

# Precision Measurement of the W Boson Mass with CDF



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*Les Rencontres de Physique  
de la Vallée d'Aoste  
March 7, 2007*



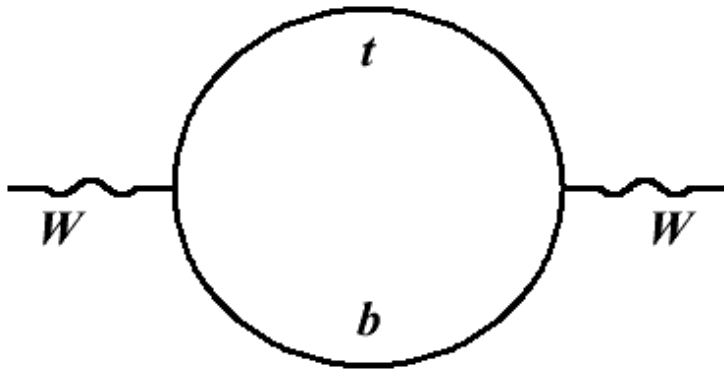
# W Boson Mass

Given precise measurements of  $m_Z$  and  $\alpha_{EM}(m_Z)$ , we can predict  $m_W$ :

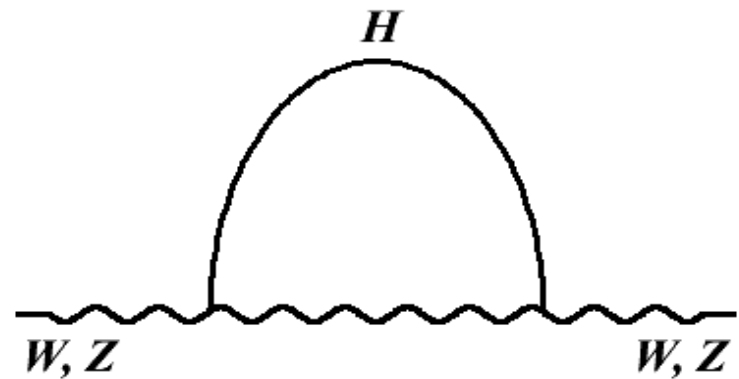
$$m_W^2 = \frac{\pi\alpha_{EM}}{\sqrt{2}G_F (1 - m_W^2/m_Z^2)(1 - \Delta r)}$$

(“on-shell scheme”)

$\Delta r$ : O(3%) radiative corrections dominated by  $tb$  and Higgs loops



$$\Delta m_W \propto m_t^2$$



$$\Delta m_W \propto \ln(m_H/m_Z)$$

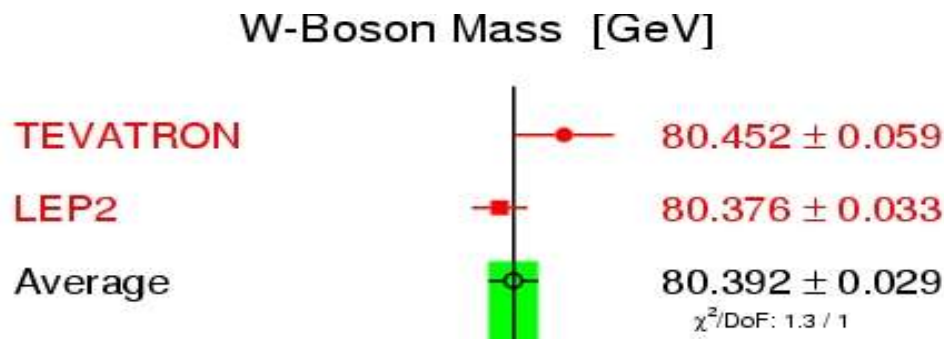
# W Mass Prediction and Measurement

*W mass uncertainty from input parameters:*

Next talk

Parameter Shift	$m_W$ Shift (MeV/c <sup>2</sup> )
$\Delta m_H = +100 \text{ GeV}/c^2$	-41.3
$\Delta m_t = +2.1 \text{ GeV}/c^2$	12.8
$\Delta m_Z = +2.1 \text{ MeV}/c^2$	2.6
$\Delta \alpha_{EM} = +0.00013$	-2.3

## *Direct W mass measurement*



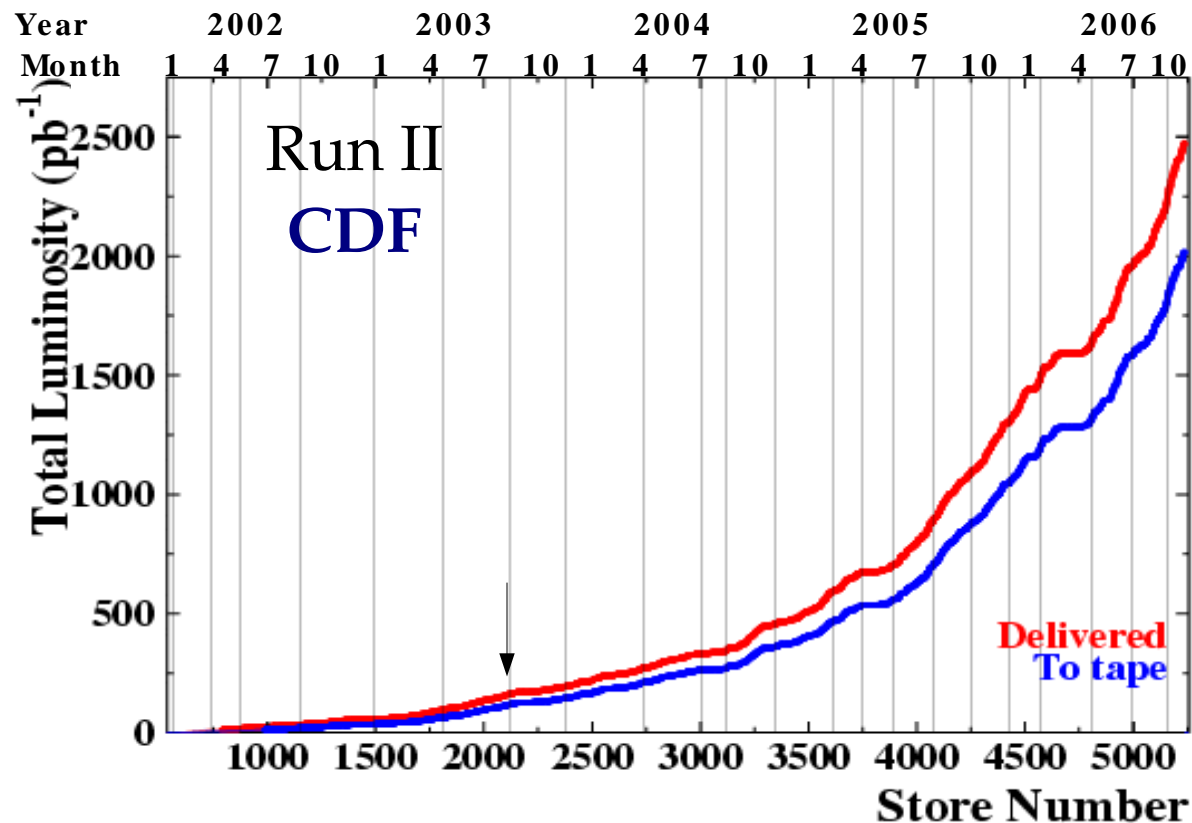
*W mass predicted much more precisely (13 MeV) than measured (29 MeV)*

Need to reduce  $\delta m_W$  to further constrain  $m_H$  and other new physics

# Tevatron Run II

Each experiment has collected  $>2 \text{ fb}^{-1}$  of 1.96 TeV  $\sqrt{s}$   $p\bar{p}$  collisions

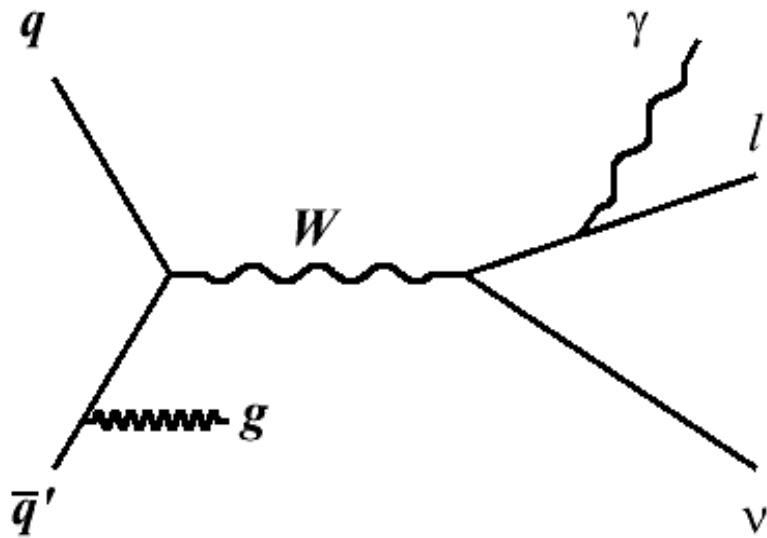
Current Run II:  $>15\times$  Run I data set



*First Run II  $W$  mass measurement  
uses  $200 \text{ pb}^{-1}$  of CDF data*

# W & Z Boson Production and Decay

*Dominant production mechanism:  $q\bar{q}^{(\prime)}$  annihilation*



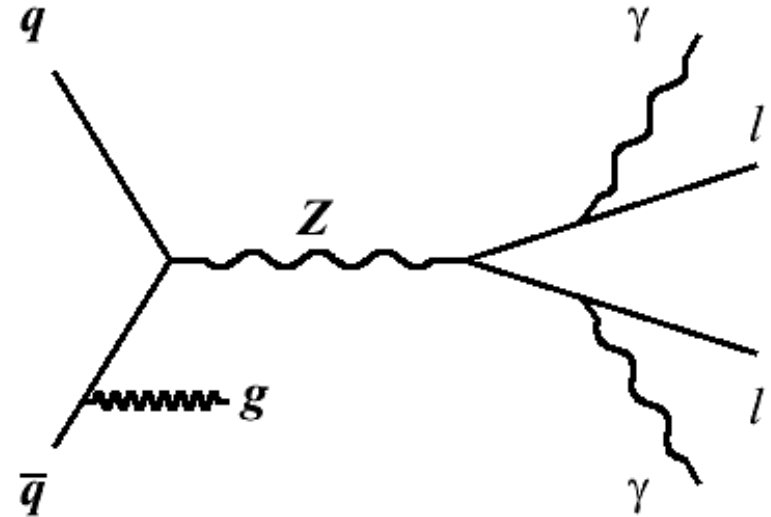
$$\sigma(W \rightarrow l\nu) = 2775 \text{ pb}$$

After event selection

$(l, \nu E_T > 30 \text{ GeV})$ :

51,128  $W \rightarrow \mu\nu$  candidates

63,964  $W \rightarrow e\nu$  candidates



$$\sigma(Z \rightarrow ll) = 254.9 \text{ pb}$$

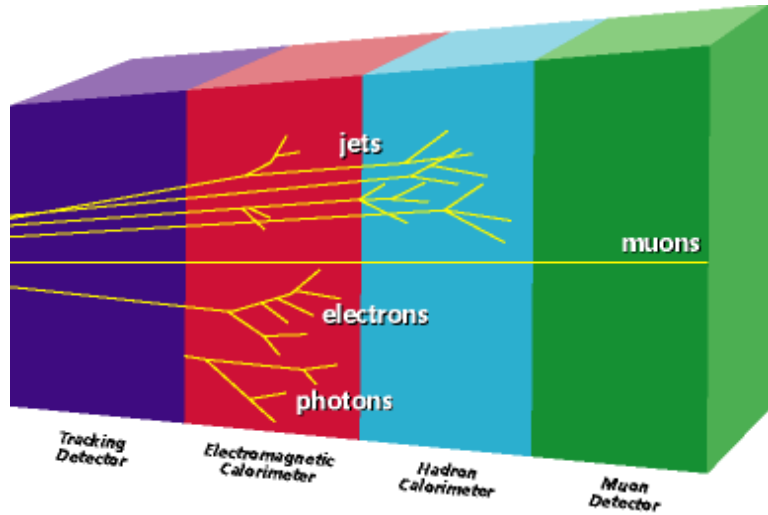
After event selection

$(l E_T > 30 \text{ GeV})$ :

4,960  $Z \rightarrow \mu\mu$  candidates

2,919  $Z \rightarrow ee$  candidates

# CDF Detector



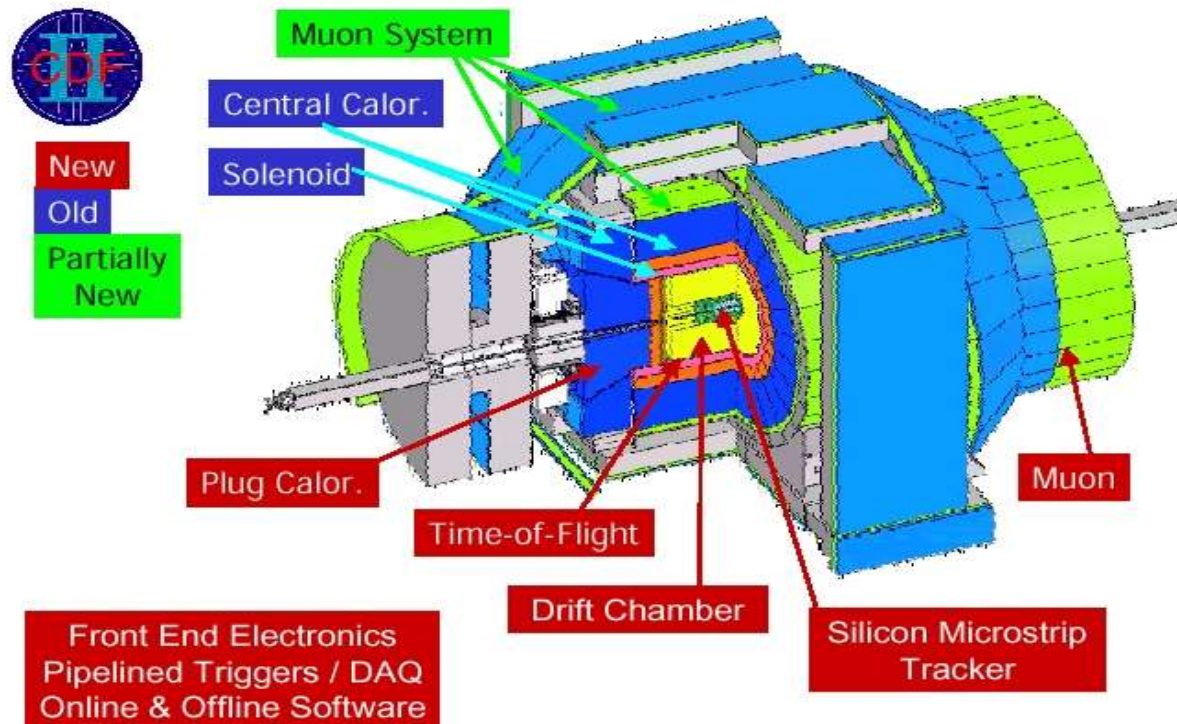
*High-precision tracking drift chamber*

$$\delta p_T/p_T = 0.05\% p_T : 2\% \text{ for } 40 \text{ GeV } \mu$$

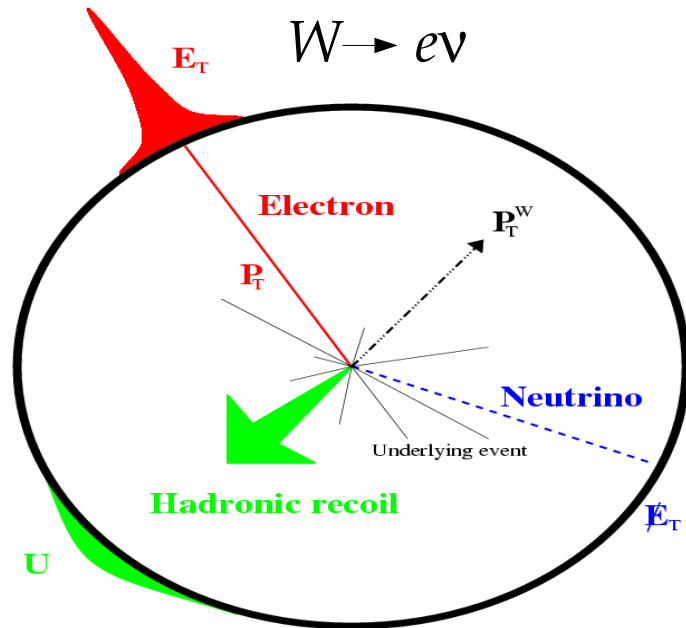
*High-precision electromagnetic calorimeter*

$$\delta E_T/E_T = 13.5\%/\sqrt{E_T} \oplus 1.7\%:$$

3% for 40 GeV  $e$



# Measurement Strategy



Calibrate  $l^\pm$  track momentum with mass measurements of  $J/\psi$  and  $Y$  decays to  $\mu$

Calibrate calorimeter energy using track momentum of  $e$  from  $W$  decays

*Cross-check with  $Z$  mass measurement, then add  $Z$ 's as a calibration point*

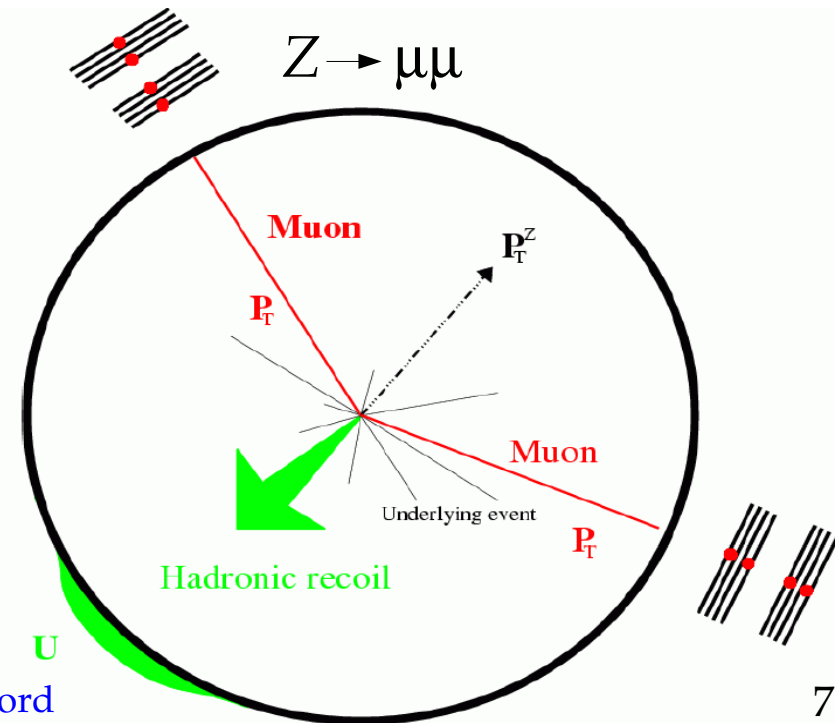
Calibrate recoil measurement with  $Z$  decays to  $e, \mu$

