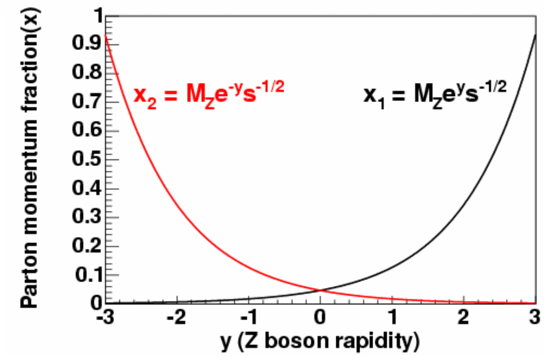
large y->one parton carries large and the other small momentum fraction x.

use di-electrons

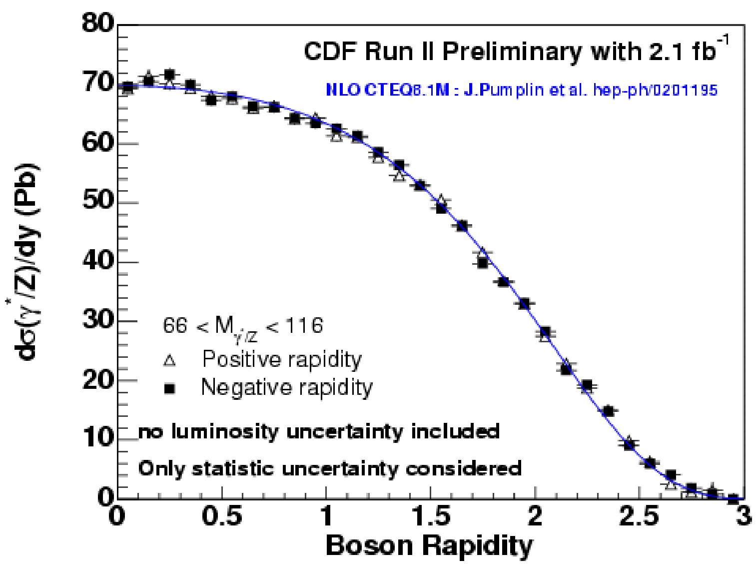
three Z->ee topologies (up to y=2.9)

mass range
66 < M < 116 GeV



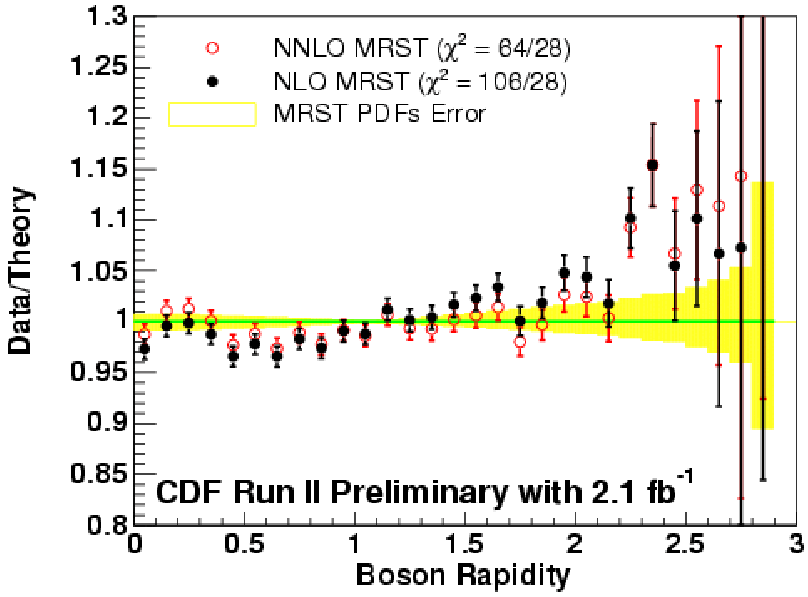


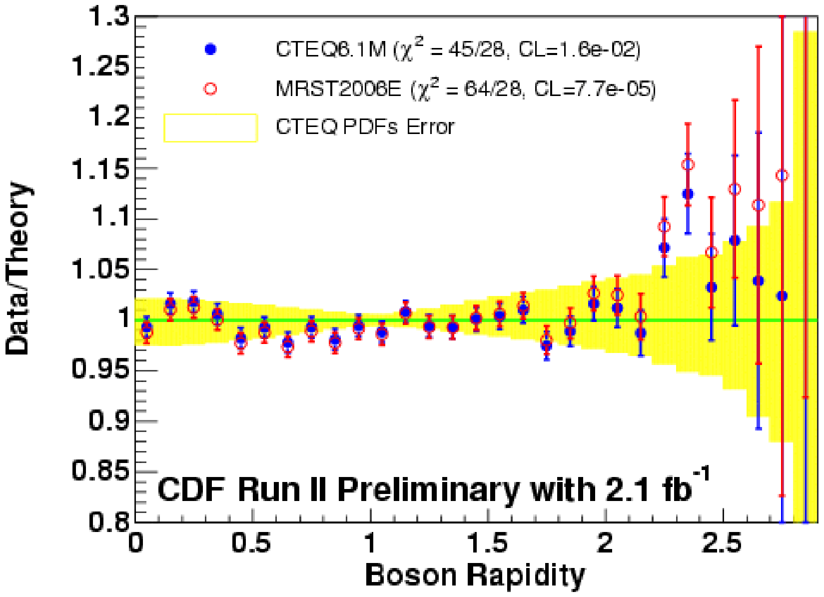
Total cross section
σ=256.0±0.7(stat)±2.0(syst) pb
+ 6% luminosity error (not included)
Theory:
$236.1_{-9.2}^{+9.3}$ pb NLO CTEQ6.1M(NLO))
$251.6_{-3.1}^{+2.8}$ pb NNLO MRST 2006(NNLO))



Z Boson Rapidity Data/Theory (CDF)

Data agree best with NLO calculation using the NLO CTEQ6.1M PDF





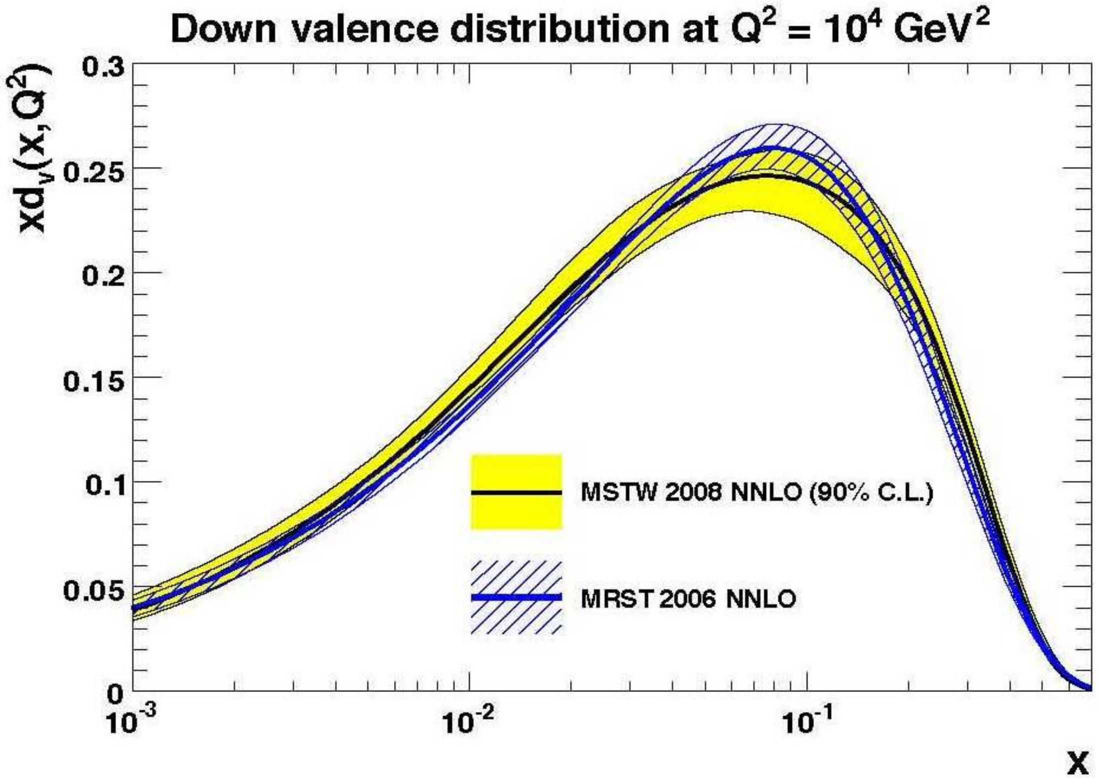
Additional tuning of both the NLO and NNLO PDF models may be needed

