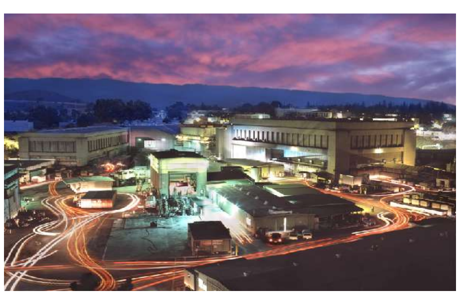
First Run II Measurement of the *W* Boson Mass with CDF

Chris Hays,
University of Oxford



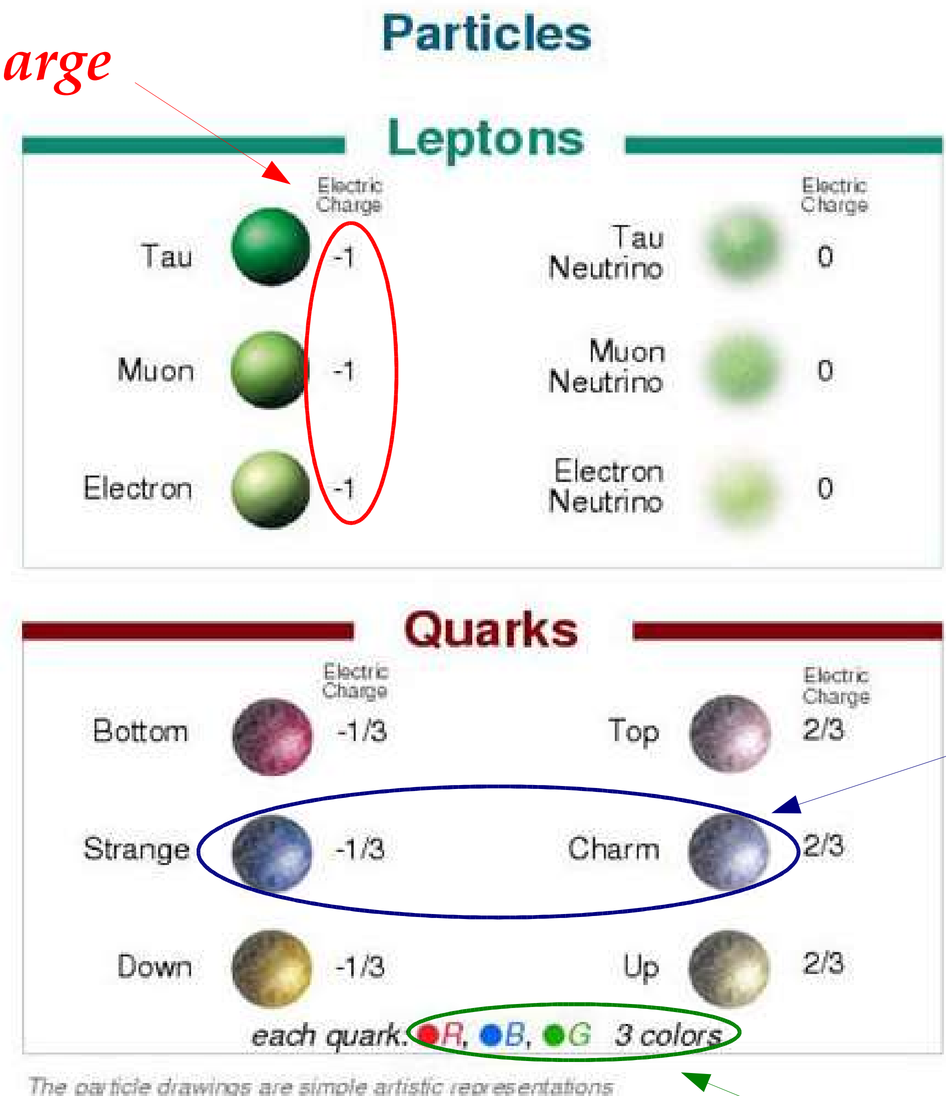
SLAC Experimental Seminar

April 10, 2007

The Standard Model

"Electromagnetic" charge

Interact via γ



"Weak" charge

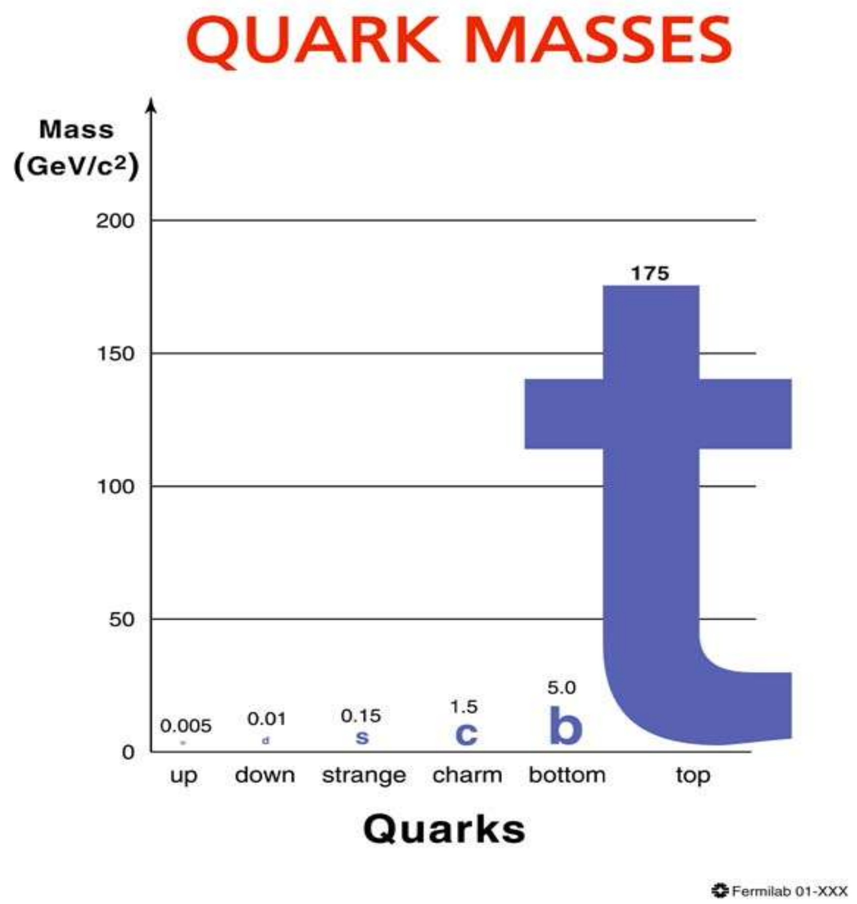
Interact via *W, Z*

"Strong" charge

Interact via *g*

Electroweak Symmetry Breaking

Non-zero particle mass breaks the weak symmetry

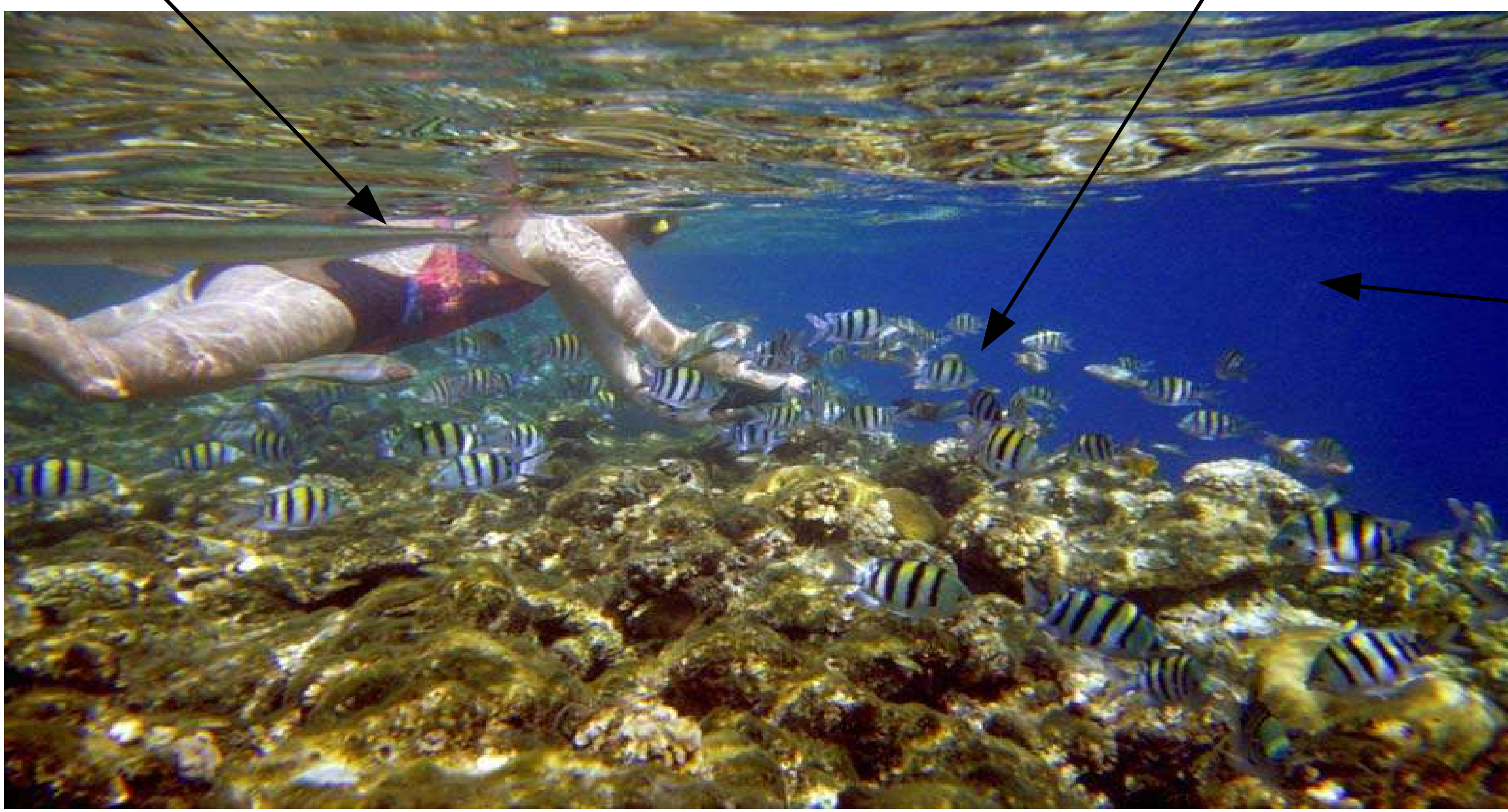


Particle Mass

Particle mass determined by viscosity in the Higgs sea

Top quark

Up quarks



Higgs
Vacuum
Energy

Higgs Boson

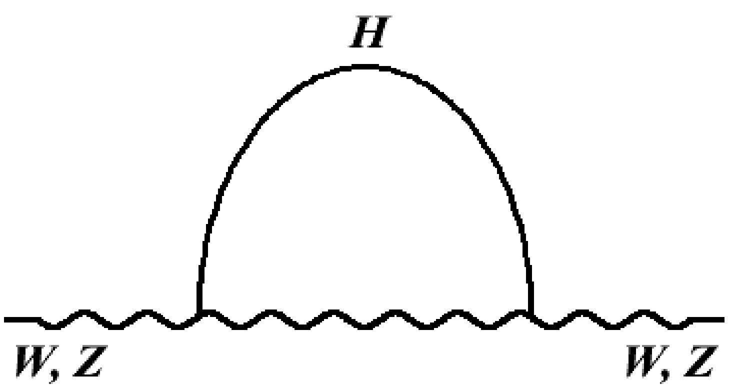
Vacuum expectation value determined by effective weak coupling:

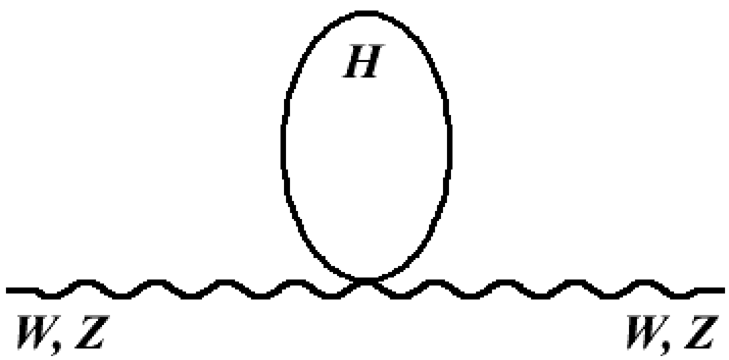
$$\langle \phi \rangle = 1/(\sqrt{8} G_F)^{1/2} = 174 \text{ GeV}$$

(G_F measured from muon decay to 0.0009%)

Higgs mass and self-couplings not predicted by Standard Model

→ However, Higgs mass indirectly affects gauge boson masses via loop corrections:





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

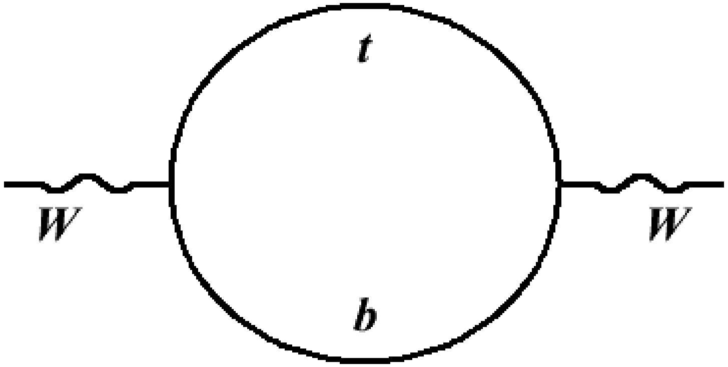
W Boson Mass

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

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

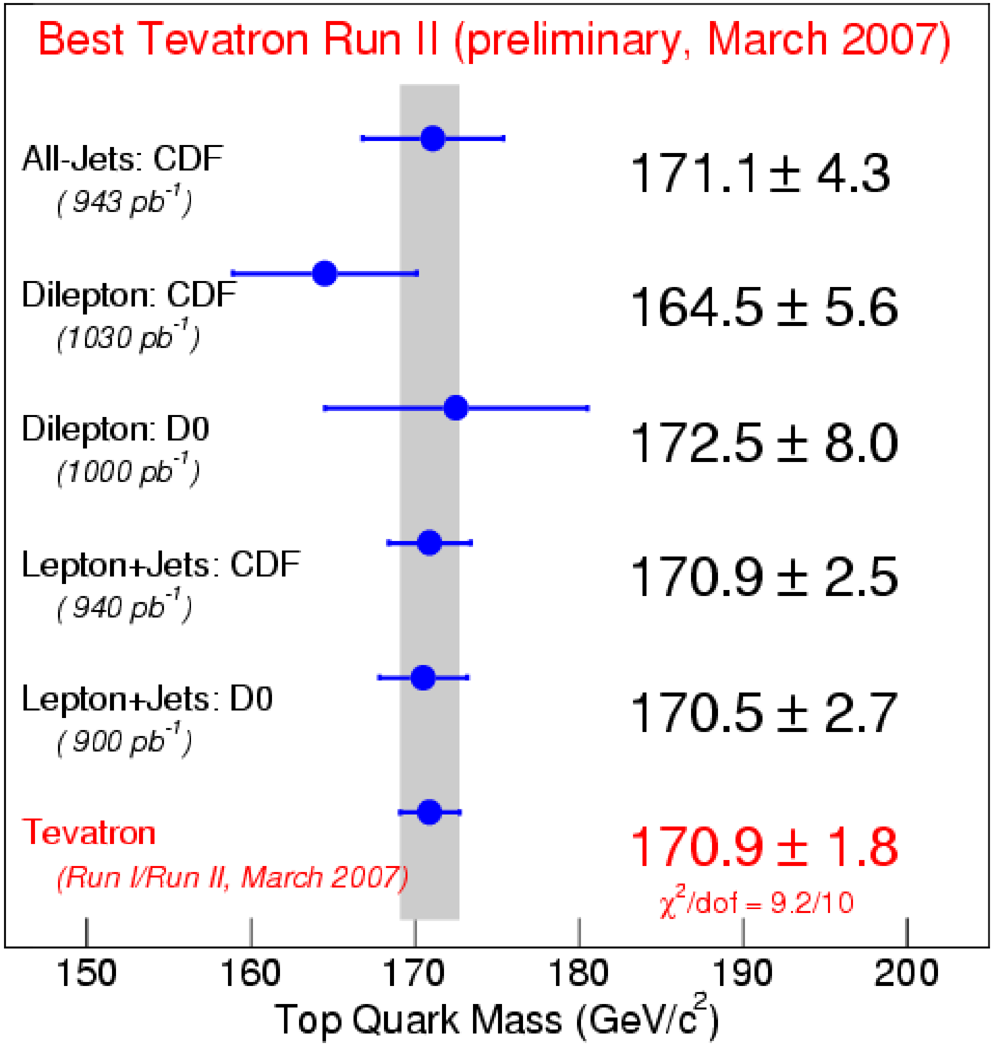
(“on-shell scheme”)

Δr: O(3%) radiative corrections dominated by *tb* and Higgs loops



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

Measured Top Mass



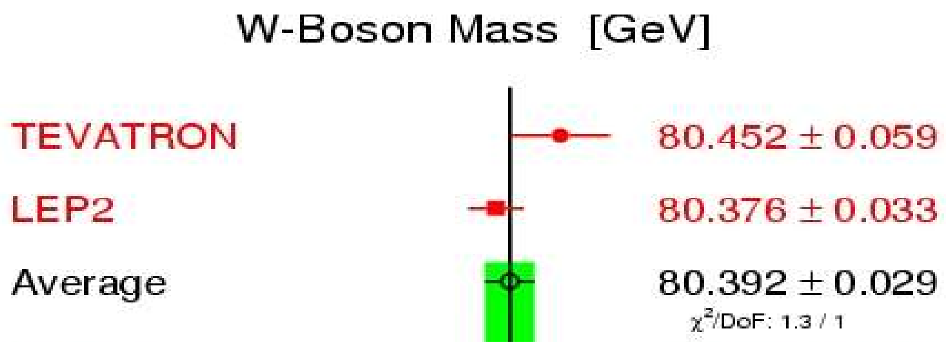
Top mass now measured to 1.8 GeV (1.1%)

W Mass Prediction and Measurement

W mass uncertainty from input parameters:

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

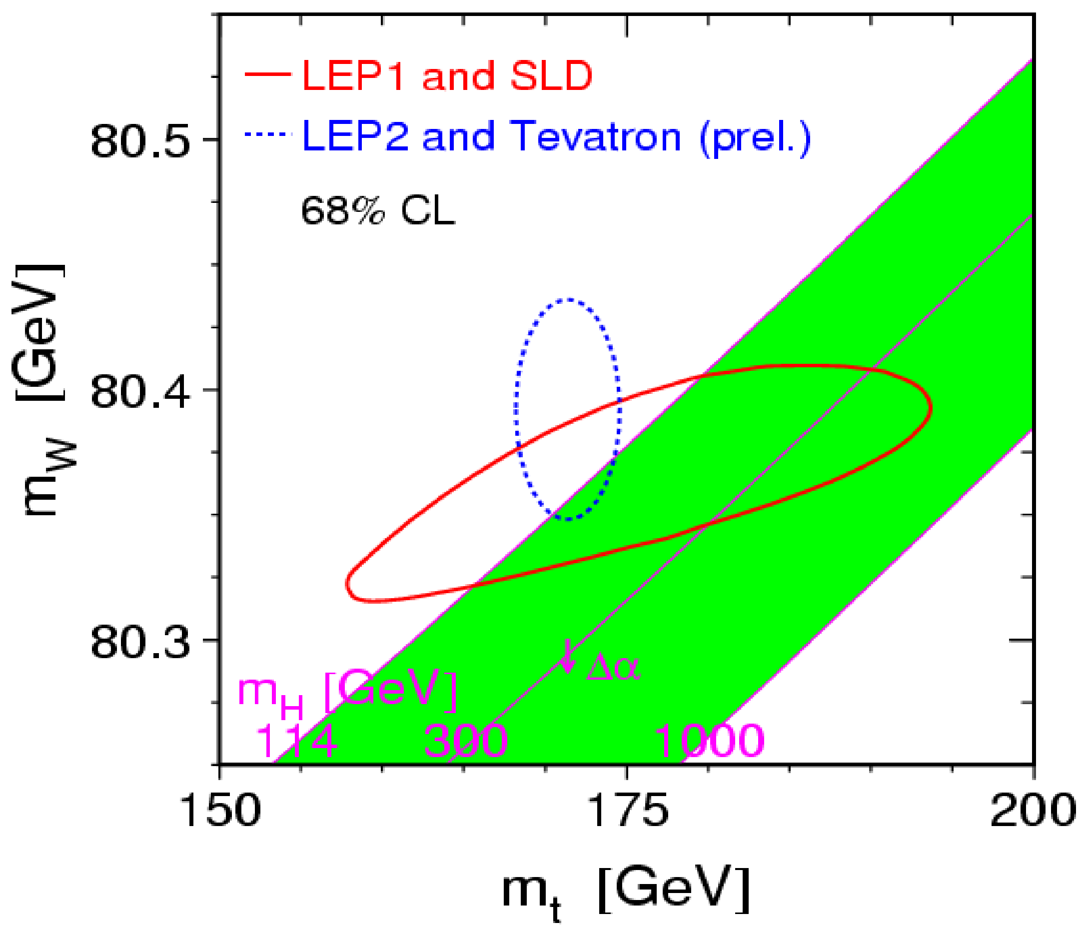
Direct W mass measurement



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

Need to reduce δm_W to further constrain Higgs mass

Higgs Mass Prediction

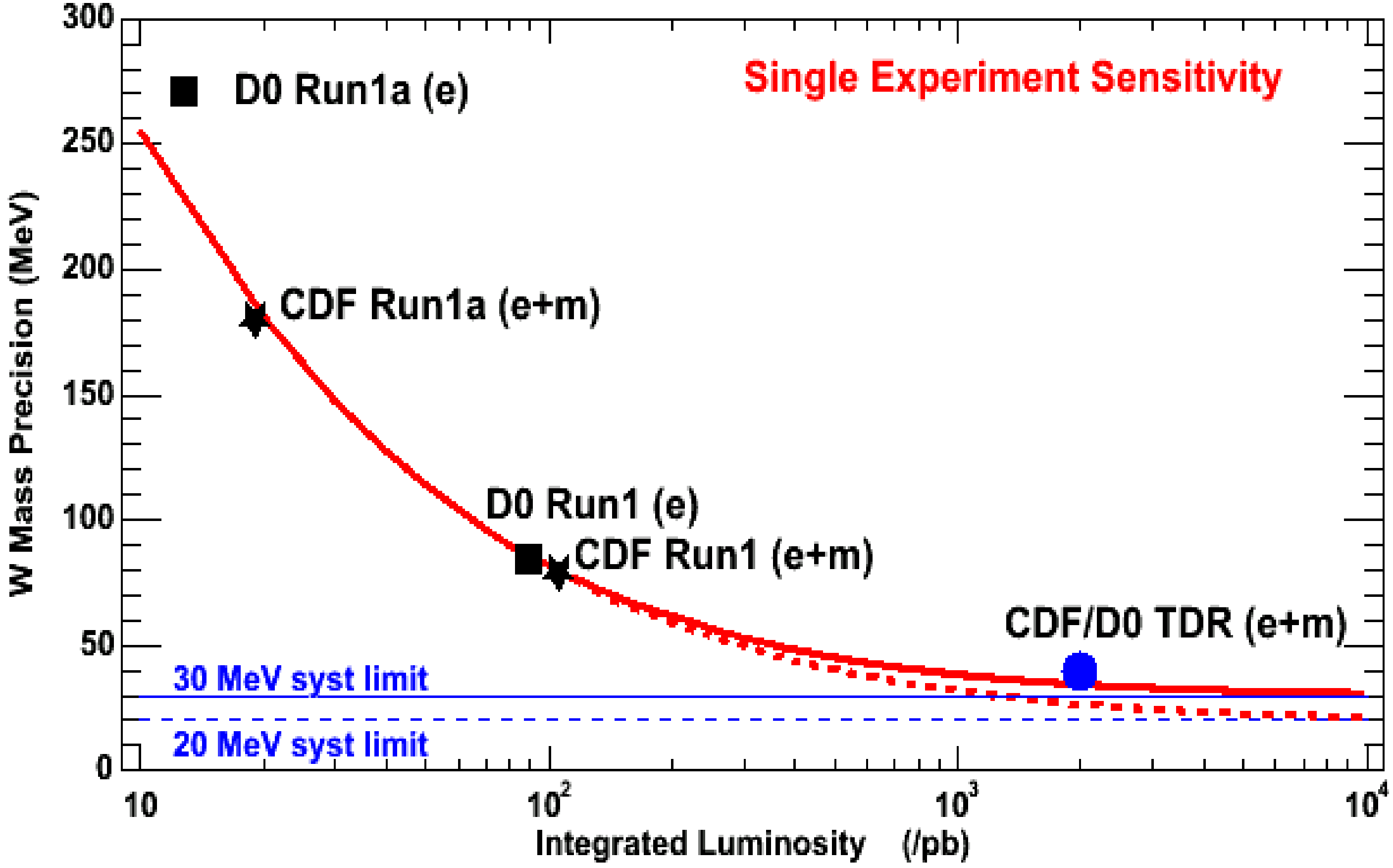


Predicted Higgs mass from W loop corrections:

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

Direct search from LEP II: $m_H > 114.4$ GeV at 95% CL

Tevatron *W* Mass Measurement



Projection with 2 fb^{-1} of data:

δm_W = 40 MeV per experiment

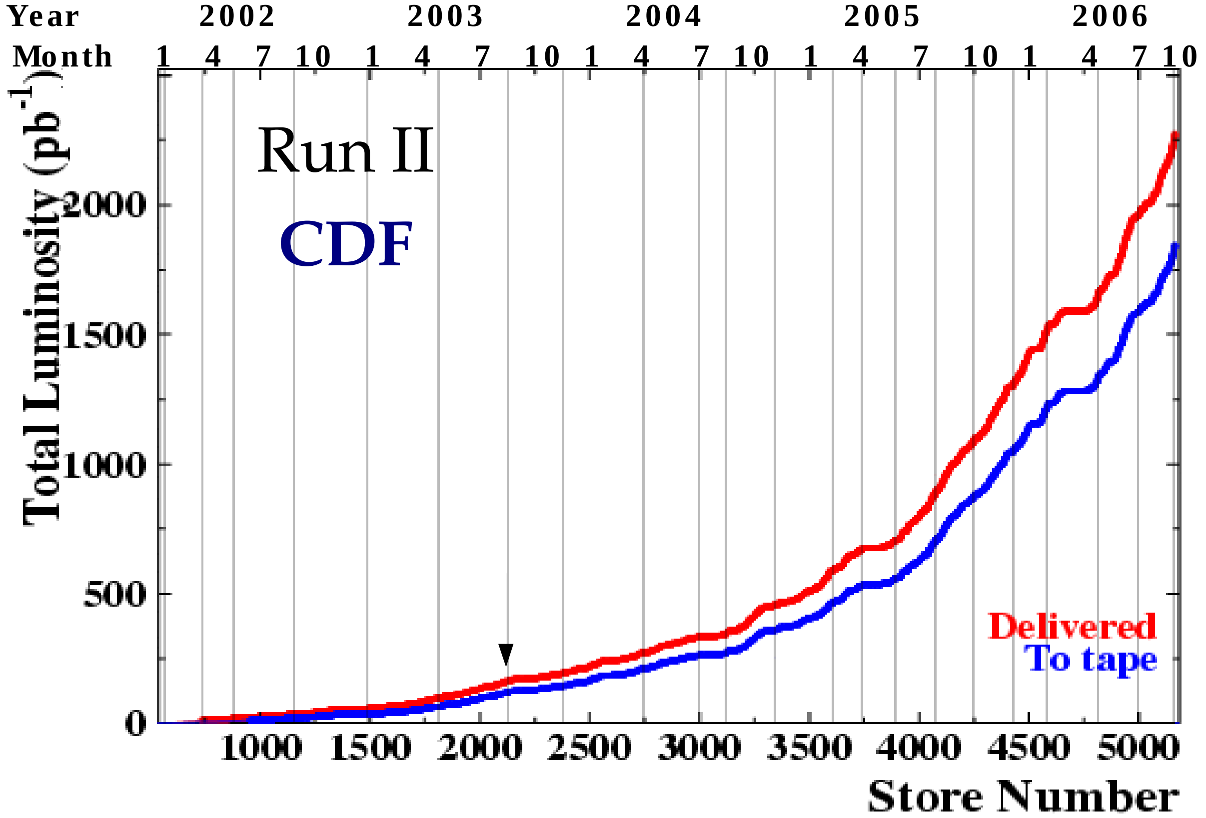
Tevatron Run I Uncertainties

	CDF μ	CDF e	DØ e
W statistics	100	65	60
Lepton energy scale	85	75	56
Lepton resolution	20	25	19
Recoil model	35	37	35
$pT(W)$	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

Tevatron Run II

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

Current Run II: **15**x Run I data set

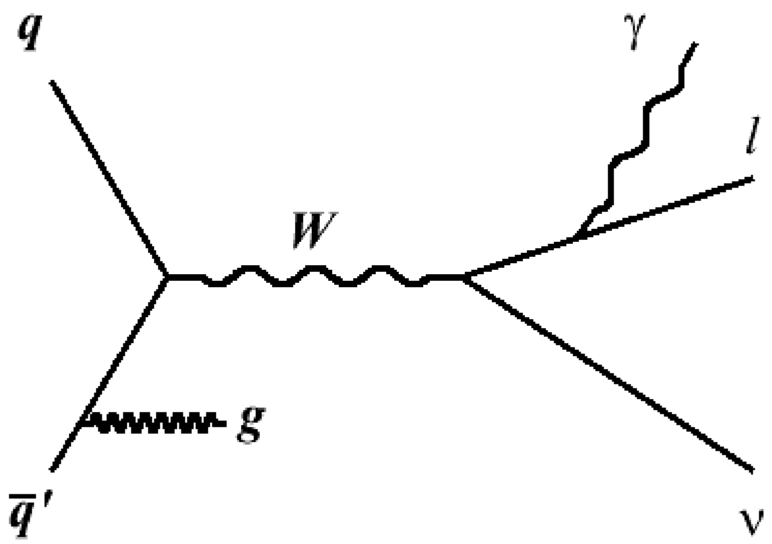


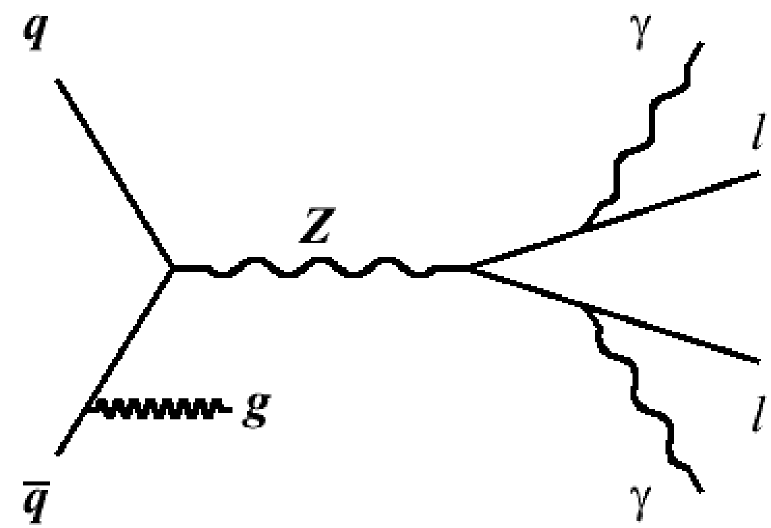
Today: First Run II W mass measurement

(CDF 200 pb^{-1})

W & Z Boson Production and Decay

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





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

$\sigma(Z \rightarrow ll)$ = 254.9 pb

After event selection
(l, ν E_T > 30 GeV):

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

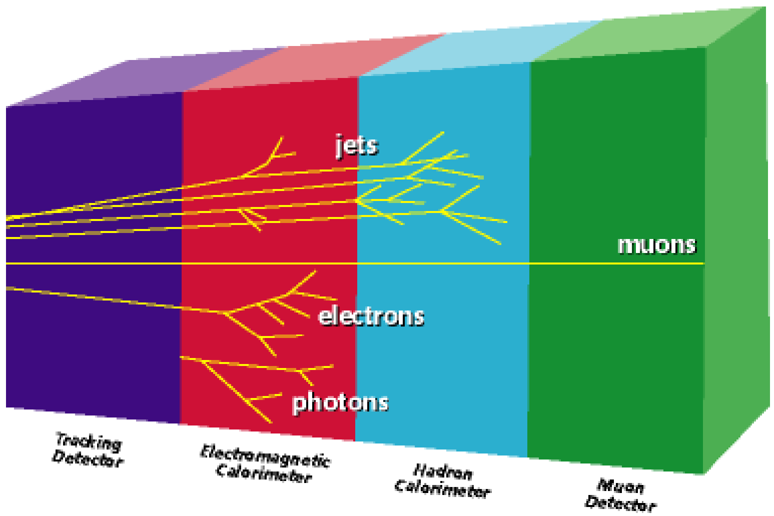
63,964 $W \rightarrow e\nu$ candidates

After event selection
(l E_T > 30 GeV):

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

2,919 $Z \rightarrow ee$ candidates

CDF Detector



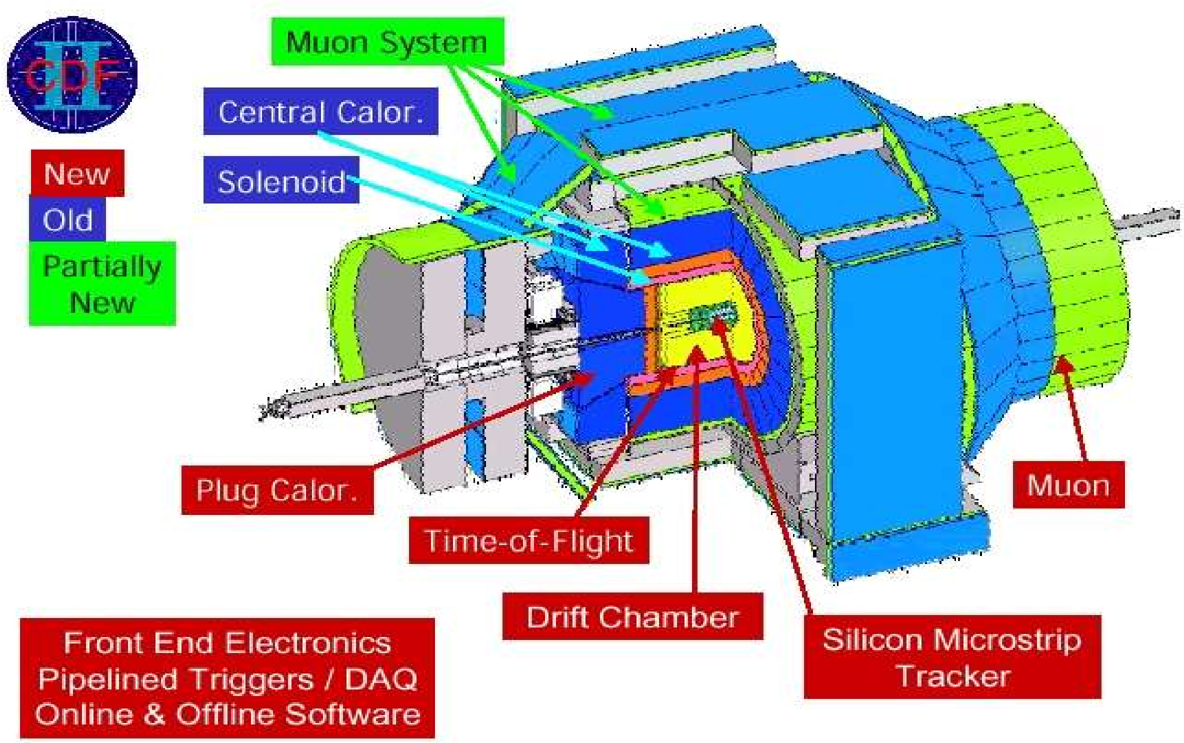
High-precision tracking drift chamber

$\delta p_T/p_T = 0.05\%\ p_T$: 2% for 40 GeV μ

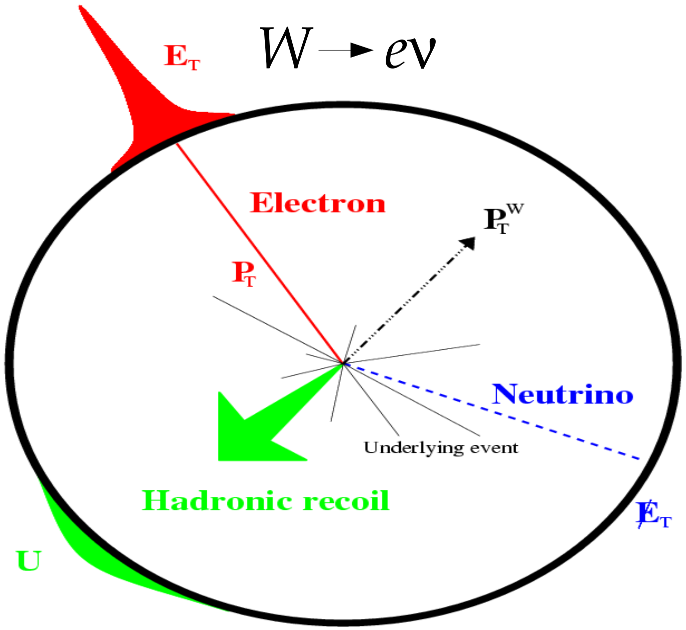
High-precision electromagnetic calorimeter

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

3% for 40 GeV e



Measurement Strategy



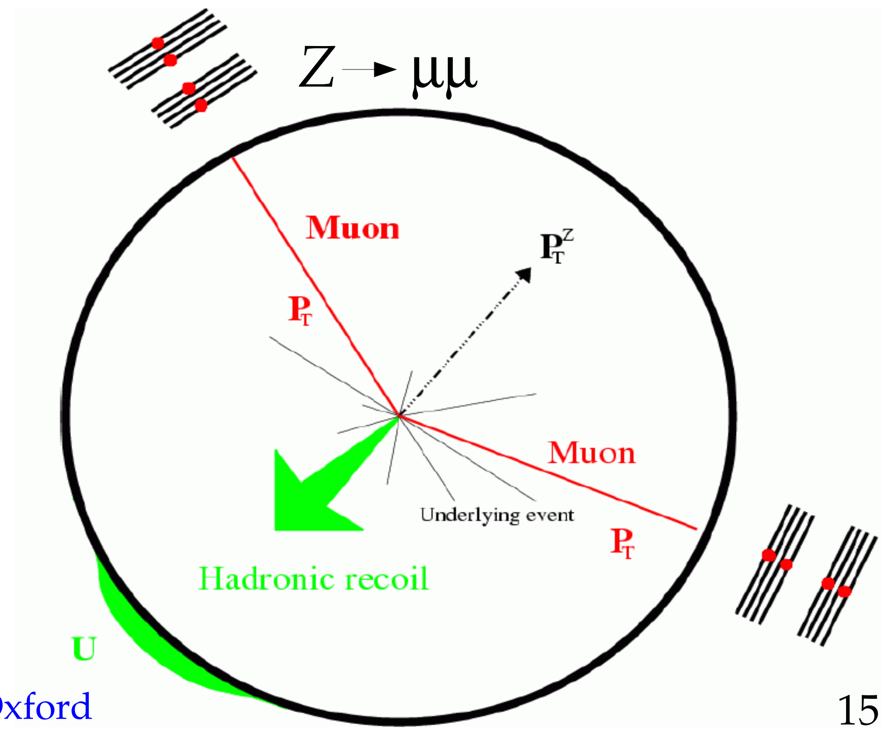
Calibrate $l^{\pm}$ track momentum with mass measurements of J/ψ and Y decays to μ

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*, μ

Cross-check with W recoil distributions

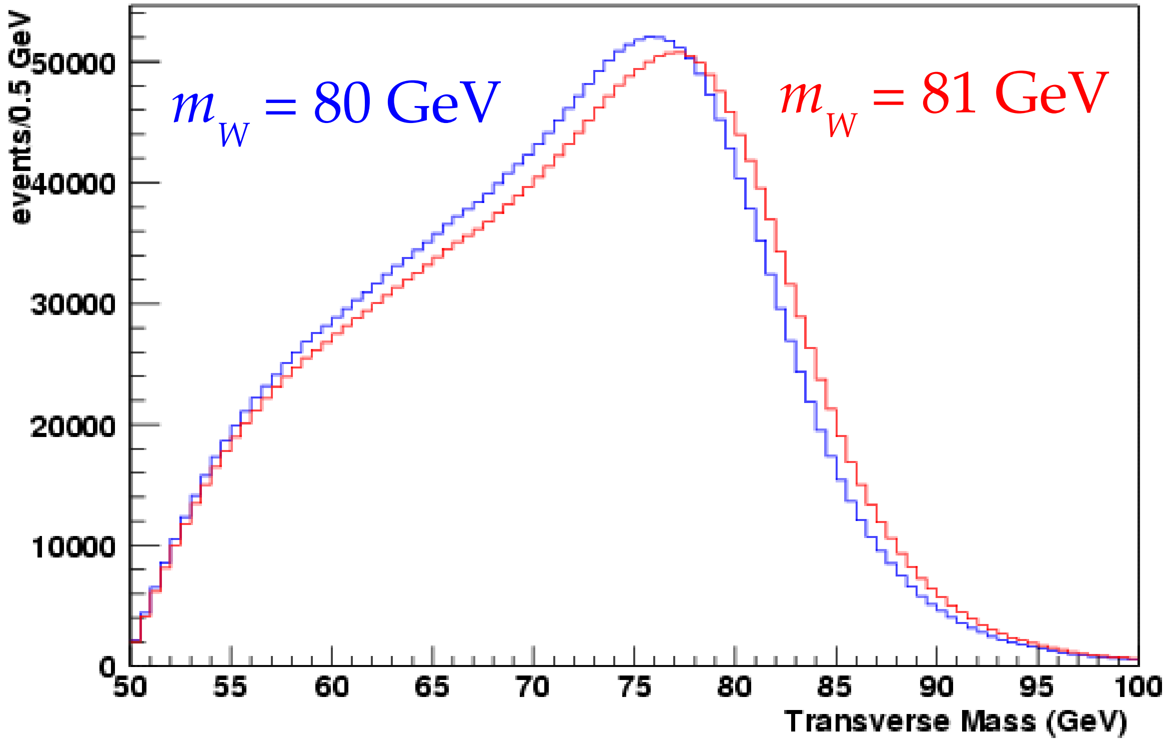


Combine information into transverse mass:

$$m_T = \sqrt{E_T \not{E}_T (1 - \cos\Delta\phi)}$$

Statistically most powerful quantity for m_W fit

Transverse Mass Distribution



Distribution peaks just below m_W and falls sharply just above m_W

Momentum Scale Calibration

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

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

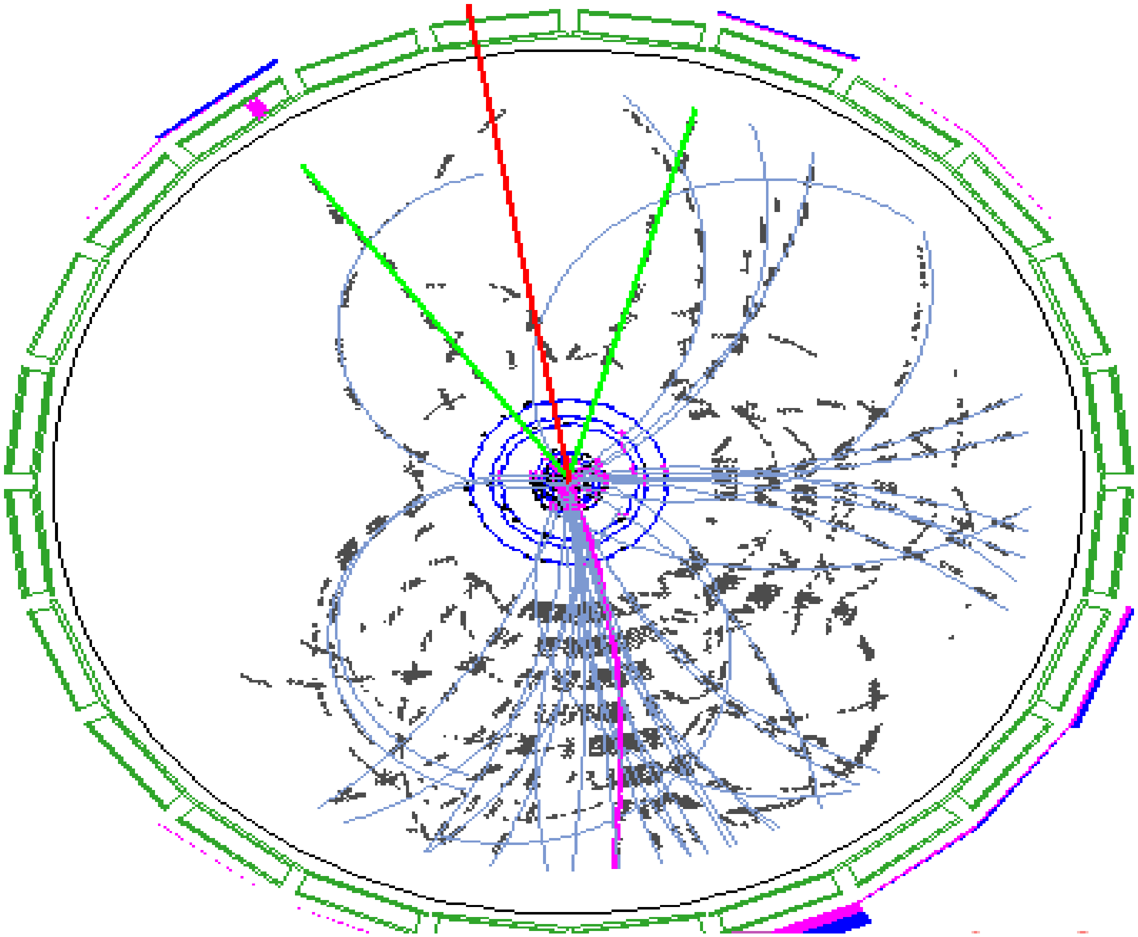
$$p_T = eBR$$

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

In-situ calibration:

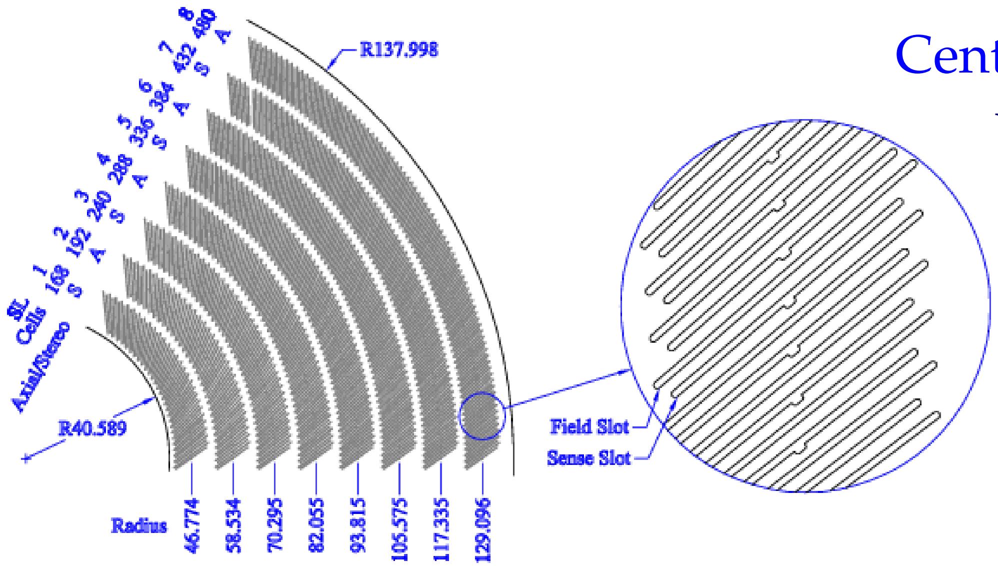
(1) Apply relative alignment of drift chamber wires

(2) Determine momentum scales such that J/ψ, Υ, and Z mass measurements result in the world-average values →



Combine results to obtain scale for m_W measurement

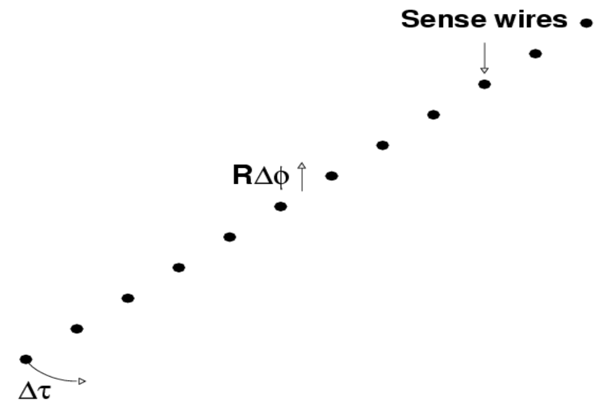
Tracker Alignment

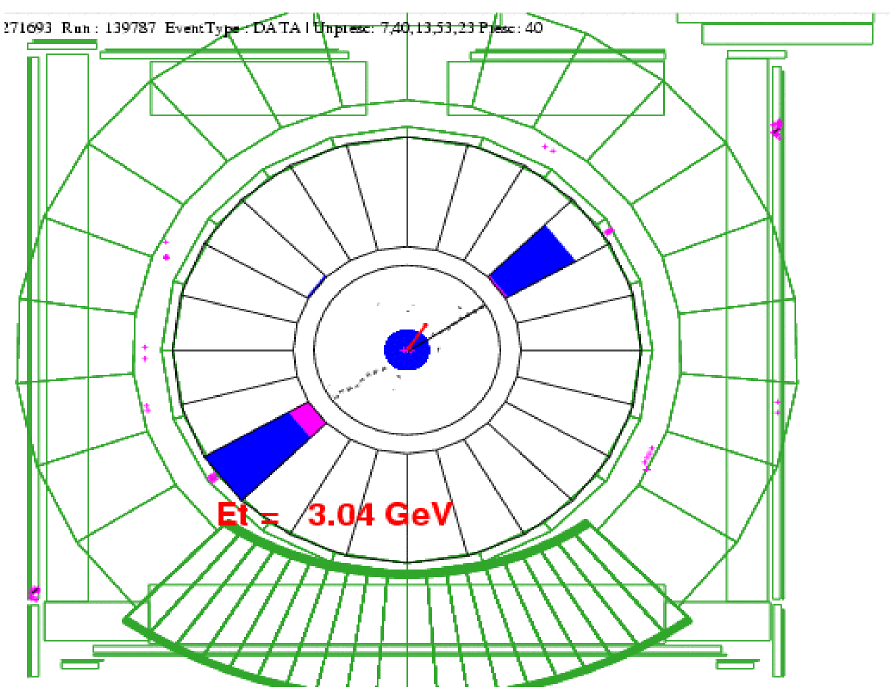


Central Outer Tracker: Open-cell drift chamber

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

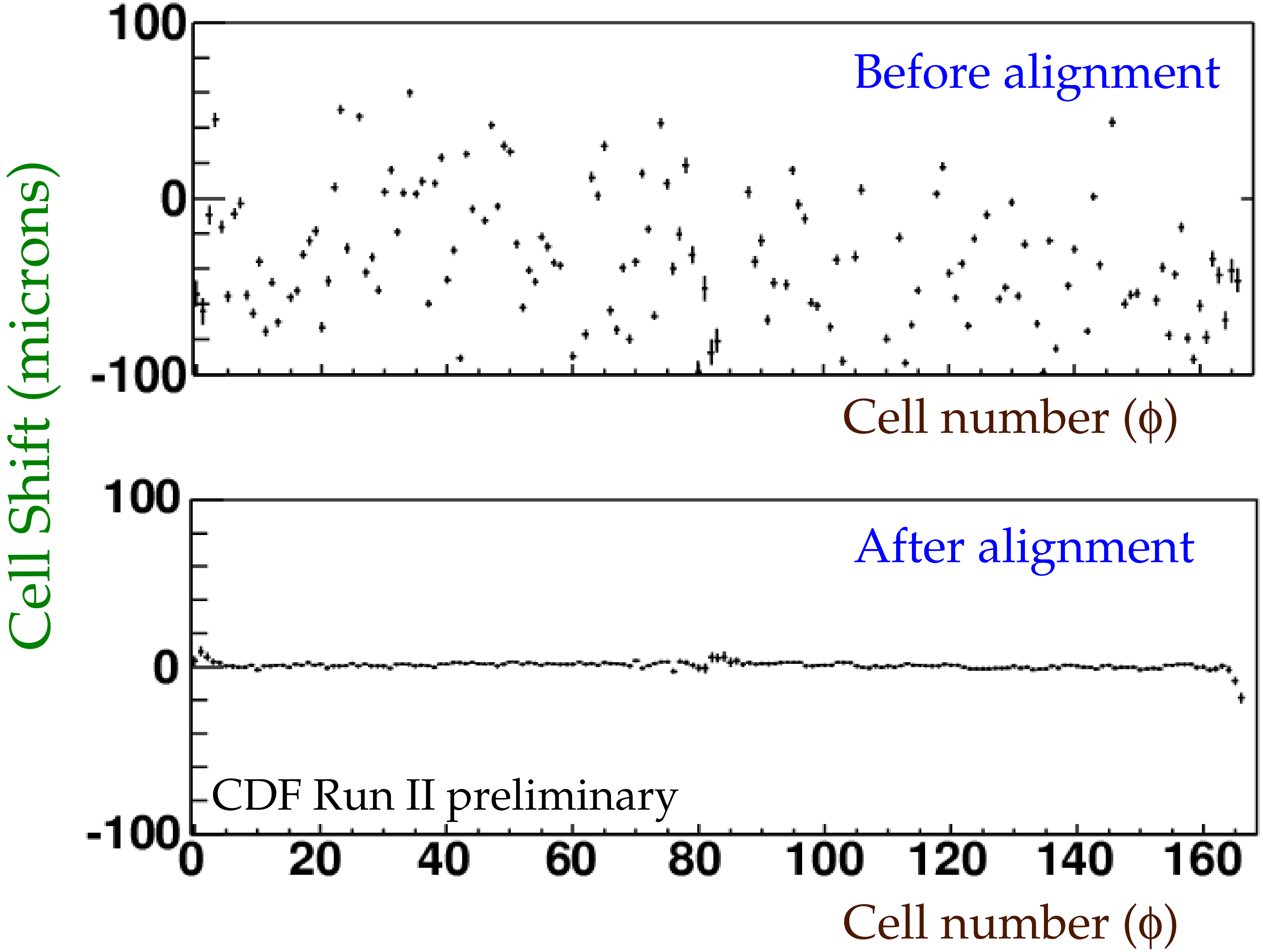
Fit a single 'dicosmic' to track segments on opposite sides of the chamber

Measure cell displacement

(Kotwal, Gerberich, Hays, NIM A 506, 110 (2003))

Alignment Example

Inner 'Superlayer:'

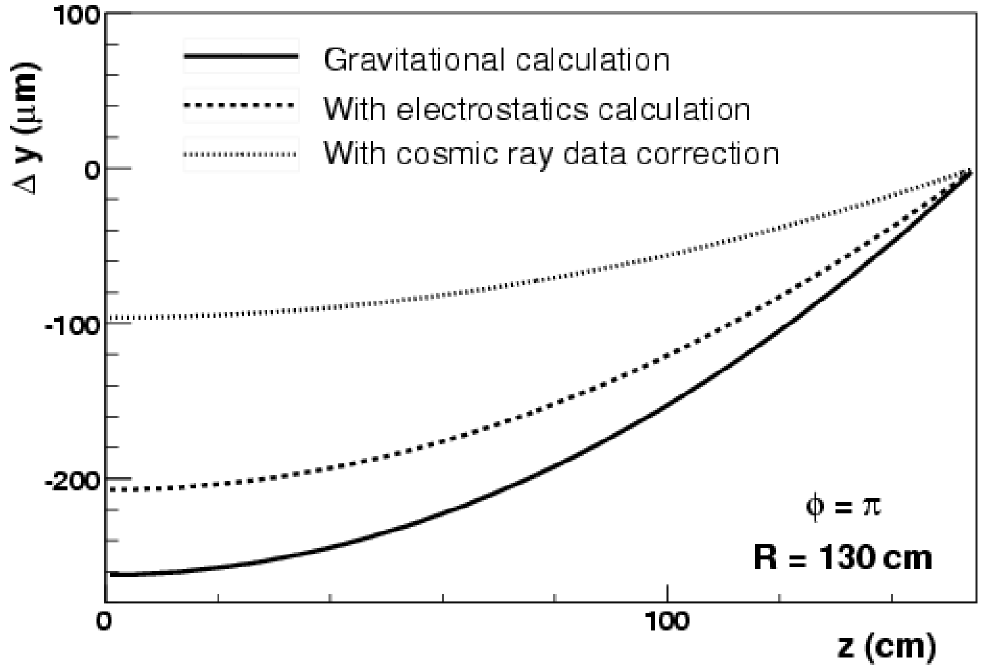


Wire Alignment

Wire shape along z-axis determined by:

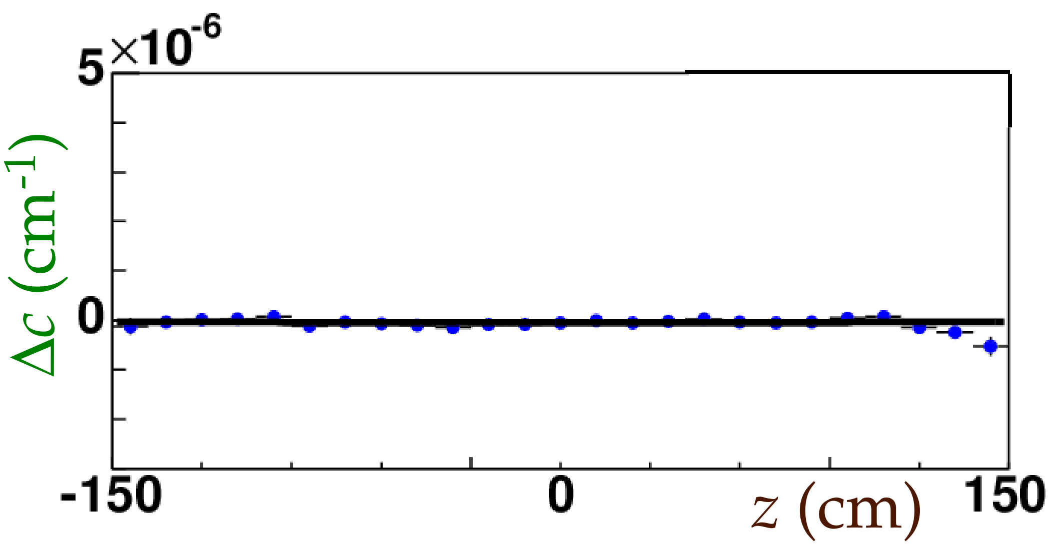
Gravitational sag

Electrostatic effects



Apply additional correction based on cosmic ray study

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



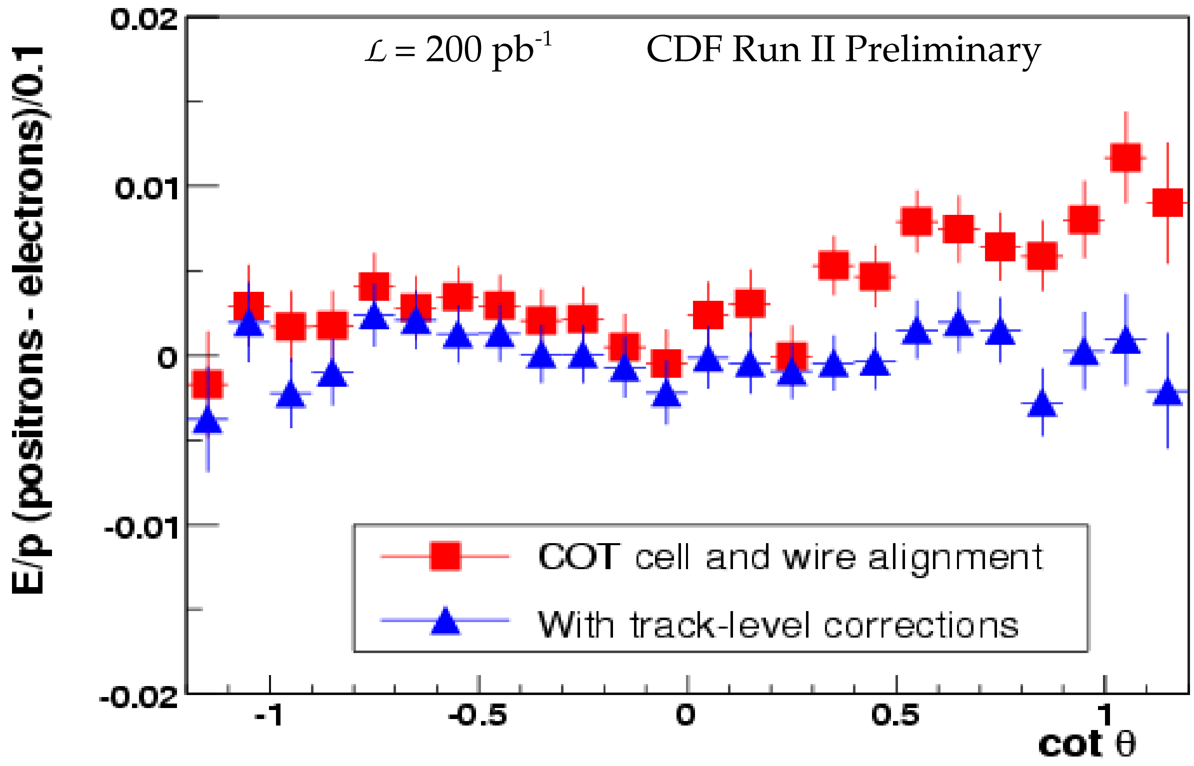
Final correction removes z-dependent curvature biases

Track-Level Corrections

Determine curvature 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 δm_W = **6 MeV**

Mass Measurements

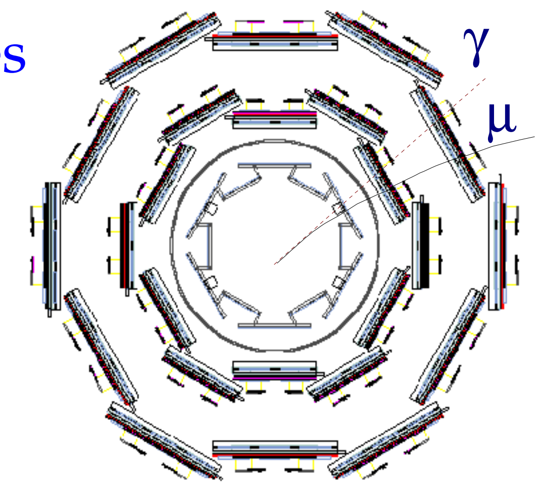
Template mass fits to J/ψ, Υ, Z resonances in muon decay channels

Fast detector simulation models relevant physical processes

internal bremsstrahlung

ionization energy loss

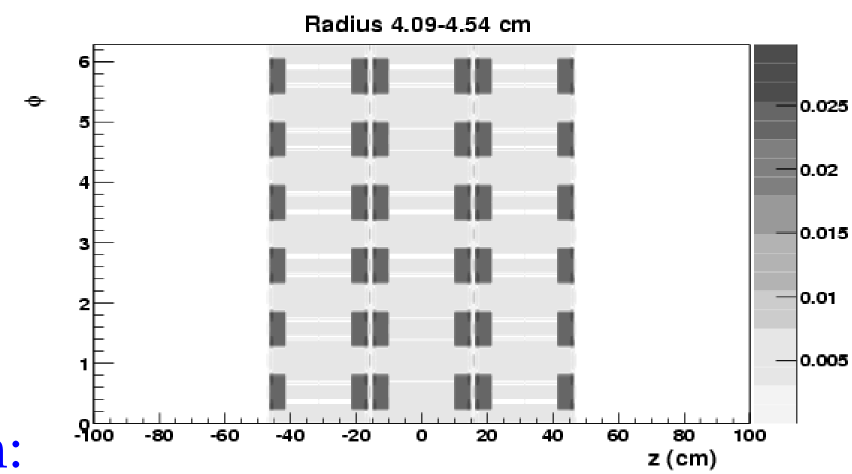
multiple scattering



Simulation includes event reconstruction and selection

Detector material model

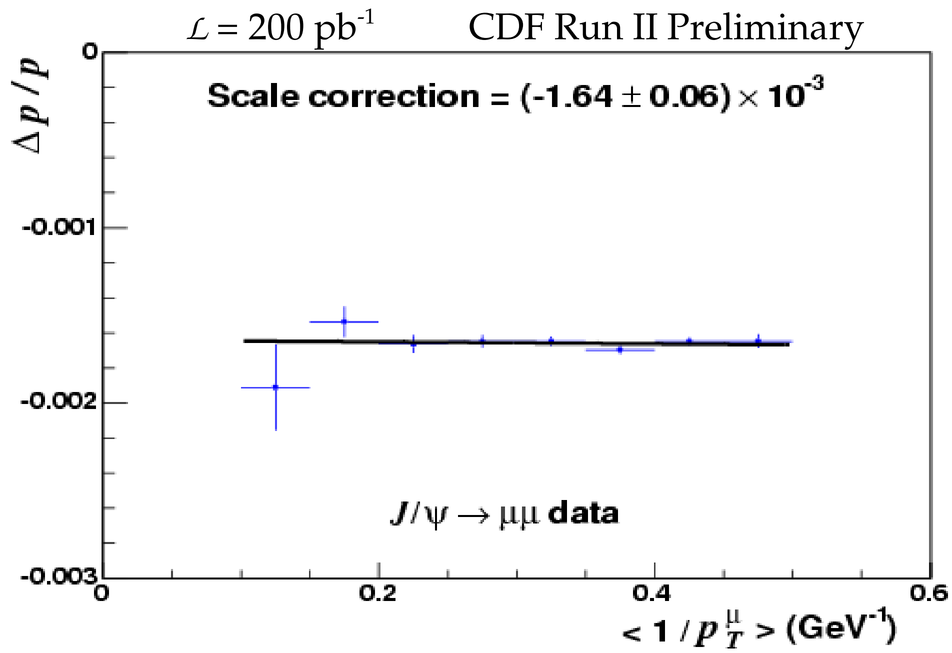
Map energy loss and radiation lengths in each detector layer



One material parameter determined from data:

Overall material scale

J/ψ Mass Measurement



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

Fit mass as a function of mean inverse p_T

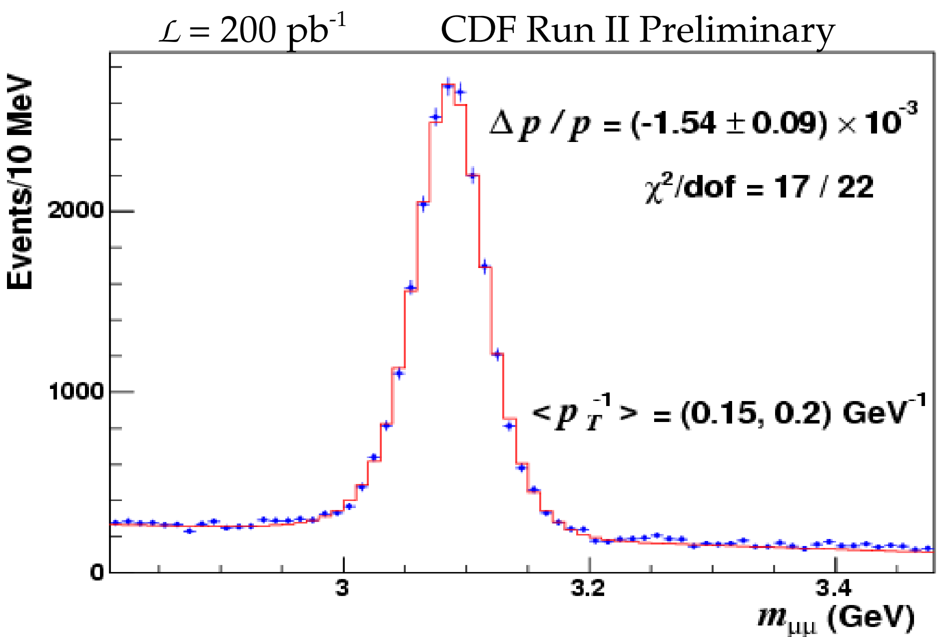
Slope affected by energy loss modelling

Scale detector material by 0.94 to remove slope

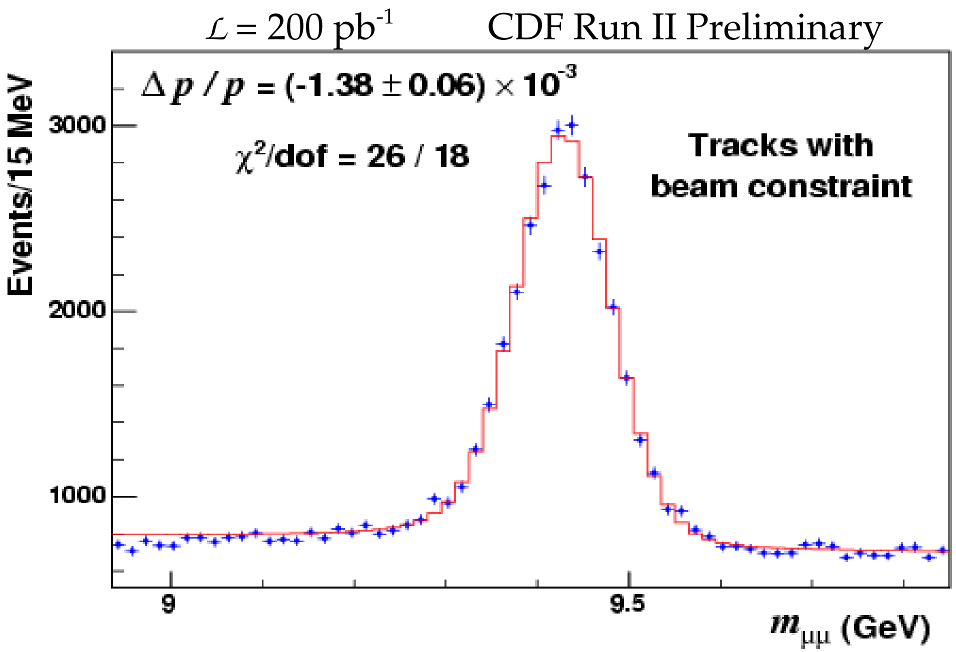
Measurement dominated by systematic uncertainties

QED and energy loss model:

0.20×10^{-3}



Mass Measurement



34,618 Υ → μμ candidates

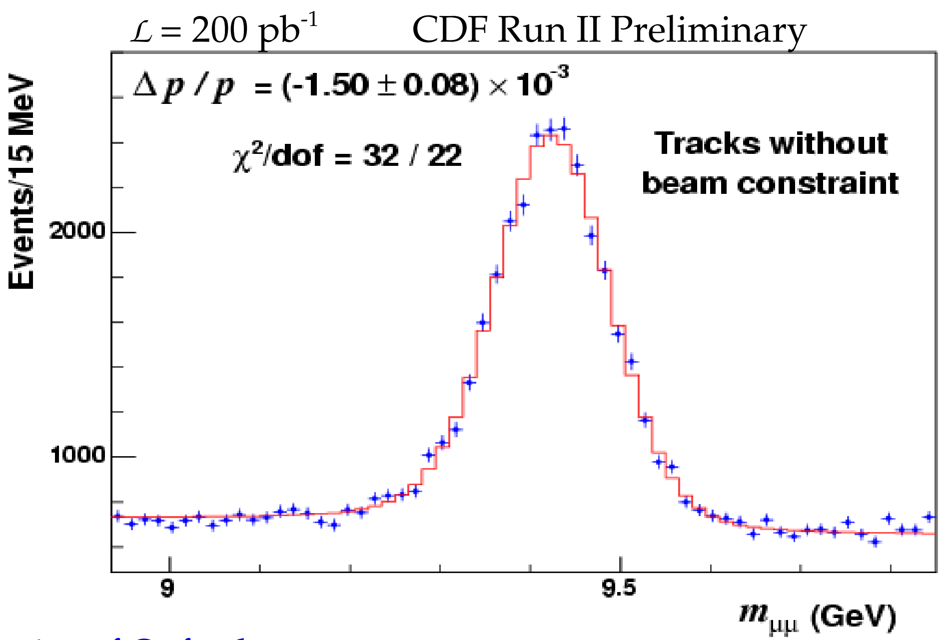
Short lifetime allows a track constraint to the beam line

Improves resolution by a factor of ≈3

Test beam constraint by measuring mass using unconstrained tracks

Correct by half the difference between fits

Take correction as a systematic uncertainty



Combined Momentum Scale

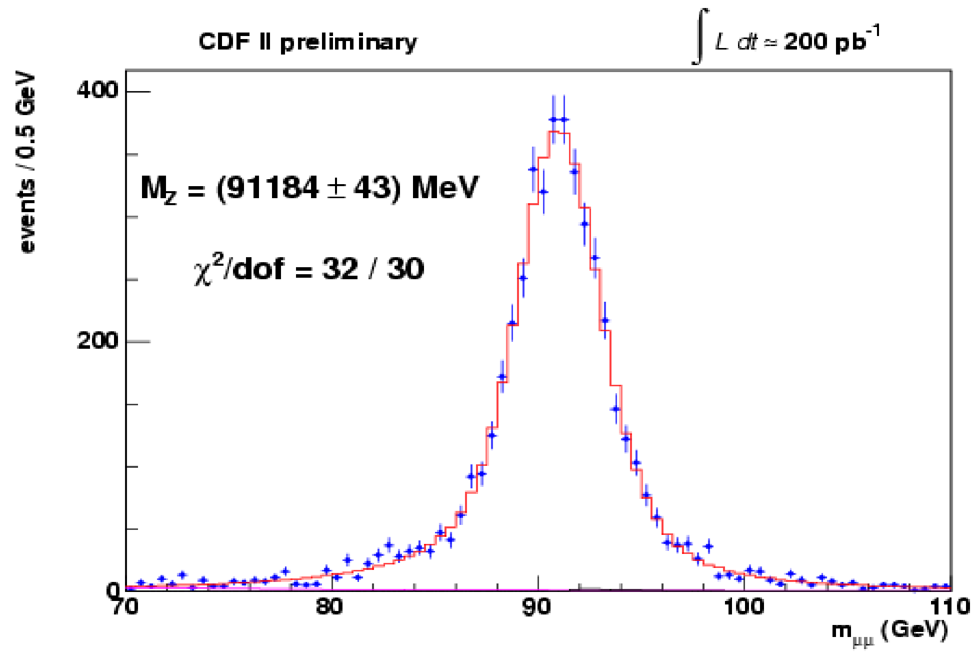
$\Delta p/p = (1.50 \pm 0.19) \times 10^{-3}$

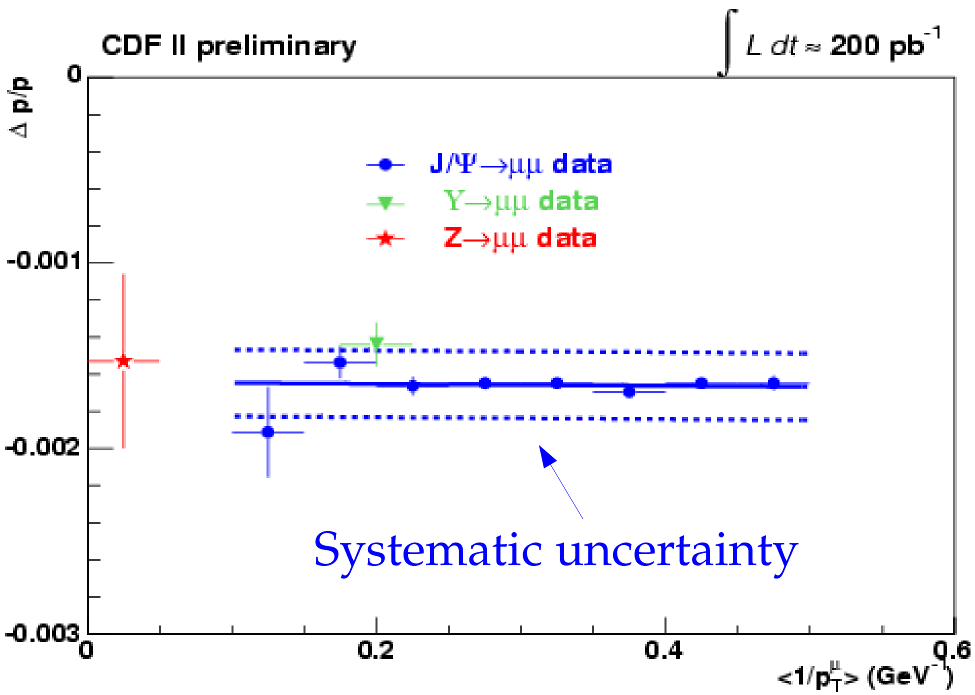
Systematic uncertainties:

Source	J/ψ ($\times 10^{-3}$)	Υ ($\times 10^{-3}$)	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

Momentum Scale Cross-Check

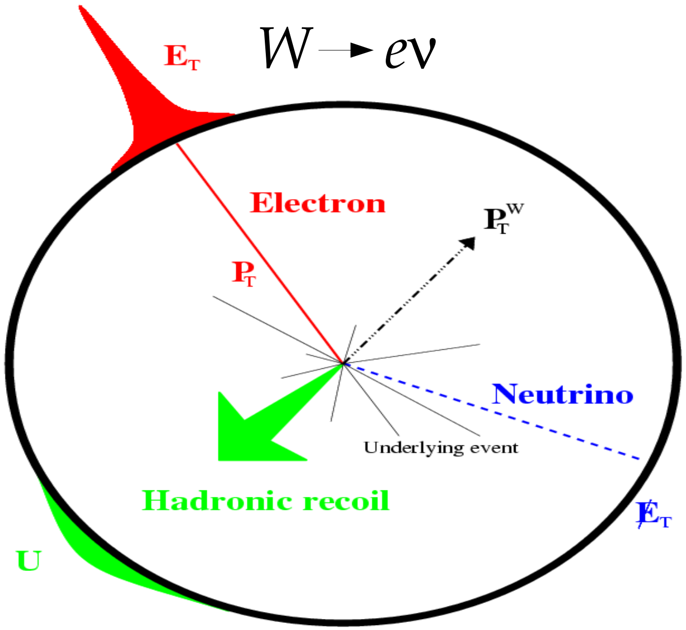
Use calibrated momentum scale to measure *Z* mass





All measurements consistent

Measurement Strategy



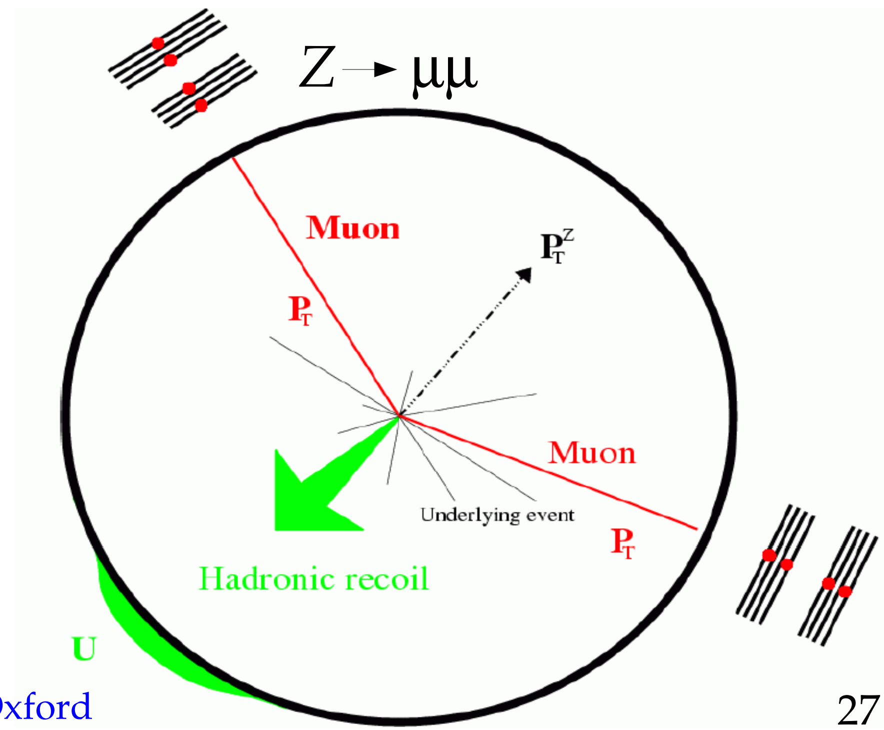
✔ Calibrate $l^{\pm}$ track momentum with mass measurements of J/ψ and Y decays to μ

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*, μ

Cross-check with W recoil distributions



Combine information into transverse mass:

$$m_T = \sqrt{E_T \not{E}_T (1 - \cos\Delta\phi)}$$

Statistically most powerful quantity for m_W fit

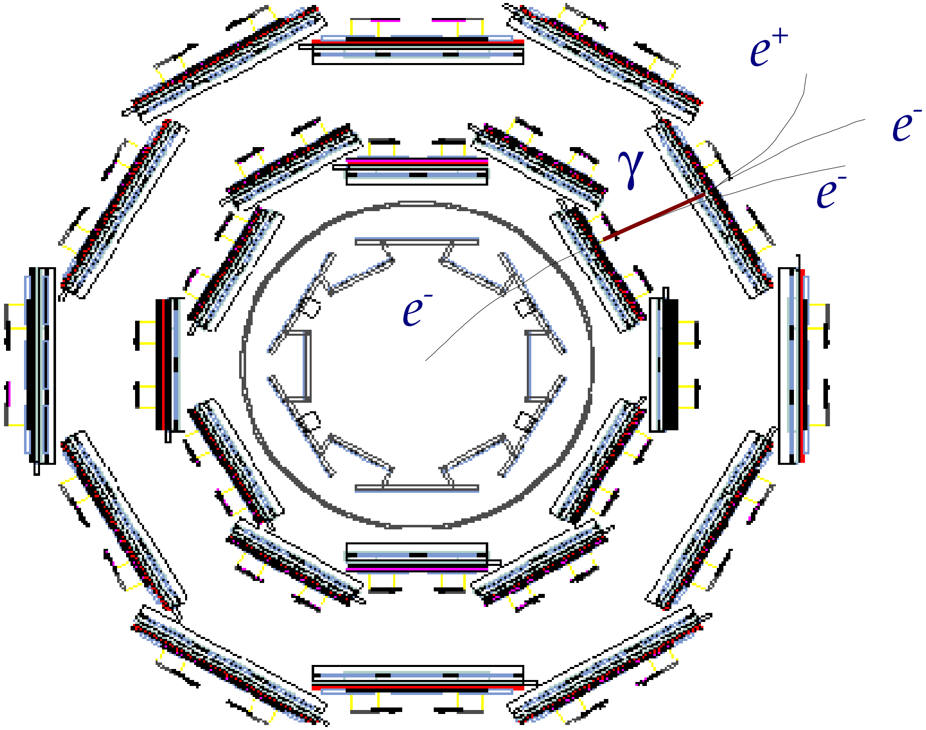
Calorimeter Energy Calibration

Calibrate electron energy using electron track momentum

First step: validate model of electrons in tracker

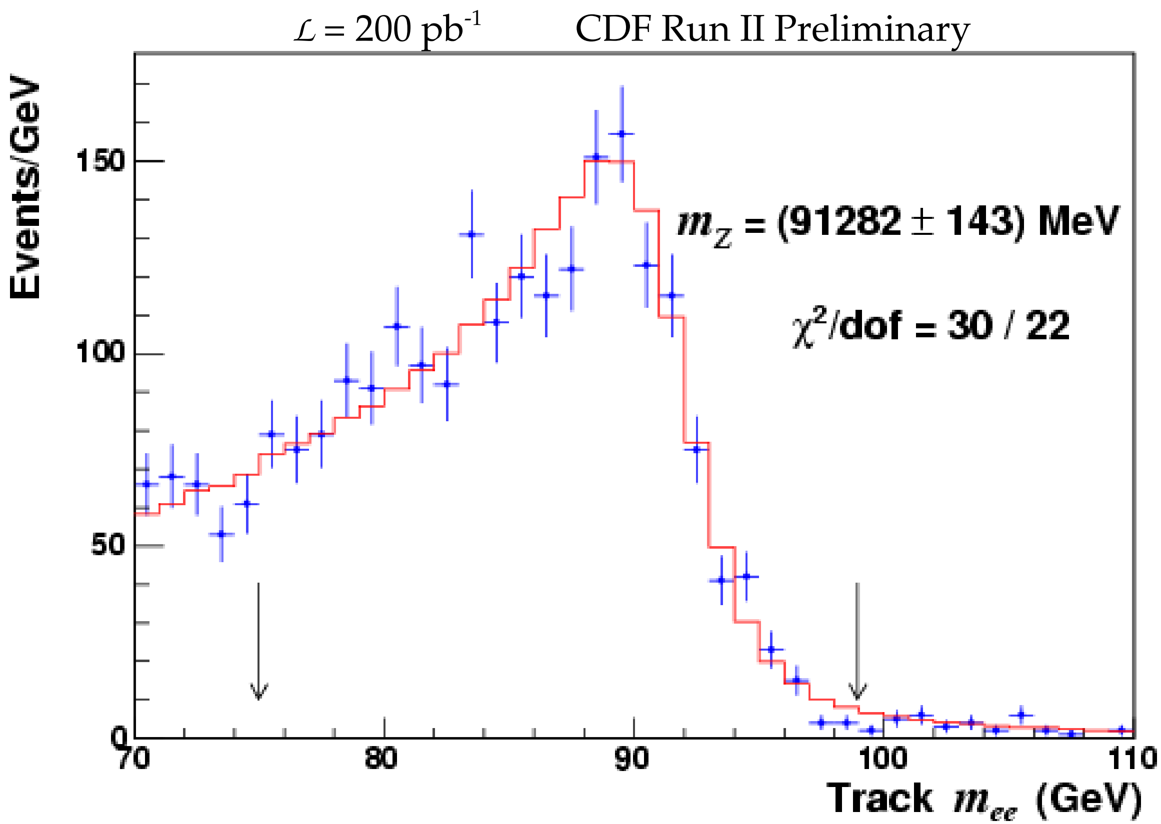
Additional physical effects beyond those associated with muons:

Photon radiation and conversion in tracker



Electron Track Model Validation

Fit Z mass reconstructed from electron track momenta



Measured value consistent with world average value (91188 MeV)

Full Electron Simulation

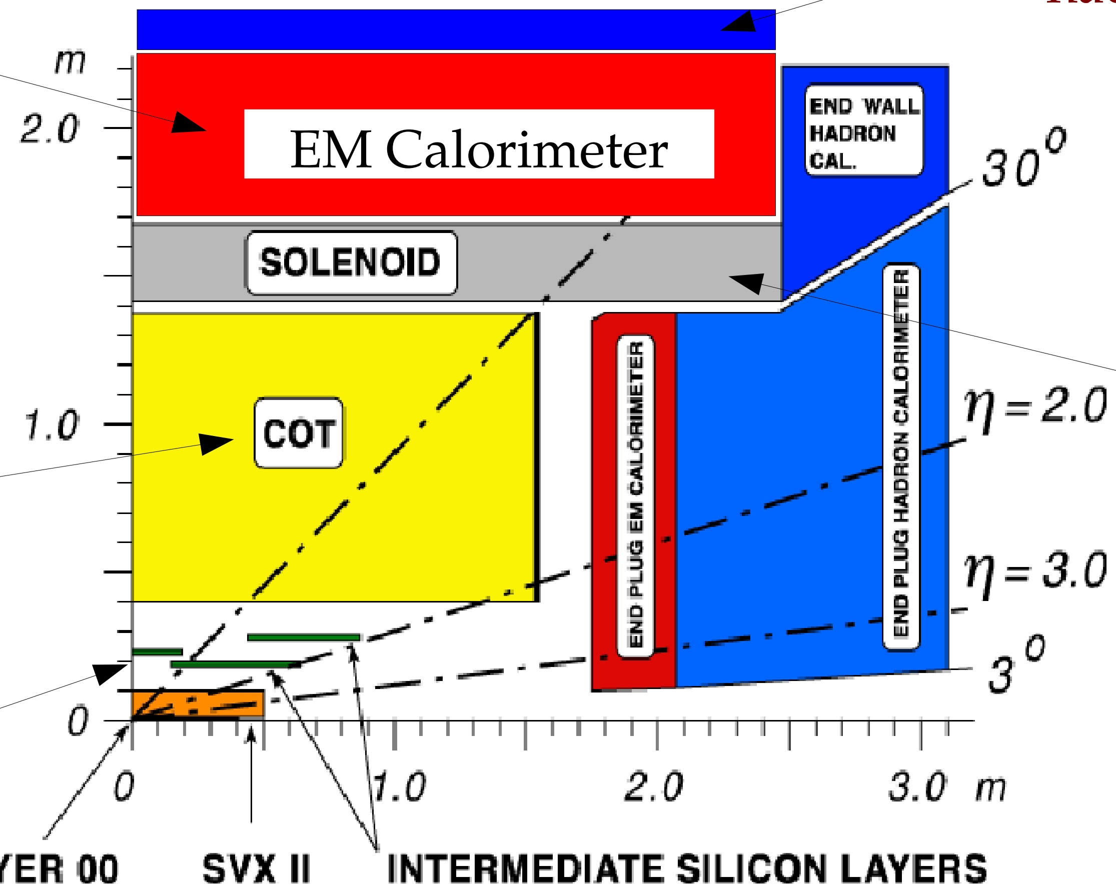
Response and resolution in EM calorimeter

