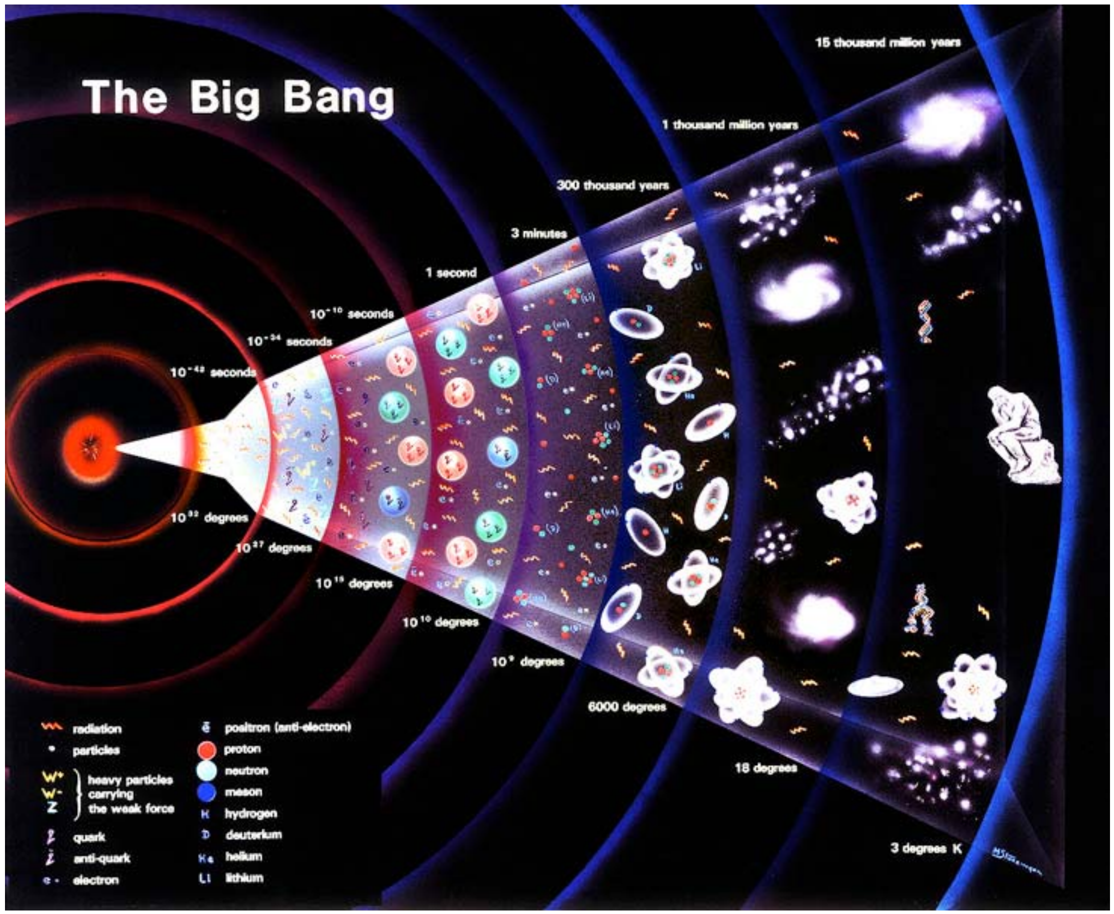
Measurement of the W Boson Mass at CDF

Ashutosh Kotwal
Duke University



Riken Brookhaven Research Center Workshop
June 24-25, 2010

Spontaneous Symmetry Breaking

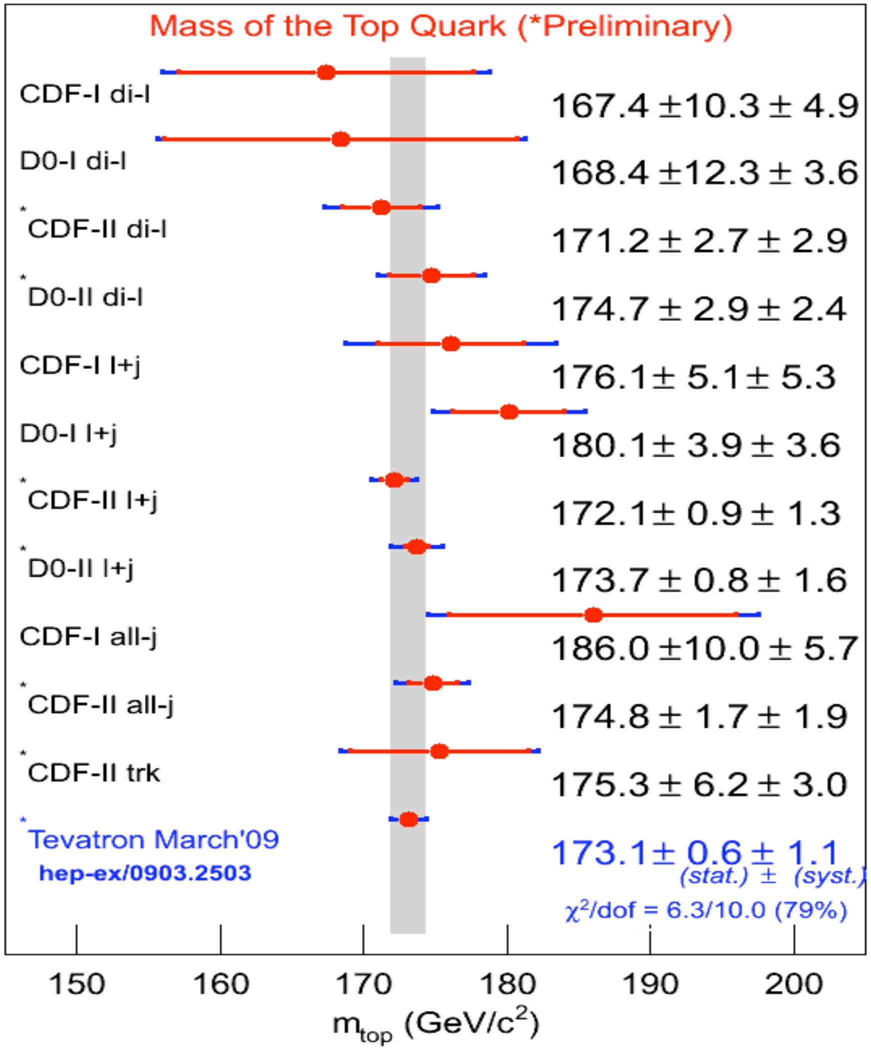
- 2008 Nobel Prize in Physics

  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"

Yoichiro Nambu

- Experimentally, jury is still out on Higgs mechanism of Electroweak Symmetry Breaking in the Standard Model of Particle Physics

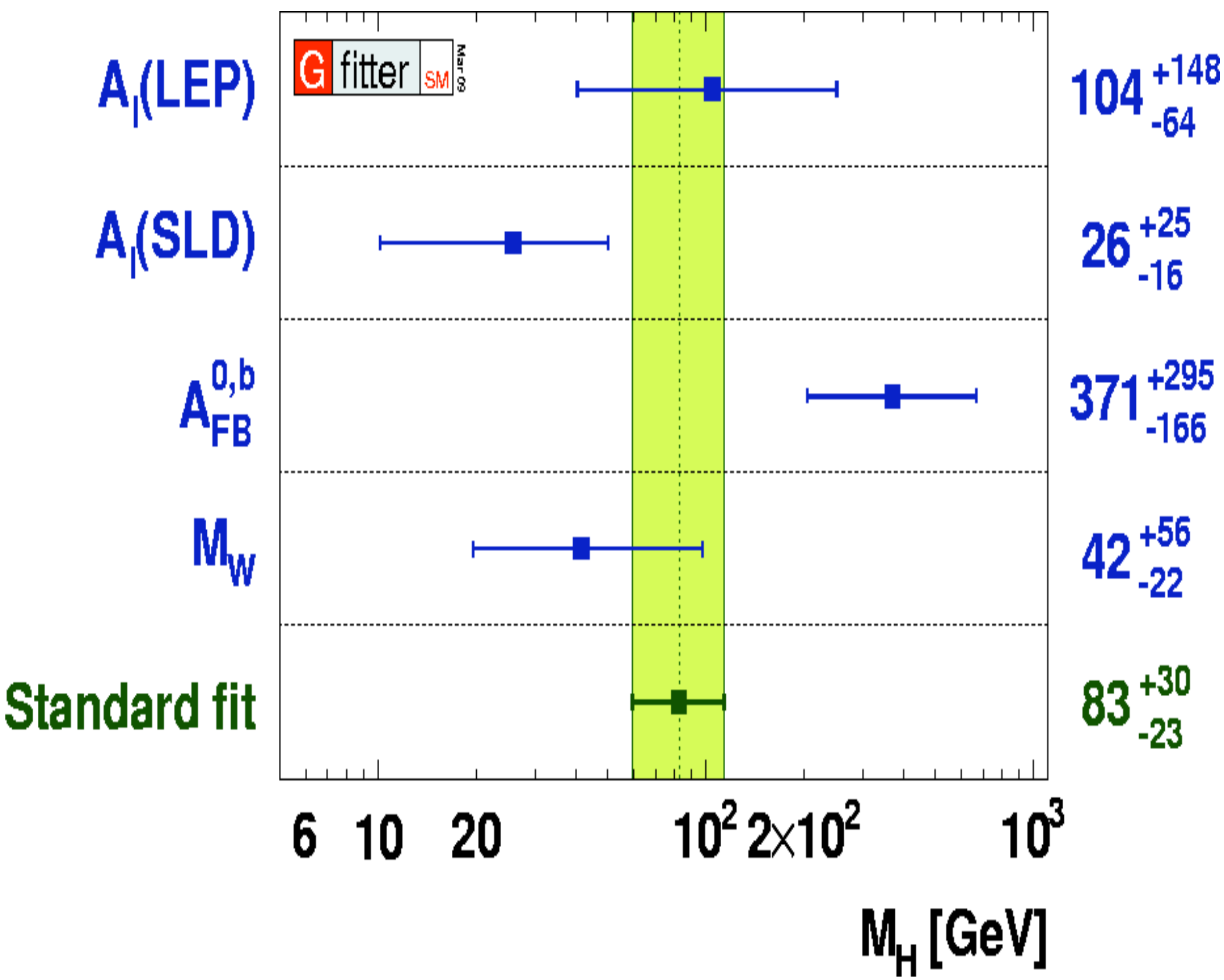
Progress on M_{top} at the Tevatron



- From the Tevatron, δM_{top} = 1.3 GeV => δM_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 II

- 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 and better

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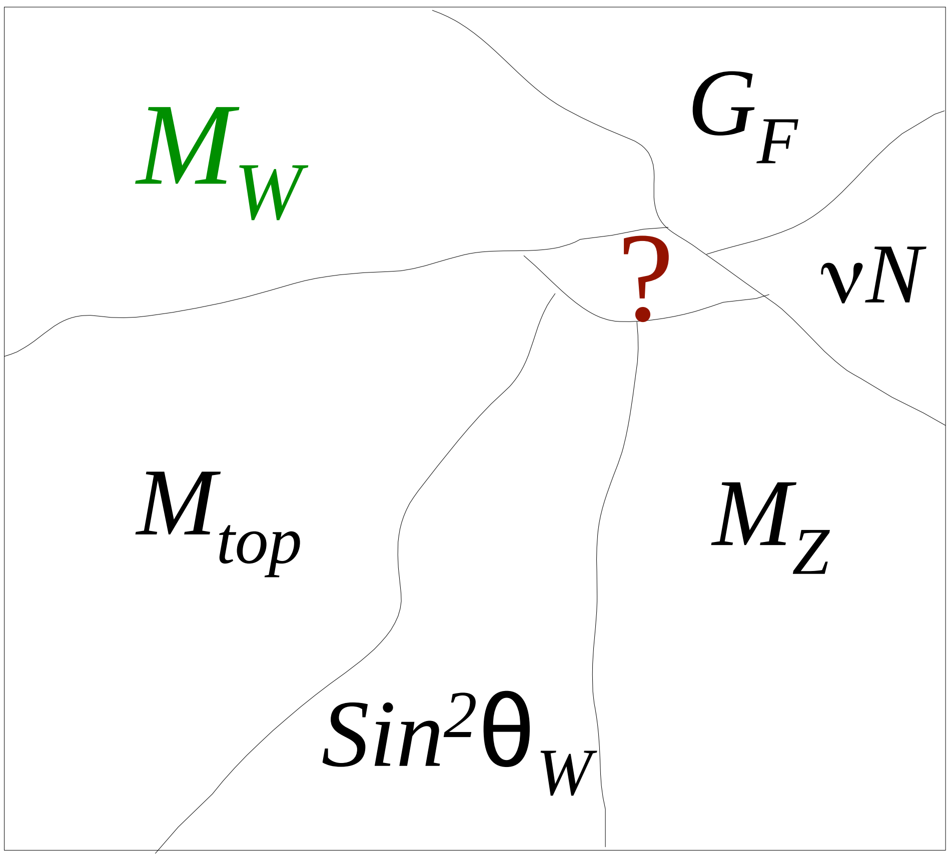