*Cross-check with  $W$  recoil distributions*

Combine information into transverse mass:

$$m_T = \sqrt{E_T \cancel{E}_T (1 - \cos\Delta\phi)}$$

*Statistically most powerful quantity for  $m_W$  fit*



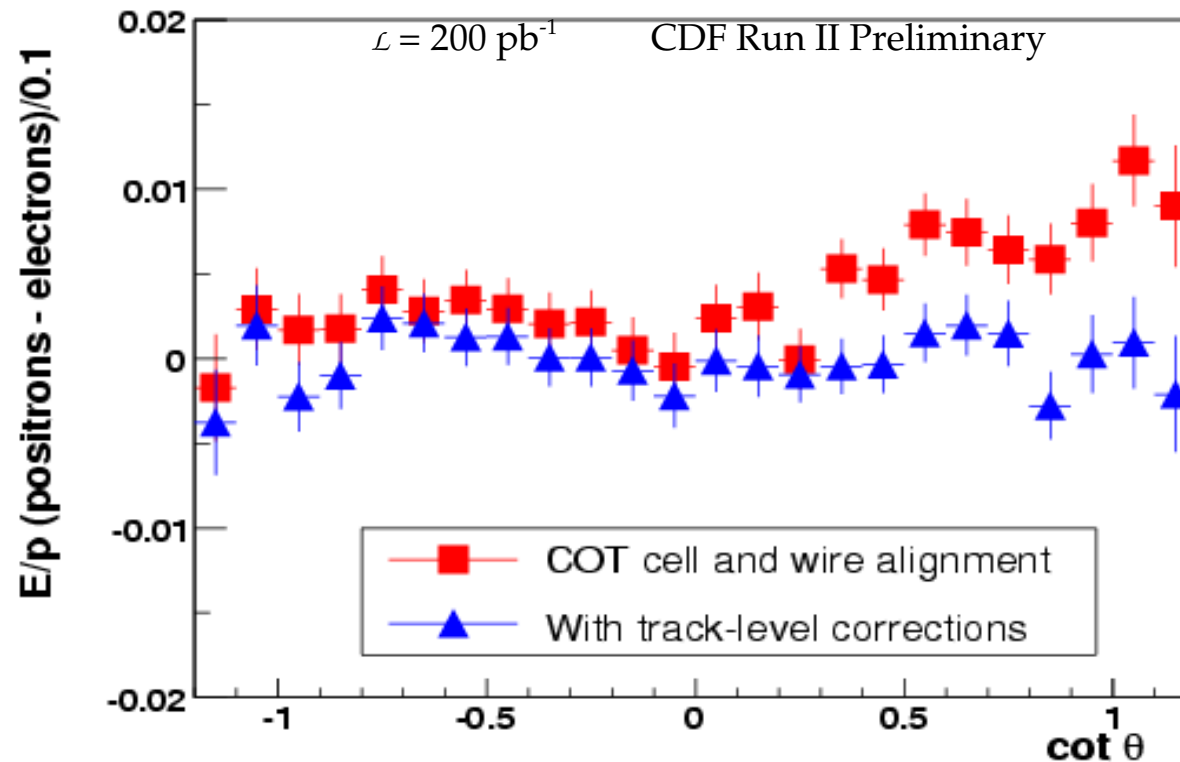
# Alignment and Corrections

Align tracker using cosmic-ray data

Determine track-level corrections from electron-positron differences

Use ratio of calorimeter energy to track momentum

*Curvature biases affect  $e^+$ ,  $e^-$  differently, but calorimeter measurement independent of charge*



Statistical uncertainty of track-level corrections leads to  $\delta m_w = 6 \text{ MeV}$

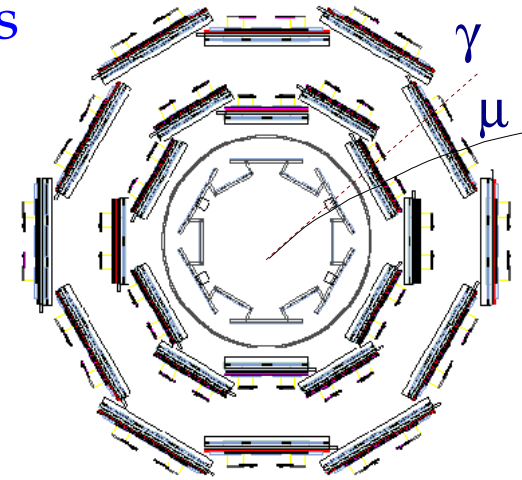


# Mass Measurements

Template mass fits to  $J/\psi$ ,  $Y$ ,  $Z$  resonances in muon decay channels

Fast detector simulation models relevant physical processes

*internal bremsstrahlung*  
*ionization energy loss*  
*multiple scattering*



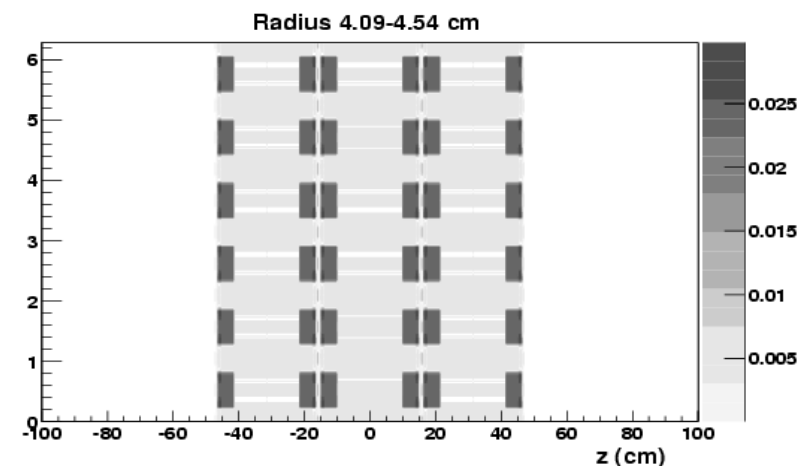
Simulation includes event reconstruction and selection

Detector material model

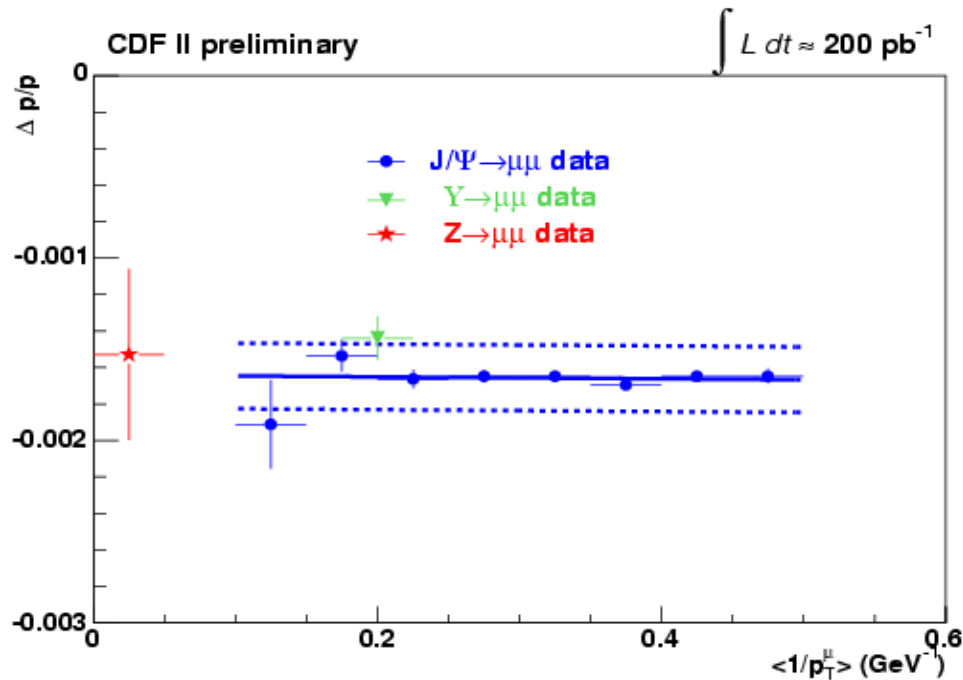
*Map energy loss and radiation lengths in each*  
*detector layer*

One material parameter determined from data:

*Overall material scale*



# Momentum Scale Calibration



606,701  $J/\psi \rightarrow \mu\mu$  candidates

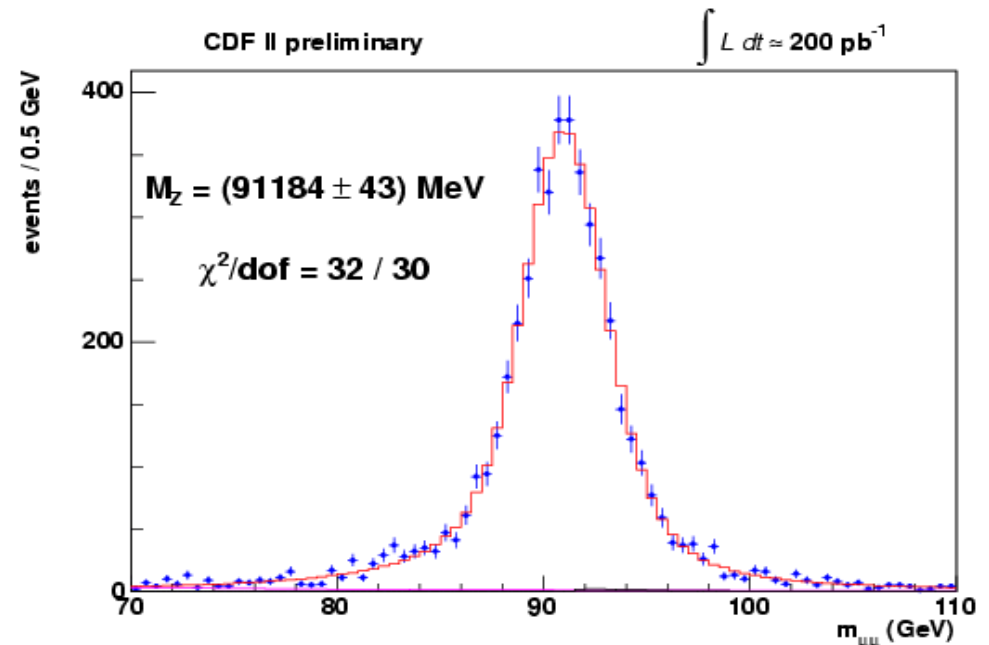
Fit mass as a function of mean inverse  $p_T$

Slope affected by energy loss modelling  
*Scale detector material by 0.94 to remove slope*

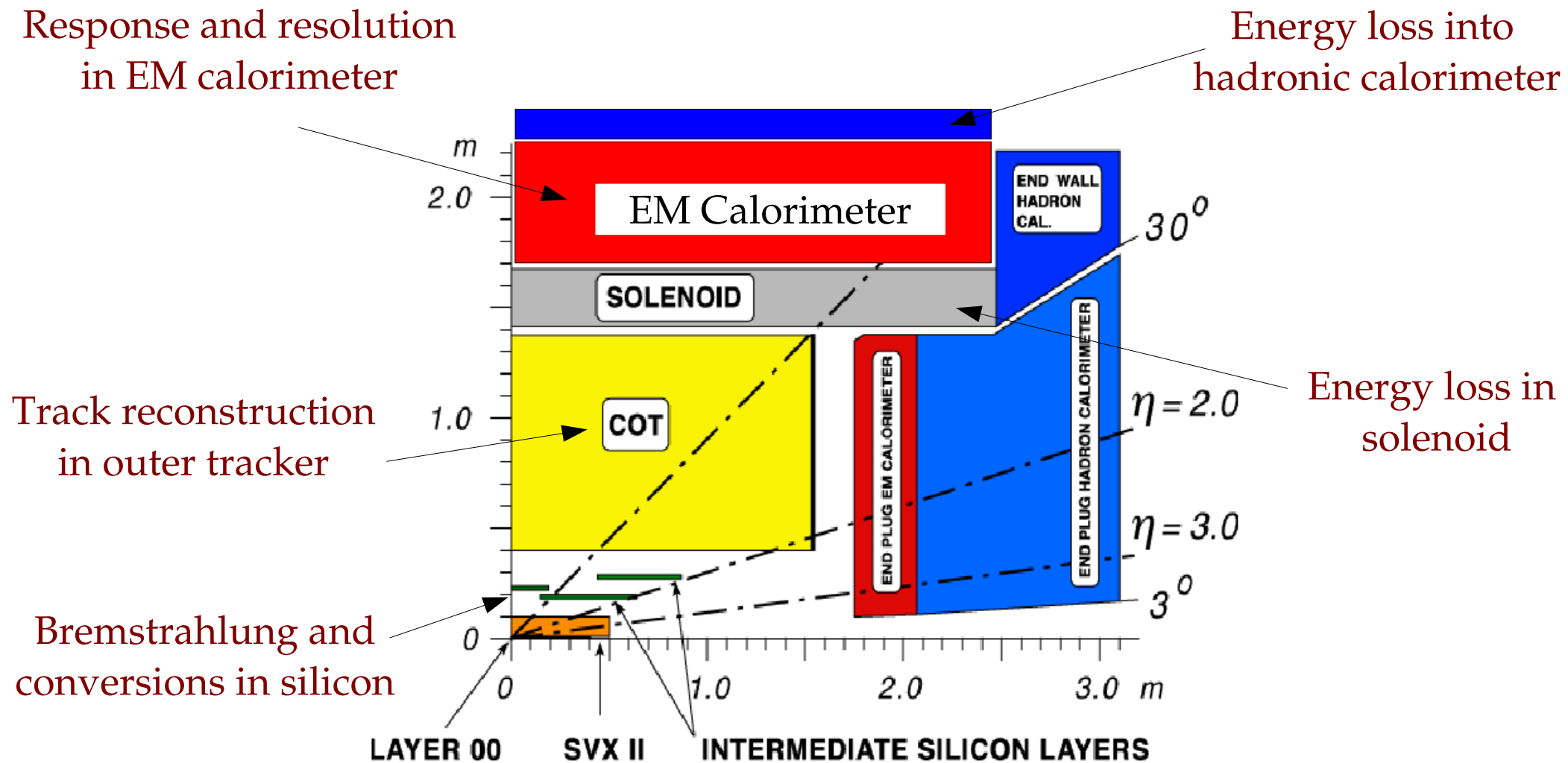
Use calibrated momentum scale to  
measure  $Z$  mass

Constrain tracks to originate from  
the beam line

*Improves resolution by a factor of  $\approx 3$*



# Full Electron Simulation

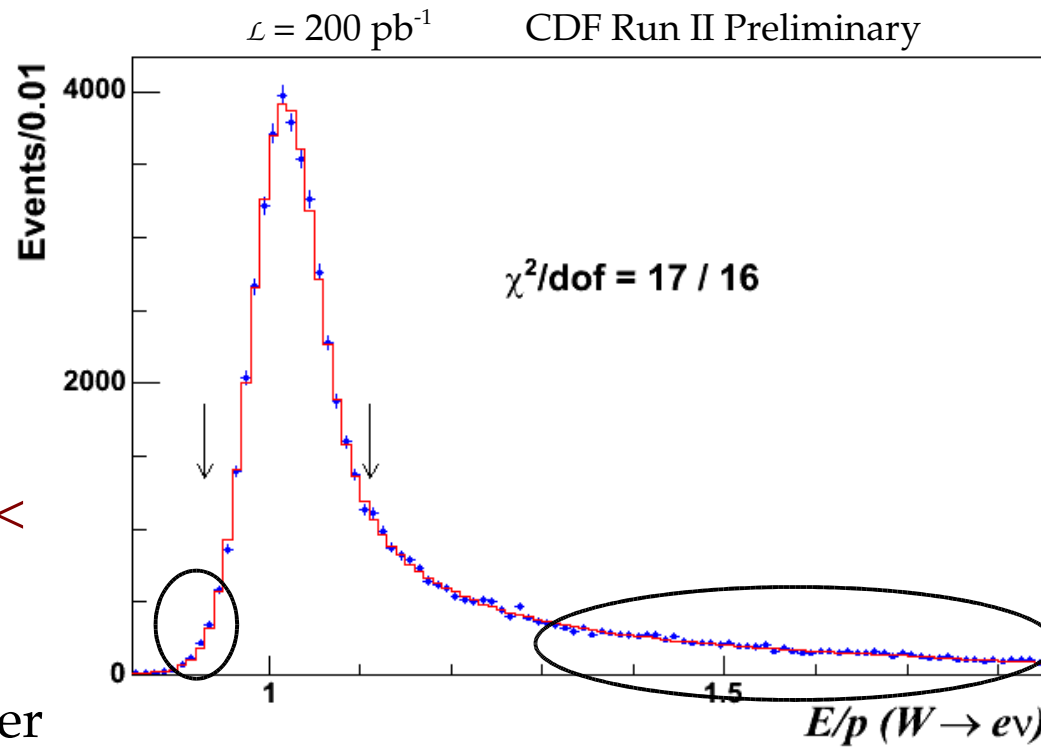


# Energy Scale Calibration

Calibrate calorimeter energy with peak of  $W$  electron  $E/p$  distribution

One free parameter for  $X_0$  scale (set with high  $E/p$  region)