Constraints on $xd_v(x,Q^2)$ from the Tevatron

The new CDF and D0 results **(W asymmetry and Z rapidity)** have allowed a better (more robust) parametrization of valence d-quark distribution:

Martin, Stirling, Thorne, Watt, hep-ph/0901.0002 (MSTW 2008)

⇒ increase at x≈0.3, decrease at x≈0.07, wider error band, more flexible

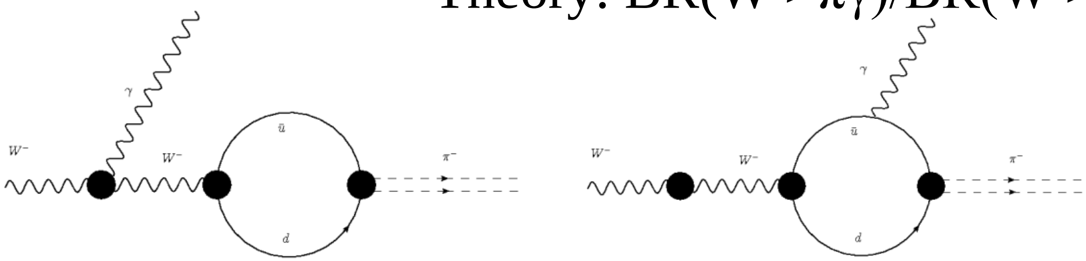


Limit on the rare decay W→π γ (CDF)

W/Z rare decays to a photon and a meson predicted in the SM remain unobserved

W ->πγ: clean final state

Theory: $BR(W\to\pi\gamma)/BR(W\to e\nu) \approx 10^{-6} - 10^{-8}$



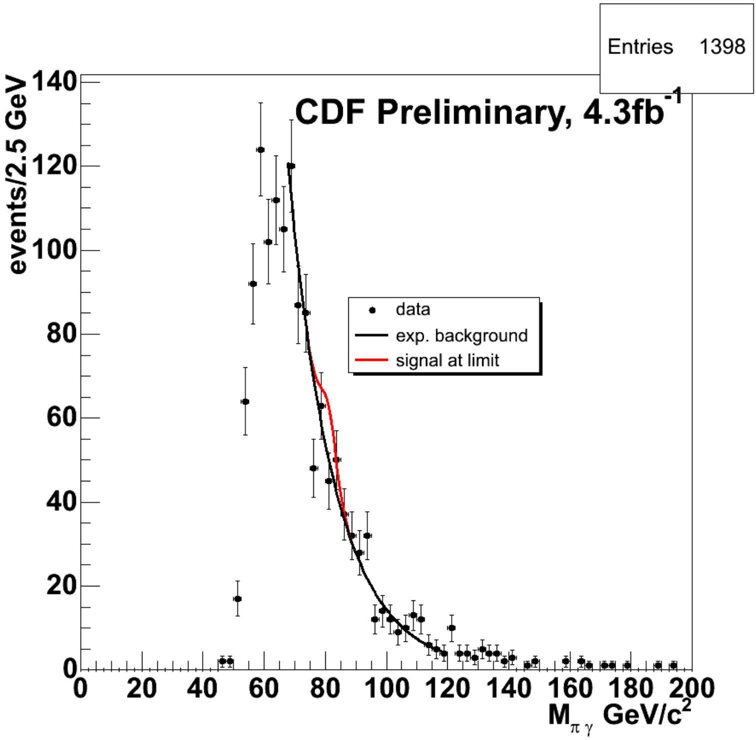
Event Selection:

-- central photon (Et>25 GeV)

-- central charged track(pt>25 GeV) pointing to a calorimeter energy cluster

Limit extraction: four M(π-γ) bins around M(W)