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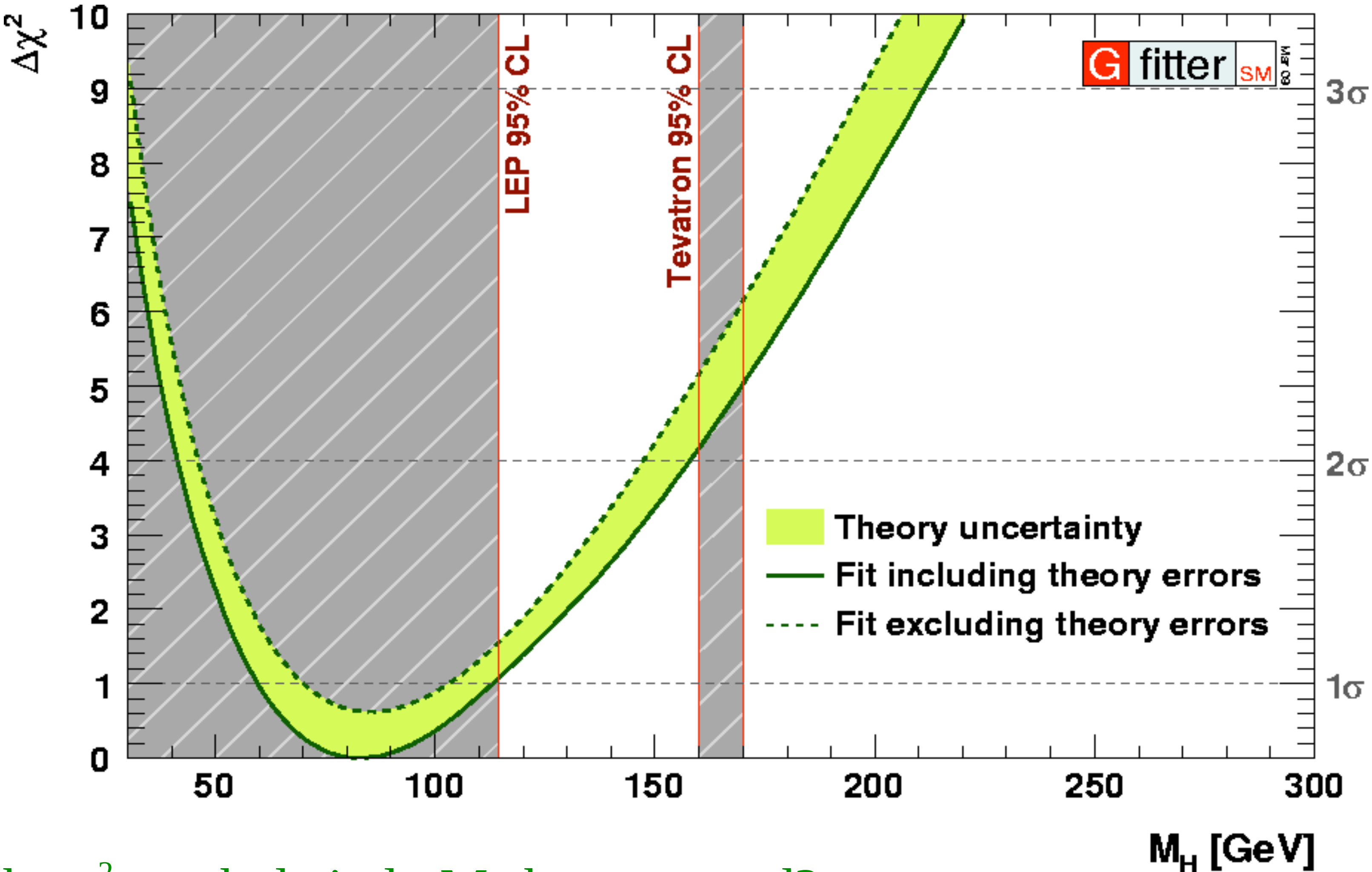
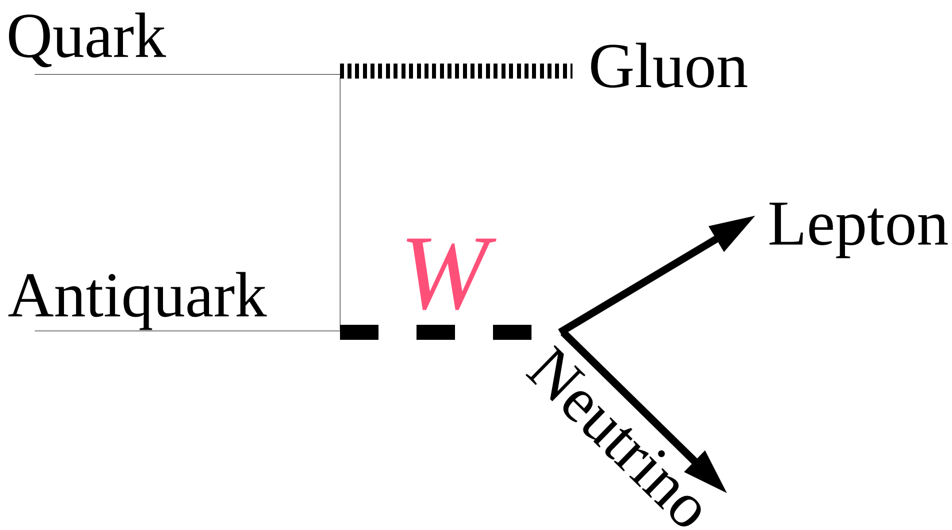
Current Higgs Constraint from SM Electroweak Fit

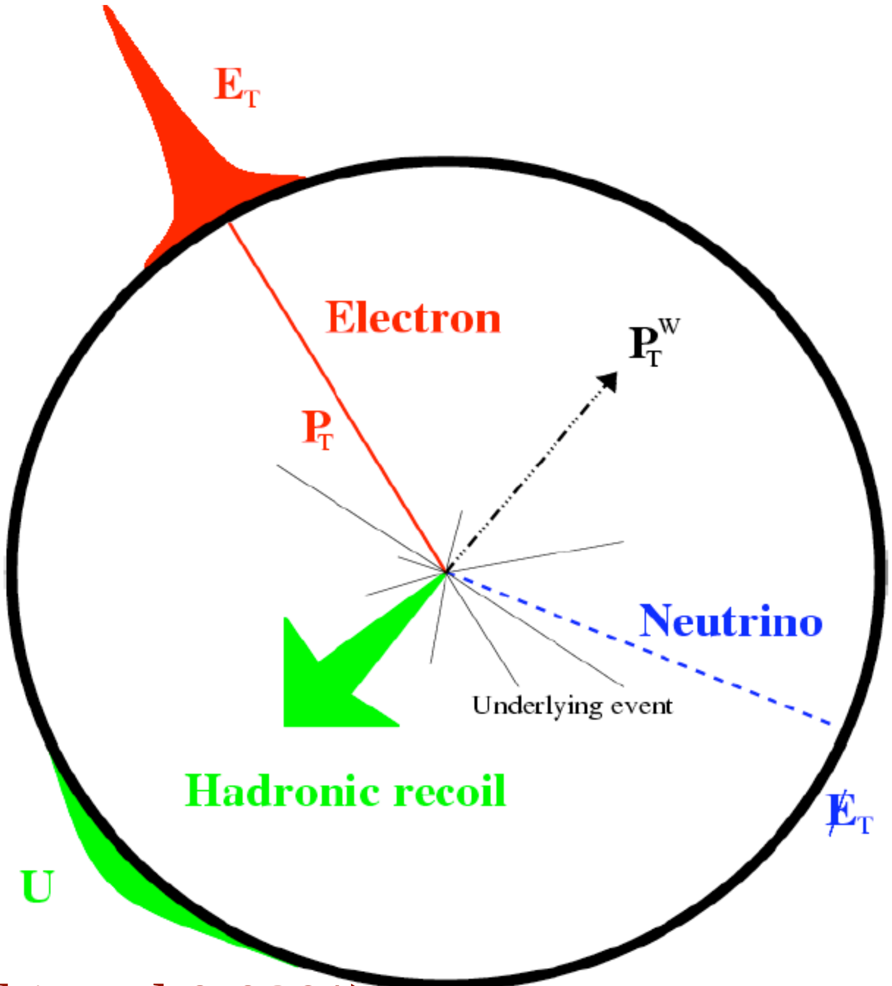


- Can the χ^2 parabola in ln M_H be narrowed?
- Where will it minimize in the future?
- Will Tevatron exclude the Higgs in the preferred (M_H<200 GeV) range?
- Will LHC see the (SM or non-SM) Higgs inside or outside the preferred mass range?

W Mass 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 $p_T(W) << M_W$

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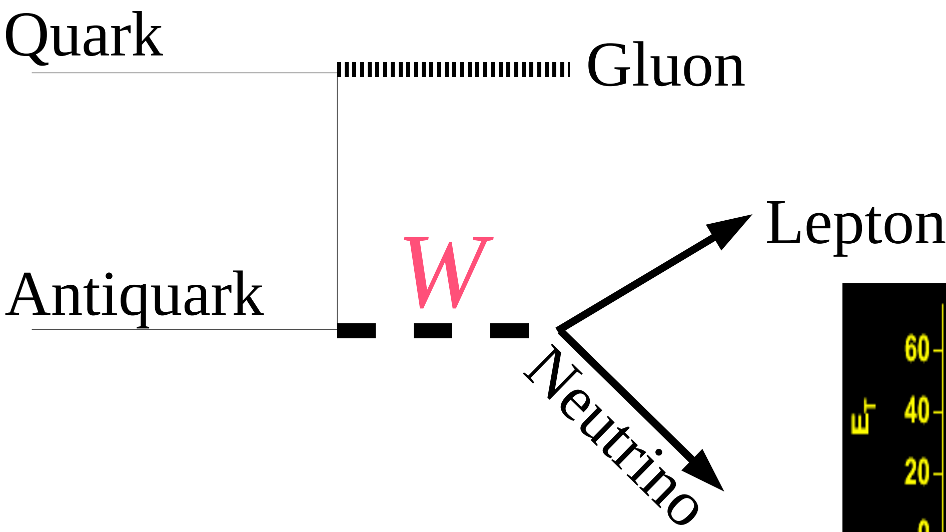

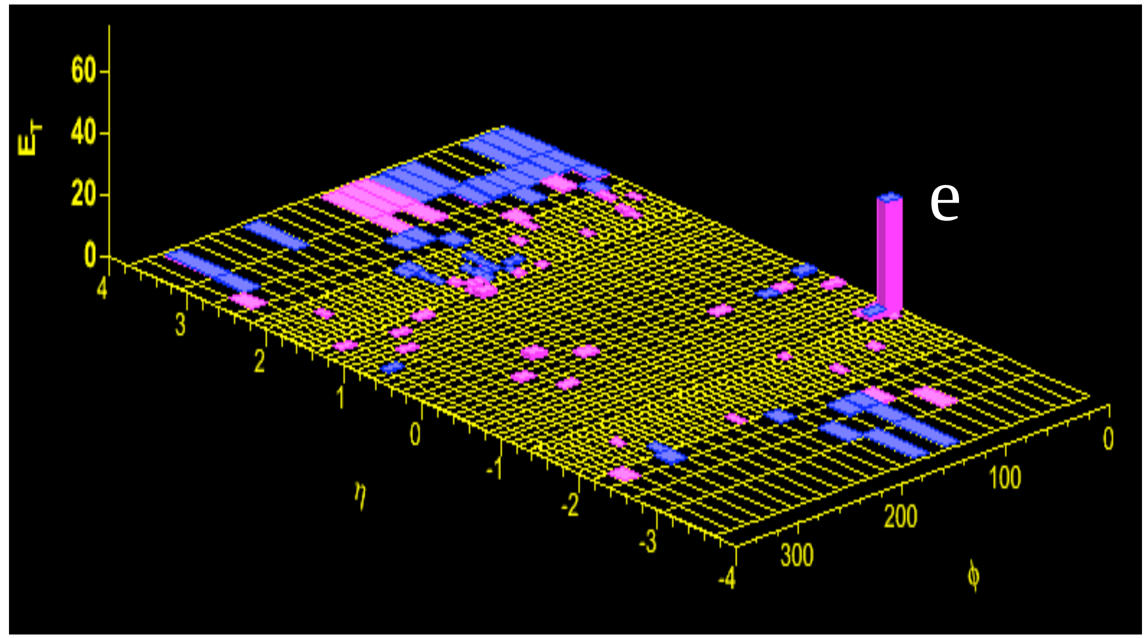

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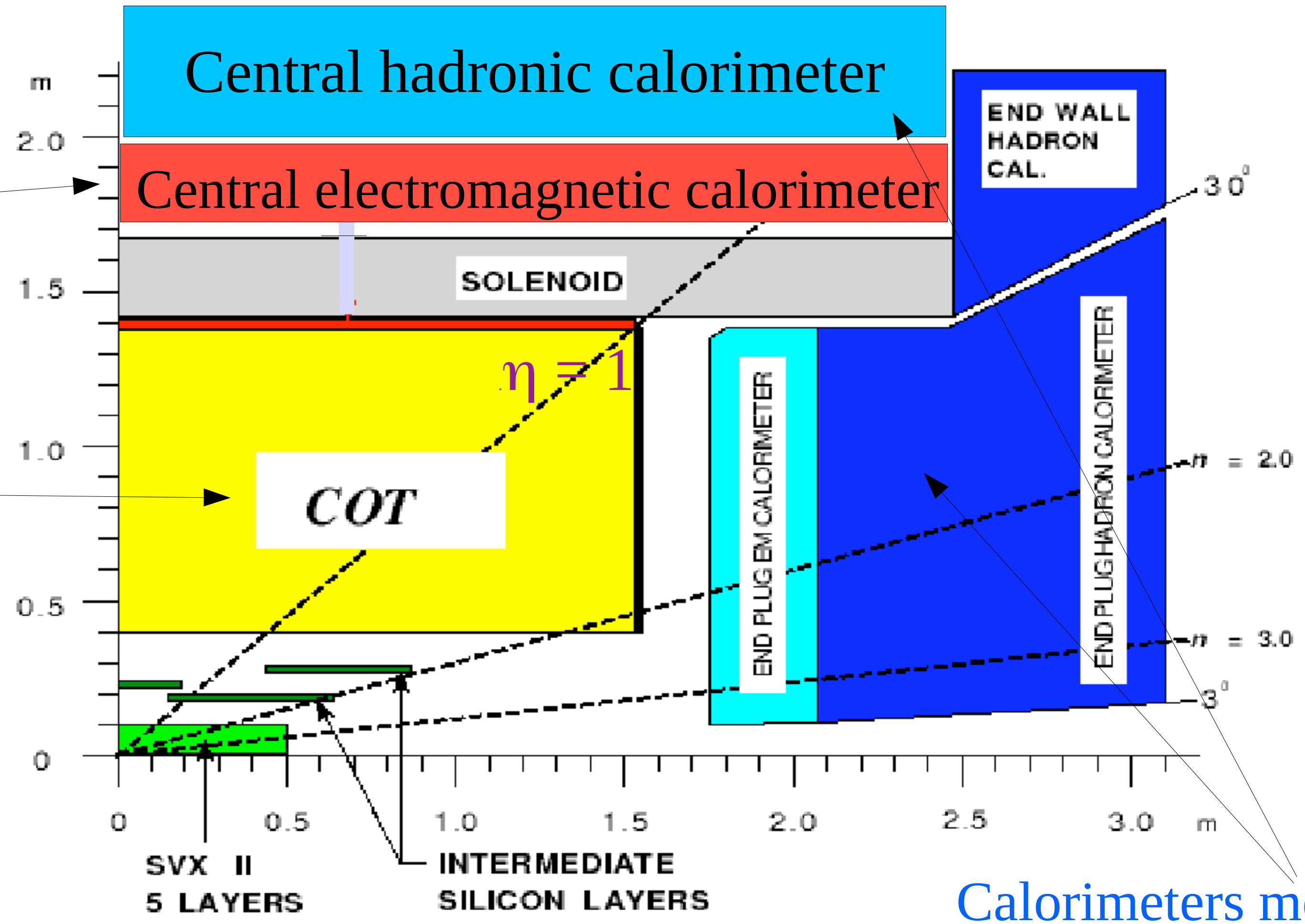
Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

