First Run II Measurement of the W Boson Mass with CDF

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on behalf of the CDF Collaboration

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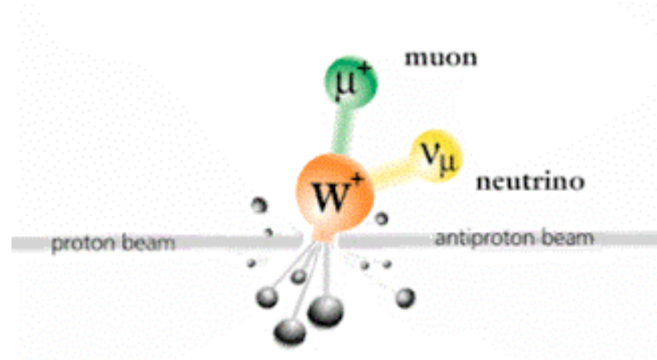


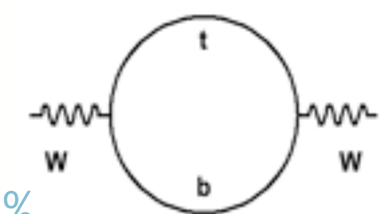
Motivation

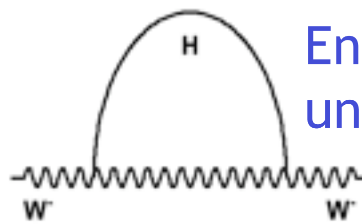
- Derive W mass from precisely measured electroweak quantities

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

- Radiative corrections r dominated by top quark and Higgs loop
  $\Rightarrow$allows constraint on Higgs mass

Current top mass uncertainty 1.1% (1.8 GeV)
→ equivalent 0.014% (11 MeV) on δM_W





End 2006: W mass uncertainty 0.036% (29 MeV)

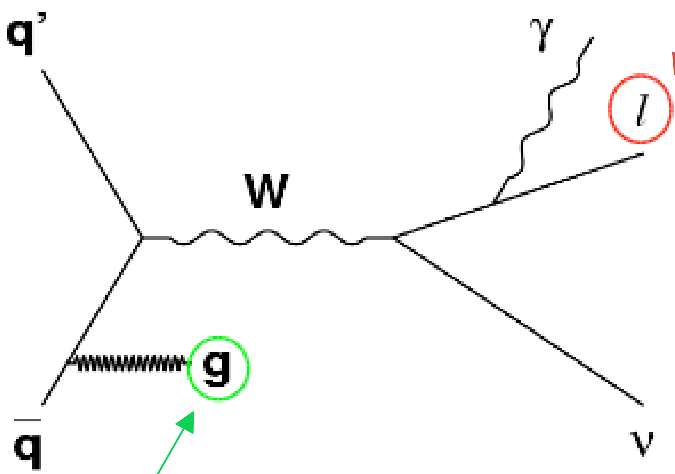
→ End 2006:
Higgs mass predicted: 85^{+39}_{-28} GeV

- Progress on W mass uncertainty now has the biggest impact on Higgs mass constraint

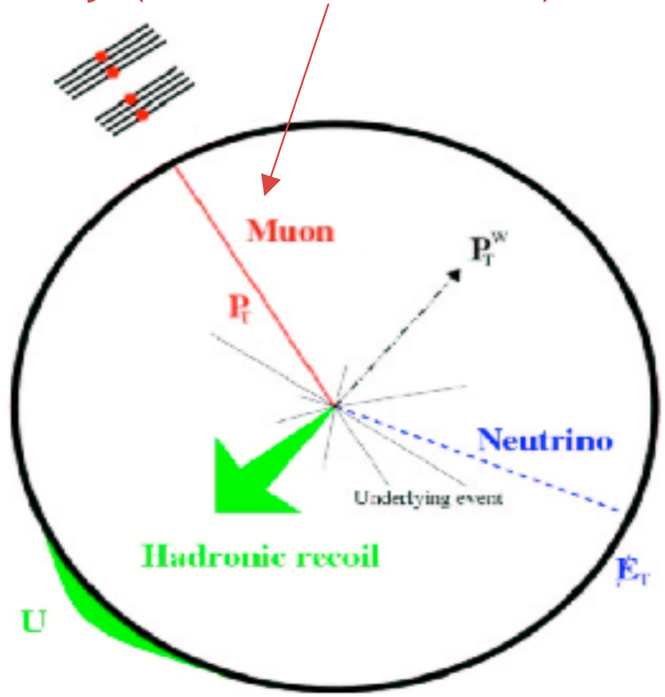
- With improved precision also sensitive to possible exotic radiative corrections

W Production at the Tevatron

Quark-antiquark annihilation dominates



precise charged lepton measurement is the key (achieved ~0.03%)



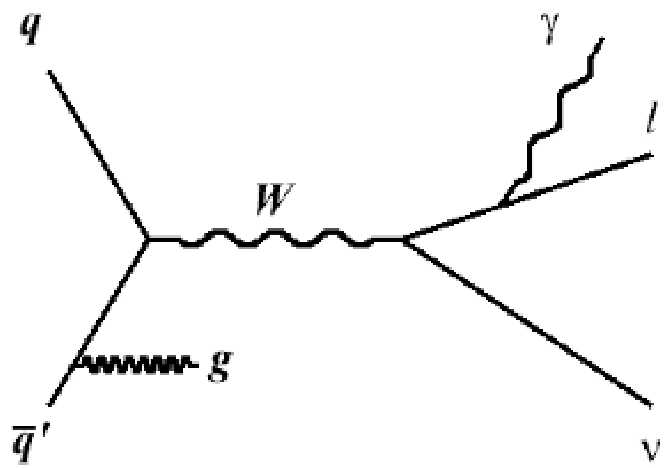
Recoil measurement allows inference of neutrino E_T (restricted to u<15 GeV)

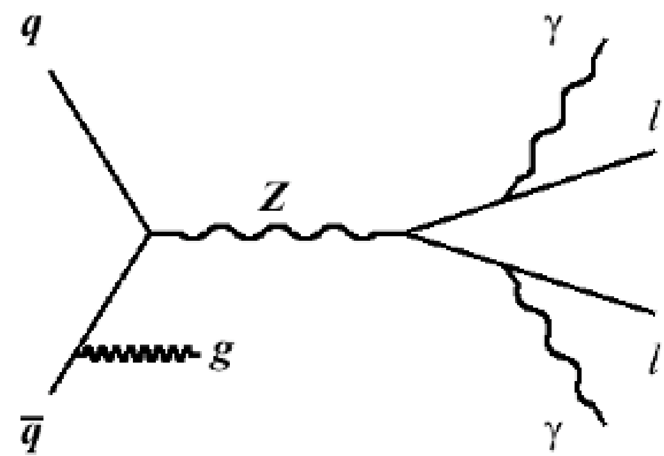
Combine information into transverse mass: $m_T = \sqrt{2 p_T^{\,l} p_T^{\,\nu} (1 - \cos\phi_{l\nu})}$

Use $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events to derive recoil model

W/Z Production at the Tevatron

200 pb^{-1}





From the high p_T lepton triggers (p_T>18 GeV)

After event selection
$E_T(l,\nu)$ > 30 GeV

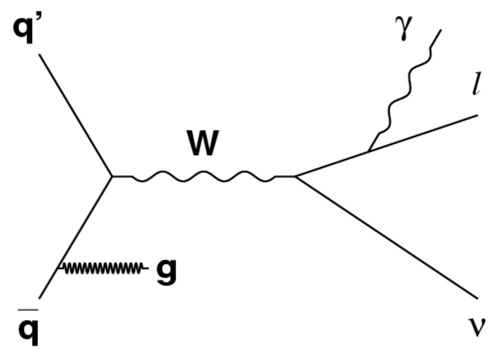
51,128 W→μν candidates
63,964 W→eν candidates

After event selection
$E_T(l)$ > 30 GeV

4,960 Z→μμ candidates
2,919 Z→ee candidates

Measurement Strategy

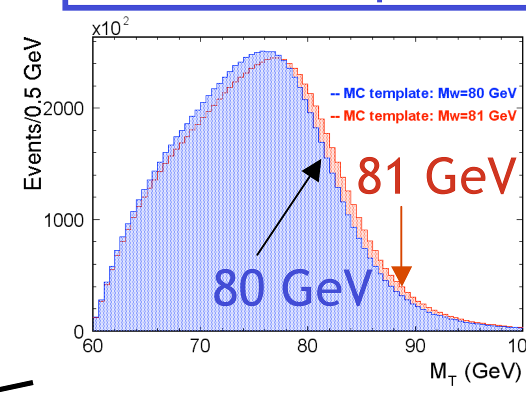
W mass is extracted from transverse mass, transverse momentum and transverse missing energy distribution



