Electroweak Results from the Tevatron

Chris Hays, University of Oxford

for the CDF and DØ Collaborations

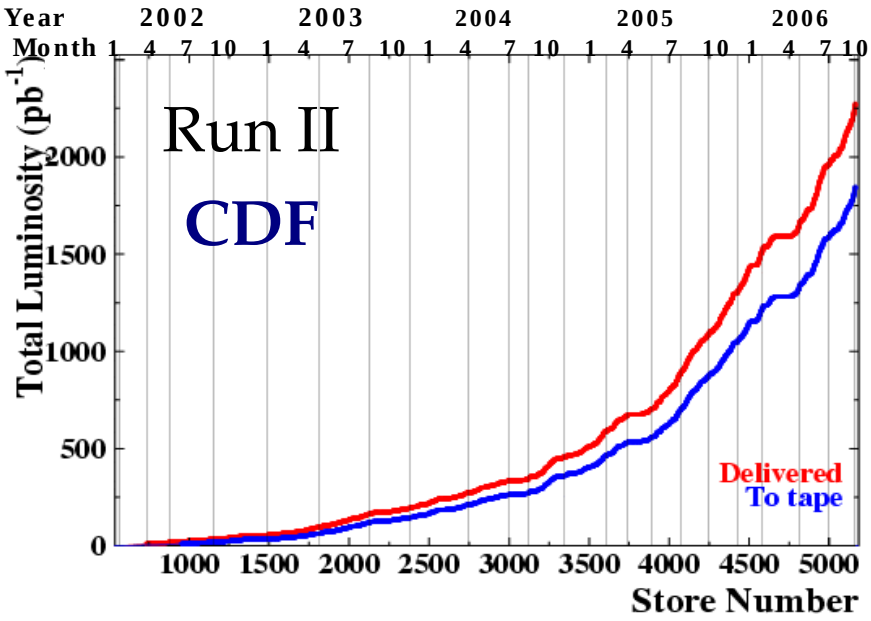
21st Workshop on Weak Interactions and Neutrinos

Kolkata, India

January 16, 2007

Tevatron Weak Boson Physics

Each experiment has collected ~**1.5 fb^{-1}**
of 1.96 TeV $\sqrt{s}$ $p\bar{p}$ collisions
Current Run II: **15**x Run I data set



Increased statistics allows:

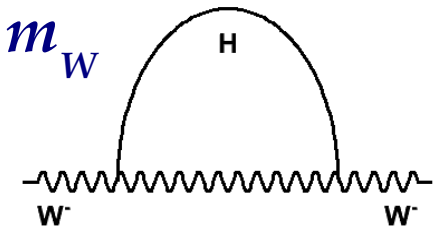
World's most precise measurements & ***Study of rare SM phenomena***

W boson mass measurement

W charge asymmetry measurement

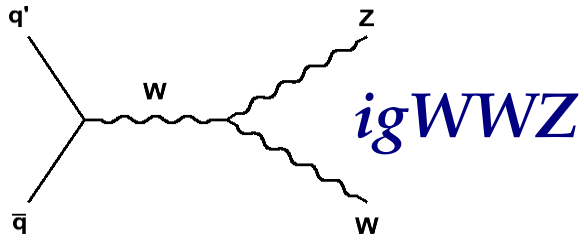
$d\sigma_Z/dy$

$d\sigma_Z/dp_T$



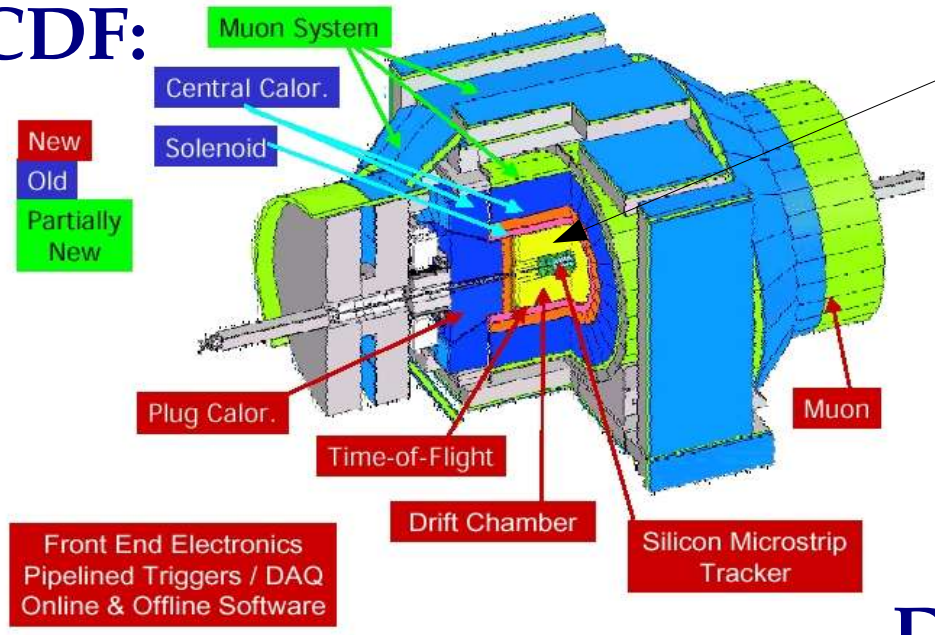
WZ production

$W\gamma$ radiation amplitude zero



Tevatron Detectors

CDF:



High-precision tracking system

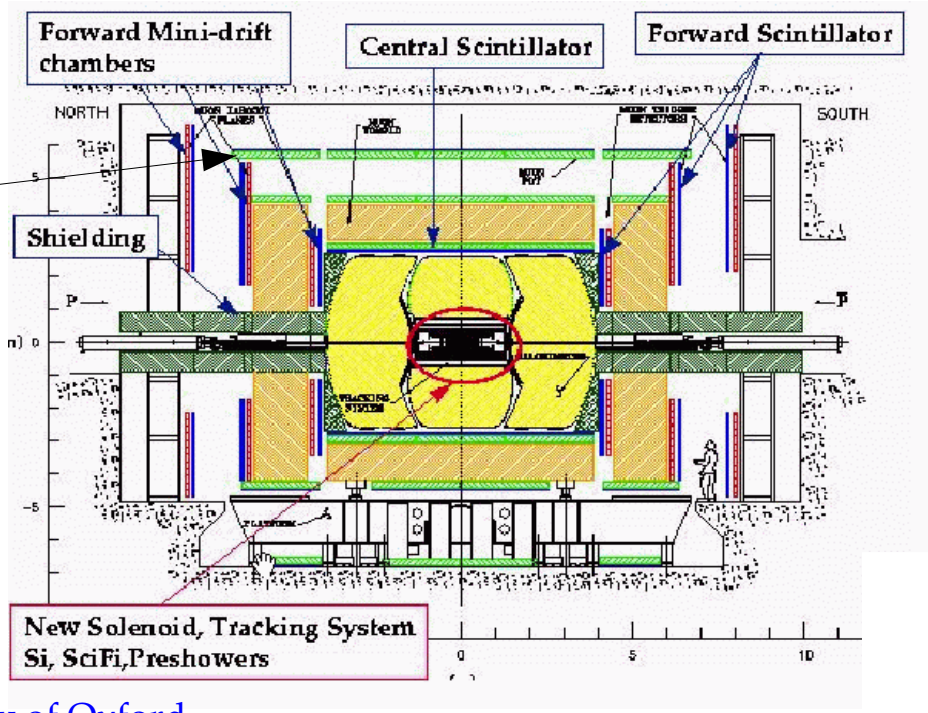
$\delta p_T = 0.05\% \; p_T^2$: *800 MeV for 40 GeV* μ

High-precision electromagnetic calorimeter

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

1100 MeV for 40 GeV e

DØ:



Wide tracking & muon acceptance

Full coverage to $|\eta| < 2$

Large region of e/γ separation

Discrimination to $|\eta| < 2.5$

W Boson Mass Measurement

Derive *W* mass from precisely measured electroweak quantities:

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

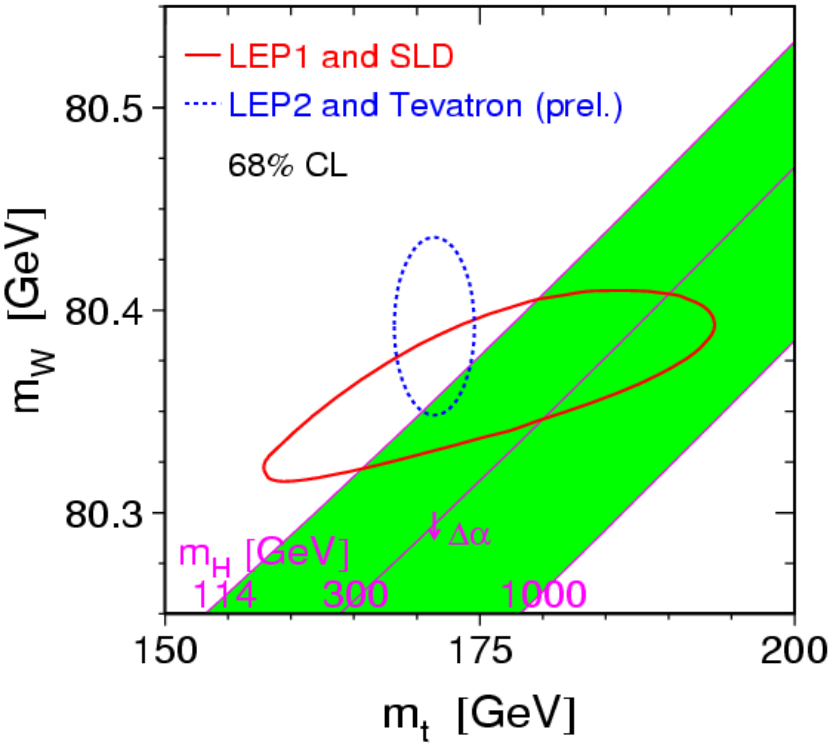
Radiative corrections dominated by top, Higgs

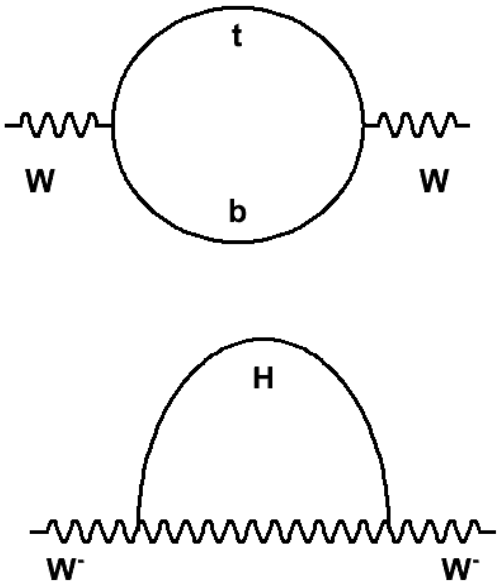
Top mass uncertainty (1.2%) contributes 0.016% to δm_W

Higgs mass predicted to ~45%

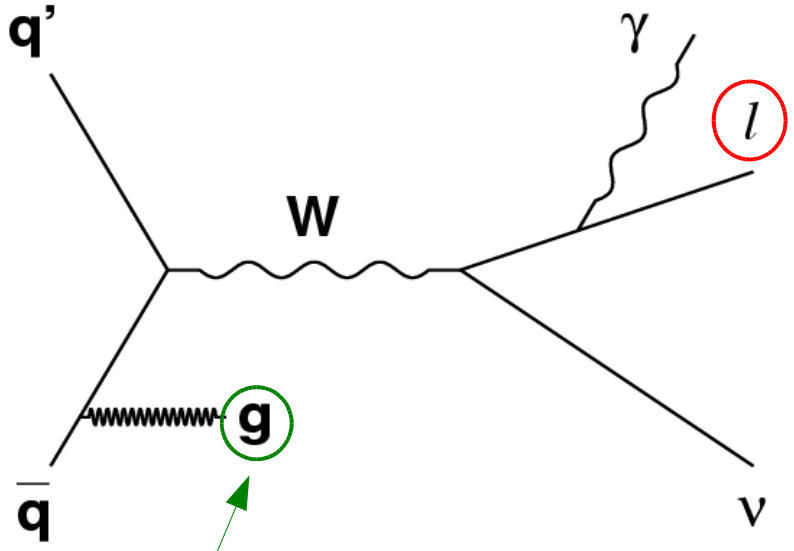
W mass uncertainty of 29 MeV (0.036%) limiting constraint