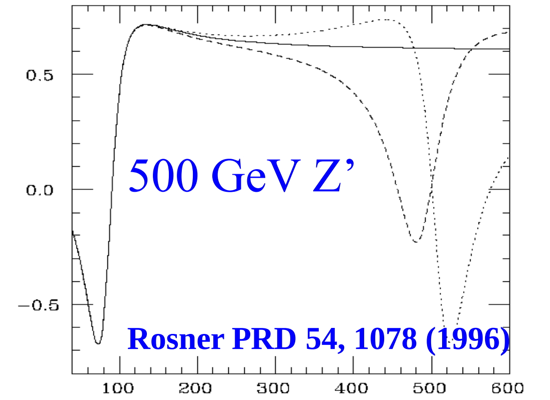
Background: sideband fit

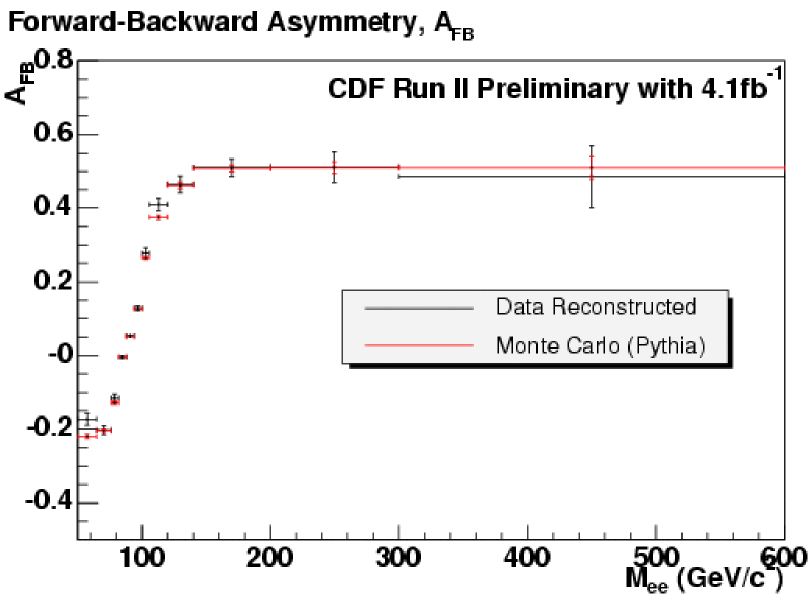


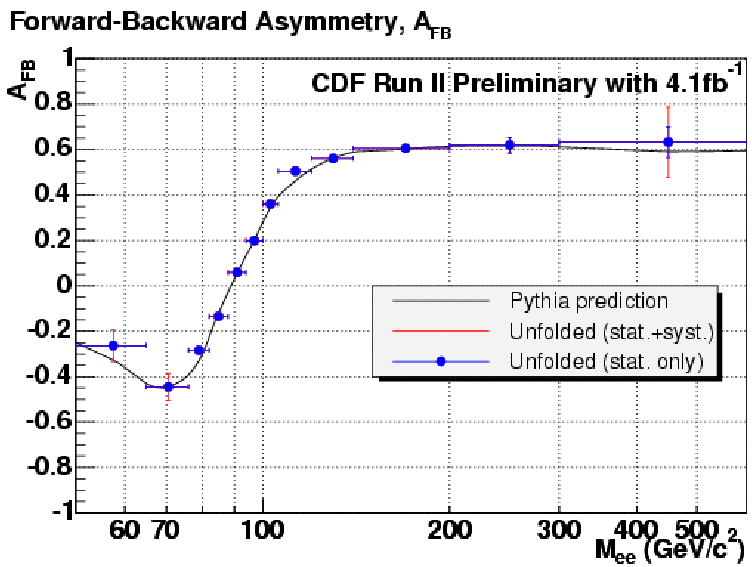
$BR(W\to\pi\gamma)/BR(W\to e\nu) < 6.4 \times 10^{-5}$ at 95% CL (best limit)

Z/γ*→ee Forward-Backward Asymmetry (CDF)

- Measure of relative strength between vector and V-A couplings and search for new physics (Z')
- Two high PT electrons (CC and CP topologies)
- M(Z/γ*) > 50 GeV
- Unfolded Afb compared with PYTHIA v6.216







Good agreement between data and theory

Summary

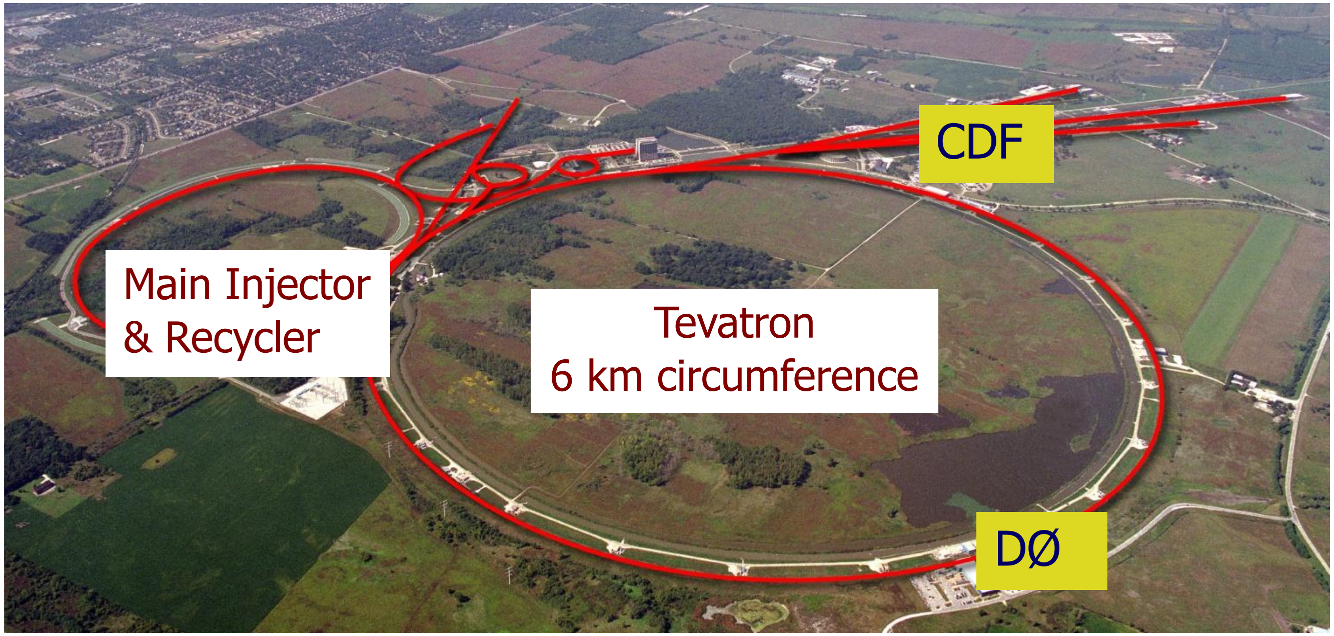
- Lots of interesting measurements of W/Z properties at the Tevatron, e.g.
  - improving experimental knowledge of the Standard Model (W width)
  - unique key to understanding electroweak symmetry breaking (W Mass)
  - powerful tools for constraining PDFs (W asymmetry, Z rapidity)
  - probes for new physics (rare decay searches, Afb)
- More data are being analyzed, expecting significant improvements in precision soon
- Theoretical uncertainties are becoming increasingly important, need more interaction with theorists
- Stay tuned for new results

Backup Slides Start Here

The Tevatron

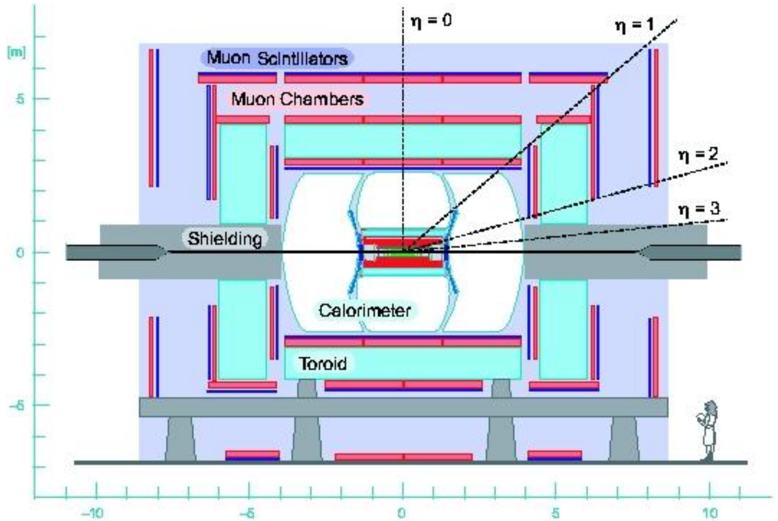
Proton-antiproton collisions with center-of-mass = 1.96 TeV

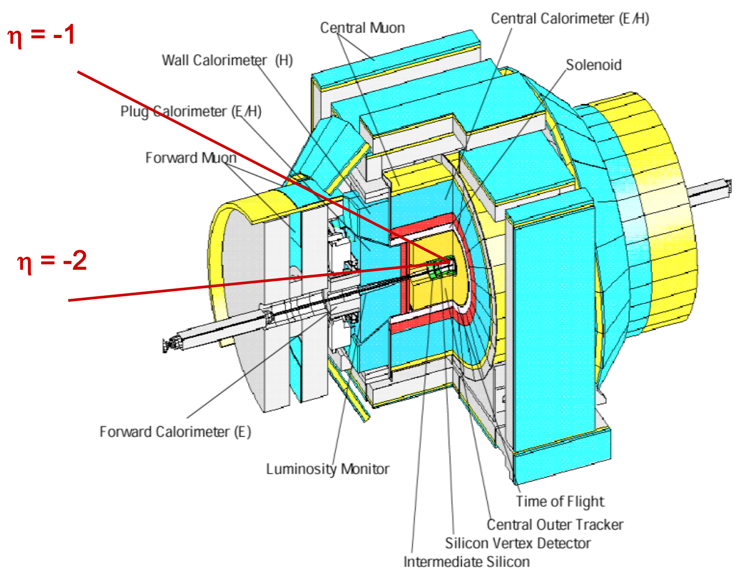
36 p and pbar bunches
396 ns between bunch crossing