Dedicated Fast Simulation

- NLO event generator
- Model detector effects

W Mass templates



Detector Calibration

- Tracking momentum scale
- Calorimeter energy scale
- Recoil

Data

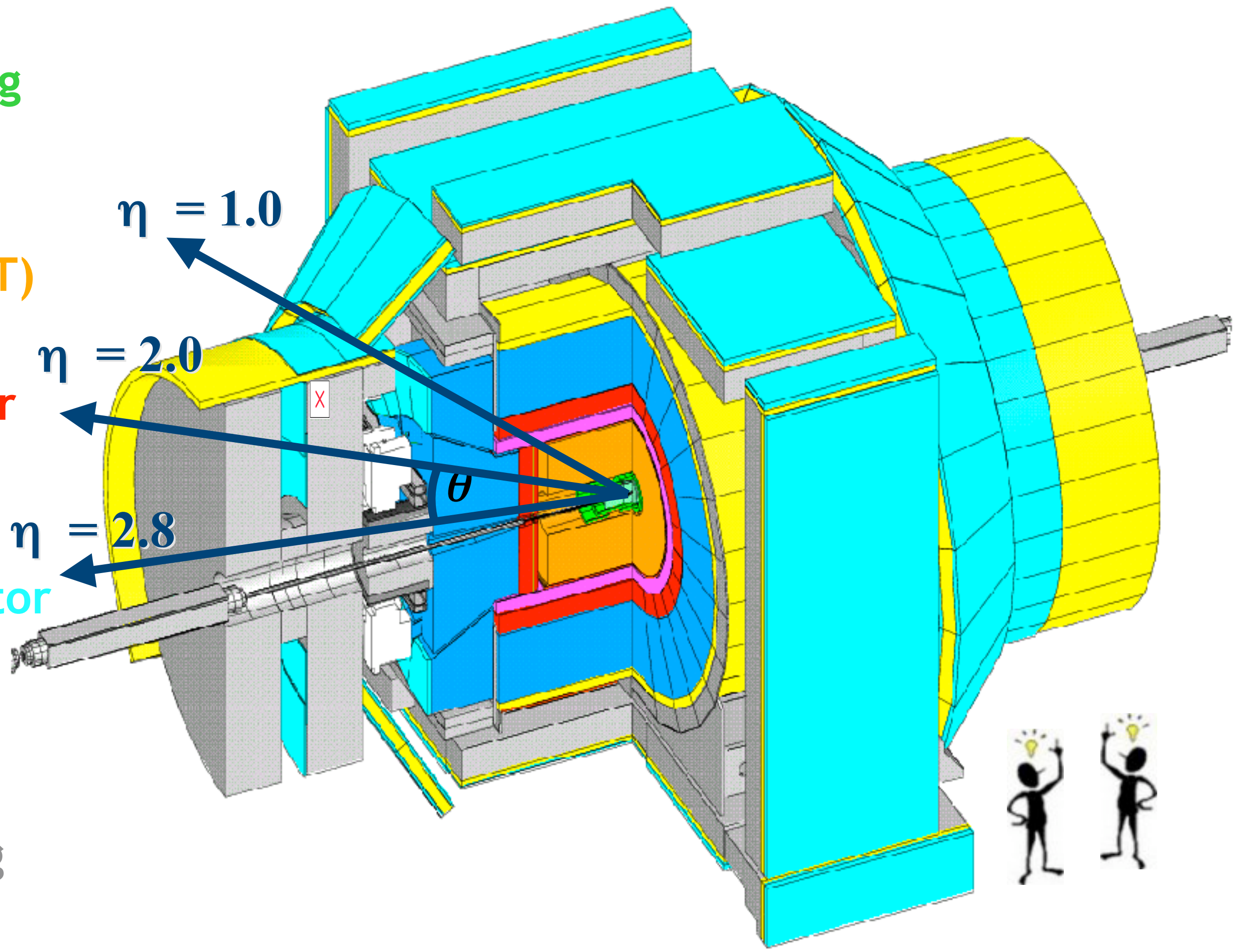
+ Backgrounds

Binned likelihood fit

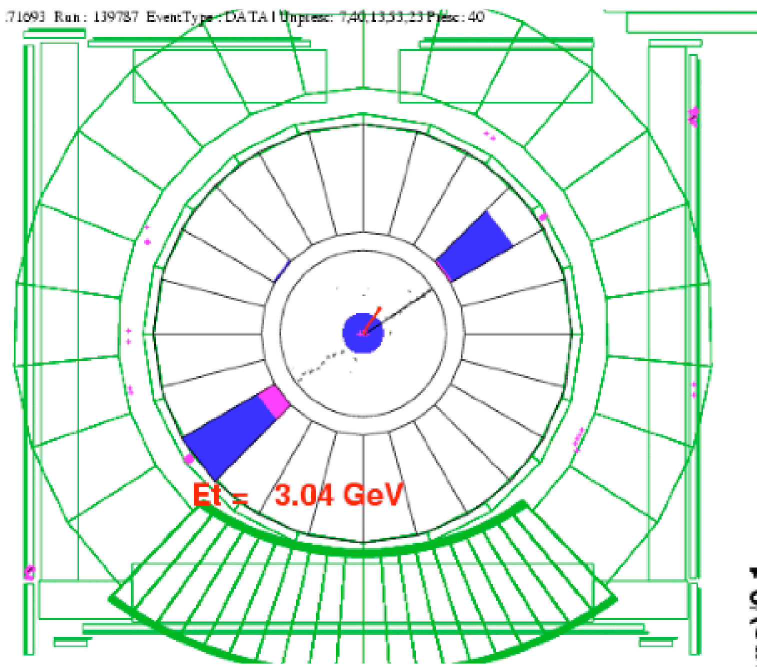
W Mass

CDF Detector

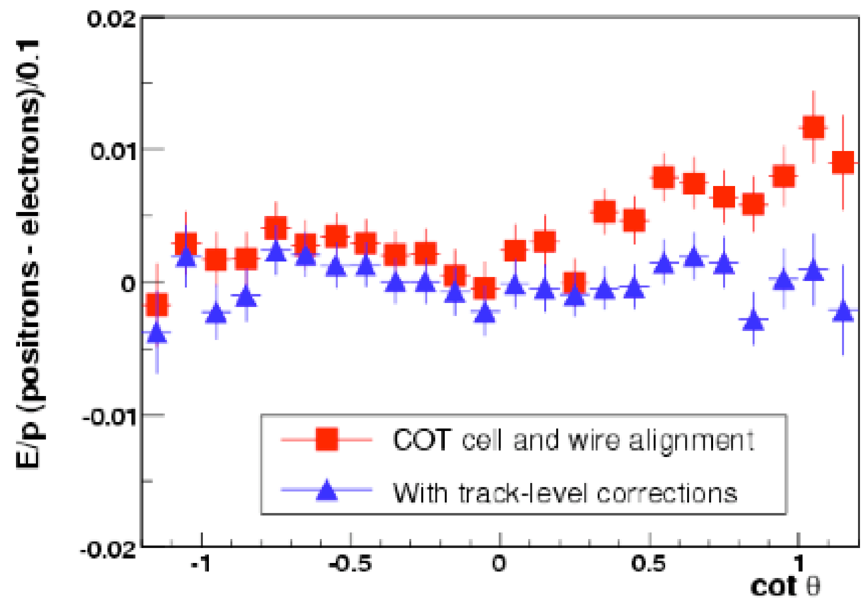
- Silicon tracking detectors
- Central drift chambers (COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding



Momentum Scale/Tracker Alignment



- Internal alignment is performed using a large sample of cosmic rays → Fit hits on both sides to one helix
- Determine final track-level curvature corrections from electron-positron E/p difference in $W \rightarrow e\nu$ decays

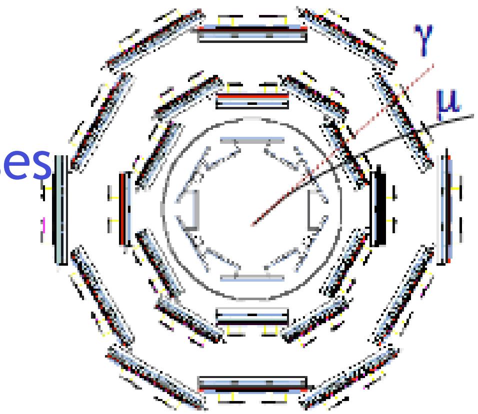


- Statistical uncertainty of track-level corrections leads to systematic uncertainty

$\Delta M_W = 6$ MeV

Mass Measurements

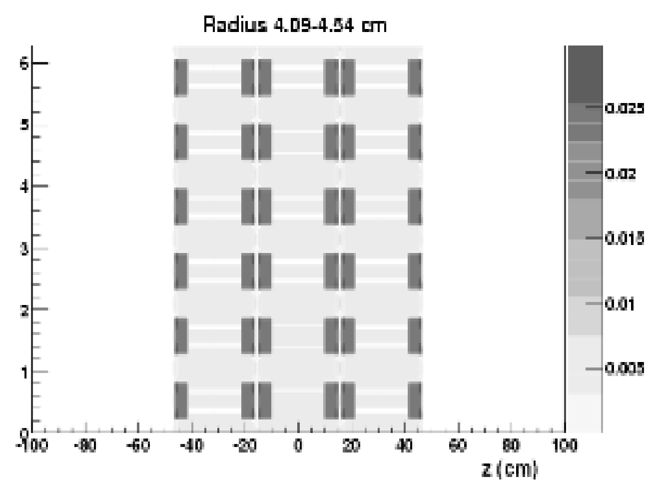
- Template mass fits to J/Ψ→μμ, ϒ→μμ, Z→μμ resonances to obtain momentum scale calibration



- Fast simulation models relevant physics processes
  - internal bremßstrahlung
  - ionization energy loss
  - multiple scattering

- Hit level simulation of tracking

- Detector material model
  - map energy loss and radiation lengths in each detector layer



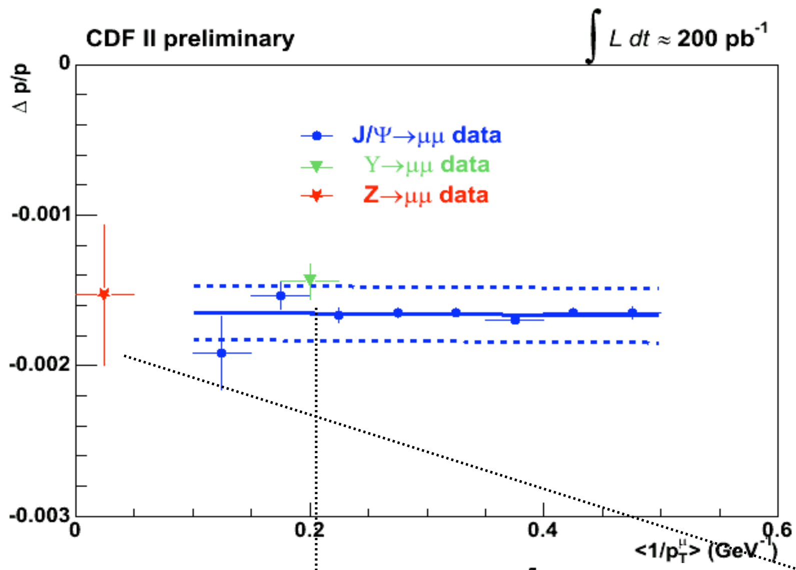
- Overall material scale determined from data

Momentum Scale Calibration

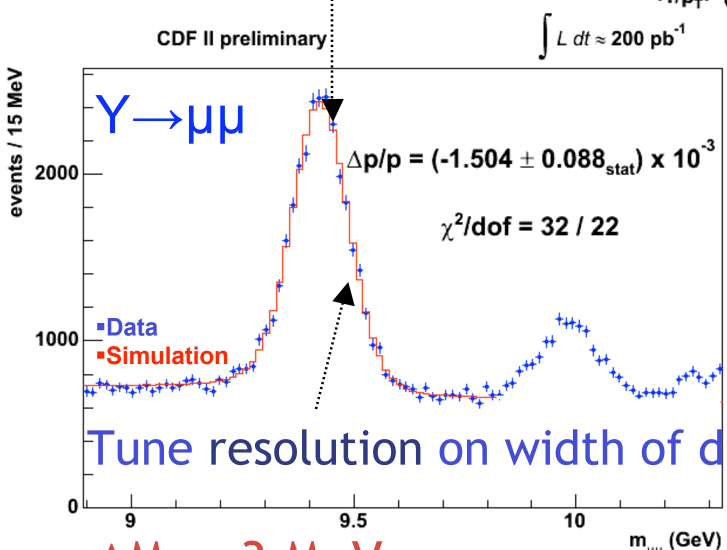
Exploit large J/ψ and Upsilon datasets to set momentum scale

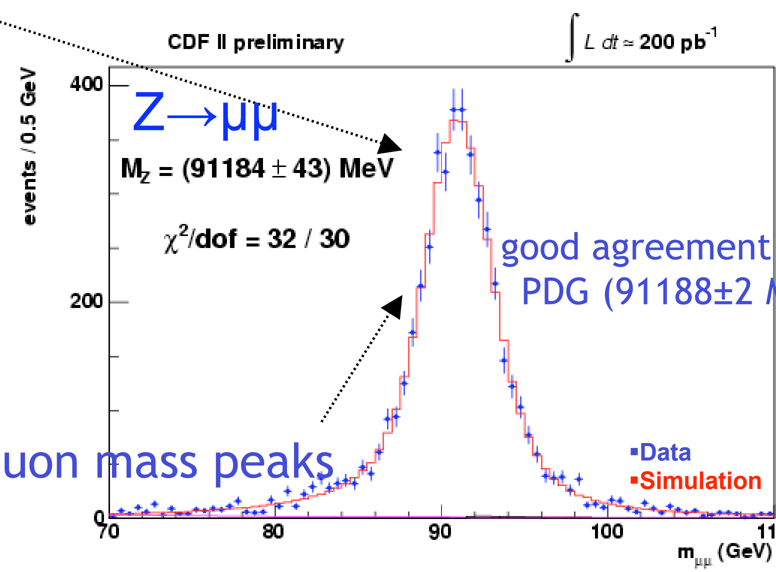
Tune model of energy loss
→ J/ψ independent of muon p_T