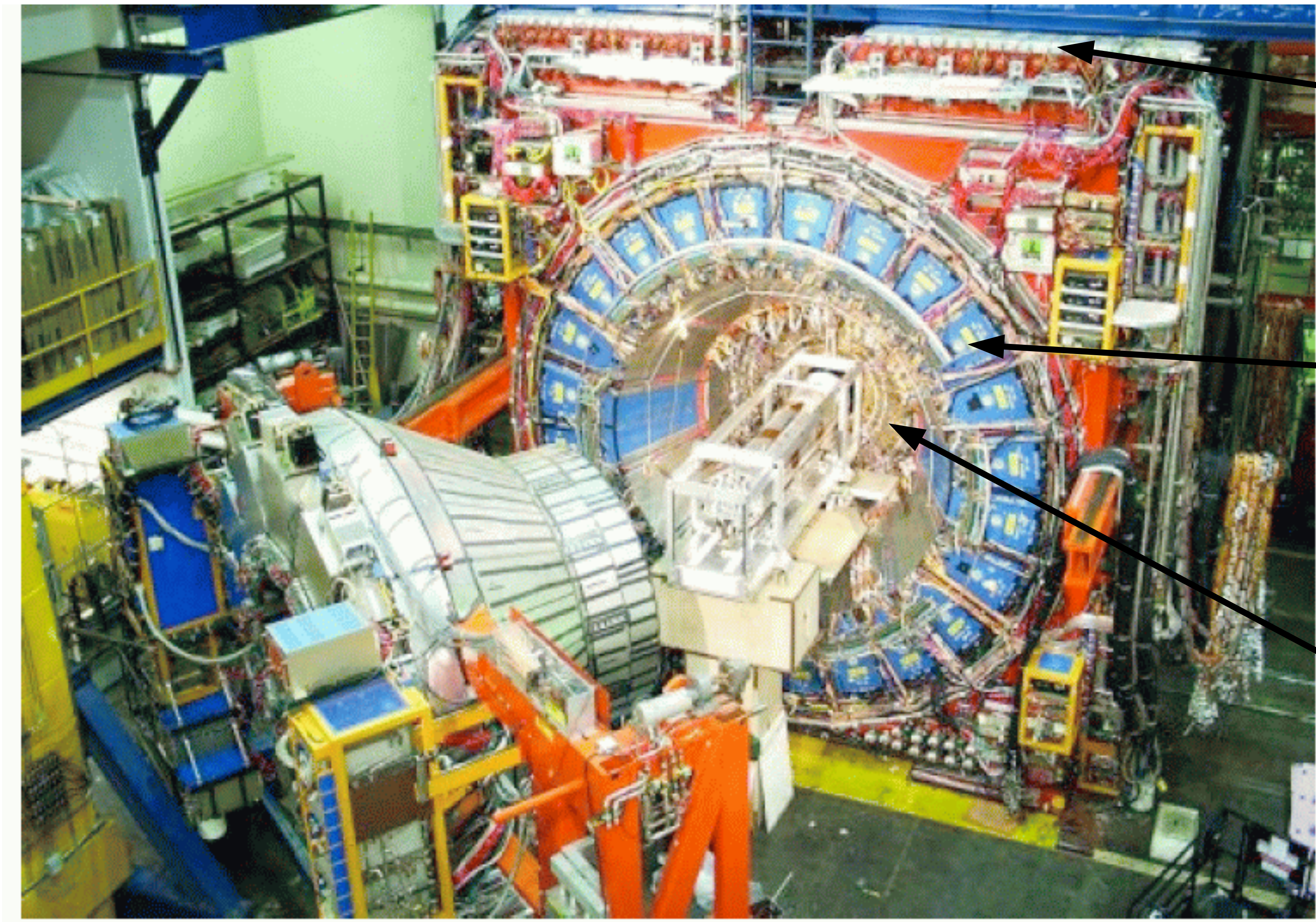
COT provides precise lepton track momentum measurement



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: L = 218 pb^{-1}
  - Muon channel: 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%

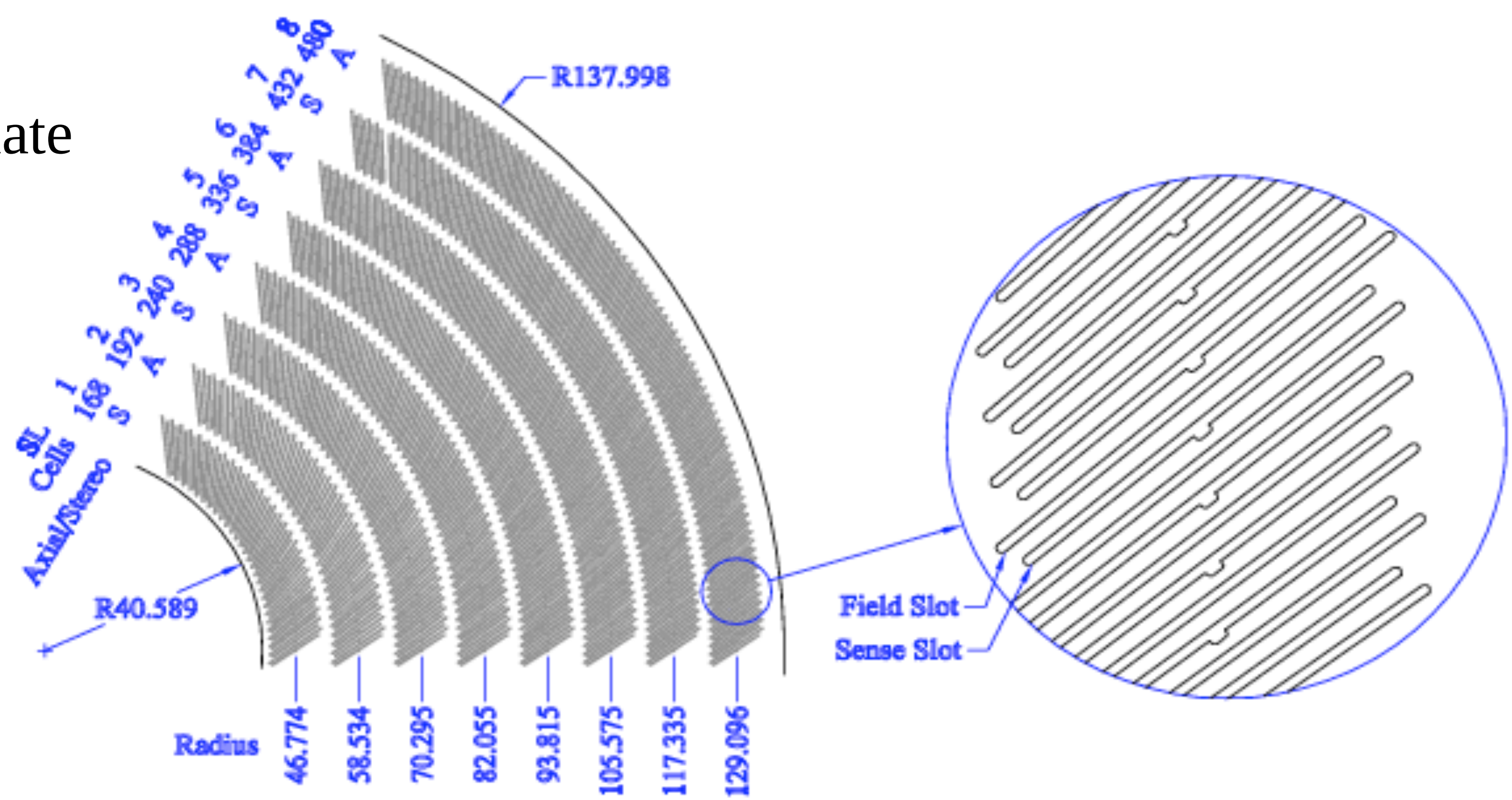
Outline of CDF Analysis

Energy scale measurements drive the W mass measurement

- Tracker Calibration
  - alignment of the central drift chamber (COT with ~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

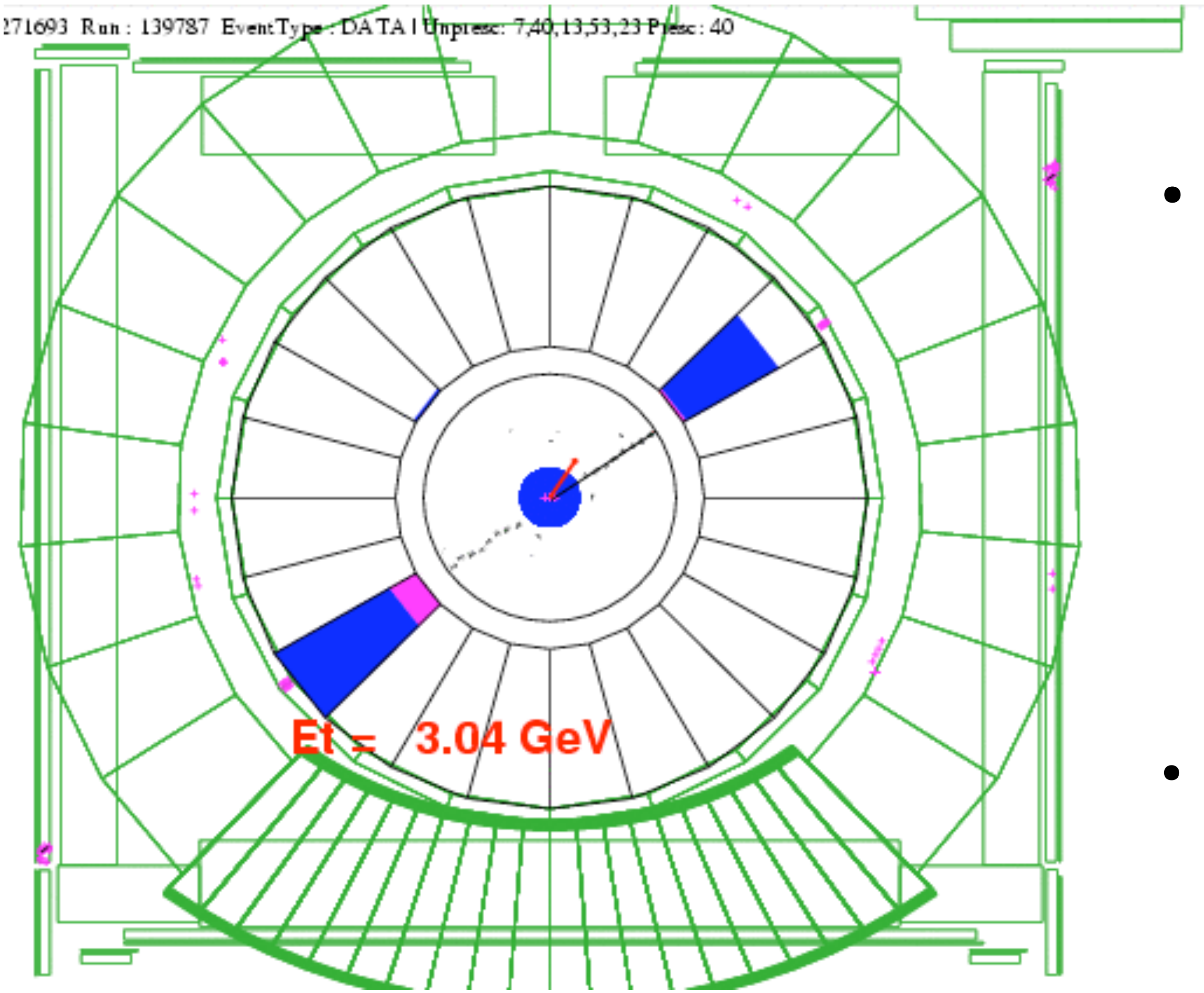
Drift Chamber (COT) Alignment

COT endplate geometry



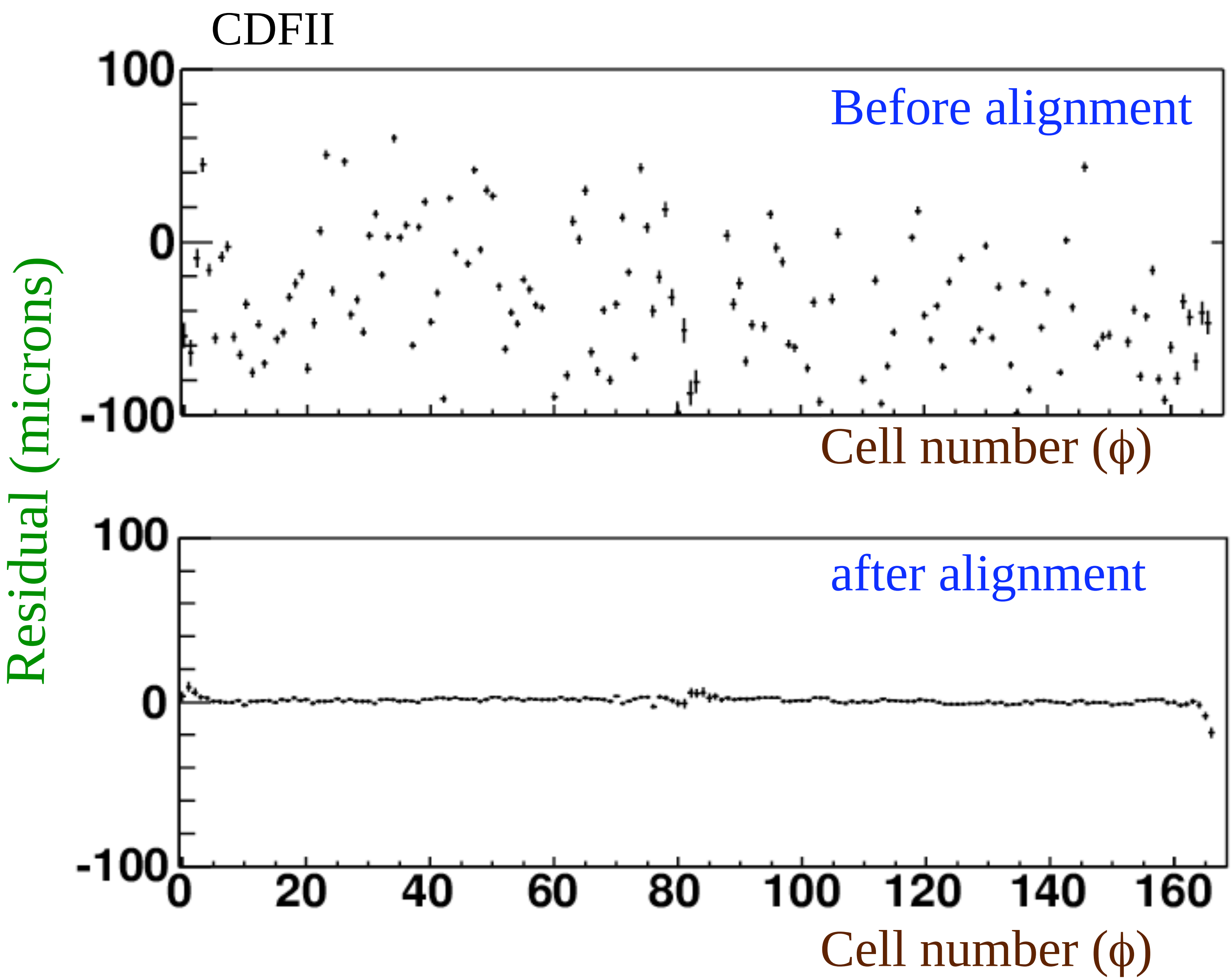
Internal Alignment of COT

- 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
- Same technique being used on ATLAS and CMS