Currently the only place in the world where W and Z bosons can be produced directly

Detectors





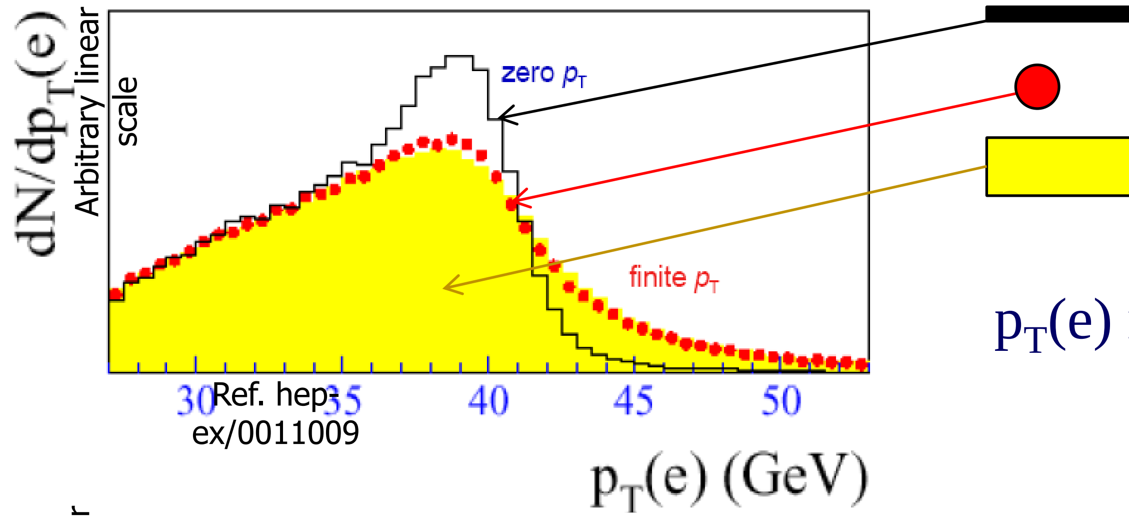
DZero Run II upgrades

- 2T solenoid
- inner tracking
- Preshower
- extended μ coverage
- and shielding
- Trigger, DAQ

CDF Run II upgrades

- Inner tracking
- Forward calorimeter
- extended μ coverage
- Trigger, DAQ

What Affects Observable Shapes

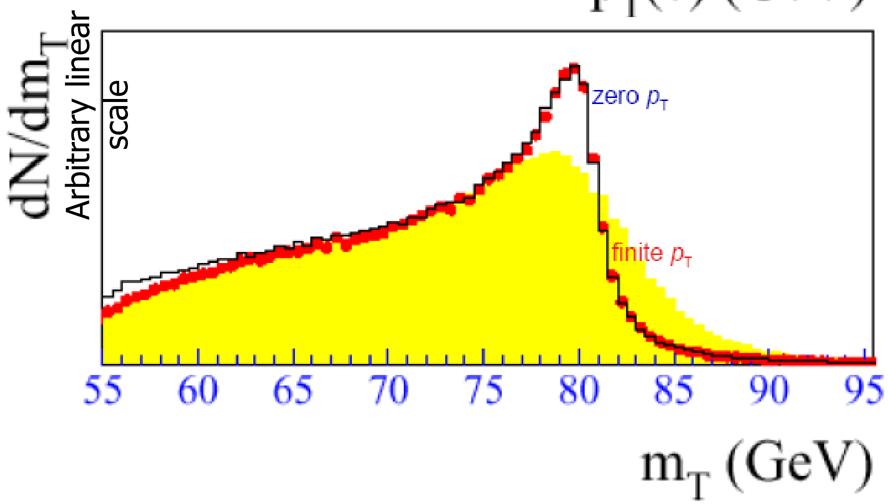


$P_T(W)=0$, no detector effects

$P_T(W)$ included

detector effects added

$p_T(e)$ most affected by $p_T(W)$



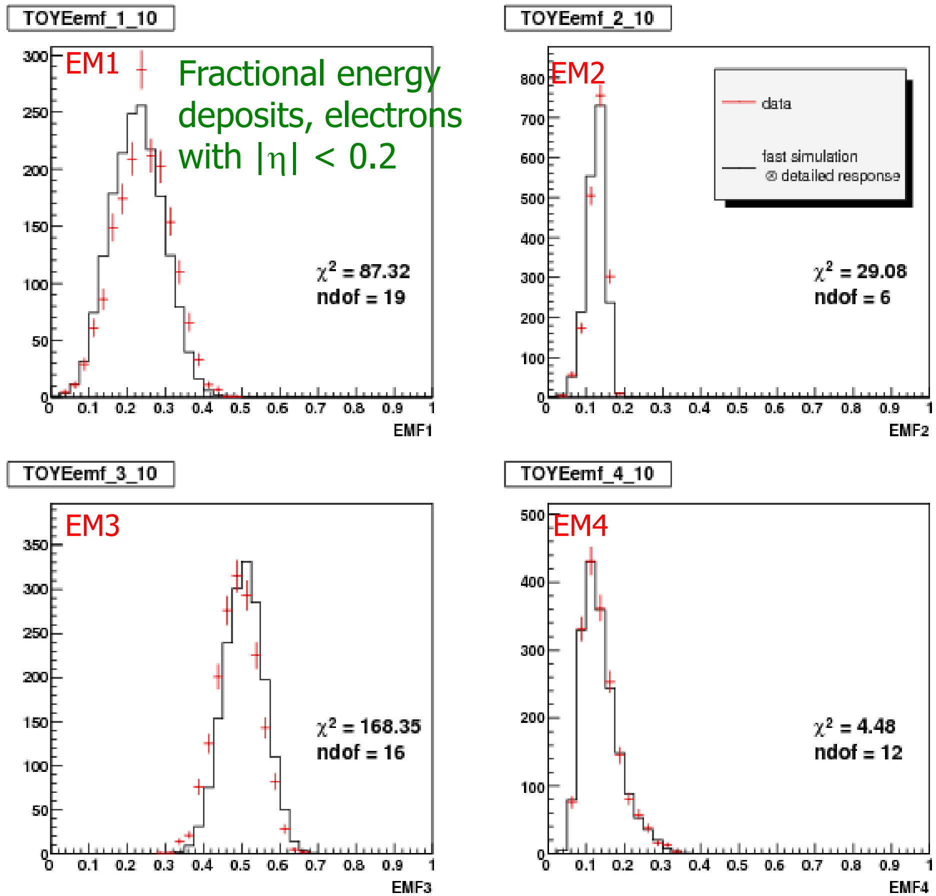
$$M_T = \sqrt{2E_T^l \not{E}_T (1 - \cos \Delta\phi)}$$