Energy loss into hadronic calorimeter

Track reconstruction in outer tracker

Energy loss in solenoid

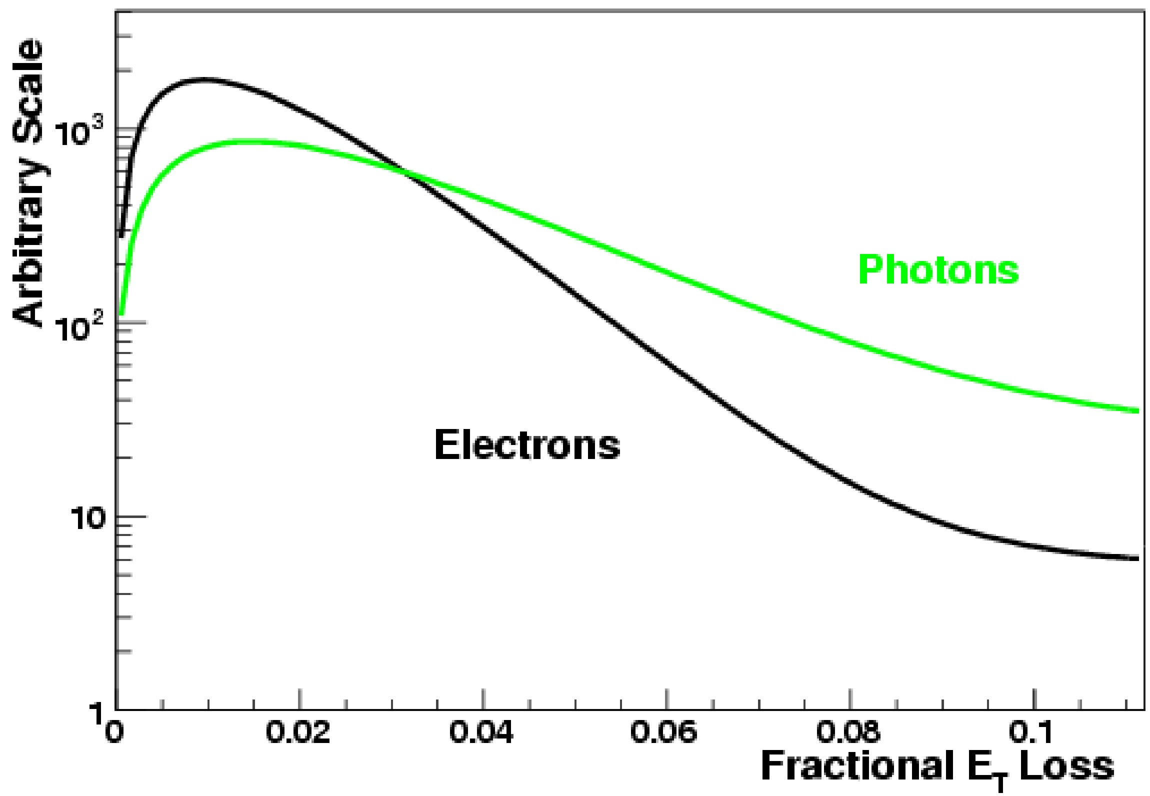
Bremstrahlung and conversions in silicon



Energy Loss Model

Use GEANT to parametrize energy loss in solenoid and hadronic calorimeter

Energy loss in hadronic calorimeter:



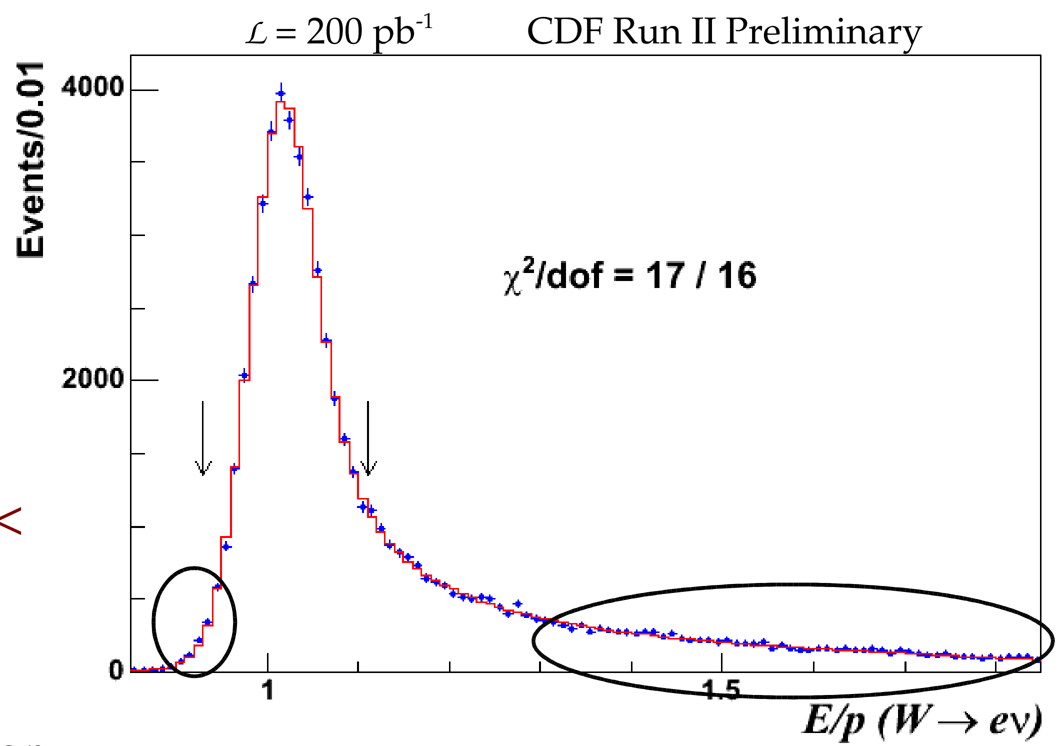
Energy Scale Calibration

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 ± 0.009

Calorimeter Energy < Track Momentum:
Energy loss in hadronic calorimeter



Calorimeter Energy > Track Momentum:
Energy loss in tracker

Energy scale uncertainty: 0.034%

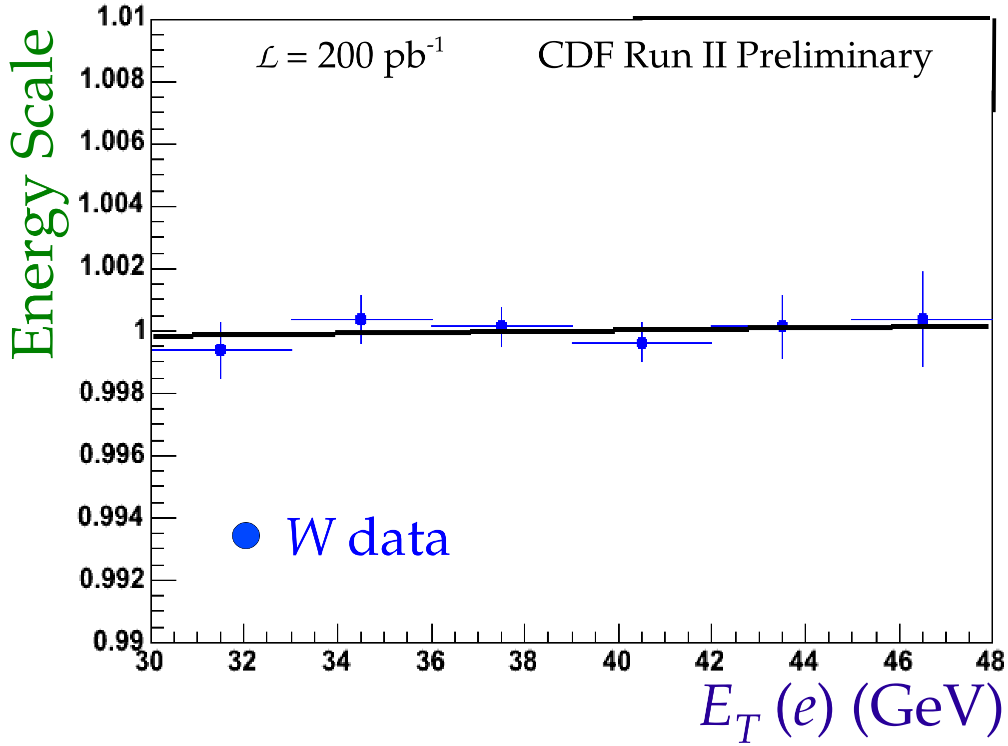
Scale Energy Dependence

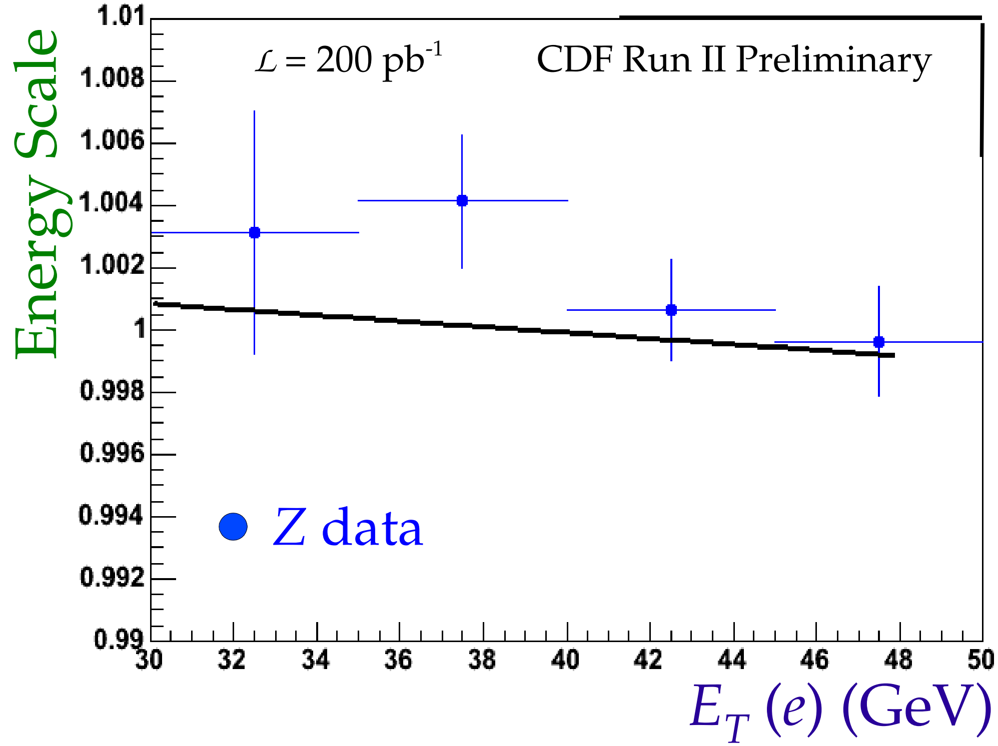
Apply energy-dependent scale to each simulated electron and photon

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

Scale: $1 + (\mathbf{6 \pm 7}) \times 10^{-5}\,[E_T/\mathrm{GeV} - 39]$ **(δm_W = 23 MeV)**

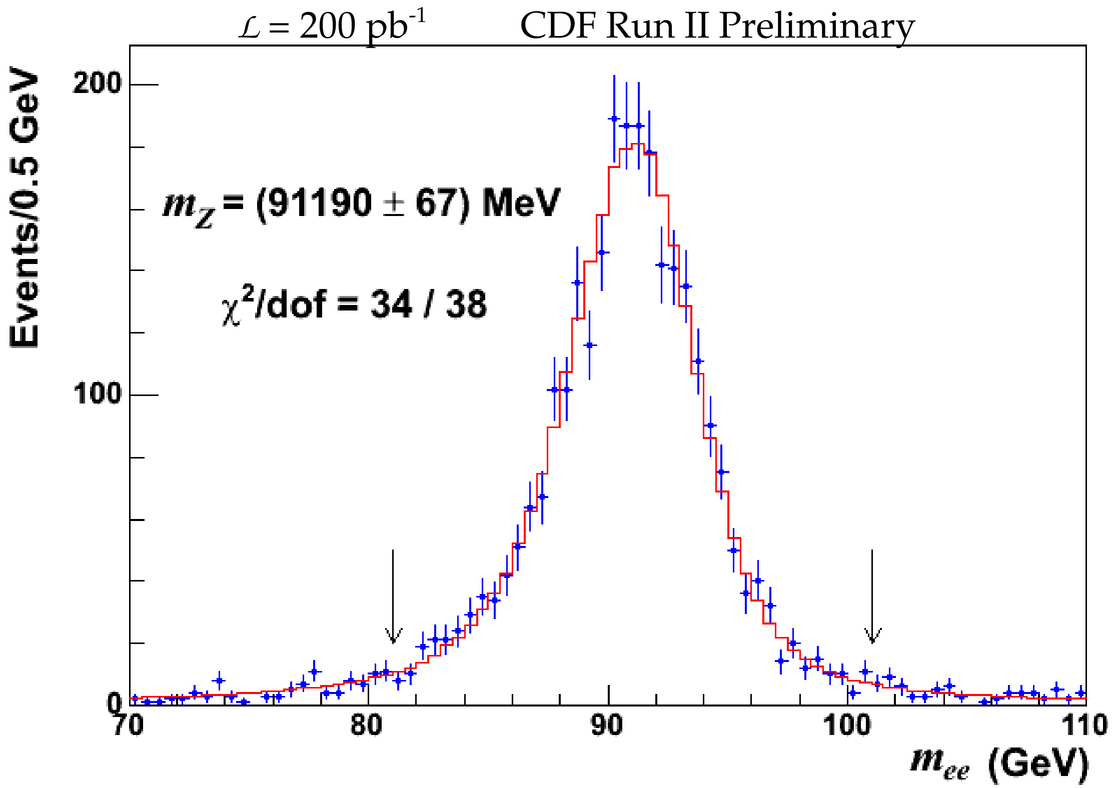
Most energy dependence implicitly accounted for by detector model





Z Mass Measurement

Fit Z mass using scale from E/p calibration

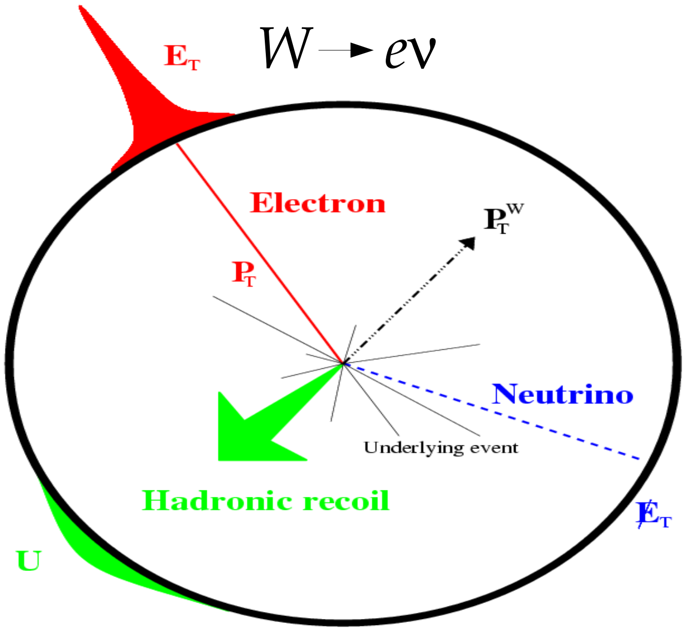


Measured value consistent with world average value (91188 MeV)

Incorporate mass fit into calibration to reduce scale uncertainty

δm_W = 30 MeV

Measurement Strategy



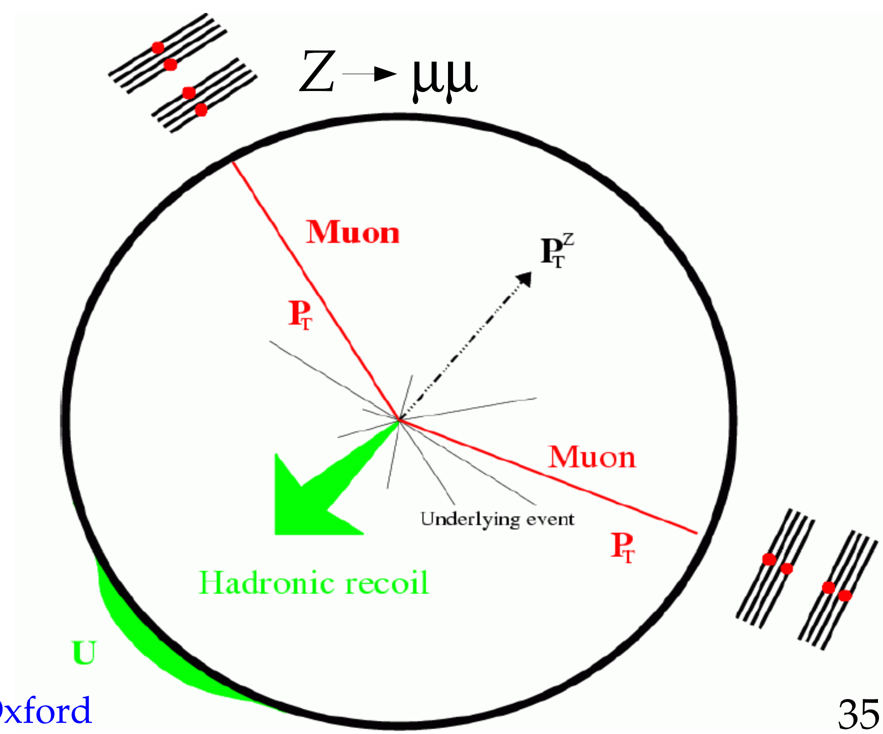
✔ Calibrate $l^{\pm}$ track momentum with mass measurements of J/ψ and Y decays to μ

✔ 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*, μ

Cross-check with W recoil distributions



Combine information into transverse mass:

$$m_T = \sqrt{E_T \not{E}_T (1 - \cos\Delta\phi)}$$

Statistically most powerful quantity for m_W fit

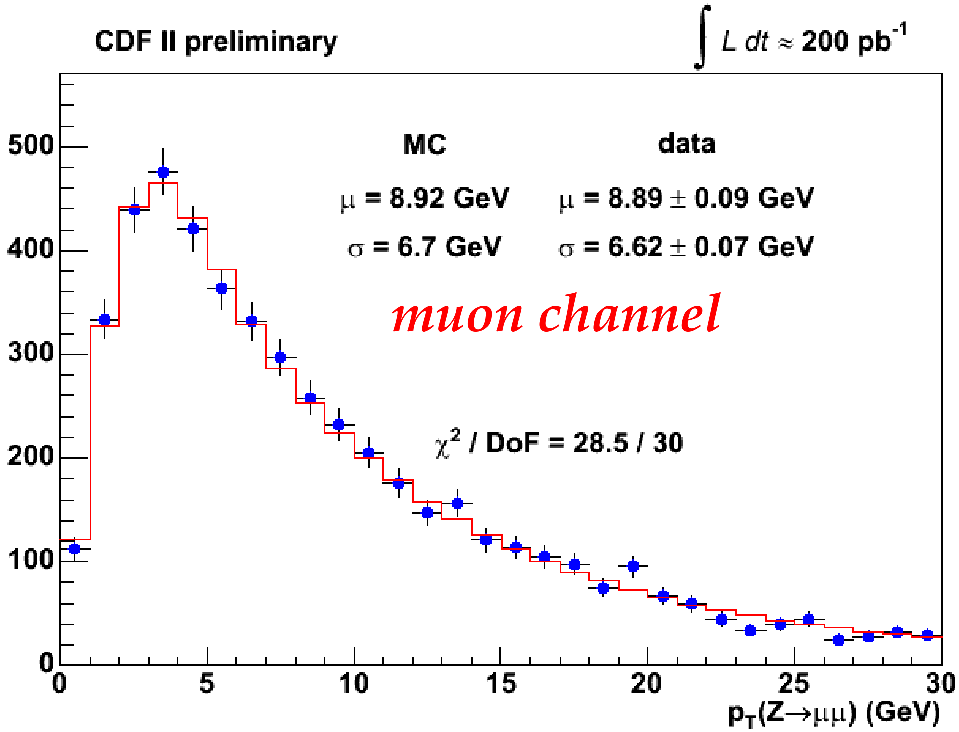
Boson p_T Model

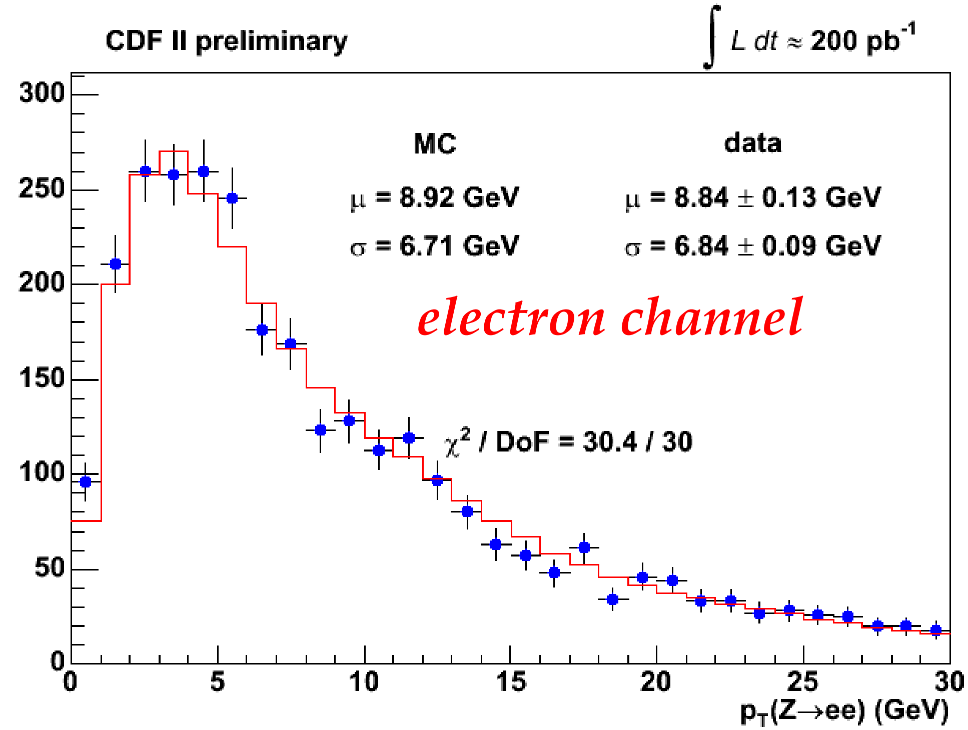
Model boson p_T using RESBOS generator with tunable non-perturbative parameters

"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)