ΔM_W= 17 MeV



Apply momentum scale to Z's



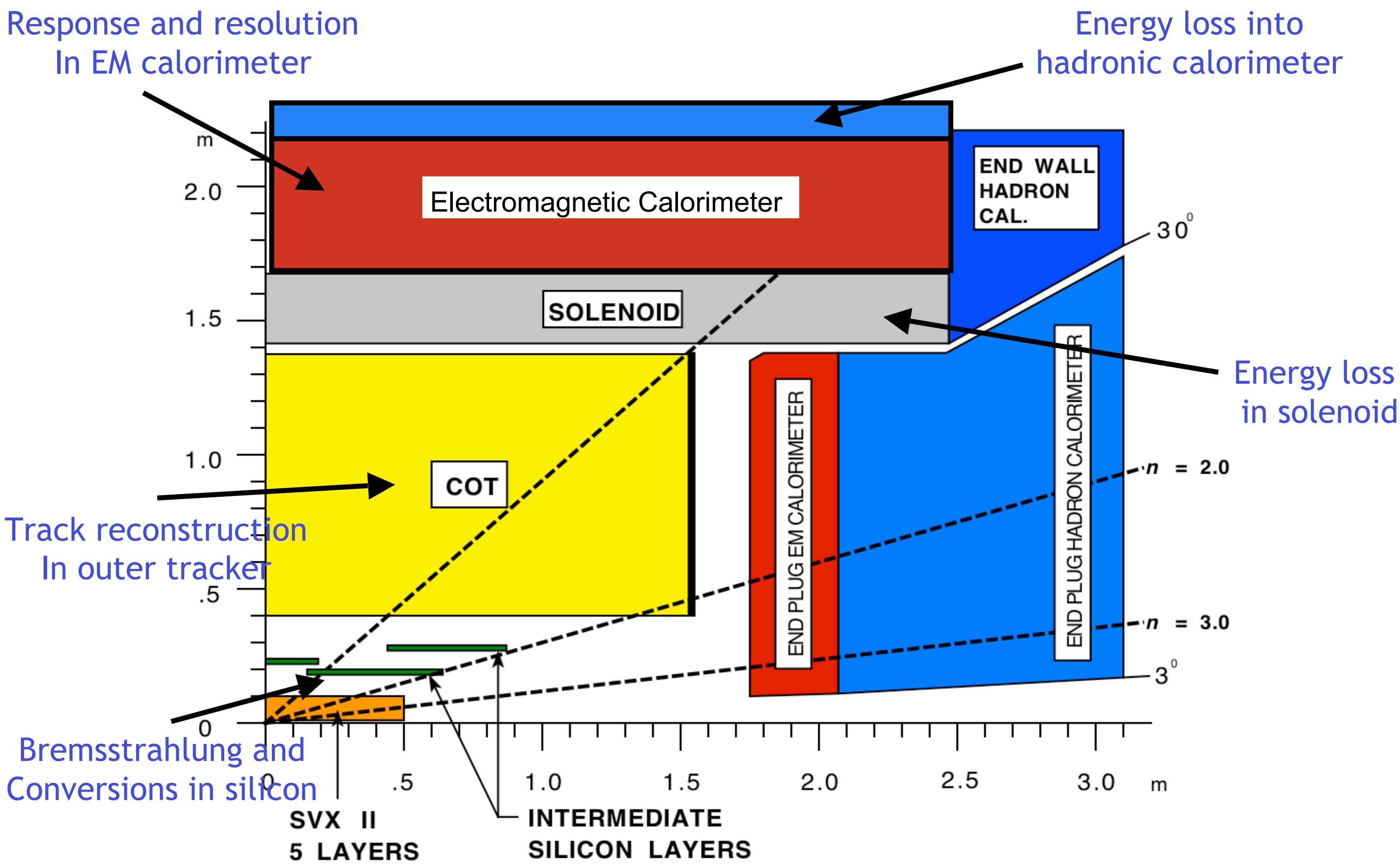


good agreement with PDG (91188±2 MeV)

Tune resolution on width of di-muon mass peaks

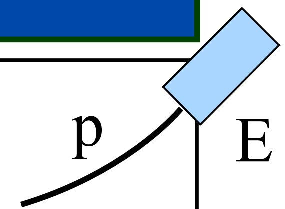
ΔM_W= 3 MeV

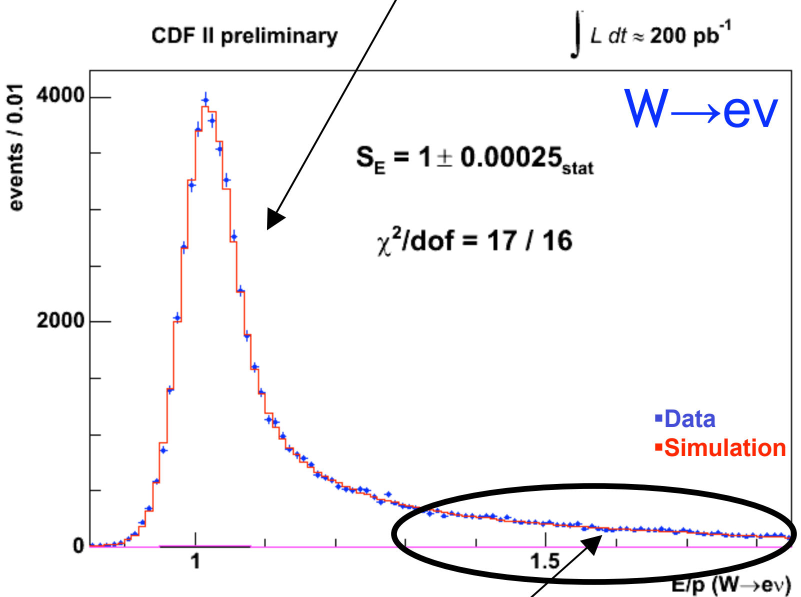
Electron Simulation



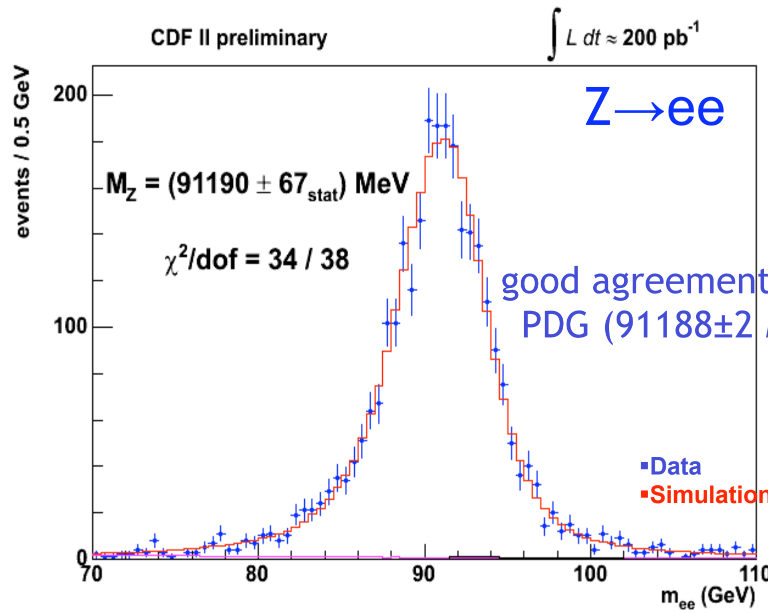
Energy Scale Calibration

Transfer momentum calibration to calorimeter using E/p distribution of electrons from W decay by fitting peak of E/p





Apply energy scale to Z's



good agreement with PDG (91188±2 MeV)

Tune number of radiation lengths with E/p radiative tail

Add Z Mass fit to energy scale calibration (30% weight)

Correct for calibration E_T dependence ΔM_W= 30 MeV

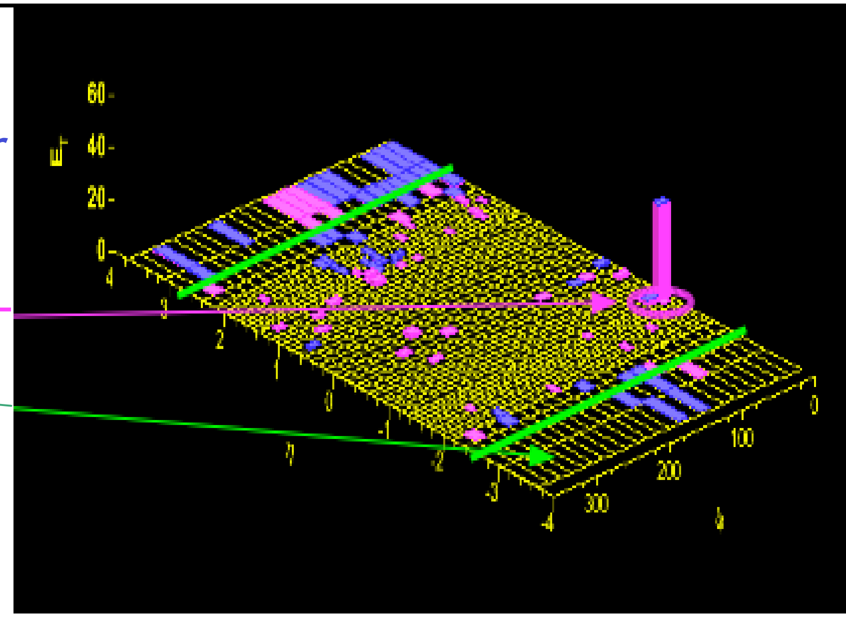
Tune resolution on E/p and Z mass peak ΔM_W= 9 MeV

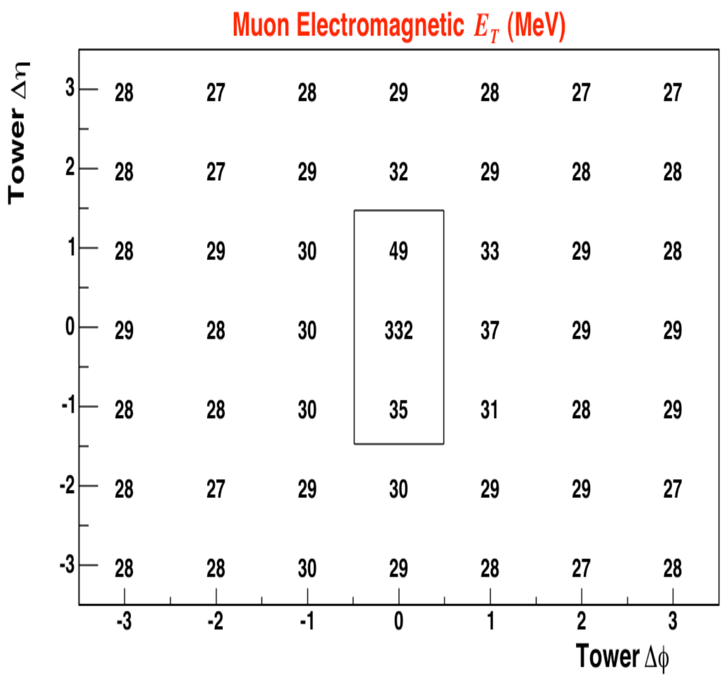
Hadronic Recoil Definition

Recoil definition:

→Vector sum over all calorimeter towers, excluding:

- lepton towers
- towers near beamline ("ring of fire")





Electrons: Remove 7 towers keystone
ΔM_W= 8 MeV

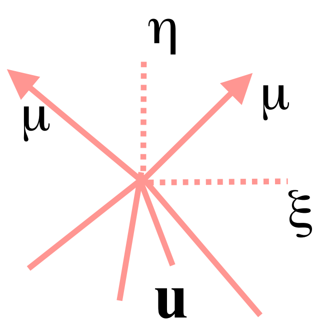
Muons: Remove 3 towers (MIP)
ΔM_W= 5 MeV