Need $\delta m_W \approx 13$ ***MeV***





CDF *W* Mass Measurement

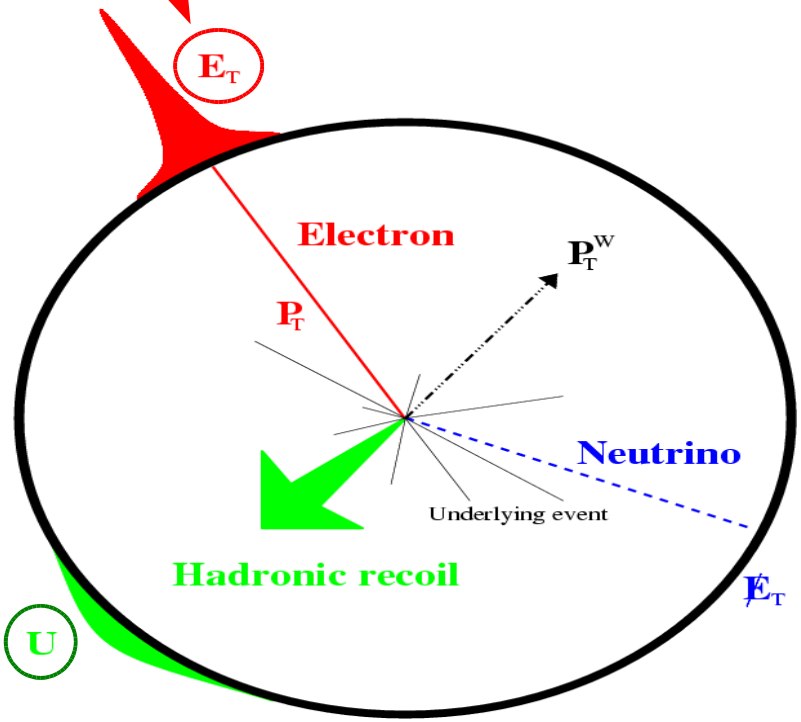


Charged lepton measurement key:

E_T precision ~ 0.03%

Gluon radiation measurement allows inference of neutrino E_T:

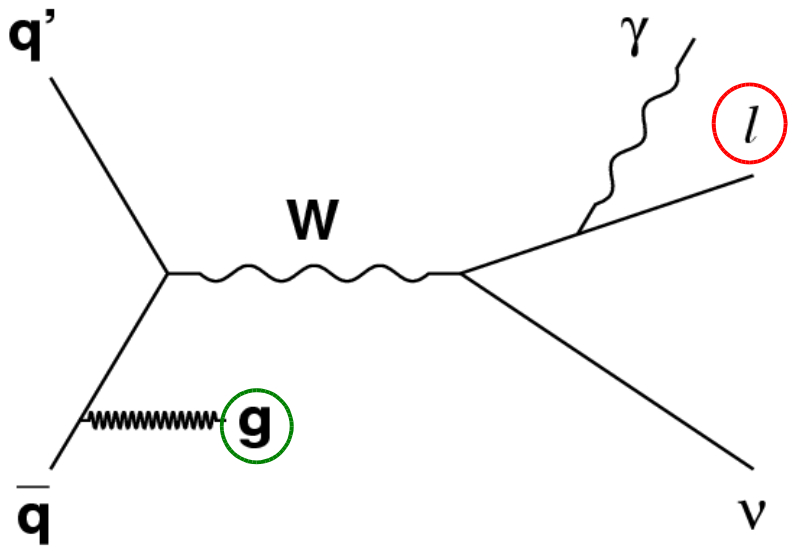
Require small recoil (< 15 GeV)



Combine information into transverse mass:

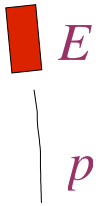
$$m_T c^2 = \sqrt{E_T \not{E}_T (1 - \cos\Delta\phi)}$$

CDF 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



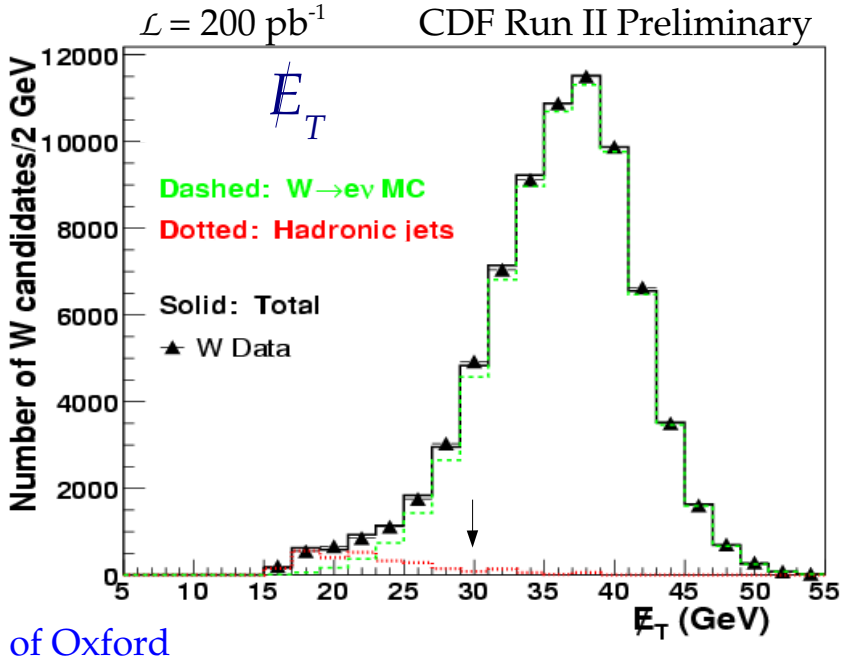
Cross-check with Z mass measurement, then add Z's as a calibration point

Calibrate recoil measurement with Z decays to e, μ

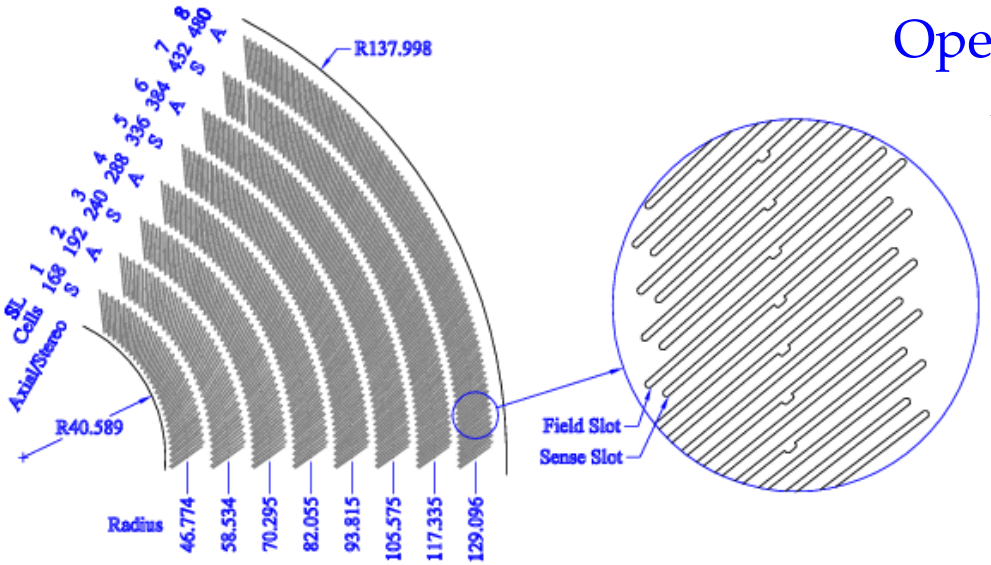
Cross-check with W recoil distributions

Measure mass with 200 pb^{-1} of high-purity W boson samples:

E_T, $\not\!\!E_T > 30$ GeV, $u_T < 15$ GeV



CDF Tracker Alignment



Open-cell drift chamber:

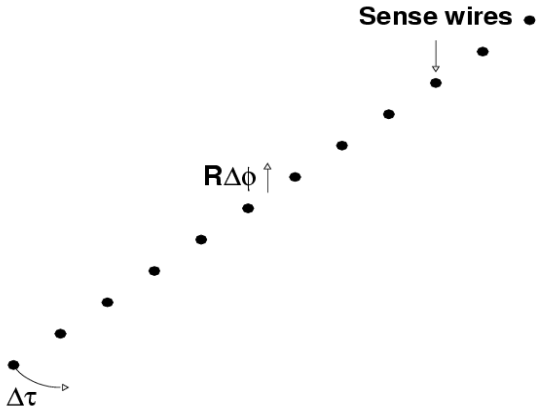
wires strung under tension between two endplates

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

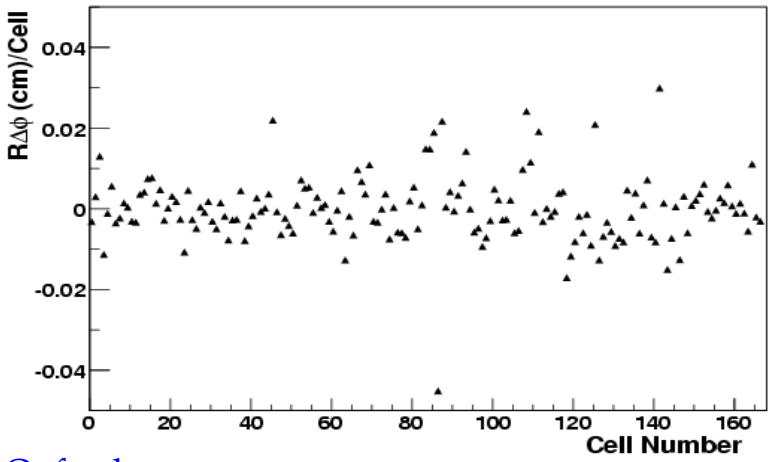
Determine cell tilts & shifts using cosmic-ray data

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

Measure cell displacement with hit residuals



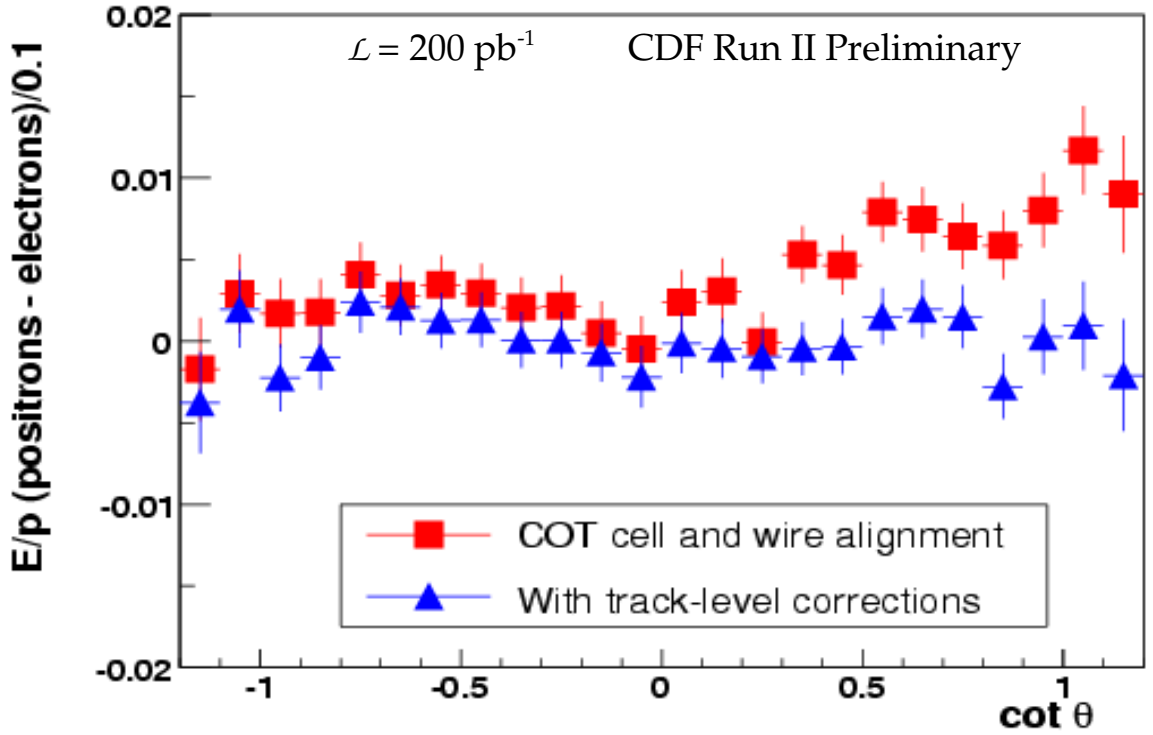
RΔϕ corrections to inner cells:



CDF Tracker Alignment

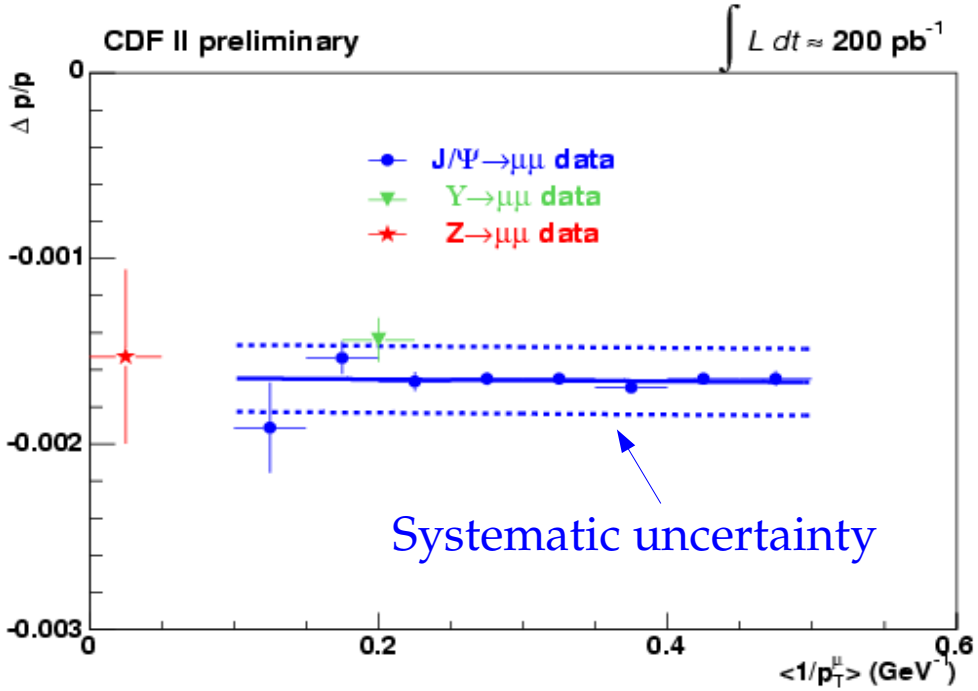
Determine track-level curvature corrections from electron-positron *E/p* differences:

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



Statistical uncertainty of track-level corrections leads to δm_W = **6 MeV**

CDF Momentum Scale



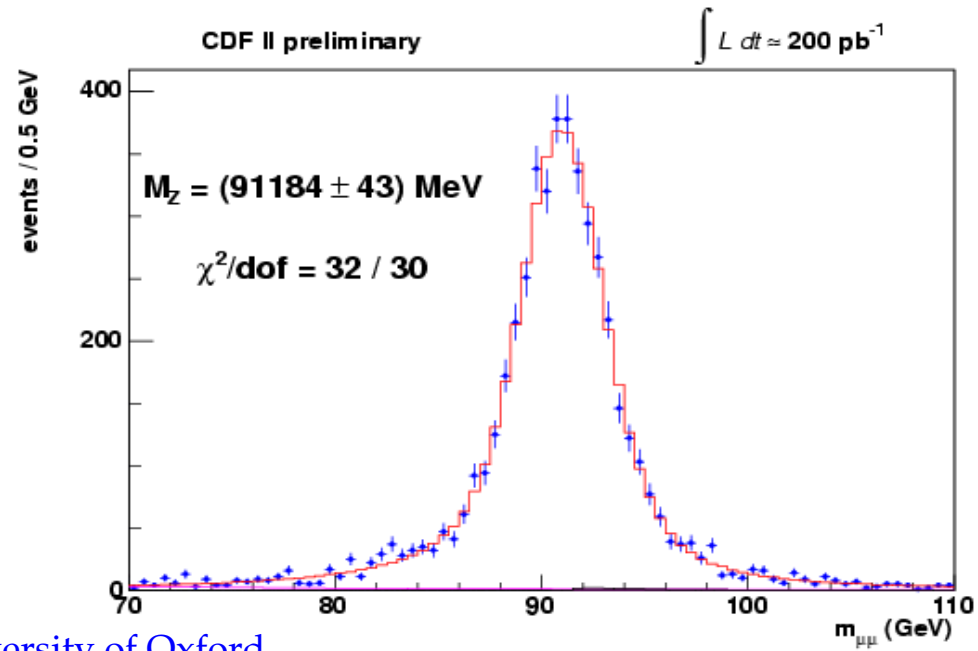
High-statistics J/ψ allows calibration as function of mean muon curvature

Tune model of energy loss in upstream detector (low p_T = higher fractional energy loss)

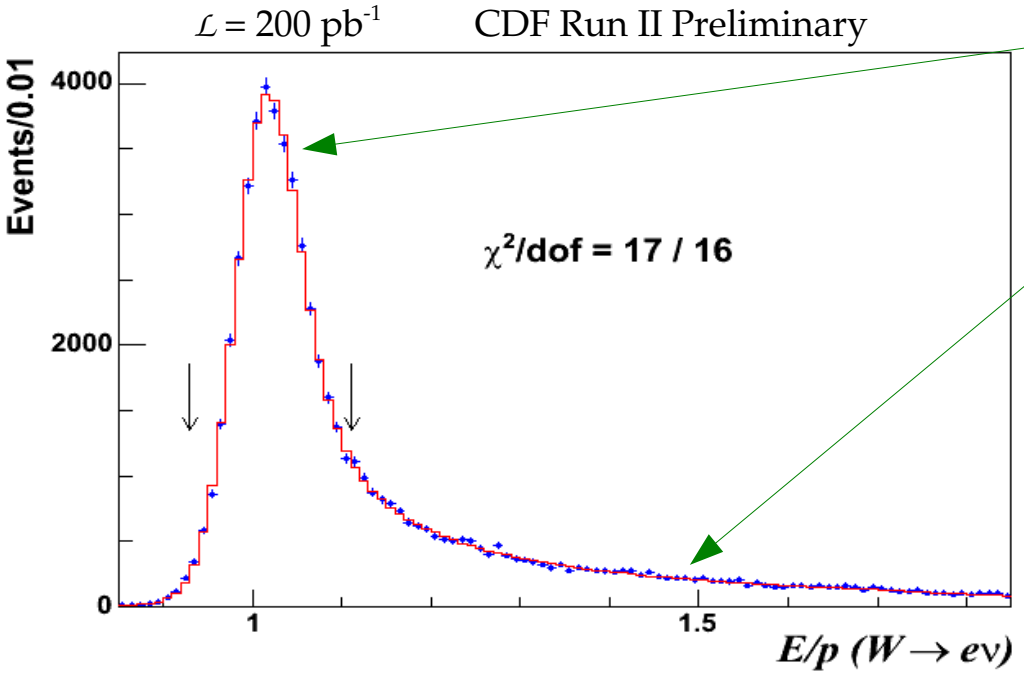
Tune tracker resolution, test beam constraint with Υ *decays*

Use calibrated momentum scale to measure Z mass

Corresponding $\delta m_W = 17$ *MeV*



CDF Energy Scale



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

Tune energy loss with high E/p tail (= high E-loss)

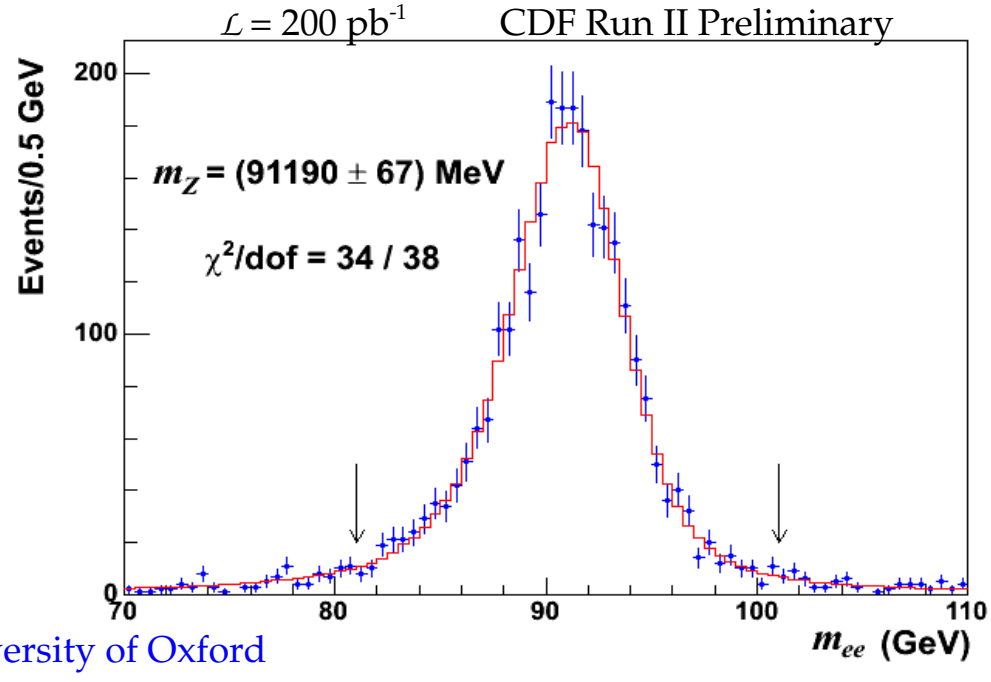
Statistical precision 0.9% X_0

Correct for calibration E_T-dependence (1σ significance)

Use calibrated energy scale to measure Z mass

Add Z mass fit to calibration (30% weight):

δm_W = 30 MeV



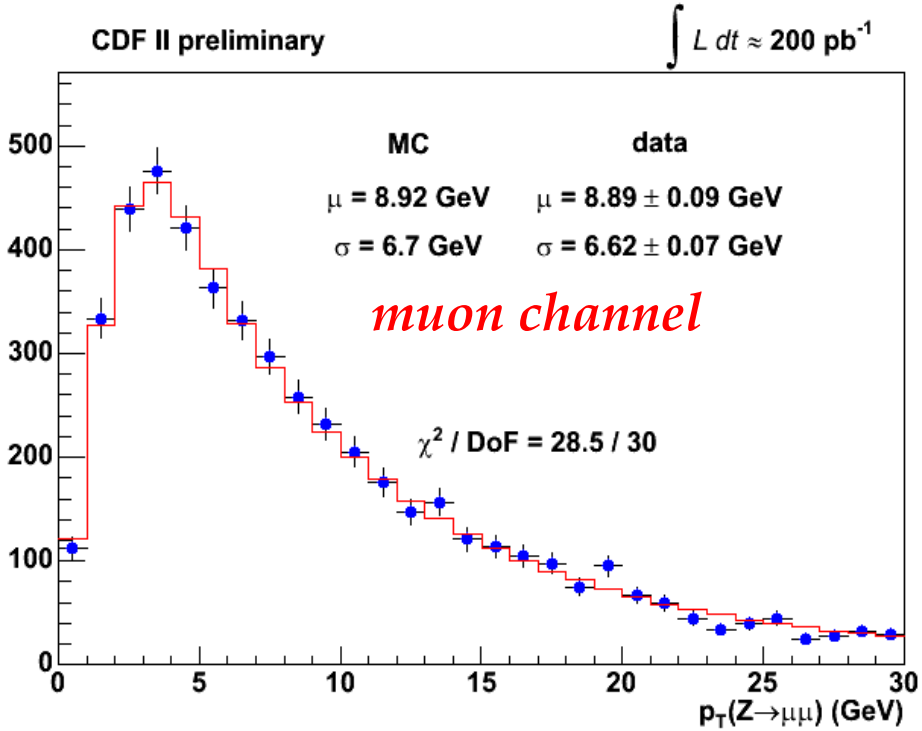
CDF Boson p_T Model

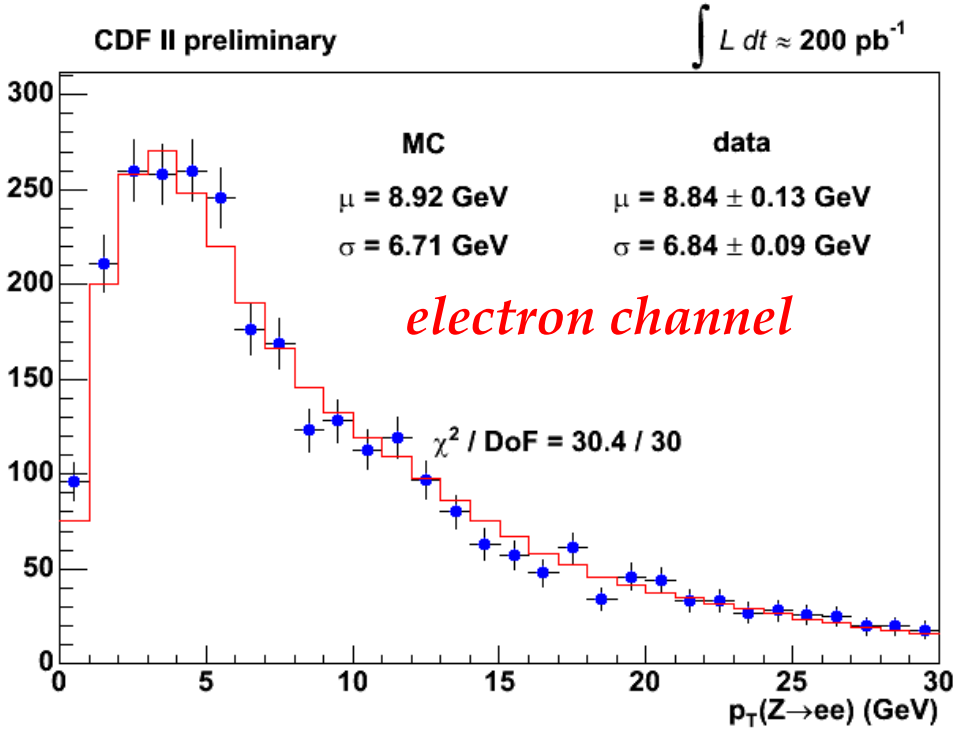
Model boson p_T using RESBOS generator with tunable non-perturbative parameters

