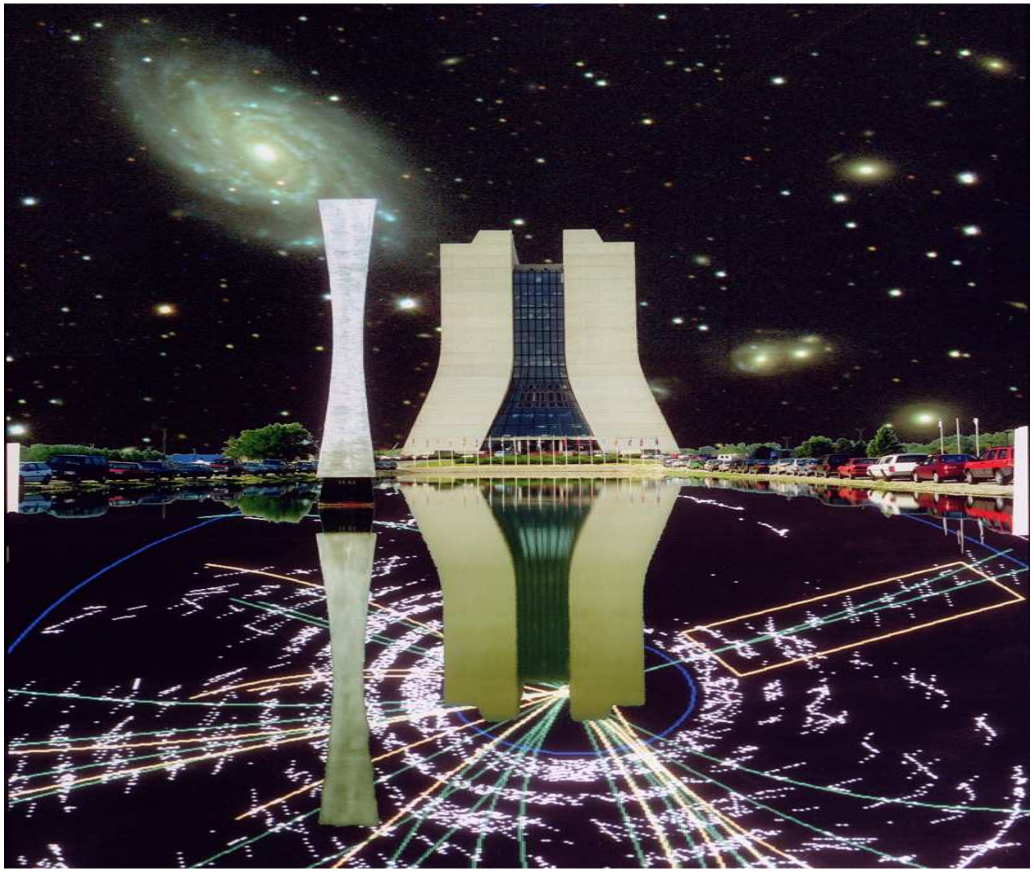
Measurement of the W Boson Mass

Ashutosh Kotwal
Duke University



High Energy Physics Seminar
DESY
July 14-15, 2009

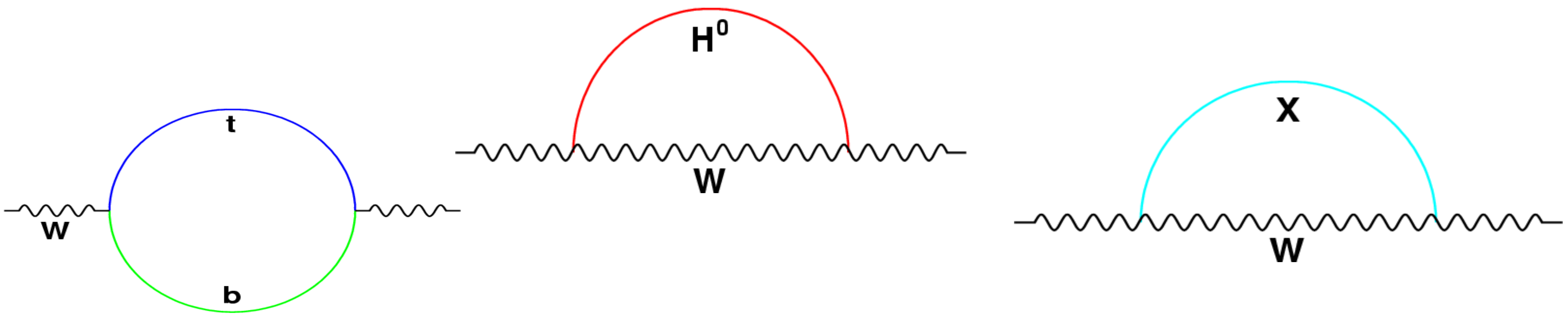
Motivation

- The electroweak gauge sector of the standard model is constrained by three precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\ (1) \times 10^{-5}\ GeV^{-2}$

    $M_Z = 91.1876\ (21)\ GeV$
- At tree-level, these parameters are related to M_W by
  - $M_W^2 = \pi\alpha_{EM} / \sqrt{2} G_F \sin^2\theta_W$
    - Where θ_W is the weak mixing angle, defined by $\cos\theta_W = M_W/M_Z$

Motivation

- Radiative corrections due to heavy quark and Higgs loops and exotica

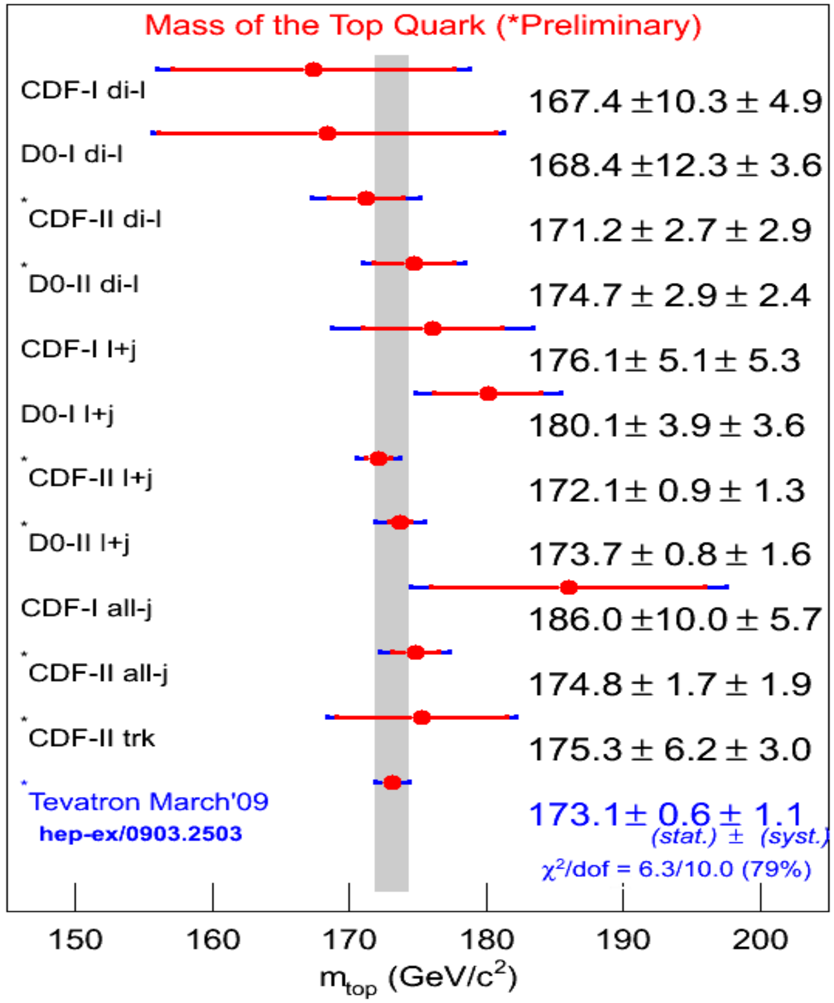


Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\text{tree})]^2$

with the predictions $(\rho-1) \sim M_{top}^2$ and $(\rho-1) \sim \ln M_H$

- In conjunction with M_{top}, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

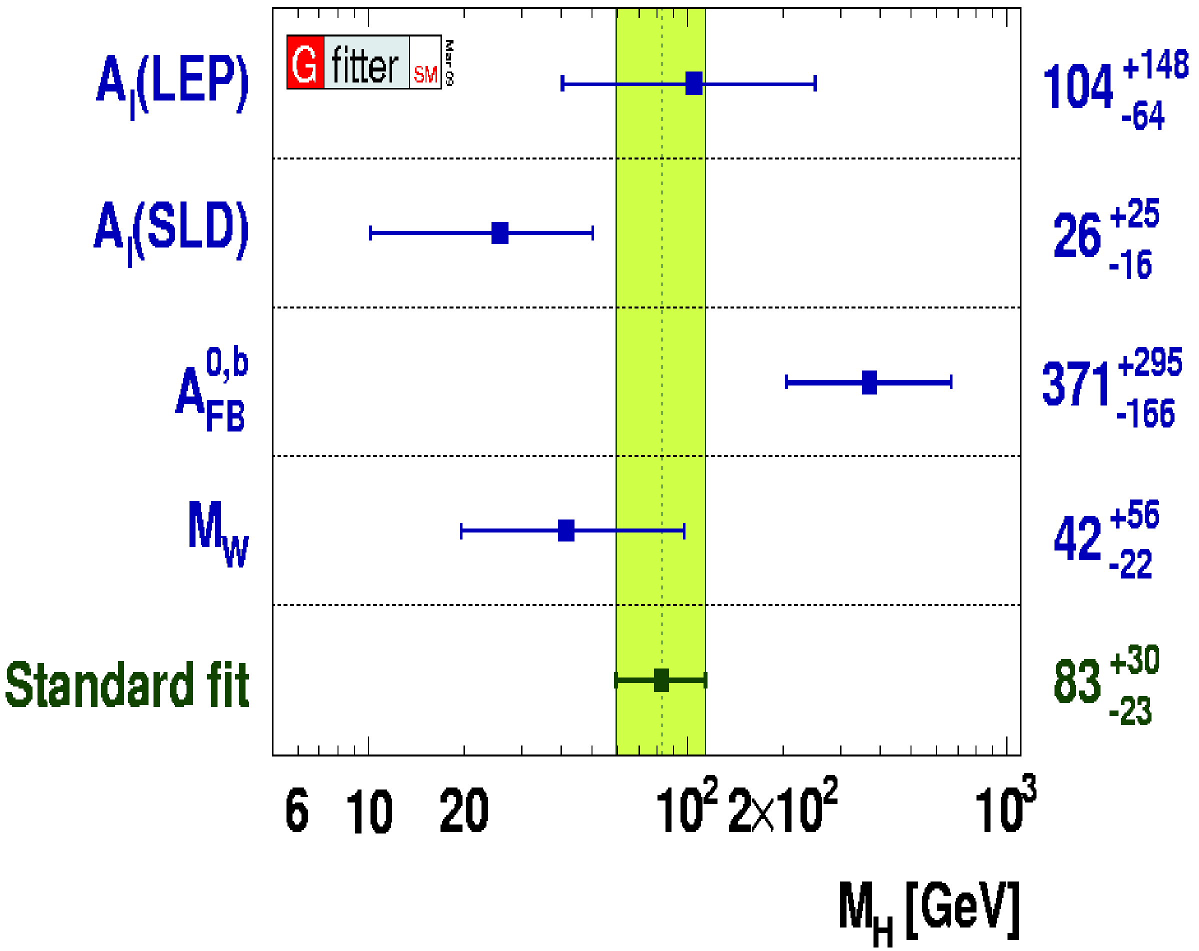
Progress on M_{top} at the Tevatron



- From the Tevatron, δM_{top} = 1.3 GeV => $\delta M_H / M_H$ = 11%
- equivalent δM_W = 8 MeV for the same Higgs mass constraint
- Current world average δM_W = 23 MeV
  - progress on δM_W now has the biggest impact on Higgs constraint!

Motivation

- SM Higgs fit: $M_H = 83^{+30}_{-23}$ GeV (gfitter.desy.de)
- LEPII direct searches: $M_H > 114.4$ GeV @ 95% CL (PLB 565, 61)



In addition to the Higgs, is there another missing piece in this puzzle?

(A_{FB}^{b} *vs* A_{LR}: 3.2σ)

Must continue improving precision of M_W, M_{top} ...

other precision measurements constrain Higgs, equivalent to $\delta M_W \sim 15$ MeV

Motivate direct measurement of M_W at the 15 MeV level

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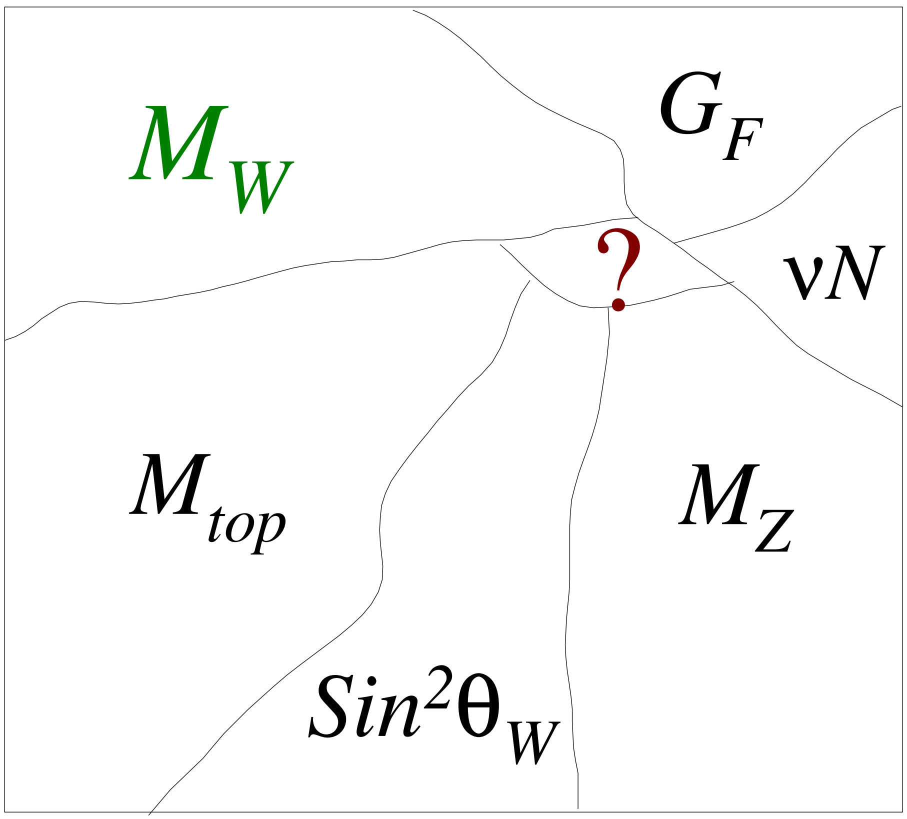

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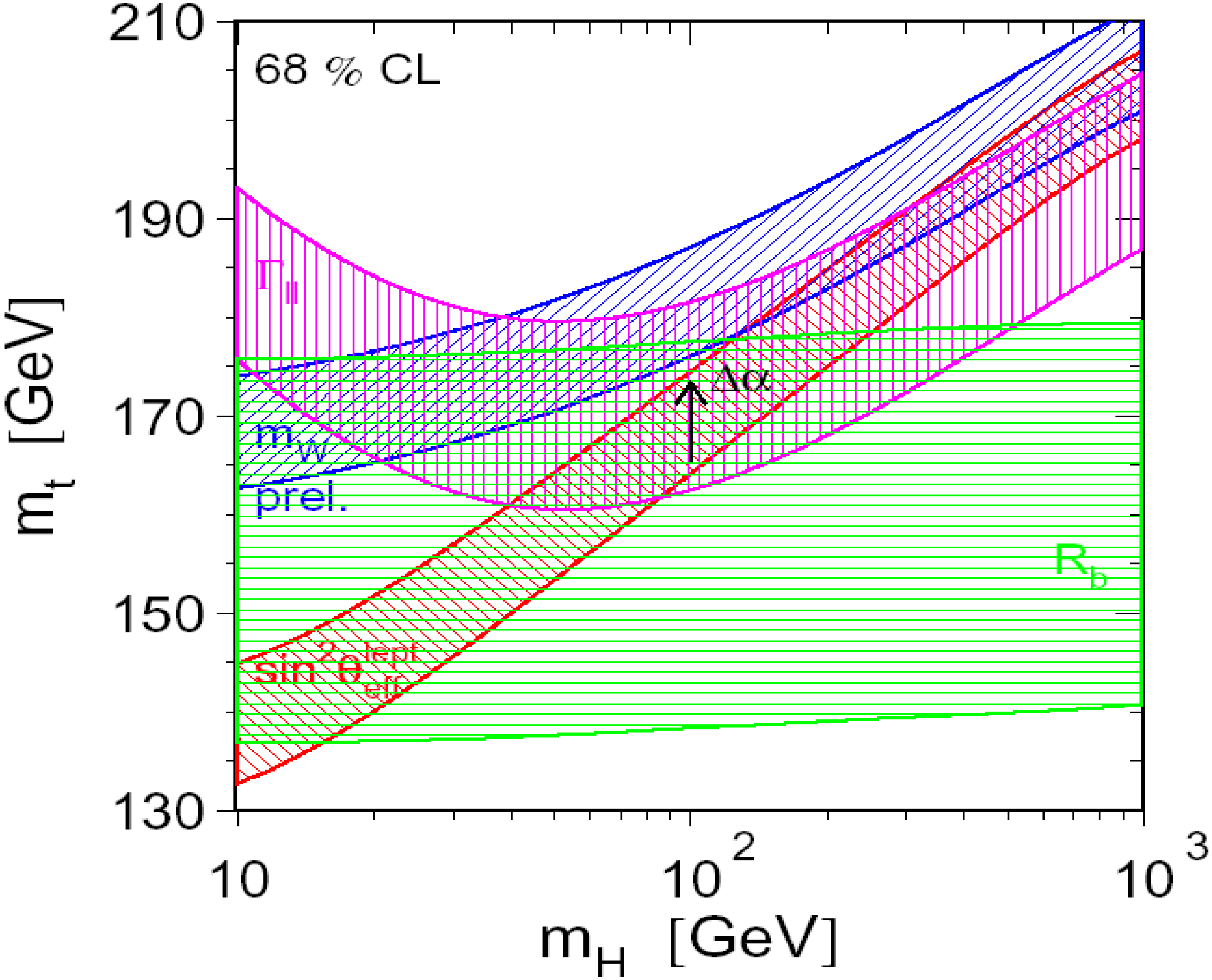
M_{top} *vs* M_{Higgs}

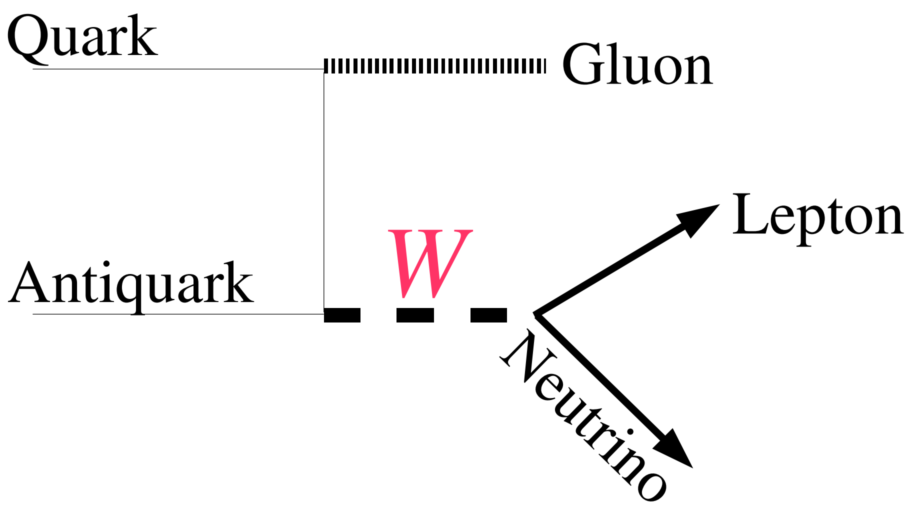
(LEP & SLD Collaborations and LEPEWWG, SLD EW & HF Groups, Physics Reports, Vol. 427 Nos. 5-6, 257 (May 2006))

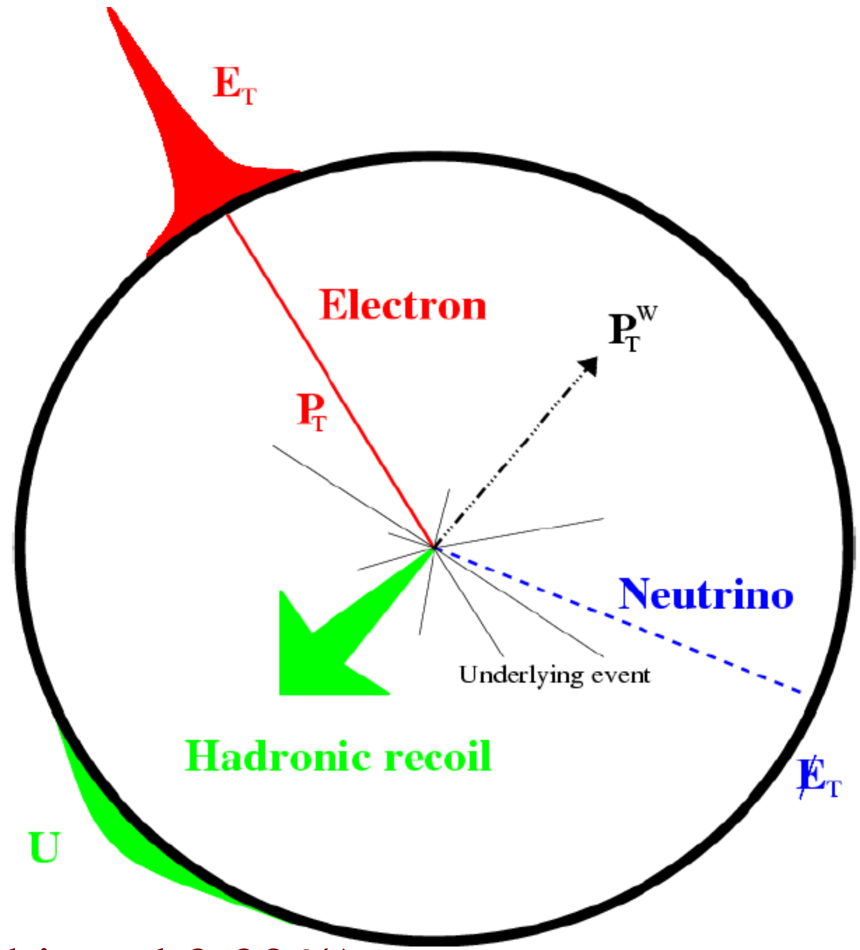


M_W and $\sin^2\theta_{eff}$ provide complementary constraints on M_{Higgs}

Analysis Strategy

W Boson Production at the Tevatron





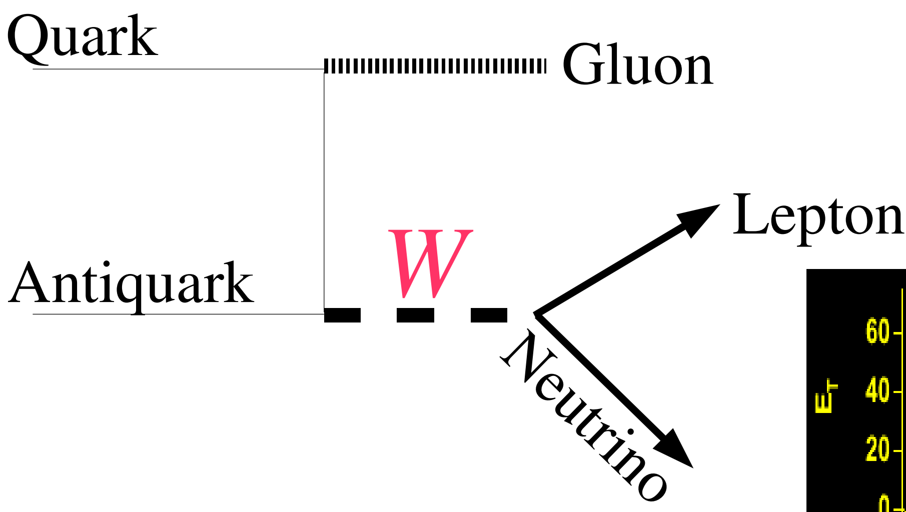
Quark-antiquark annihilation dominates (80%)