Material scale:  $1.004 \pm 0.009$



*Calorimeter Energy <  
Track Momentum:*  
Energy loss in  
hadronic calorimeter

*Calorimeter Energy >  
Track Momentum:*  
Energy loss in tracker

**Energy scale uncertainty: 0.034%**

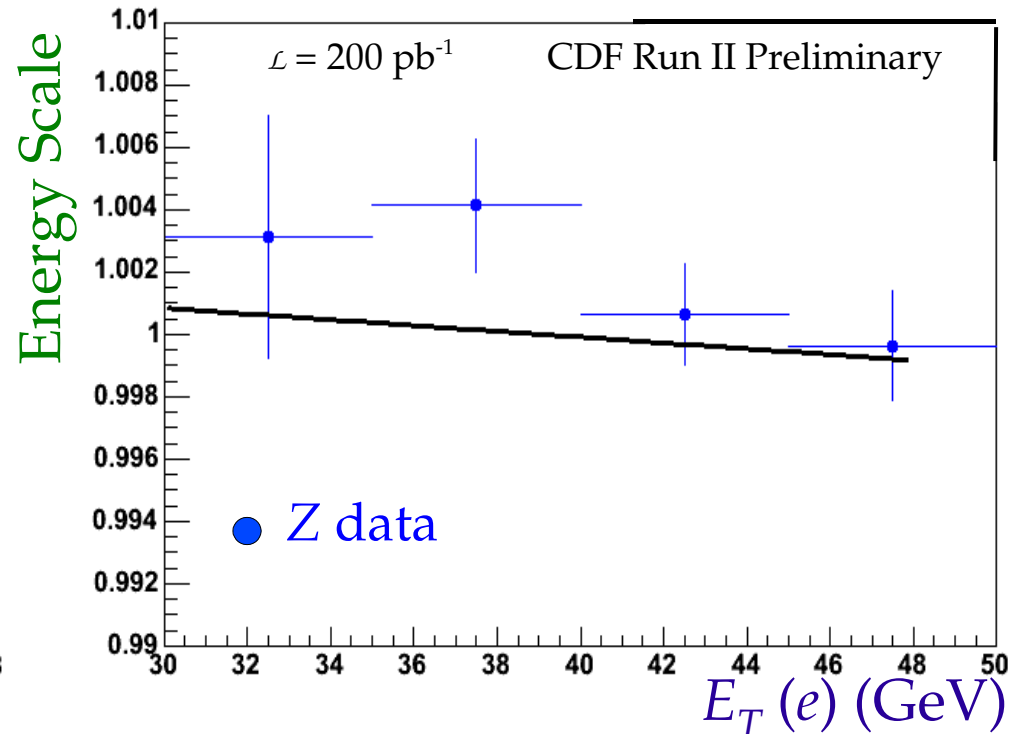
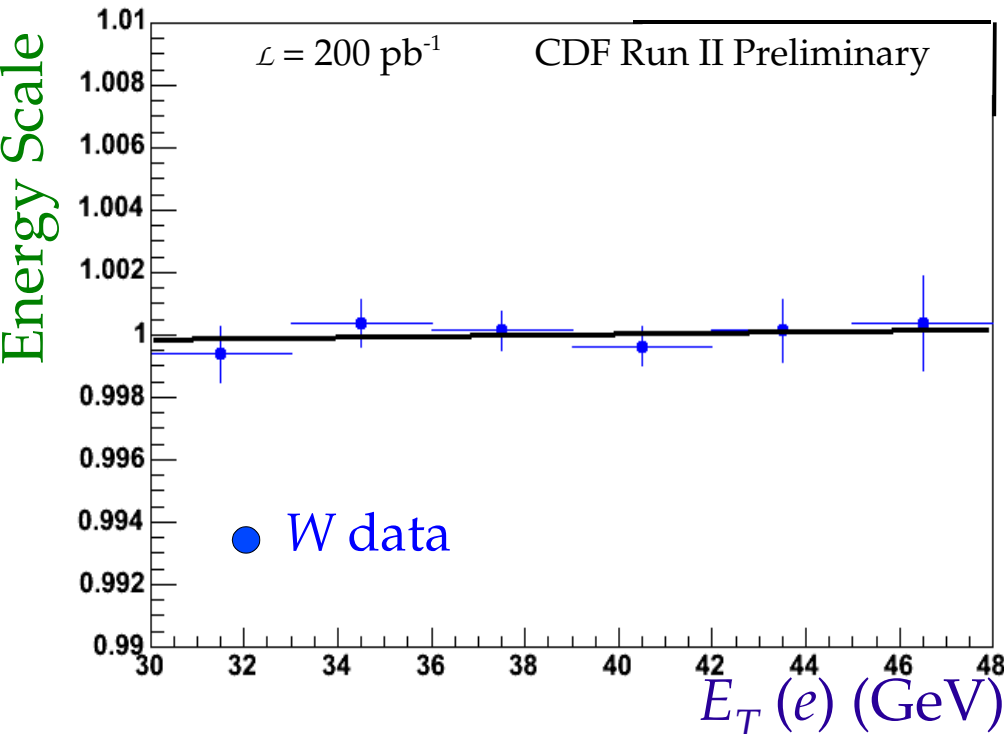
# Scale Energy Dependence

Apply energy-dependent scale to each simulated electron and photon

Determine energy dependence from  $E/p$  fits as functions of electron  $E_T$

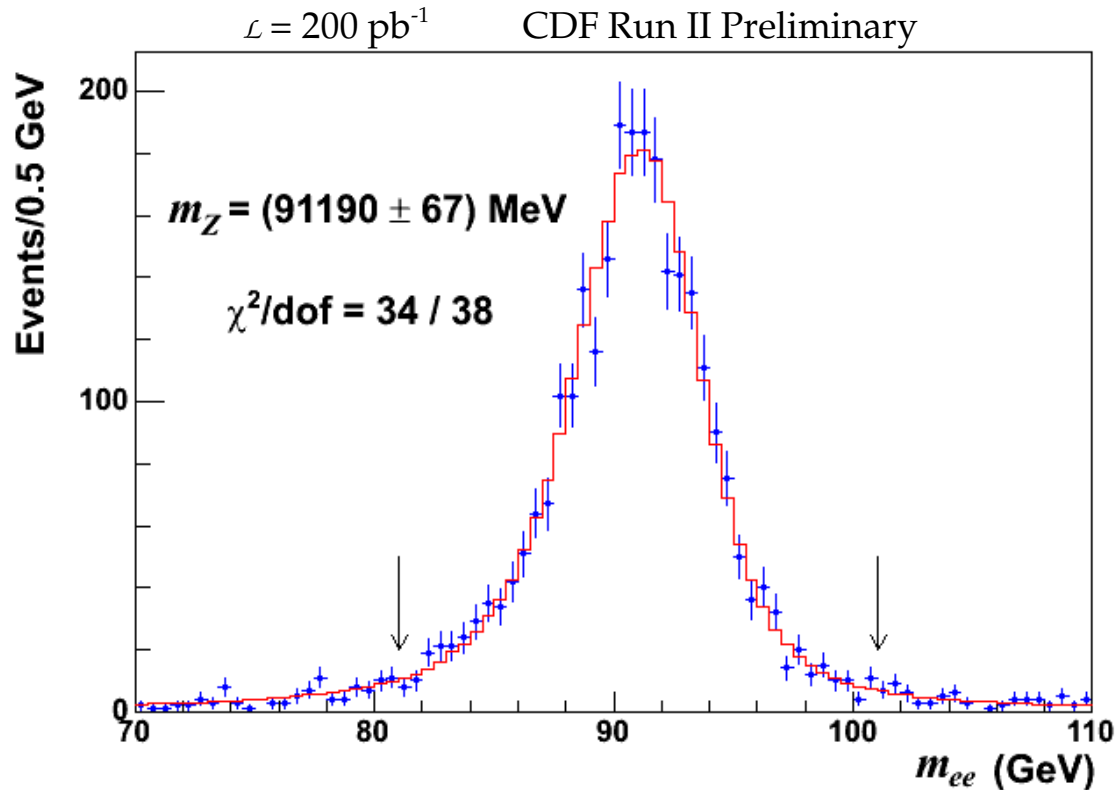
$$\text{Scale: } 1 + (6 \pm 7) \times 10^{-5} [E_T/\text{GeV} - 39] \quad (\delta m_W = 23 \text{ MeV})$$

*Most energy dependence implicitly accounted for by detector model*



# Z Mass Measurement

*Fit Z mass using scale from  $E/p$  calibration*



Measured value consistent with world average value (91188 MeV)  
*Incorporate mass fit into calibration to reduce scale uncertainty*

$$\delta m_W = 30 \text{ MeV}$$

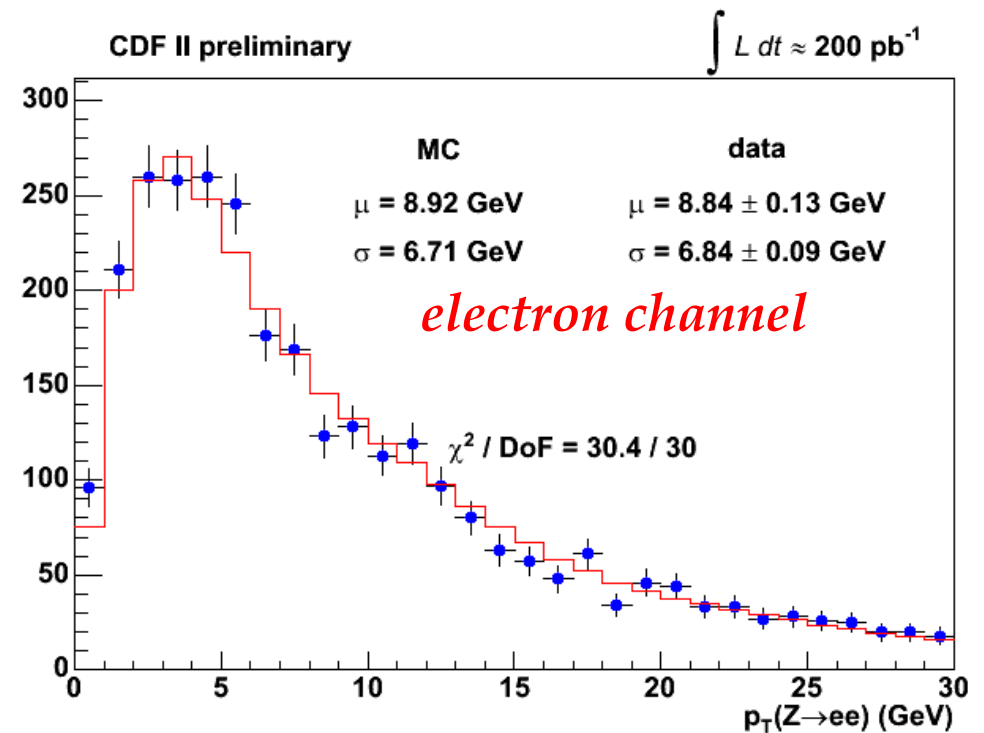
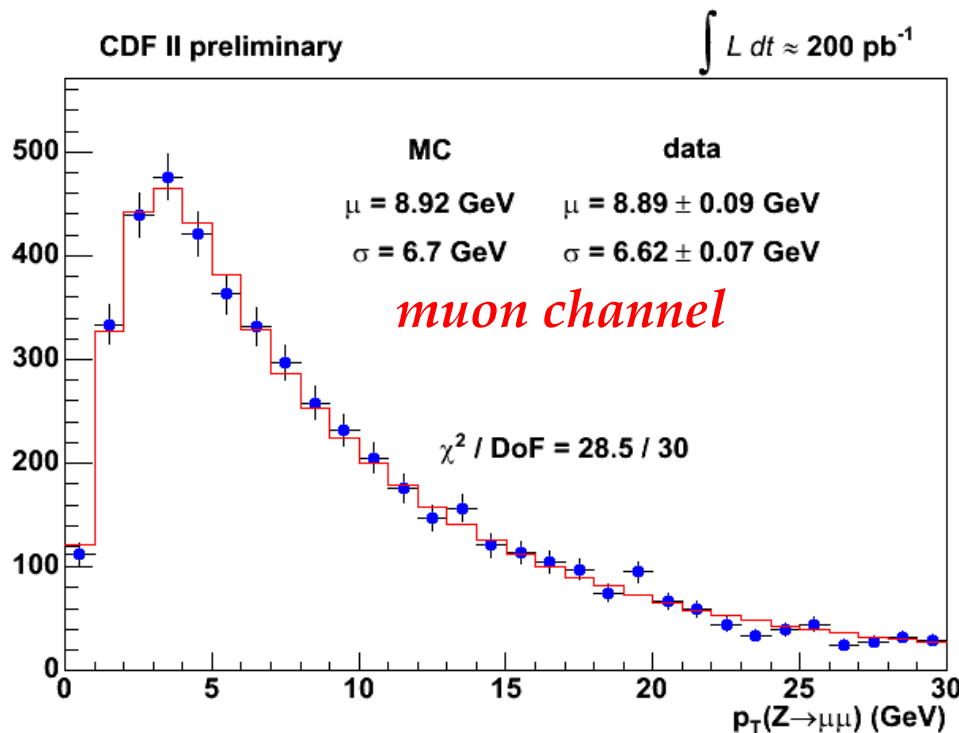
# Boson $p_T$ Model

Model boson  $p_T$  using RESBOS generator with tunable non-perturbative parameters

“ $g_2$ ” parameter determines position of peak in  $p_T$  distribution

Measure  $g_2$  with Z boson data (other parameters have negligible effect on W mass)

$$g_2 = 0.685 \pm 0.048: \delta m_W = 3 \text{ MeV}$$

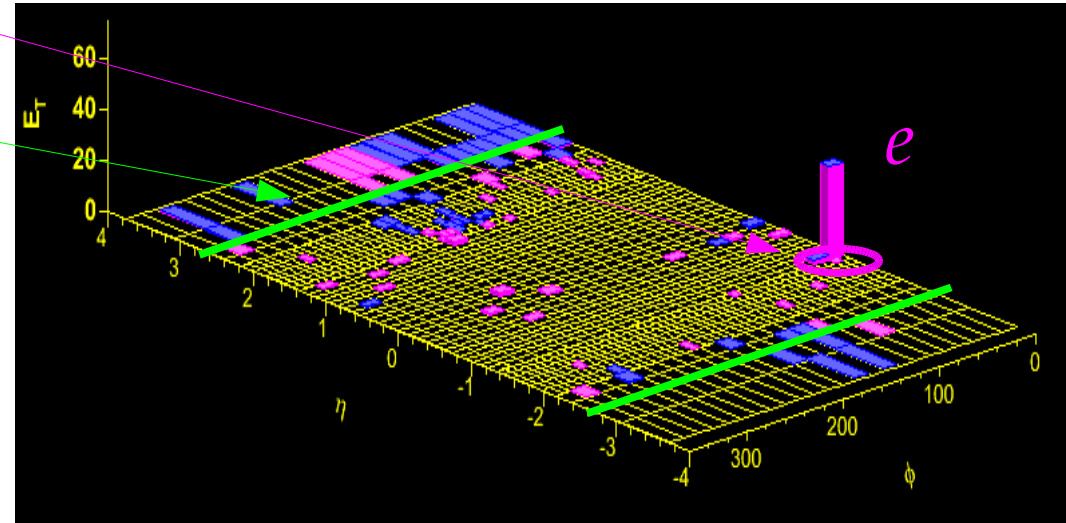
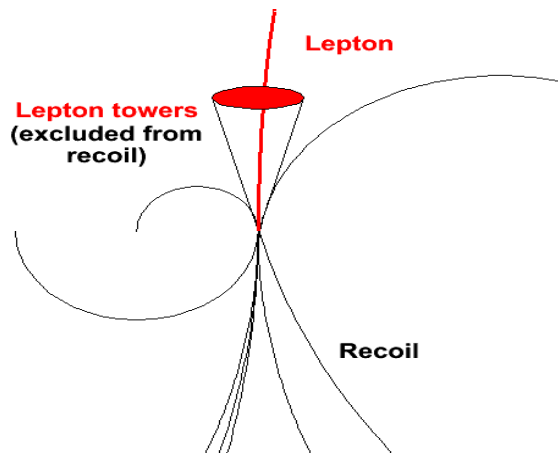


# Recoil Measurement

Calculate recoil by summing over calorimeter towers, excluding:

*Towers with lepton energy deposits*

*Towers near the beam line*



Electron Electromagnetic  $E_T$  (MeV)

3	29	29	29	31	29	27	28
2	28	28	29	37	31	29	28
1	29	29	32	1915	56	31	29
0	28	31	46	35646	138	34	30
-1	29	28	30	398	34	29	29
-2	29	29	29	31	30	29	28
-3	28	28	28	29	28	28	29
	-3	-2	-1	0	1	2	3

$\mathcal{L} = 200 \text{ pb}^{-1}$

CDF Run II Preliminary

Tower  $\Delta\phi$

C. Hays, University of Oxford

Electron: Remove 7 towers (shower)

Muon: Remove 3 towers (MIP)

Model tower removal in simulation

$$\delta m_W = 8 \text{ (5) MeV for } e \text{ (}\mu\text{)}$$



# Recoil Model

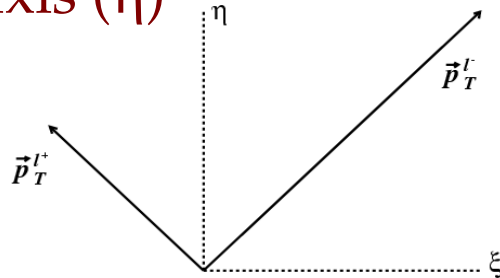
Components:

Recoil scale ( $R = u_{meas} / u_{true}$ )

Recoil resolution

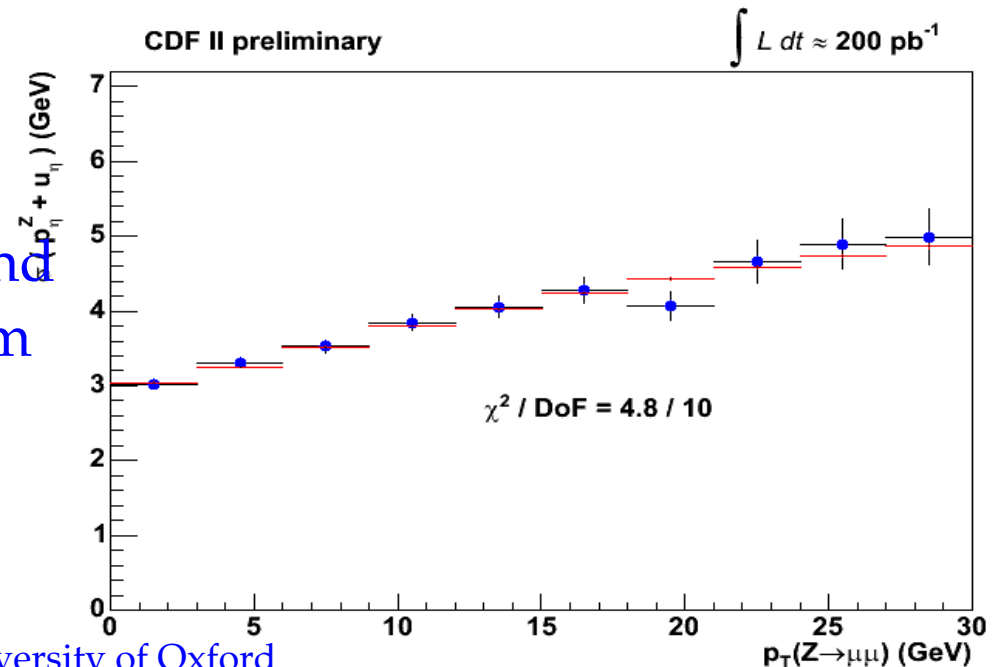
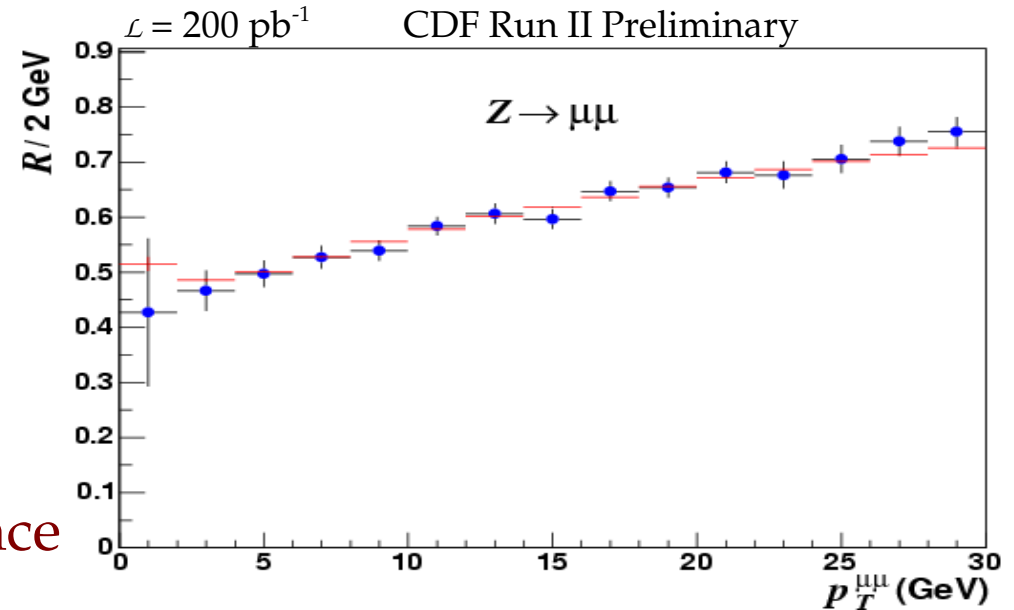
Spectator and additional interactions  
(contribute to resolution)