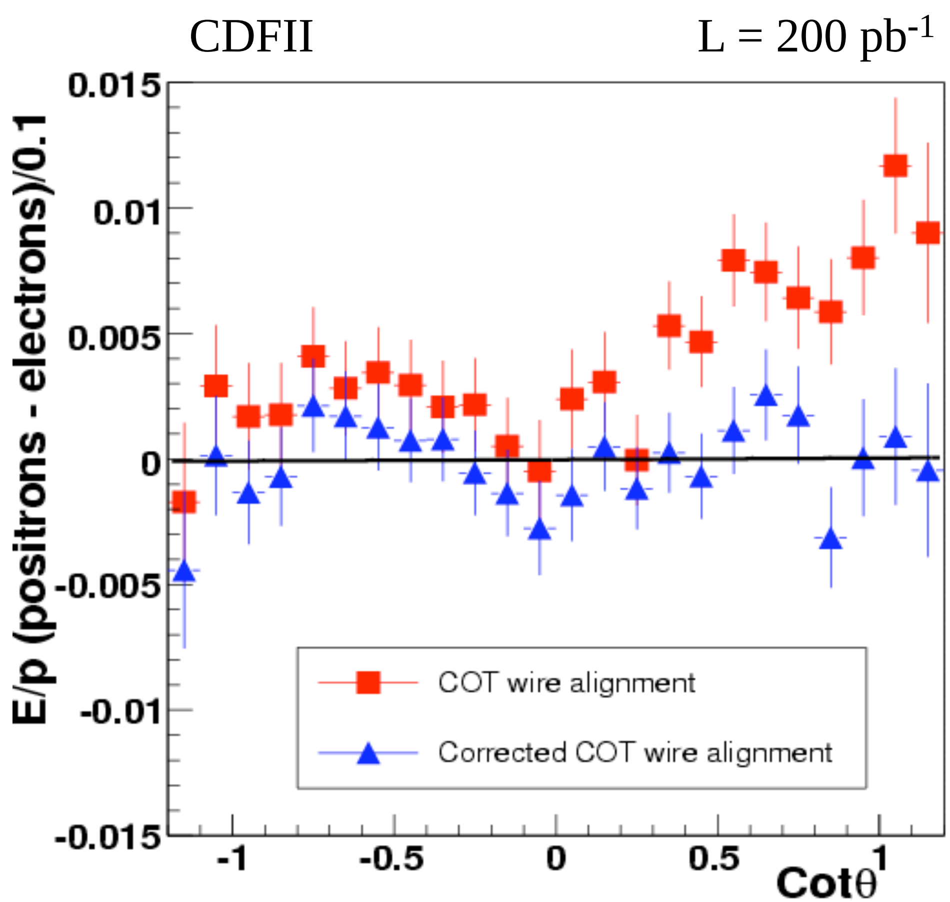
Residuals of COT cells after alignment



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

Cross-check of COT alignment

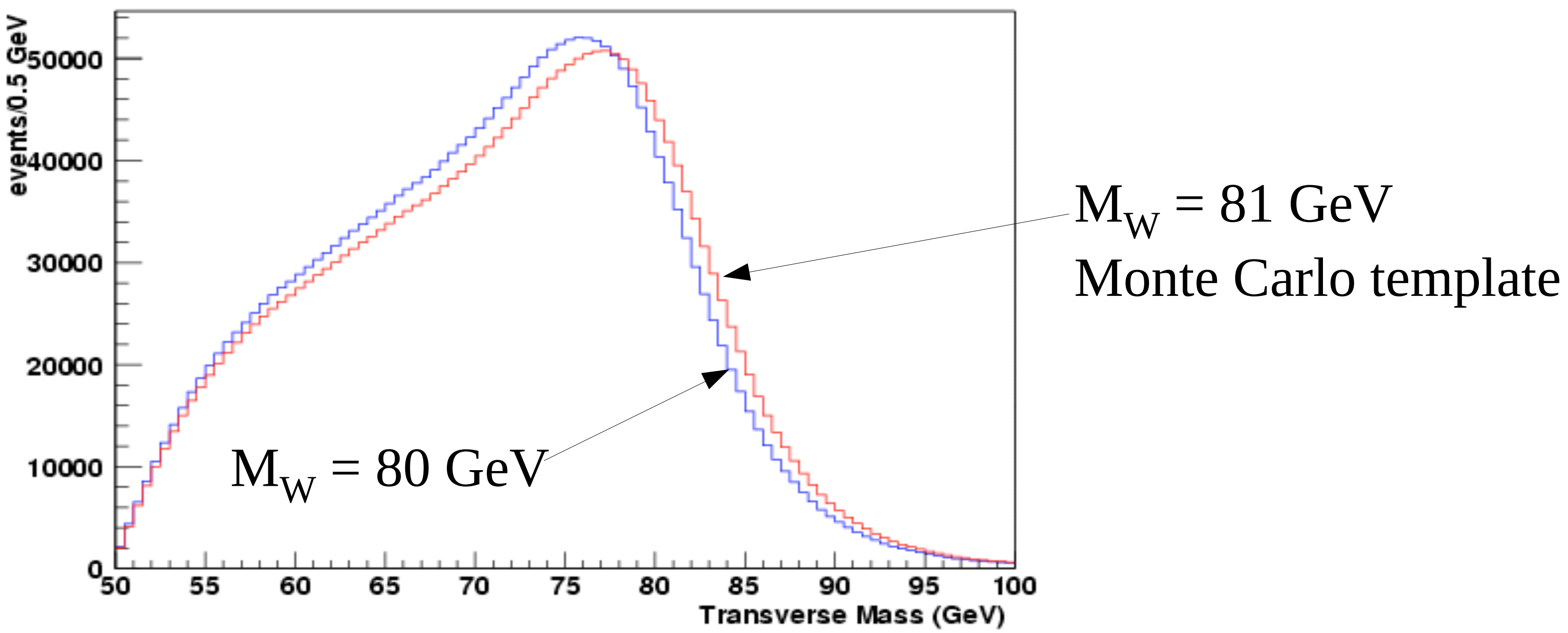
- Final cross-check and correction to track curvature based on difference of <E/p> for positrons *vs* electrons (red points)
- Smooth ad-hoc curvature corrections applied => δM_W = 6 MeV
- Systematic effects also relevant for LHC trackers



Signal Simulation and Fitting

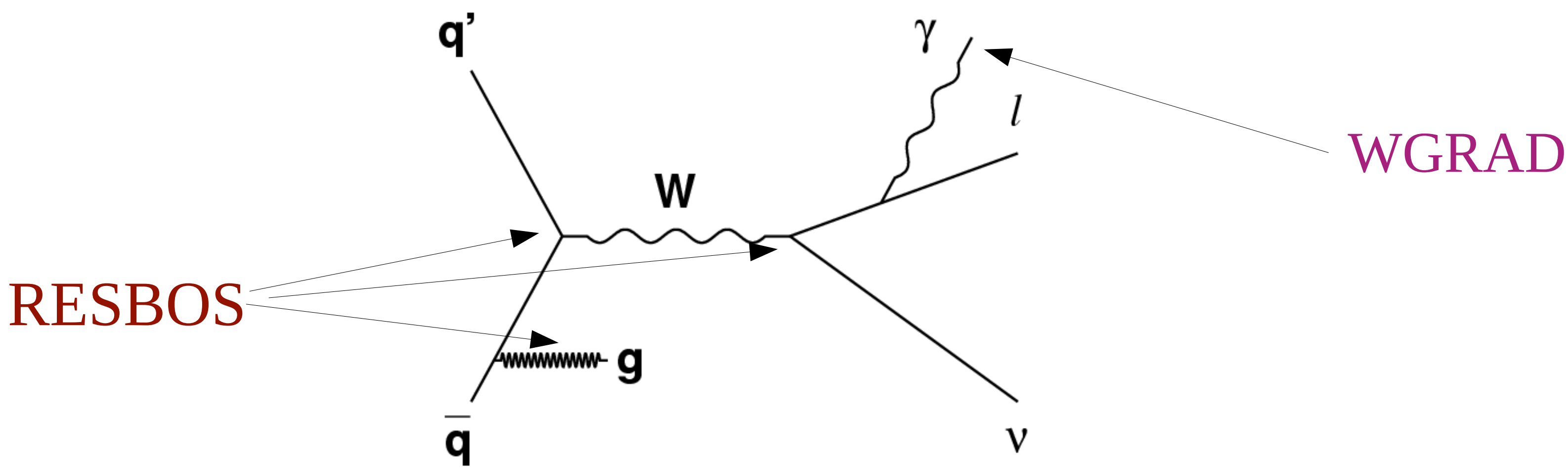
Signal Simulation and Template Fitting

- All signals simulated using a custom 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



- CDF and D0 extract the W mass from three kinematic distributions: Transverse mass, charged lepton p_T and neutrino p_T

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))

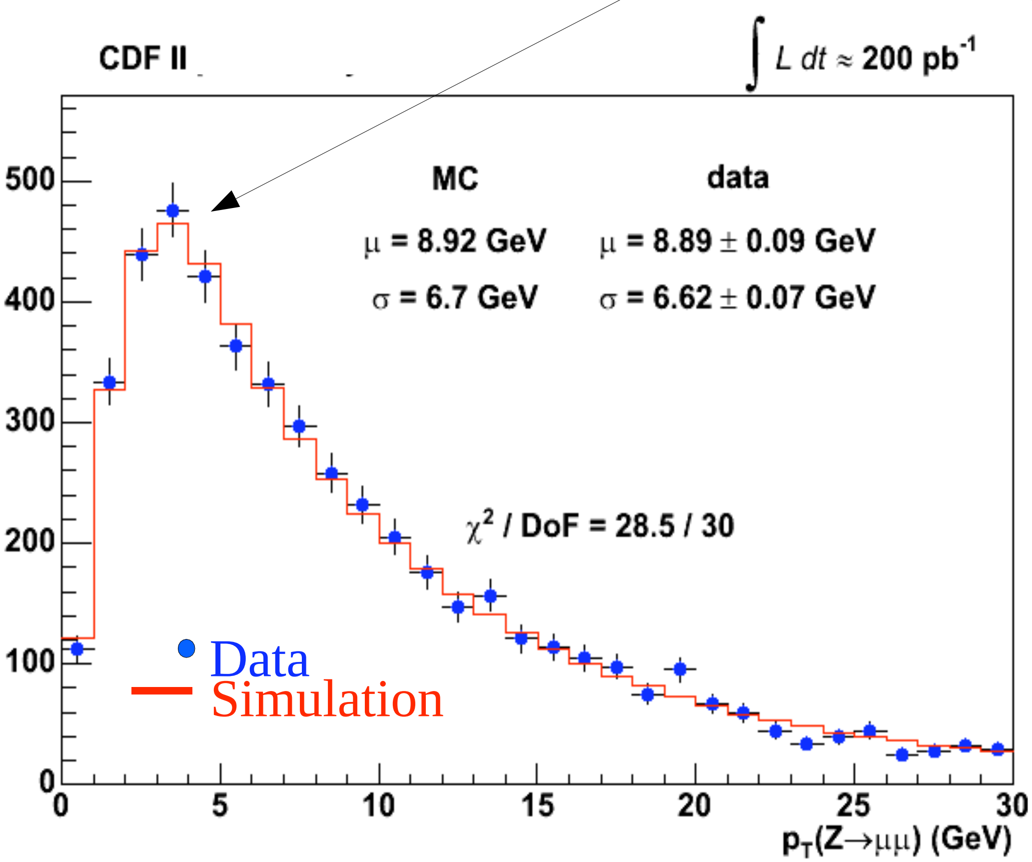
Constraining Boson p_T Spectrum

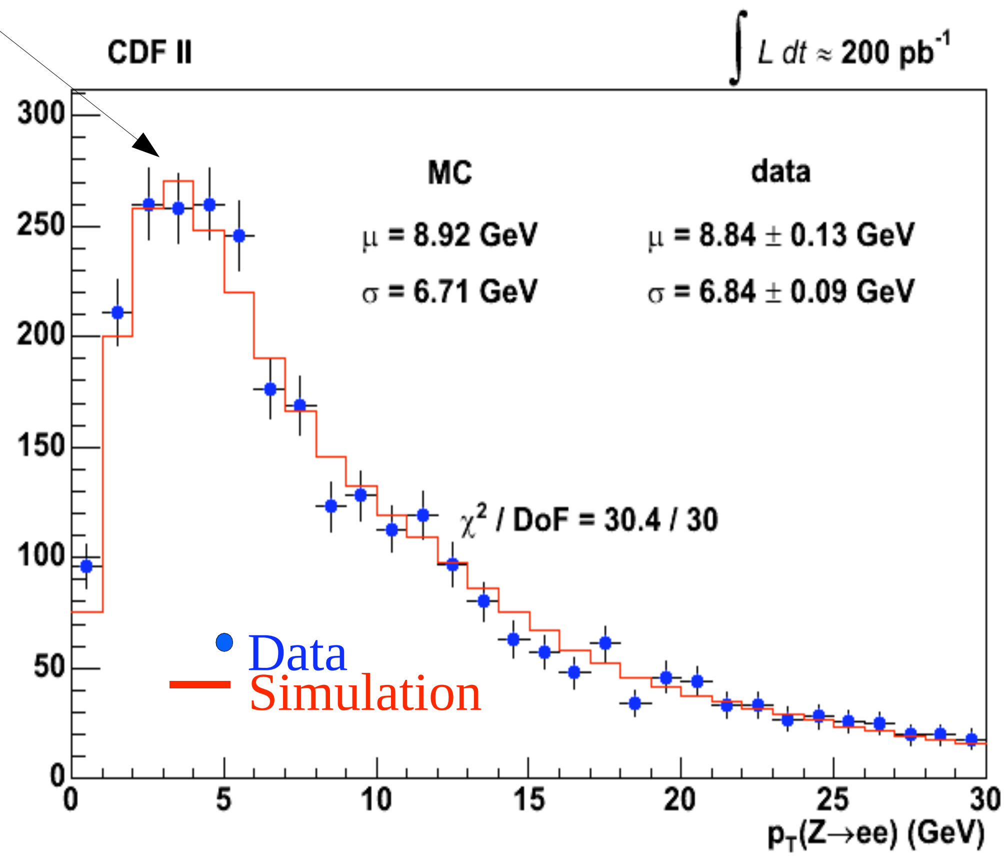
- Fit the non-perturbative parameter g_2 in RESBOS to $p_T(ll)$ spectra: find $g_2 = 0.685 \pm 0.048$