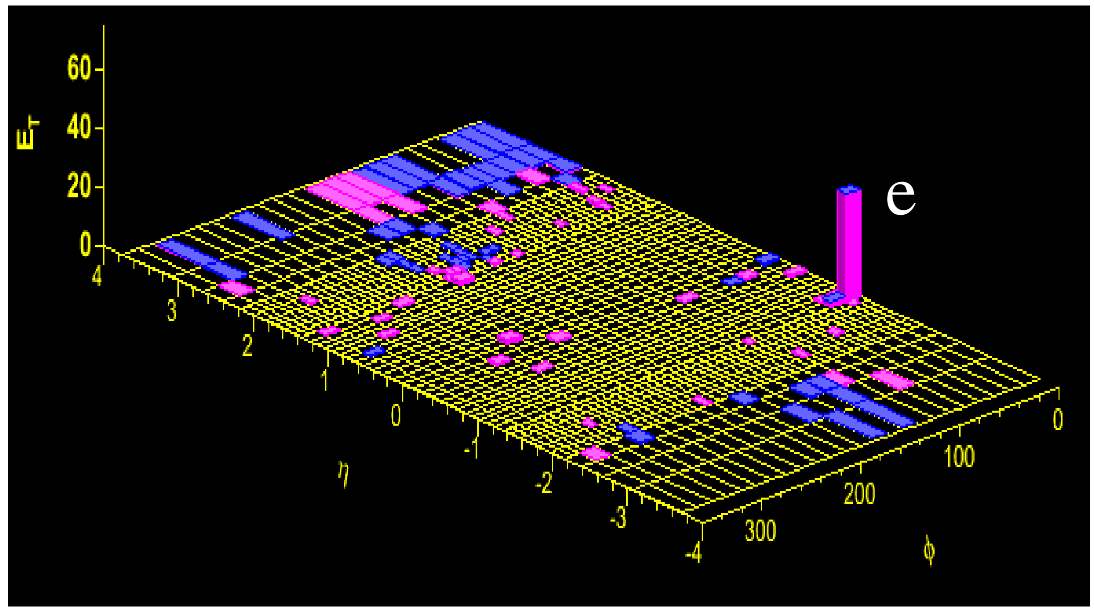
Lepton p_T carries most of *W* mass information, can be measured precisely (achieved 0.03%)

Initial state QCD radiation is *O*(10 GeV), measure as soft 'hadronic recoil' in calorimeter (calibrated to ~1%)

Pollutes *W* mass information, fortunately $p_T(W) << M_W$

W Boson Production at the Tevatron





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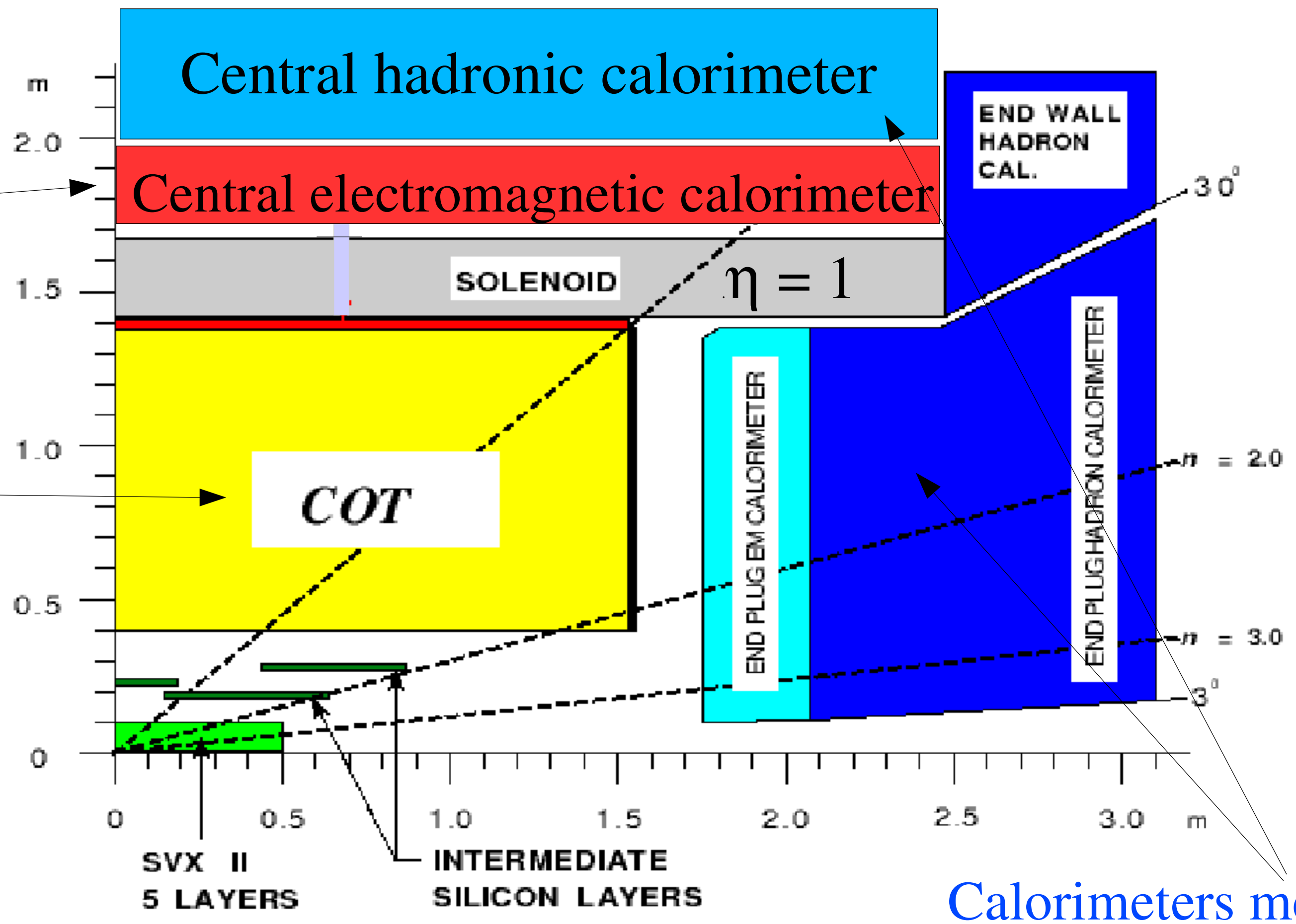
Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

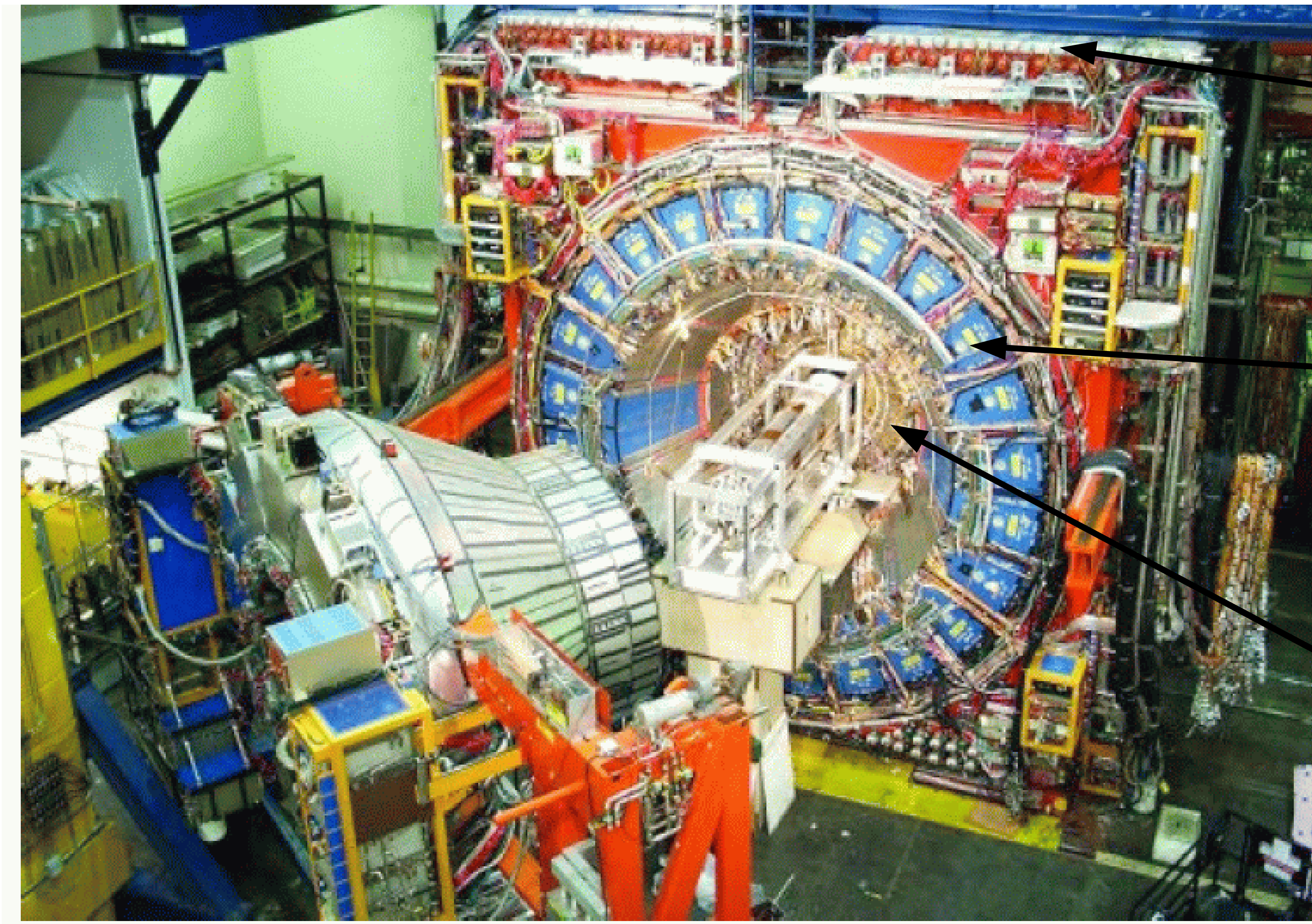
COT provides precise lepton track momentum measurement



Calorimeters measure hadronic recoil particles

Select W and Z bosons with central (| η | < 1) leptons

Collider Detector at Fermilab (CDF)



Muon detector

Central hadronic calorimeter

Central outer tracker (COT)

CDF W & Z Data Samples

- W, Z, J/ψ and Upsilon decays triggered in the dilepton channel
- Analysis of 2.3 fb^{-1} data in progress
- CDF's analysis published in 2007, based on integrated luminosity (collected between February 2002 – September 2003):
  - Electron channel: $\mathcal{L} = 218\ pb^{-1}$
  - Muon channel: $\mathcal{L} = 191\ pb^{-1}$

Sample	Candidates
$W \to e\nu$	63964
$W \to \mu\nu$	51128
$Z \to e^+e^-$	2919
$Z \to \mu^+\mu^-$	4960

- Event selection gives fairly clean samples
  - W boson samples' mis-identification backgrounds ~ 0.5%

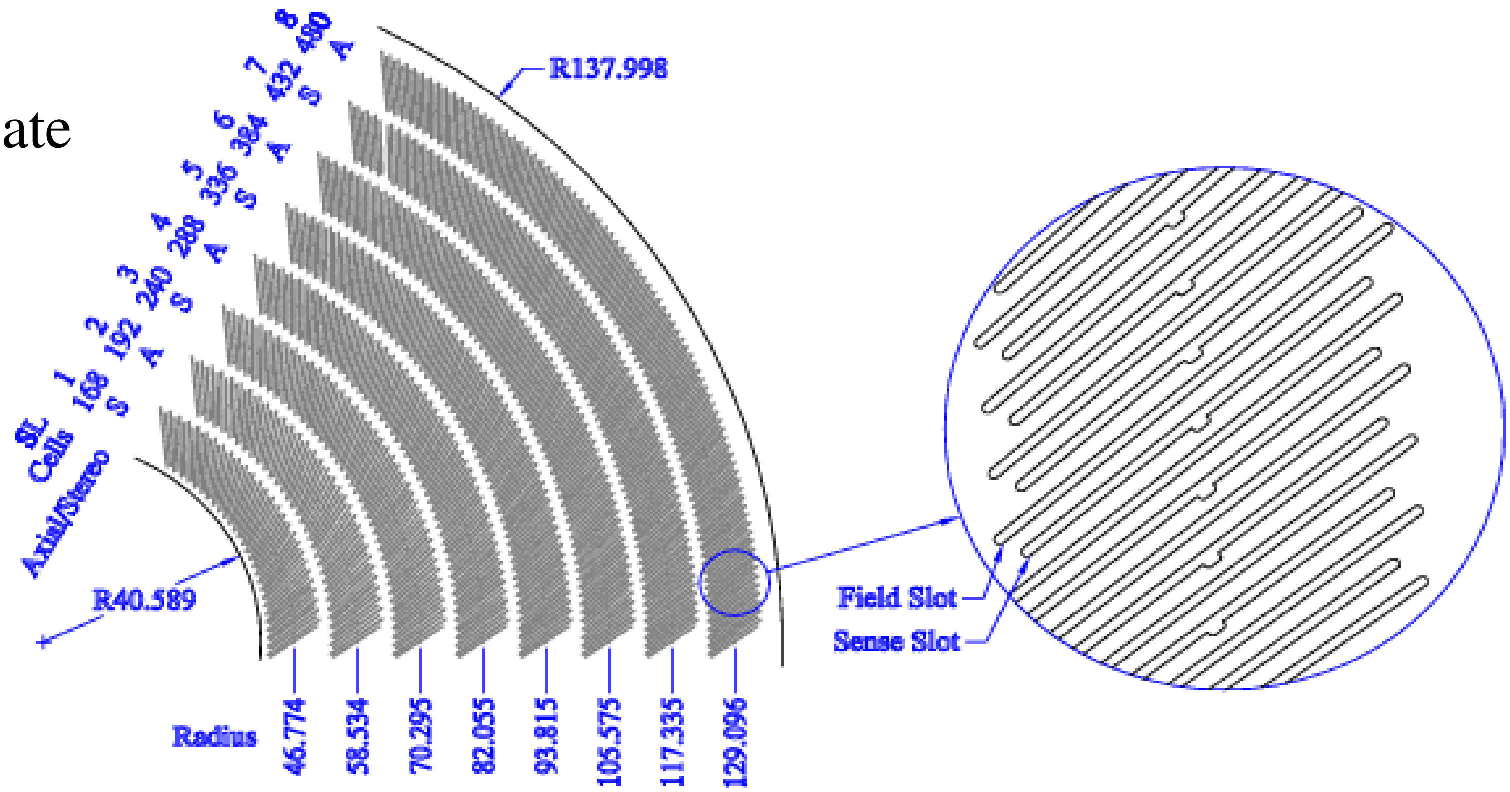
Outline of Analysis

Energy scale measurements drive the W mass measurement

- Tracker Calibration
  - alignment of the COT (~2400 cells) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
    - Confirmed using $Z \rightarrow \mu\mu$ mass fit
- EM Calorimeter Calibration
  - COT momentum scale transferred to EM calorimeter using a fit to the peak of the E/p spectrum, around E/p ~ 1
  - Calorimeter energy scale confirmed using $Z \rightarrow ee$ mass fit
- Tracker and EM Calorimeter resolutions
- Hadronic recoil modelling
  - Characterized using p_T-balance in $Z \rightarrow ll$ events

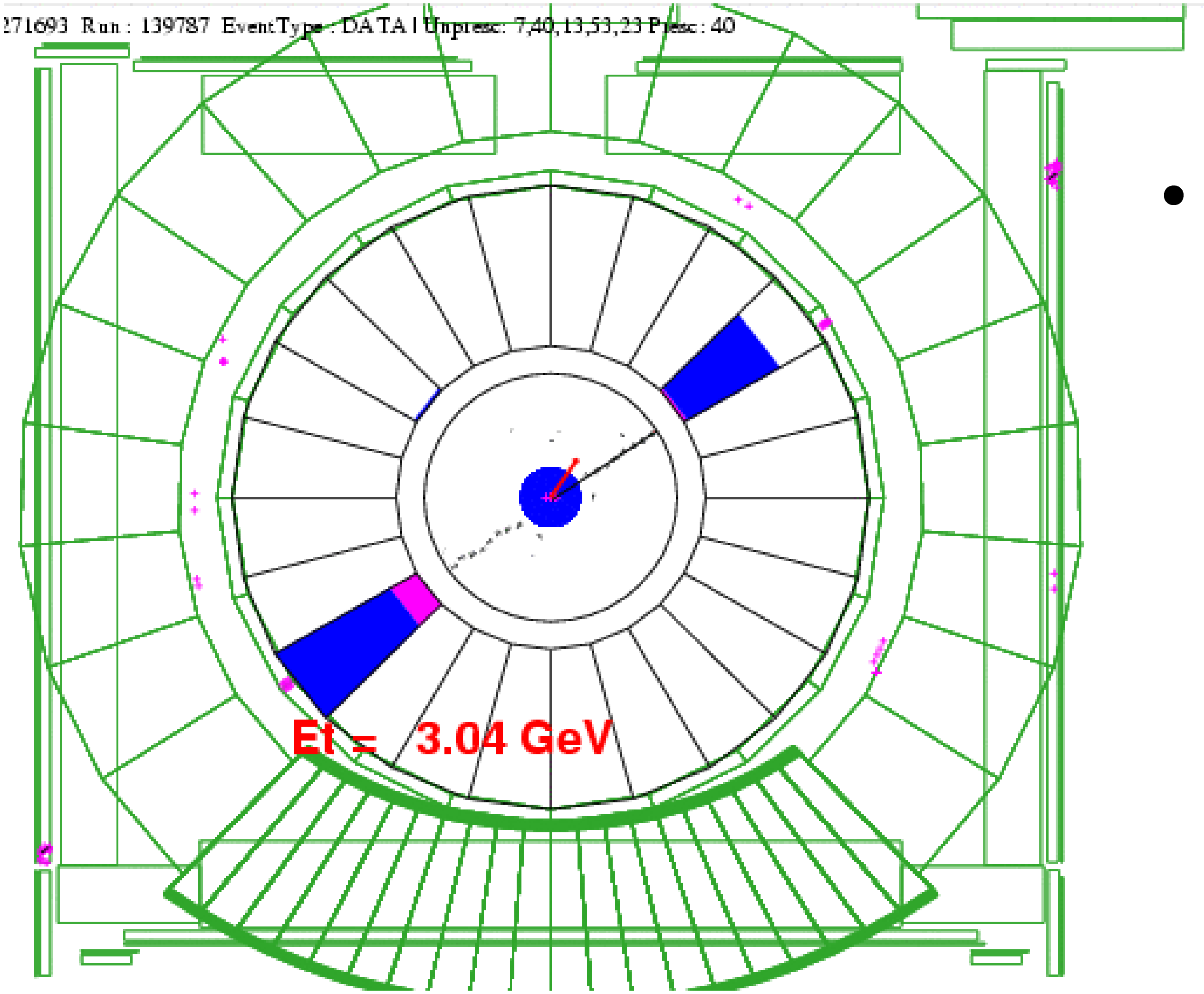
Drift Chamber (COT) Alignment

COT endplate geometry



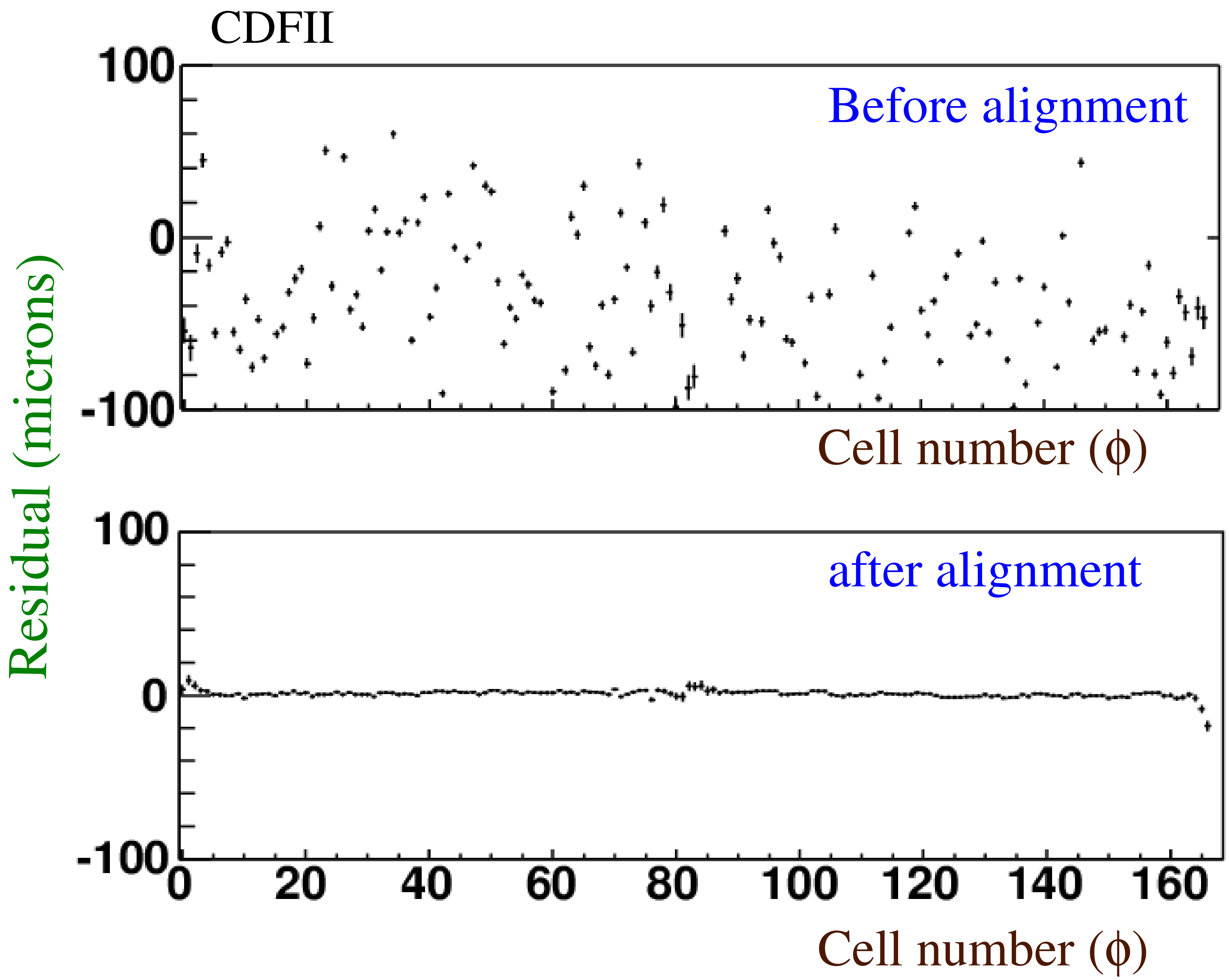
Internal Alignment of COT

- Use a clean sample of ~200*k* cosmic rays for cell-by-cell internal alignment



- Fit COT hits on both sides simultaneously to a single helix (AK, H. Gerberich and C. Hays, NIMA 506, 110 (2003))
  - Time of incidence is a floated parameter in this 'dicosmic fit'