"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**



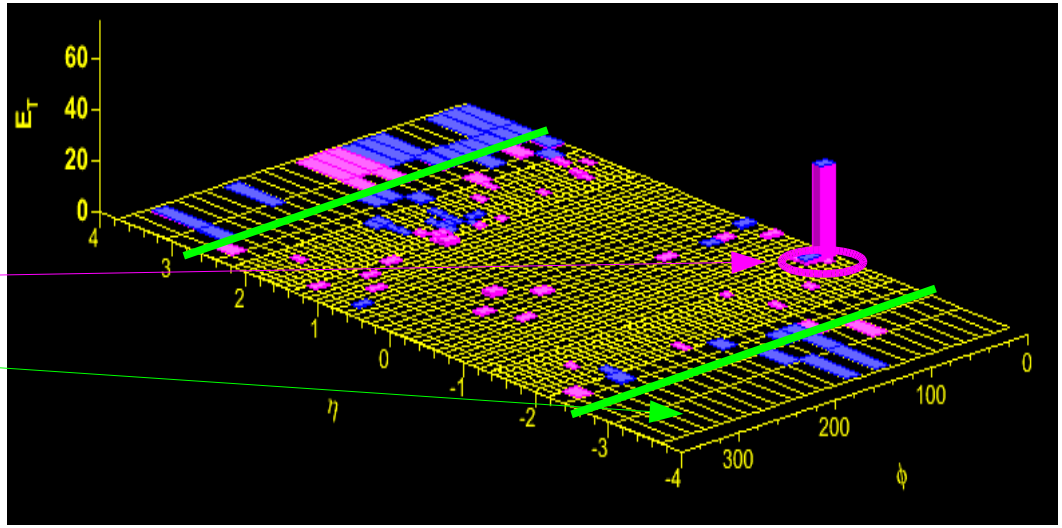


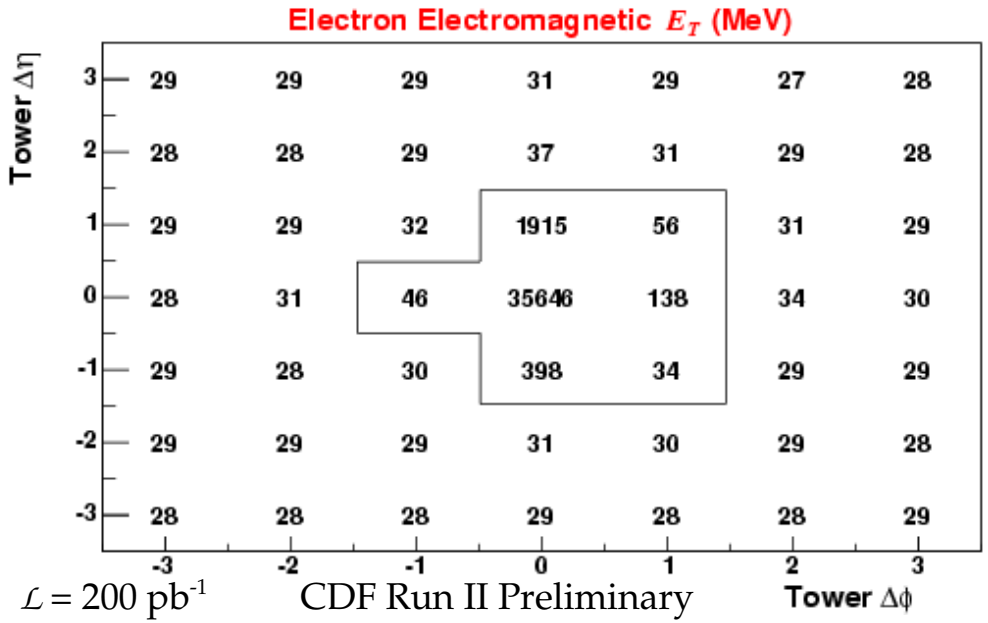
CDF Recoil Measurement

Calculate recoil by summing over calorimeter towers, excluding:

Towers with lepton energy deposits

Towers near the beam line





Electron: Remove 7 towers (shower)

Muon: Remove 3 towers (MIP)

Model tower removal in simulation

δm_W = 8 (5) MeV for *e* (μ)

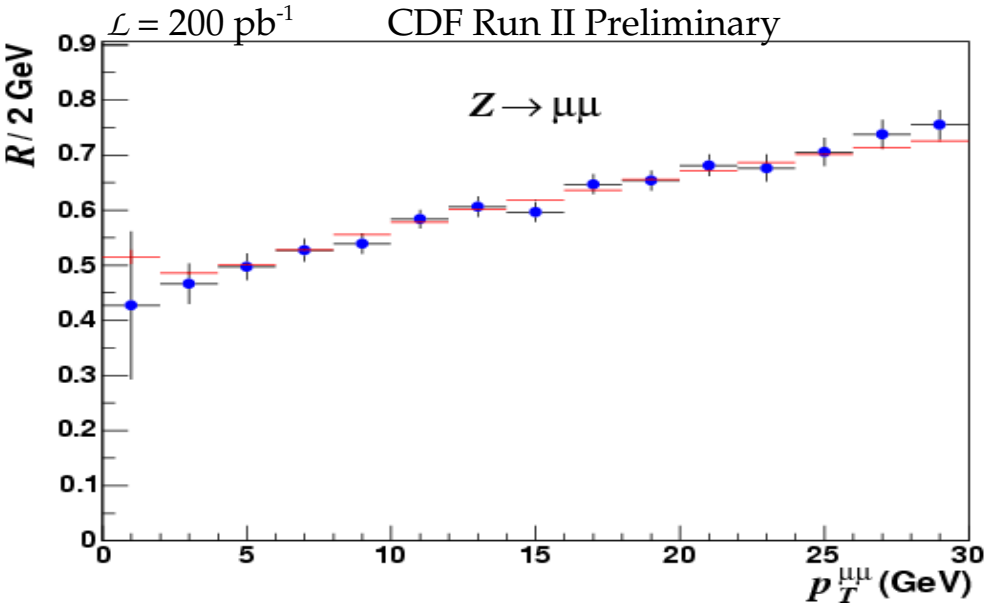
CDF Recoil Model

Components:

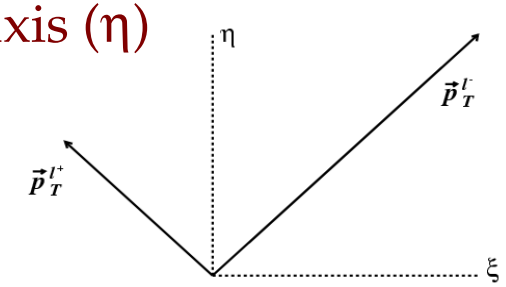
Recoil scale ($R = u_{meas} / u_{true}$)

Recoil resolution

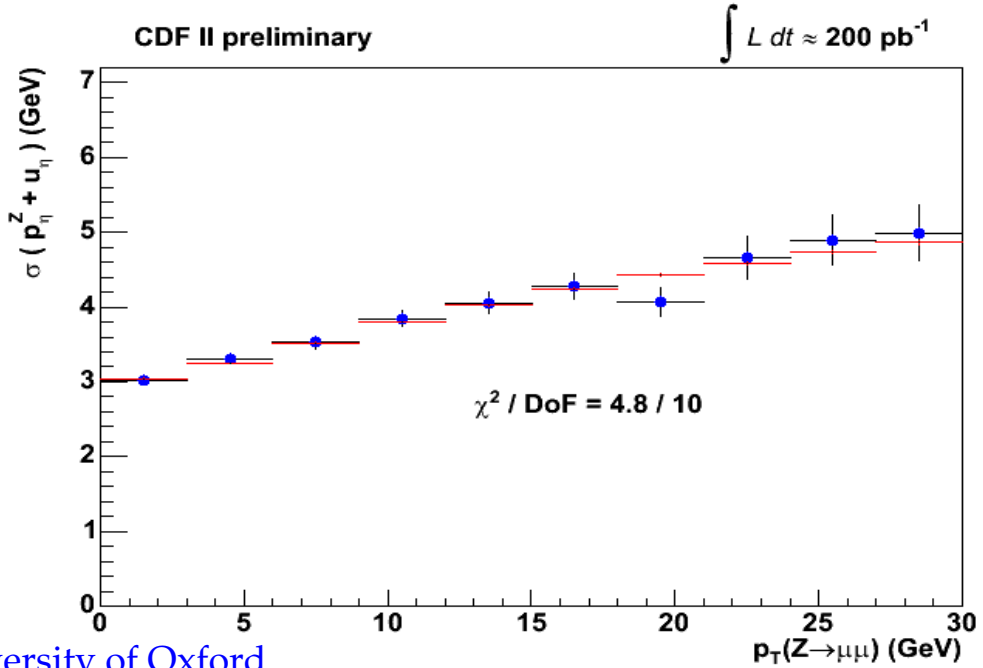
Spectator and additional interactions (contribute to resolution)



Calibrate scale with momentum balance along bisector axis (η)