$\Delta M_W = 3$ 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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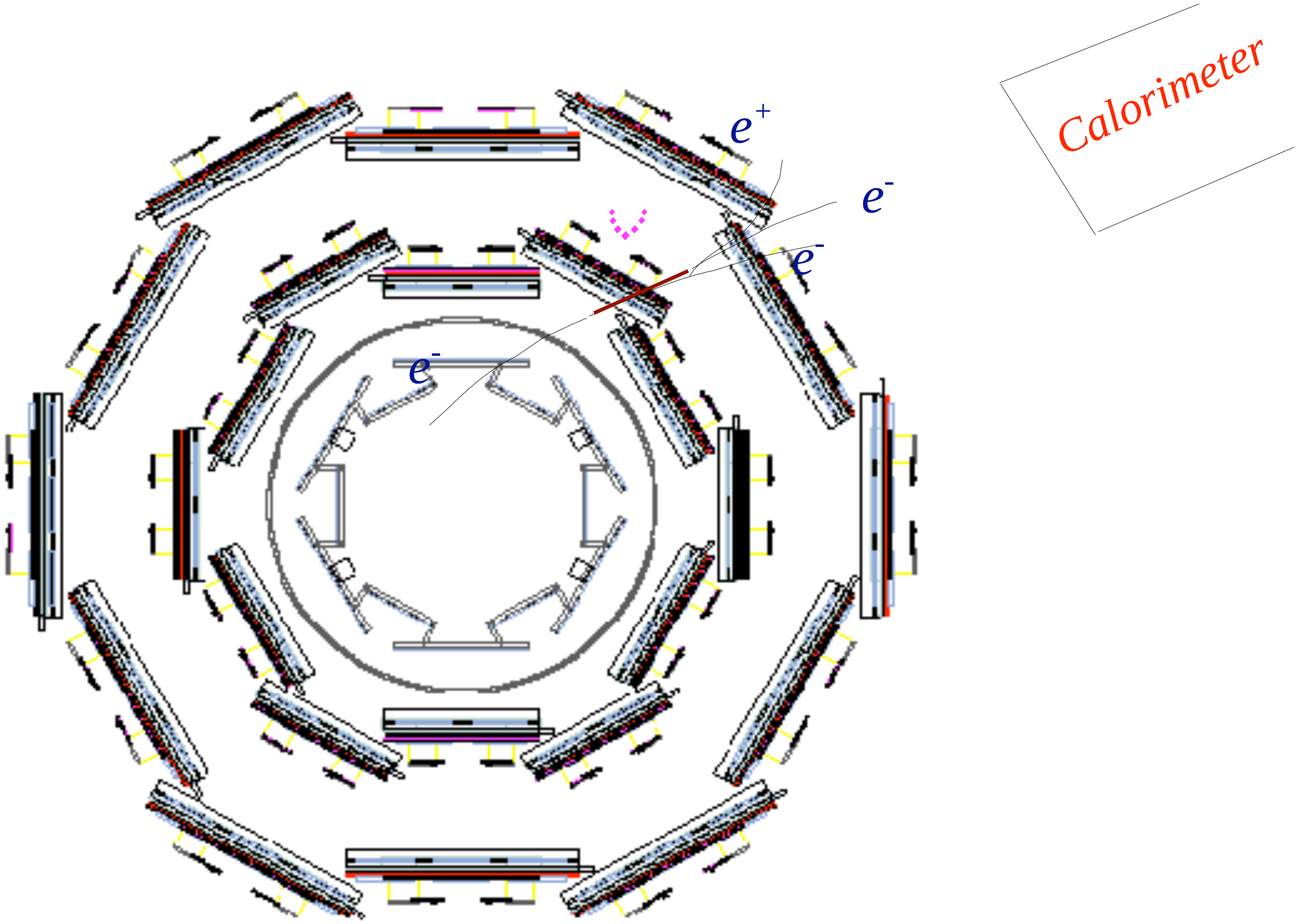


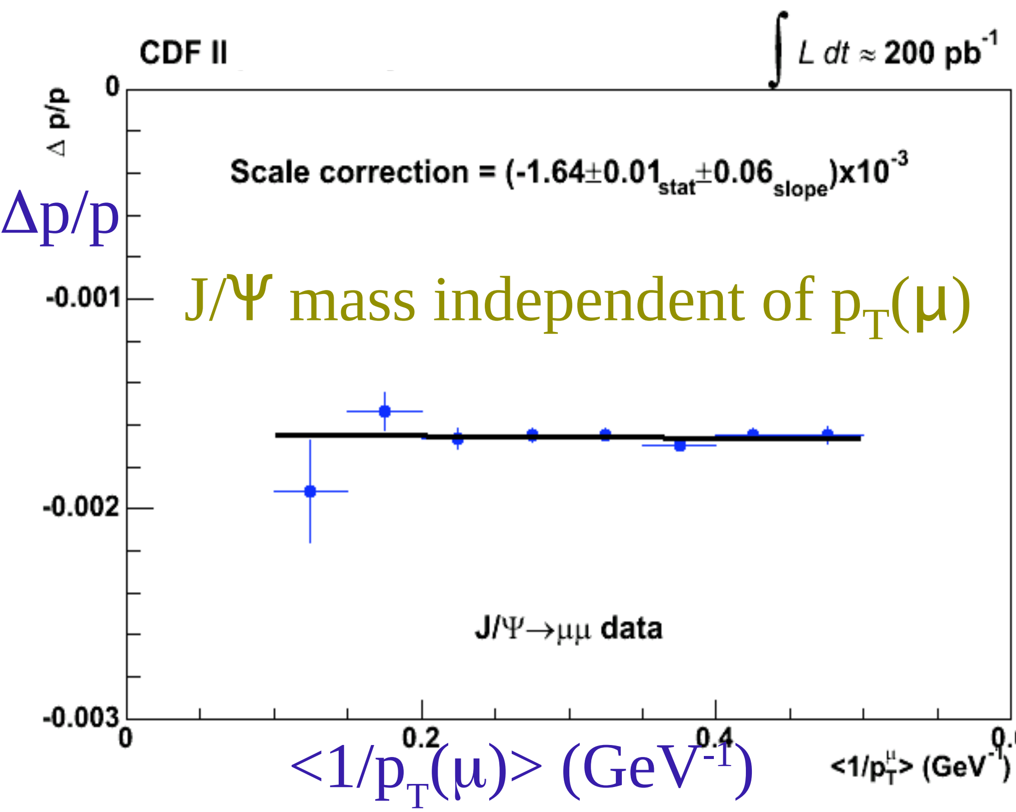
Tracking Momentum Scale

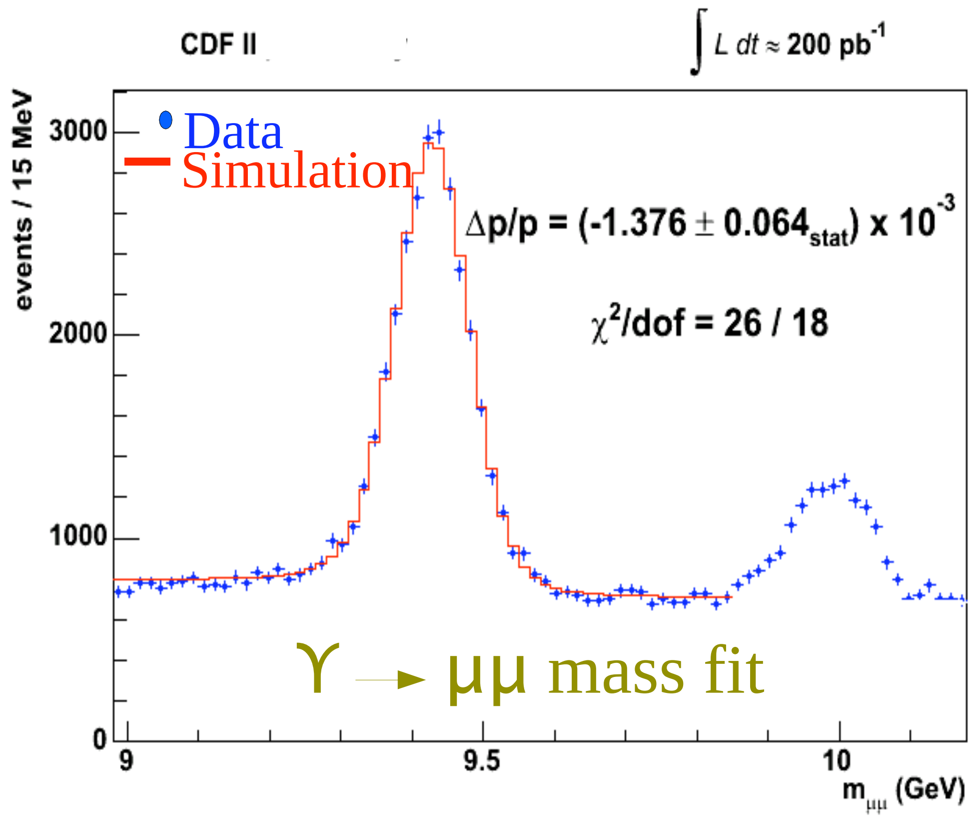
Tracking Momentum Calibration

- Set using $J/\Psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ resonances
  - Consistent within total uncertainties

- Use J/Ψ to study and calibrate non-linear response of tracker

- Systematics-dominated, improved detector modelling required





Tracking Momentum Scale Systematics

Systematic uncertainties on momentum scale

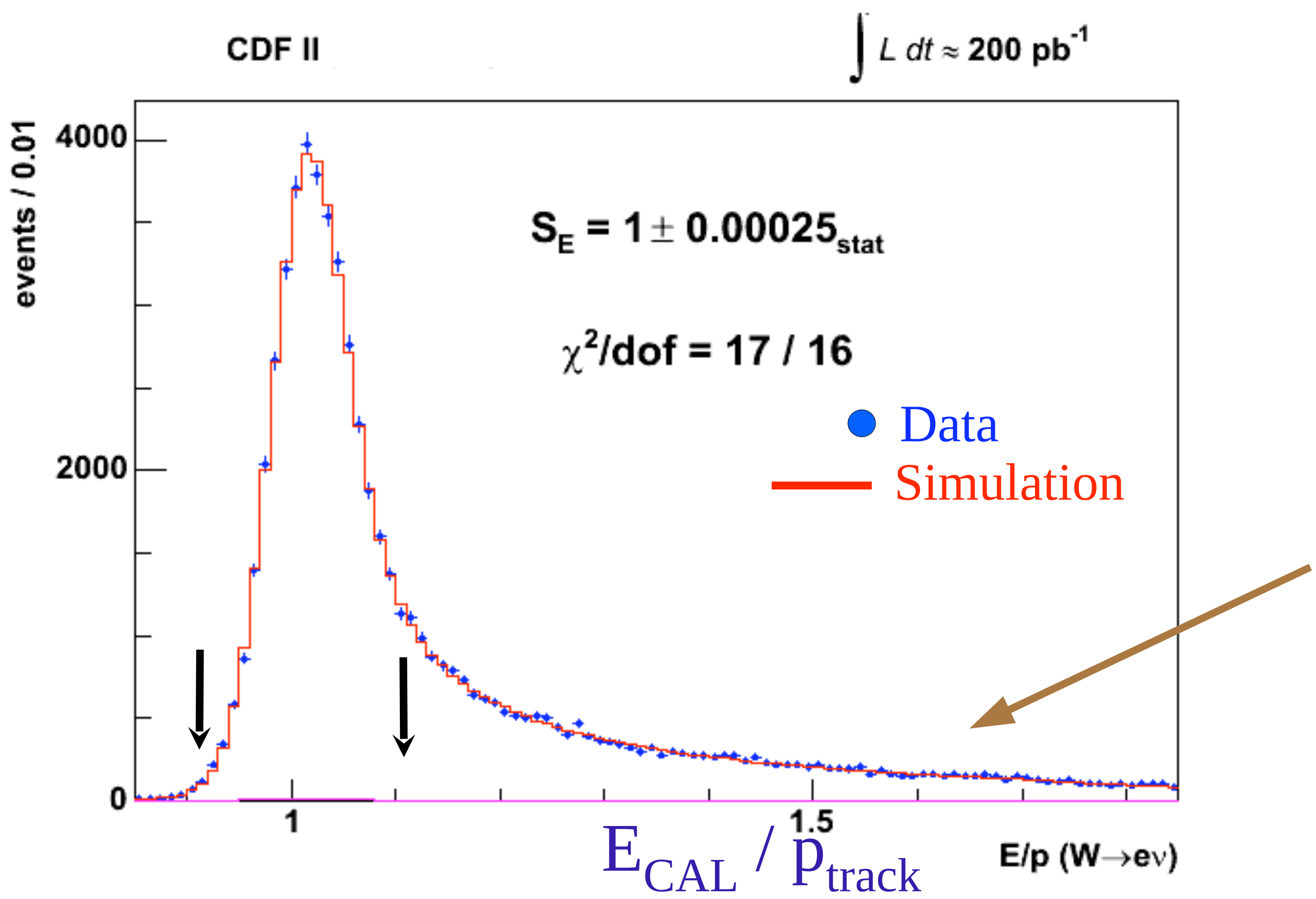
Source	J/ψ ($\times 10^{-3}$)	Υ ($\times 10^{-3}$)	Common ($\times 10^{-3}$)
QED and energy loss model	0.20	0.13	0.13
Magnetic field nonuniformities	0.10	0.12	0.10
Beam constraint bias	N/A	0.06	0
Ionizing material scale	0.06	0.03	0.03
COT alignment corrections	0.05	0.03	0.03
Fit range	0.05	0.02	0.02
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