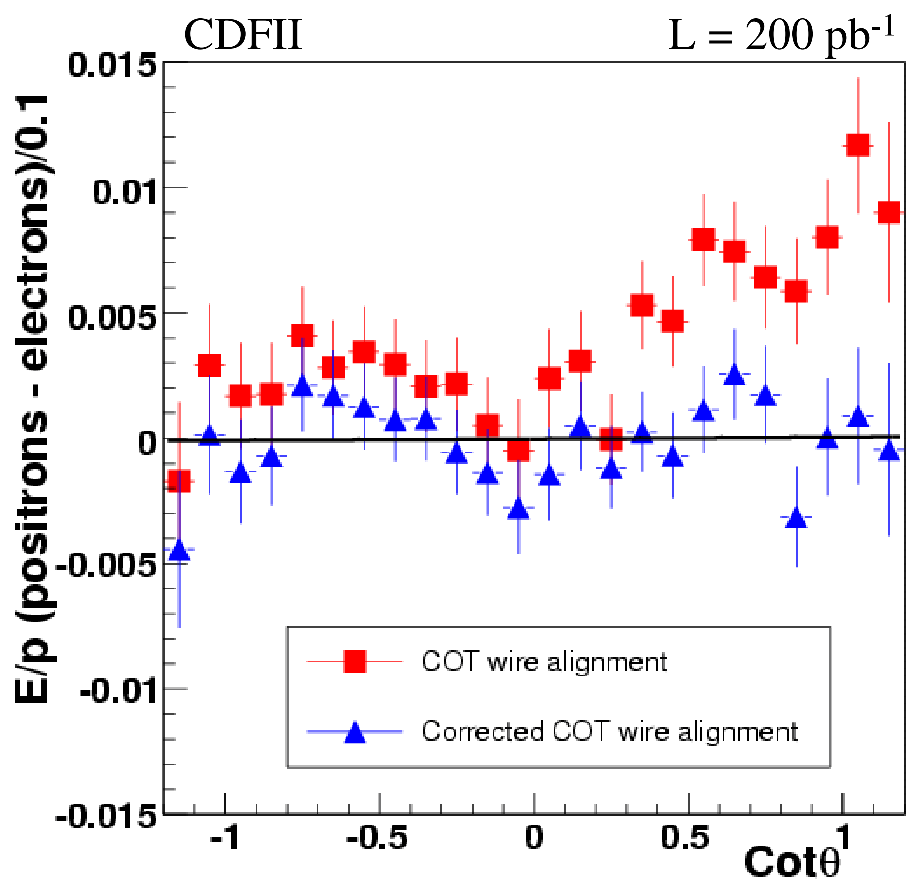
Residuals of COT cells after alignment



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

Cross-check of COT alignment

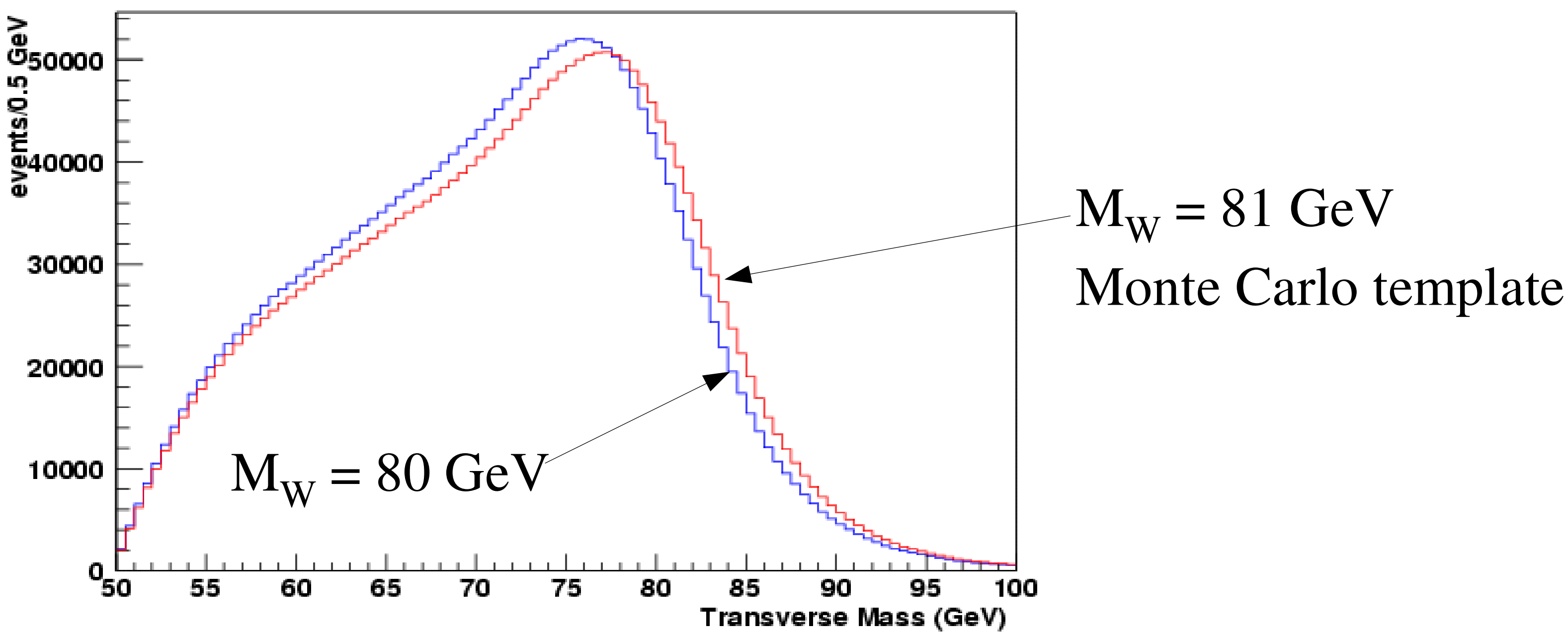
- Final cross-check and correction to beam-constrained track curvature based on difference of <E/p> for positrons *vs* electrons
- Smooth ad-hoc curvature corrections fitted and applied as a function of polar and azimuthal angle: statistical errors => δM_W = 6 MeV



Signal Simulation and Fitting

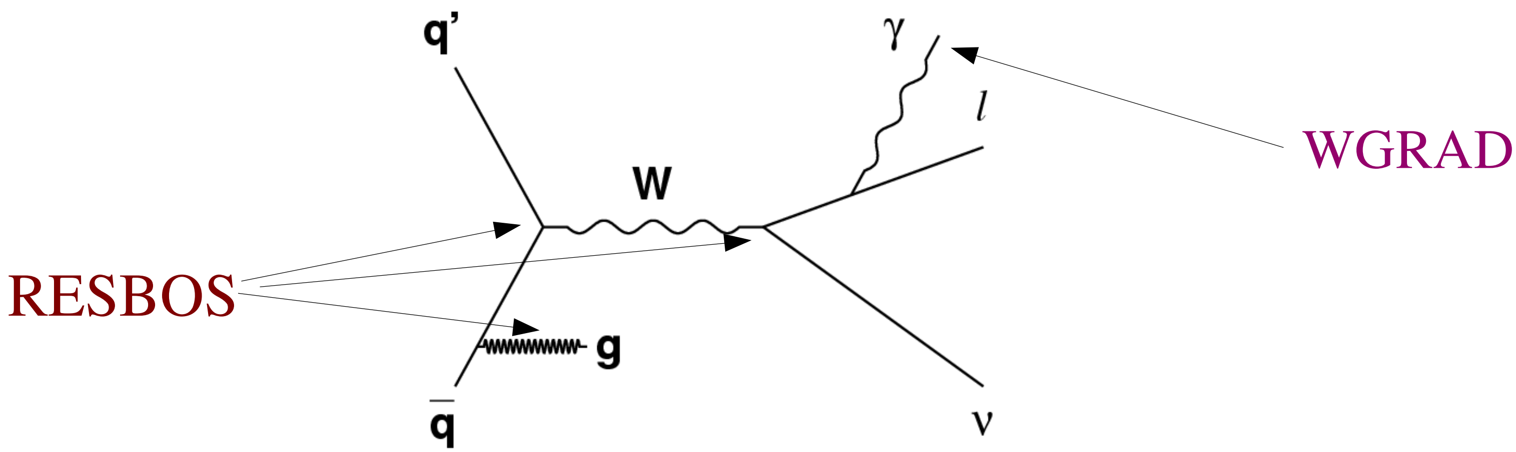
Signal Simulation and Template Fitting

- All signals simulated using a fast Monte Carlo
  - Generate finely-spaced templates as a function of the fit variable
  - perform binned maximum-likelihood fits to the data
- Custom fast Monte Carlo makes smooth, high statistics templates
  - And provides analysis control over key components of the simulation



- We will extract the W mass from six kinematic distributions: Transverse mass, charged lepton p_T and neutrino p_T using both electron and muon channels

Generator-level Signal Simulation



- Generator-level input for W & Z simulation provided by RESBOS (C. Balazs & C.-P. Yuan, PRD56, 5558 (1997) and references therein), which
  - Calculates triple-differential production cross section, and p_T-dependent double-differential decay angular distribution
  - calculates boson p_T spectrum reliably over the relevant p_T range: includes tunable parameters in the non-perturbative regime at low p_T
- Radiative photons generated according to energy *vs* angle lookup table from WGRAD (U. Baur, S. Keller & D. Wackeroth, PRD59, 013002 (1998))

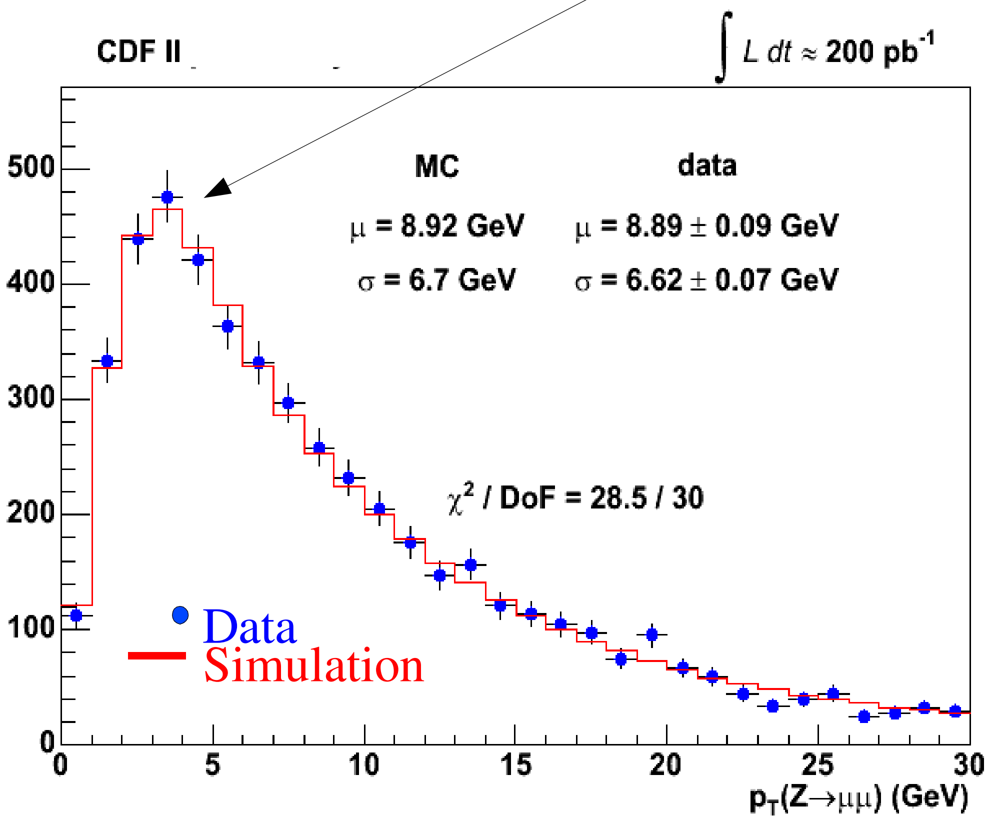
Constraining Boson p_T Spectrum

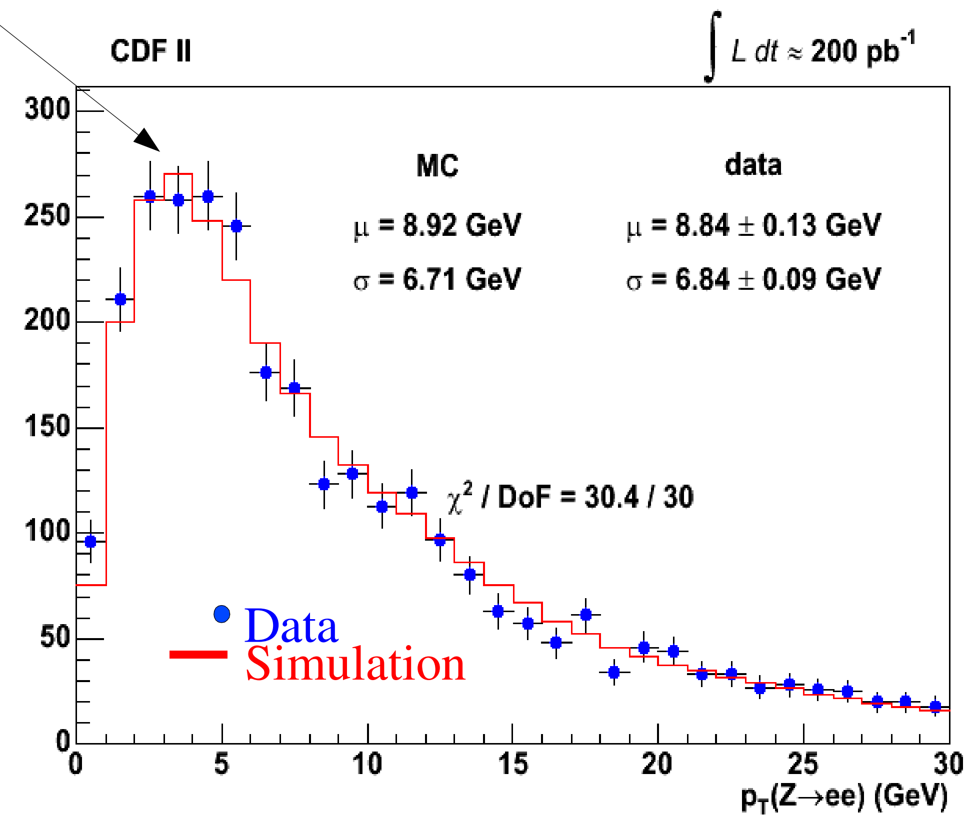
- Fit the non-perturbative parameter g_2 in RESBOS to $p_T(ll)$ spectra: find $g_2 = 0.685 \pm 0.048$

$\Delta M_W = 3$ MeV

  - Consistent with global fits (Landry *et al,* PRD67, 073016 (2003))
- Negligible effect of second non-perturbative parameter g_3

Position of peak in boson p_T spectrum depends on g_2





Fast Monte Carlo Detector Simulation

- A complete detector simulation of all quantities measured in the data
- First-principles simulation of tracking
  - Tracks and photons propagated through a high-resolution 3-D lookup table of material properties for silicon detector and COT
  - At each material interaction, calculate
    - Ionization energy loss according to complete Bethe-Bloch formula
    - Generate bremsstrahlung photons down to 4 MeV, using detailed cross section and spectrum calculations
    - Simulate photon conversion and compton scattering
    - Propagate bremsstrahlung photons and conversion electrons
    - Simulate multiple Coulomb scattering, including non-Gaussian tail
  - Deposit and smear hits on COT wires, perform full helix fit including optional beam-constraint

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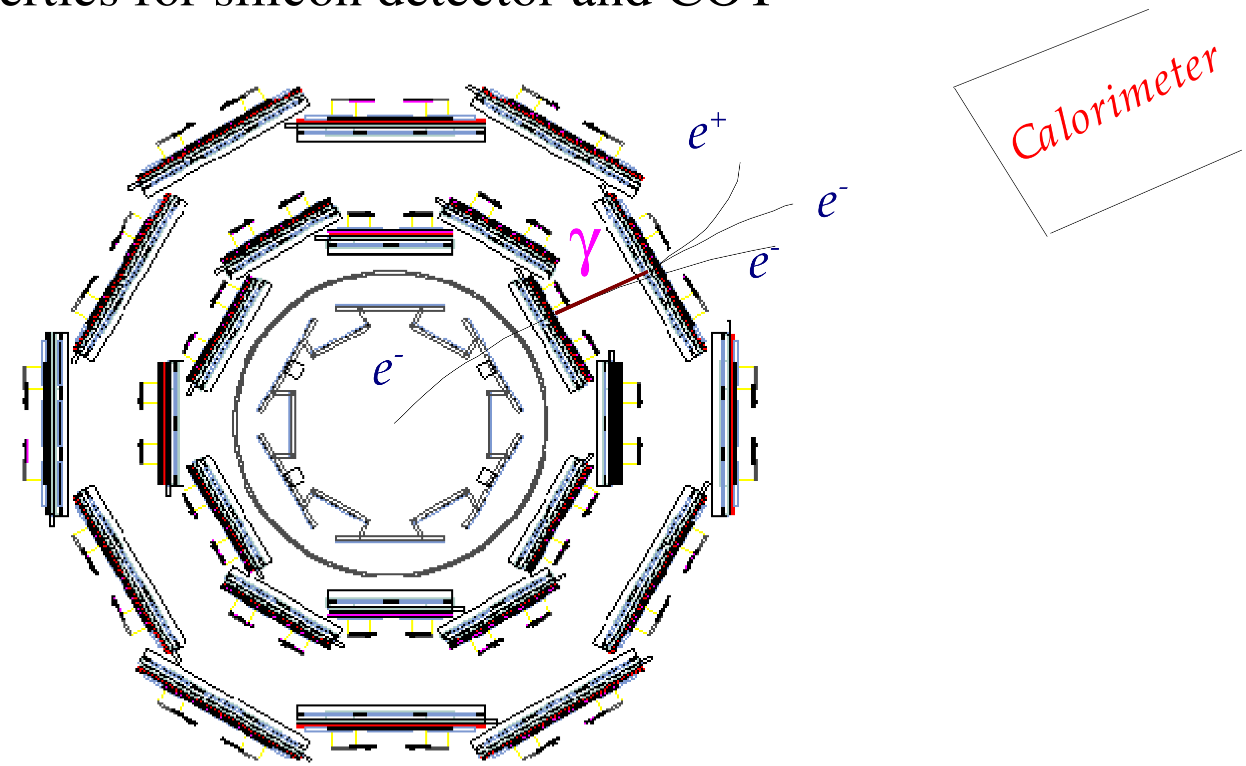