$g_2 = 0.685 \pm 0.048$: δm_W = **3 MeV**



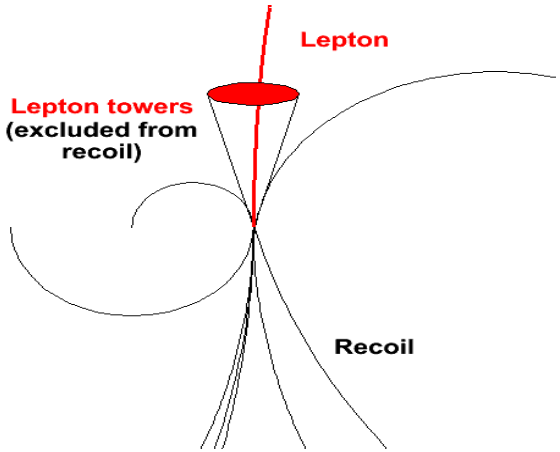


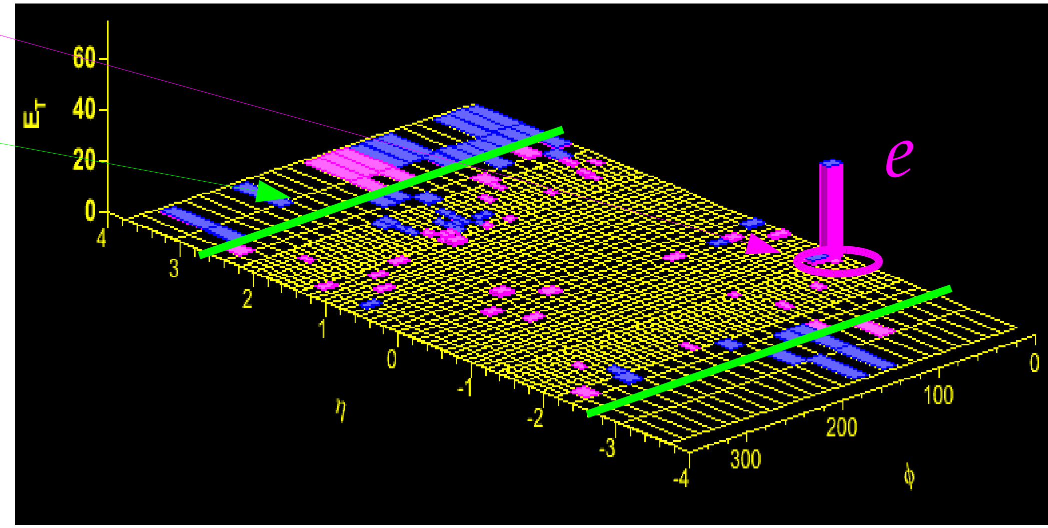
Recoil Measurement

Calculate recoil by summing over calorimeter towers, excluding:

Towers with lepton energy deposits

Towers near the beam line





Electron Electromagnetic E_T (MeV)

Tower Δη \ Tower Δφ	-3	-2	-1	0	1	2	3
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

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

Electron: Remove 7 towers (shower)

Muon: Remove 3 towers (MIP)

Model tower removal in simulation

δm_W = 8 (5) MeV for *e* (μ)

Recoil Model

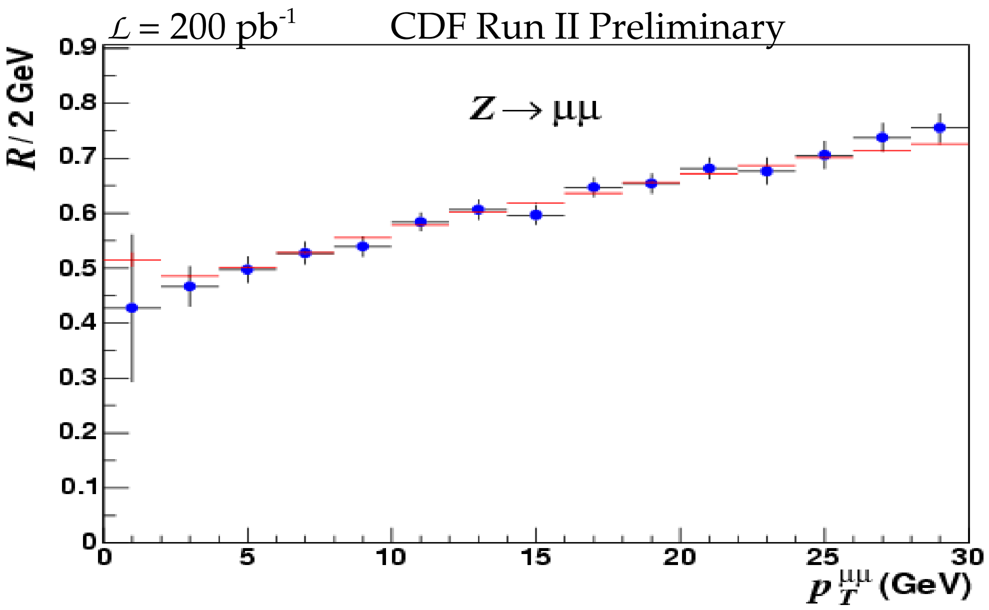
Components:

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

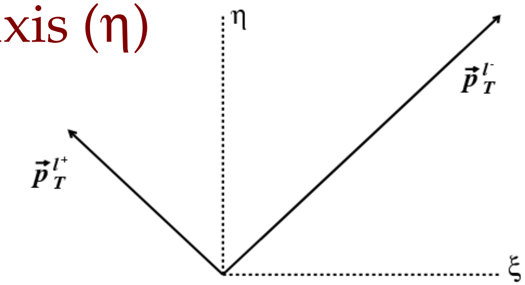
Recoil resolution

Spectator and additional interactions

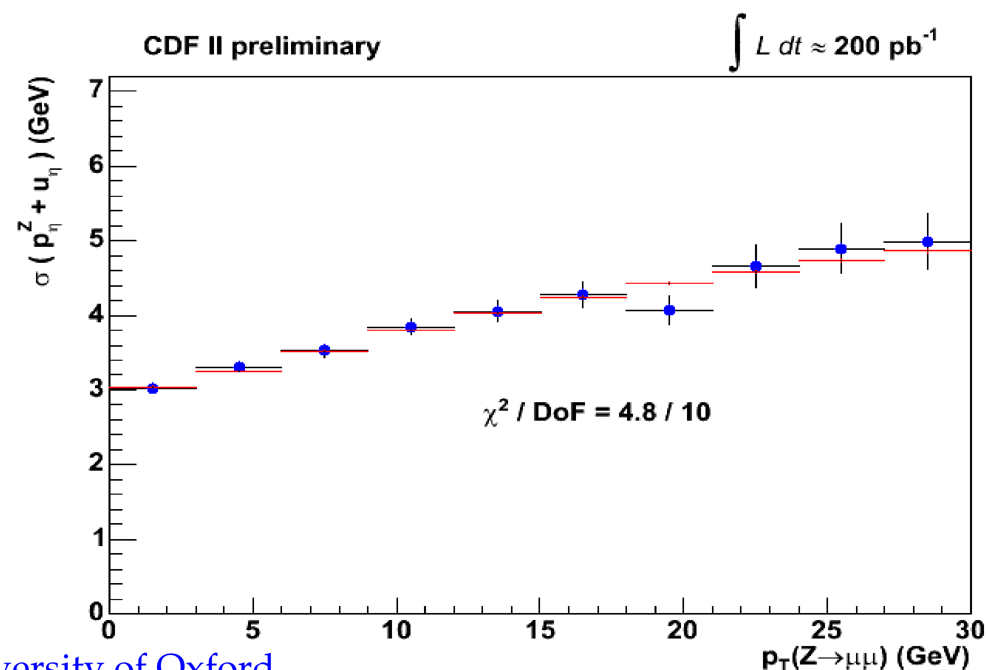
(contribute to resolution)



Calibrate scale with momentum balance along bisector axis (η)



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



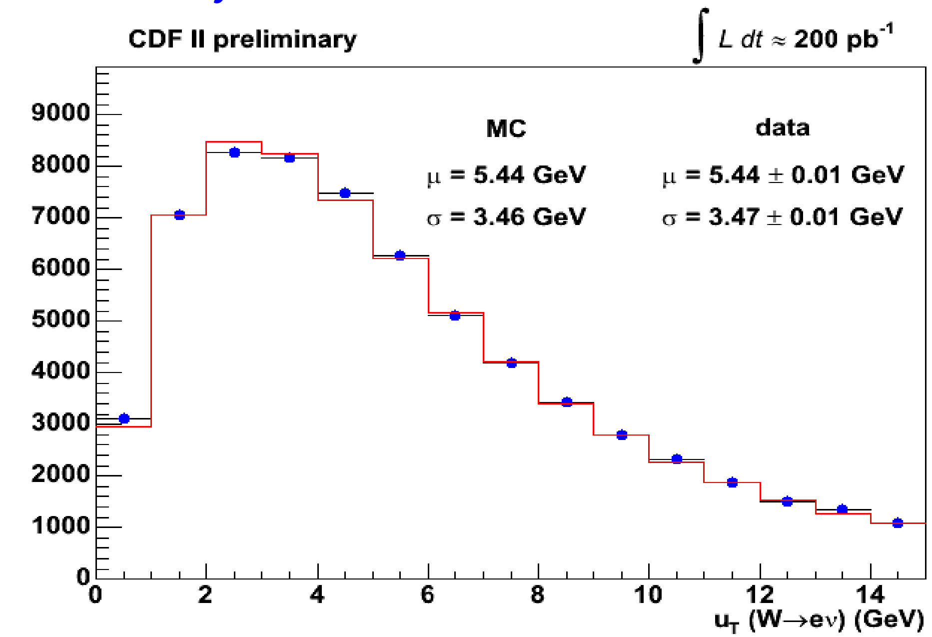
δm_W = 11 MeV

Recoil Model Checks

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

Recoil distribution

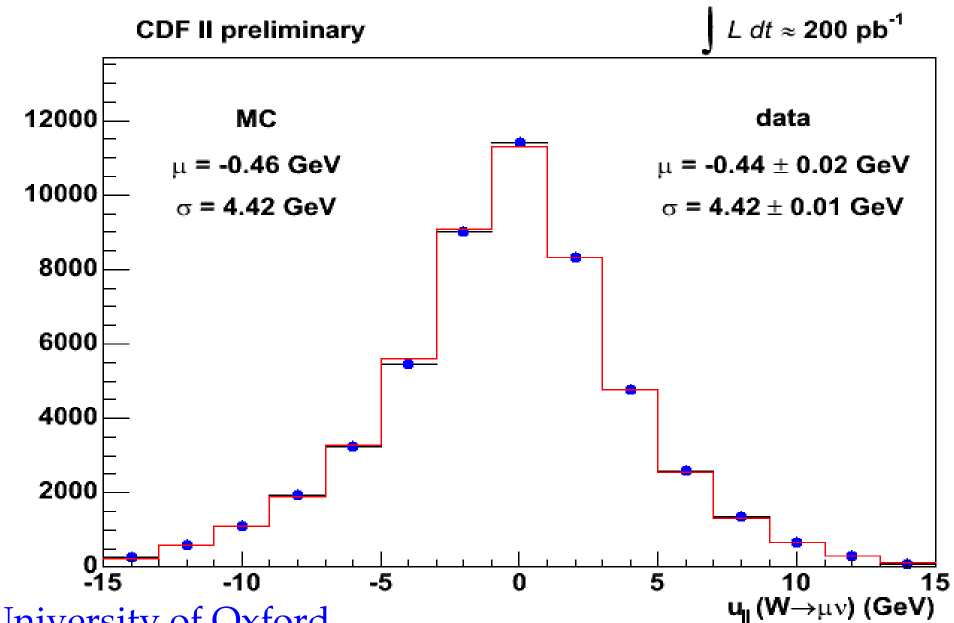
Sensitive to scale, resolution, boson p_T



$u_{||}$ distribution

Sensitive to lepton removal, efficiency model, scale, resolution, W decay

Directly affects m_T *fit result*

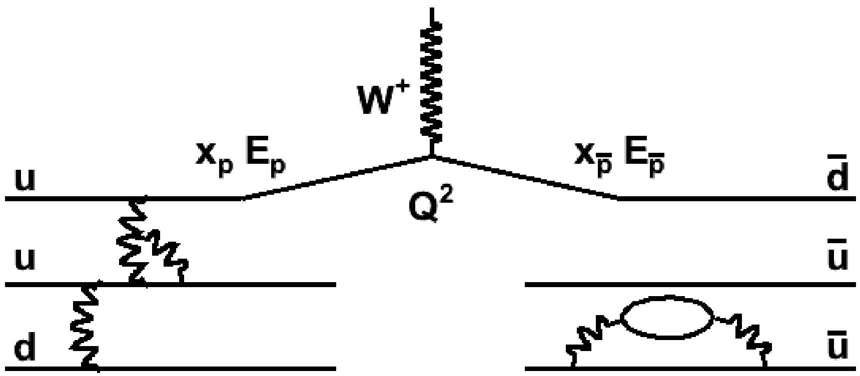


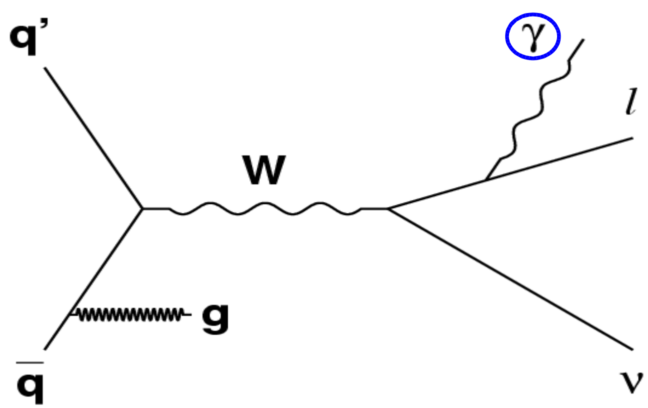
Production, Decay, Background

Boson p_z determined by parton distribution functions

Vary PDFs according to uncertainties

δm_W = 11 MeV





Bremsstrahlung reduces charged lepton p_T

Predict using NLO QED calculation, apply NNLO correction

δm_W = 11 (12) MeV for *e* (μ)

Background affects fit distributions

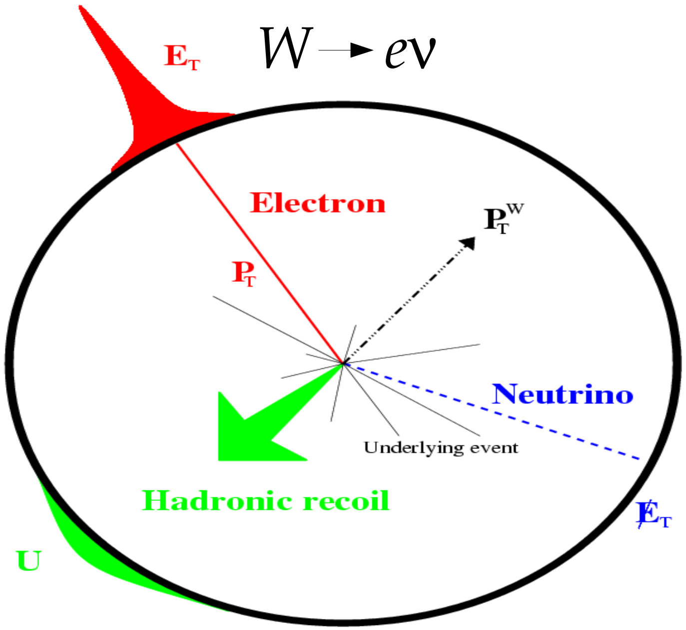
QCD: Measure with data

Electroweak: Predict with MC

δm_W = 8 (9) MeV for *e* (μ)

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

Measurement Strategy



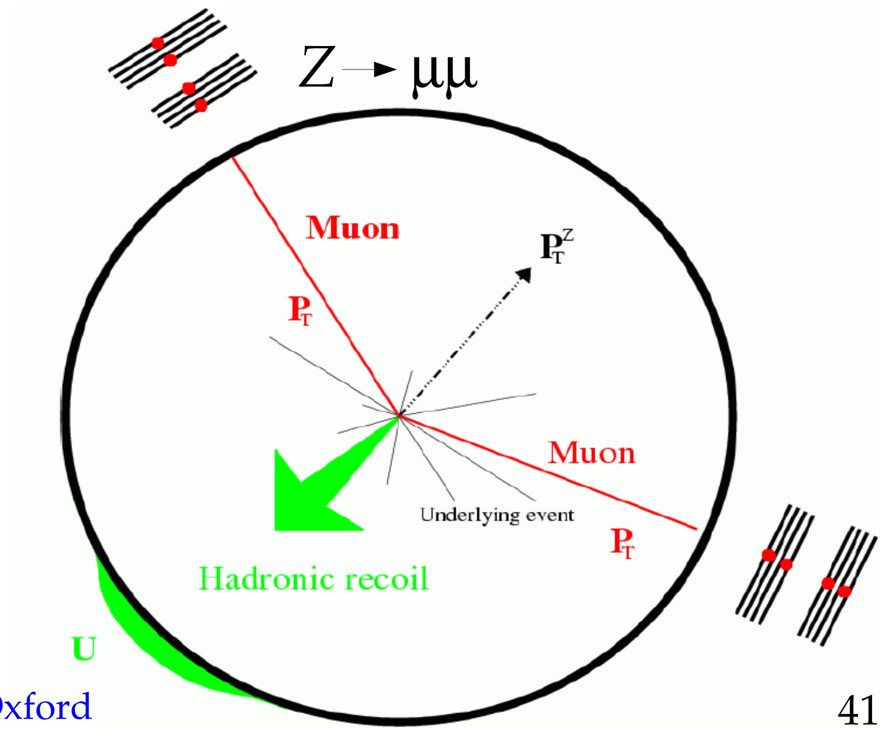
✔ Calibrate $l^{\pm}$ track momentum with mass measurements of J/ψ and Υ decays to μ

✔ 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*, μ ✔

Cross-check with W recoil distributions ✔



Combine information into transverse mass:

$$m_T = \sqrt{E_T \not{E}_T (1 - \cos\Delta\phi)}$$

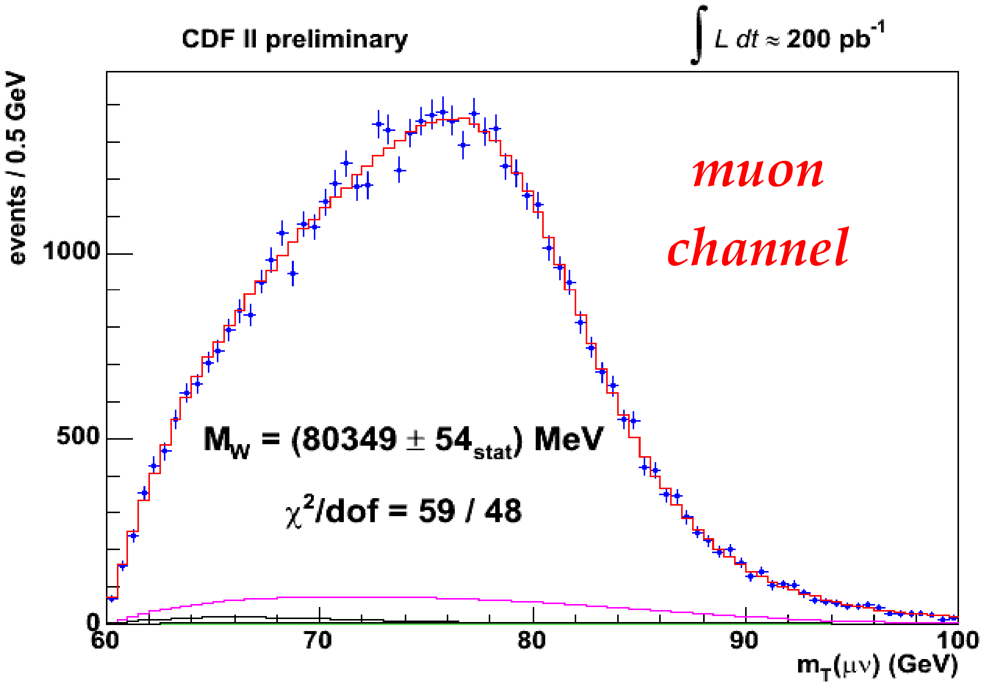
Statistically most powerful quantity for m_W fit

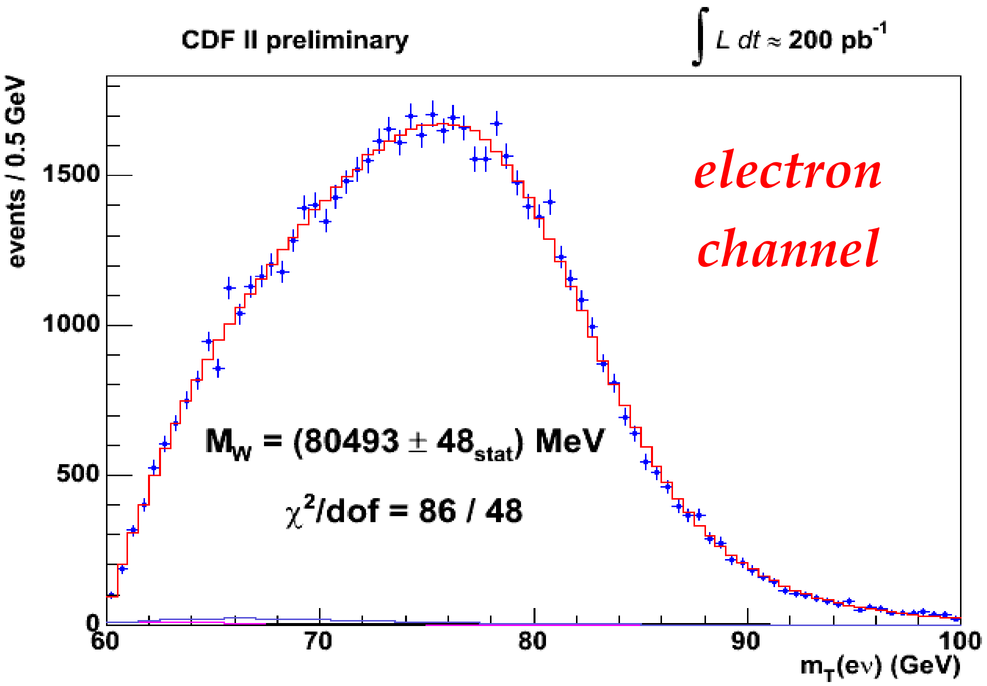
W Mass Fits

Mass fit results blinded with [-100,100] MeV offset throughout analysis

Upon completion, offset removed to determine final result

Transverse mass fits:





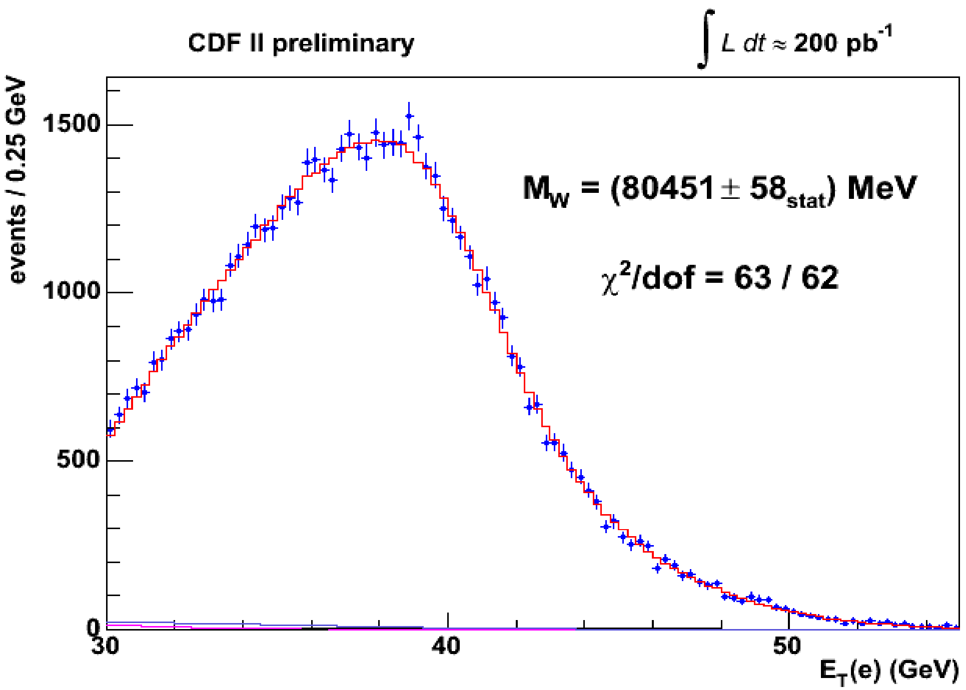
m_W = 80417 ± 48 MeV (stat + sys)

for $e + \mu$ combination ($P(\chi^2) = 7\%$)

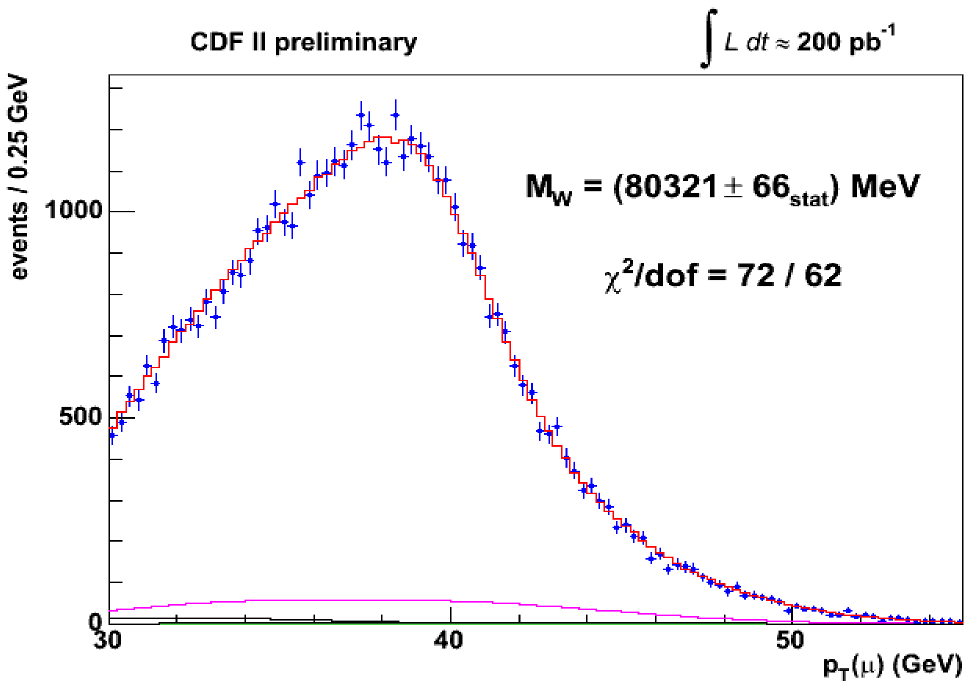
W Mass Fits

Fit E_T, $\not{E}_T$ distributions and combine with m_T to extract most precise result

Electron E_T fit:



Muon p_T fit:



m_W = 80388 ± 59 MeV (stat + sys)

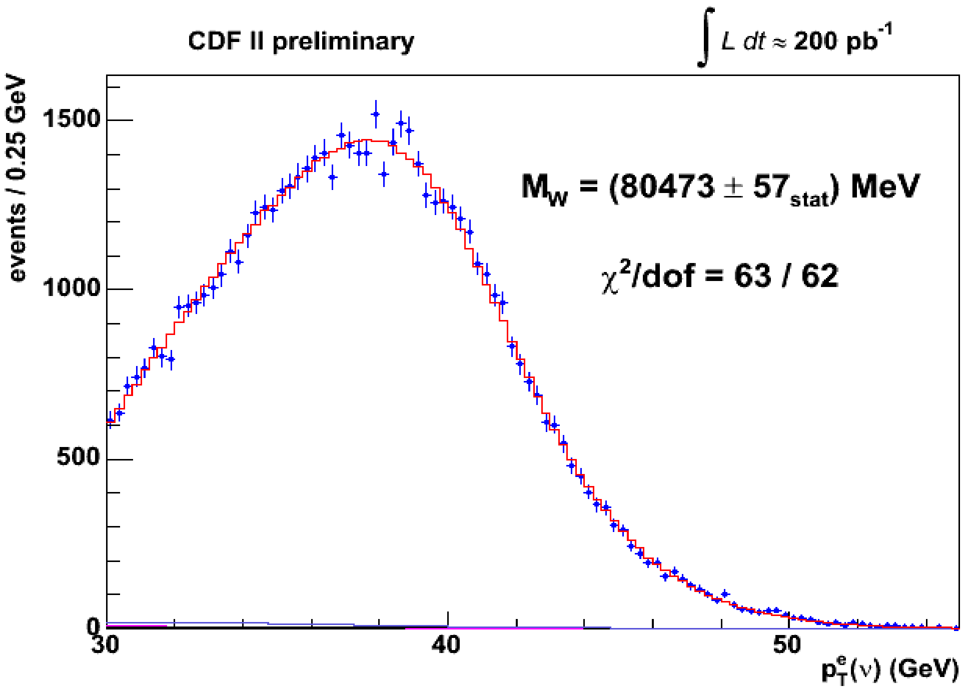
for lepton p_T $e + \mu$ combination ($P(\chi^2)$ = 18%)

W Mass Fits

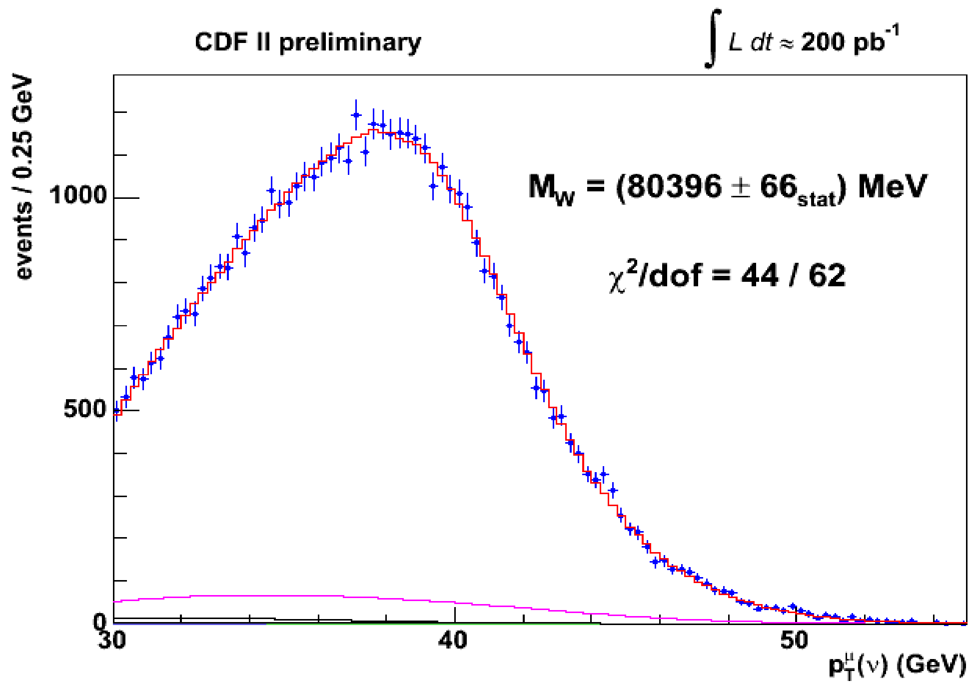
m_W = 80434 ± 65 MeV (stat + sys)

for neutrino p_T e + μ combination ($P(\chi^2)$ = 43%)

Electron $\not\!E_T$ fit:



Muon $\not\!E_T$ fit:



m_W = 80413 ± 48 MeV (stat + sys)

for six-fit combination ($P(\chi^2)$ = 44%)

W Mass Uncertainties

CDF II preliminary **$L = 200\ pb^{-1}$**

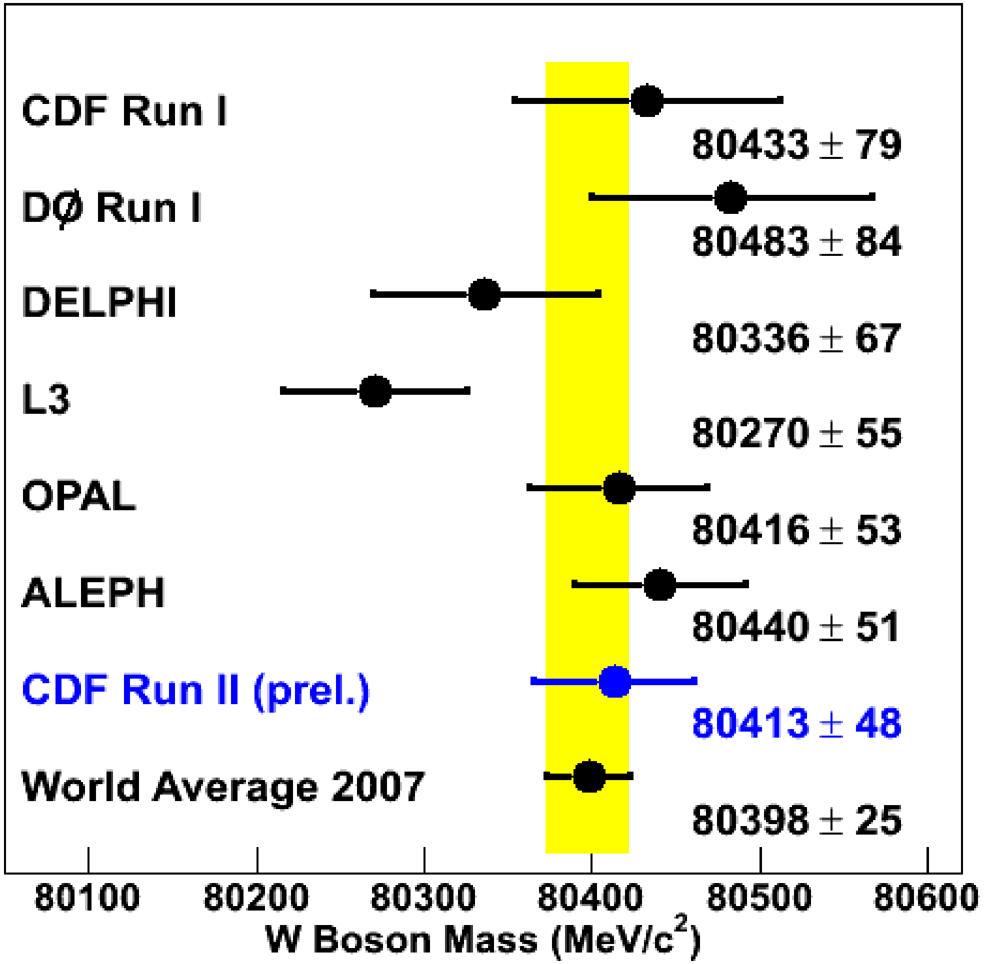
m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\|\|}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

W Mass Result

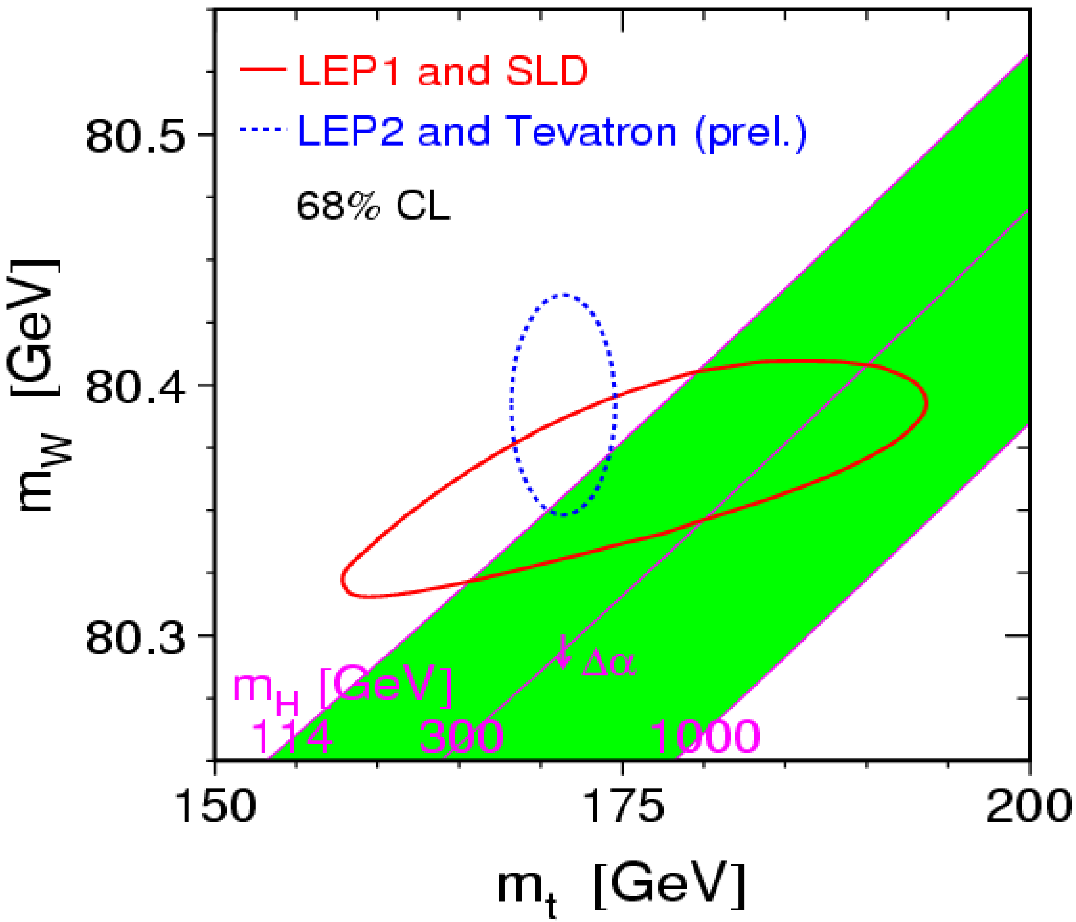
New CDF result is world's most precise single measurement

Central value increases: 80392 to 80398 MeV

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



Previous Higgs Mass Prediction

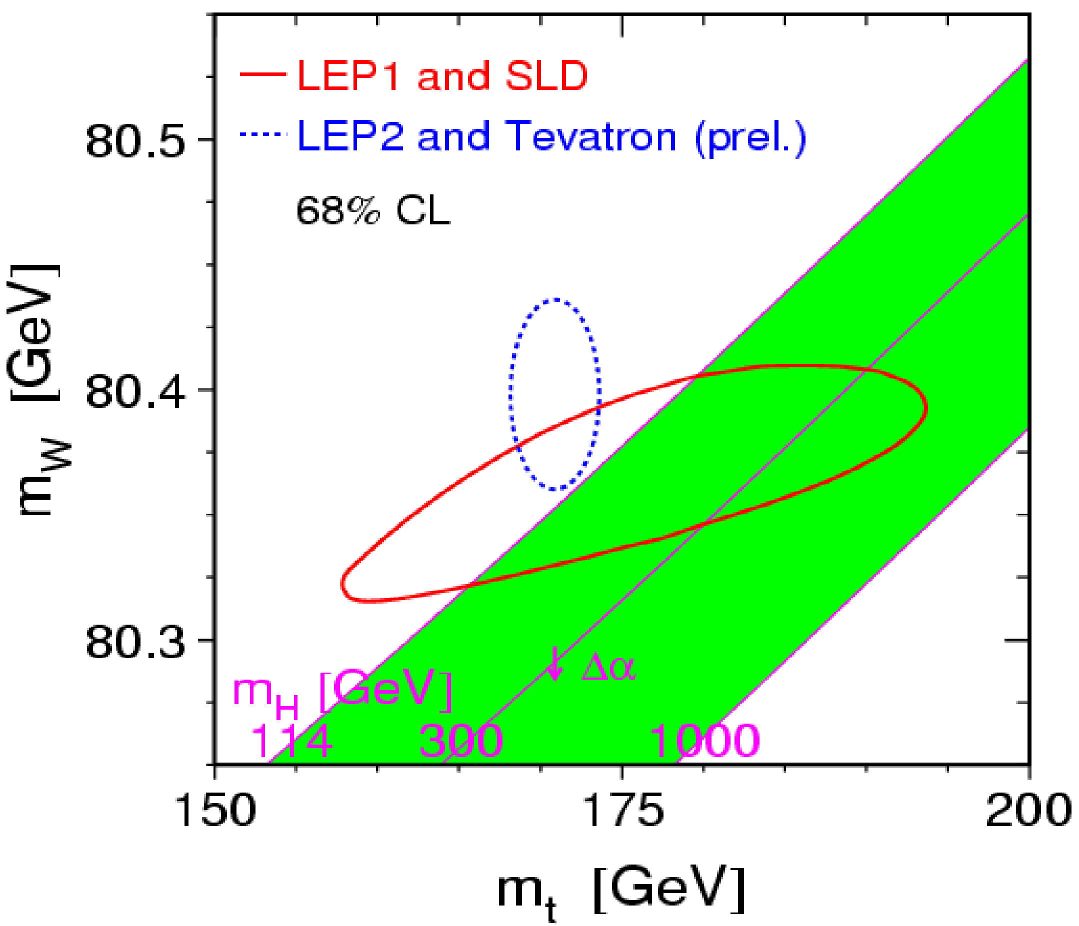


Predicted Higgs mass from W loop corrections:

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

Direct search from LEP II: $m_H > 114.4$ GeV at 95% CL

New Higgs Mass Prediction



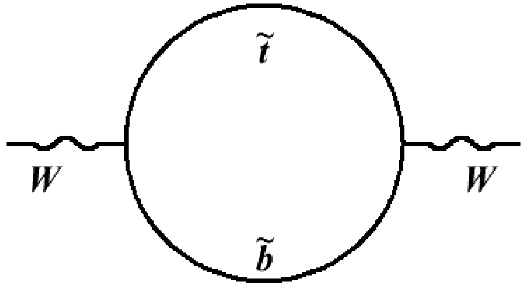
Predicted Higgs mass from W loop corrections:

$m_H = 76^{+33}_{-24}$ GeV (< 144 GeV at 95% CL)

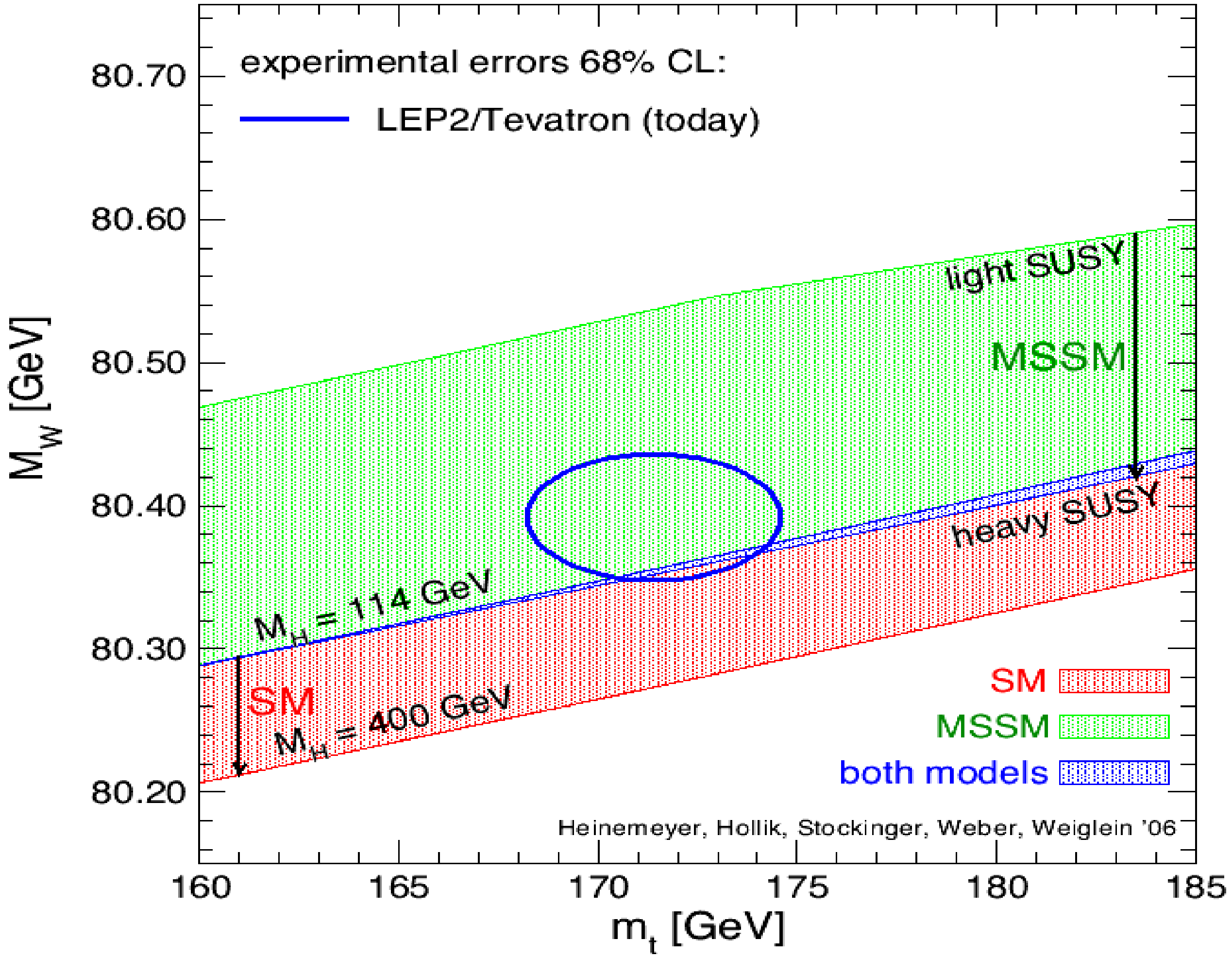
Direct search from LEP II: $m_H > 114.4$ GeV at 95% CL