Model tower removal in simulation

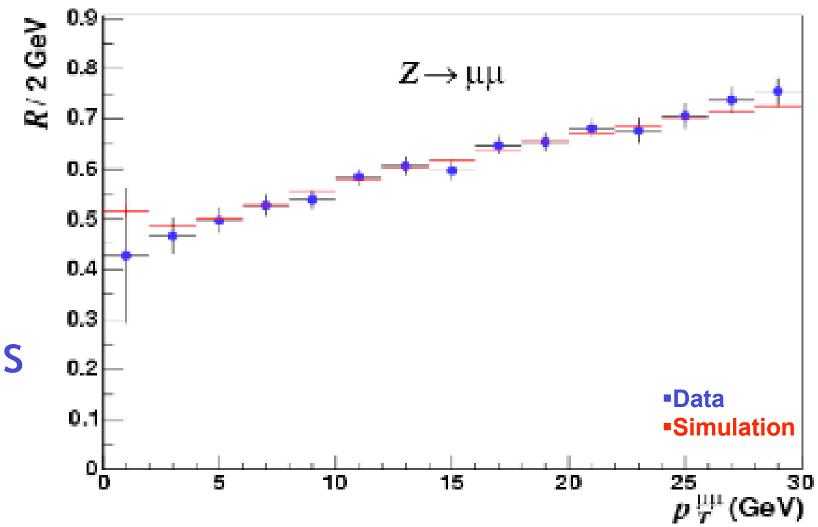
Hadronic Recoil Model Calibration

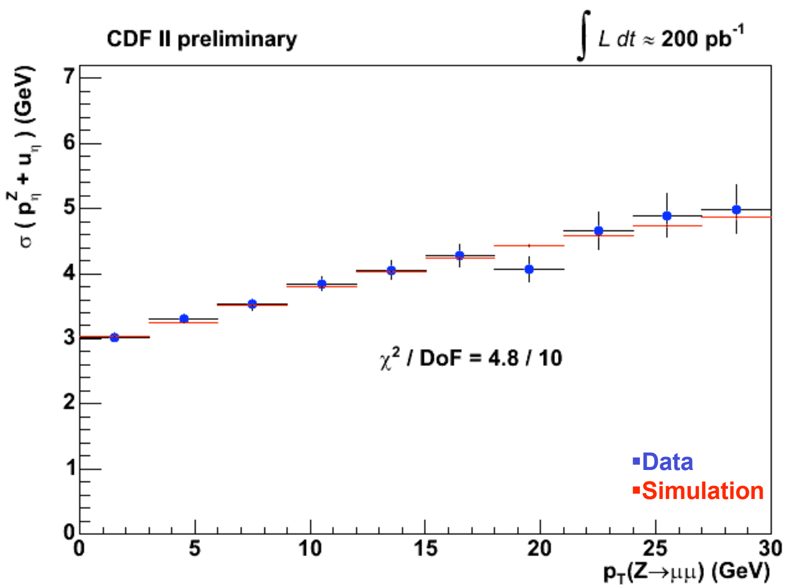
- Use Z balancing to calibrate recoil energy scale and to model resolution

- Calibrate scale ($R=u_{meas}/u_{true}$) with balance along bisector axis
  ΔM_W= 9 MeV



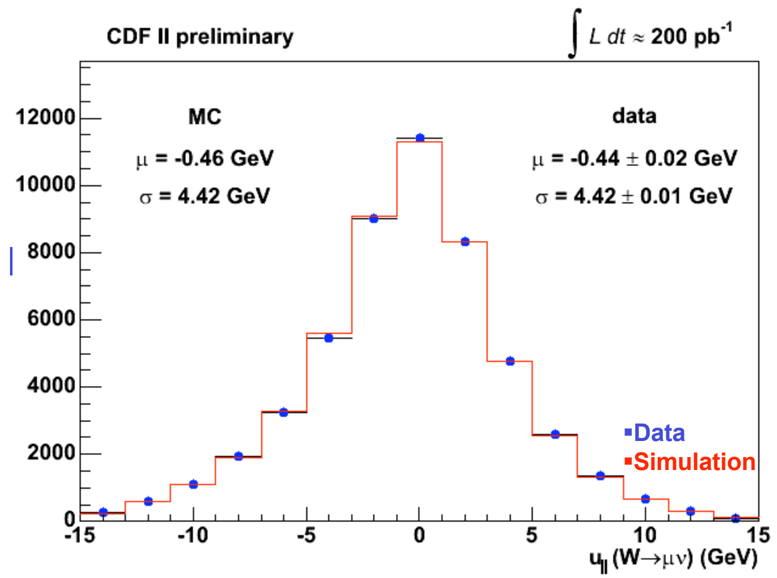
- Resolution has two components
  -soft (underlying event)
  -hard (jets)
- Calibrate along both axes, η & ξ
  ΔM_W= 7 MeV

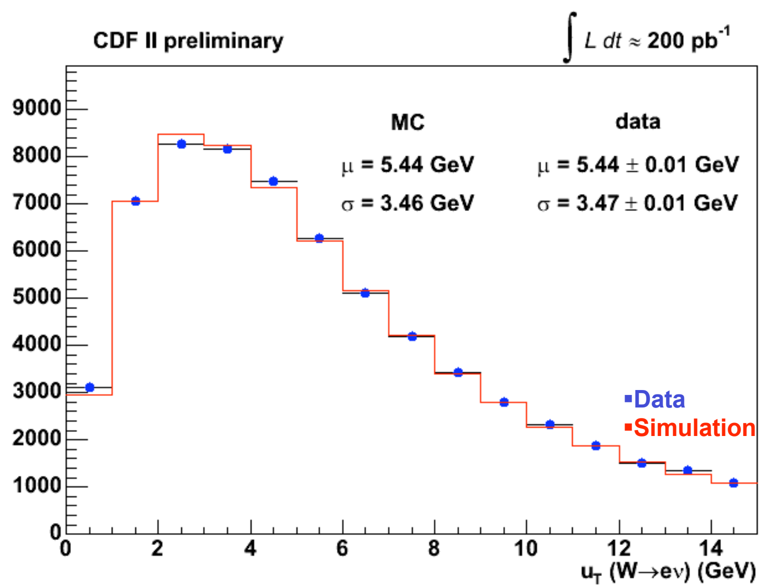




Recoil Model Checks

- Apply model to W sample to check recoil model from Z's
- Recoil projection along lepton $u_{||}$
  → directly affects m_T fits
  → Sensitive to lepton removal, scale, resolution, W decay

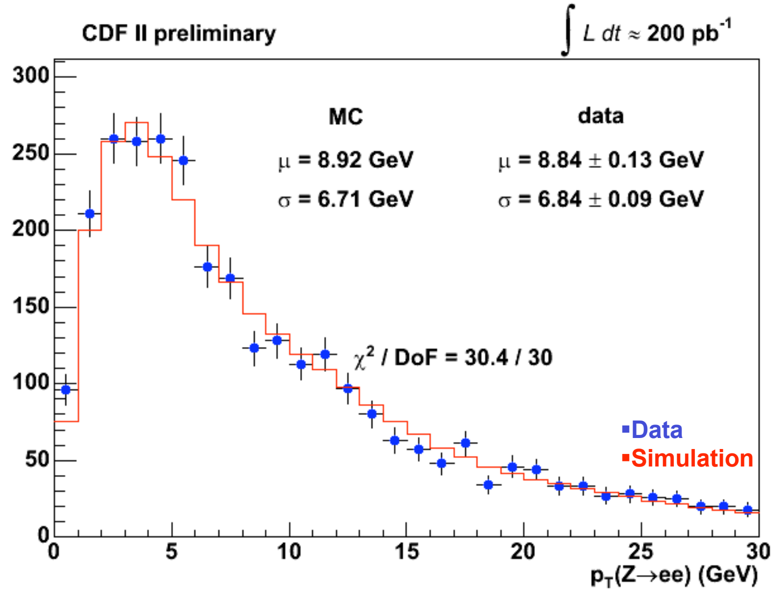


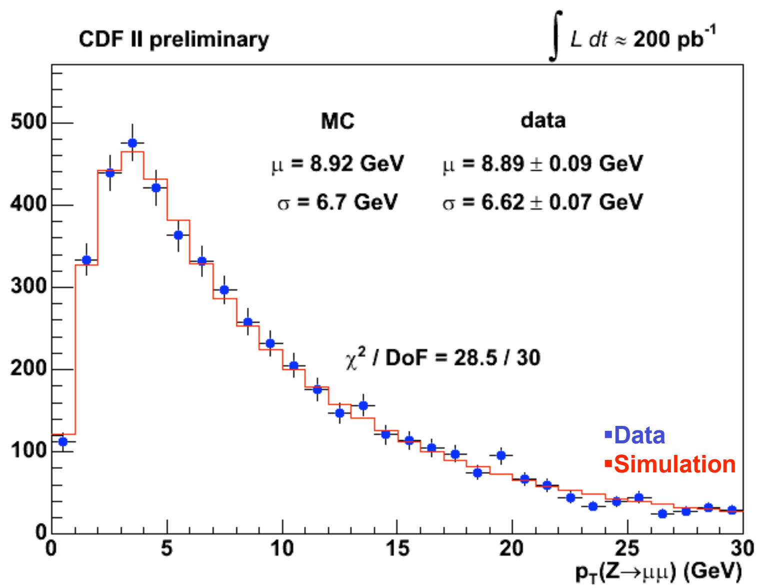


- Recoil distribution
  → sensitive to recoil scale resolution and boson p_T
- Recoil model validation plots confirm consistency of the model

Boson p_T Model

- Model boson p_T using RESBOS generator [Balazs *et.al.* PRD56, 5558 (1997)]
- Non-pertubative regime at low p_T parametrized



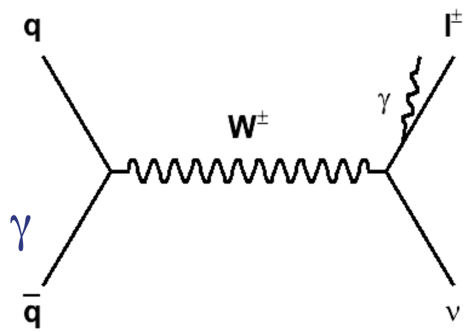


- Main parameter g_2 determines position of peak in p_T distribution
- Measure g_2 with Z boson data
- Find: g_2 = 0.685±0.048

  ΔM_W= 3 MeV

Production, Decay and Backgrounds

- QED radiative corrections:
  - use complete NLO calculation (WGRAD) [Baur *et.al*. PRD59, 013002 (1998)]
  - simulate FSR, apply (10±5)% correction for 2nd γ [Calame *et.al*. PRD69, 037301 (2004)]



ΔM_W= 11 (12) MeV for e (μ)

- Parton Distribution Functions:
  - affect kinematics through acceptance cuts
  - use CTEQ6 ensemble of 20 uncertainty PDFs