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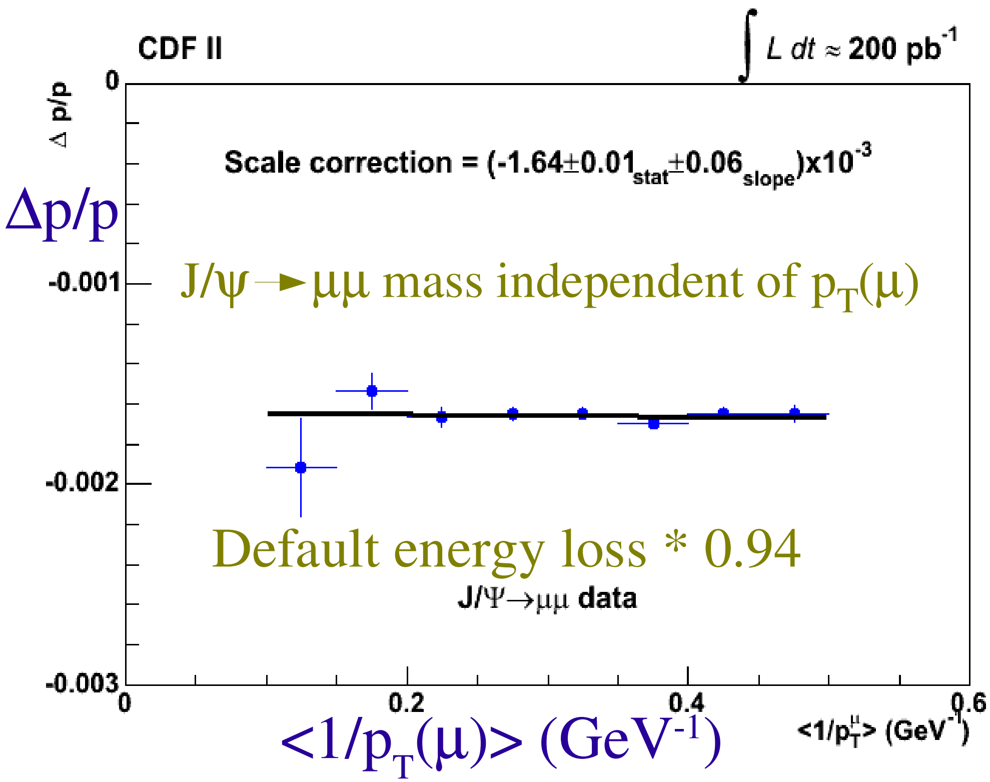
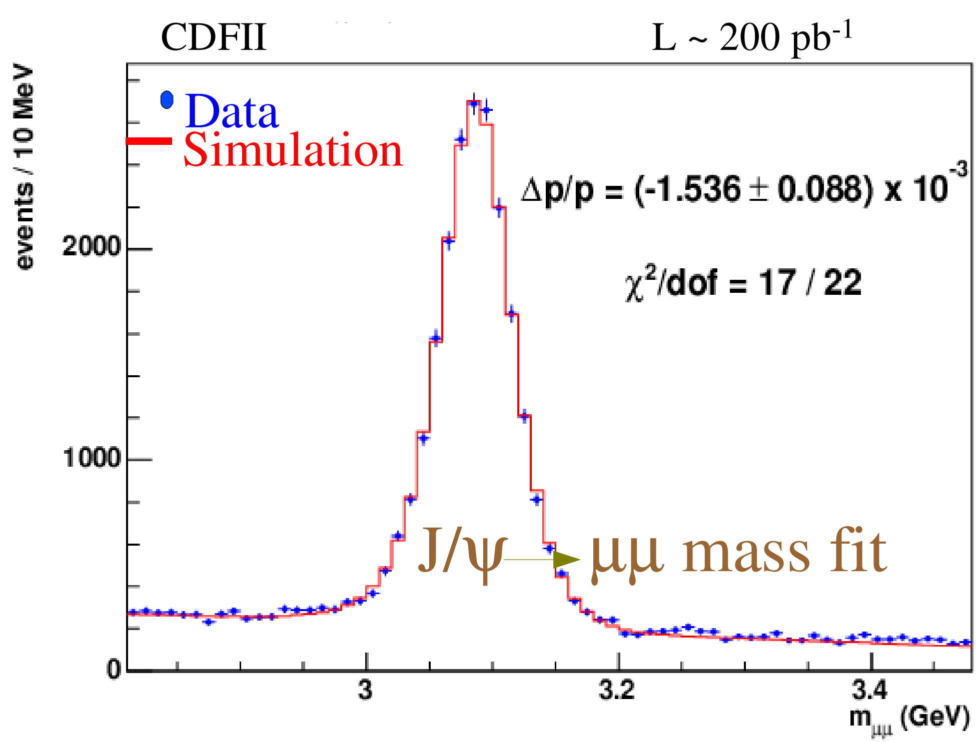
Tracking Momentum Scale

Tracking Momentum Scale

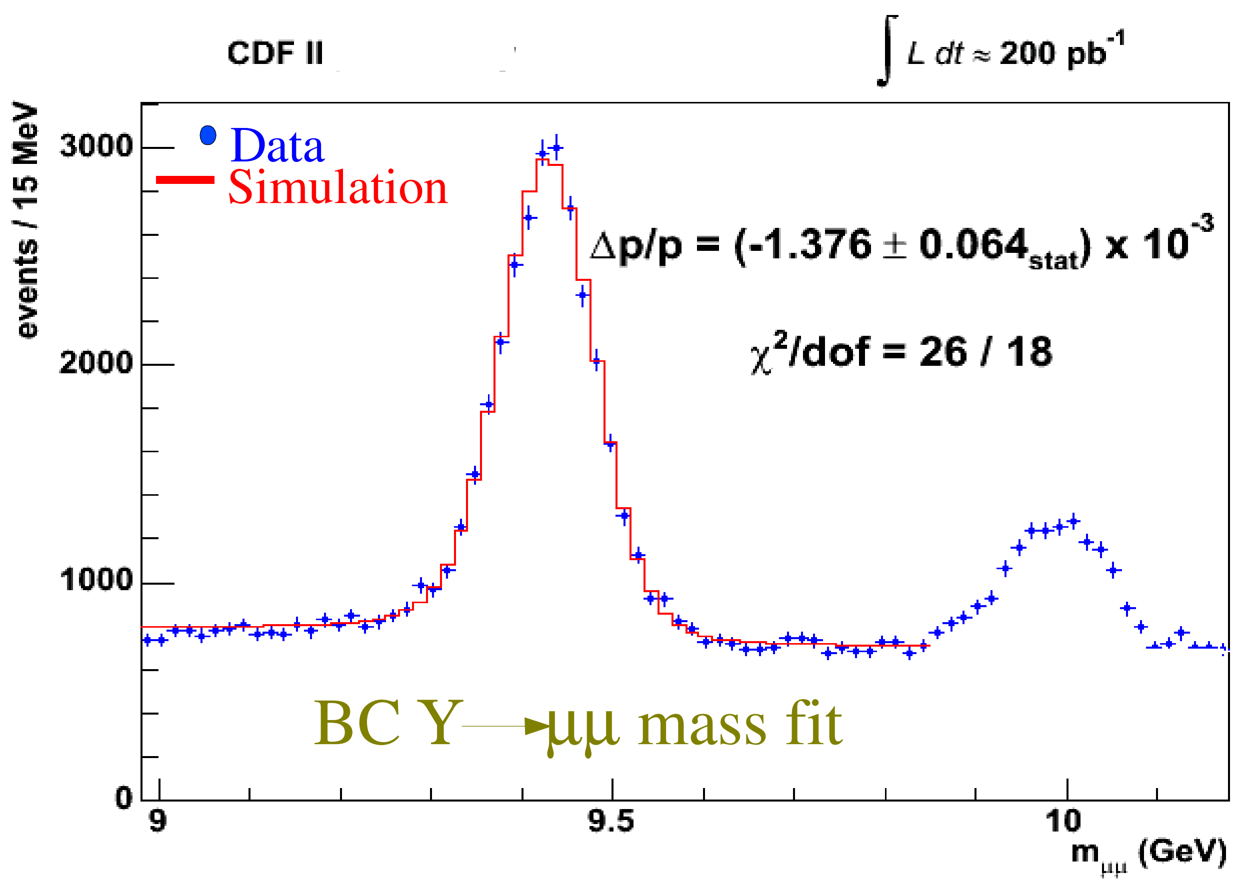
- Set using $J/\psi \rightarrow \mu\mu$ and $Y \rightarrow \mu\mu$ resonance and $Z \rightarrow \mu\mu$ masses
  - All are individually consistent with each other
- J/ψ: $\Delta p/p = (-1.64 \pm 0.06_{stat} \pm 0.24_{sys}) \times 10^{-3}$
  - Extracted by fitting J/ψ mass in bins of $<1/p_T(\mu)>$, and extrapolating momentum scale to zero curvature





Tracking Momentum Scale

- $\Upsilon \rightarrow \mu\mu$ resonance provides
  - Momentum scale measurement at higher p_T
  - Validation of beam-constaining procedure (upsilons are promptly produced)
  - Non-beam-constrained and beam-constrained (BC) fits statistically consistent



Tracking Momentum Scale Systematics

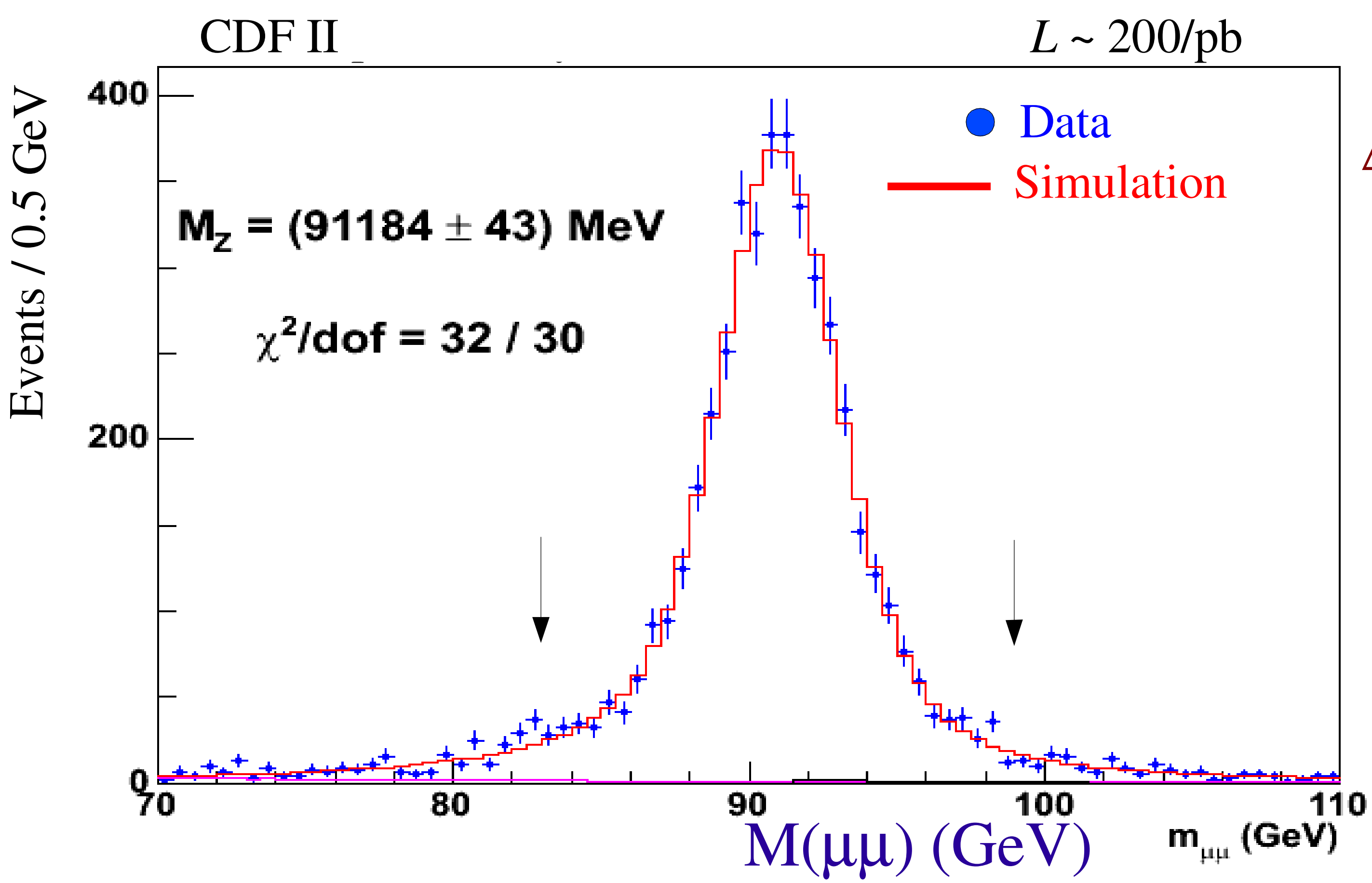
Systematic uncertainties on momentum scale

Source	J/ψ ($\times10^{-3}$)	Υ ($\times10^{-3}$)	Common ($\times10^{-3}$)
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

Uncertainty dominated by QED radiative corrections and magnetic field non-uniformity

$Z \rightarrow \mu\mu$ Mass Cross-check & Combination

- Using the J/ψ and Υ momentum scale, measured *Z* mass is consistent with PDG value
- Final combined: $\Delta p/p = (-1.50 \pm 0.15_{independent} \pm 0.13_{QED} \pm 0.07_{align}) \times 10^{-3}$

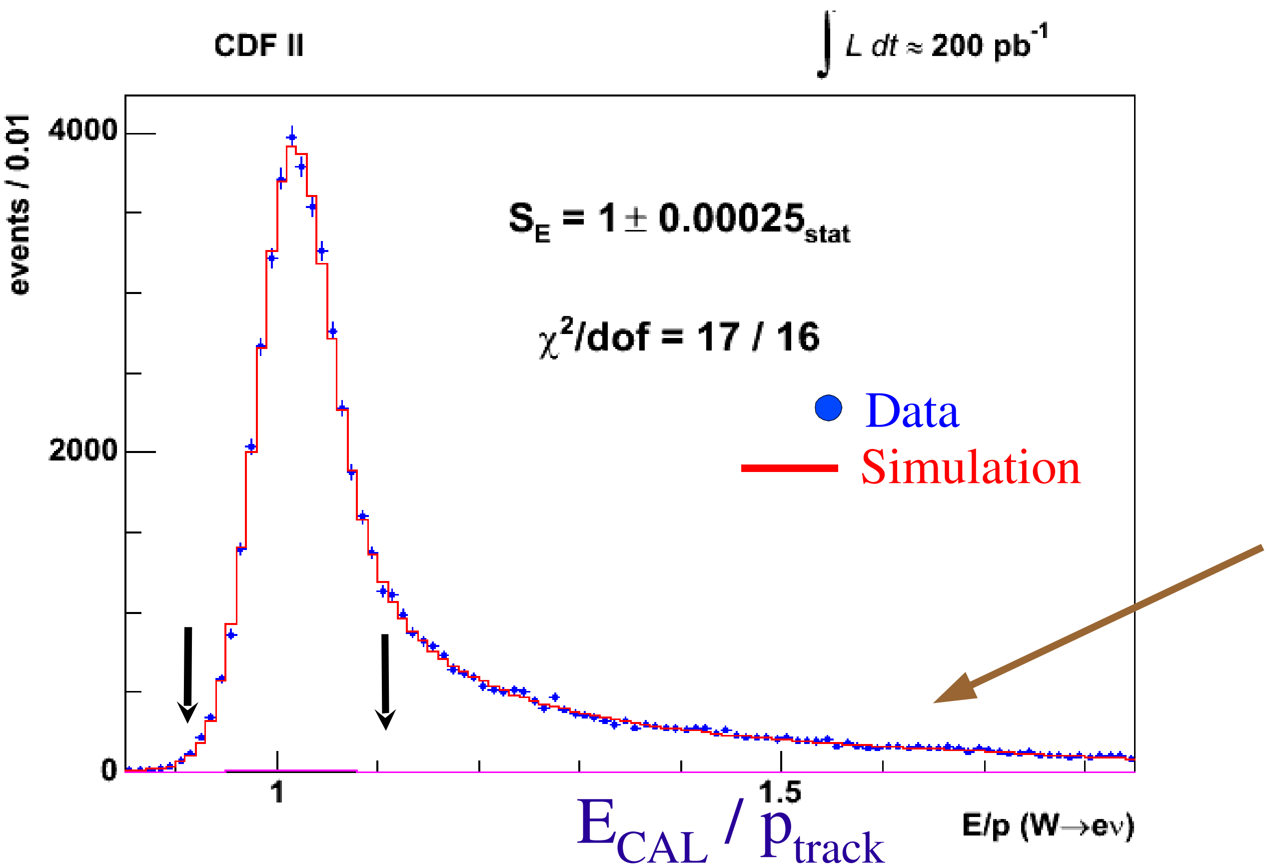


ΔM_W = 17 MeV

EM Calorimeter Response

EM Calorimeter Scale

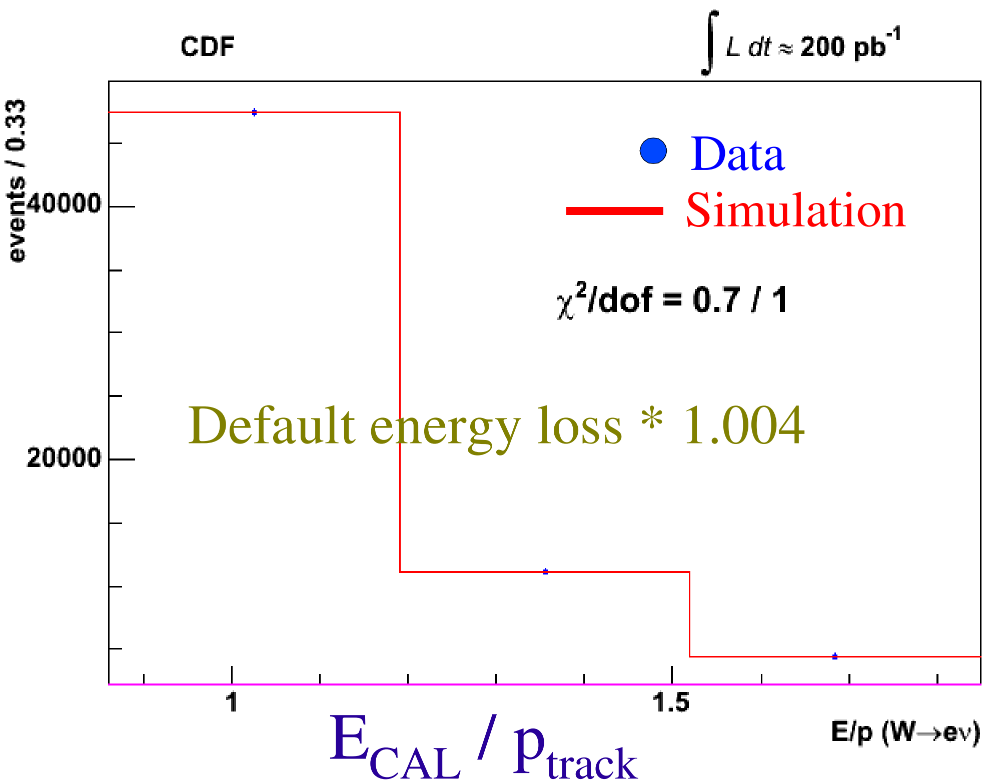
- E/p peak from $W \rightarrow e\nu$ decays provides measurements of EM calorimeter scale and its (E_T-dependent) non-linearity
  - $S_E = 1 \pm 0.00025_{stat} \pm 0.00011_{X0} \pm 0.00021_{Tracker}$
- Setting S_E to 1 using E/p calibration

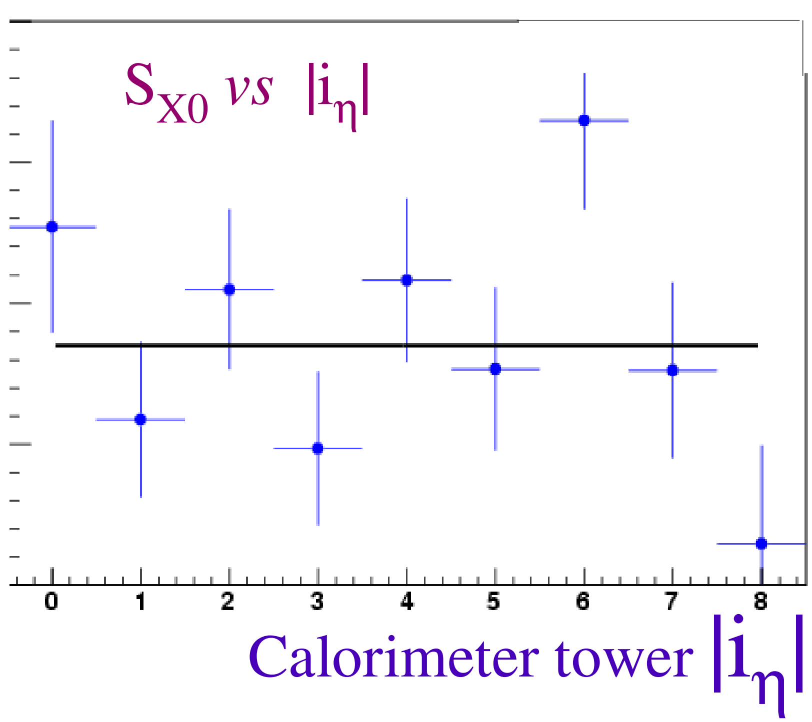


Tail region of E/p spectrum used for tuning model of radiative material

Consistency of Radiative Material Model

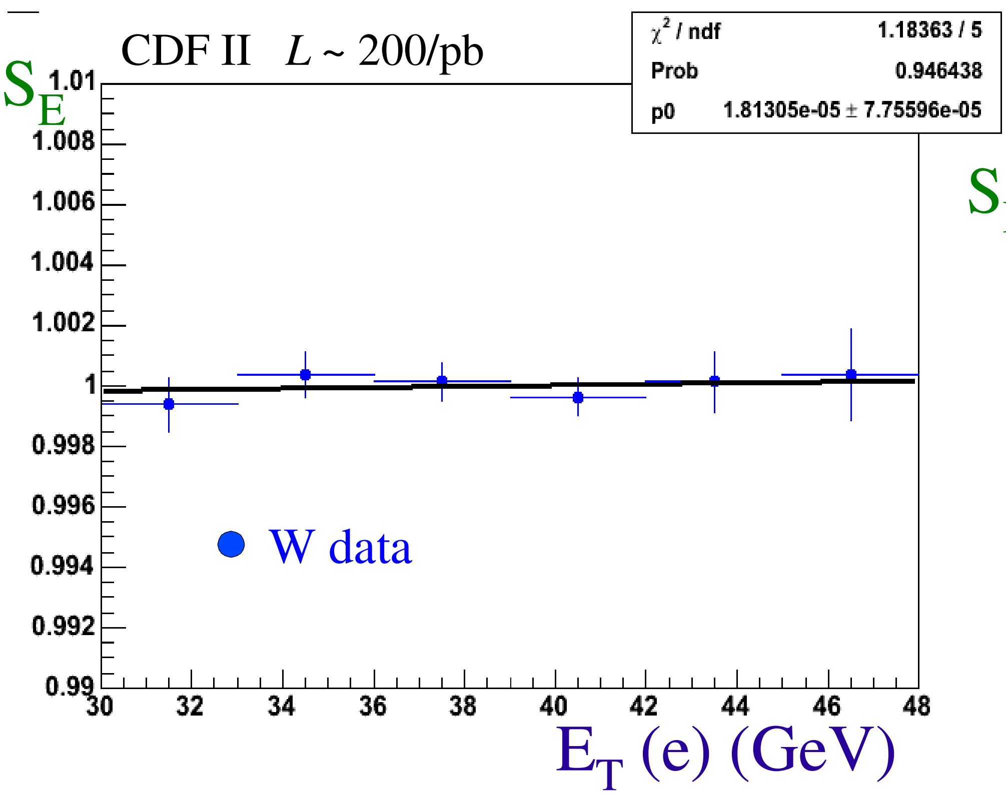
- Excellent description of E/p spectrum tail
- radiative material tune factor: $S_{X0} = 1.004 \pm 0.009_{stat} \pm 0.002_{background}$ achieves consistency with E/p spectrum tail
  - CDFSim geometry confirmed as a function of pseudorapidity: S_{MAT} independent of | η |