M_T most affected by measurement of missing transverse momentum

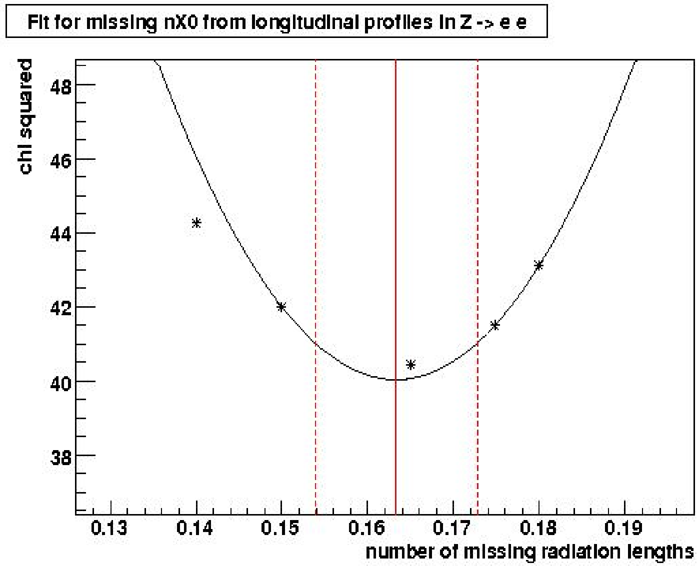
For W/Z production and decay both CDF and DØ use **ResBos (**Balazs, Yuan; Phys Rev D56, 5558,1997);
For photons CDF:**WGRAD** (Baur, Keller, Wackeroth PRD59, 013002 (1998)) ,
DØ: **Photos** (Barbiero, Was, Comp Phys Com 79, 291 (1994))

Before tuning of material model

Before tuning of material model:
distributions of fractional energy deposits
do not quite match between data and the simulation.



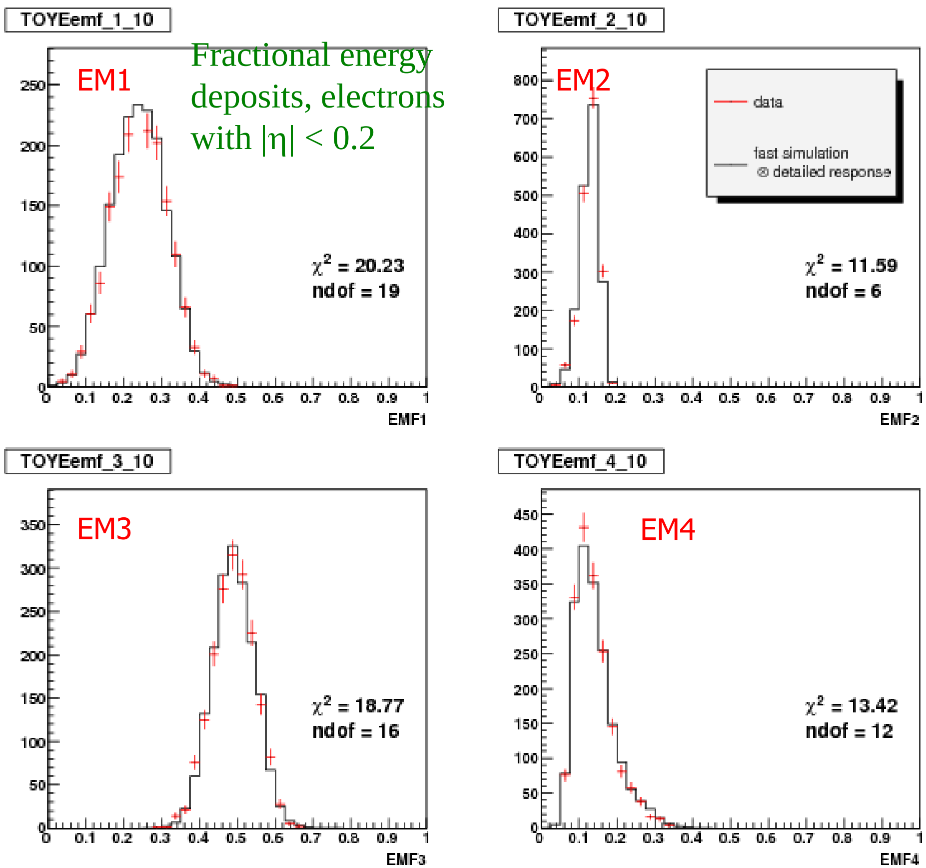
FIT



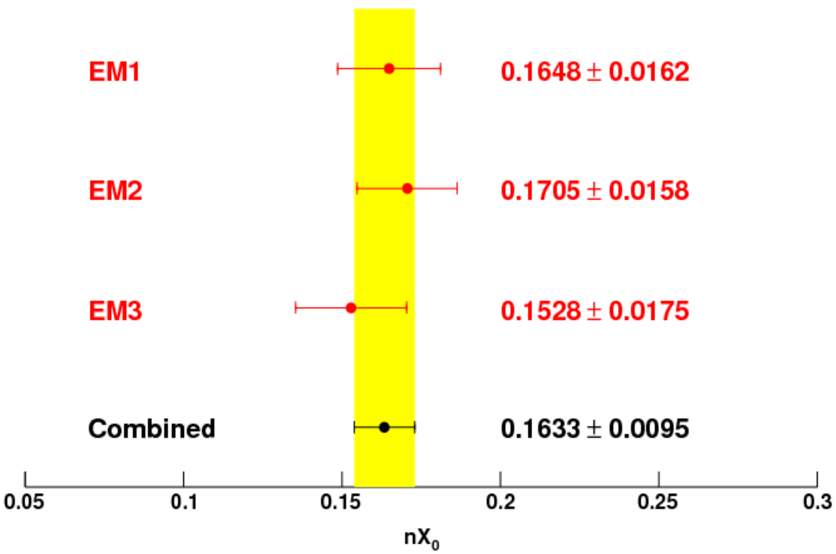
Amount of fudge material to within less than $0.01X_0$!
With comparatively small systematics from background (underlying event) subtraction and modeling of cut efficiencies.

After Tuning of Material Model

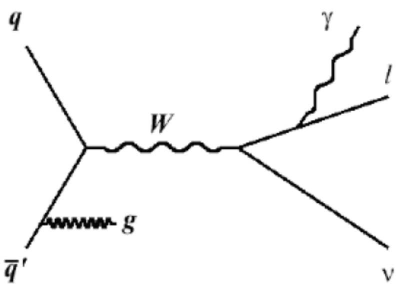
After tuning of material model:
distributions of fractional energy deposits
are very well described by the simulation.



As a cross-check:
Repeat fit for nX_0,
separately for each EM layer.
Good consistency is found.



Model of W production and decay



Tool	Process	QCD	EW
RESBOS	W,Z	NLO	-
WGRAD	W	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
ZGRAD	Z	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
PHOTOS			QED FSR, ≤ 2 photons

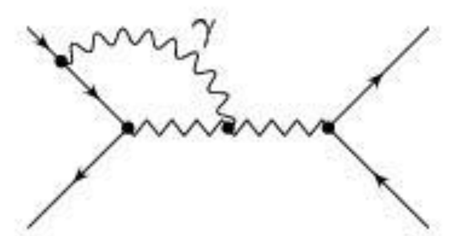
Our main generator is "**ResBos+Photos**". The NLO QCD in **ResBos** allows us to get a reasonable description of the p_T of the vector bosons. The two leading EWK effects are the first FSR photon and the second FSR photon. **Photos** gives us a reasonable model for both.