  ΔM_W= 11 MeV

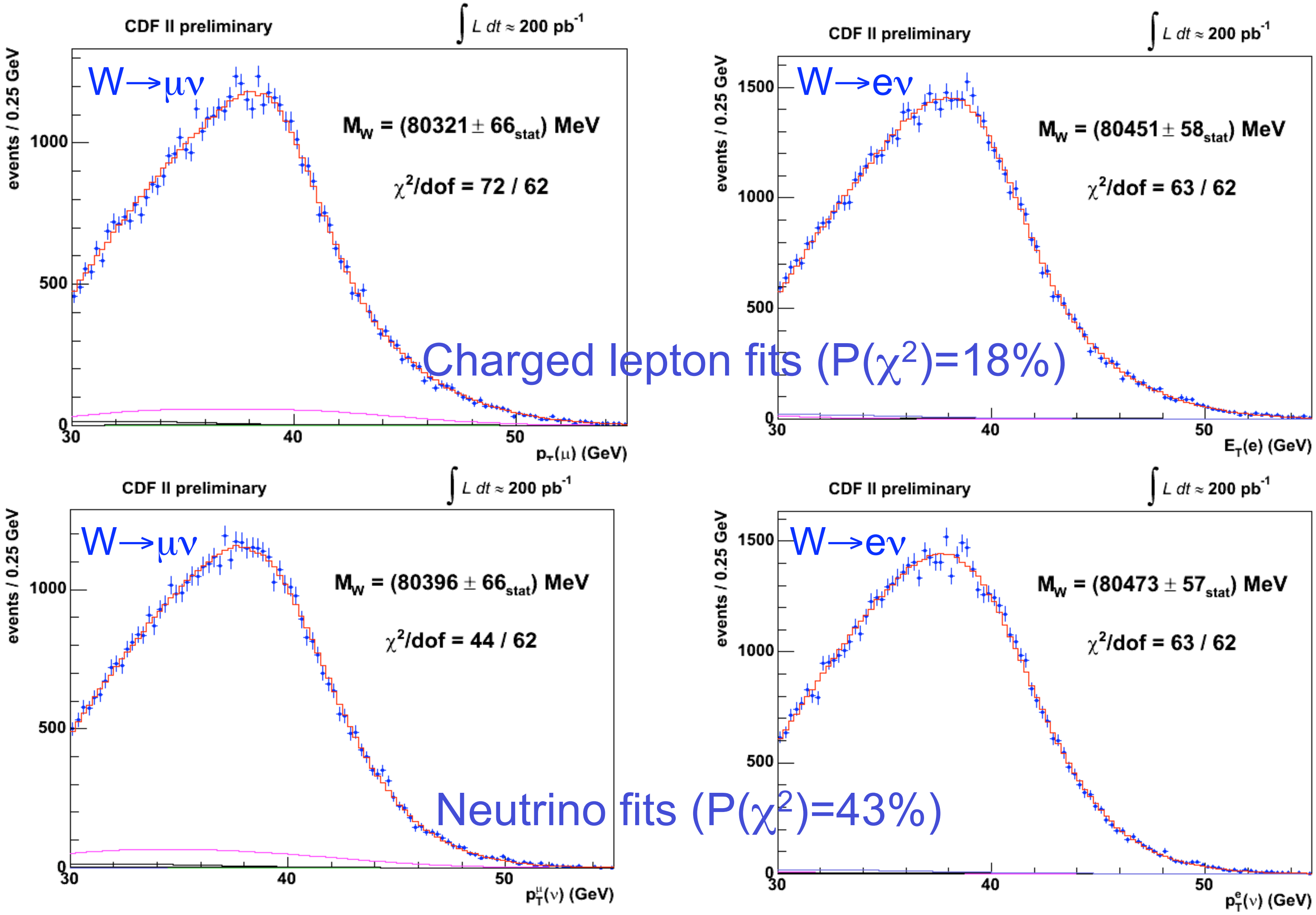
- Backgrounds:
  - have very different lineshapes compared to W signal
  - distributions are added to template
  - QCD measured with data
  - EWK predicted with Monte Carlo

  ΔM_W= 8 (9) MeV for e (μ)

Background	%(Muons)	%(Electrons)
Hadronic Jets	0.1±0.1	0.25±0.15
Decay 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

W Mass Fits

Fit m_T, E_T and $\not{E}_T$ distributions in muon and electron channel:

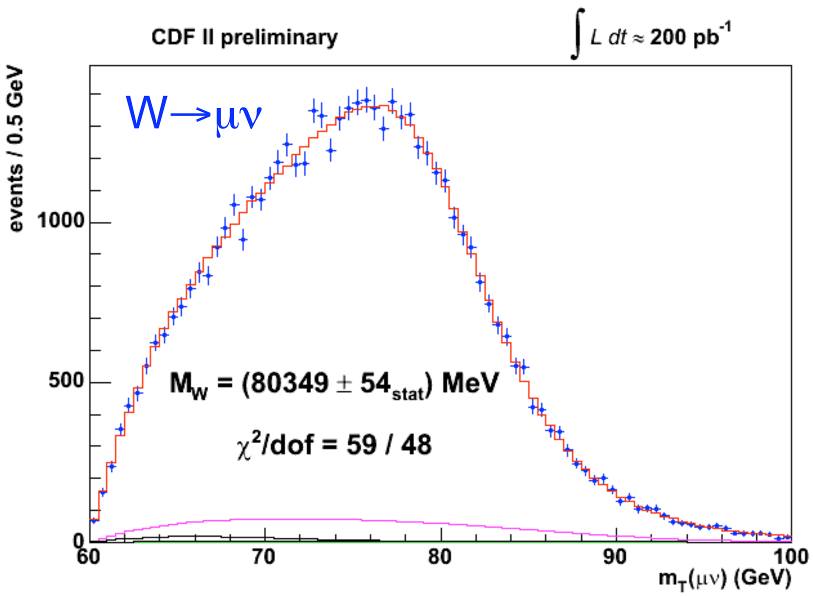


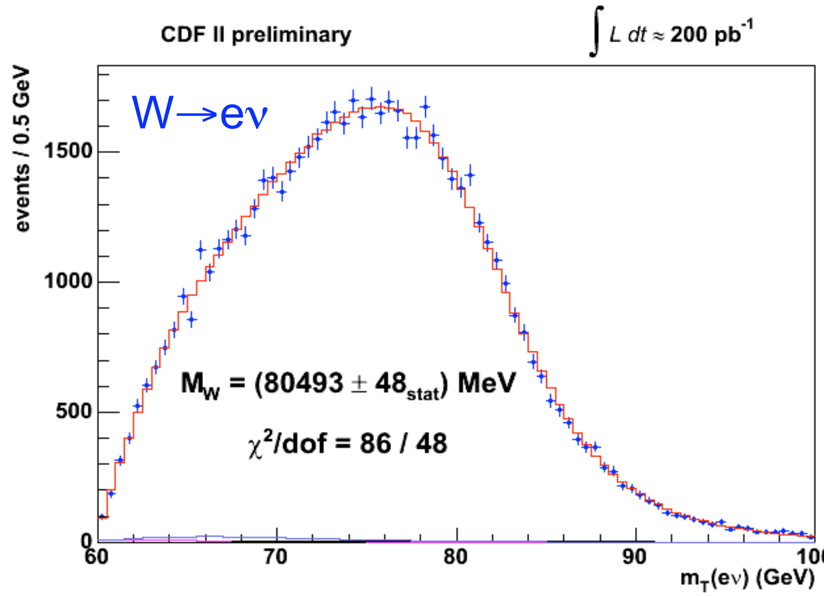
Charged lepton fits ($P(\chi^2)$=18%)

Neutrino fits ($P(\chi^2)$=43%)

W Mass Fits

Transverse mass fits ($P(\chi^2)=7\%$)





Combined result:

$m_W = 80413 \pm 34_{stat} \pm 34_{syst}$ MeV

$= 80413 \pm 48$ MeV

Combination of all six fits yields $P(\chi^2) = 44\%$

Systematic Uncertainty

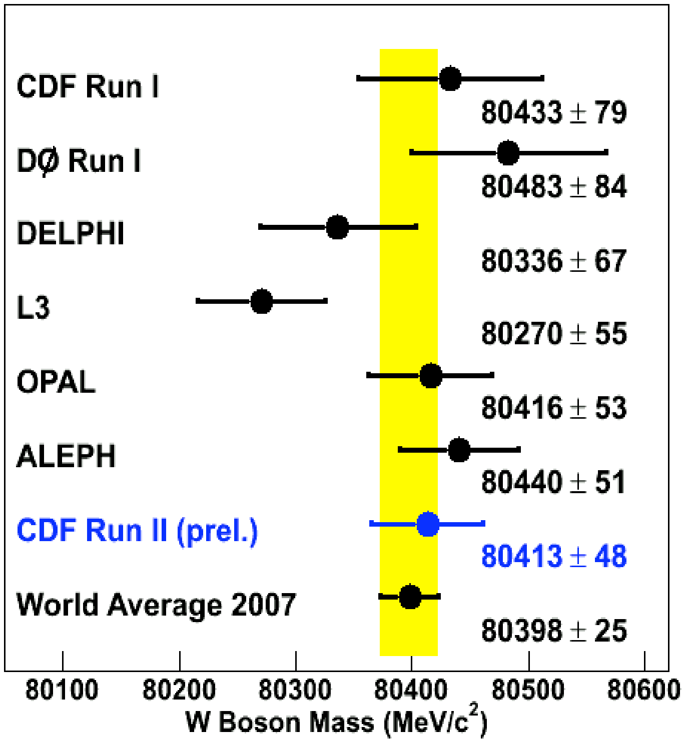
Systematic uncertainty on transverse mass fit

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

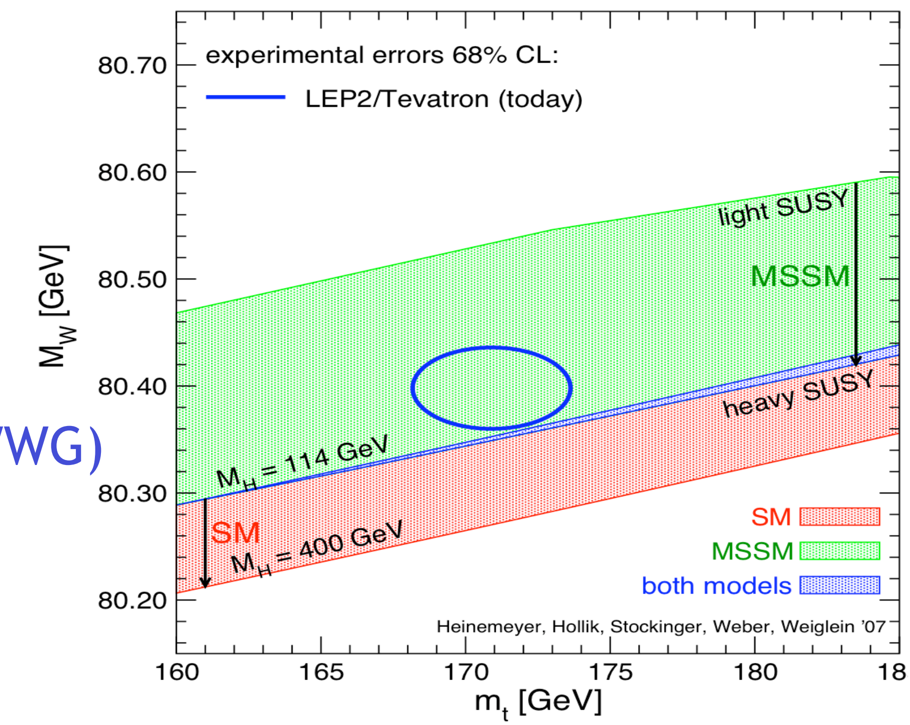
m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\|\|}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