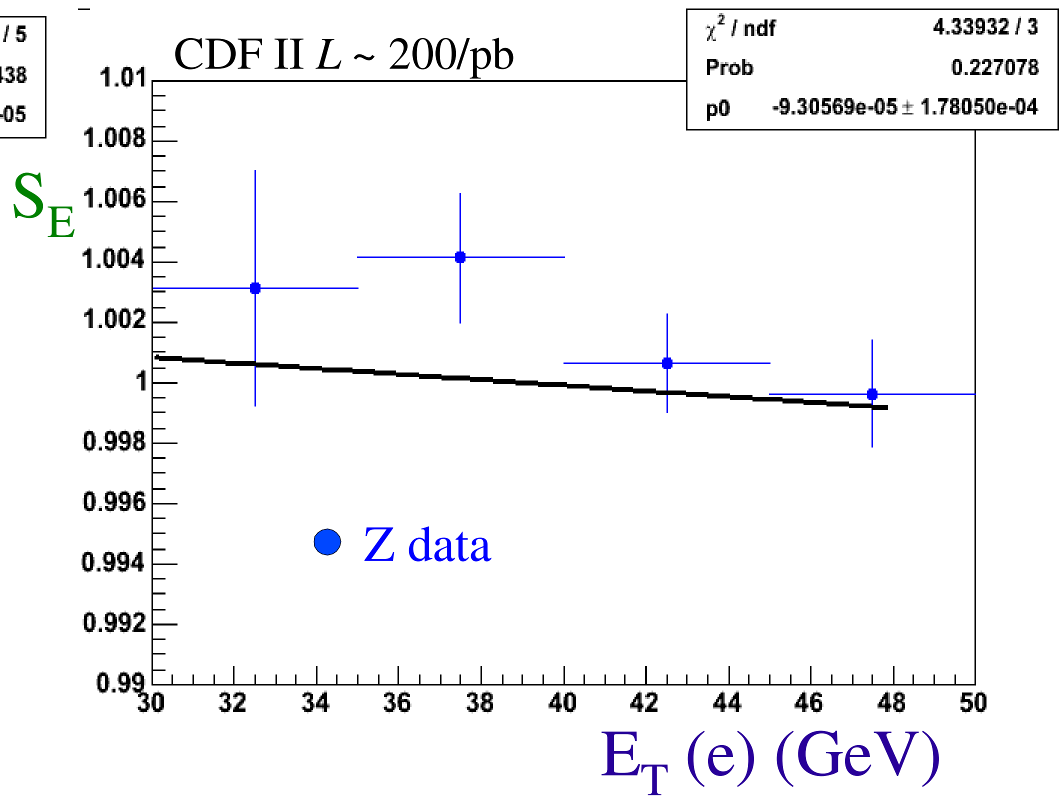




Measurement of EM Calorimeter Non-linearity

- Perform E/p fit-based calibration in bins of electron E_T
- Pameterize non-linear response as: $S_E = 1 + \xi\ (E_T/\text{GeV} - 39)$
- Tune on W and Z data: $\xi = (6 \pm 7_{stat}) \times 10^{-5}$
  - => $\Delta M_W = 23$ MeV

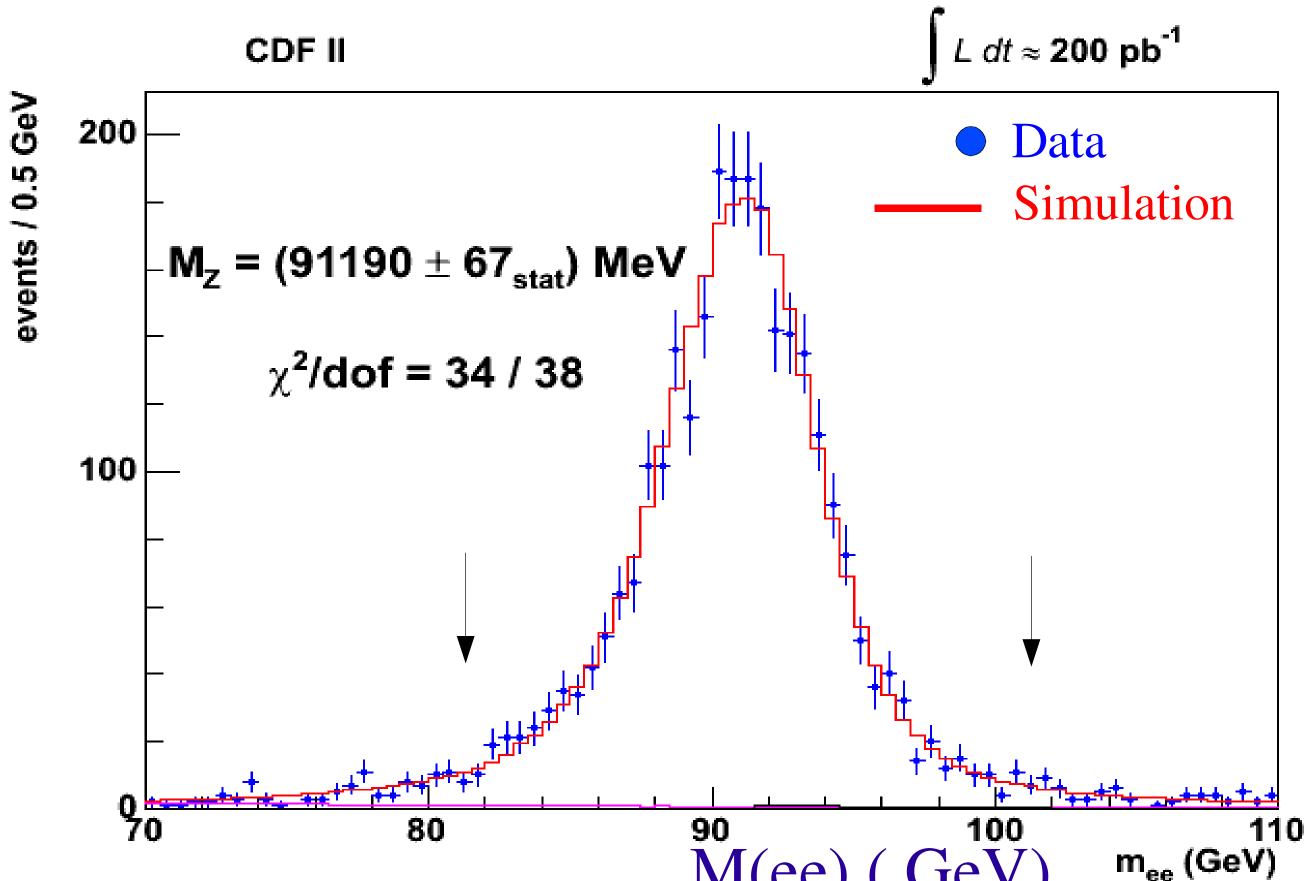




$Z \rightarrow$ ee Mass Cross-check and Combination

- Z mass consistent with E/p-based measurements
- Combining E/p-derived scale & non-linearity measurement with $Z \rightarrow ee$ mass yields the most precise calorimeter energy scale:
  - $S_E = 1.00001 \pm 0.00037$

$\Delta M_W = 30$ MeV



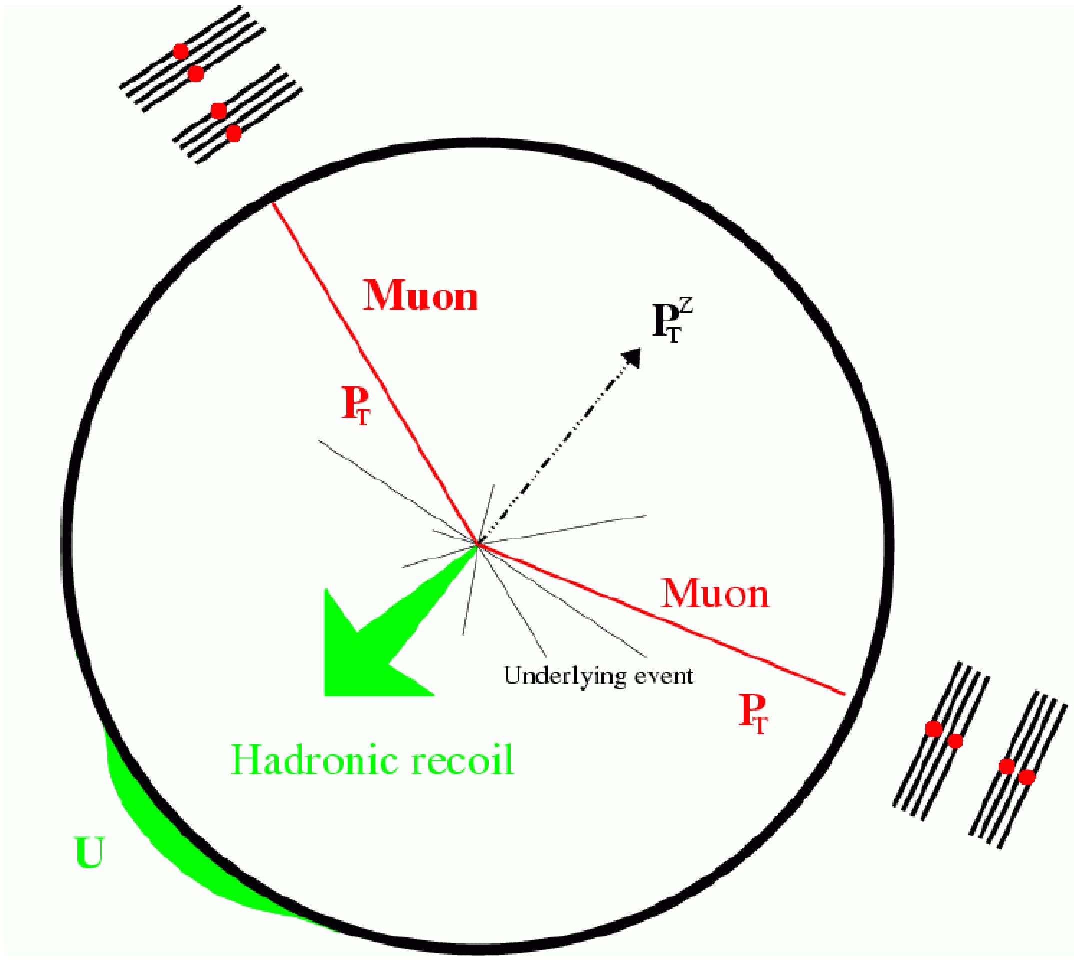
M(ee) (GeV)

Hadronic Recoil Model

Constraining the Hadronic Recoil Model

Exploit similarity in production and decay of *W* and *Z* bosons

Detector response model for hadronic recoil tuned using p_T-balance in $Z \rightarrow ll$ events



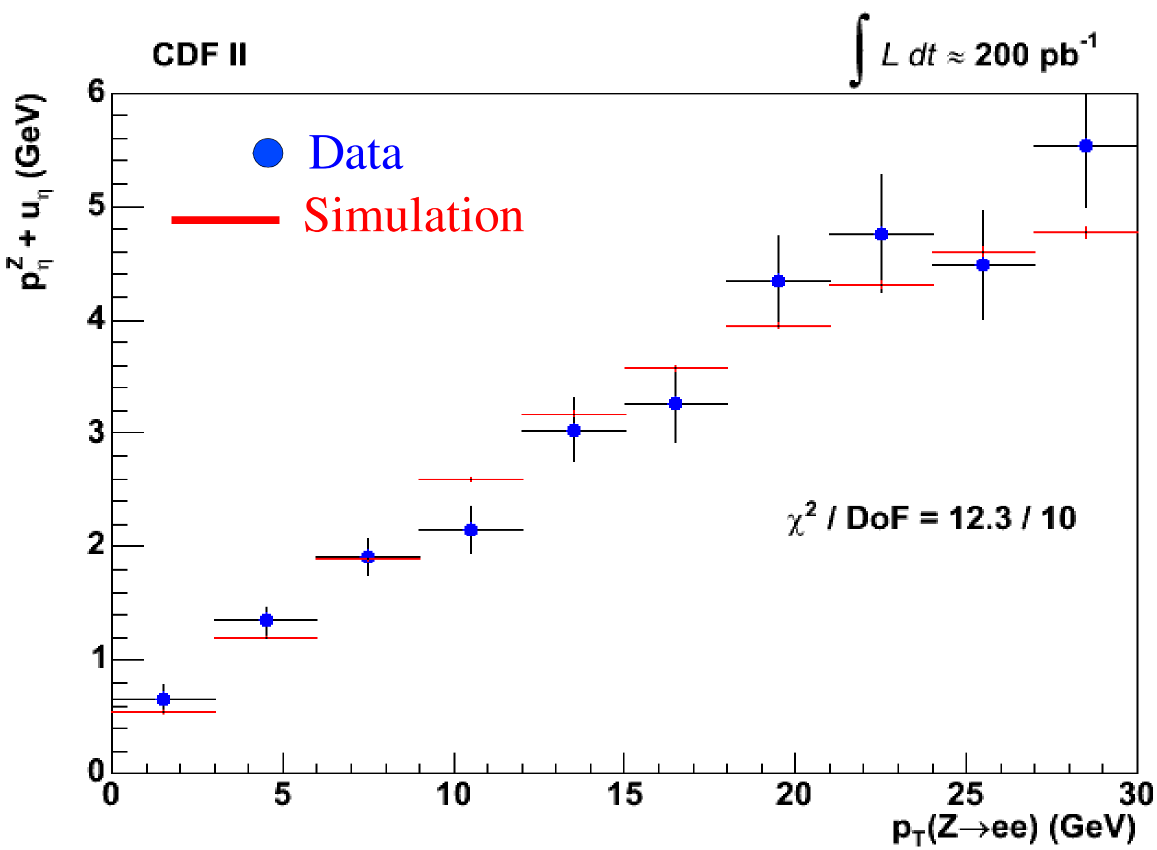
Transverse momentum of Hadronic recoil (***u***) calculated as 2-vector-sum over calorimeter towers

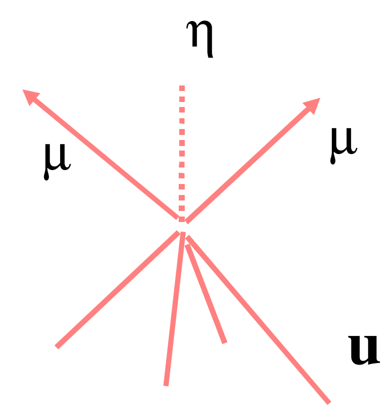
Tuning Recoil Response Model with *Z* events

Project the vector sum of $p_T(ll)$ and ***u*** on a set of orthogonal axes defined by lepton directions

Mean and rms of projections as a function of $p_T(ll)$ provide information hadronic model parameters

mean of p_T-balance (GeV)



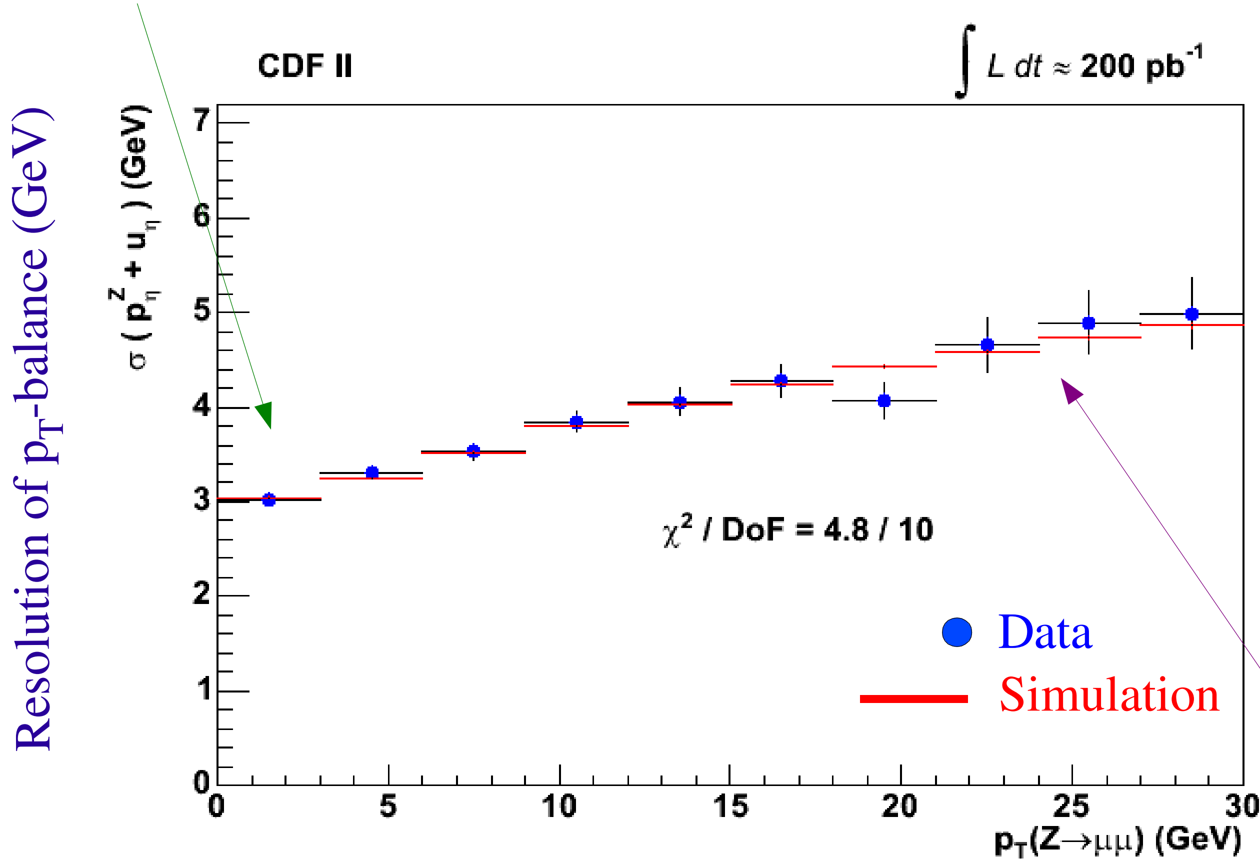


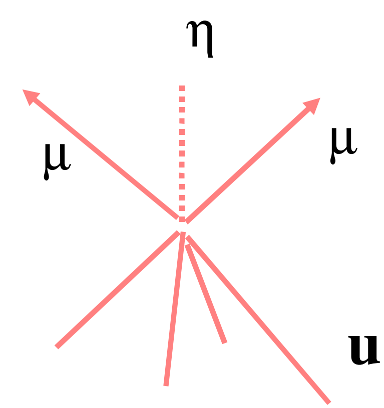
Hadronic model parameters tuned by minimizing χ^2 between data and simulation

$\Delta M_W = 9$ MeV

Tuning Recoil Resolution Model with *Z* events

At low $p_T(Z)$, p_T-balance constrains hadronic resolution due to underlying event



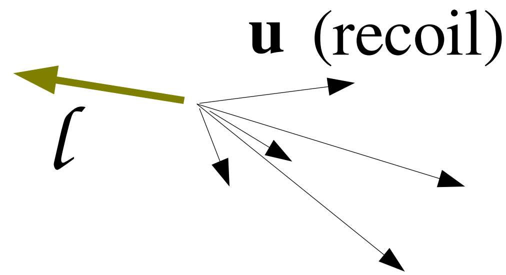


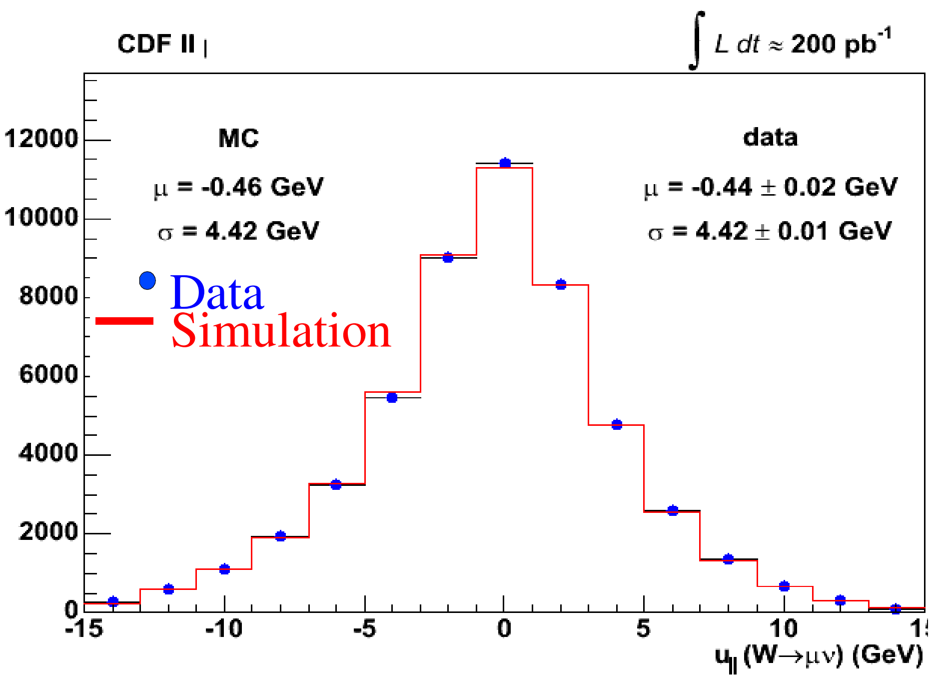
ΔM_W = 7 MeV

At high $p_T(Z)$, p_T-balance constrains jet resolution

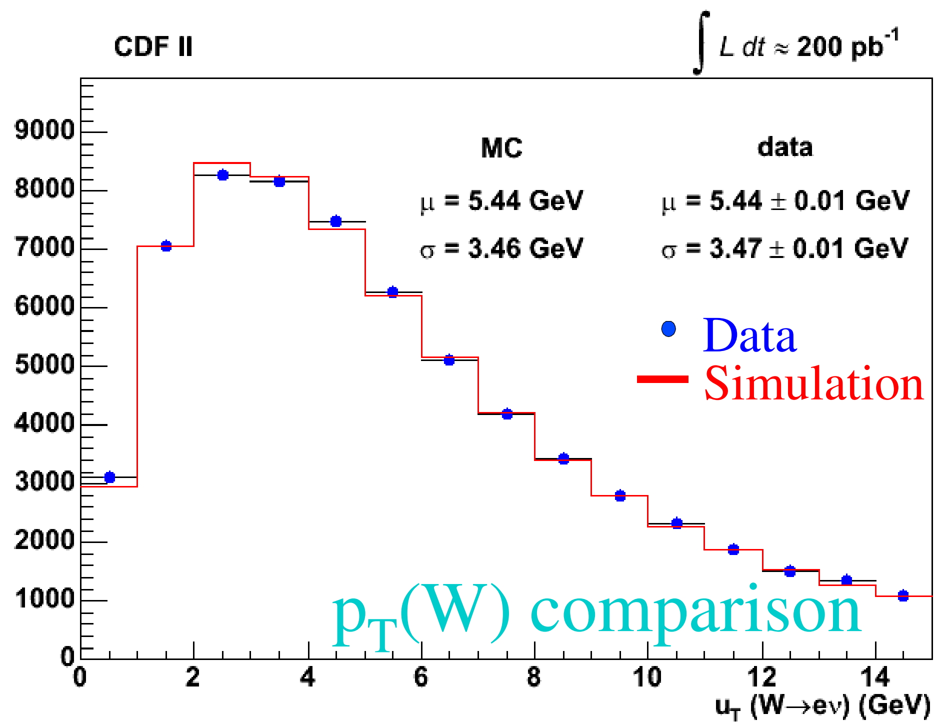
Testing Hadronic Recoil Model with *W* events