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



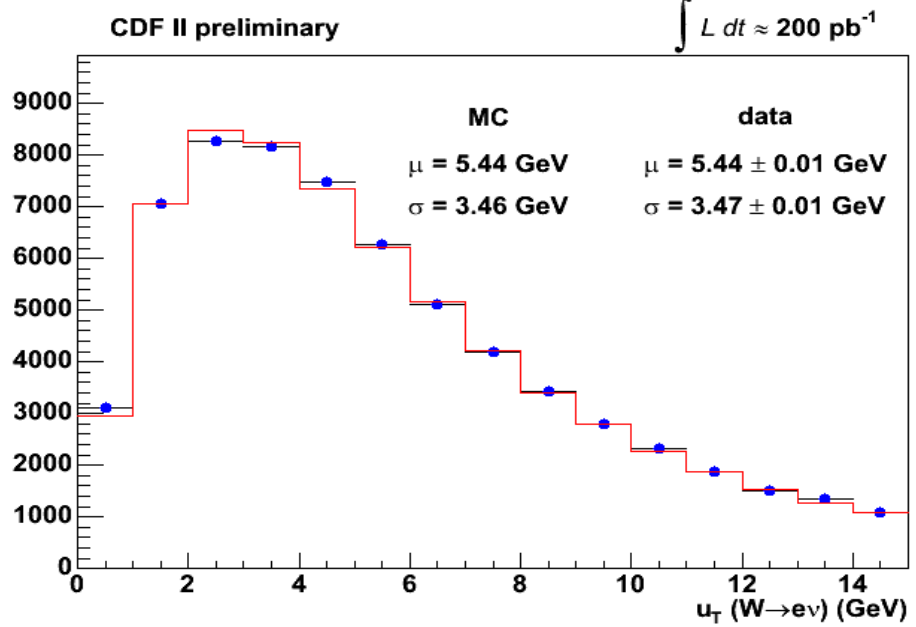
δm_W = **11 MeV**

CDF Recoil Model Checks

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

Recoil distribution

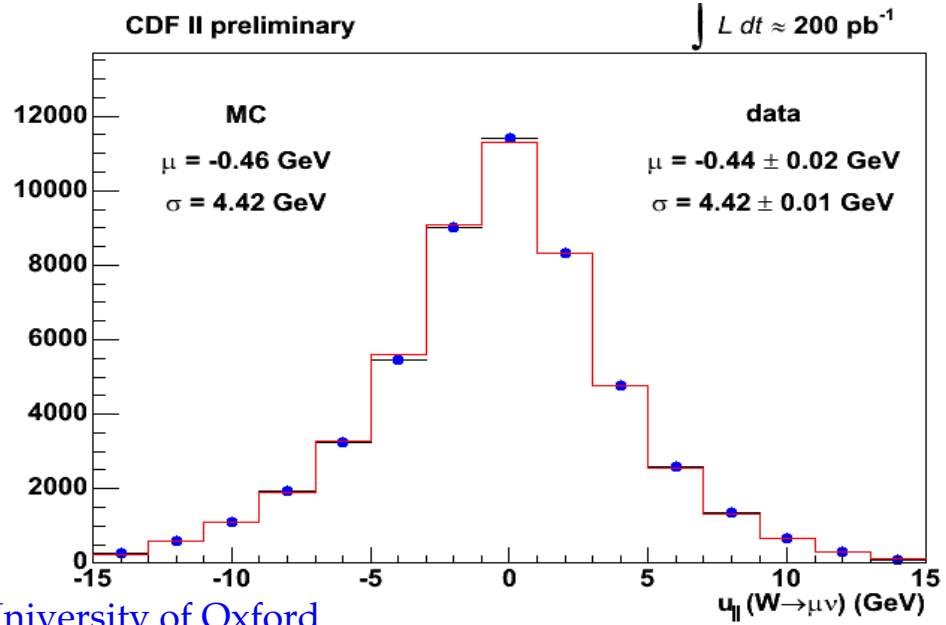
Sensitive to scale, resolution, boson p_T



$u_{||}$ distribution

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

Directly affects m_T fit result



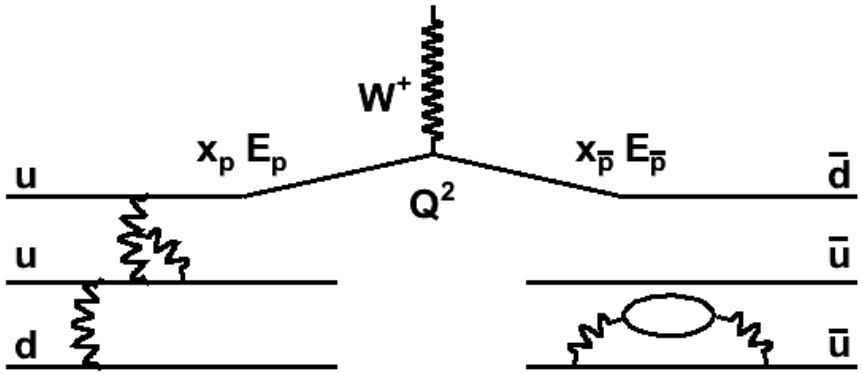
Production, Decay, Background

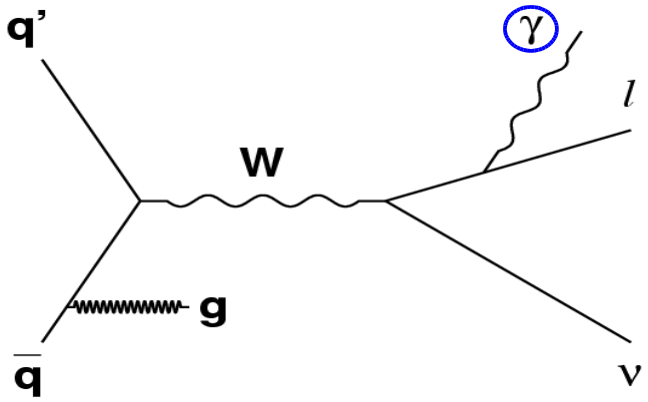
Boson p_z determined by

parton distribution functions

Vary PDFs according to uncertainties

δm_W = **11 MeV**





Brembtrahlung 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)**

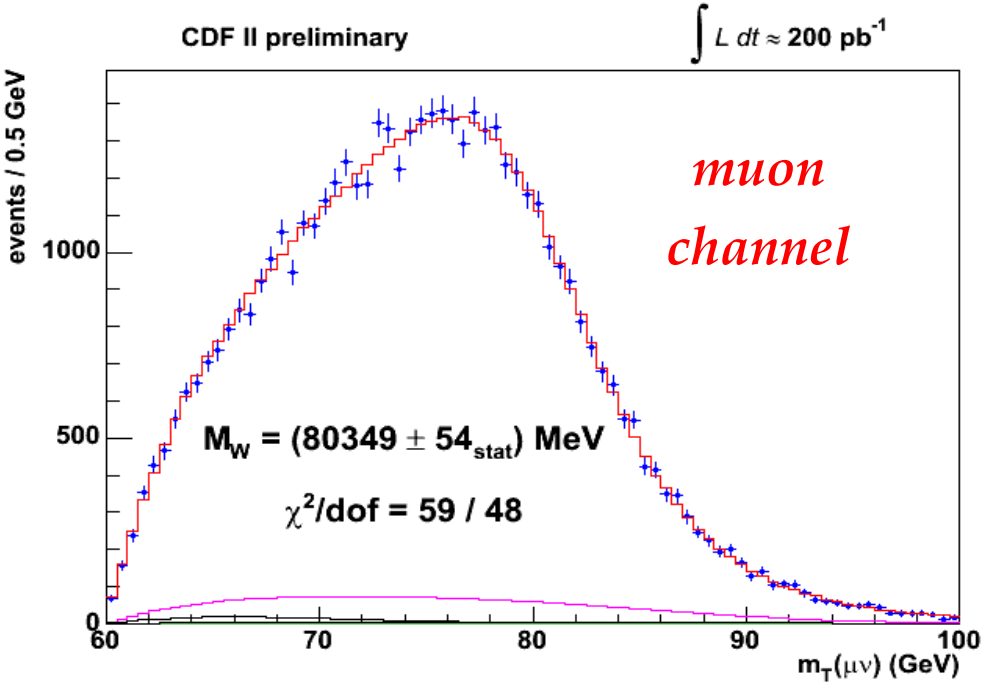
Background	% (μ)	% (*e*)
Hadronic Jets	0.1 ± 0.1	0.25 ± 0.15
Decays in Flight	0.3 ± 0.2	-
Cosmic Rays	0.05 ± 0.05	-
$Z \longrightarrow ll$	6.6 ± 0.3	0.24 ± 0.04
$W \longrightarrow \tau\nu$	0.89 ± 0.02	0.93 ± 0.03

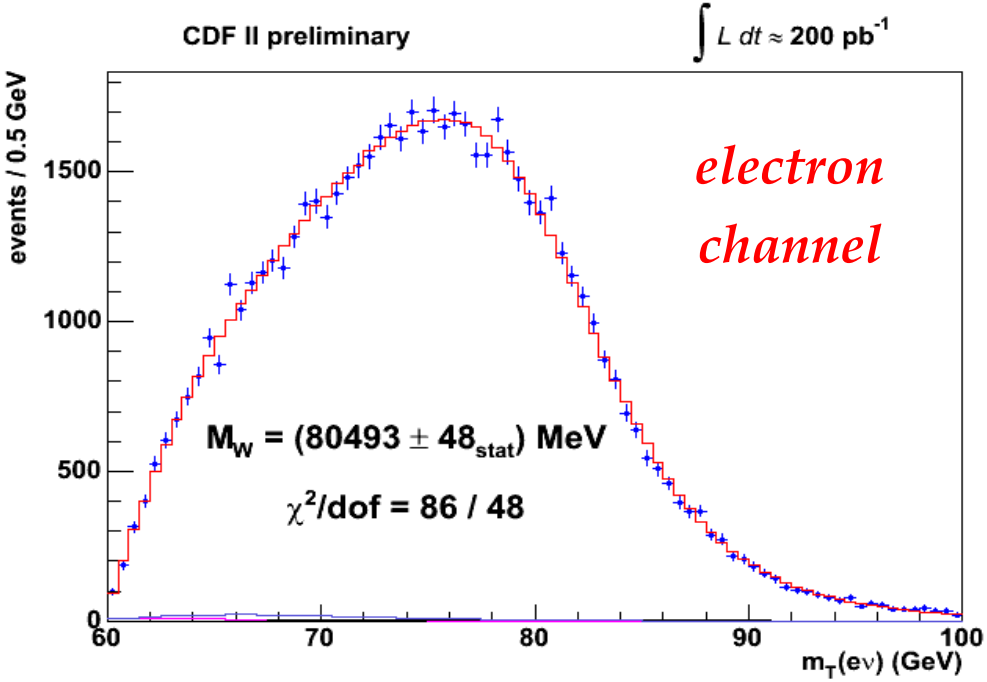
CDF *W* Mass Fits

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

Upon completion, offset removed to determine final result

Transverse mass fits:





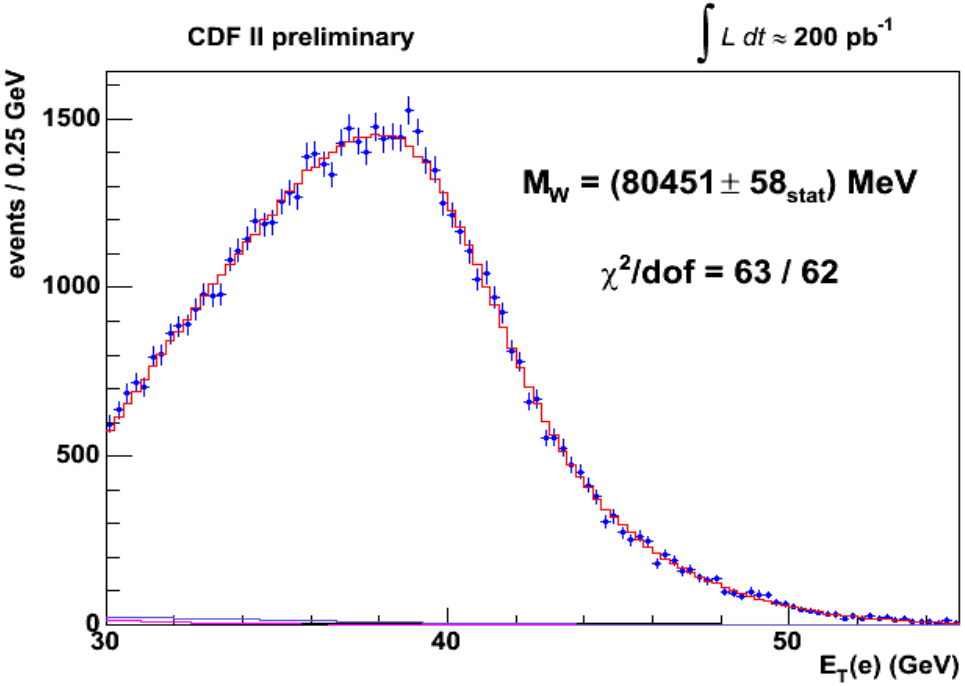
m_W = 80417 ± 48 MeV (stat + sys)

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

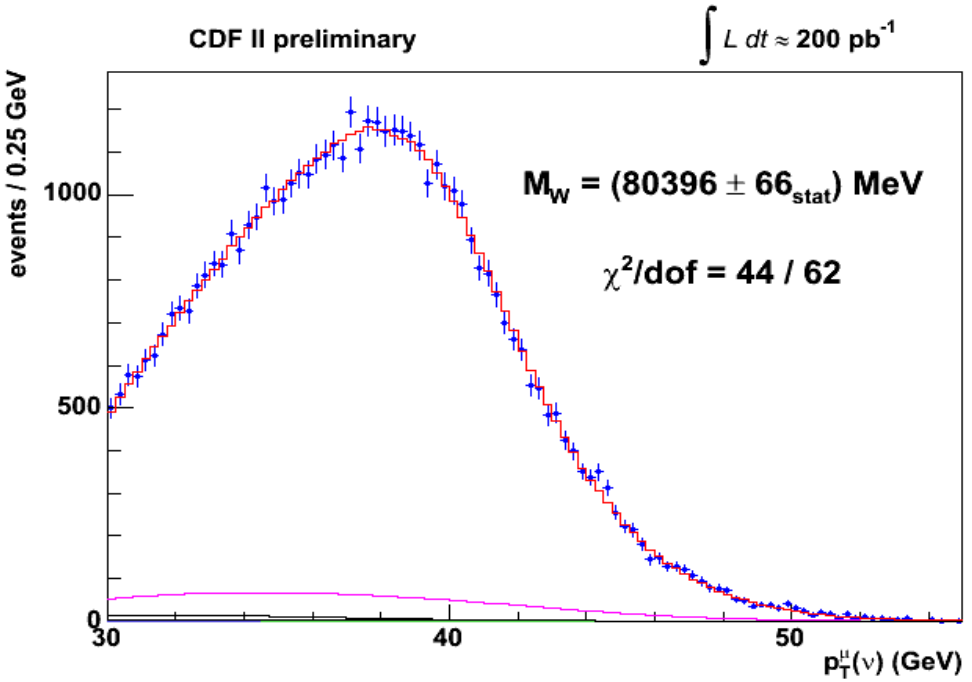
CDF *W* Mass Fits

Fit E_T, $\not\!\!E_T$ distributions and combine with m_T to extract most precise result