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

EM Calorimeter Response

Electromagnetic Calorimeter Calibration

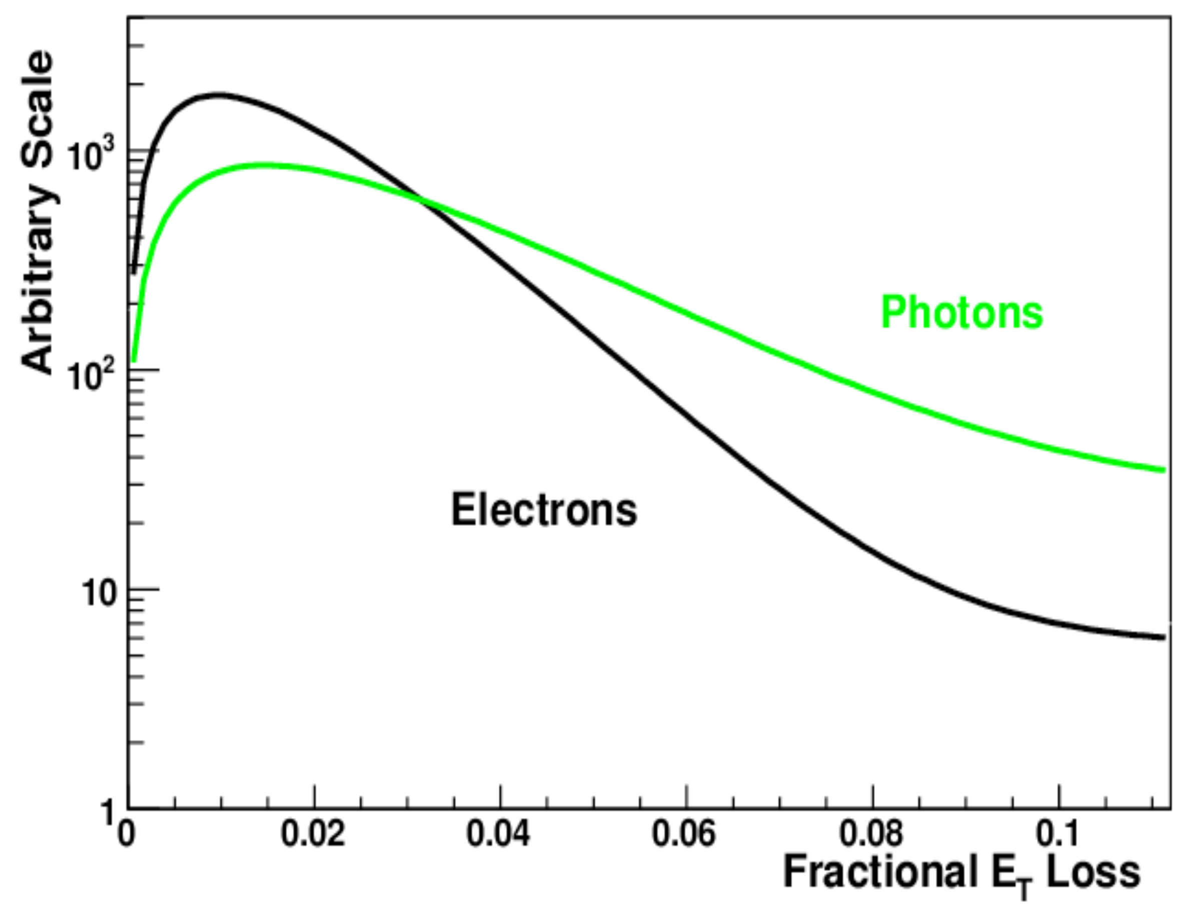
- E/p peak from $W \rightarrow e\nu$ decays provides EM calorimeter calibration relative to the tracker
  - Calibration performed in bins of electron energy



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

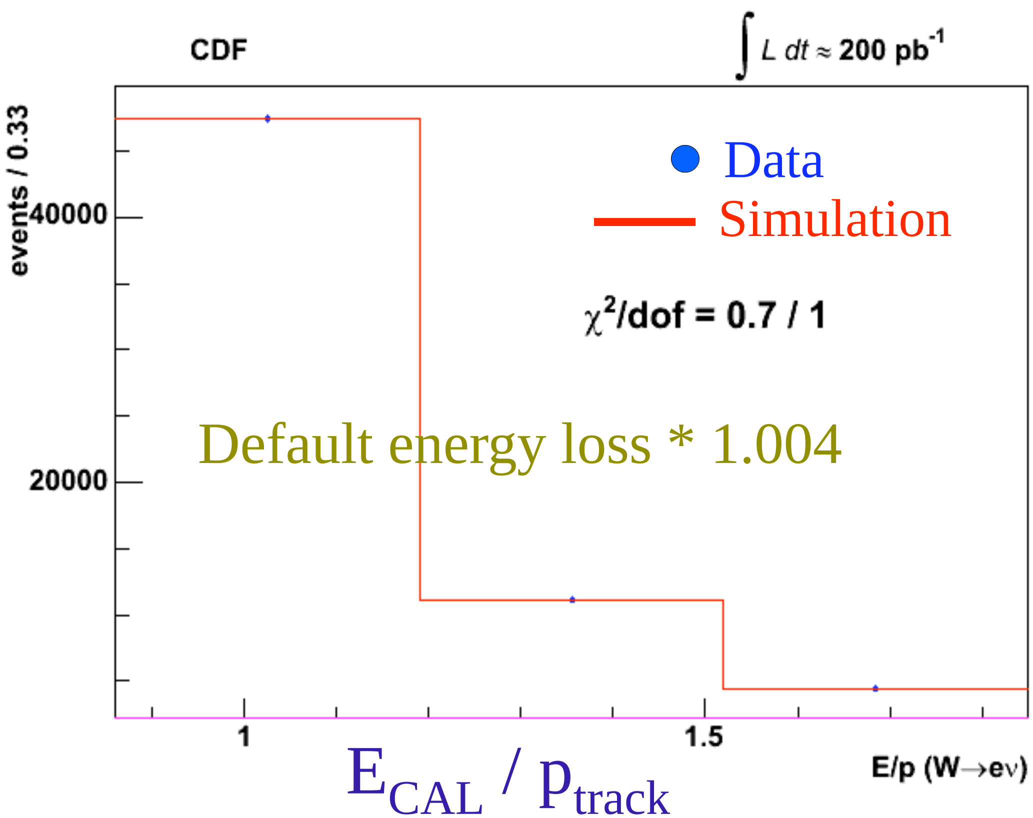
Calorimeter Simulation for Electrons and Photons

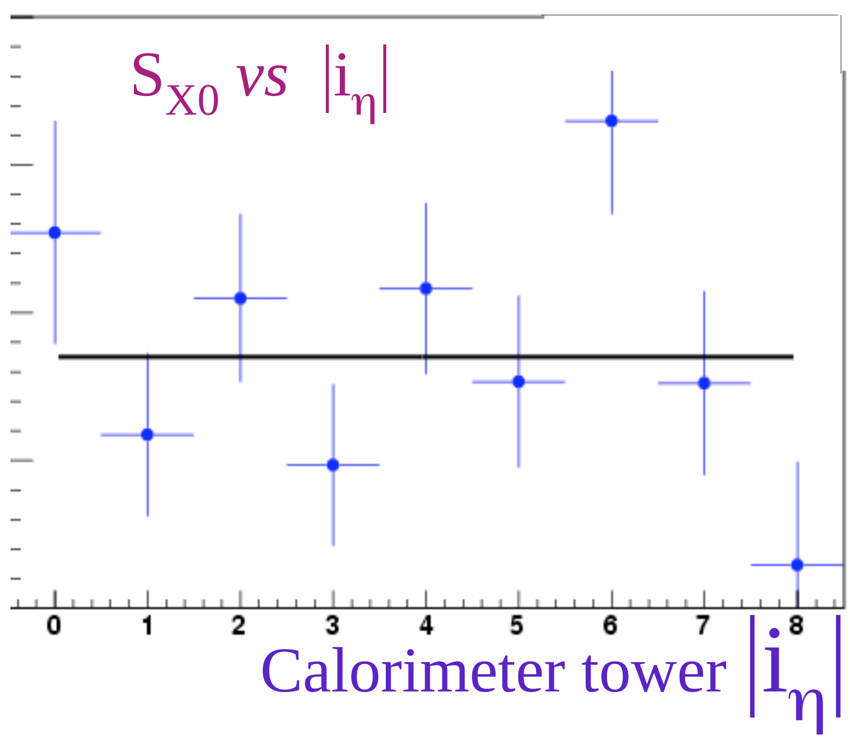
- Distributions of energy loss calculated based on expected shower profiles as a function of E_T
  - Leakage into hadronic calorimeter
  - Absorption in the coil
  - Relevant for E/p lineshape



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
  - CDF detector geometry confirmed as a function of pseudorapidity: S_{MAT} independent of $| \eta |$

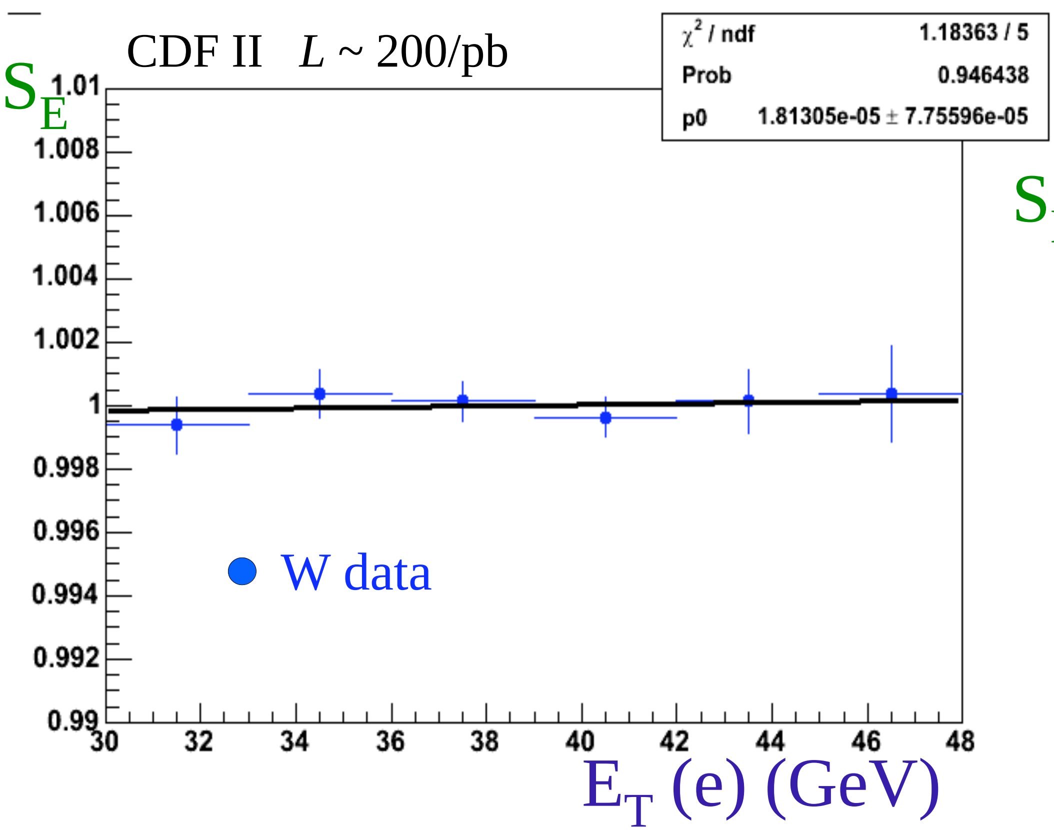


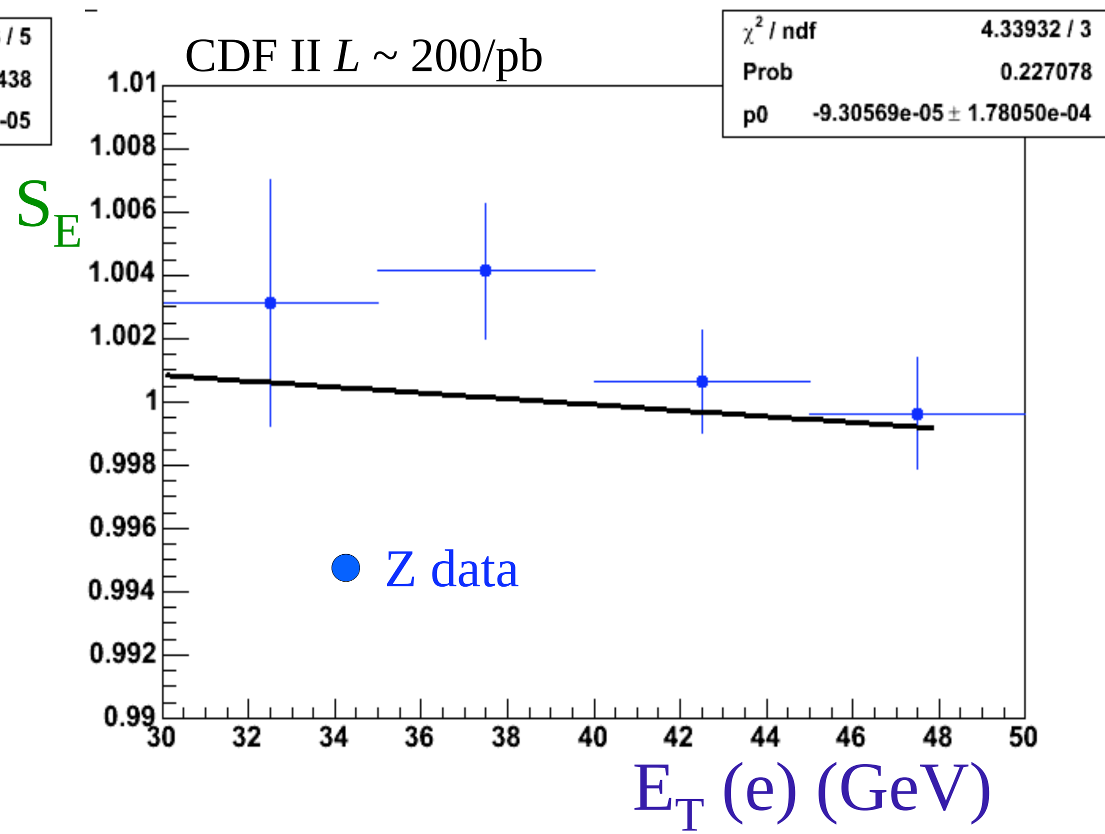


Measurement of EM Calorimeter Non-linearity

- Perform E/p fit-based calibration in bins of electron E_T
- Parameterize non-linear response as: $S_E = 1 + \zeta\,(E_T/\mathrm{GeV} - 39)$
- Tune on W and Z data: $\zeta = (6 \pm 7_{stat}) \times 10^{-5}$