We use W/ZGRAD to get a feeling for the effect of the full EWK correctio

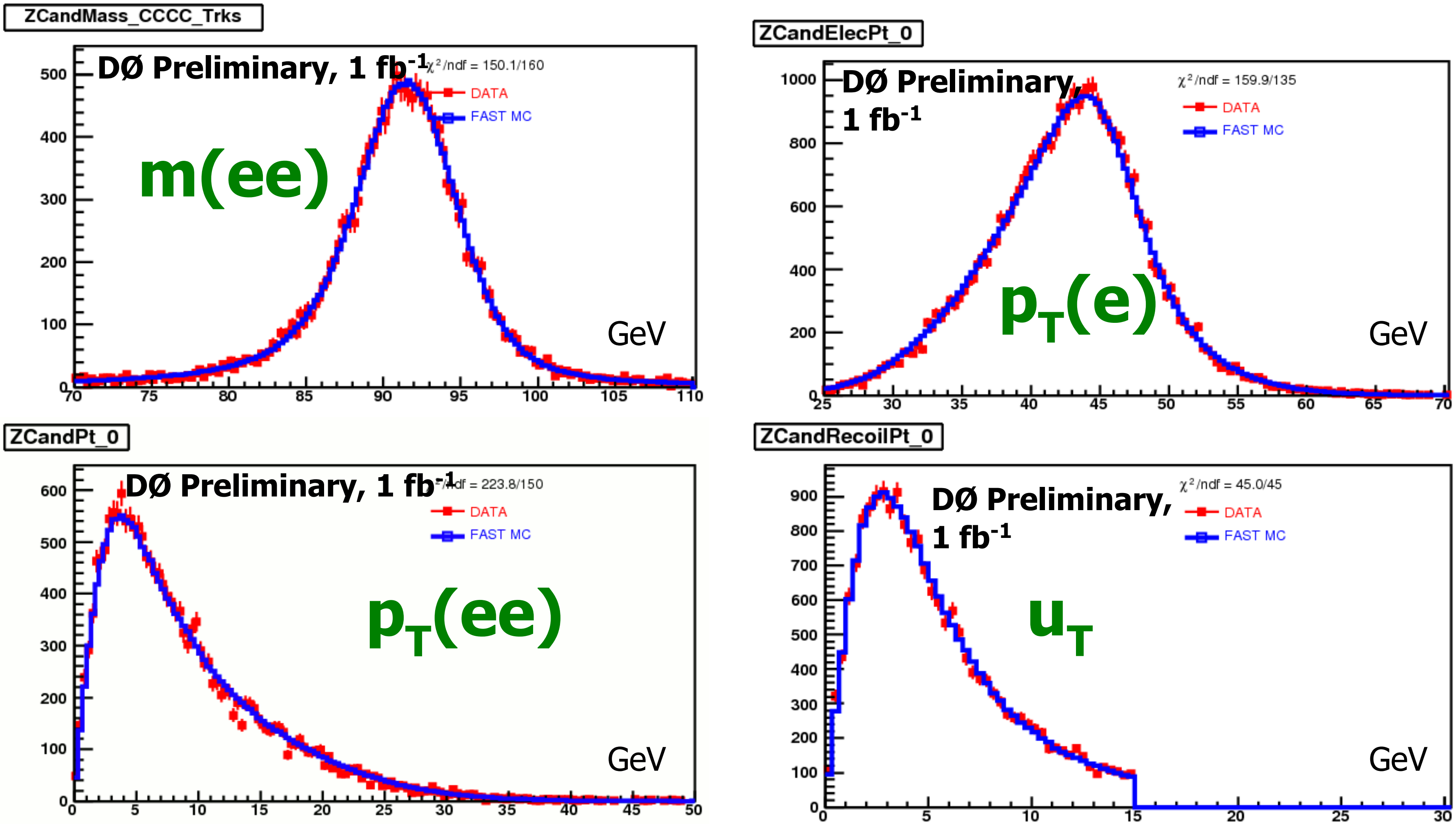
The final "QED" uncertainty we quote is **7/7/9 MeV (m_T,p_T,MET).**

This is the sum of different effects; the two main ones are:

- Effect of full EWK corrections, from comparison of W/ZGRAD in "FSR only" and in "full EWK" modes **(5/5/5 MeV).**
- Very simple estimate of "quality of FSR model", from comparison of W/ZGRAD in FSR-only mode vs **Photos** **(5/5/5 MeV).**



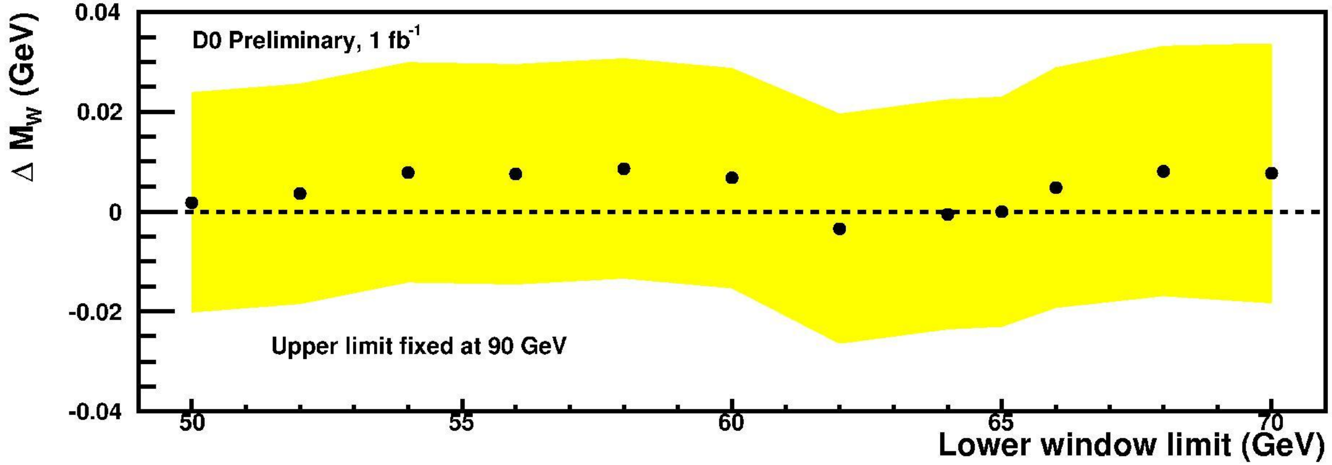
Results: Z → e e data

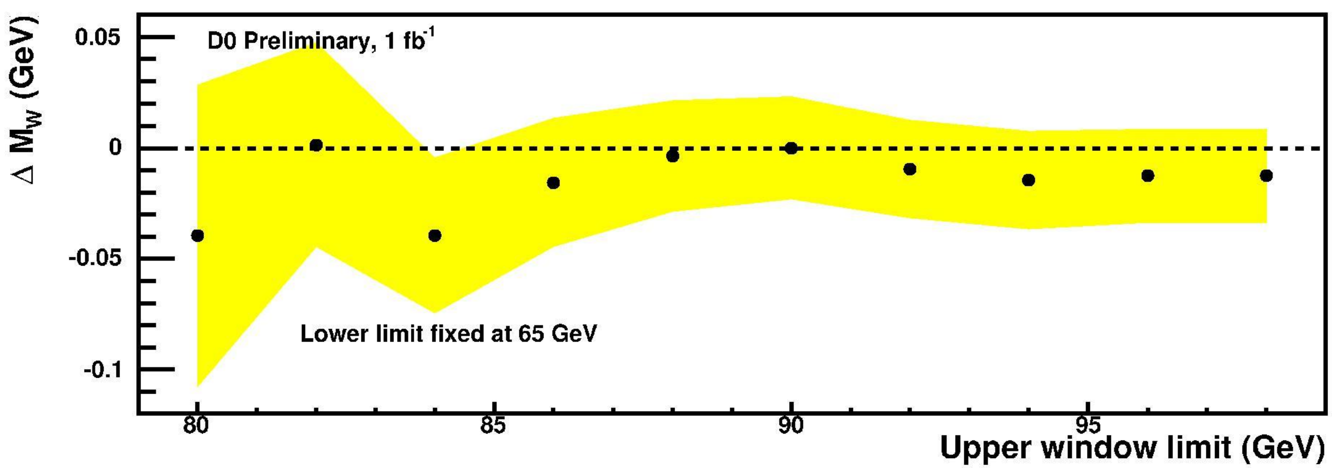


Good agreement between parameterized MC and collider data.