Electron E_T fit:



Muon $\not\!\!E_T$ fit:



m_W = 80413 ± 48 MeV (stat + sys)

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

CDF *W* Mass Systematics

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
$u_{\parallel}$ 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

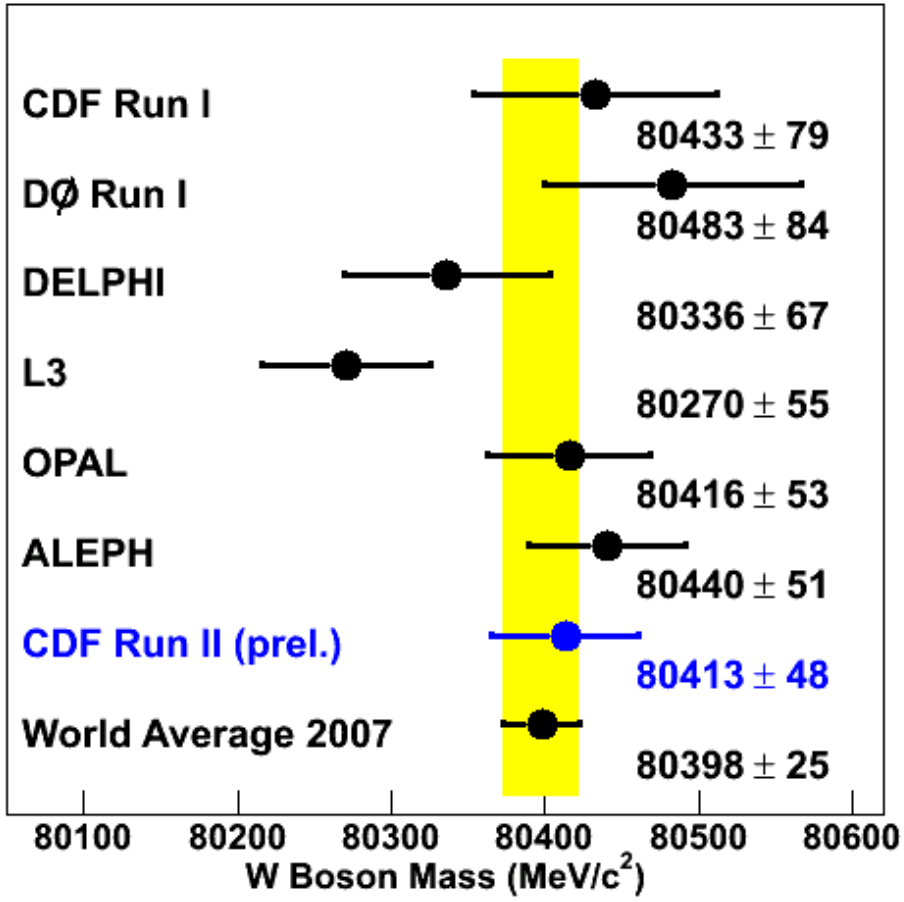
W Mass Results

New CDF result is world's most precise single measurement

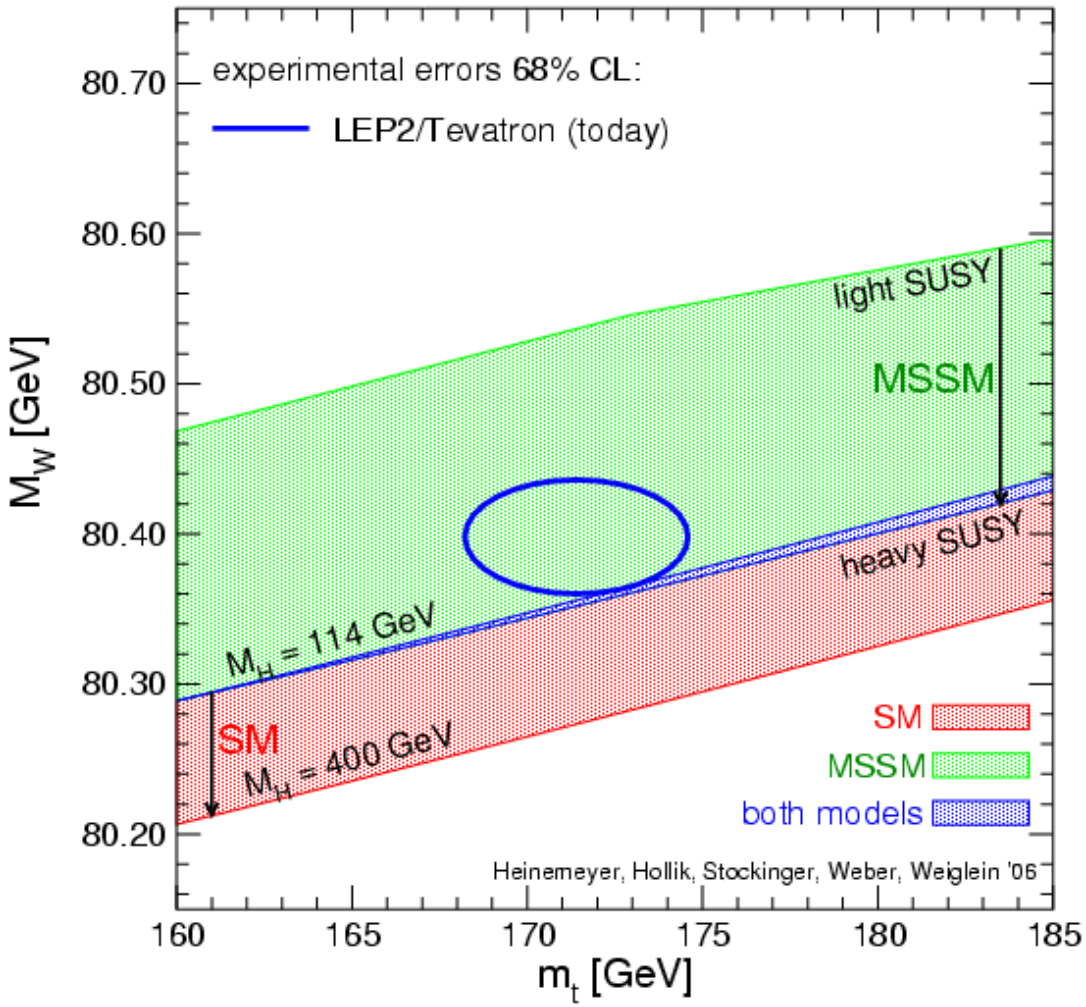
Central value increases: 80392 to 80398 MeV

World average uncertainty reduced ~15%

(29 to 25 MeV)



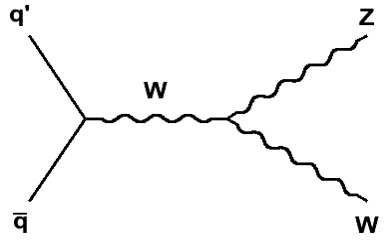
SM Higgs mass: 80^{+36}_{-26} GeV



WZ Boson Production

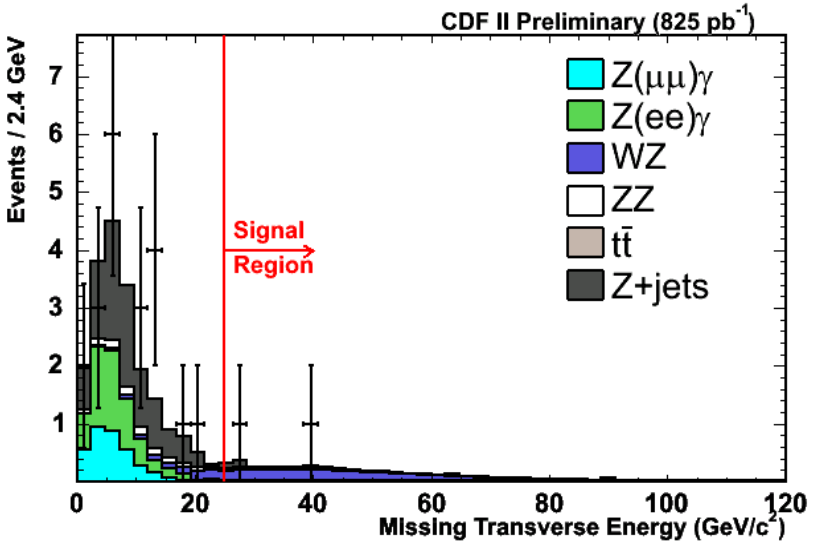
Direct probe of *WWZ* vertex unique to Tevatron

* Low background in trilepton decay channel

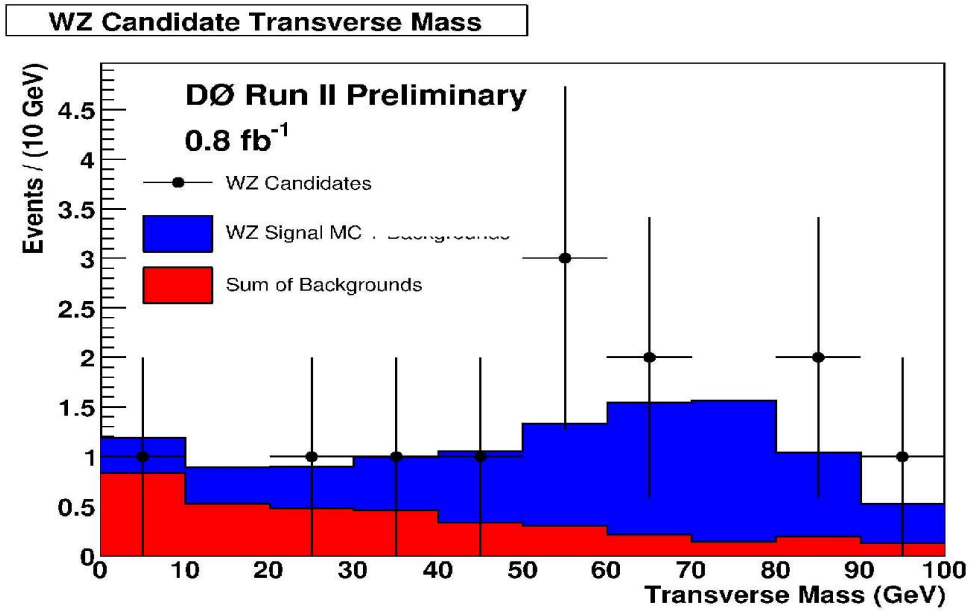


Summer '06 Results:

CDF: Expect 4.6 events, observe **2**



DØ: Expect 11.1 events, observe **12**



$\sigma_{WZ} = 4.0\ ^{+1.9}_{-1.5}$ pb

3.3σ significance

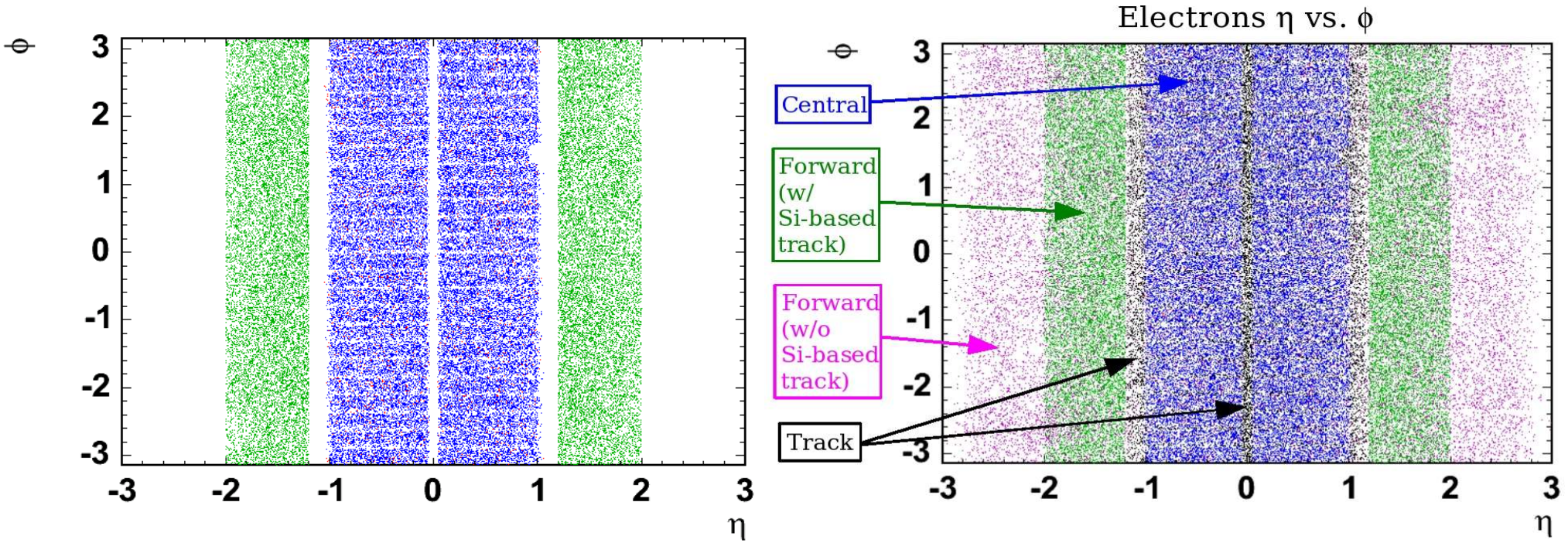
First evidence of *WZ* production at the Tevatron

(*WZ* + *ZZ* significance : 4.2σ)

WZ Boson Production

Fall '06, CDF: significant increase in lepton acceptance for *WZ* search

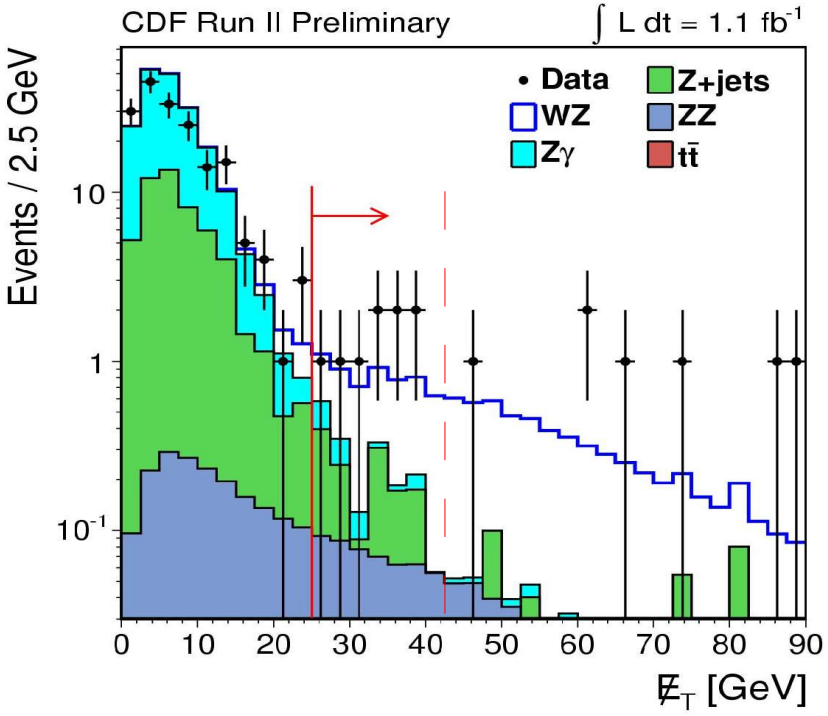
* *Extend lepton coverage further forward*
* *Add electrons passing through calorimeter cracks*



Factor of **2.5** increase in *WZ* acceptance

WZ Boson Observation

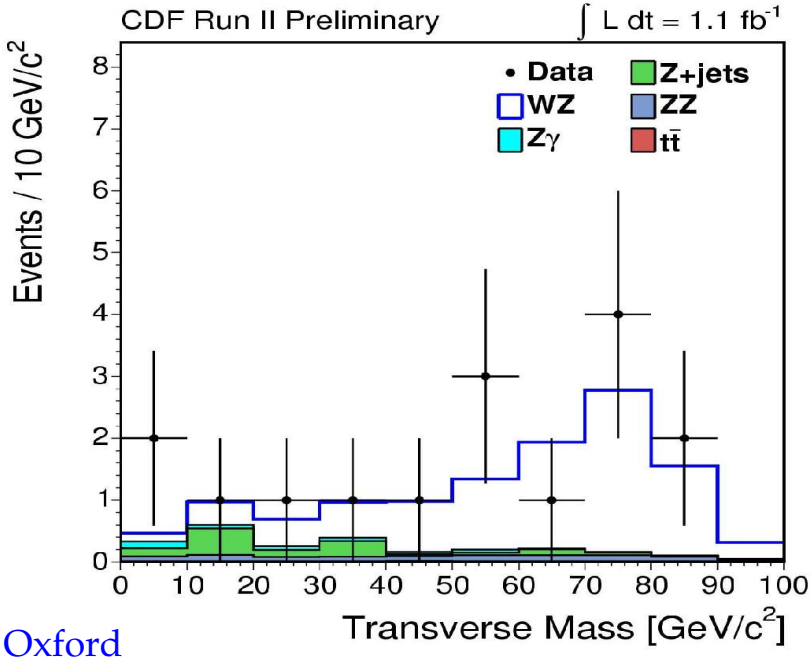
Increase expected sensitivity by fitting in two $\not\!\!E_T$ bins (25-45 GeV and >45 GeV)



CDF: Observe 6σ signal in 2-bin fit

Source	Expectation ± Stat ± Syst ± Lumi
Z+jets	1.22 ± 0.27 ± 0.28 ± -
ZZ	0.89 ± 0.01 ± 0.09 ± 0.05
$Z\gamma$	0.48 ± 0.06 ± 0.15 ± 0.03
$t\bar{t}$	0.12 ± 0.01 ± 0.01 ± 0.01
WZ	9.79 ± 0.03 ± 0.31 ± 0.59
Total Background	2.70 ± 0.28 ± 0.33 ± 0.09
Total Expected	12.50 ± 0.28 ± 0.46 ± 0.68
Observed	**16**

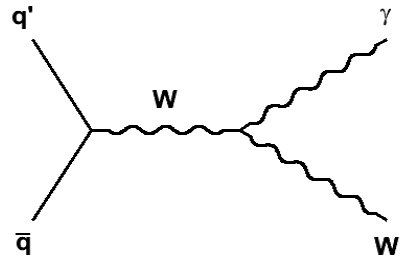
$\sigma_{WZ} = 5.0\ ^{+1.8}_{-1.6}$ pb

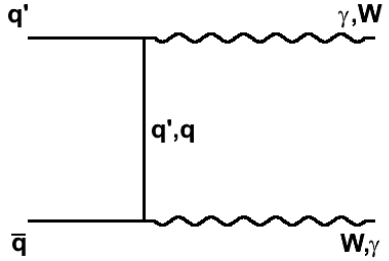


First observation of WZ production

Wγ Boson Production

High-statistics sample allows precise cross section measurement



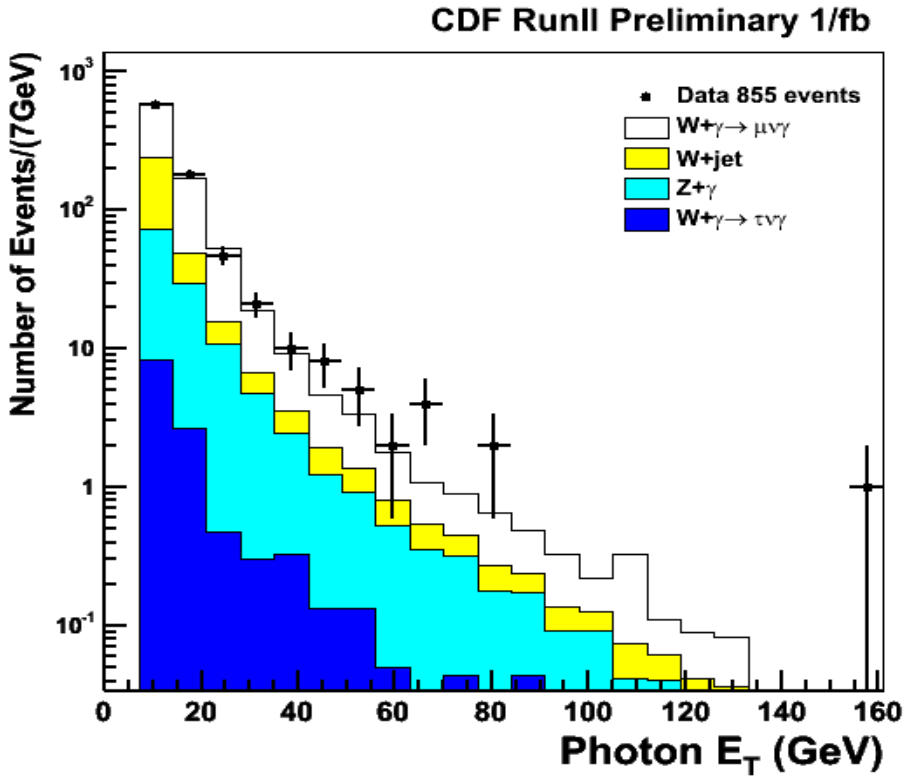


CDF:

$\sigma_{W\gamma}$ = 19.1 ± 1.0 (stat) ± 2.4 (sys) ± 1.1 (lum) pb

(Theory 19.3 ± 1.4)

	Number of Events
$W\gamma$	541.7±4.02(stat.)±1.57(sys.)
W+jet	194.3±0.15(stat.)±66.91(sys.)
$Z\gamma$	112.0±0.39(stat.)±0.32(sys.)
$W\gamma(\tau)$	12.4±0.60(stat.)±0.04(sys.)
Number of Total	860.4±29.25(stat.)±66.95(sys.)
Number of Observed	855



$W\gamma$ Radiation Amplitude Zero

High-statistics sample allows study of quantum interference effects

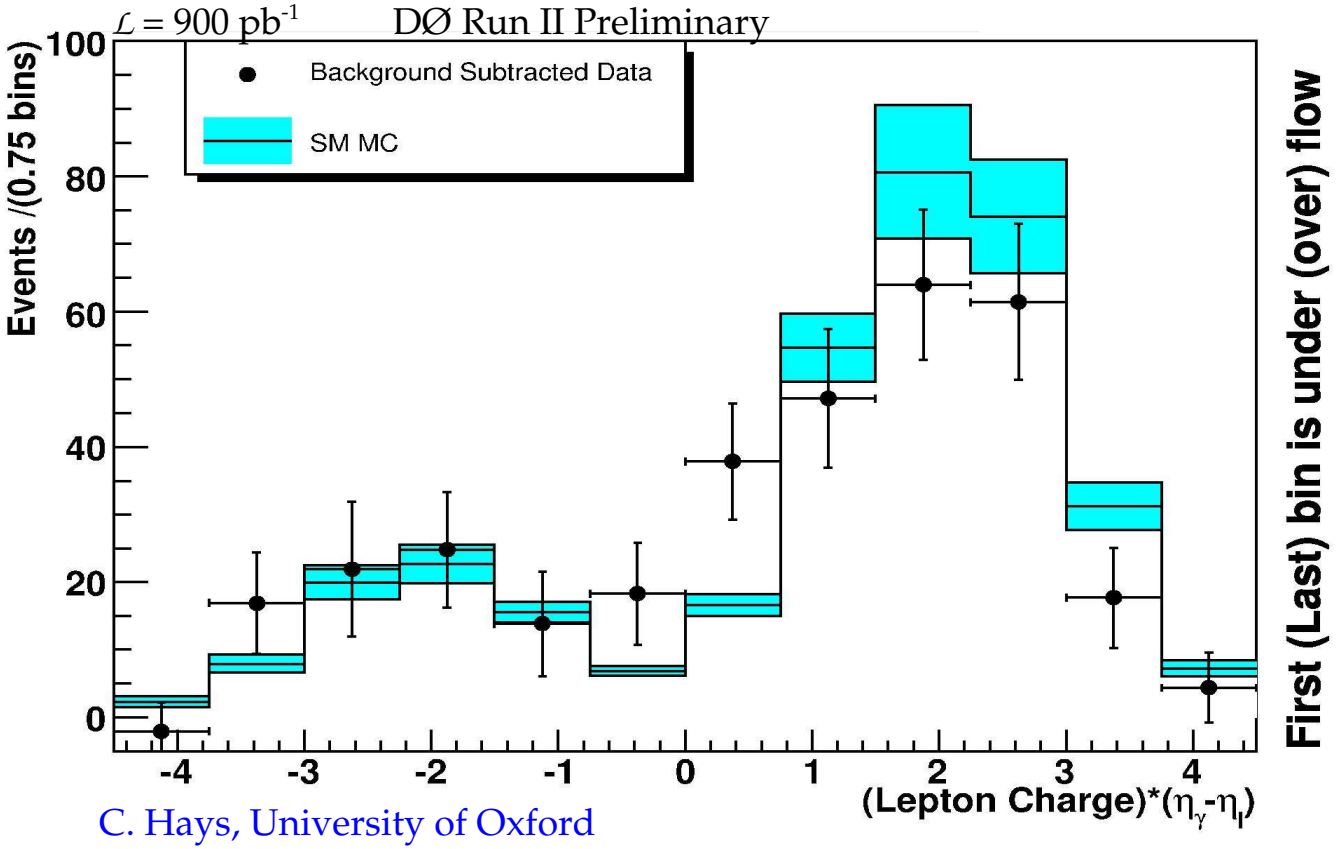
Interference produces a zero at $\cos(\theta^*) = \pm 1/3$