Calibrate scale with momentum balance  
along bisector axis ( $\eta$ )



Calibrate models of recoil resolution and  
spectator interactions using momentum  
resolution along both axes

$$\delta m_W = 11 \text{ MeV}$$

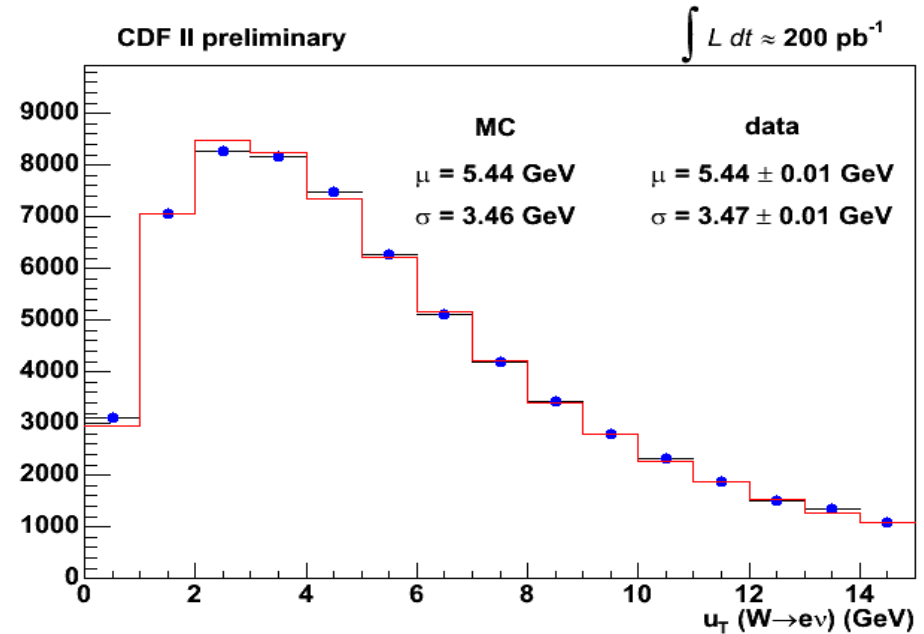


# Recoil Model Checks

Apply model to  $W$  boson sample, test consistency with data

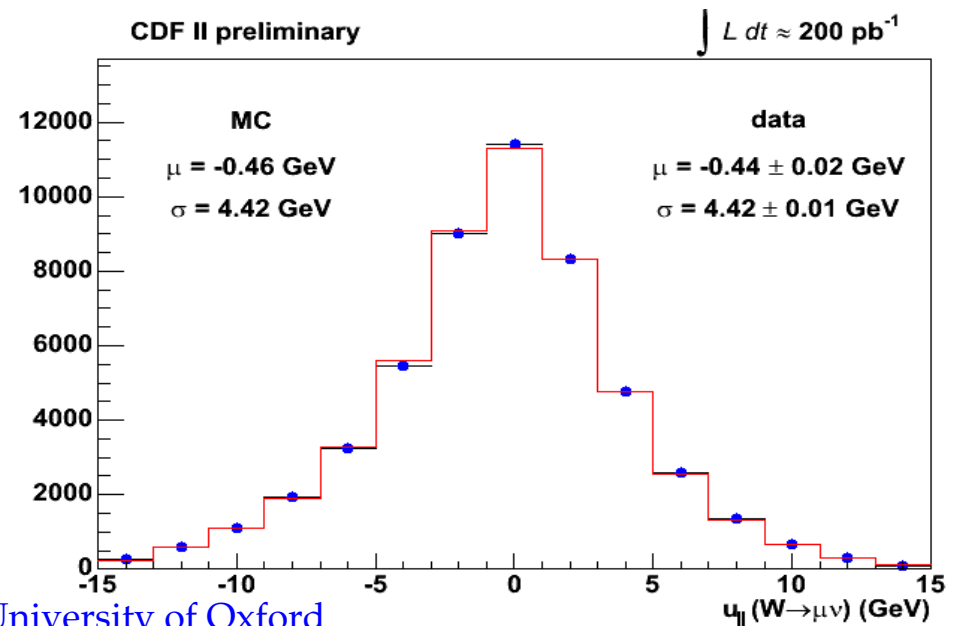
## Recoil distribution

*Sensitive to scale, resolution,  
boson  $p_T$*



## $u_{||}$ distribution

*Sensitive to lepton removal,  
efficiency model, scale,  
resolution,  $W$  decay*  
*Directly affects  $m_T$  fit result*



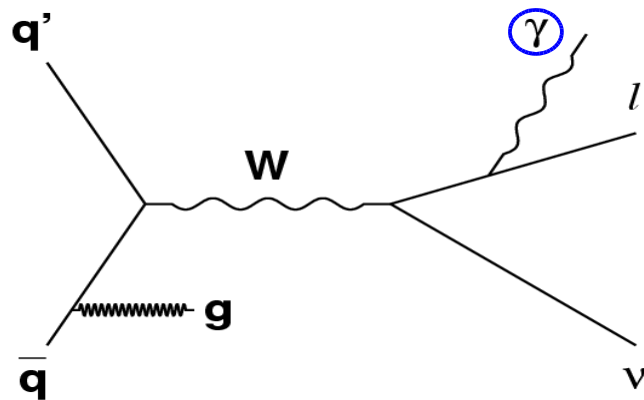
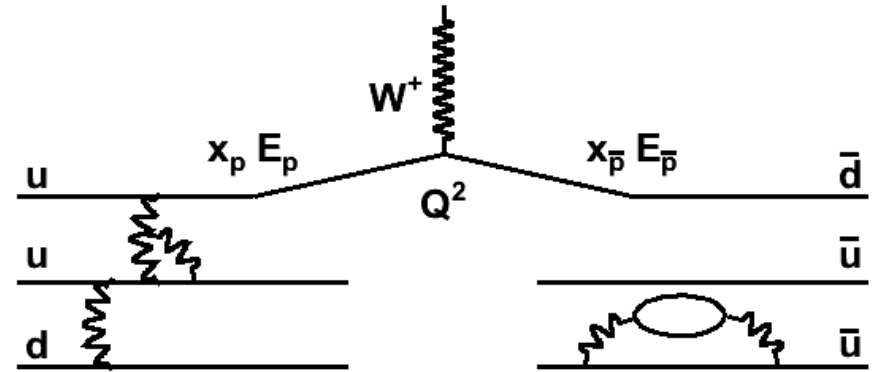
# Production, Decay, Background

Boson  $p_z$  determined by

parton distribution functions

Vary PDFs according to uncertainties

$$\delta m_W = 11 \text{ MeV}$$



Bremsstrahlung reduces charged lepton  $p_T$

Predict using NLO QED calculation,  
apply NNLO correction

$$\delta m_W = 11 \text{ (12) MeV for } e \text{ (}\mu\text{)}$$

Background affects fit distributions

QCD: Measure with data

Electroweak: Predict with MC

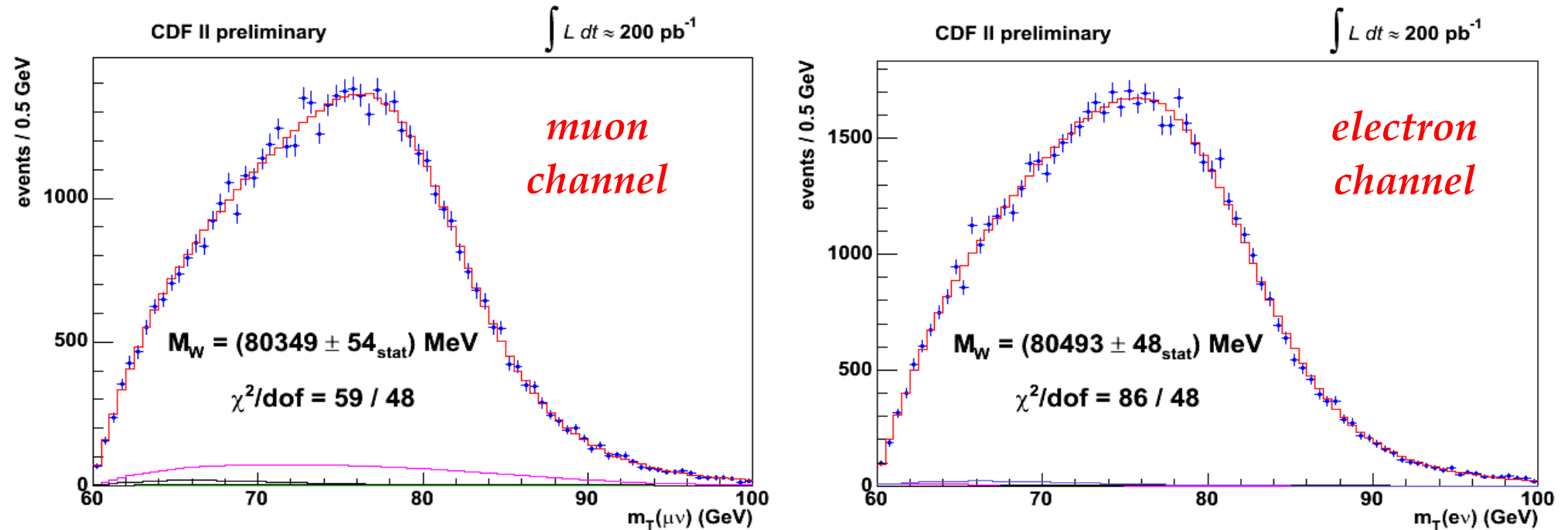
$$\delta m_W = 8 \text{ (9) MeV for } e \text{ (}\mu\text{)}$$

Background	% ( $\mu$ )	% ( $e$ )
Hadronic Jets	$0.1 \pm 0.1$	$0.25 \pm 0.15$
Decays in Flight	$0.3 \pm 0.2$	-
Cosmic Rays	$0.05 \pm 0.05$	-
$Z \rightarrow ll$	$6.6 \pm 0.3$	$0.24 \pm 0.04$
$W \rightarrow \tau\nu$	$0.89 \pm 0.02$	$0.93 \pm 0.03$

# W Mass Fits

Mass fit results blinded with  $[-100,100]$  MeV offset throughout analysis  
Upon completion, offset removed to determine final result

*Transverse mass fits:*



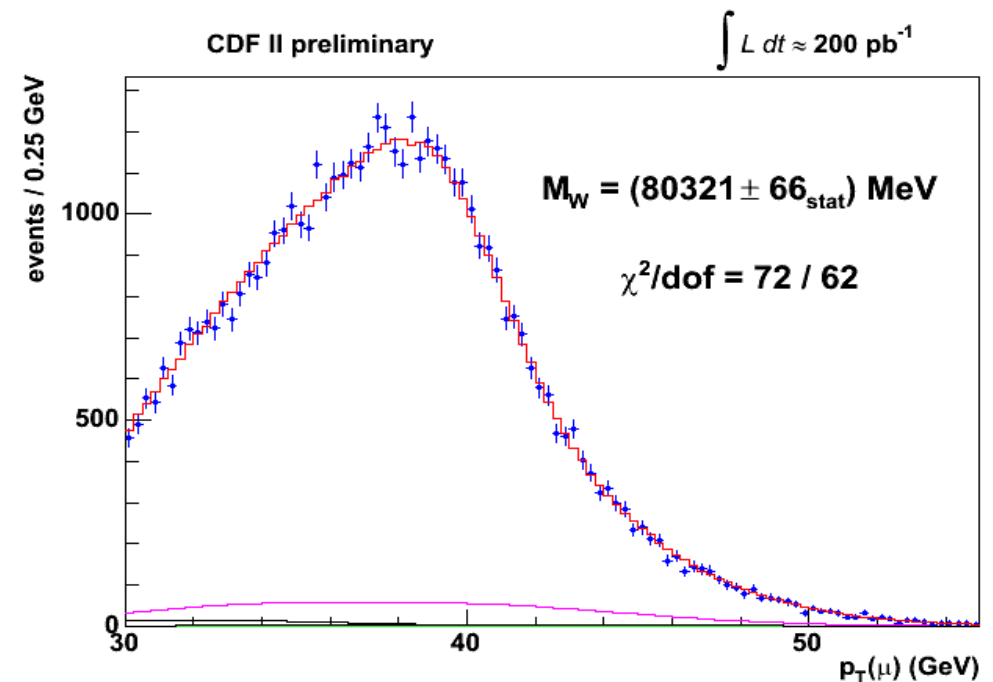
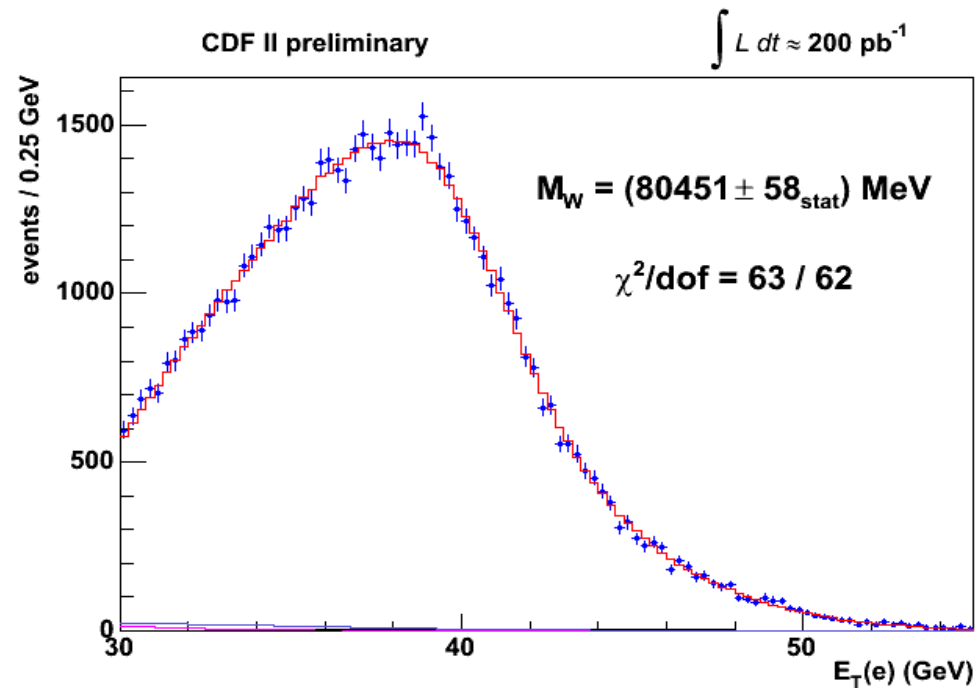
$m_W = 80417 \pm 48 \text{ MeV (stat + sys)}$   
for  $e + \mu$  combination ( $P(\chi^2) = 7\%$ )

# W Mass Fits

Fit  $E_T$ ,  $E_{\tau T}$  distributions and combine with  $m_T$  to extract most precise result

*Electron  $E_T$  fit:*

*Muon  $p_T$  fit:*

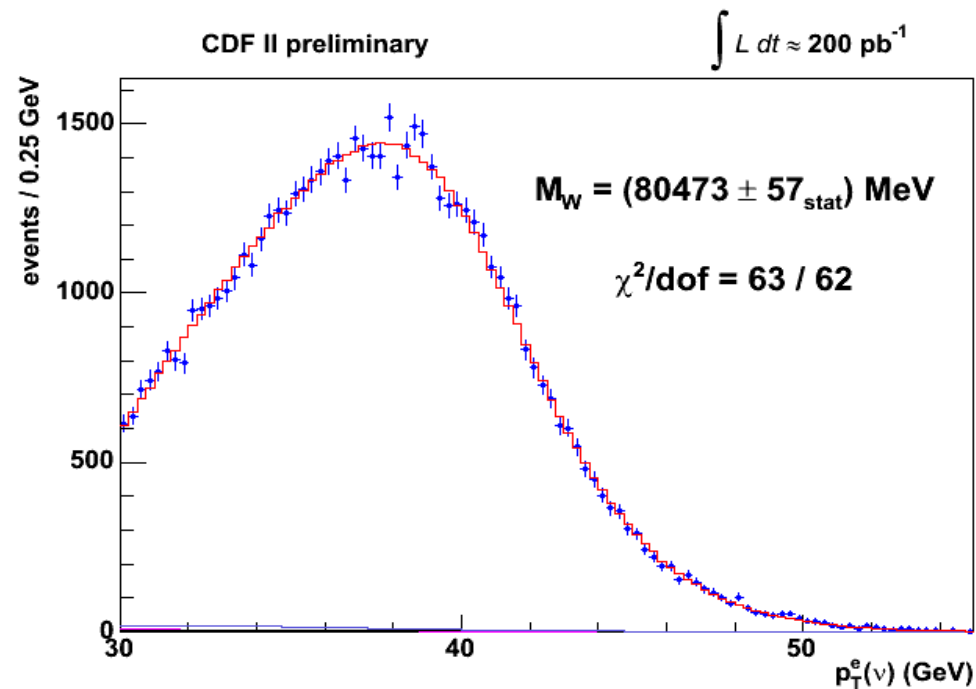


**$m_W = 80388 \pm 59 \text{ MeV (stat + sys)}$**   
**for lepton  $p_T e + \mu$  combination ( $P(\chi^2) = 18\%$ )**

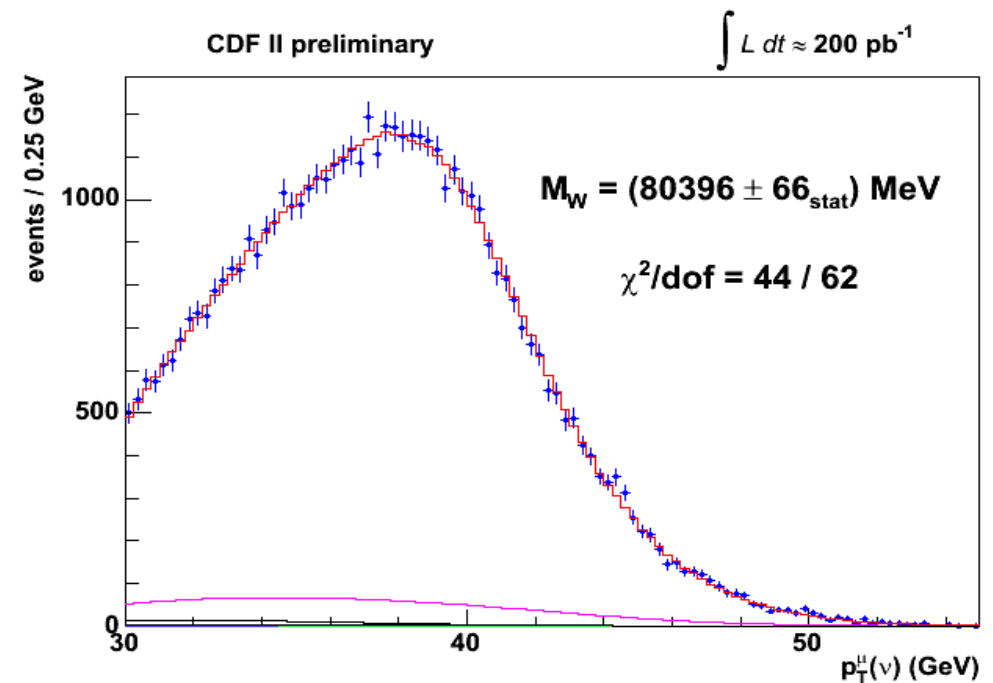
# W Mass Fits

$m_W = 80434 \pm 65 \text{ MeV (stat + sys)}$   
for neutrino  $p_T e + \mu$  combination ( $P(\chi^2) = 43\%$ )