Stability checks

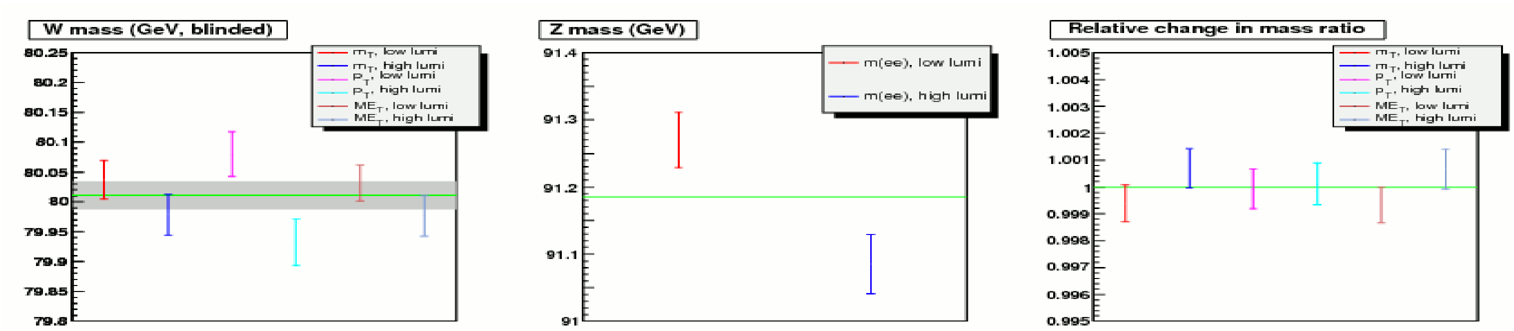
Changes in the fitted m_W when the fitting range (m_T observable) is varied



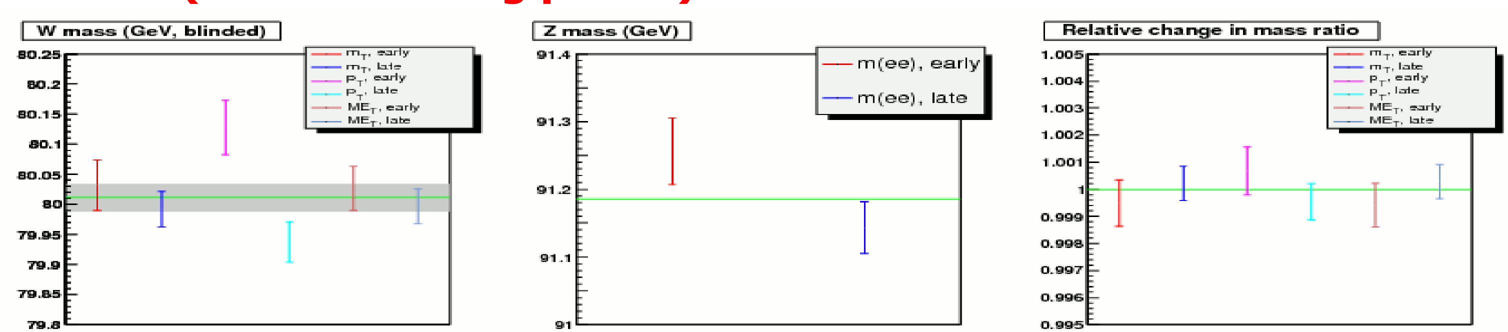


Stability checks

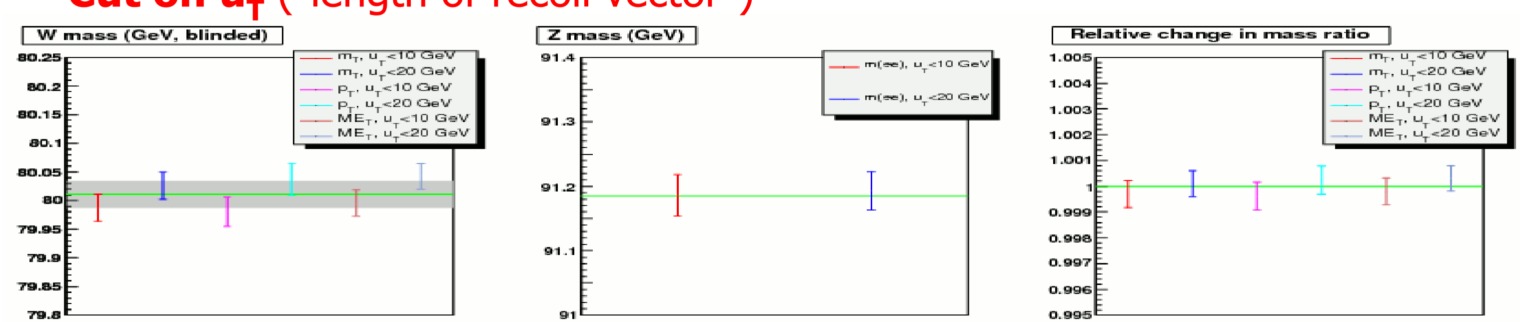
Instantaneous luminosity (split data into two subsets – high and low inst. luminosity)



Time (i.e. data-taking period)



Cut on u_T ("length of recoil vector")



Sorry, plots still in terms of blinded mass, but it does not matter here.

Main Differences between CDF and DØ M(W) Analyses

	CDF	DØ
Luminosity	0.2 fb^{-1}	1.0 fb^{-1}
W Decay Channels	electron, muon	electron
Lepton Energy Scale	tracker information	Z->ee calorimeter data
Interpretation	absolute M(W)	M(W)/M(Z) ratio
MC Closure Test		full analysis performed first on Monte Carlo
Beyond M(W)	$M(W^+)$ and $M(W^-)$ comparison (intriguing!)	

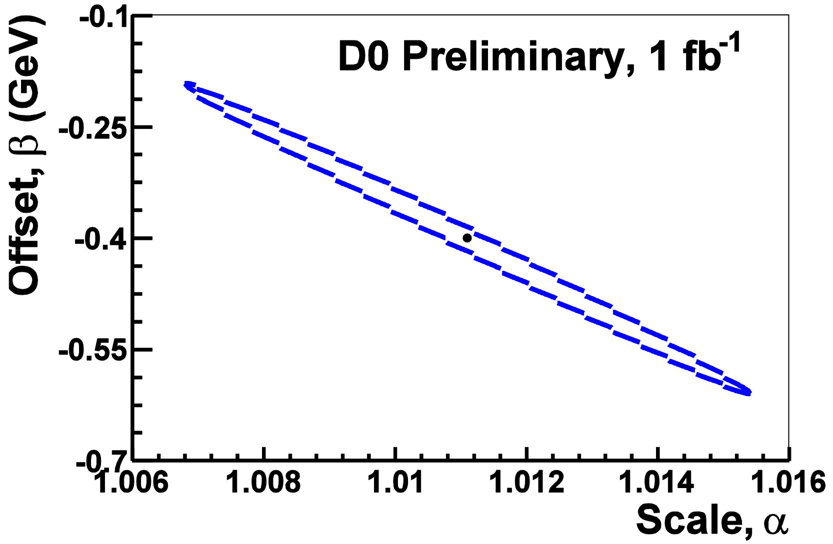
Final M(W) Calibration

- Linear response model : E_measured(e) = **α** × E_true(e) + **β**
  α → scale **β** → offset
- Use Z->ee electrons to constrain **α** and **β** (precision limited by statistics)
- Calibrate to M(Z) measured by LEP with 2 MeV precision
- Two observables to fit the data
  - Z->ee invariant mass
  - f_Z variable "scans" the response as a function of energy