(θ^*: center of mass angle between $W^{\pm}$ and incoming quarks)

Observable as a dip in delta rapidity spectrum at $\pm[y(\gamma) - y(l^{\pm})] \approx -0.3$

DØ:

Probability of dip ~90%
in 900 pb^{-1} of data



Summary

High-luminosity data samples at Tevatron opening new physics windows

Most precise *W* mass measurement (CDF)

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

First observation of *WZ* production

Expect most sensitive probes to anomalous WWZ couplings

First hint of $W\gamma$ radiation amplitude zero

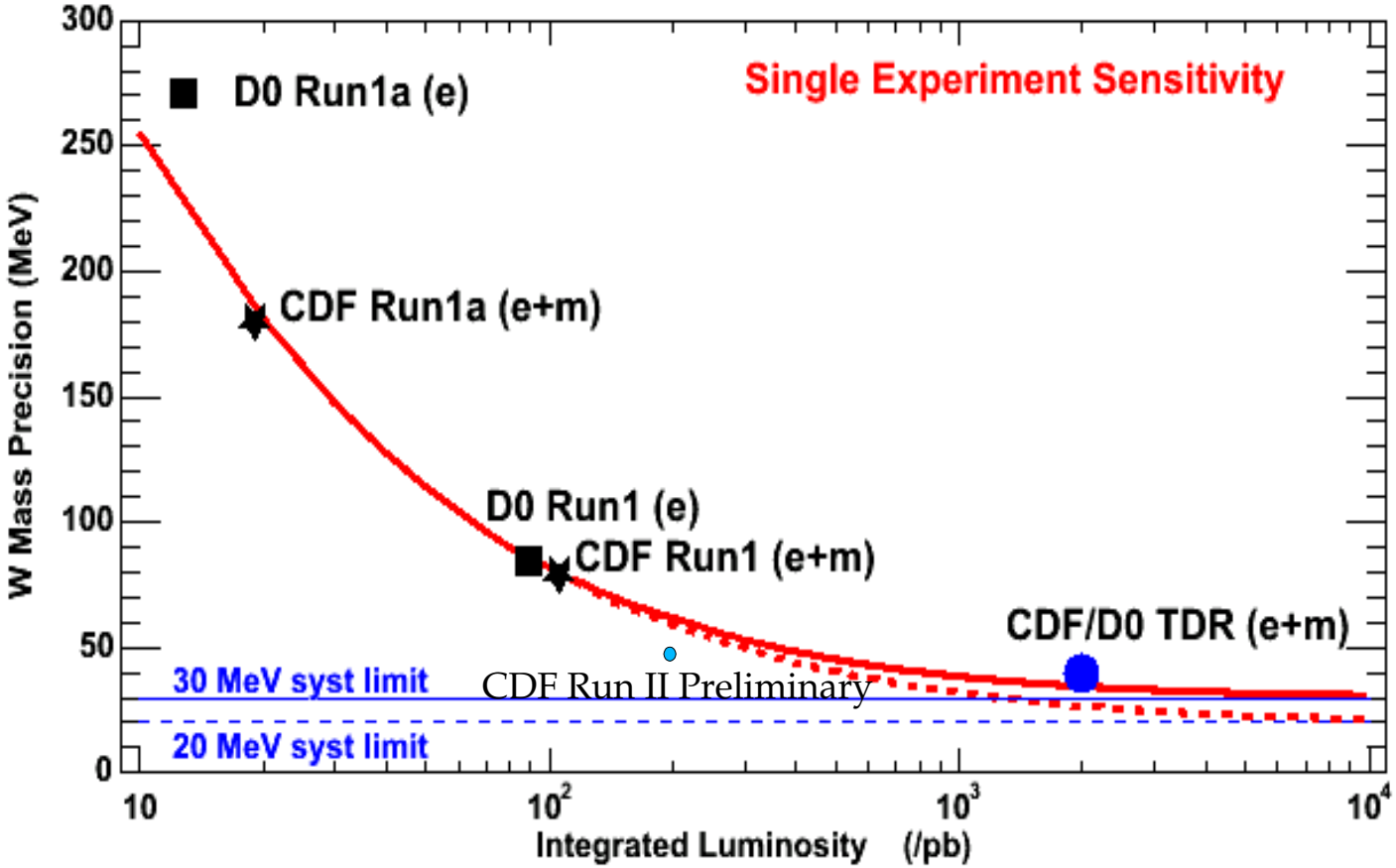
Expect to observe this quantum interference effect

Many other *W* & *Z* measurements constraining couplings and PDFs

Backup

W Mass Measurement Projections

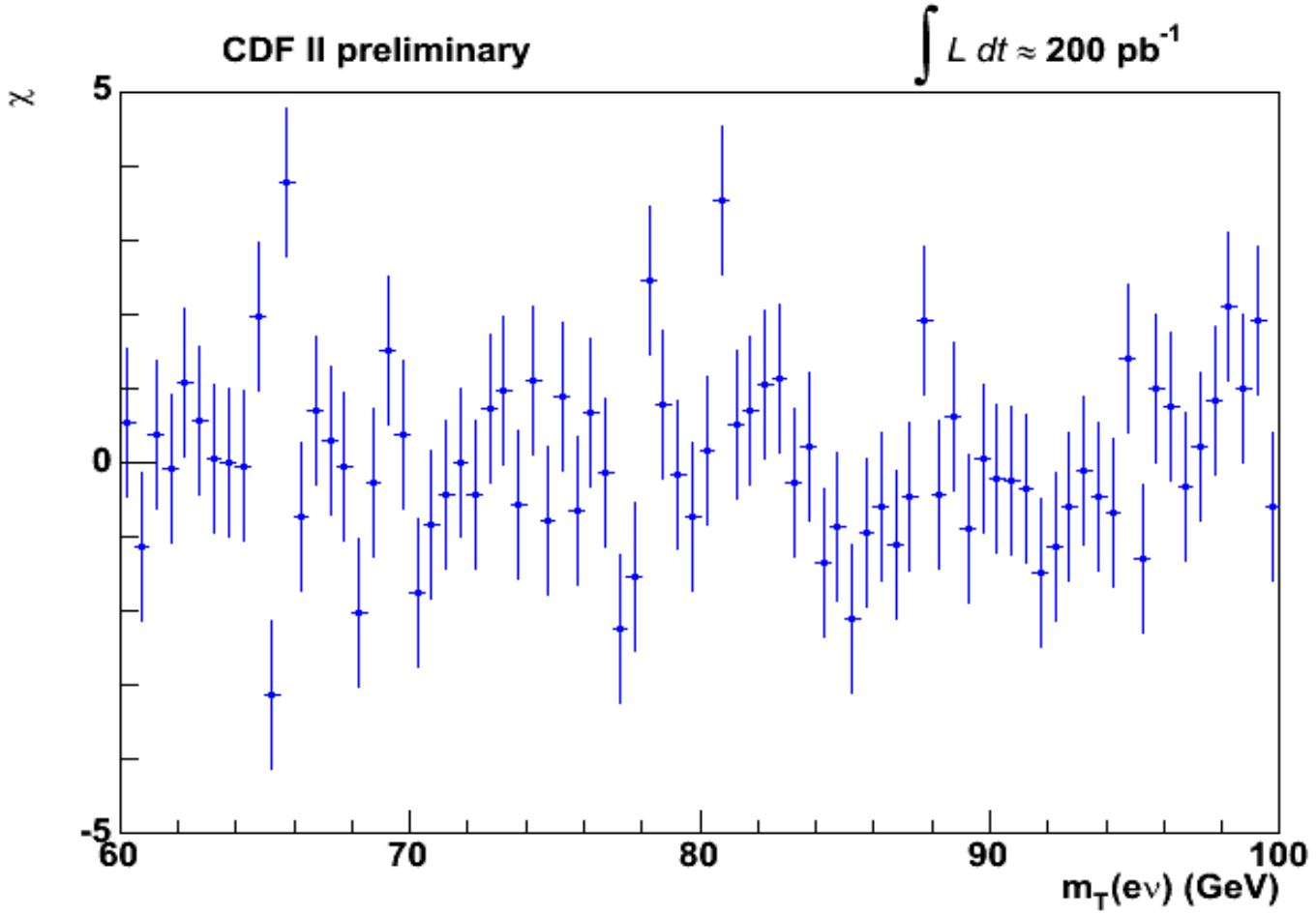
Previously projected Tevatron precision as a function of luminosity:



New expectation: <20 MeV systematic limit

Electron m_T Signed χ

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



Weak Boson Physics

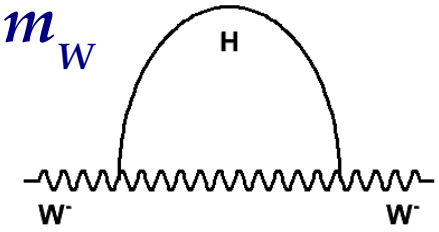
Z boson parameters measured precisely by LEP:

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

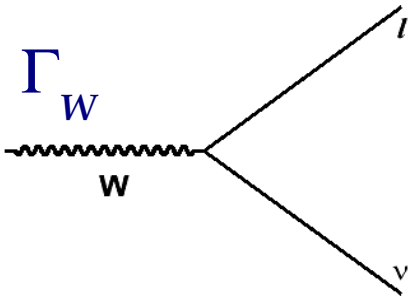
Tevatron goal:

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

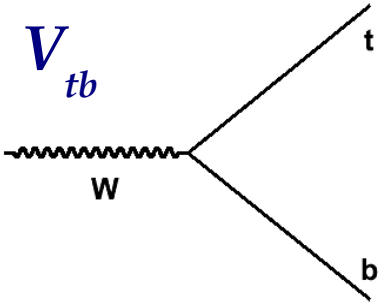
m_W



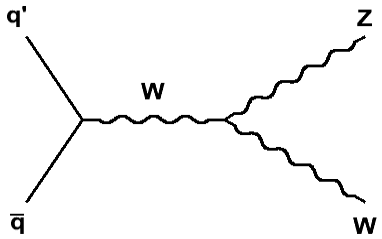
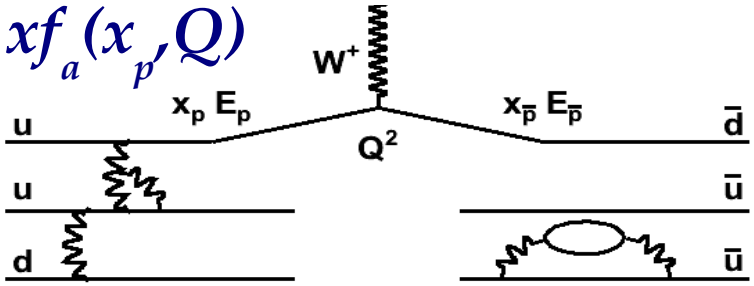
Γ_W



V_{tb}



WWZ coupling



$xf_a(x_p,Q)$