⇒ Combined Uncertainty: 48 MeV for 200 pb^{-1}

Results

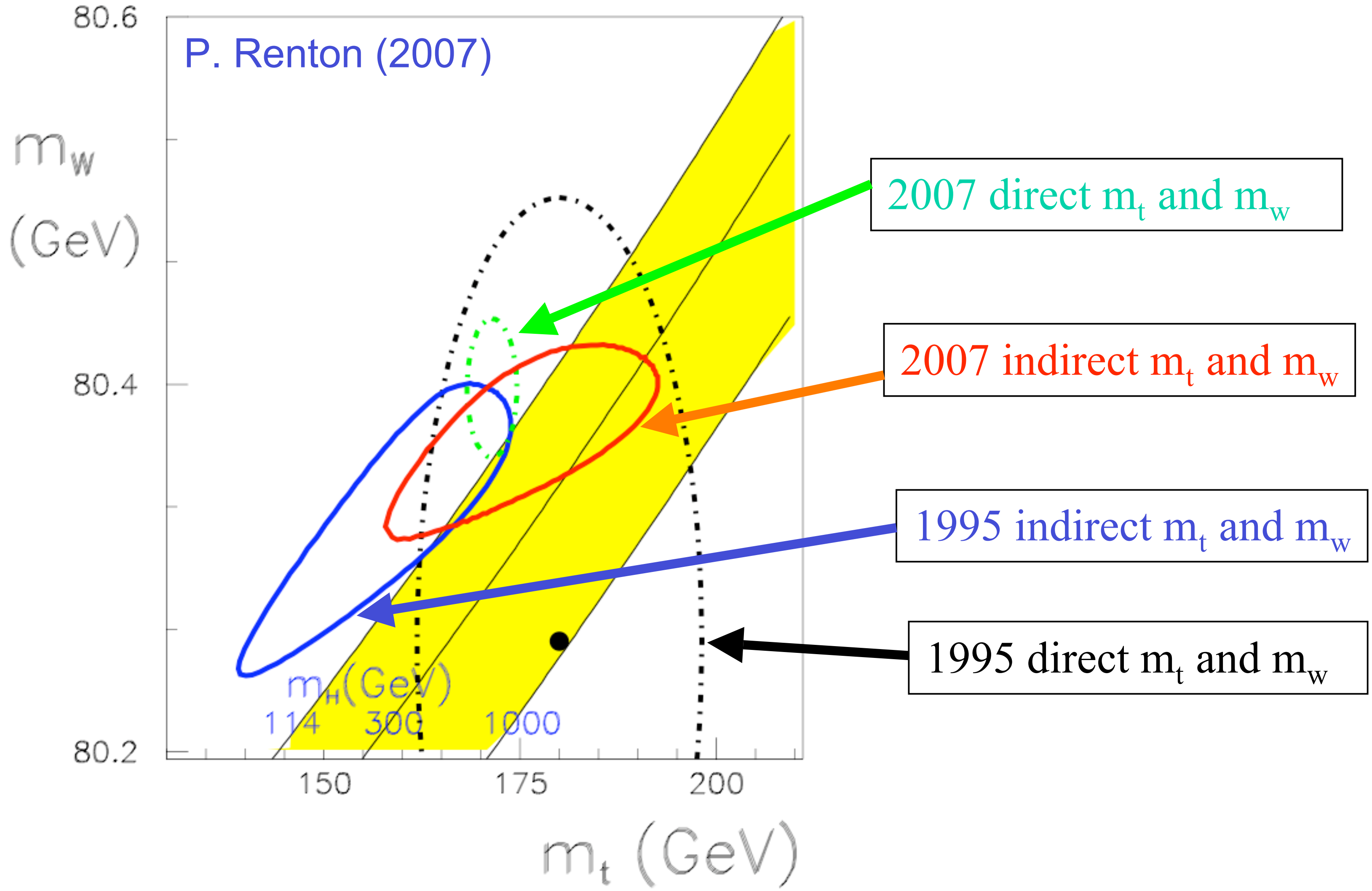


- New CDF result is the world's most precise single measurement
- World average increases: 80392 to 80398 MeV
- Uncertainty reduced ~15% (29 to 25 MeV)



- Standard Model Higgs (LEPEWWG) constraint: 76^{+33}_{-24} GeV (mean decreased by 6 GeV)

Progress since 1995

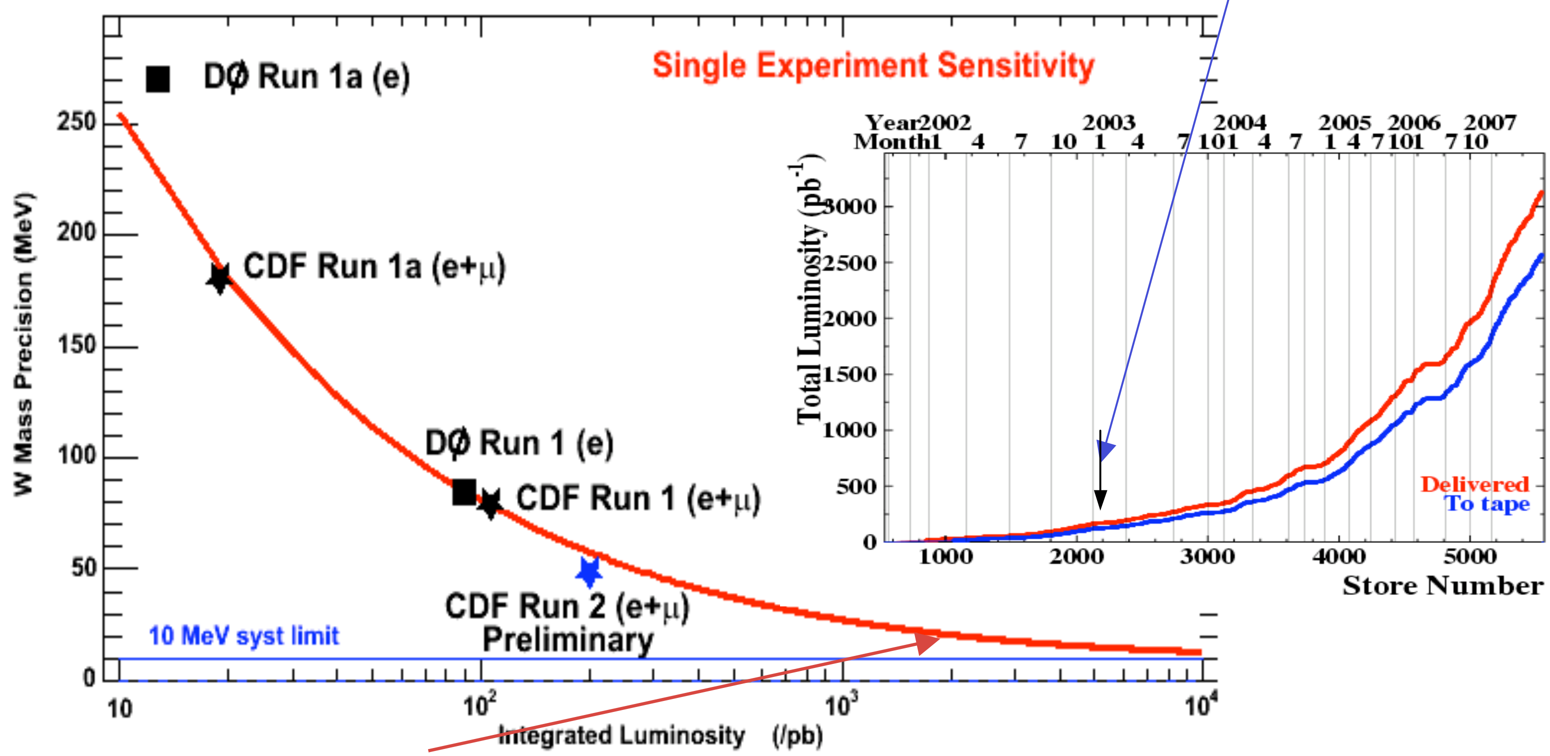


Summary/Outlook

- First Run II W mass measurement completed using 200 pb^{-1} of data

  $m_W = 80413 \pm 34_{stat} \pm 34_{syst}$ MeV
- With a total uncertainty of 48 MeV

  → worlds most precise single measurement
- Projection from previous Tevatron measurements



- Expect $\Delta M_W < 25$ MeV with ~2 fb^{-1} already collected

Backup

Standard Model Higgs Constraint

- Summer 2006 SM Higgs fit: (LEP EWWG)
  - $M_H = 85^{+39}_{-28}$ GeV
  - $M_H < 166$ GeV (95% CL)
  - $M_H < 199$ GeV (95% CL) Including LEPII direct exclusion
- Updated preliminary SM Higgs fit: (With new CDF W Mass)
  - $M_H = 80^{+36}_{-26}$ GeV (M. Grünewald, private communication)
  - $M_H < 153$ GeV (95% CL)
  - $M_H < 189$ GeV (95% CL) Including LEPII direct exclusion
- Updated preliminary SM Higgs fit: (With new Tevatron top mass)
  - $M_H = 76^{+33}_{-24}$ GeV
  - $M_H < 144$ GeV (95% CL)
  - $M_H < 182$ GeV (95% CL) Including LEPII direct exclusion

Systematic Uncertainty

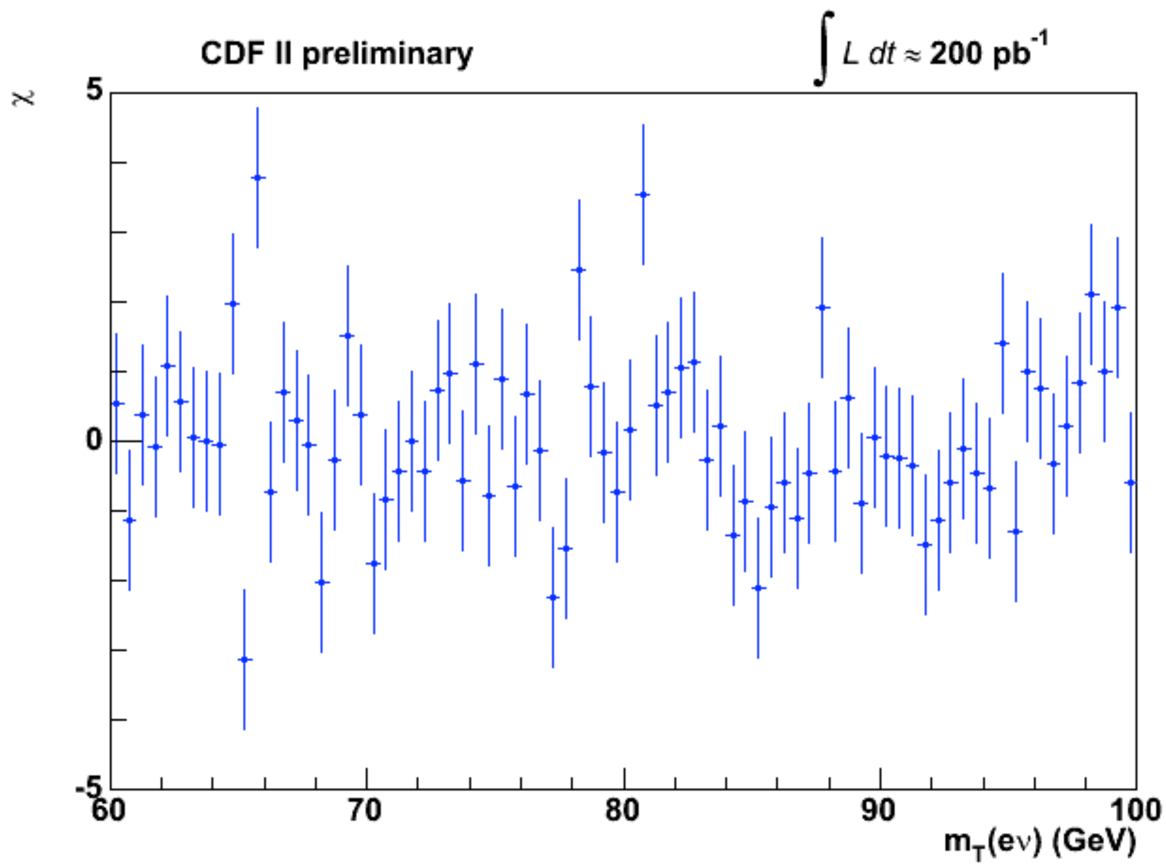
CDF II preliminary $L = 200\ pb^{-1}$

p_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	17	17	17
Recoil Resolution	3	3	3
$u_{\|\|}$ Efficiency	5	6	0
Lepton Removal	0	0	0
Backgrounds	9	19	0
$p_T(W)$	9	9	9
PDF	20	20	20
QED	13	13	13
Total Systematic	45	40	35
Statistical	58	66	0
Total	73	77	35