  => ΔM_W = 23 MeV

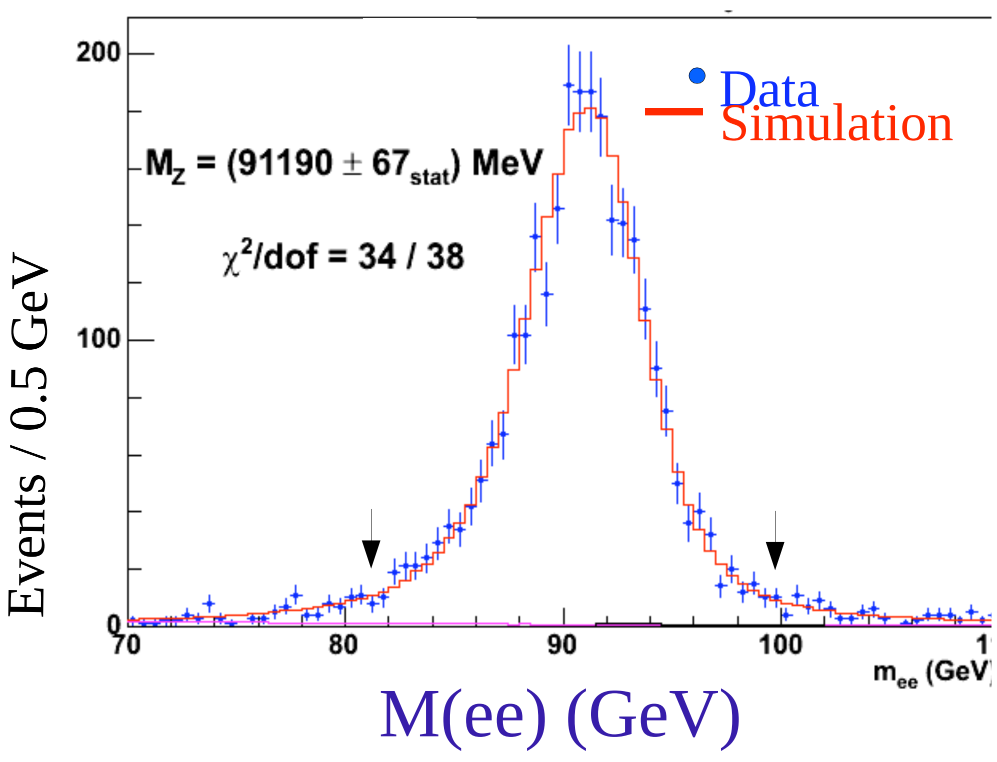


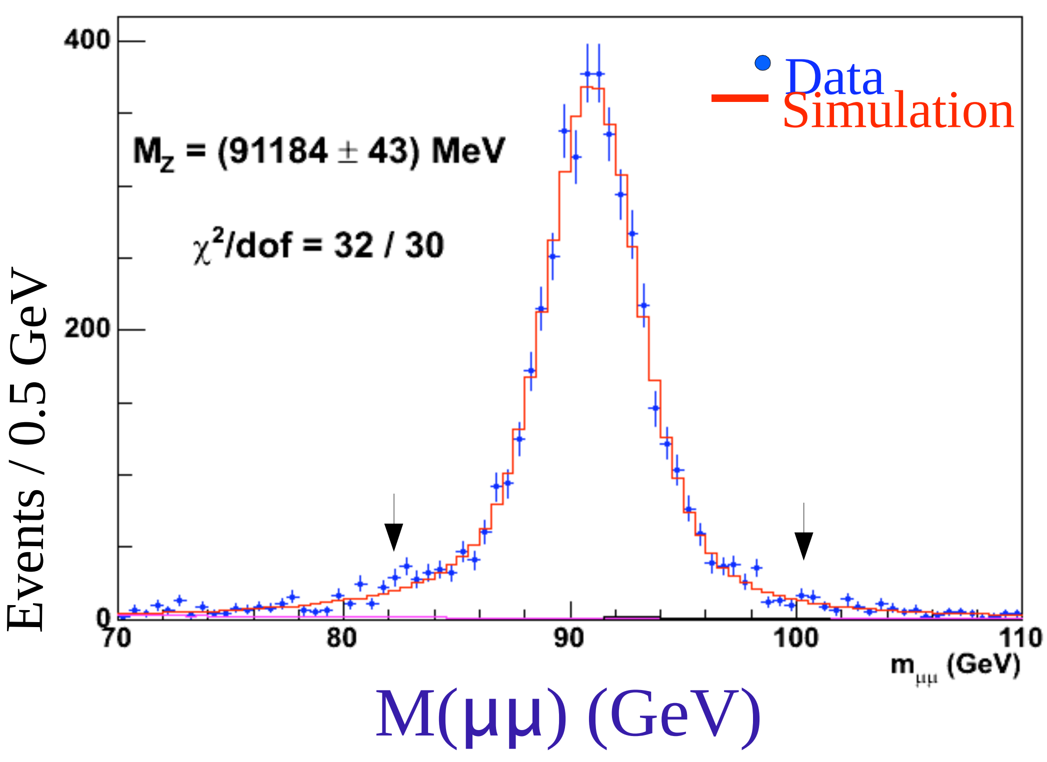


$Z \rightarrow ll$ Mass Cross-checks

- Z boson mass fits consistent with tracking and E/p-based calibrations

CDF II $L \sim 200$/pb



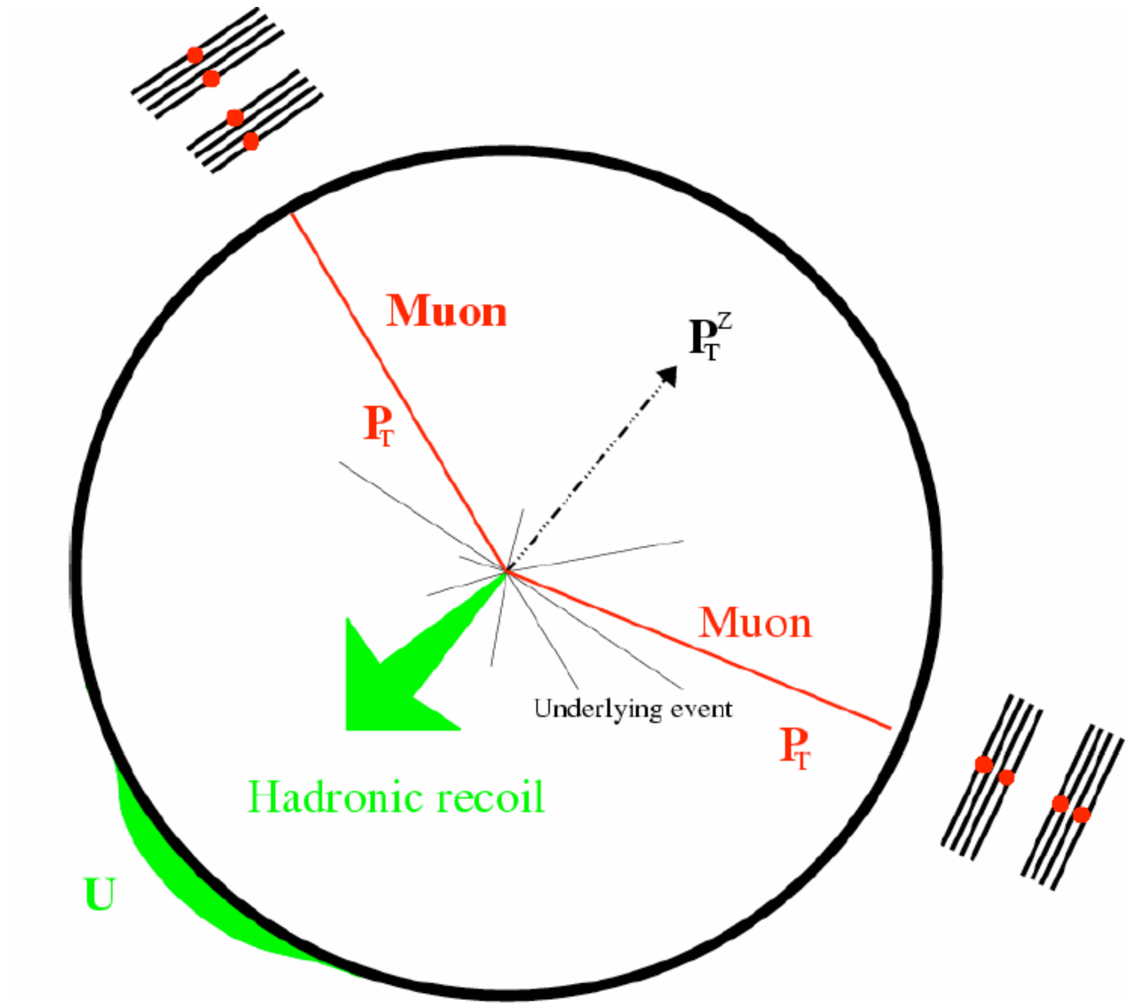


Hadronic Recoil Model

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

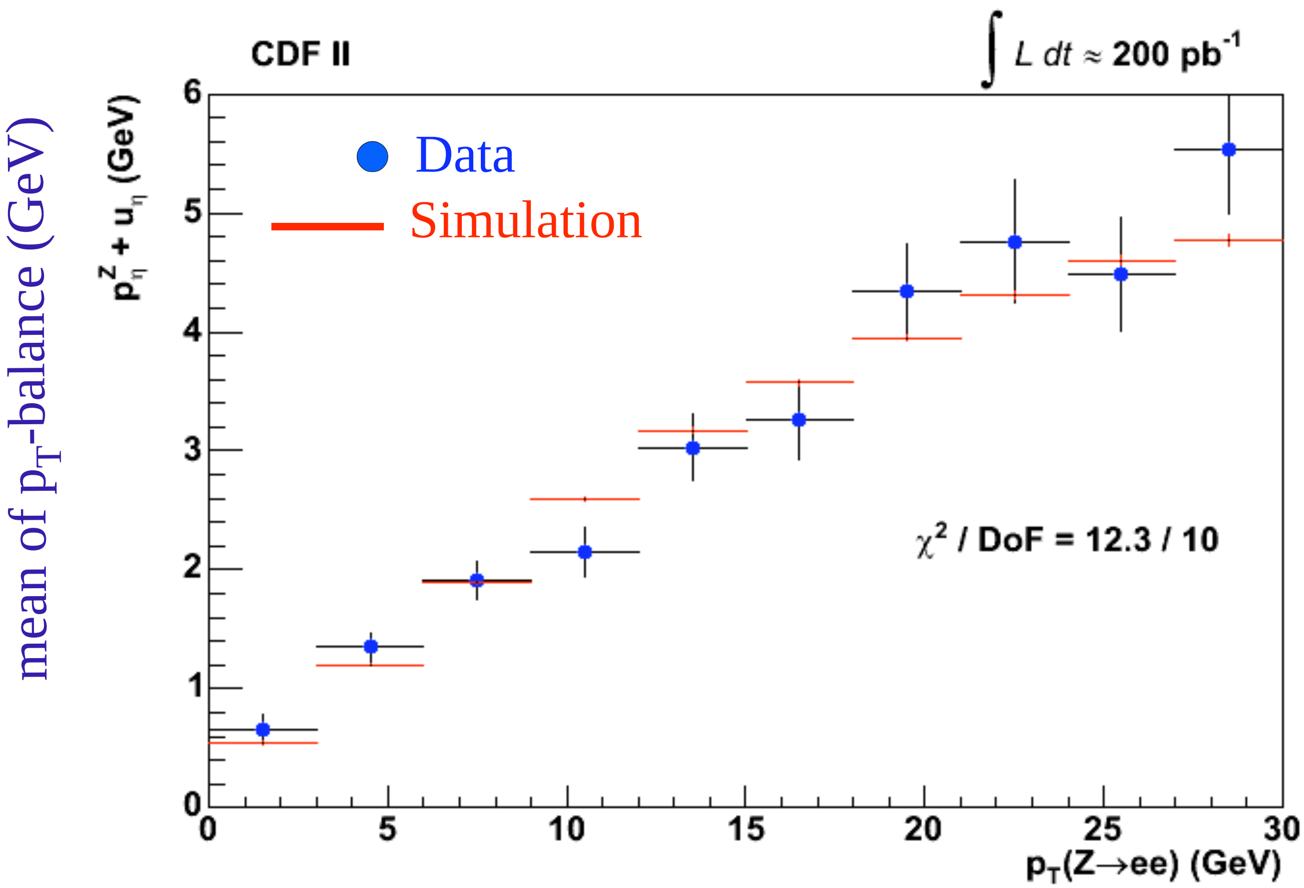


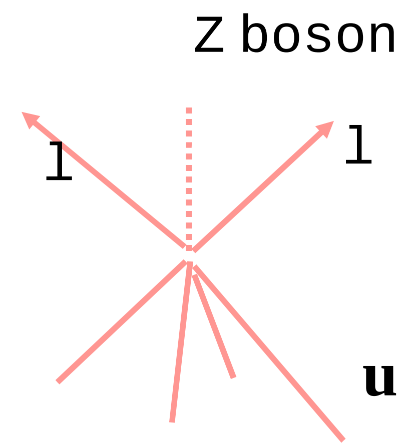
Transverse momentum of Hadronic recoil (***u***) calculated as 2-vector-sum over calorimeter towers