$$f_Z = (E(e1)+E(e2))(1-\cos(\gamma_{ee}))/m_Z$$

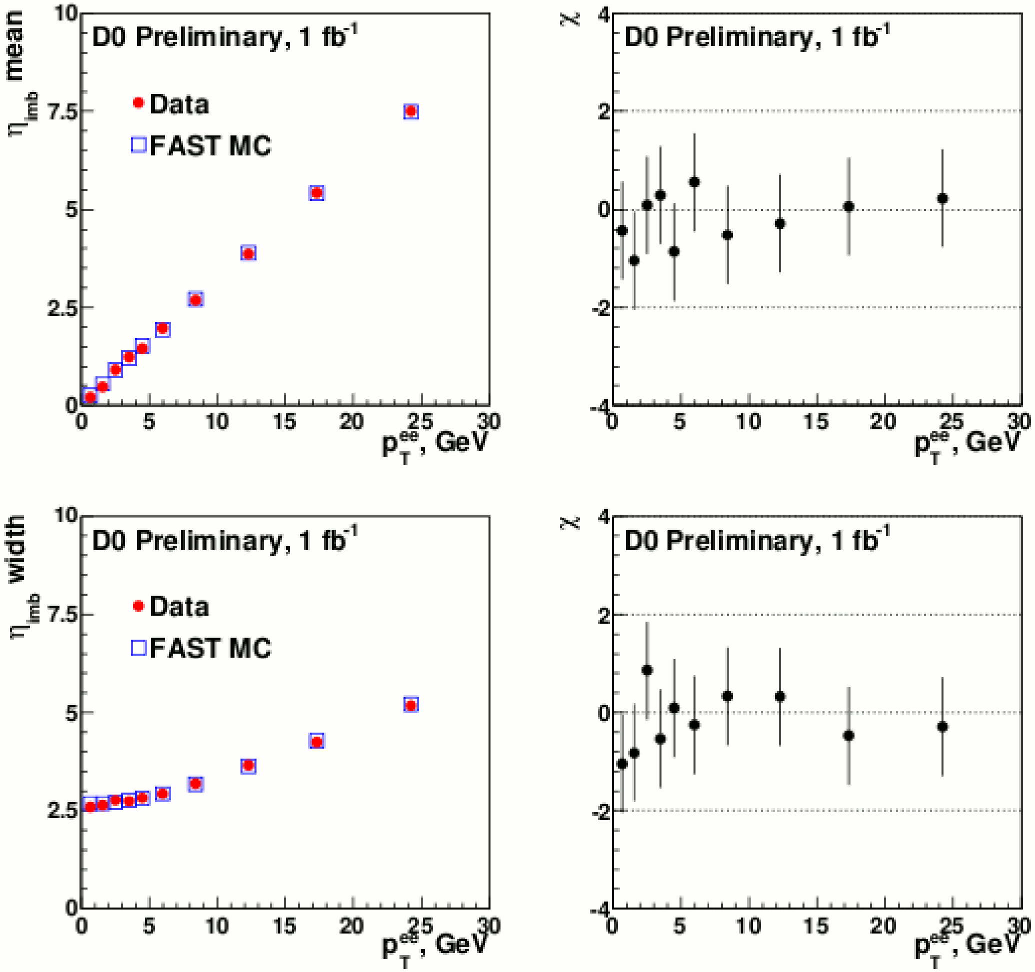
α = 1.0111 ± 0.0043
β = -0.404 ± 0.209 GeV
correlation = -0.997

⇒ dominant systematic error, 100 % correlated between three observables



Recoil calibration

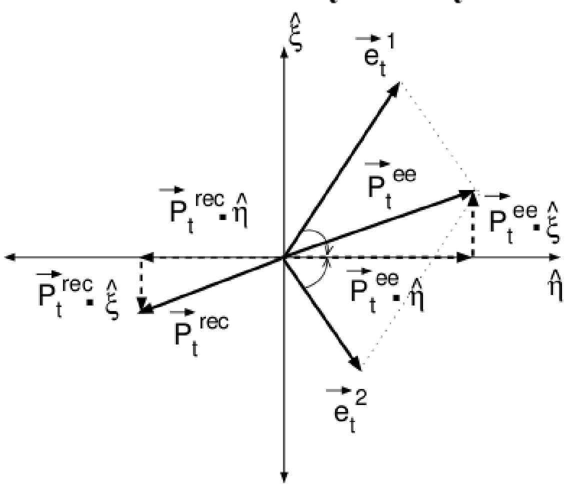
Final adjustment of free parameters in the recoil model is done *in situ* using balancing in Z → e e events and the standard **UA2 observables:**



in the transverse plane, use a coordinate system defined by the bisector of the two electron momenta.

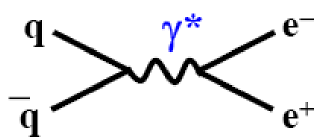
η-imbalance : $(\vec{P}_t^{ee} + \vec{P}_t^{rec}) \cdot \hat{\eta}$

ξ-imbalance : $(\vec{P}_t^{ee} + \vec{P}_t^{rec}) \cdot \hat{\xi}$

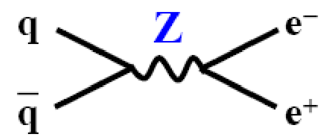


Z/γ* Forward-Backward asymmetry

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

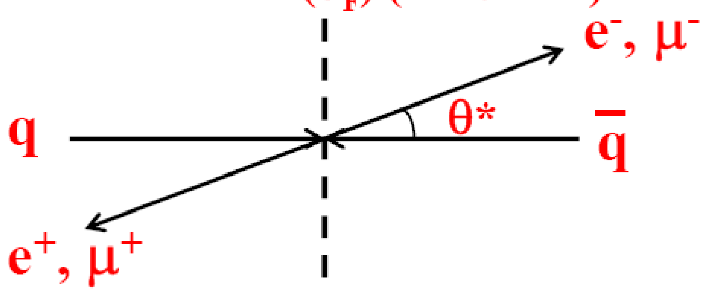


Vector coupling

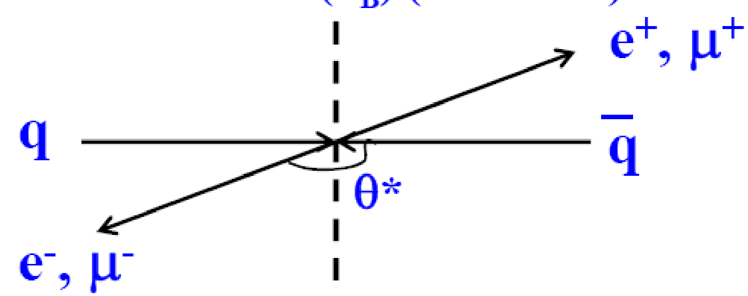


Vector & axial-vector coupling

FORWARD (σ_F) ($\cos\theta^* > 0$)



BACKWARD (σ_B) ($\cos\theta^* < 0$)



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

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