Compare recoil distributions between simulation and data





Recoil projection (GeV) on lepton direction

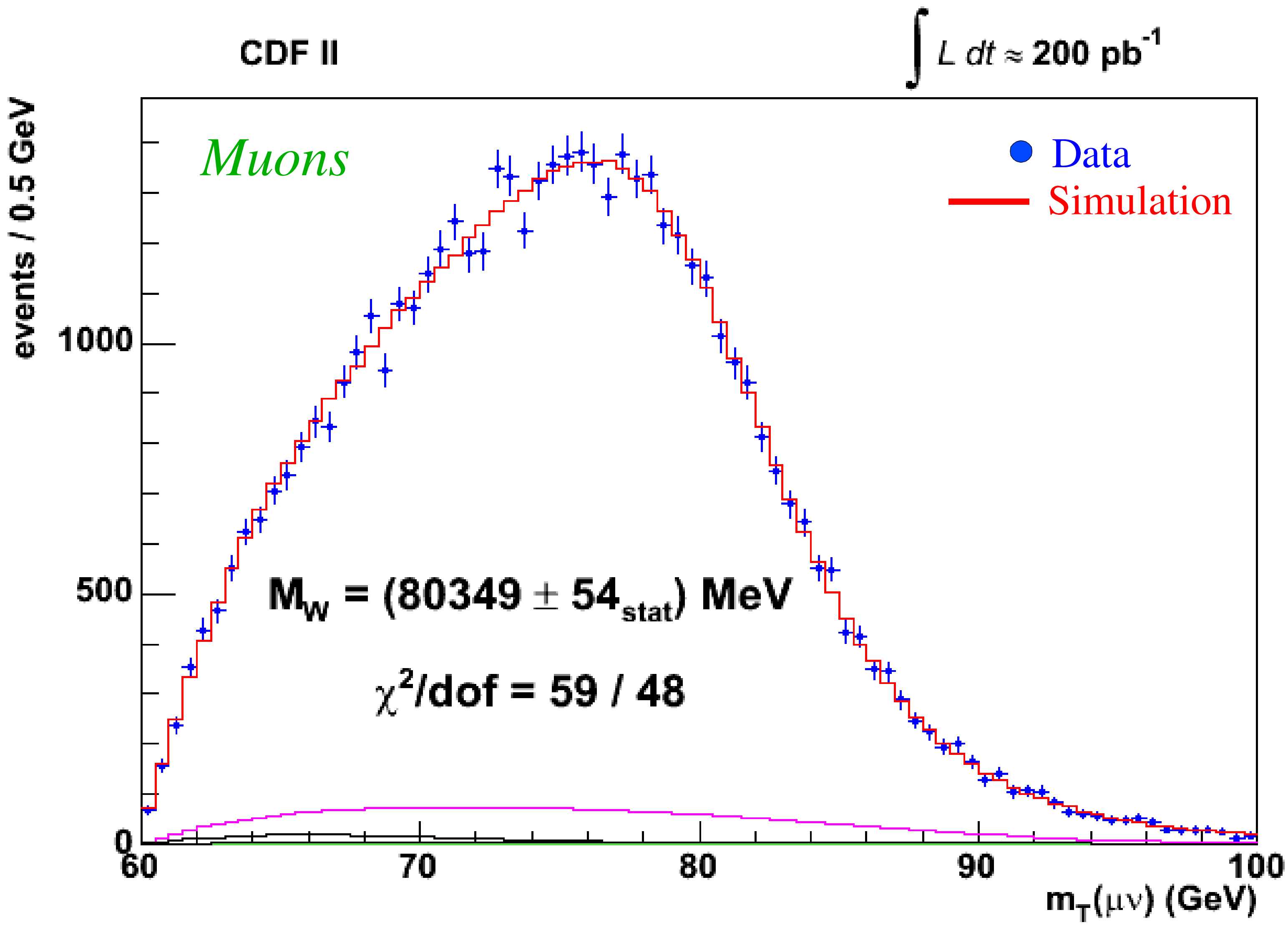


W Mass Fits

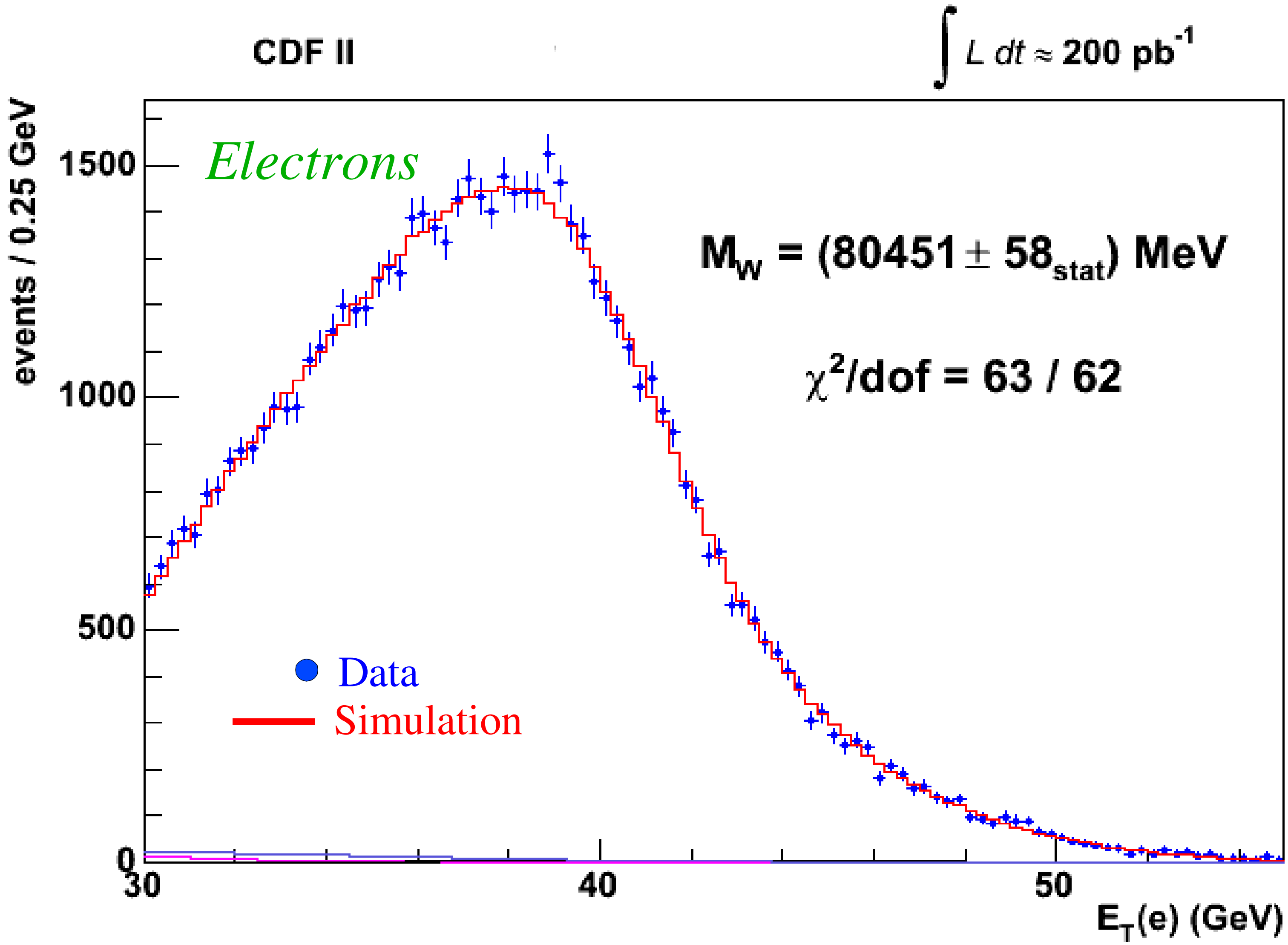
Blind Analysis Technique

- All W mass fit results were blinded with a random [-100,100] MeV offset hidden in the likelihood fitter
- Blinding offset removed after the analysis was declared frozen
- Technique allows to study all aspects of data while keeping W mass result unknown within 100 MeV

W Transverse Mass Fits



W Lepton p_T Fits



Transverse Mass Fit Uncertainties (MeV)

(CDF, PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)

	electrons	*muons*	*common*
W statistics	48	54	0
Lepton energy scale	30	17	17
Lepton resolution	9	3	-3
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
Selection bias	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
pT(W) model	3	3	3
Parton dist. Functions	11	11	11
QED rad. Corrections	11	12	11
Total systematic	**39**	**27**	**26**
Total	**62**	**60**	

W charge asymmetry from Tevatron helps with PDFs → Parton dist. Functions

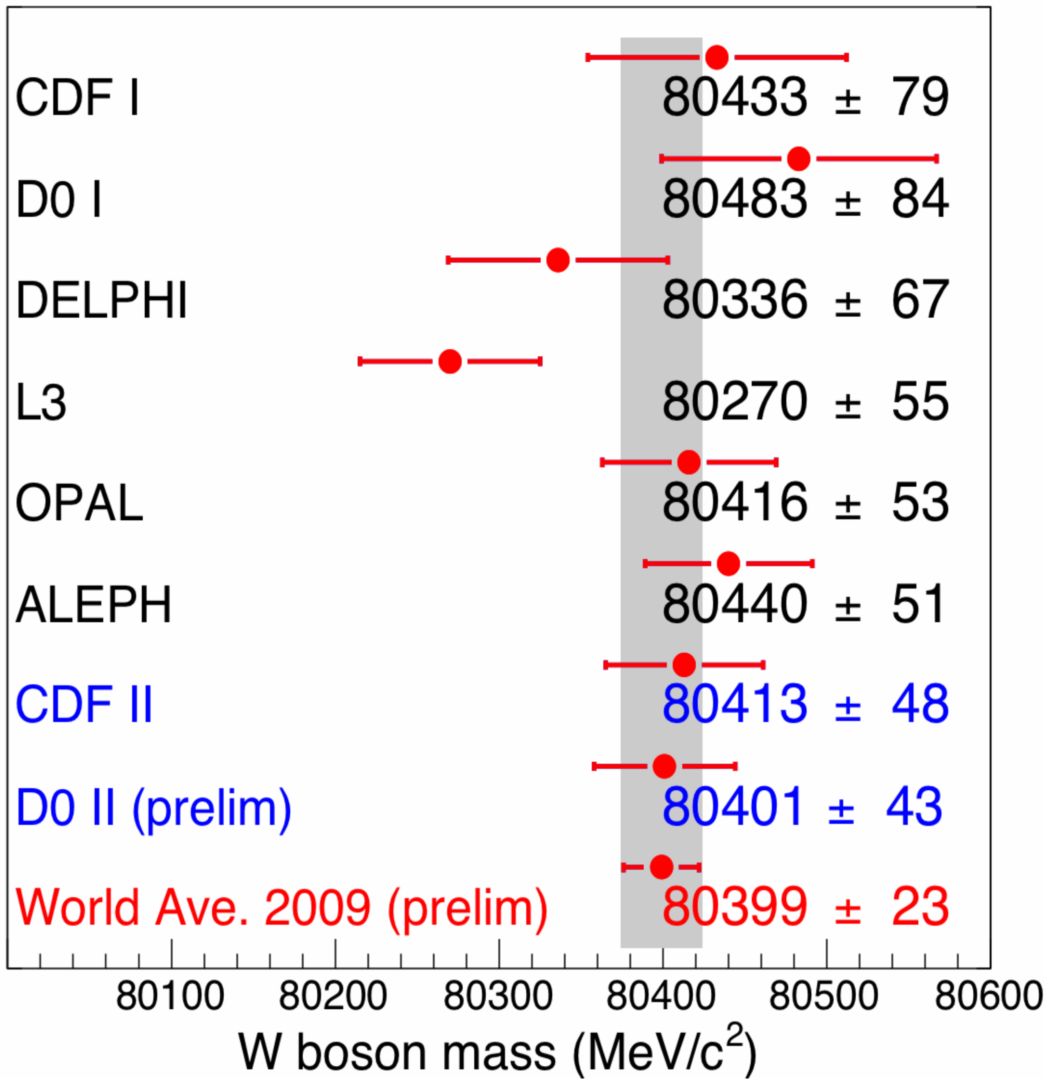
Systematic uncertainties shown in green: statistics-limited by control data samples

Tevatron Run 1 (100 pb^{-1}) *W* Mass Systematic Uncertainties (MeV)

	CDF μ	CDF e	D0 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
Γ(W)	10	10	10
Total	**144**	**113**	**84**

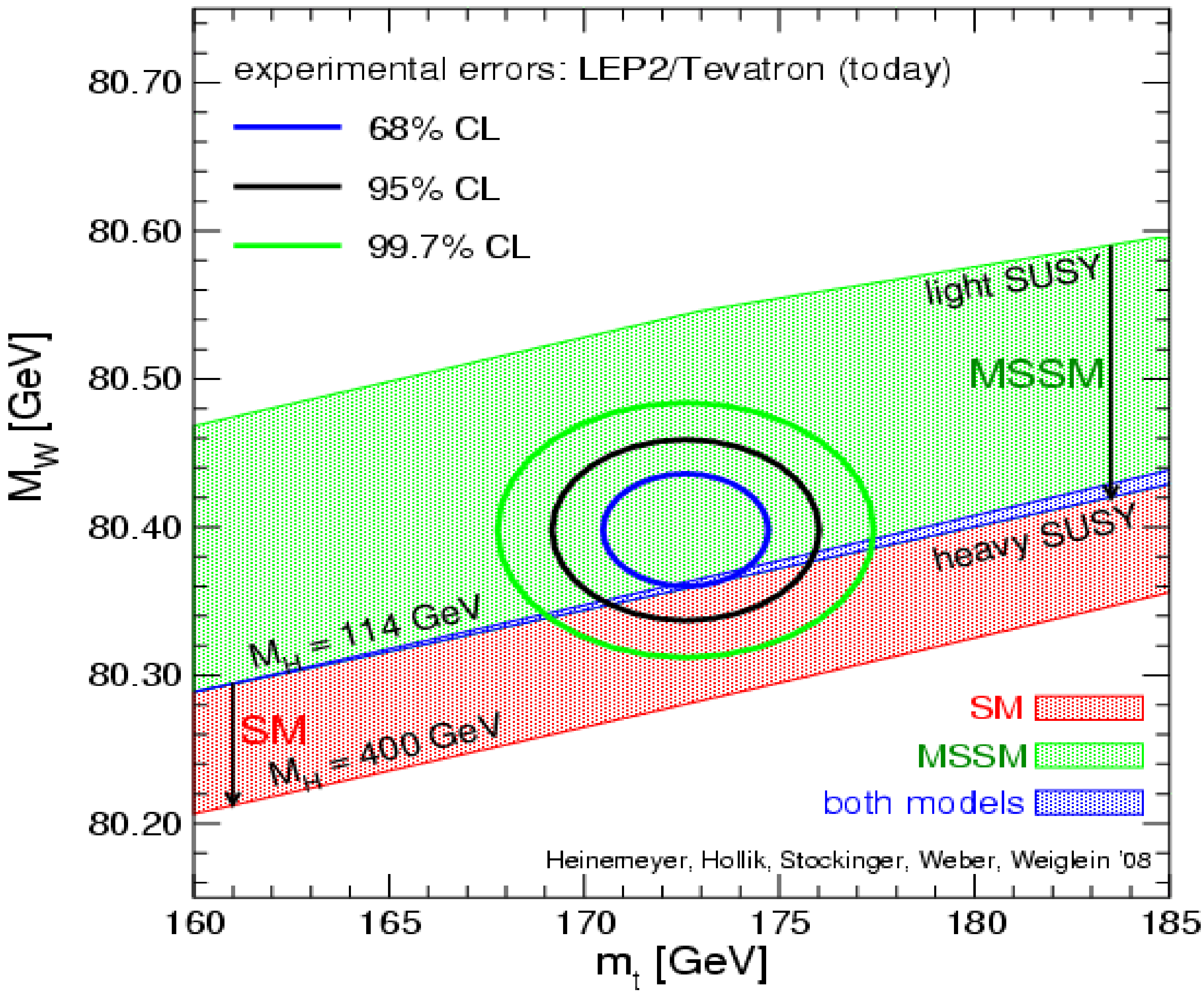
For comparison to run 2 analysis

Comparisons



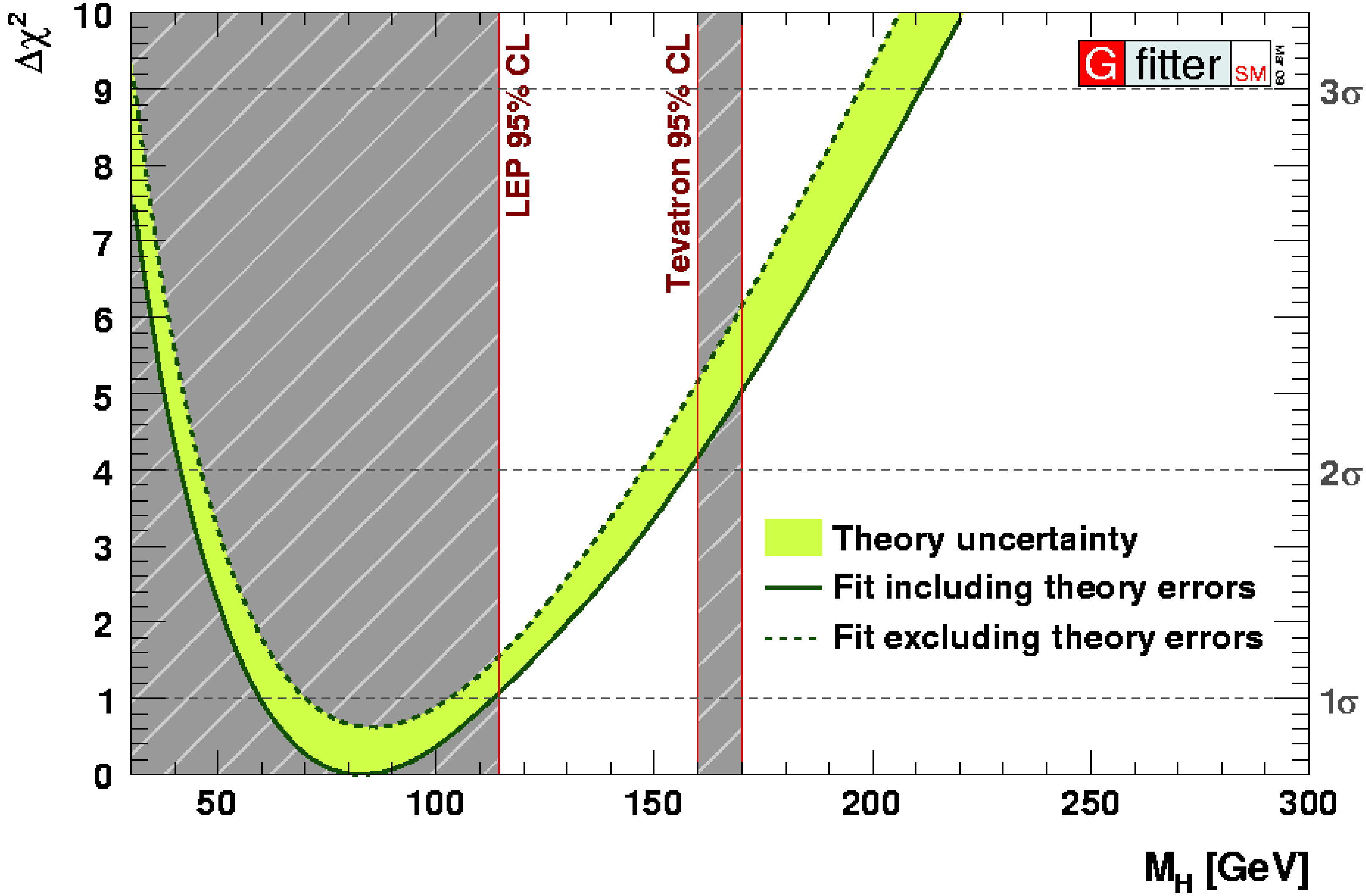
(CDF Run II: PRL 99:151801, 2007; PRD 77:112001, 2008)