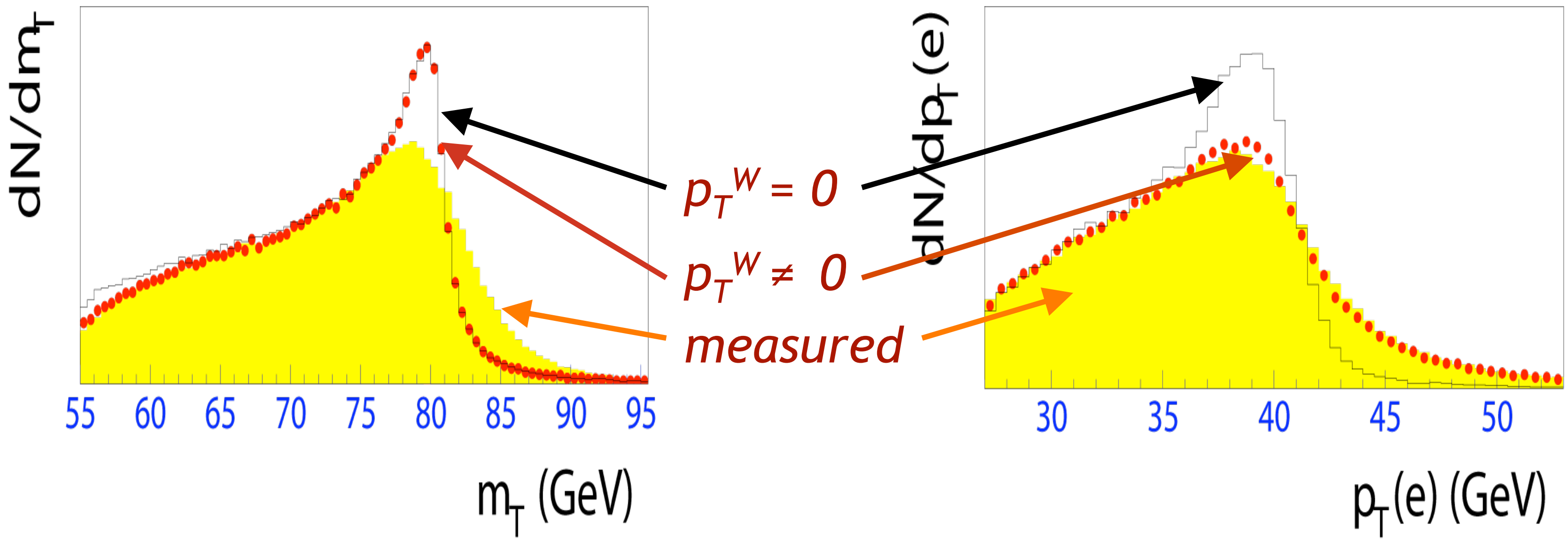
CDF II preliminary $L = 200\ pb^{-1}$

MET Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	5	0
Recoil Scale	15	15	15
Recoil Resolution	30	30	30
$u_{\|\|}$ Efficiency	16	13	0
Lepton Removal	16	10	10
Backgrounds	7	11	0
$p_T(W)$	5	5	5
PDF	13	13	13
QED	9	10	9
Total Systematic	54	46	42
Statistical	57	66	0
Total	79	80	42

Signed χ



W Mass Measurement



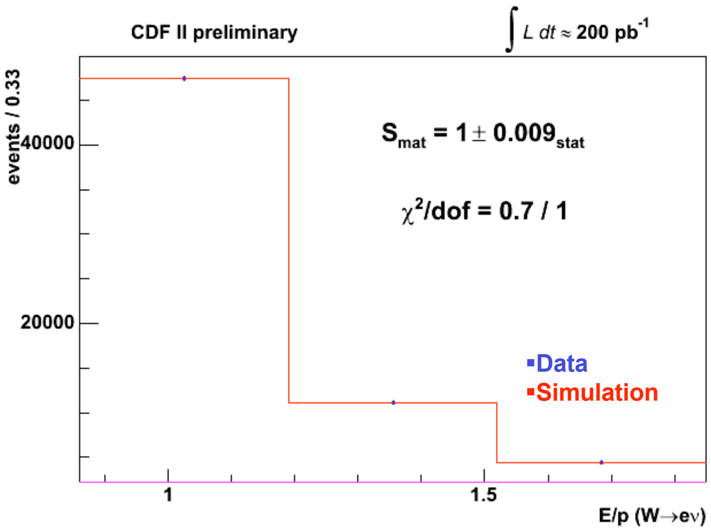
m_T

- Insensitive to p_T^W to 1st order
- Reconstruction of p_T^ν sensitive to hadronic response and multiple interactions

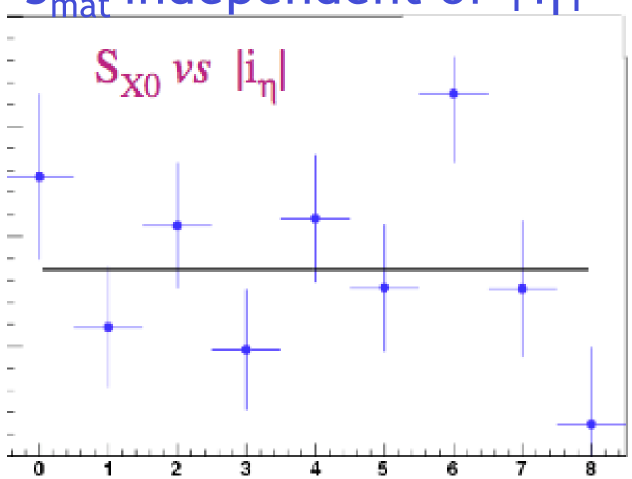
p_T

- Less sensitive to hadronic response modeling
- Sensitive to W production dynamics

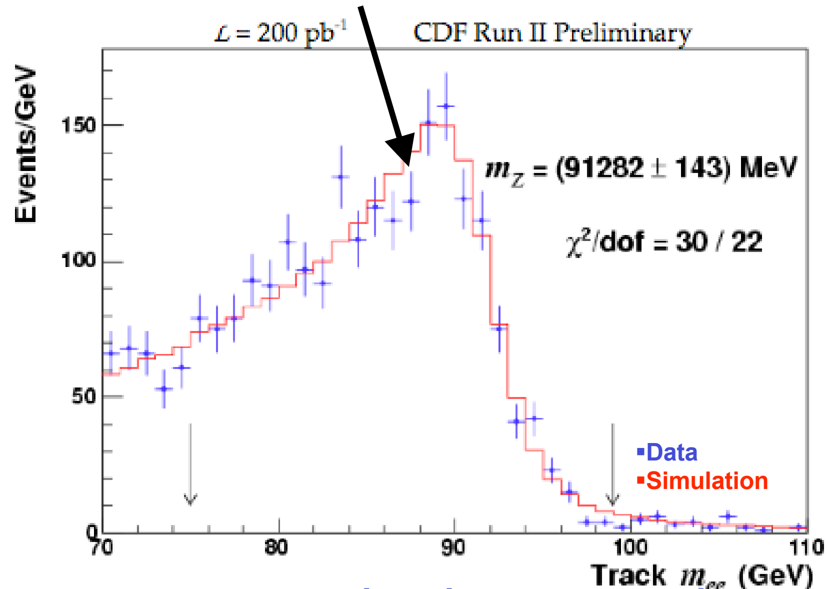
Consistency of Material Model



geometry confirmed:
S_{mat} independent of $|\eta|$



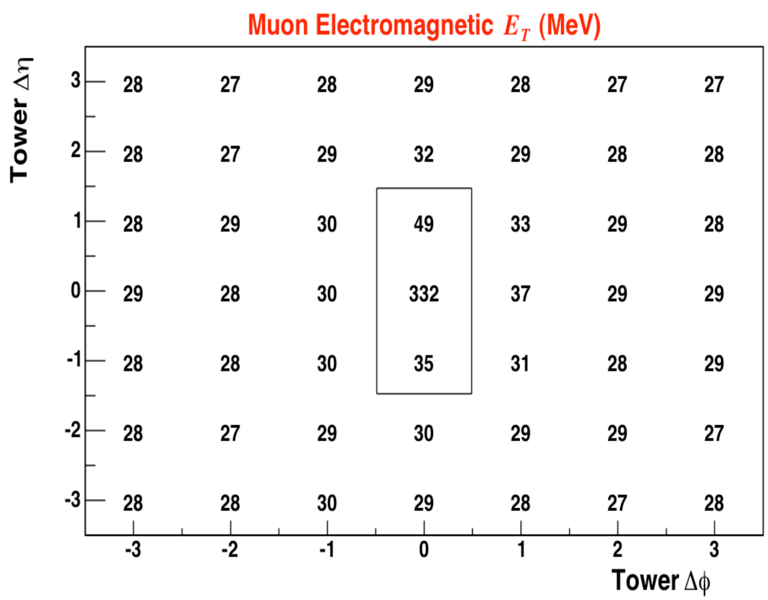
- Excellent description of E/p tail
- Radiative material tune factor:
  $S_{mat}=1.004\pm0.009_{stat}\pm0.0002_{bkg}$
- Z mass reconstructed from electron track momenta

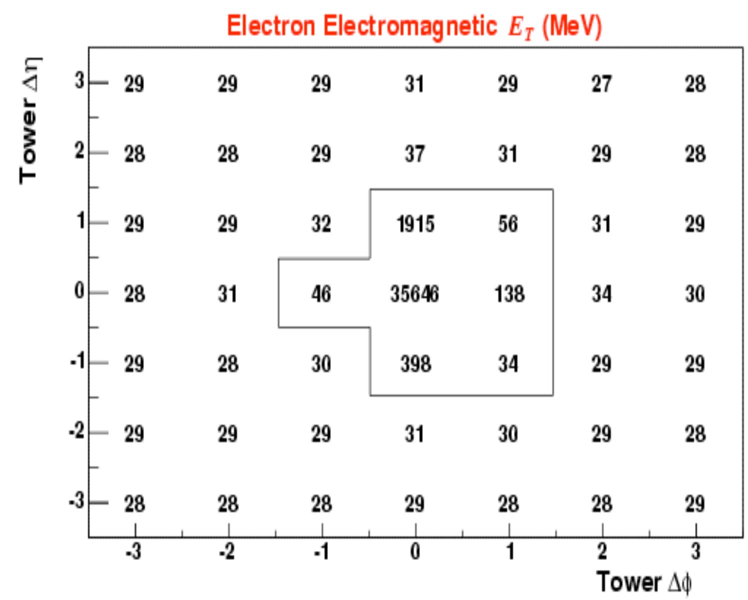


Measured value in good agreement with PDG

Lepton Removal

- Estimate removed recoil energy using towers separated in Φ
- Model tower removal in simulation