Electron  $E_T$  fit:



Muon  $E_T$  fit:



$m_W = 80413 \pm 48 \text{ MeV (stat + sys)}$   
for six-fit combination ( $P(\chi^2) = 44\%$ )

# W Mass Uncertainties

CDF II preliminary

$L = 200 \text{ pb}^{-1}$

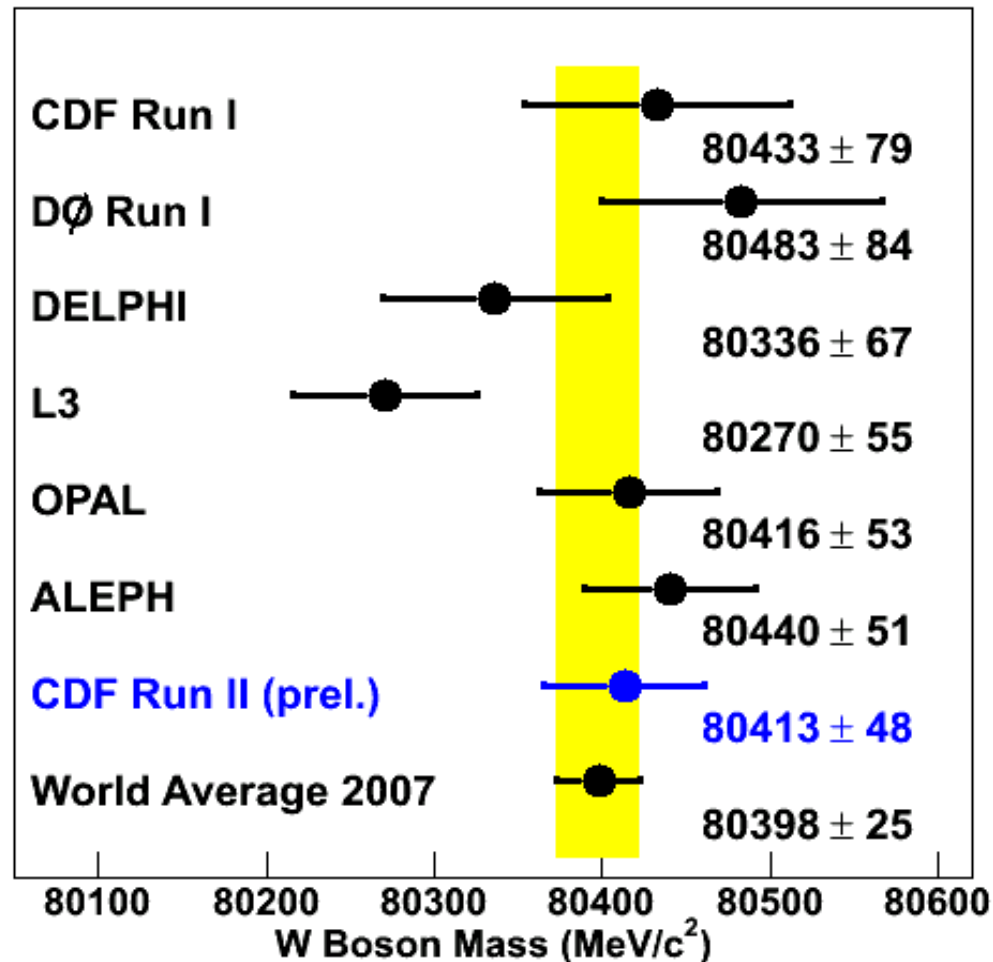
$m_T$ Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{  }$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

# W Mass Result

New CDF result is world's most precise single measurement

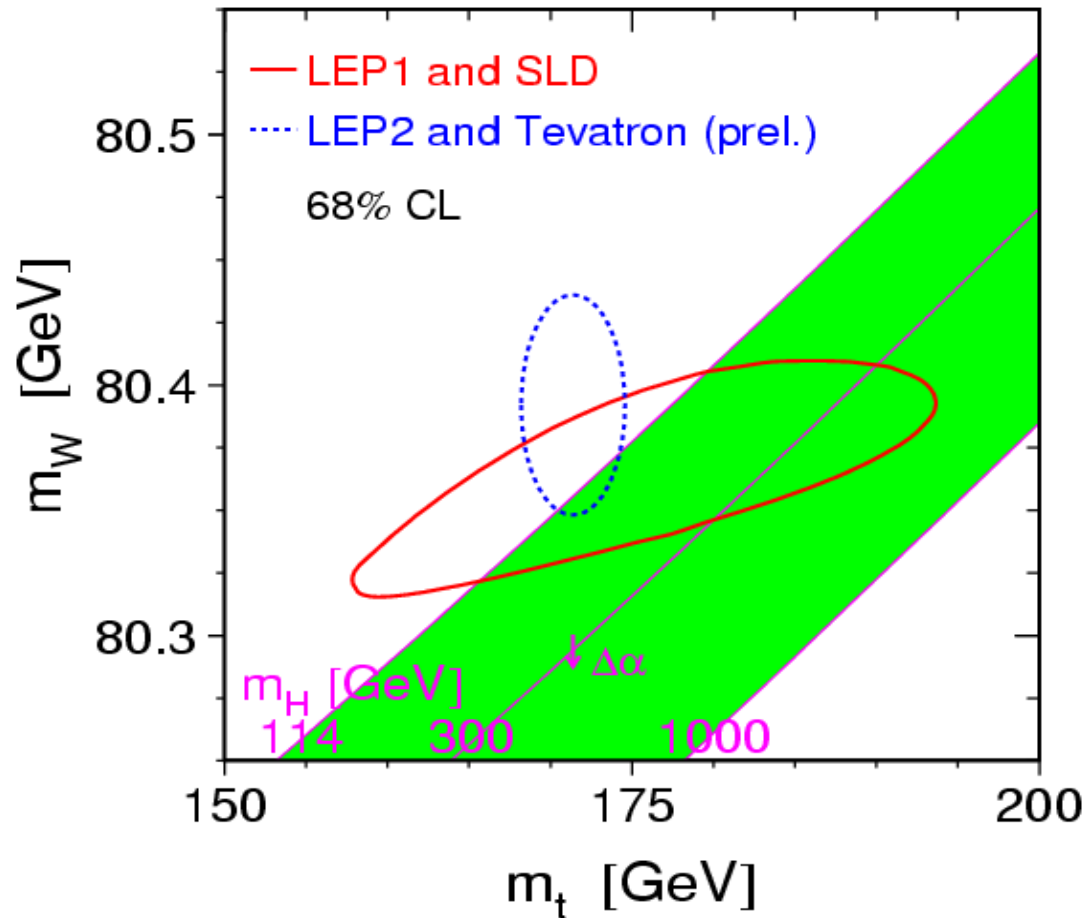
*Central value increases: 80392 to 80398 MeV*

*World average uncertainty reduced ~15% (29 to 25 MeV)*





# Previous Higgs Mass Prediction

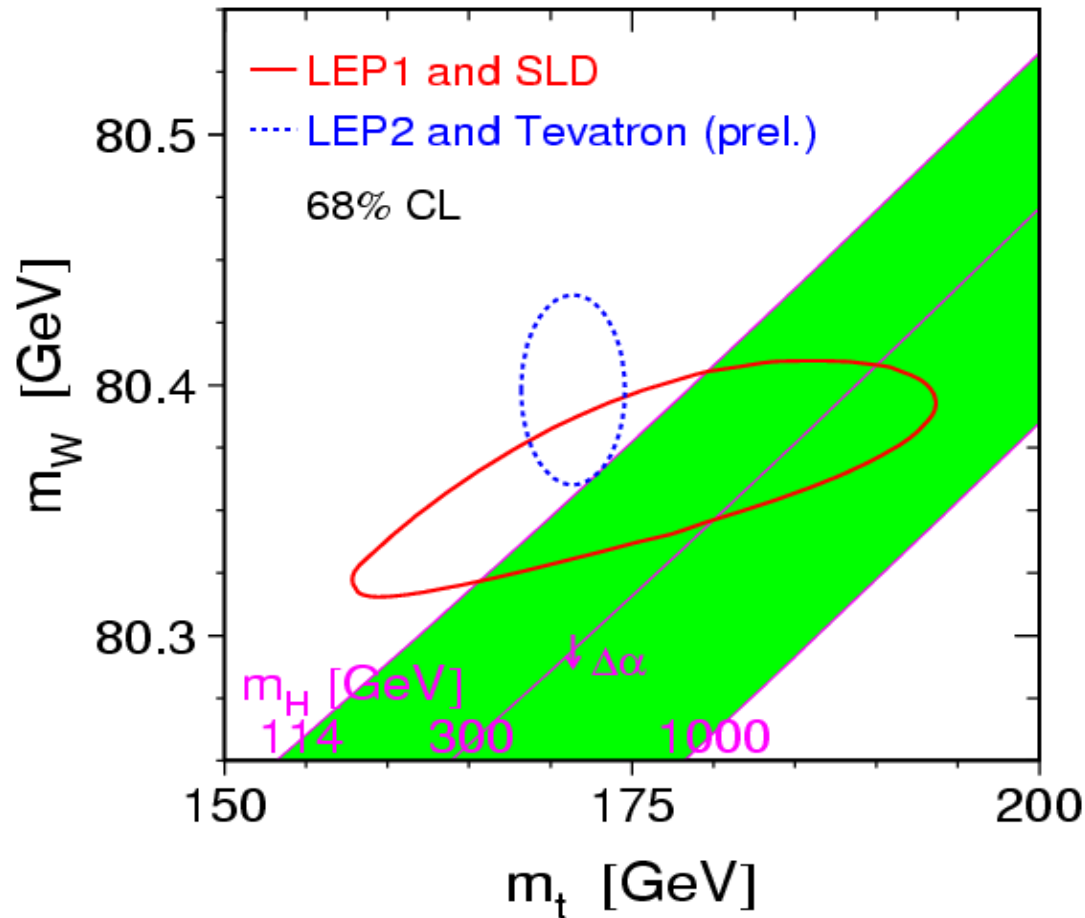


*Predicted Higgs mass from global electroweak data:*

$$m_H = 85^{+39}_{-28} \text{ GeV} (< 166 \text{ GeV at 95\% CL})$$

Direct search from LEP II:  $m_H > 114.4 \text{ GeV}$  at 95% CL

# New Higgs Mass Prediction



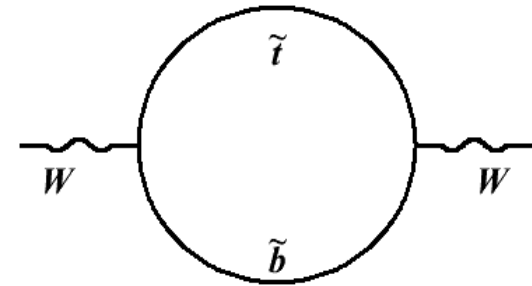
*Predicted Higgs mass from global electroweak data:*

$$m_H = 80^{+36}_{-26} \text{ GeV} (< 153 \text{ GeV at 95\% CL})$$

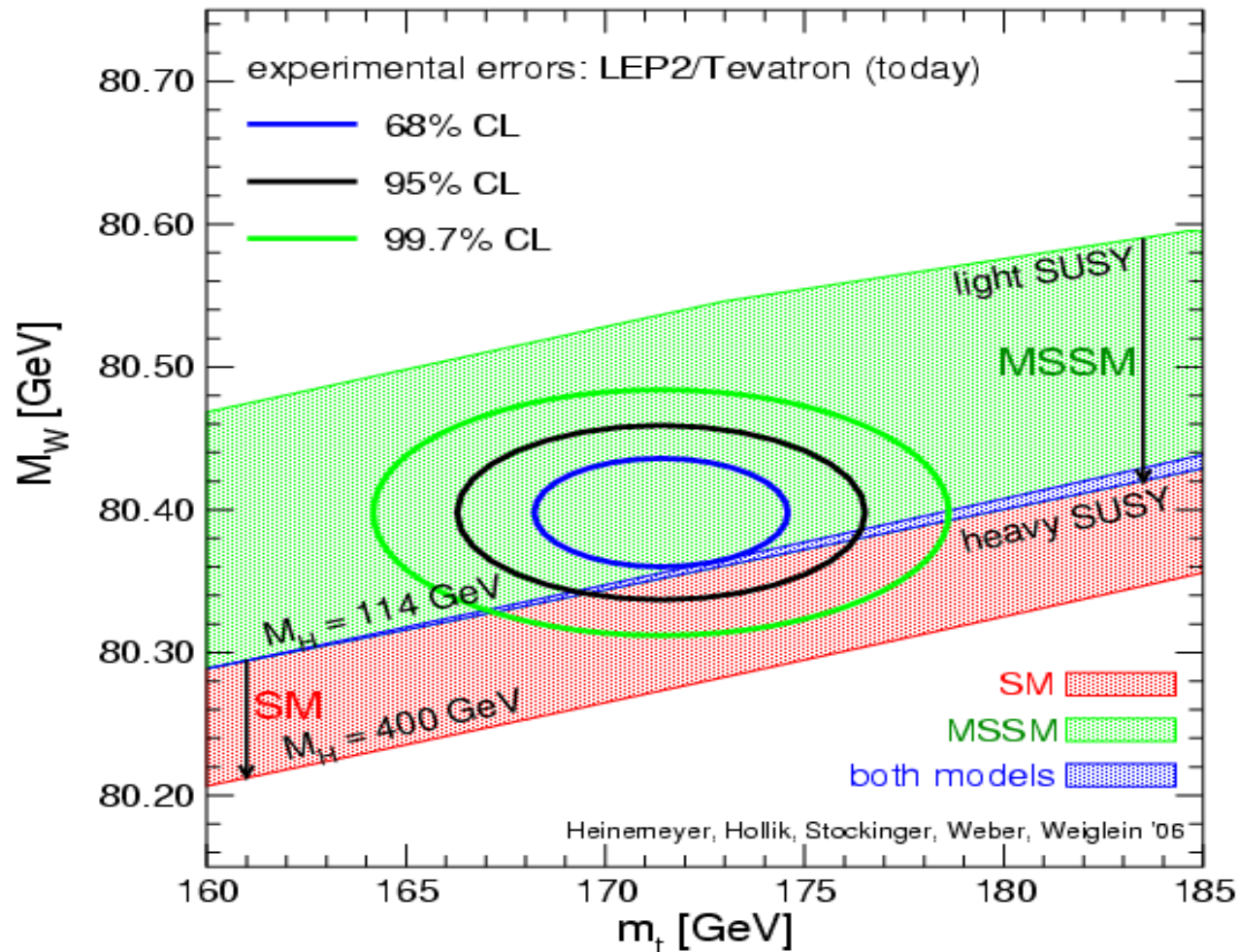
Direct search from LEP II:  $m_H > 114.4 \text{ GeV}$  at 95% CL

# Effect on New Physics Models

Supersymmetry now preferred at  $1\sigma$  level...