Effect on New Physics Models

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

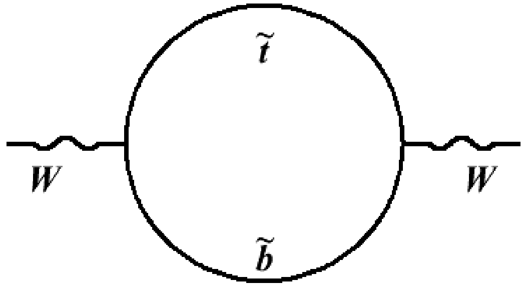


Previous world average:

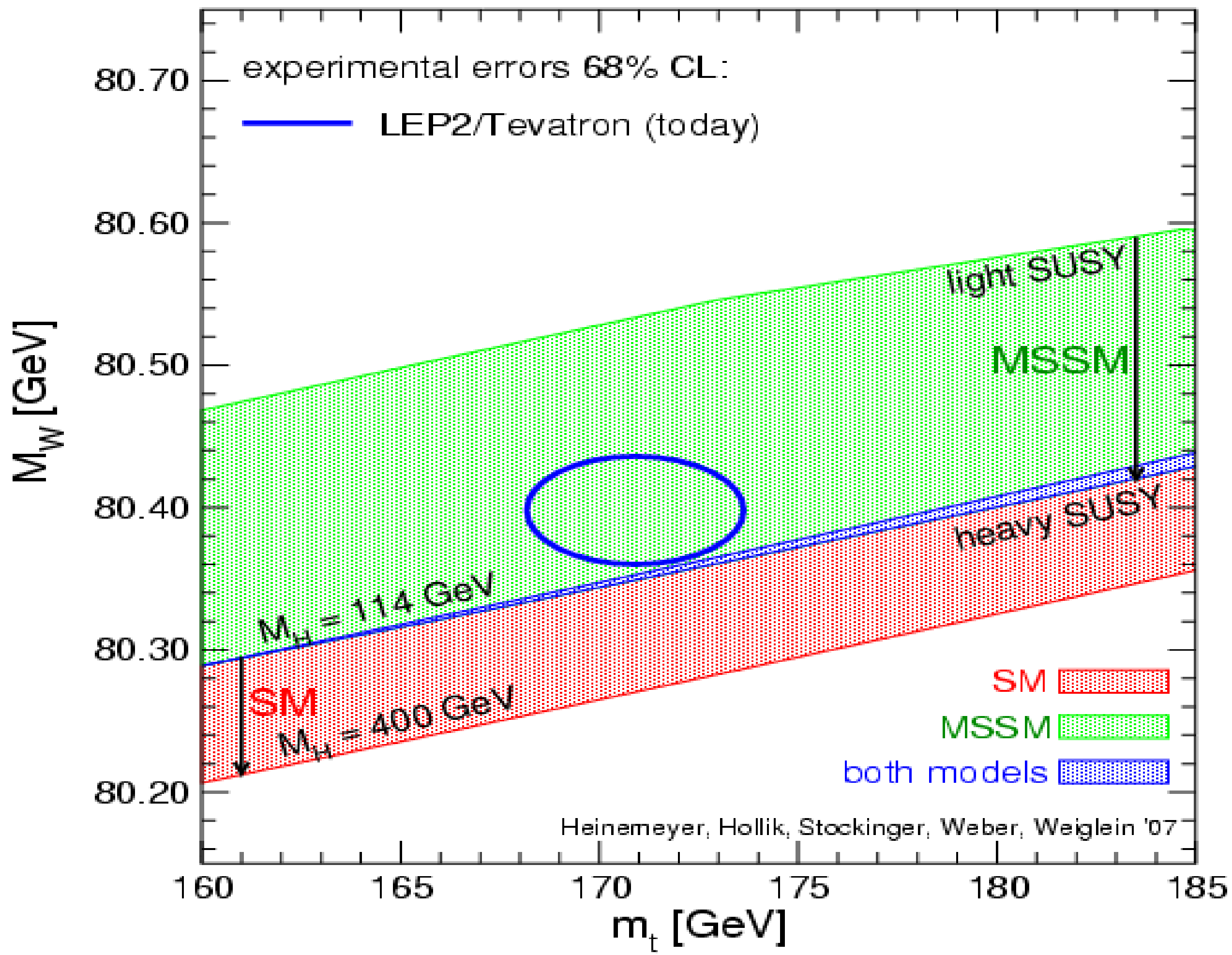


Effect on New Physics Models

Supersymmetry now preferred at >1σ level...

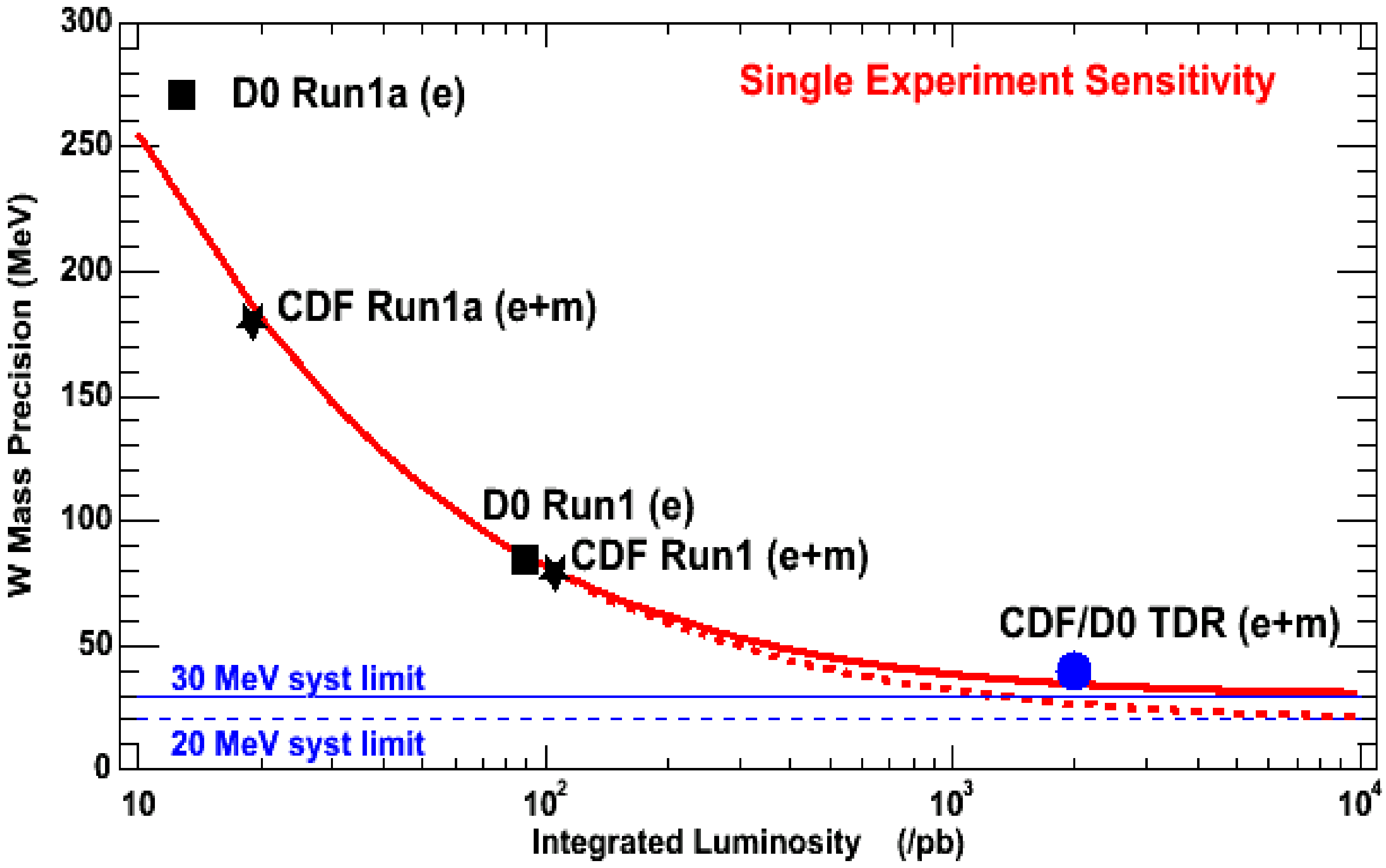


New world average:



Previous *W* Mass Projections

Previously projected Tevatron precision as a function of luminosity:

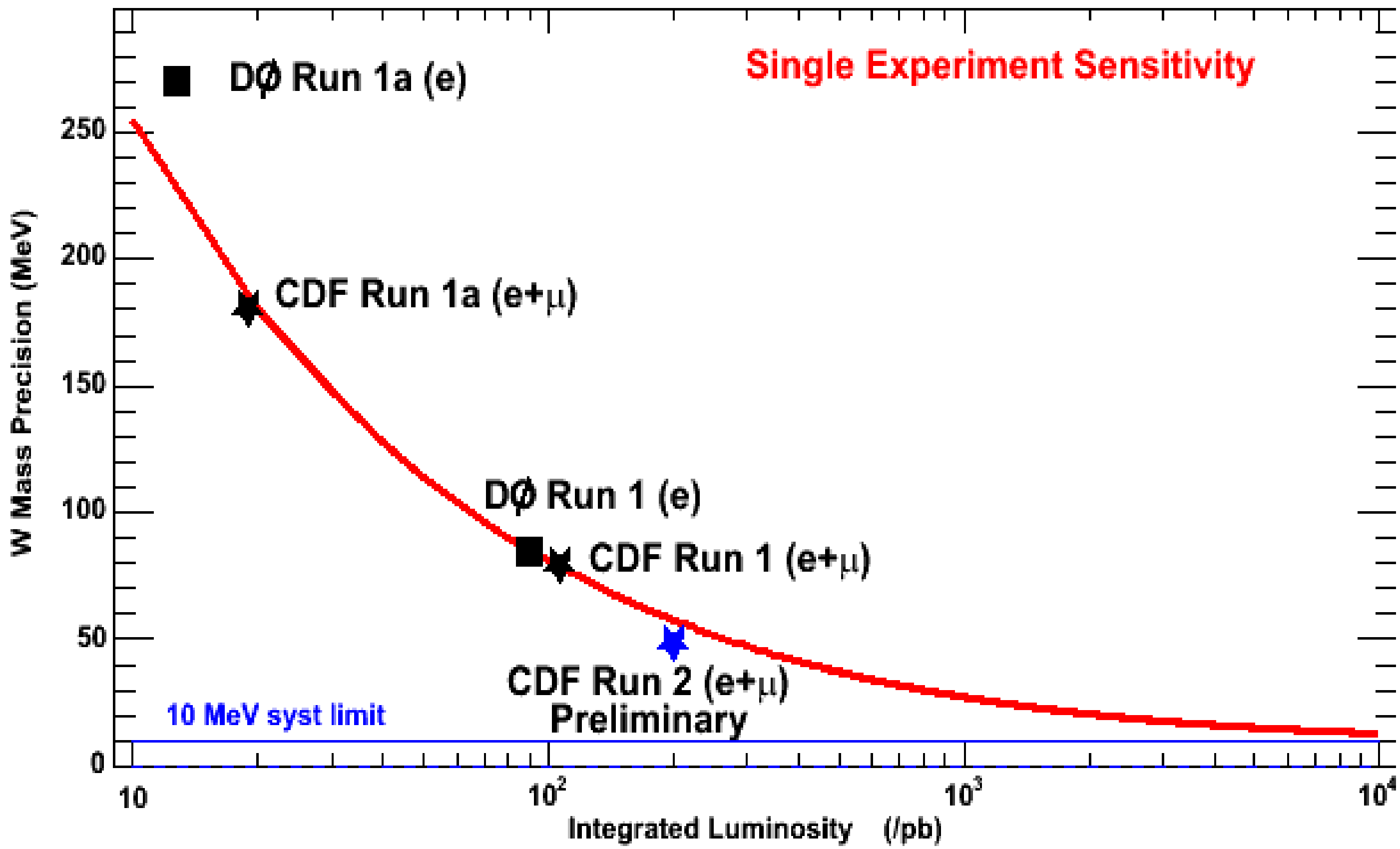


Projection with 2 fb^{-1} of data:

δm_W = 40 MeV per experiment

New *W* Mass Projections

New projected Tevatron precision as a function of luminosity:



New projection with 2 fb^{-1} of data:

$\delta m_W < 25$ 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

m_W = 80413 ± 34 MeV (stat) ± 34 MeV (sys)

= 80413 ± 48 MeV (stat + sys)

New SM Higgs mass prediction: $m_H = 76^{+33}_{-24}$ *GeV*

Mass has moved further into LEP-excluded region

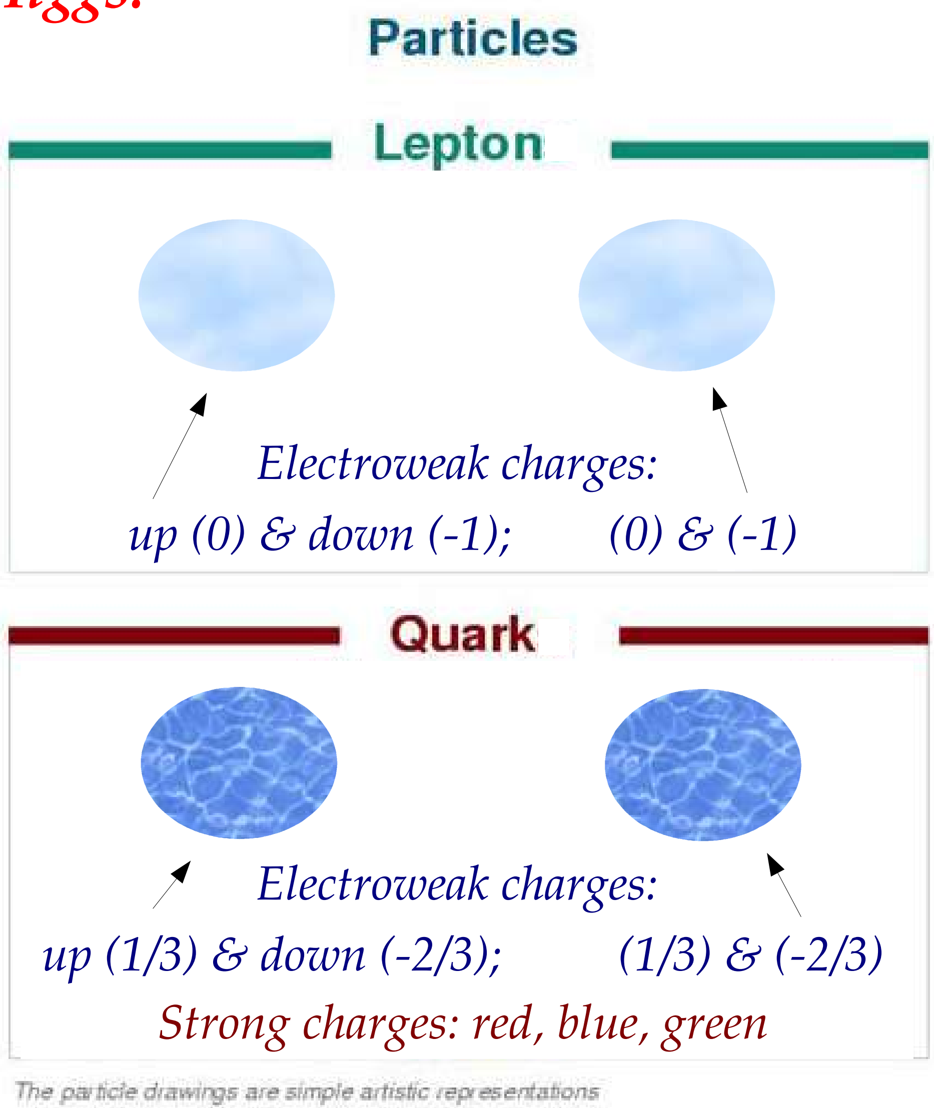
Expect CDF $\delta m_W < 25$ MeV with 2 fb^{-1} already collected

Will continue to squeeze SM in conjunction with Tevatron Higgs results

Backup

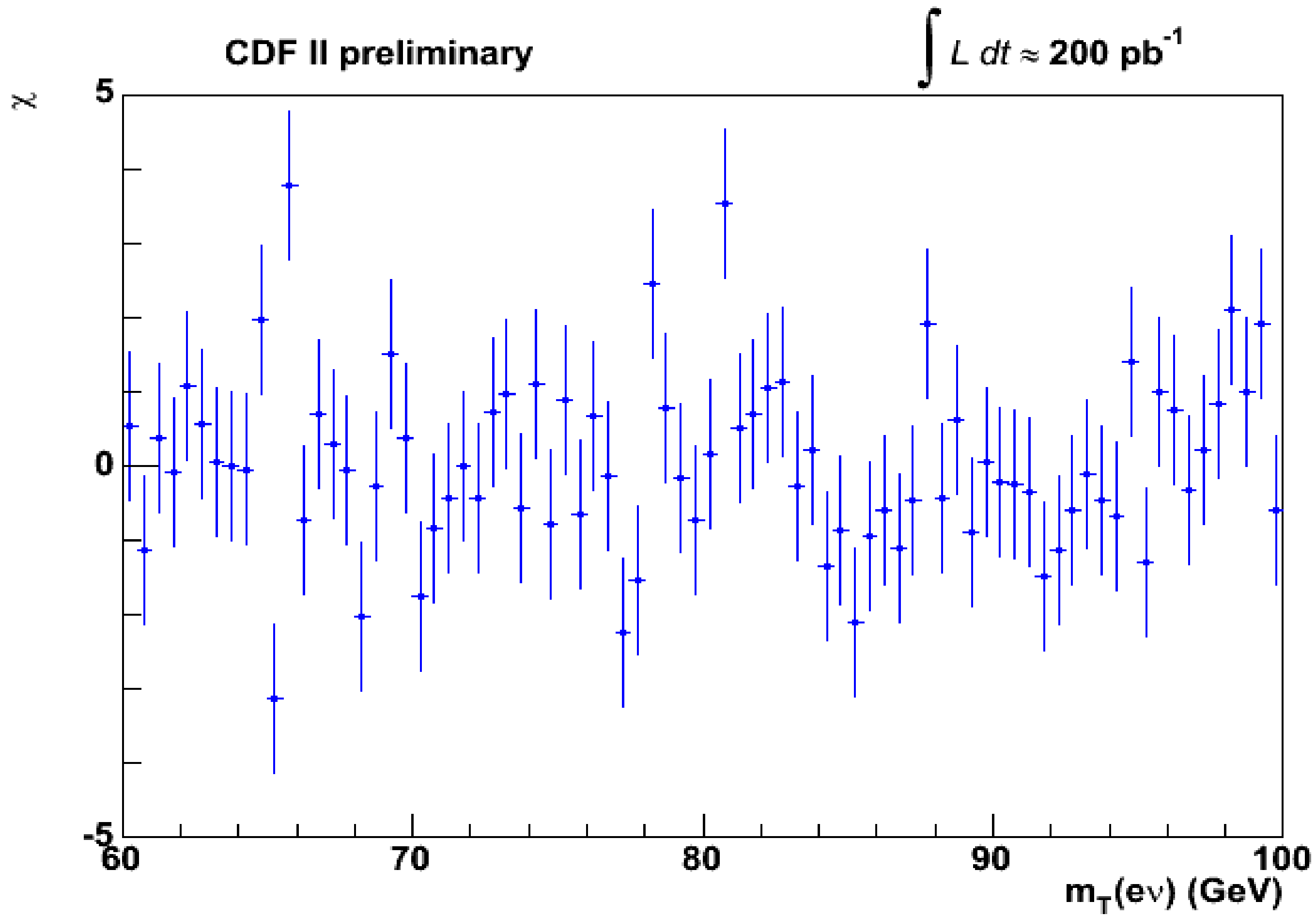
The Standard Model

World without Higgs:



Electron m_T Signed χ

High χ^2 dominated by a few bins with large fluctuations



Weak Boson Physics

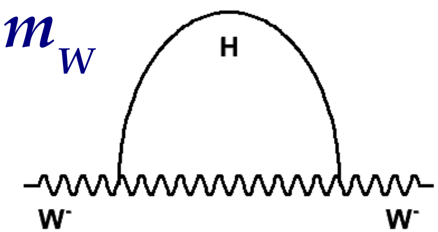
Z boson parameters measured precisely by LEP:

* **17** million measured *Z* candidates: δm_Z = **2.1** MeV, $\delta\Gamma_Z$ = **2.3** MeV

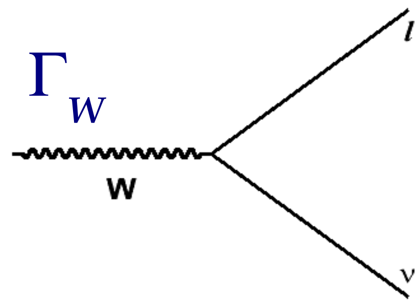
Tevatron goal:

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

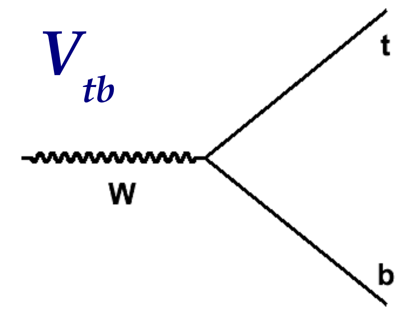
m_W



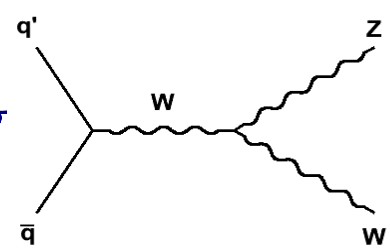
Γ_W



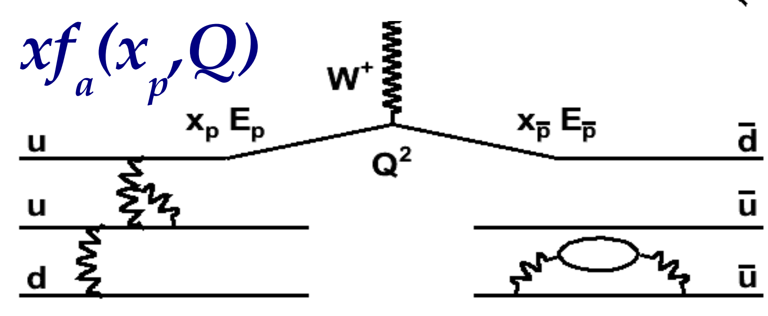
V_{tb}



WWZ coupling



$xf_a(x_p,Q)$



Filling in the Pieces

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

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

2009: $\delta m_W = 20$ MeV, $m_H = 160$ GeV, SUSY predicted at 3σ level

2011: $\delta m_W = 15$ MeV, $m_0 = 400$ GeV, $m_{1/2} = 650$ GeV

Will the data point to more physics?