Muons: Remove 3 towers (MIP)

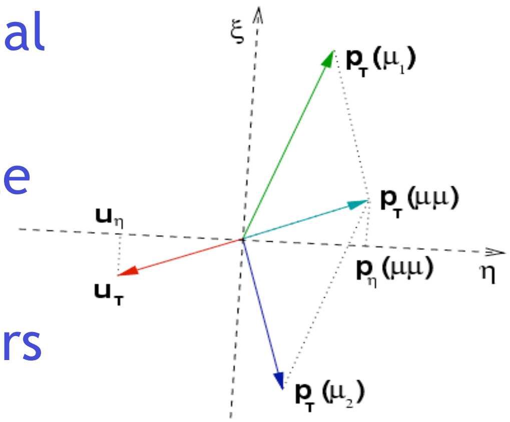
ΔM_W= 5 MeV

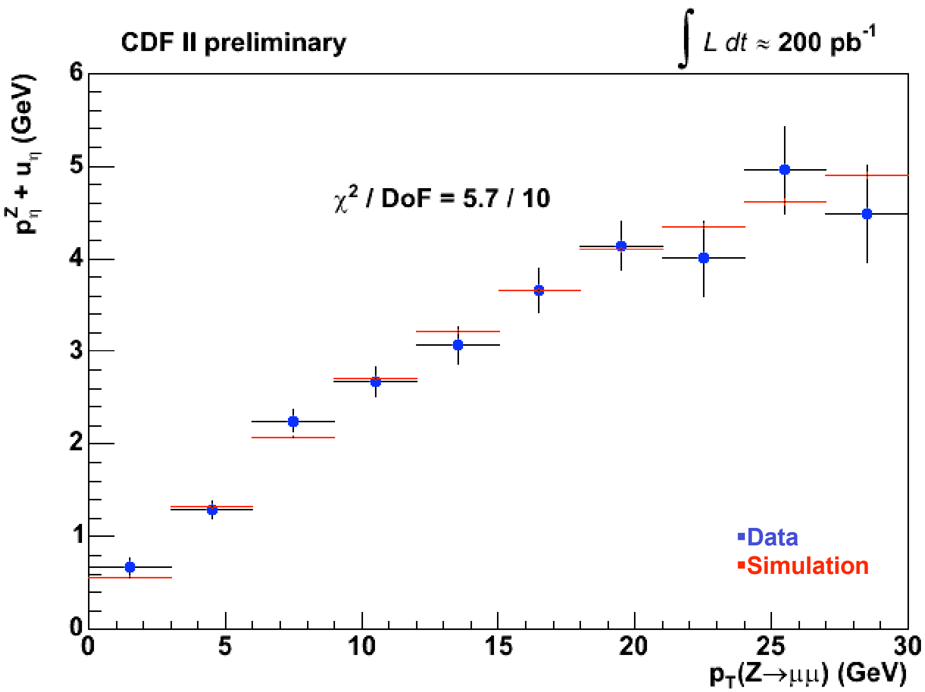
Electrons: Remove 7 towers keystone (shower)

ΔM_W= 8 MeV

Hadronic Recoil Calibration

- Project vector sum of $p_T(ll)$ and u on orthogonal axes defined by lepton directions
- Use Z balancing to calibrate recoil energy scale
- Mean and RMS of projections as a function of $p_T(ll)$ provide information for model parameters



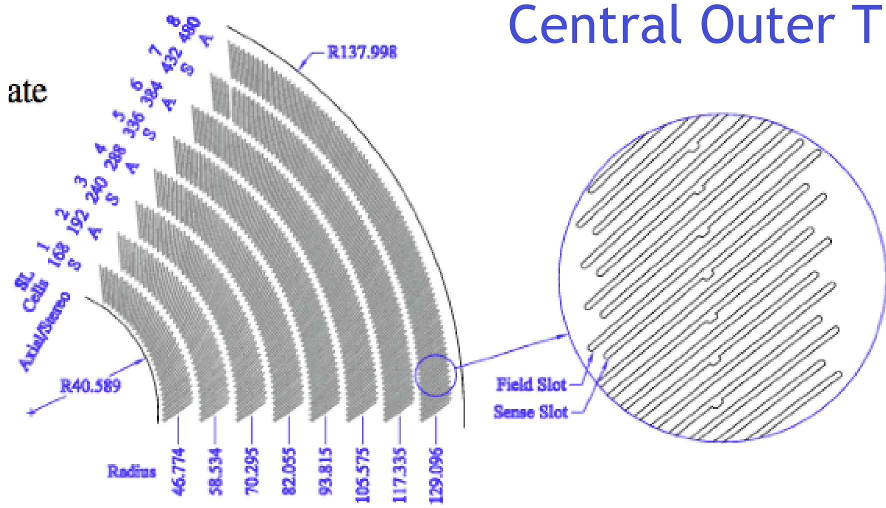


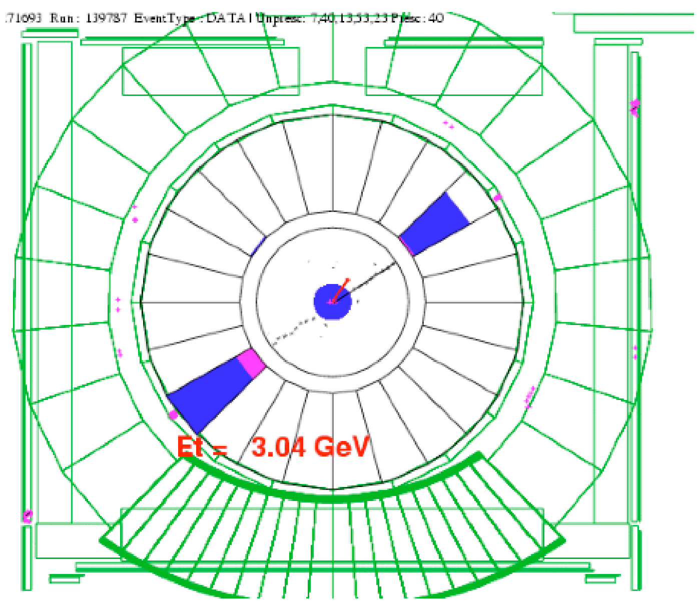
Hadronic model parameters tuned by minimizing χ^2 between data and simulation

ΔM_W= 9 MeV

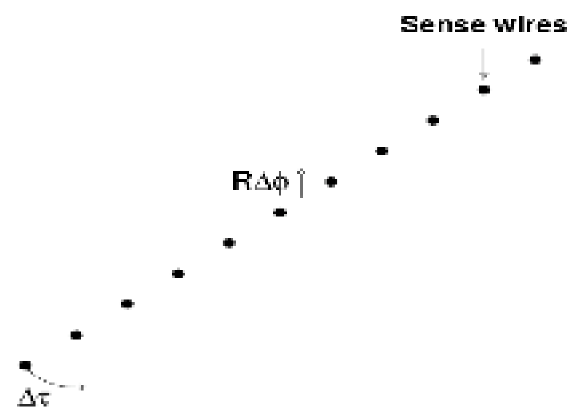
Alignment

Central Outer Tracker: Open-cell drift chamber

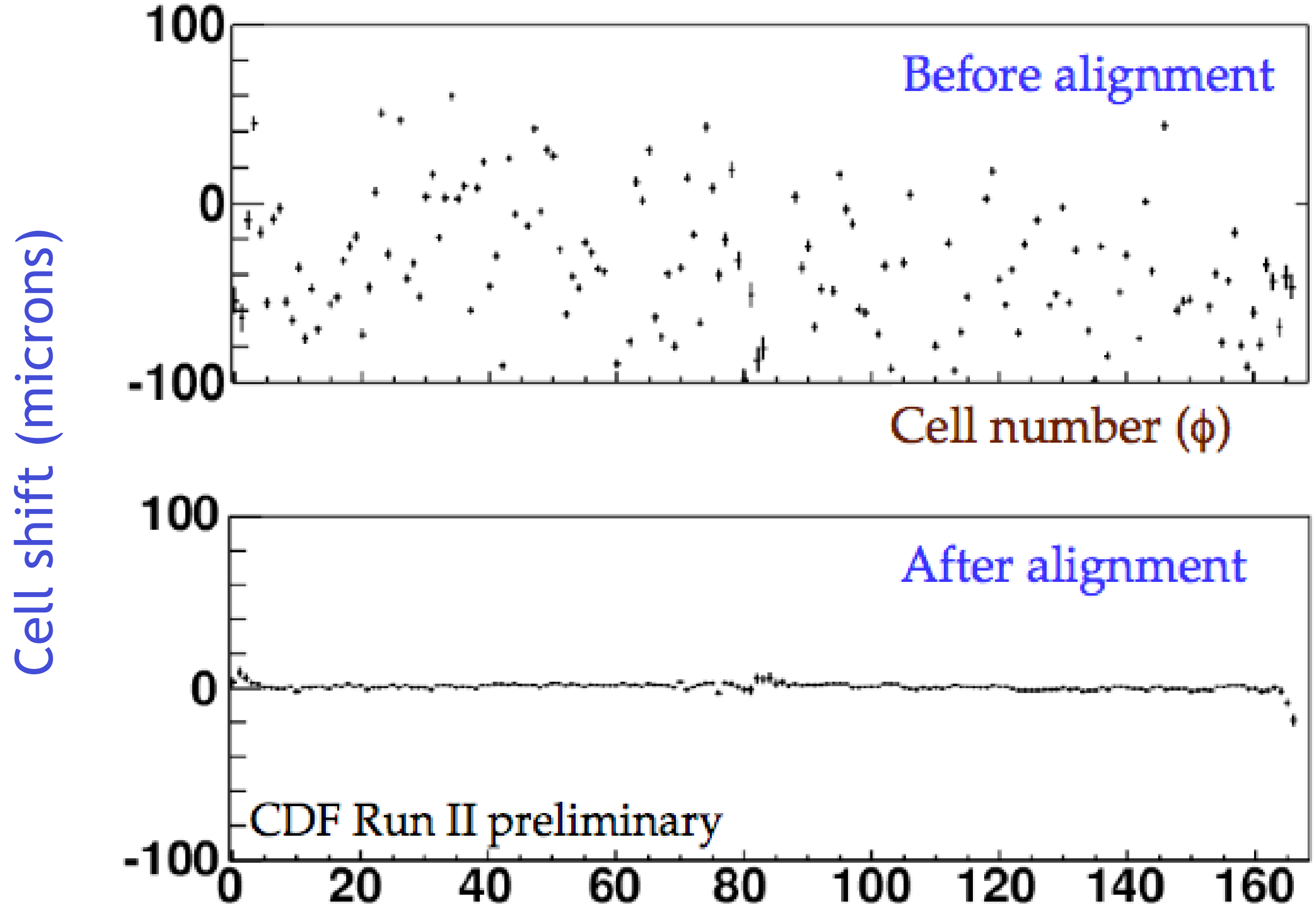




- Use clean sample of cosmic rays for cell-by-cell internal alignment
- Fit COT hits on both sides simultaneously to a single helix
- Measure cell tilts and shifts



Alignment Example



Final relative alignment of cells ~5μm (initial alignment ~50μm)