M_W *vs* M_{top}

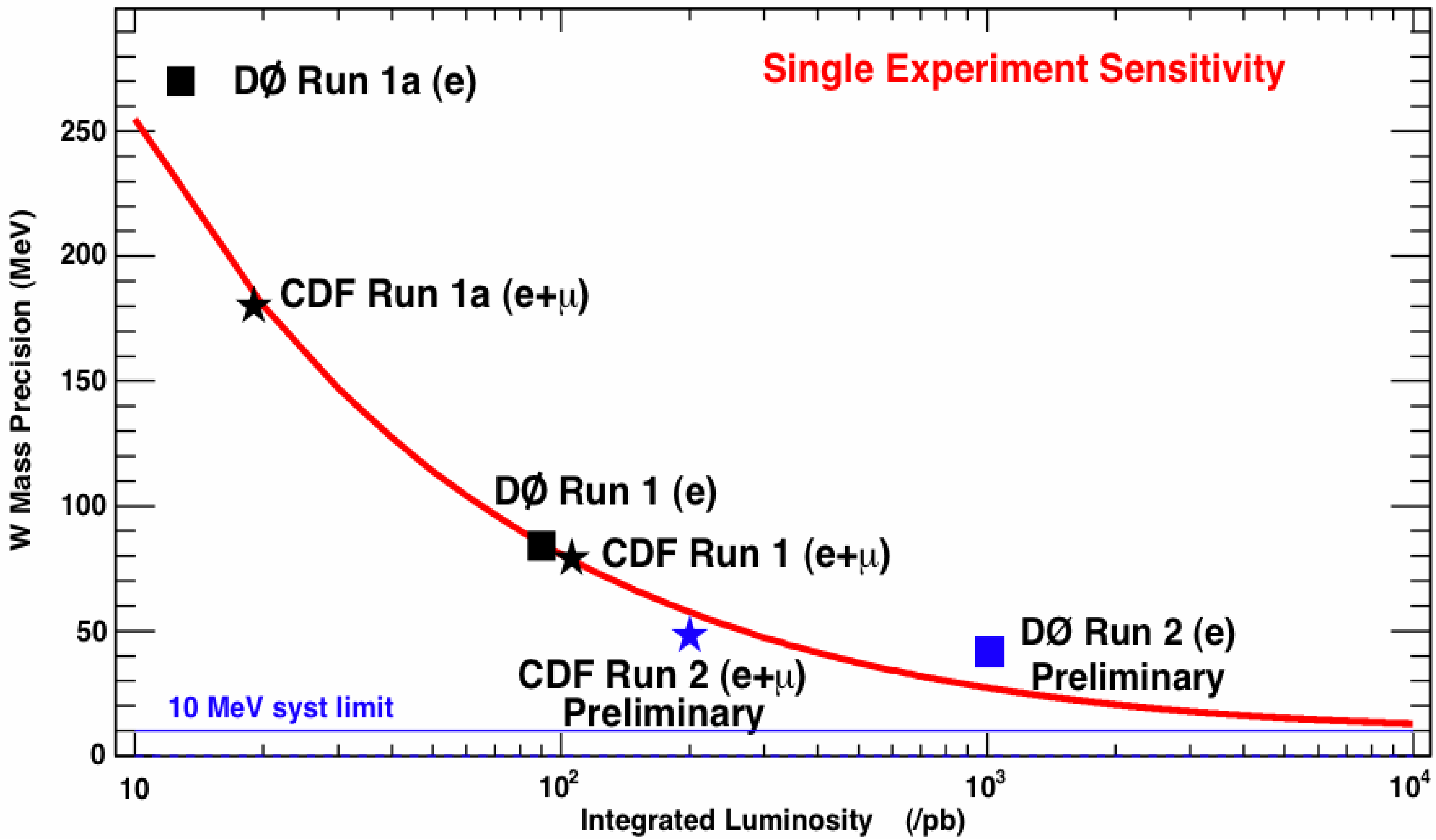


experimental errors: LEP2/Tevatron (today)
68% CL
95% CL
99.7% CL
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
SM
M_H = 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '08
80.70
80.60
80.50
80.40
80.30
80.20
M_W [GeV]
160
165
170
175
180
185
m_t [GeV]

Standard Model Higgs Constraints



Improvement of M_W Uncertainty with Sample Statistics

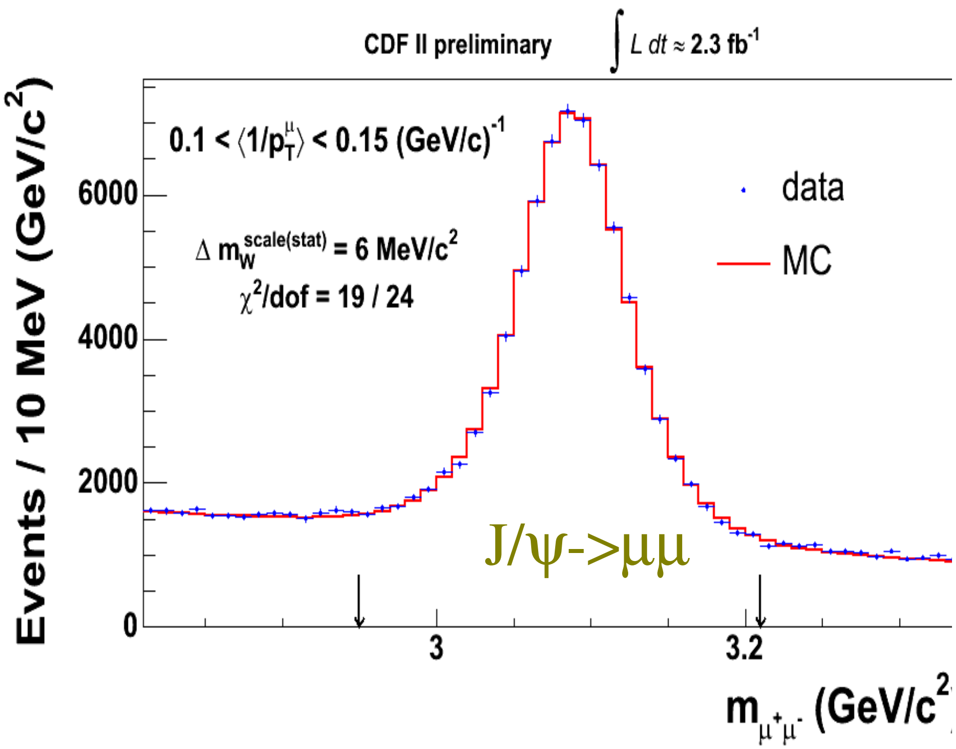


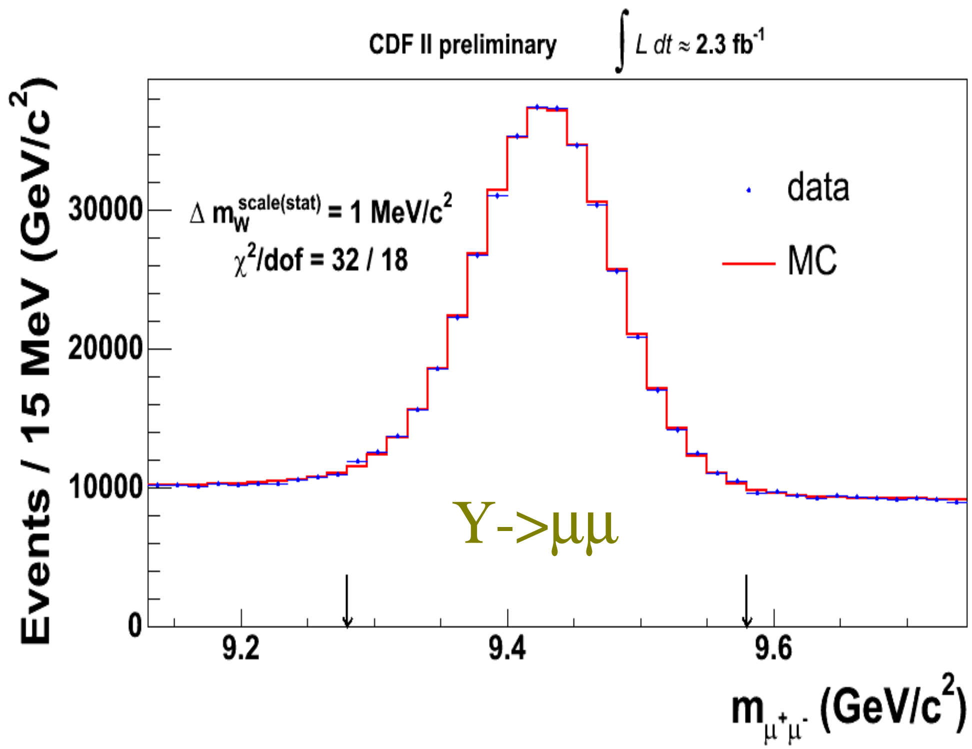
Preliminary Studies of 2.3 fb^{-1} Data

CDF has started the analysis of 2.3 fb^{-1} of data, with the goal of measuring M_W with precision better than 25 MeV

Tracker alignment with cosmic rays has been completed for this dataset

Lepton resolutions as good as they were in 200 pb^{-1} sample



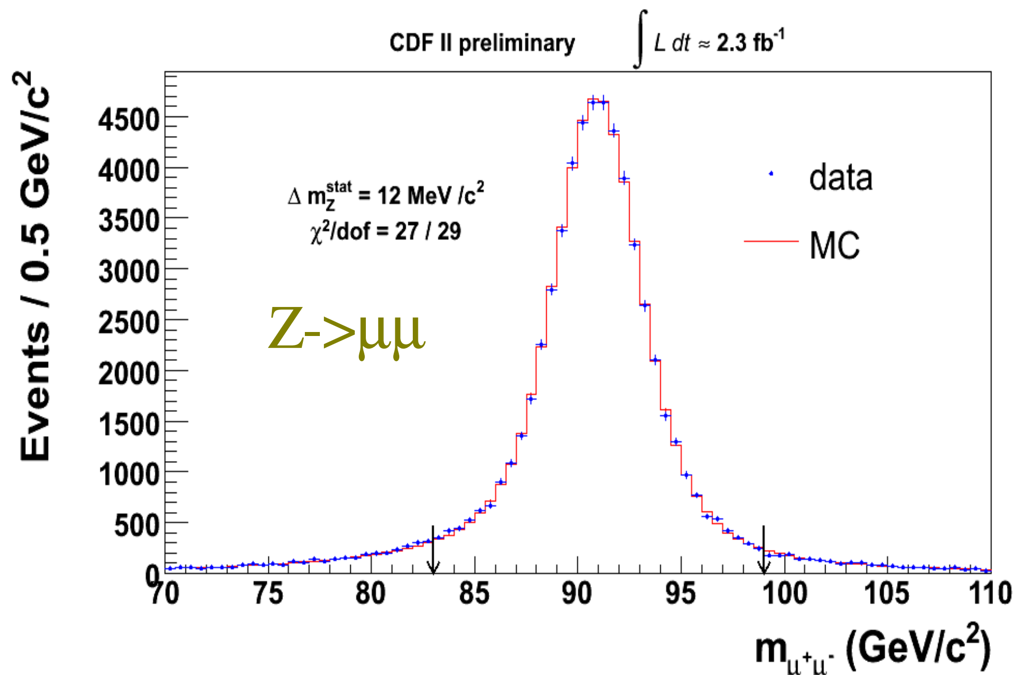


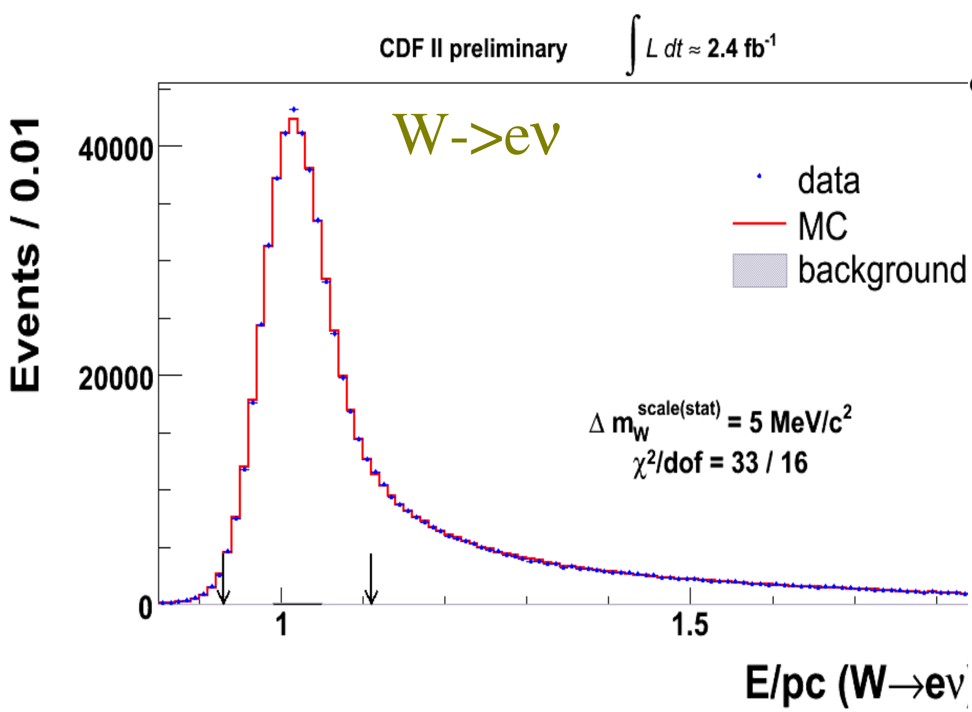
Preliminary Studies of 2.3 fb^{-1} Data

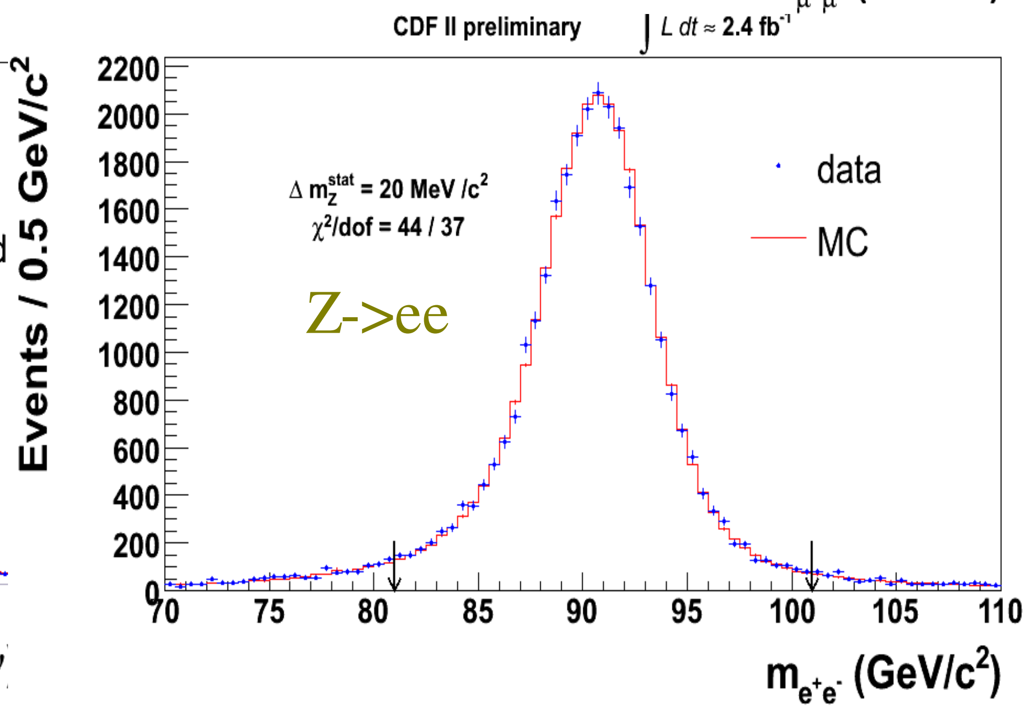
Statistical errors on all lepton calibration fits have scaled with statistics

Detector and data quality maintained over time

detailed calibrations in progress

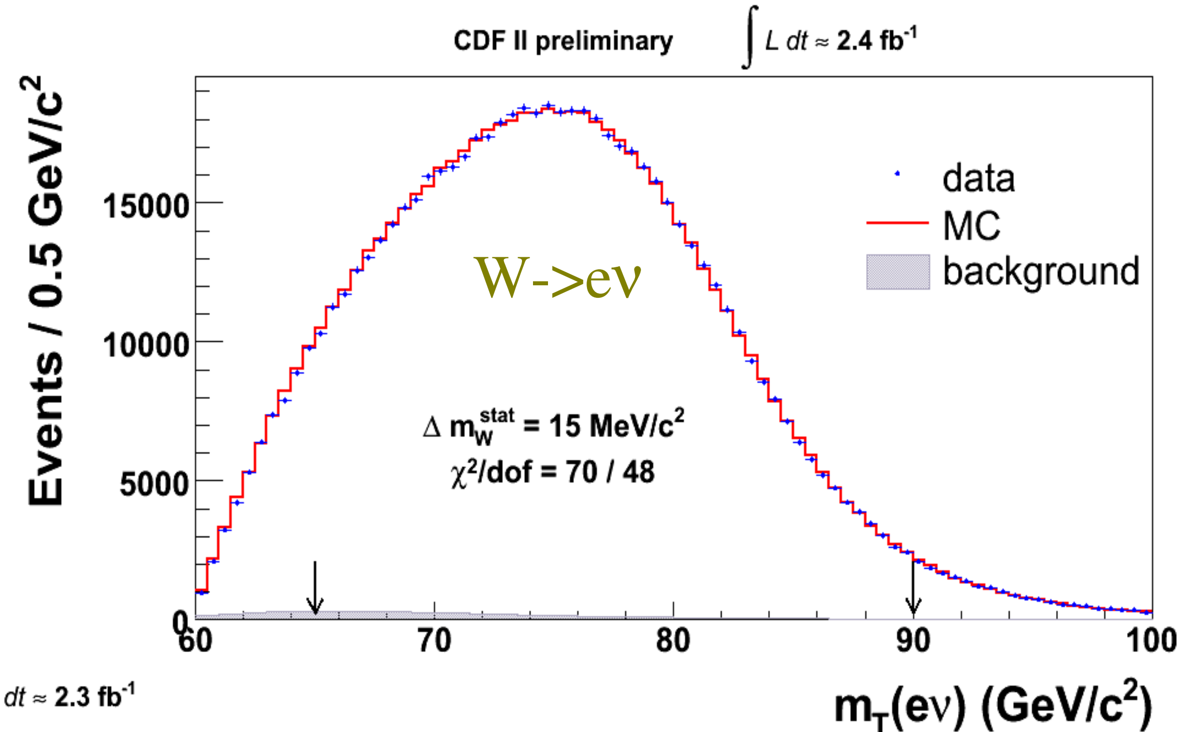


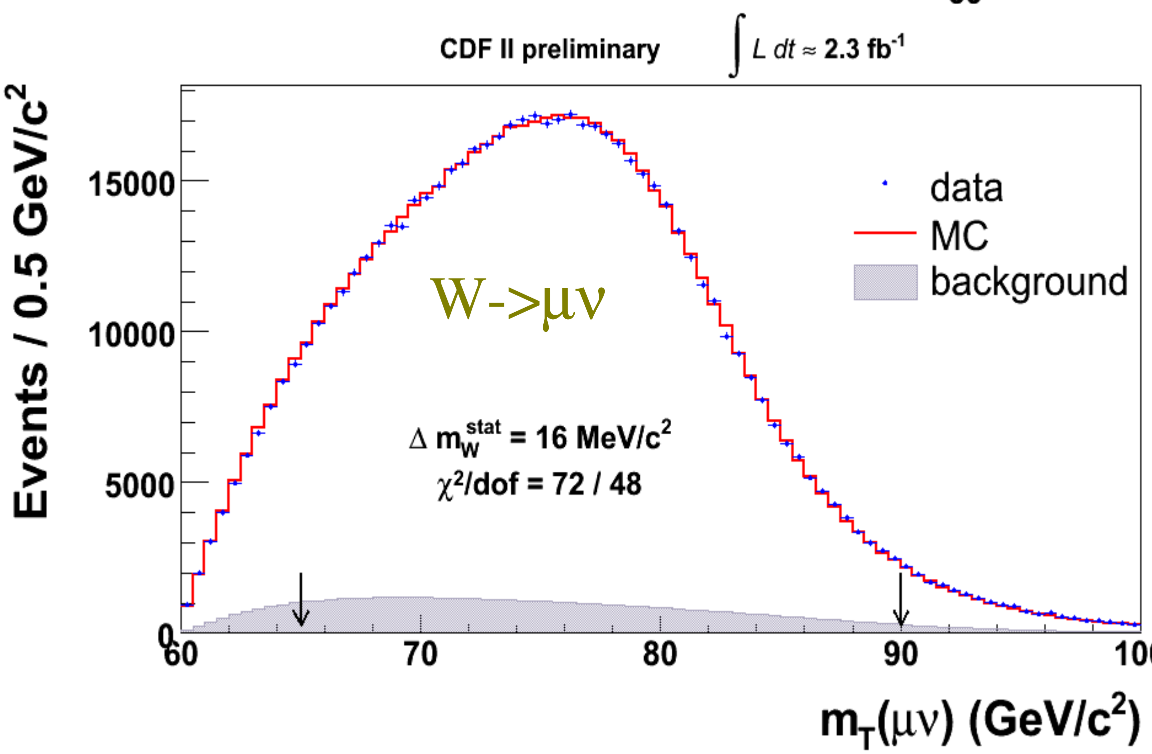




Preliminary Studies of 2.3 fb^{-1} Data

Recoil resolution not significantly degraded at higher instantaneous luminosity





statistical errors on transverse mass fits are scaling with statistics

Summary

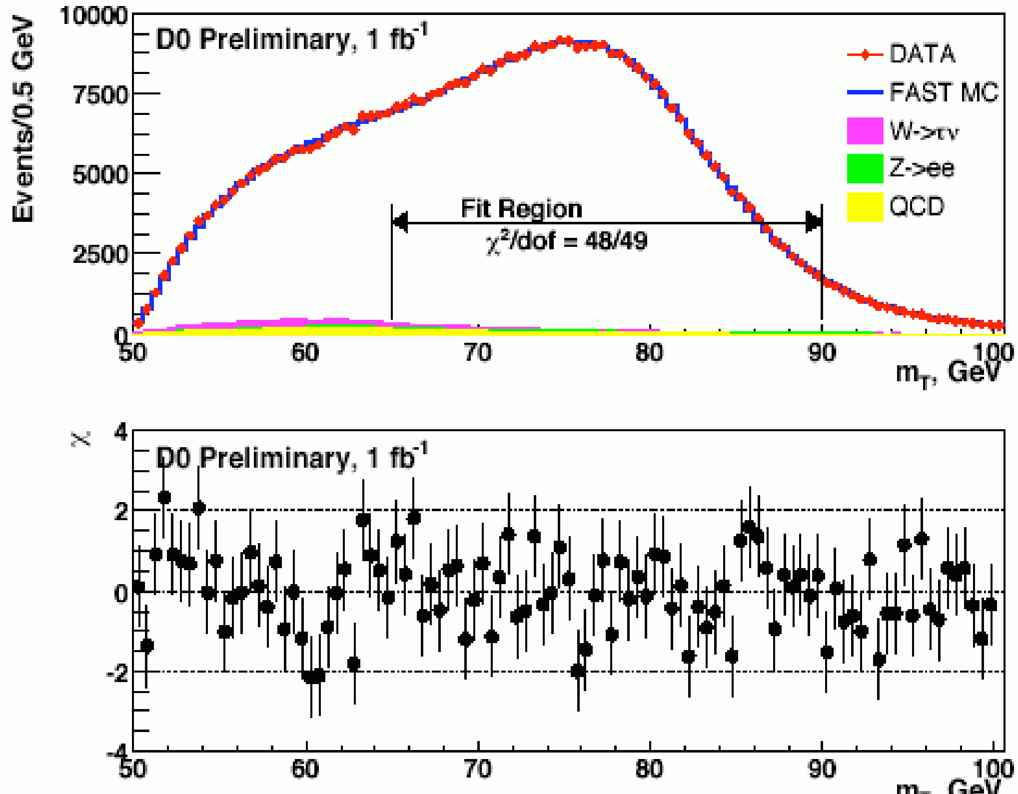
- The *W* boson mass is a very interesting parameter to measure with increasing precision