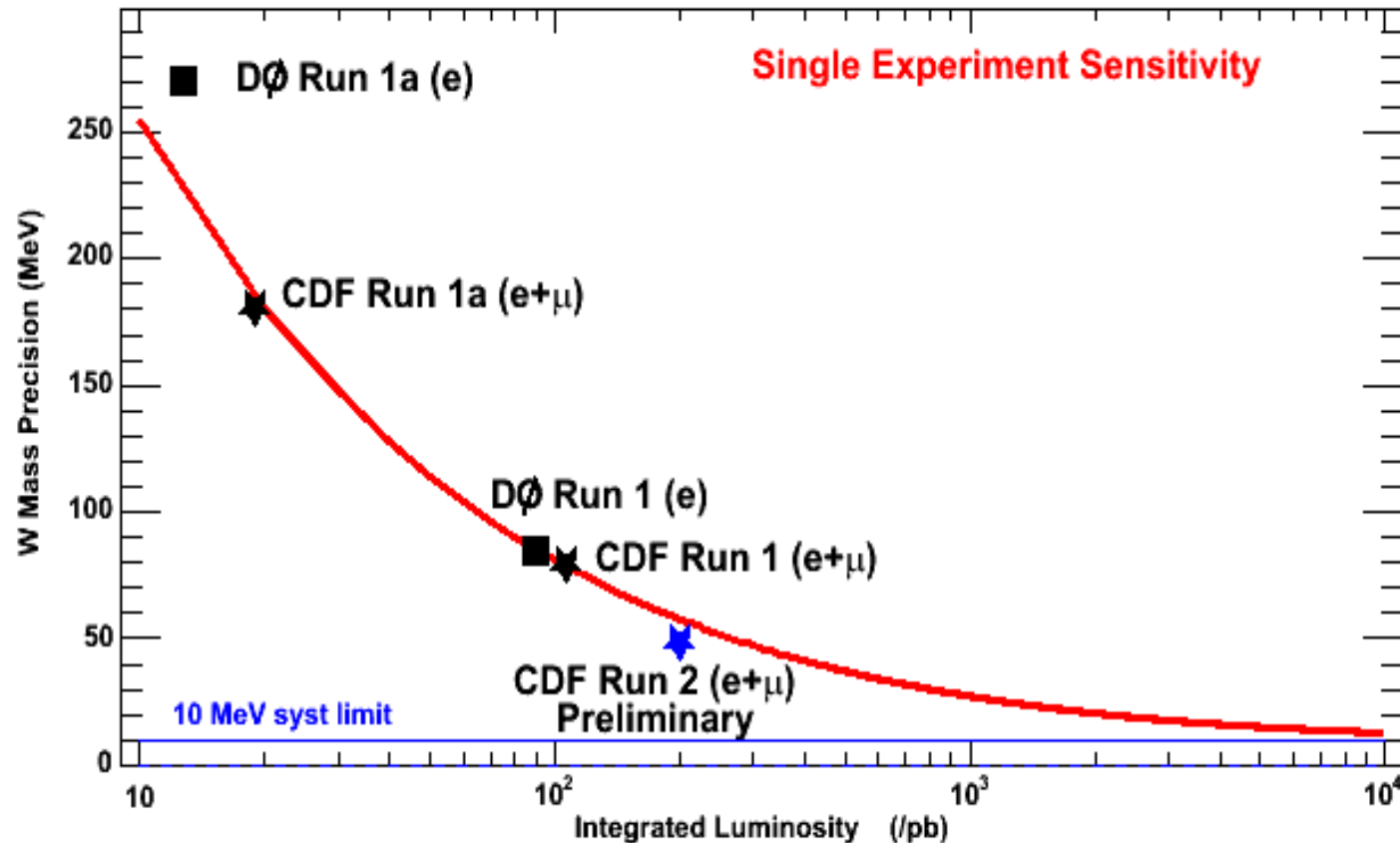


*New world average:*



# New W Mass Projections

New projected Tevatron precision as a function of luminosity:



*New projection with 1.5 fb<sup>-1</sup> of data:*

$$\delta m_W < 25 \text{ MeV with CDF}$$

# Summary

*W mass excellent probe for new particles coupling to the electroweak sector*

CDF has made the single most precise  $W$  mass measurement

$$\begin{aligned} m_W &= 80413 \pm 34 \text{ MeV (stat)} \pm 34 \text{ MeV (sys)} \\ &= 80413 \pm 48 \text{ MeV (stat + sys)} \end{aligned}$$

*New SM Higgs mass prediction:  $m_H = 80^{+36}_{-26} \text{ GeV}$*

*Mass has moved further into LEP-excluded region*

*Expect CDF  $\delta m_W < 25 \text{ MeV}$  with  $1.5 \text{ fb}^{-1}$  already collected*

*Will squeeze SM in conjunction with Tevatron Higgs results*

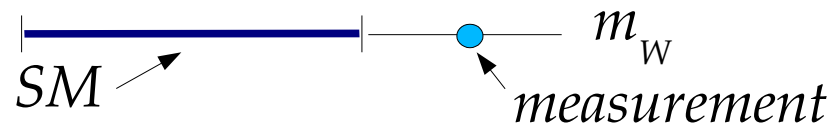
*Electroweak data will probe more new physics after the Higgs*

# Backup

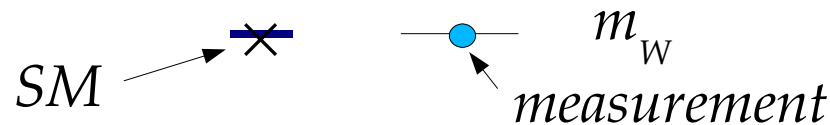
# Filling in the Pieces

Precision electroweak data will continue to guide us to the next physics

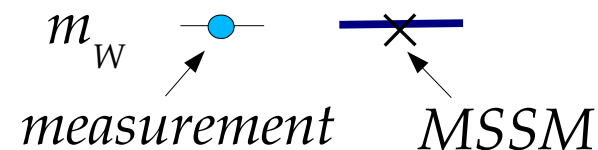
**Today:**  $\delta m_W = 25 \text{ MeV}$ ,  $m_H < 153 \text{ GeV}$  at 95% CL



**After Higgs:**  $\delta m_W = 15 \text{ MeV}$ , SUSY predicted at 95% CL?

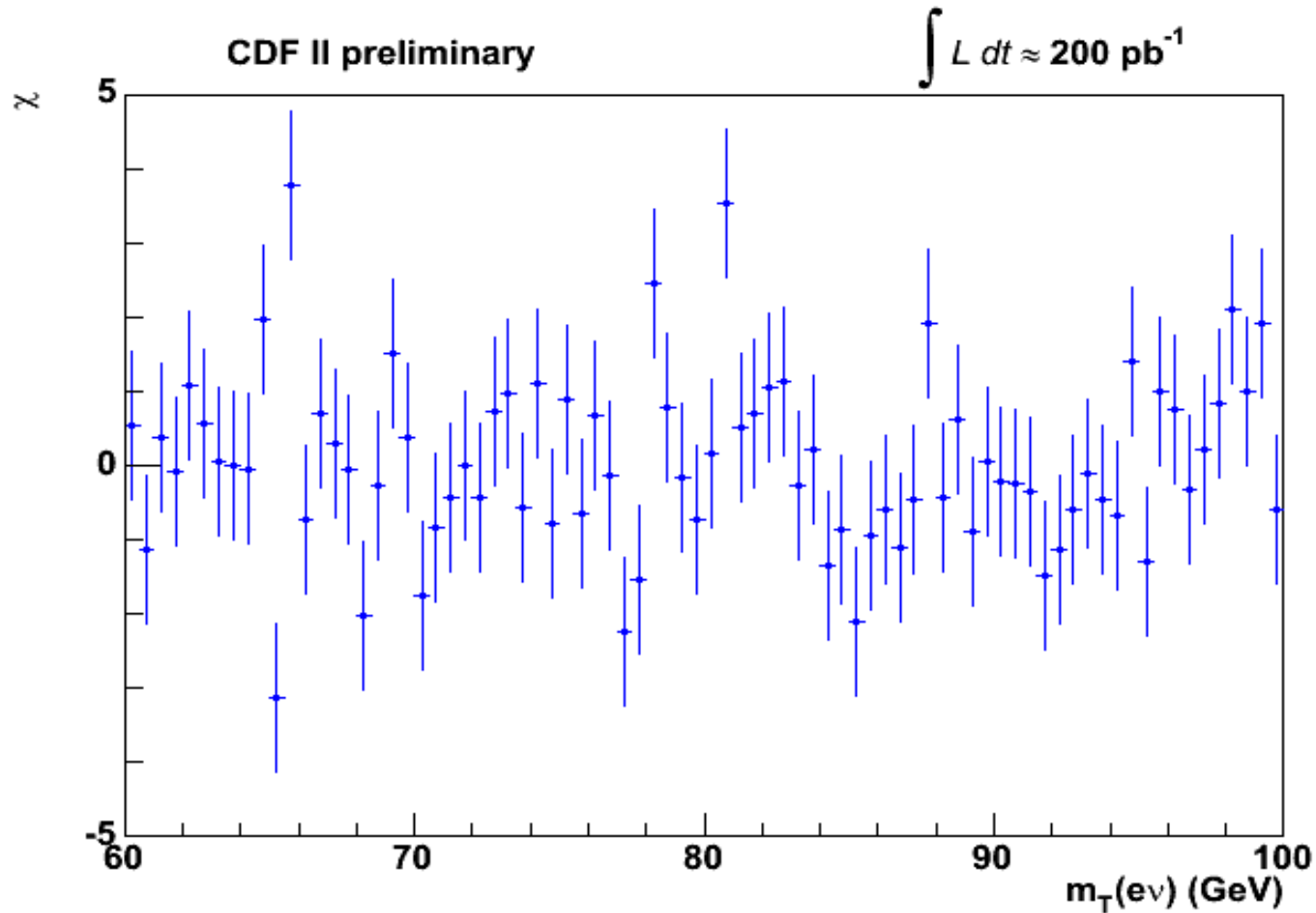


**After SUSY:**  $\delta m_W = 10 \text{ MeV}$ , more new physics?



# Electron $m_T$ Signed $\chi$

High  $\chi^2$  dominated by a few bins with large fluctuations





# Tevatron Run I Uncertainties

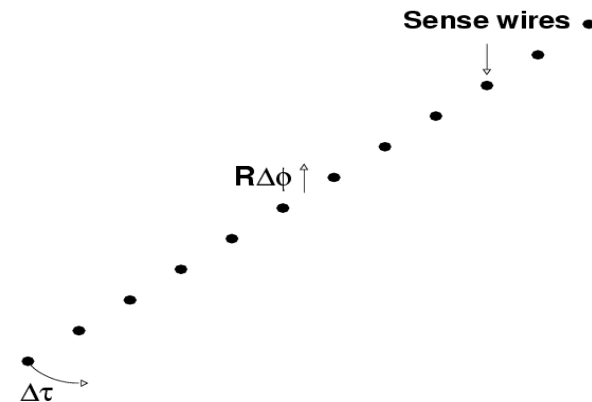
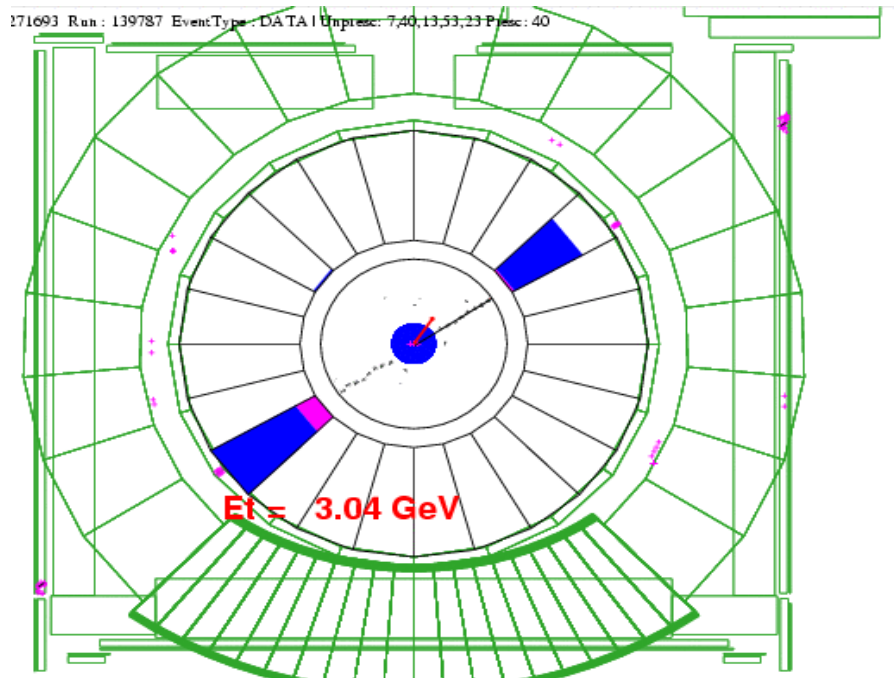
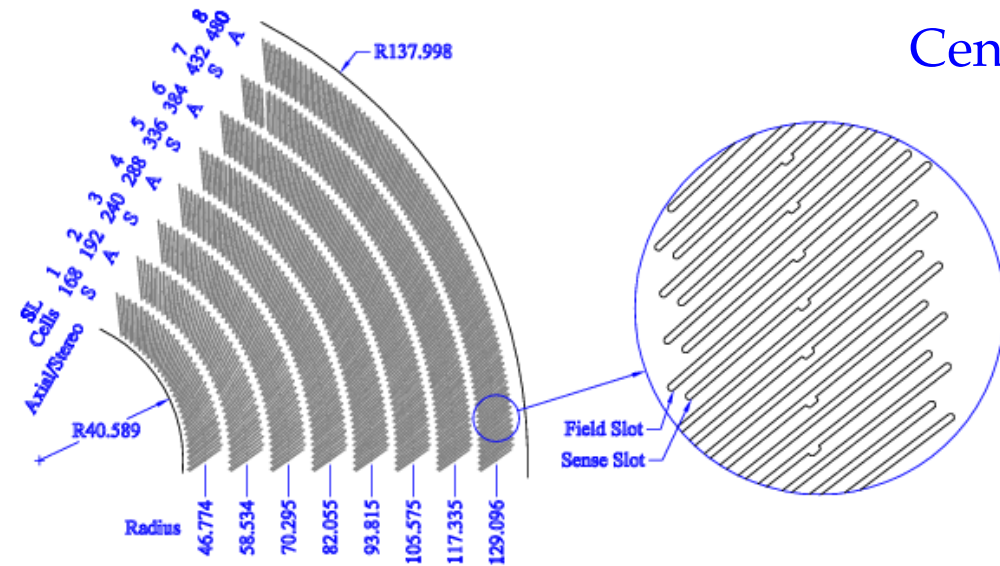
	CDF $\mu$	CDF $e$	DØ $e$
<i>W</i> statistics	100	65	60
Lepton energy scale	85	75	56
Lepton resolution	20	25	19
Recoil model	35	37	35
$p_T(W)$	20	15	15
Selection bias	18	-	12
Backgrounds	25	5	9
Parton dist. functions	15	15	8
QED rad. corrections	11	11	12
$\Gamma(W)$	10	10	10
Total	144	113	84

# Tracker Alignment

Central Outer Tracker: Open-cell drift chamber

Wires strung under tension between two endplates

Model endplate distortions and constructional variations using a cell-to-cell endplate alignment



Determine individual cell tilts & shifts using cosmic-ray data

Fit a single 'dicosmic' to track segments on opposite sides of the chamber

Measure cell displacement

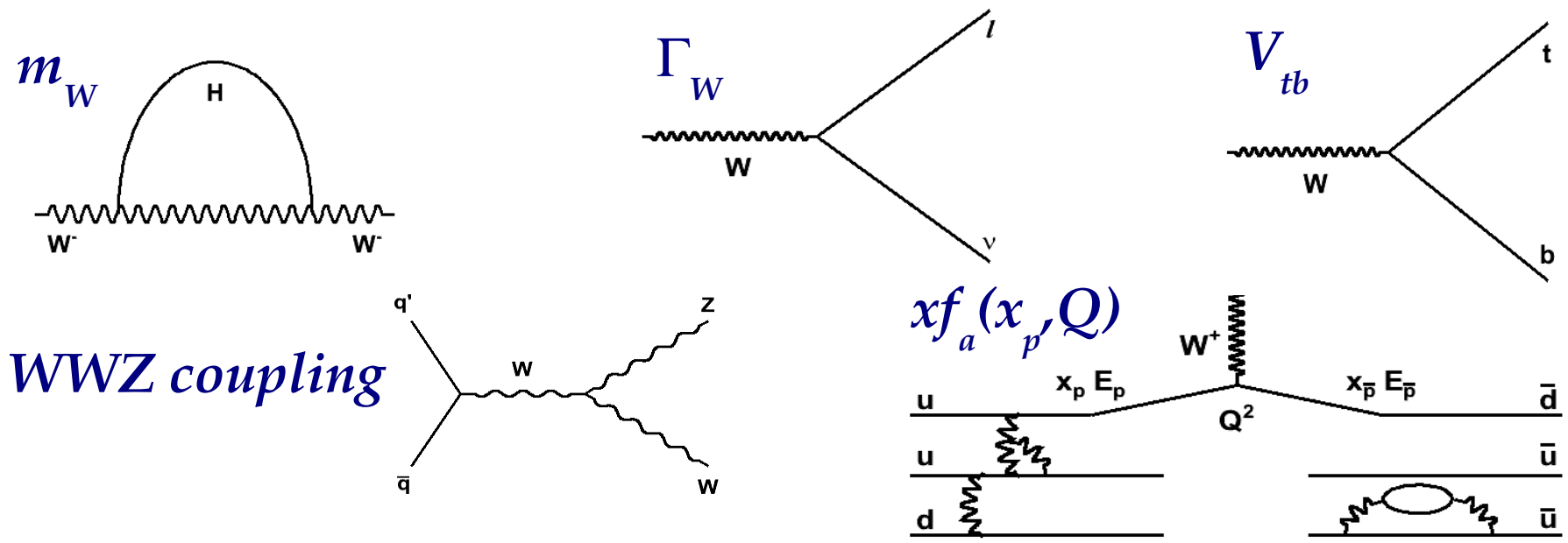
# Weak Boson Physics

Z boson parameters measured precisely by LEP:

\* **17 million measured Z candidates:**  $\delta m_Z = 2.1 \text{ MeV}$ ,  $\delta \Gamma_Z = 2.3 \text{ MeV}$

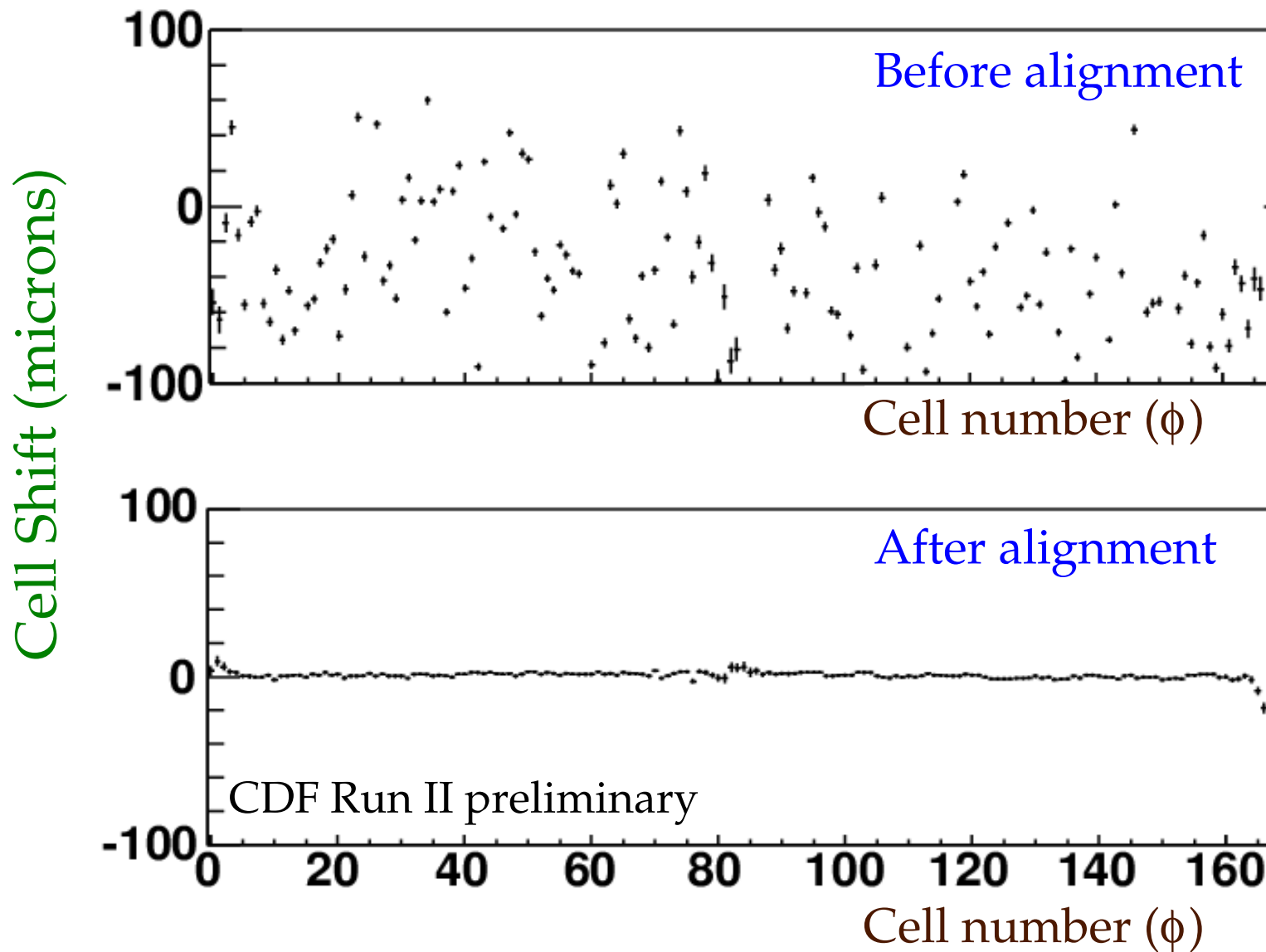
Tevatron goal:

- \* World's most precise W boson measurements
- \* Expect **15 million measured W candidates**



# Alignment Example

*Inner 'Superlayer:'*



# Wire Alignment

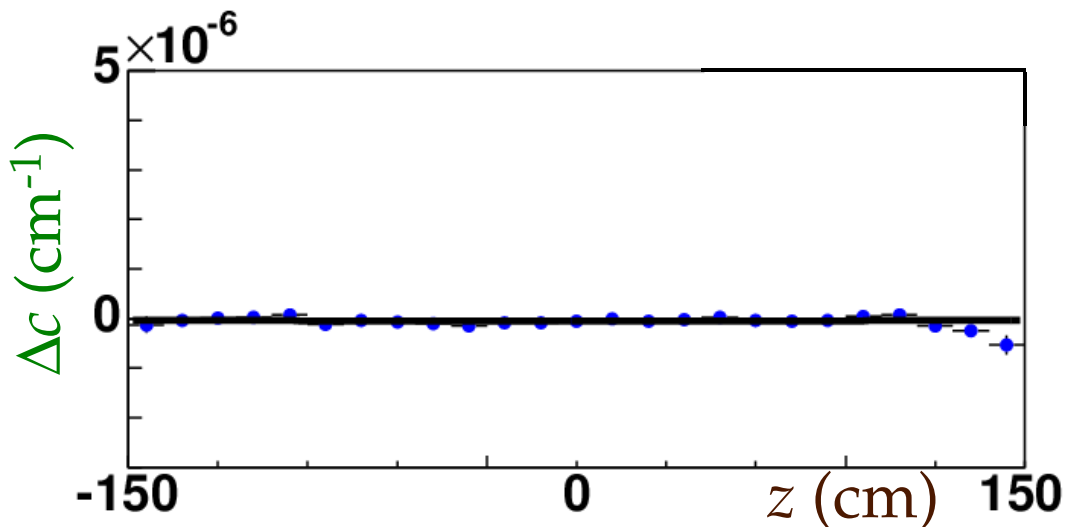
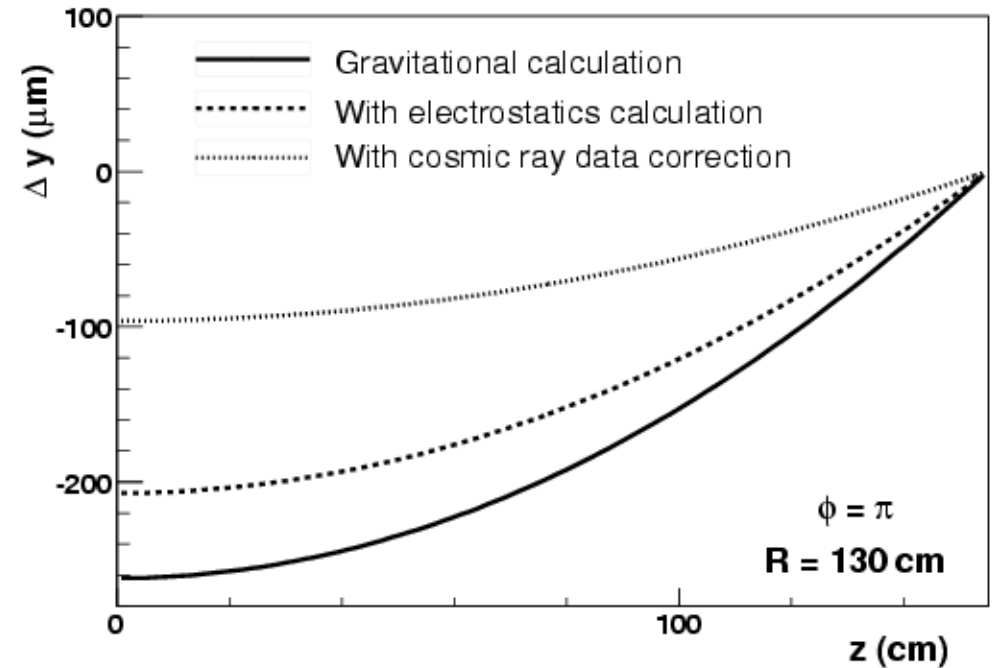
Wire shape along z-axis determined by:

*Gravitational sag*

*Electrostatic effects*

Apply additional correction based on  
cosmic ray study

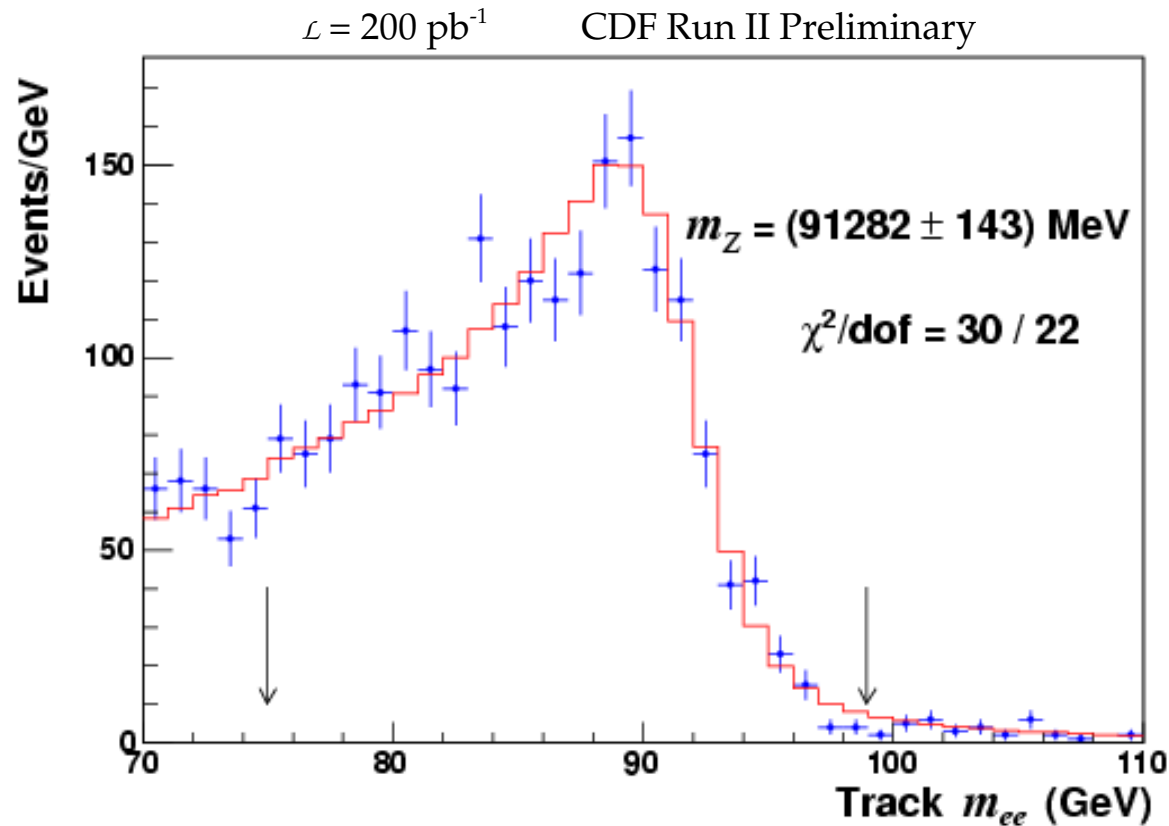
*Compare parameters of incoming and  
outgoing tracks from a cosmic ray muon*



Final correction removes z-dependent  
curvature biases

# Electron Track Model Validation

*Fit Z mass reconstructed from electron track momenta*



Measured value consistent with world average value (91188 MeV)

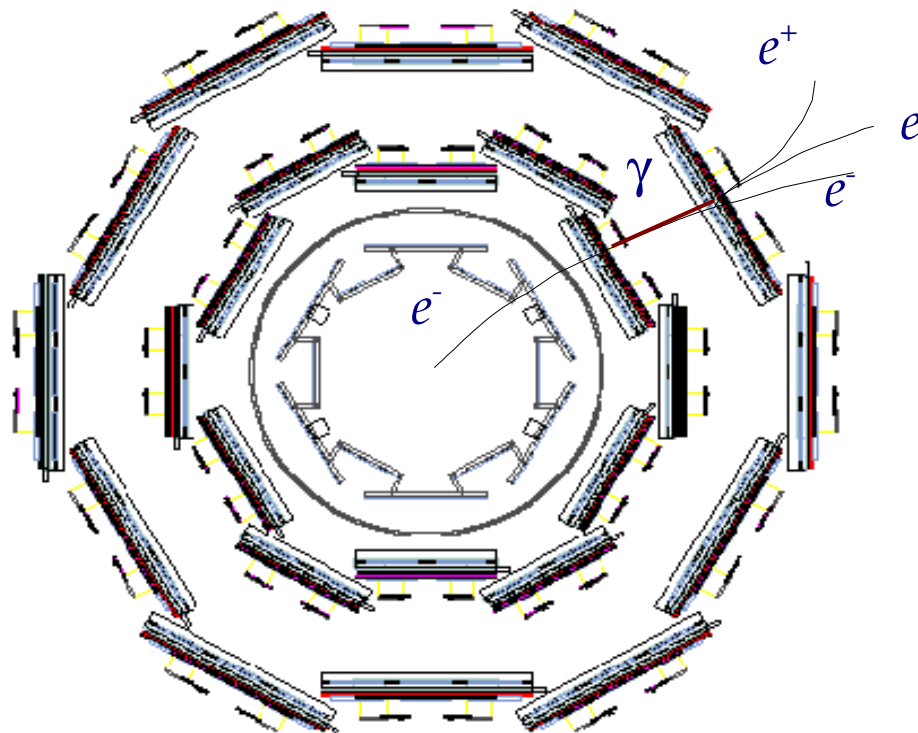
# Calorimeter Energy Calibration

*Calibrate electron energy using electron track momentum*

First step: validate model of electrons in tracker

Additional physical effects beyond those associated with muons:

*Photon radiation and conversion in tracker*



# Combined Momentum Scale

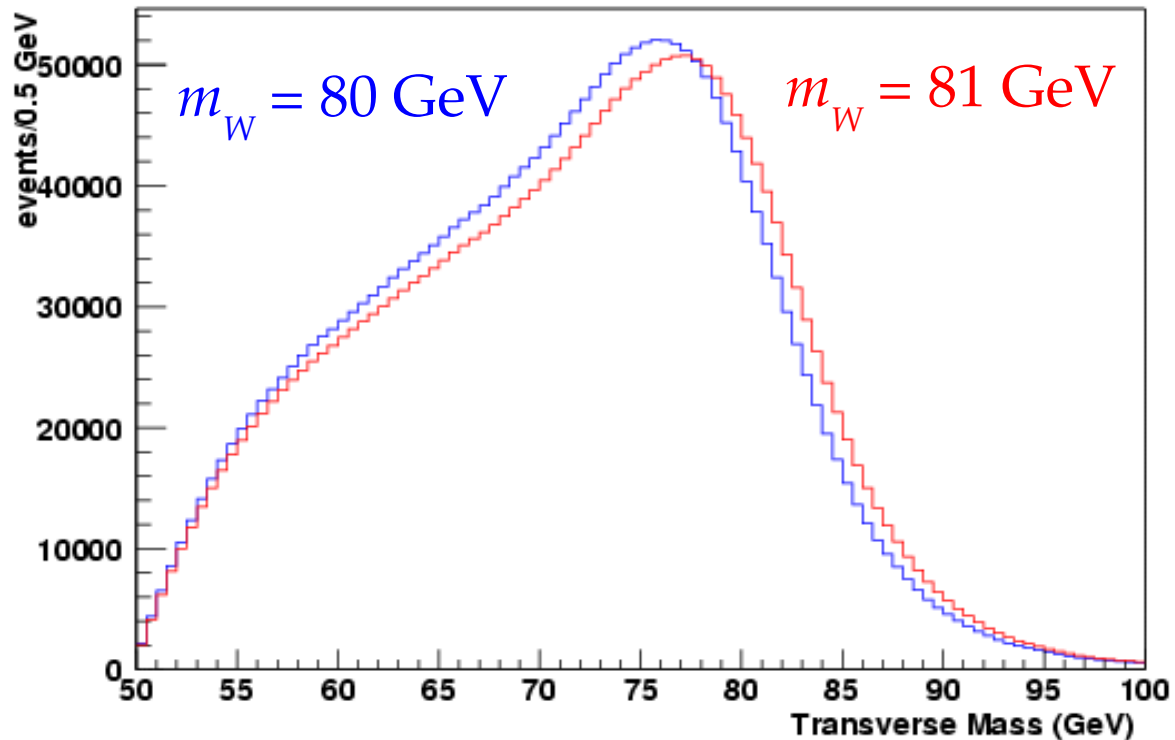
$$\Delta p/p = (1.50 \pm 0.19) \times 10^{-3}$$

*Systematic uncertainties:*

Source	$J/\psi (\times 10^{-3})$	$\Upsilon (\times 10^{-3})$	Common ( $\times 10^{-3}$ )
QED and energy loss model	0.20	0.13	0.13
Magnetic field nonuniformities	0.10	0.12	0.10
Beam constraint bias	N/A	0.06	0
Ionizing material scale	0.06	0.03	0.03
COT alignment corrections	0.05	0.03	0.03
Fit range	0.05	0.02	0.02
$p_T$ threshold	0.04	0.02	0.02
Resolution model	0.03	0.03	0.03
Background model	0.03	0.02	0.02
World-average mass value	0.01	0.03	0
Statistical	0.01	0.06	0
Total	0.25	0.21	0.17



# Transverse Mass Distribution

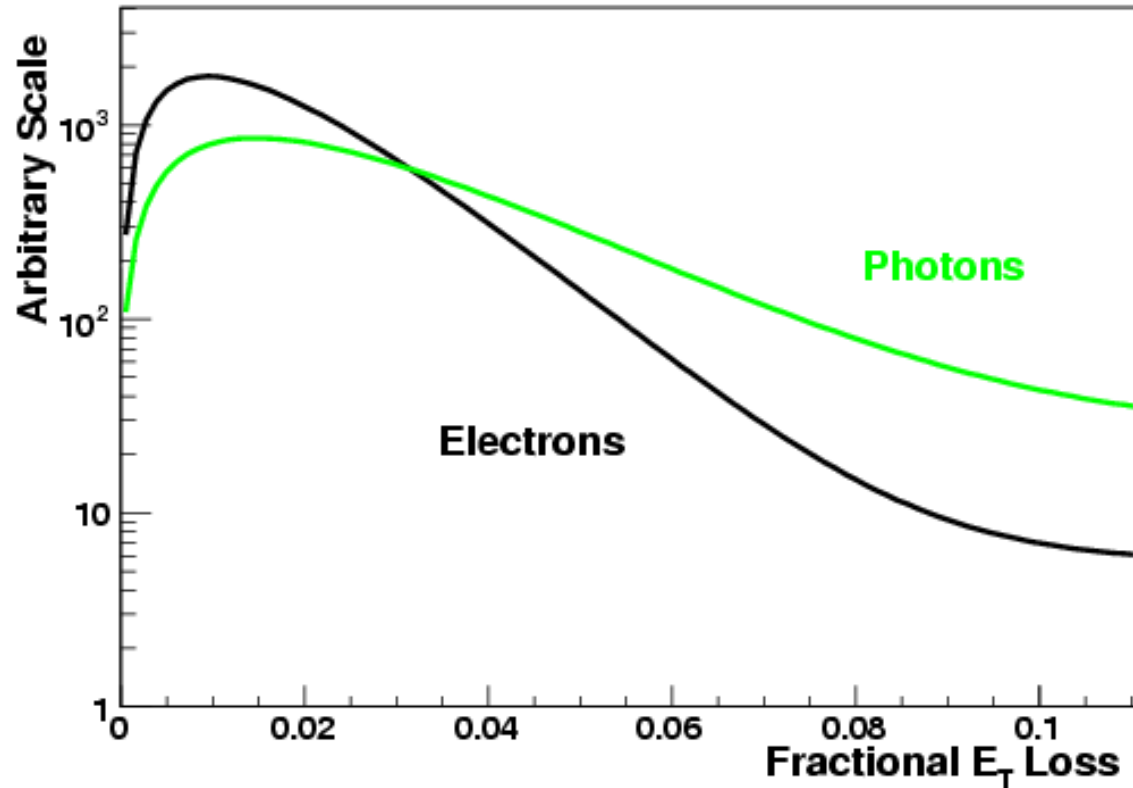


Distribution peaks just below  $m_W$  and falls sharply just above  $m_W$

# Energy Loss Model

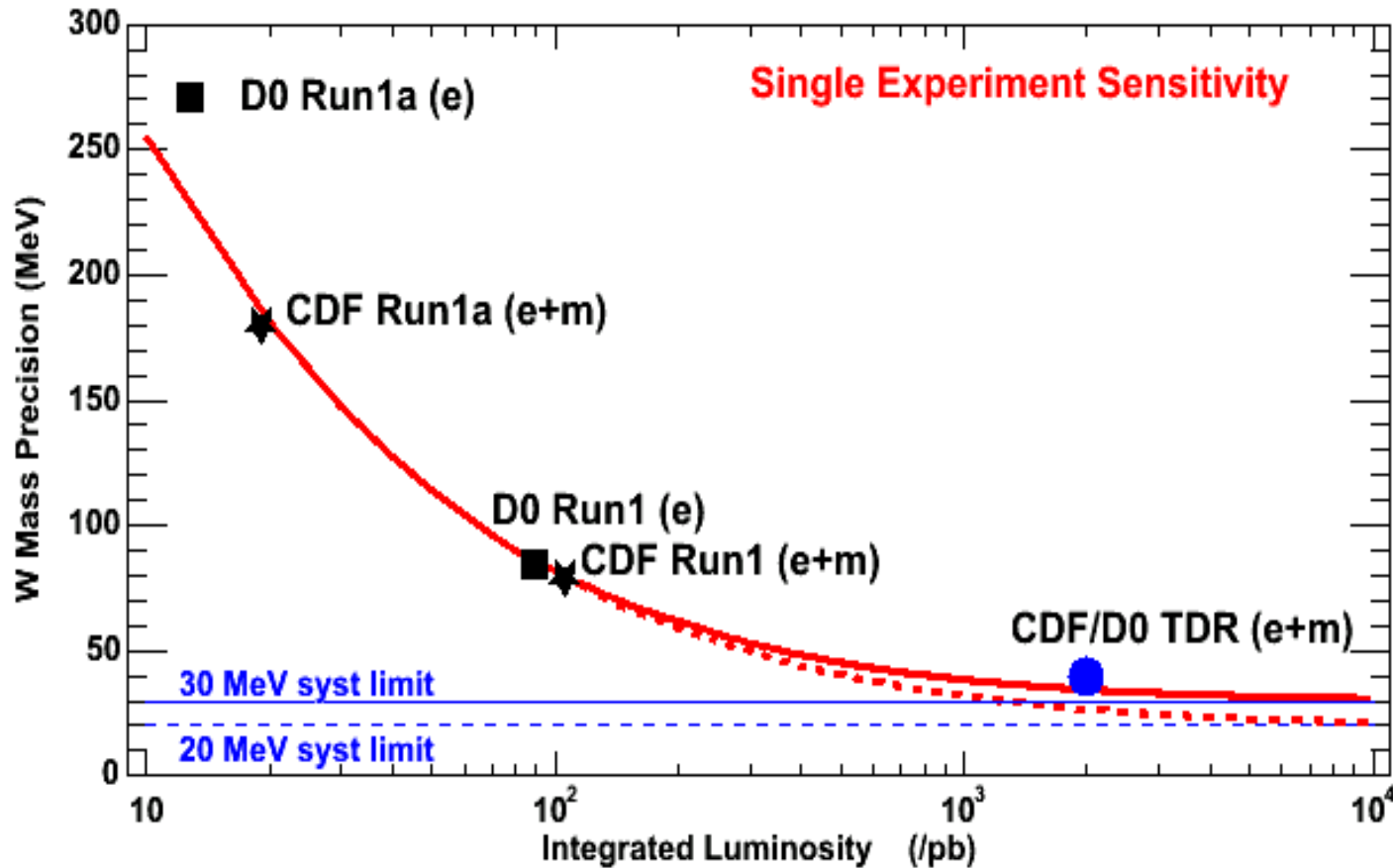
*Use GEANT to parametrize energy loss in solenoid and hadronic calorimeter*

Energy loss in hadronic calorimeter:



# Previous $W$ Mass Projections

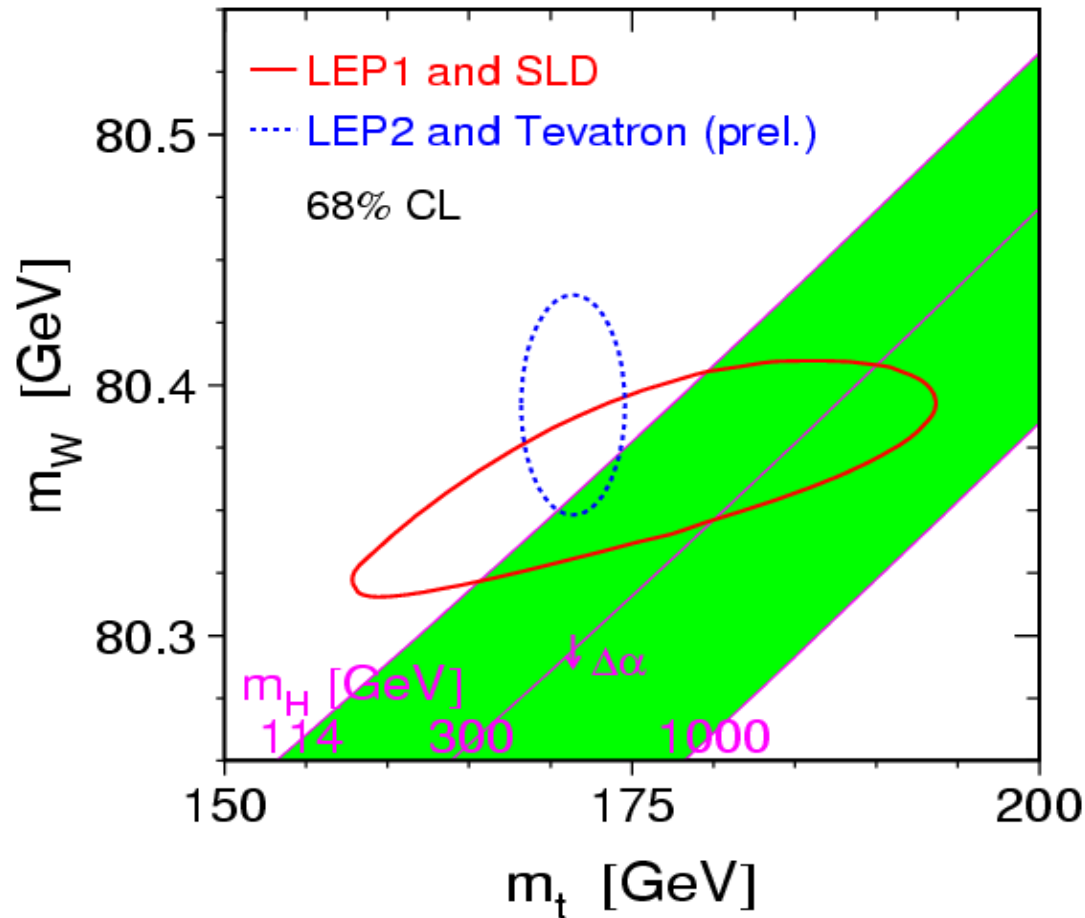
Previously projected Tevatron precision as a function of luminosity:



*Projection with  $2 \text{ fb}^{-1}$  of data:*

$$\delta m_W = 40 \text{ MeV per experiment}$$

# Higgs Mass Prediction



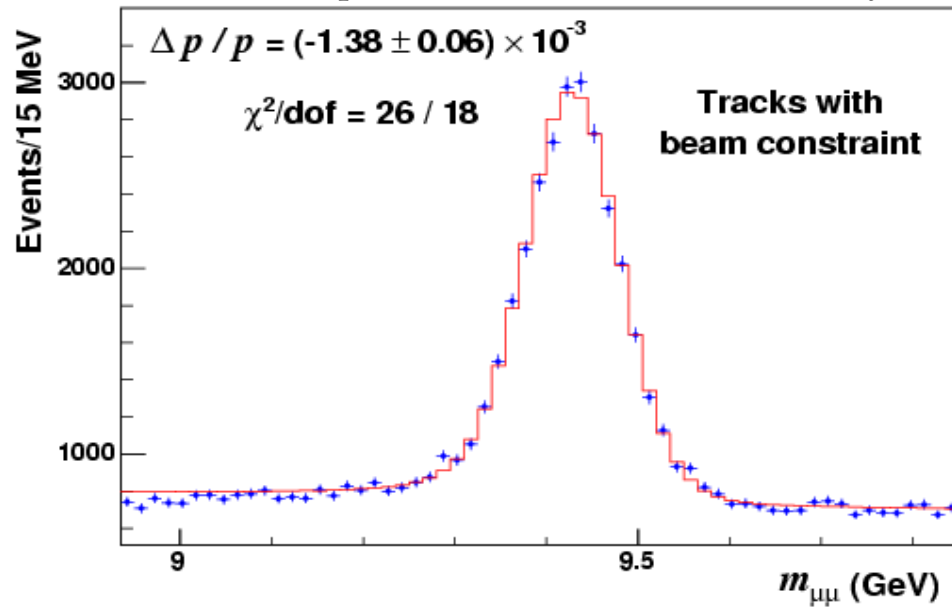
*Predicted Higgs mass from global electroweak data:*

$$m_H = 85^{+39}_{-28} \text{ GeV} (< 166 \text{ GeV at 95\% CL})$$

Direct search from LEP II:  $m_H > 114.4 \text{ GeV}$  at 95% CL

# Y Mass Measurement

$\mathcal{L} = 200 \text{ pb}^{-1}$  CDF Run II Preliminary



34,618  $Y \rightarrow \mu\mu$  candidates

Short lifetime allows a track constraint to the beam line

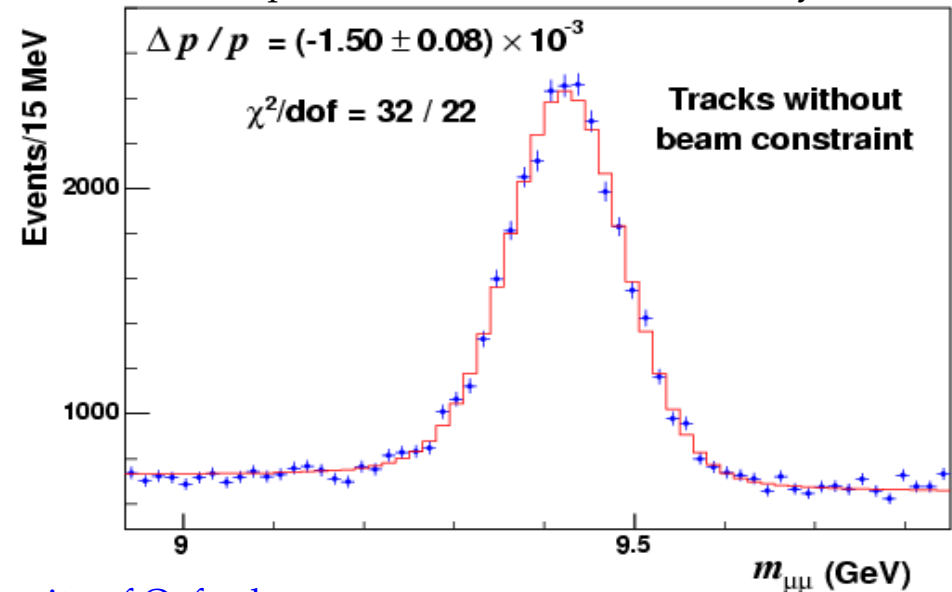
*Improves resolution by a factor of  $\approx 3$*

Test beam constraint by measuring mass using unconstrained tracks

Correct by half the difference between fits

Take correction as a systematic uncertainty

$\mathcal{L} = 200 \text{ pb}^{-1}$  CDF Run II Preliminary



# Momentum Scale Calibration

Magnetic field along z-axis causes curvature in transverse plane:

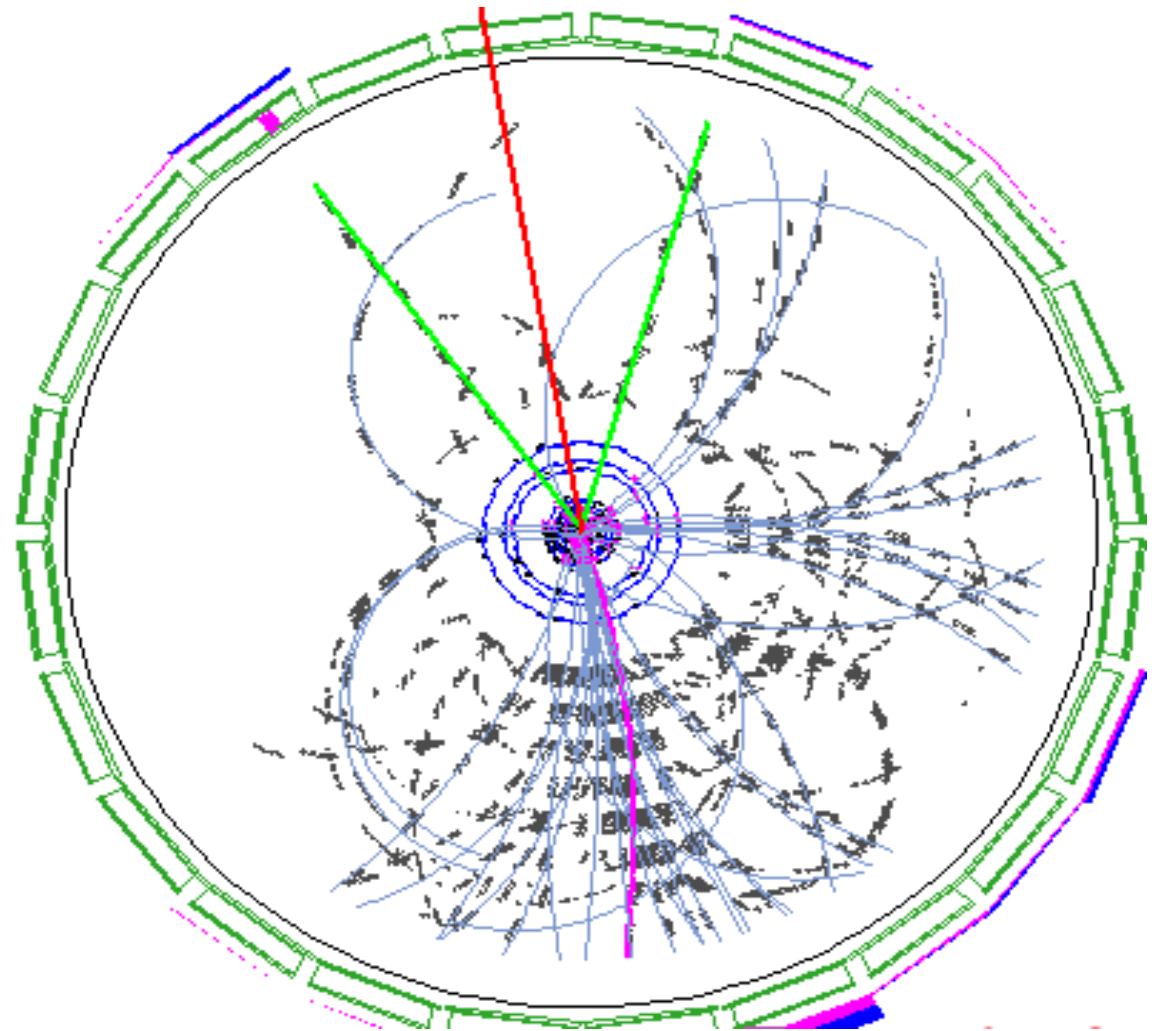
$$mv^2/R = evB,$$

$$p_T = eBR$$

CDF: Insufficient precision on  $B$  and  $R$  for  $W$  mass measurement

## *In-situ calibration:*

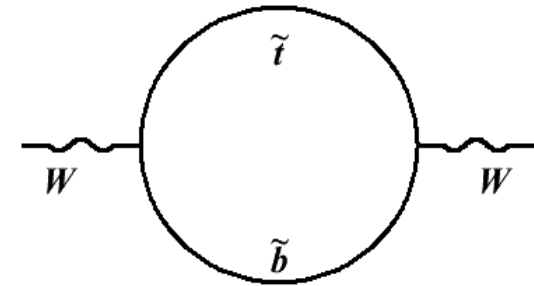
- (1) Apply relative alignment of drift chamber wires
- (2) Determine momentum scales such that  $J/\psi$ ,  $Y$ , and  $Z$  mass measurements result in the world-average values



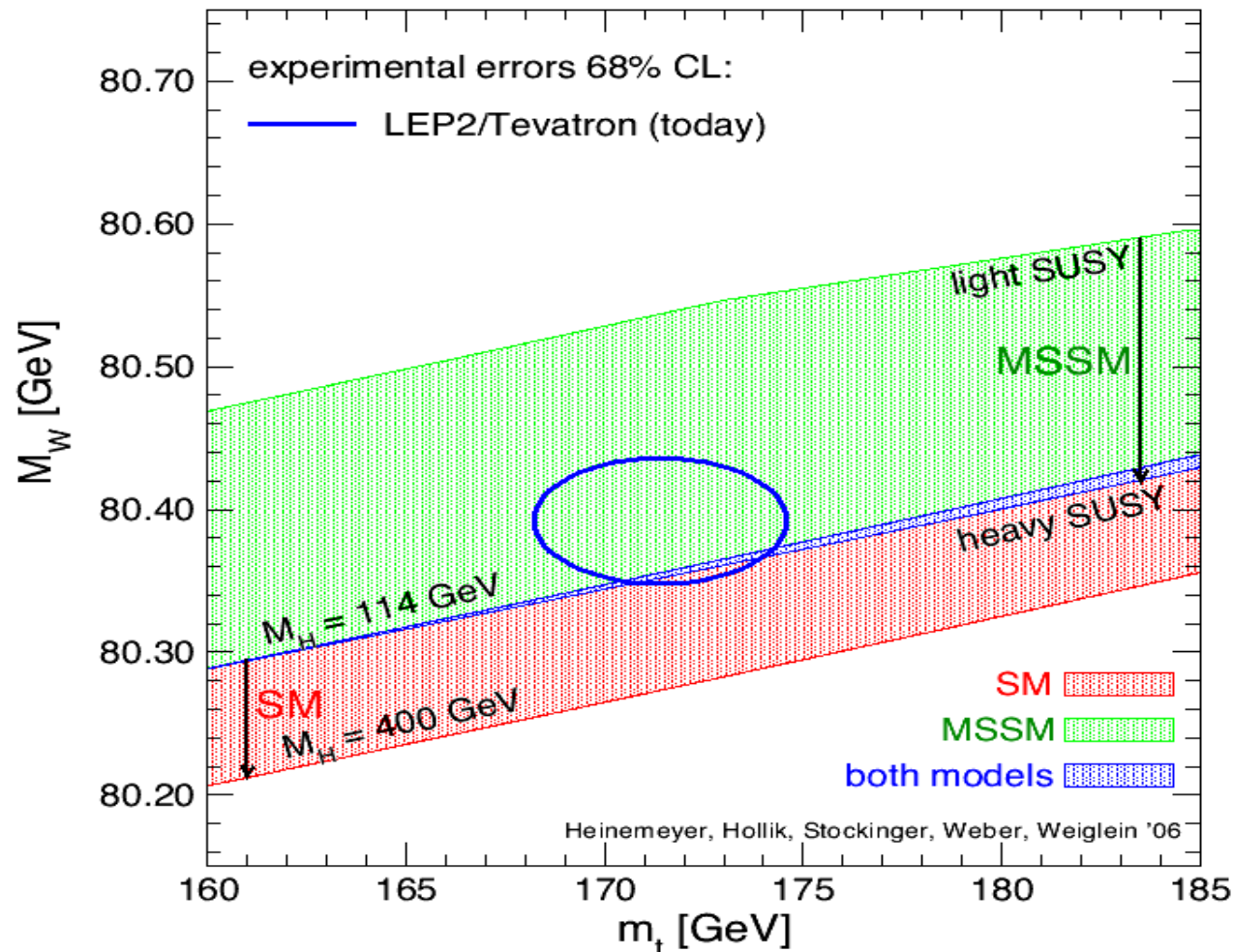
Combine results to obtain scale for  $m_W$  measurement

# Effect on New Physics Models

Additional space-time symmetry  
(Supersymmetry) would affect the  $W$  mass

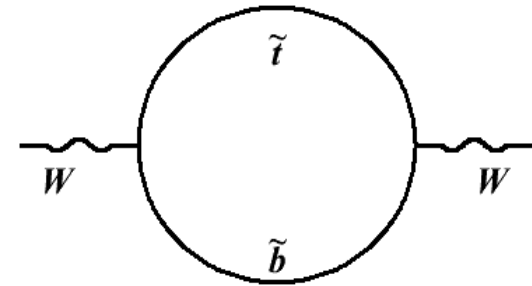


*Previous world average:*



# Effect on New Physics Models

Supersymmetry now preferred at  $1\sigma$  level...



*New world average:*