- CDF Run 2 W mass result with 200 pb^{-1} data:
  - $M_W = 80413 \pm 34_{stat} \pm 34_{syst}$ MeV
    $= 80413 \pm 48$ MeV

- D0 Run 2 W mass result with 1 fb^{-1} data:
  - $M_W = 80401 \pm 21_{stat} \pm 38_{syst}$ MeV
    $= 80401 \pm 43$ MeV

- Most systematics limited by statistics of control samples
  - CDF and D0 are both working on $\delta M_W < 25$ MeV measurements from ~ 2 fb^{-1} (CDF) and ~ 4 fb^{-1} (D0)

W mass measurement: DØ



m_T	80.401±0.044 GeV
p_T	80.400±0.048 GeV
missE_T	80.402±0.050 GeV

Source	$\sigma(m_W)$ MeV m_T
Experimental	
Electron Energy Scale	34
Electron Energy Resolution Model	2
Electron Energy Nonlinearity	4
W and Z Electron energy loss differences	4
Recoil Model	6
Electron Efficiencies	5
Backgrounds	2
Experimental Total	35
W production and decay model	
PDF	9
QED	7
Boson p_T	2
W model Total	12
Total	37

- Electron channel with 1 fb^{-1}
- Combines all 3 fits

m_W=80401±21(stat)±38(syst) MeV/c^2

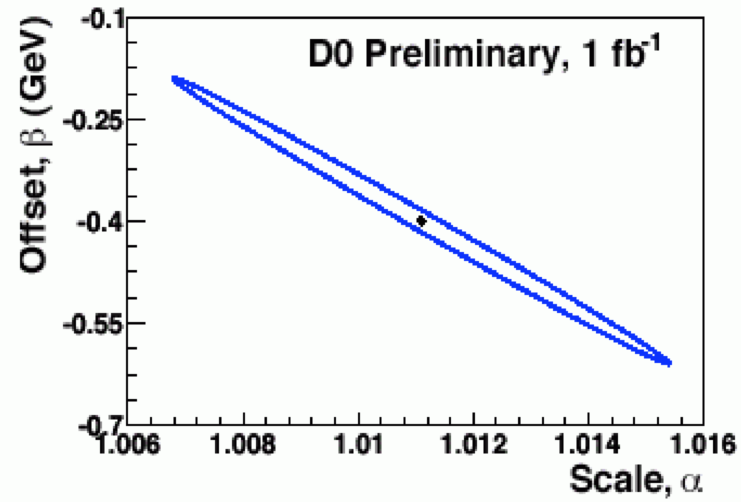
- **Single best** measurement of m_W
- Both CDF and DØ looking at larger datasets
  - ~25 MeV precision

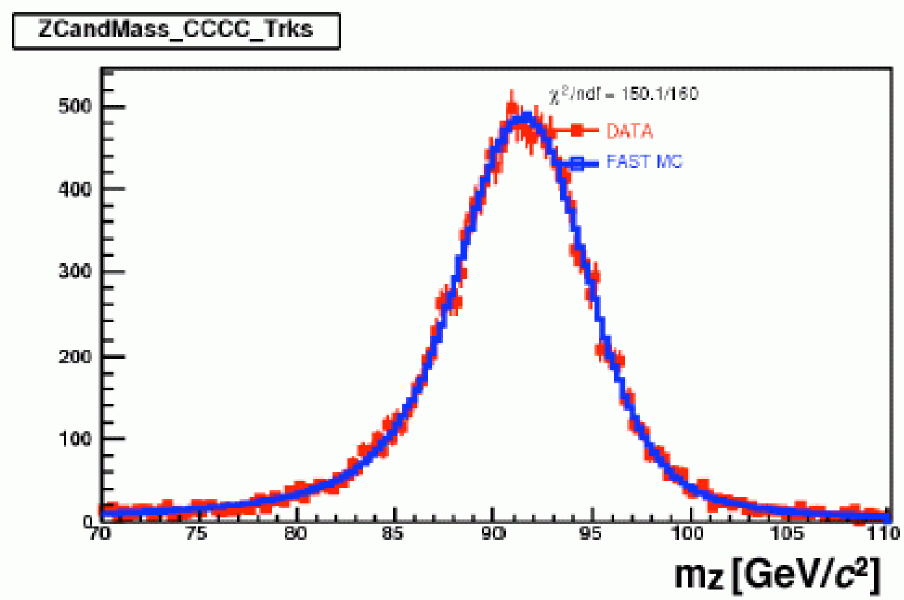
Energy scale and resolution at DØ

- Calibrate EM energy scale using $Z \to ee$ decays and LEP value for m_Z

$$R_{EM}(R_0) = \alpha \times E_0 + \beta$$

  - Δm_W=34 MeV
    - Dominant systematic, limited by Z statistics
- Parameterize energy resolution as constant term and sampling term
  - Sampling term driven by knowledge of amount of material in CAL
  - Constant term from Z peak
    - Obtain C=(2.05±0.1)%
  - Δm_W=2 MeV





E/p Calibration *vs* $Z \rightarrow ee$ mass consistency

- Inclusion of hadronic calorimeter leakage distribution has a ~150 MeV effect on the fitted EM calorimeter scale from the E/p distribution

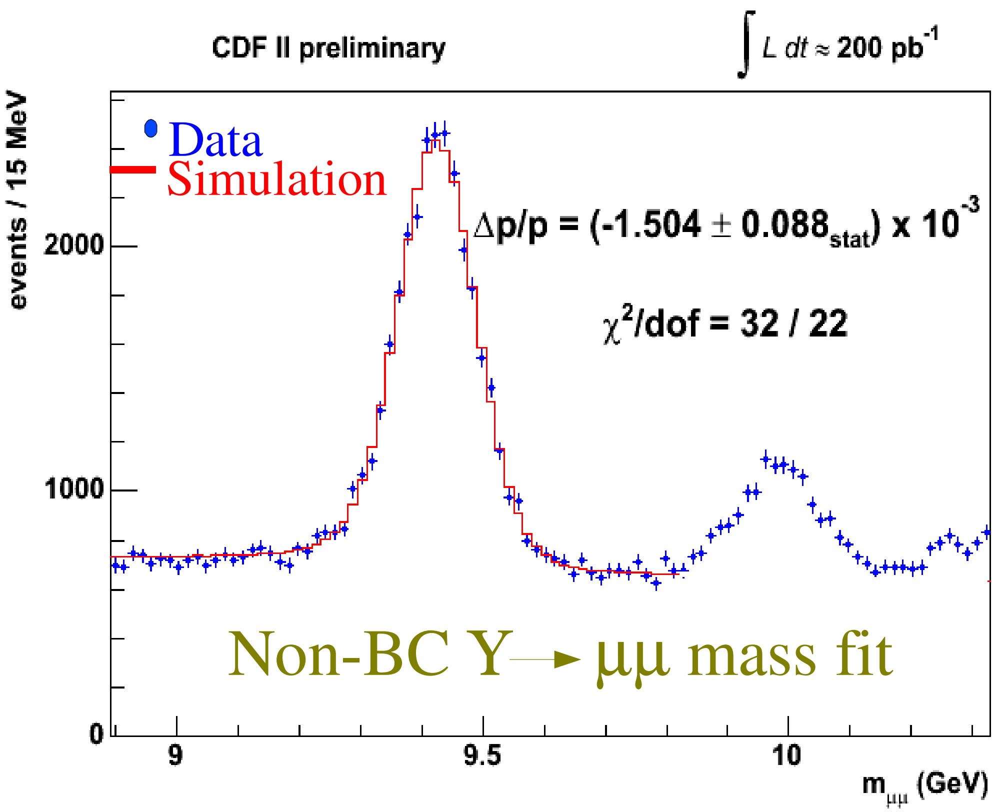
- Modelling the bremsstrahlung spectrum down to 4 MeV (from 40 MeV cutoff) has a ~60 MeV effect on the E/p calibration

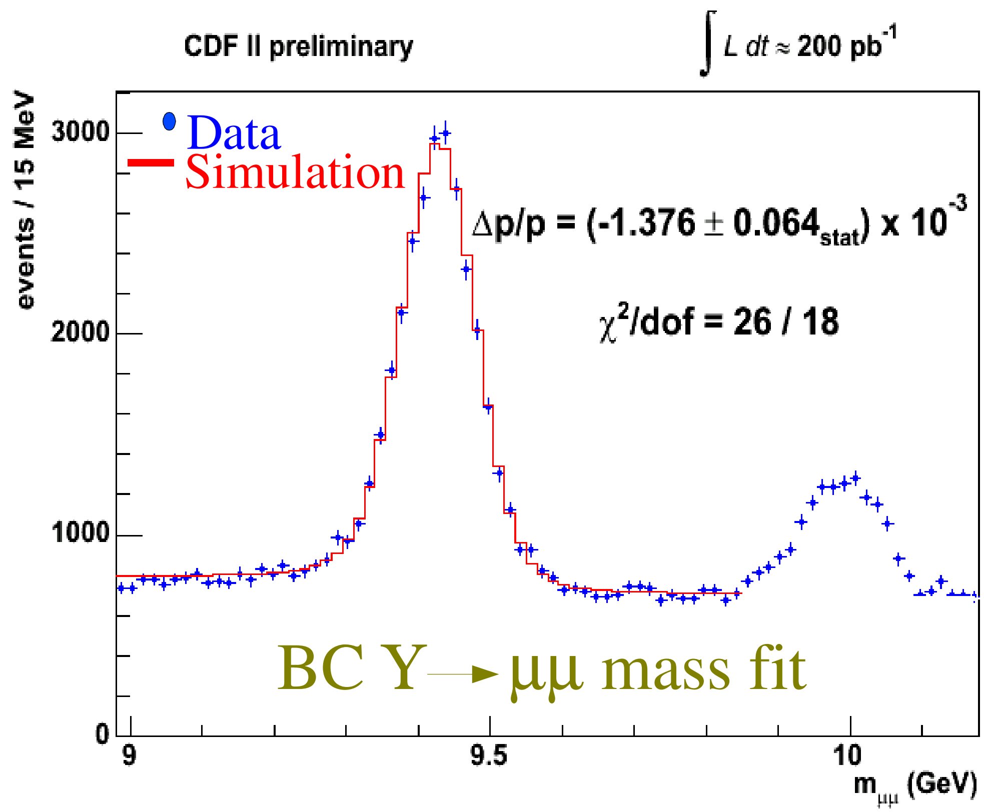
- Modelling the calorimeter non-linearity as a property of individual particles has a ~30 MeV effect

- Collectively, these simulated effects in the Run 2 analysis affect the consistency of the Z mass by ~240 MeV

Tracking Momentum Scale

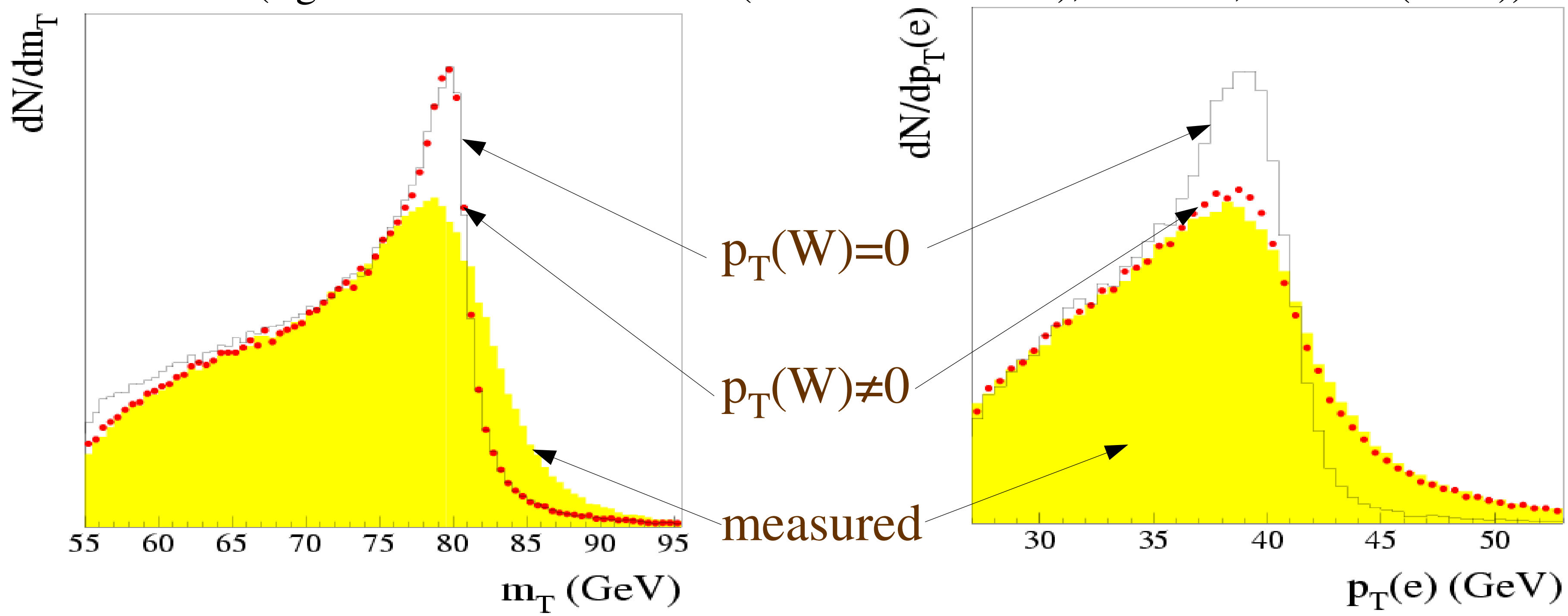
- Υ → μμ resonance provides
  - Momentum scale measurement at higher p_T
  - Validation of beam-constaining procedure (upsilons are promptly produced)
  - Non-beam-constrained and beam-constrained fits statistically consistent





W Mass Measurement at the Tevatron

(figures from Abbott *et. al.* (D0 Collaboration), PRD 58, 092003 (1998))



W mass information contained in location of transverse Jacobian edge

$M_T = \sqrt{(2\, p_T^{\,l}\, p_T^{\,\nu}\, (1 - \cos\phi_{l\nu})}$

Insensitive to $p_T(W)$ to first order

Reconstruction of $p_T^{\,\nu}$ sensitive to hadronic response and multiple interactions

$p_T(l)$ fit: provides cross-check of production model:

Needs theoretical model of $p_T(W)$

$P_T(\nu)$ fit provides cross-check of hadronic modelling

Lepton Resolutions

- Tracking resolution parameterized in the fast Monte Carlo by
  - Drift chamber hit resolution $\sigma_h = 150 \pm 3_{stat}$ μm
  - Beamspot size $\sigma_b = 39 \pm 3_{stat}$ μm
  - Tuned on the widths of the $Z \rightarrow \mu\mu$ (beam constrained) and $\Upsilon \rightarrow \mu\mu$ (both beam constrained and non-beam constrained) mass peaks

=> $\Delta M_W = 3$ MeV (muons)

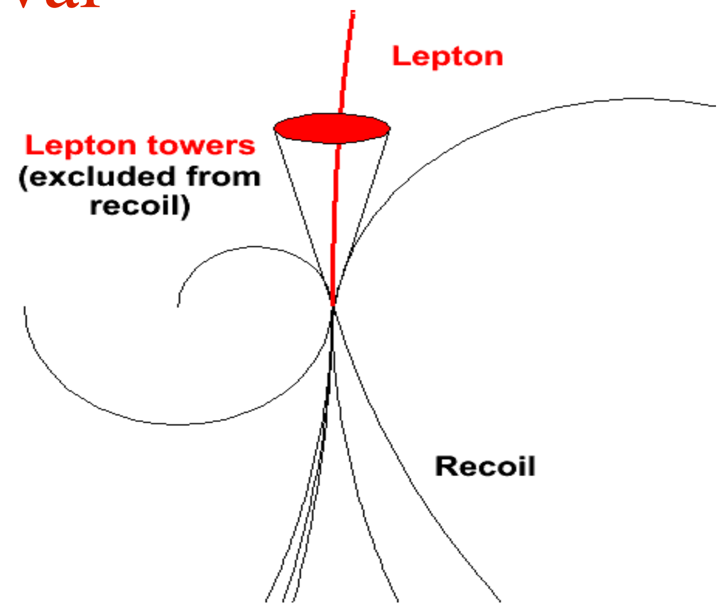
- Electron cluster resolution parameterized in the fast Monte Carlo by
  - $13.5\% / \sqrt{E_T}$ (sampling term)
  - Primary constant term $\kappa = 0.89 \pm 0.15_{stat}$ %
  - Secondary photon resolution $\kappa_\gamma = 8.3 \pm 2.2_{stat}$ %
  - Tuned on the widths of the E/p peak and the $Z \rightarrow ee$ peak (selecting radiative electrons)

=> $\Delta M_W = 9$ MeV (electrons)

Lepton Tower Removal

- We remove the calorimeter towers containing lepton energy from the hadronic recoil calculation
  - Lost underlying event energy is measured in ϕ-rotated windows

$\Delta M_W = 8$ MeV



Electron channel W data

Electron Electromagnetic E_T (MeV)

Tower Δη (η) \ Tower Δϕ (ϕ)	-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

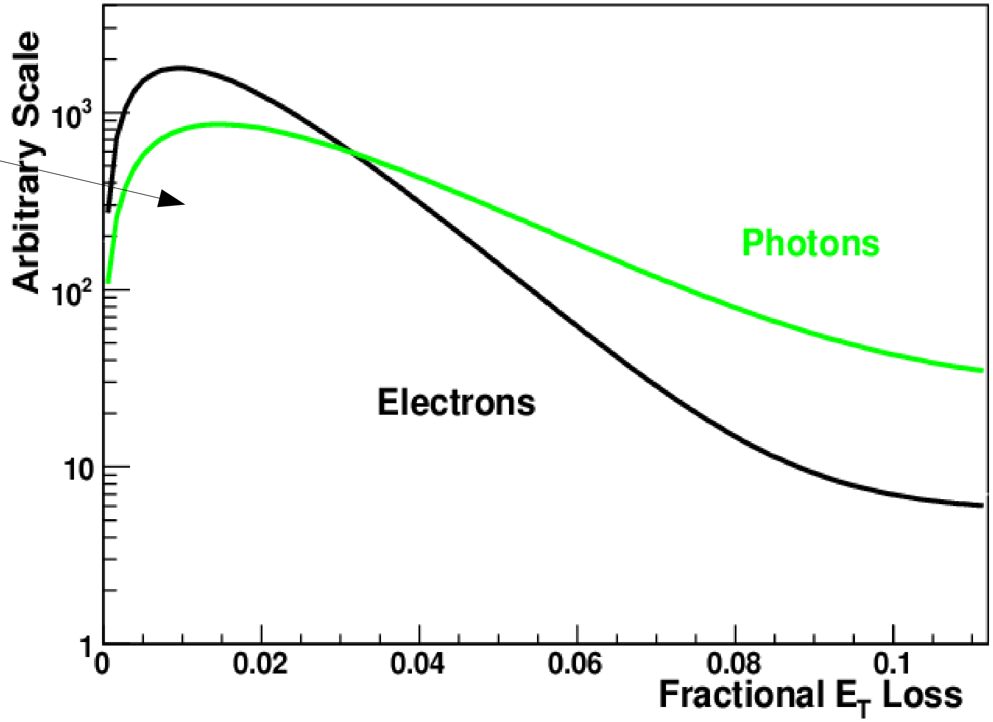
Muon channel W data

Muon Hadronic E_T (MeV)

Tower Δη (η) \ Tower Δϕ (ϕ)	-3	-2	-1	0	1	2	3
3	8	7	8	8	8	8	8
2	7	7	8	9	8	8	8
1	8	8	8	432	9	8	8
0	9	8	9	1255	11	8	8
-1	8	9	9	83	9	8	8
-2	8	8	8	8	8	7	8
-3	8	8	8	7	8	9	8

Calorimeter Simulation for Electrons and Photons

- Distributions of energy loss calculated based on expected shower profiles as a function of E_T
  - Leakage into hadronic calorimeter
  - Absorption in the coil
  - Relevant for E/p lineshape



- Energy-dependent gain (non-linearity) parameterized and fit from data
- Energy resolution parameterized as fixed sampling term and two tunable constant terms
  - Constant terms are fit from the width of E/p peak and $Z \rightarrow ee$ mass peak

Combined Results

- Combined electrons (3 fits): $M_W = 80477 \pm 62$ MeV, $P(\chi^2) = 49\%$
- Combined muons (3 fits): $M_W = 80352 \pm 60$ MeV, $P(\chi^2) = 69\%$
- All combined (6 fits): $M_W = 80413 \pm 48$ MeV, $P(\chi^2) = 44\%$

Lepton p_T and Missing E_T Fit Uncertainties

CDF II preliminary

Uncertainty (p_T)	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	17	17	17
Recoil Resolution	3	3	3
Lepton Removal	0	0	0
$u_{\|}$ Efficiency	5	6	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

Uncertainty (MET)	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	5	0
Recoil Scale	15	15	15
Recoil Resolution	30	30	30
Lepton Removal	16	10	10
$u_{\|}$ Efficiency	16	13	0
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

Backgrounds in the W sample

Source	Fraction (*electrons*)	Fraction (*muons*)
Z -> *ll*	0.24 ± 0.04 %	6.6 ± 0.3 %
W -> $\tau\nu$	0.93 ± 0.03 %	0.89 ± 0.02 %
Mis-identified QCD jets	0.25 ± 0.15 %	0.1 ± 0.1 %
Decays-in-flight		0.3 ± 0.2 %
Cosmic rays		0.05 ± 0.05 %

Backgrounds are small (except $Z \rightarrow \mu\mu$ with a forward muon)

backgrounds contribute systematic uncertainty of 9 MeV on transverse mass fit