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





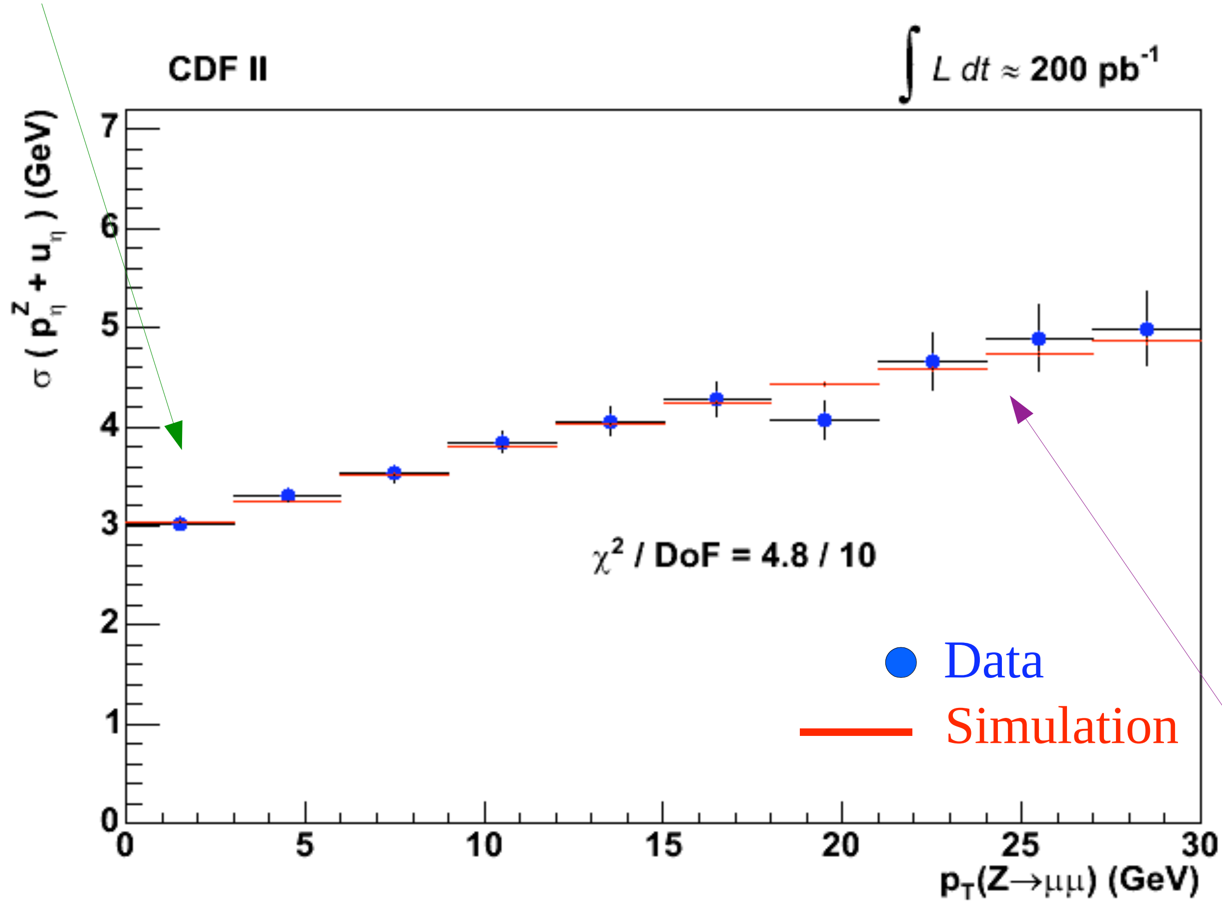
Hadronic model parameters tuned by minimizing χ^2 between data and simulation

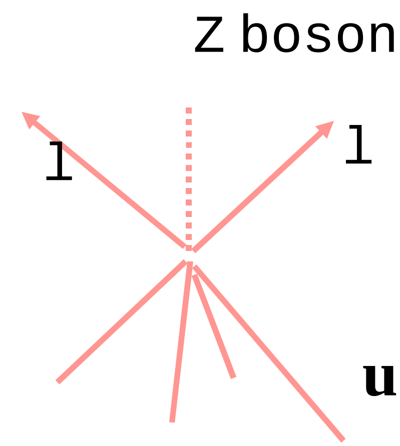
ΔM_W = 9 MeV

Tuning Recoil Resolution Model with Z events

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

Resolution of p_T-balance (GeV)



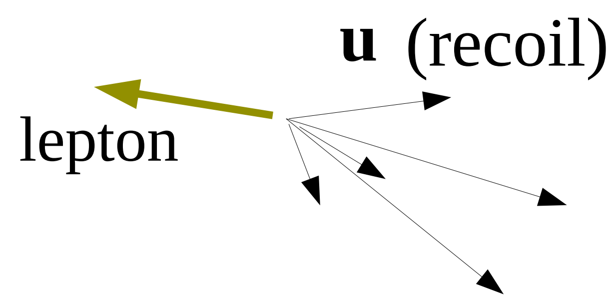


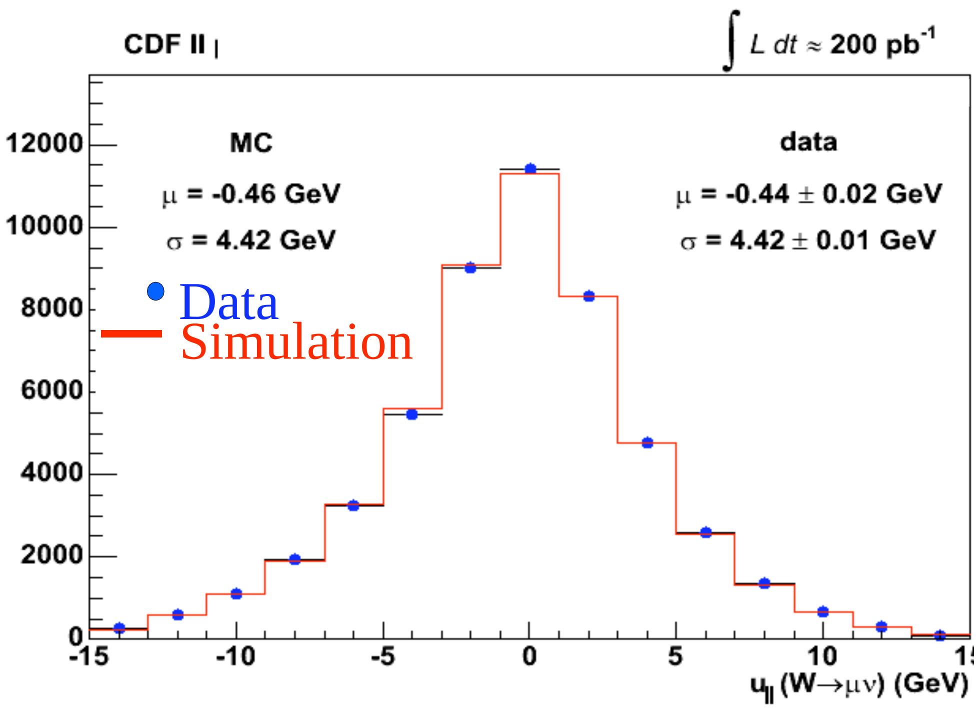
$\Delta M_W = 7$ MeV

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

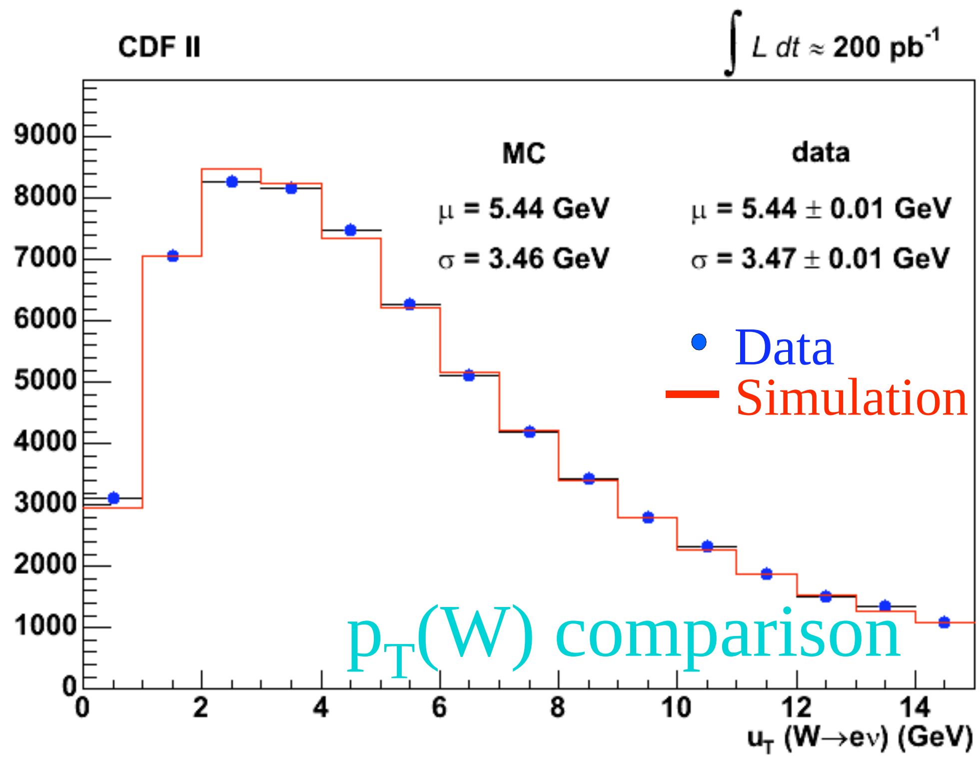
Testing Hadronic Recoil Model with *W* events

Compare recoil distributions between simulation and data



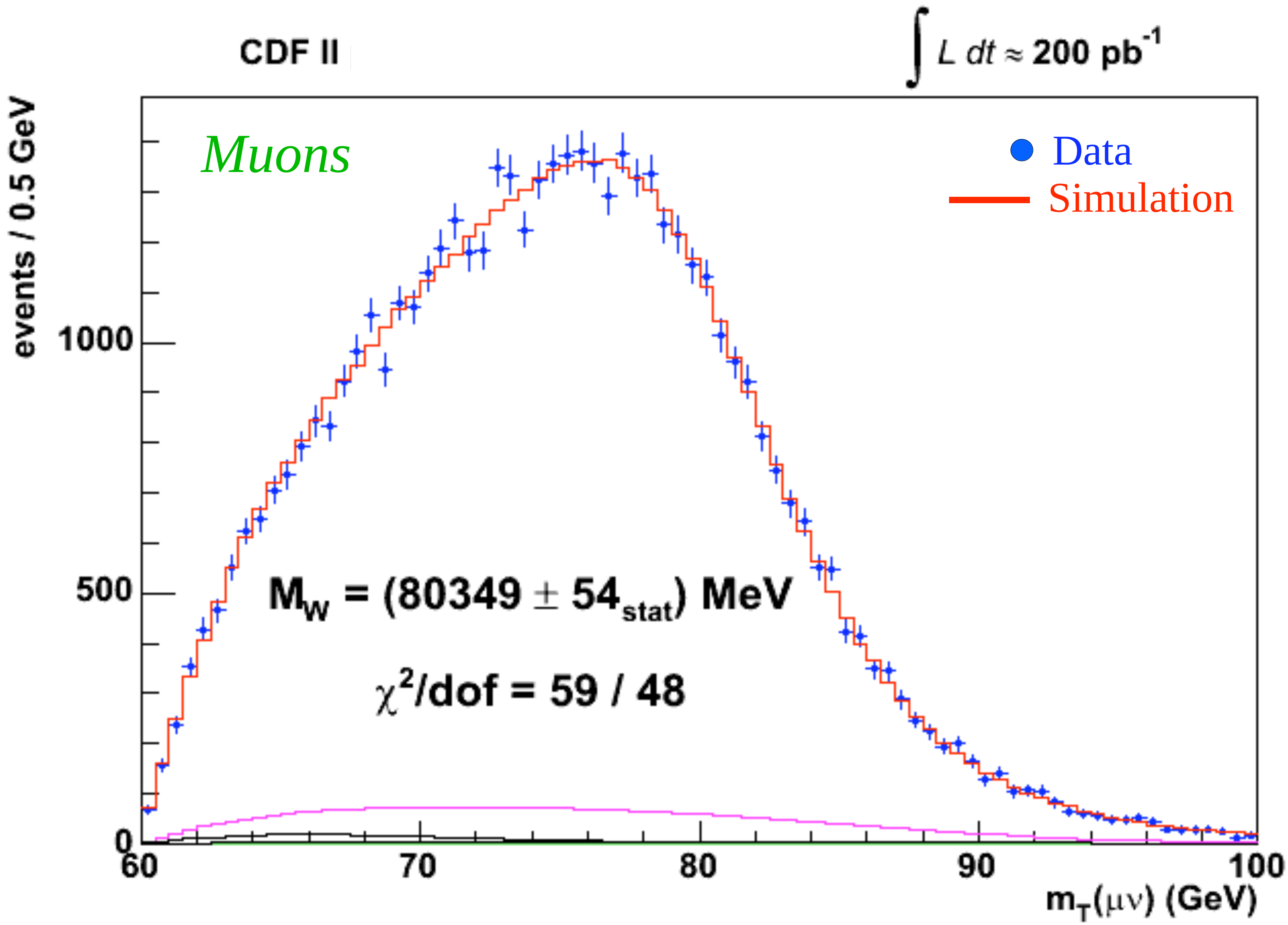


Recoil projection (GeV) on lepton direction

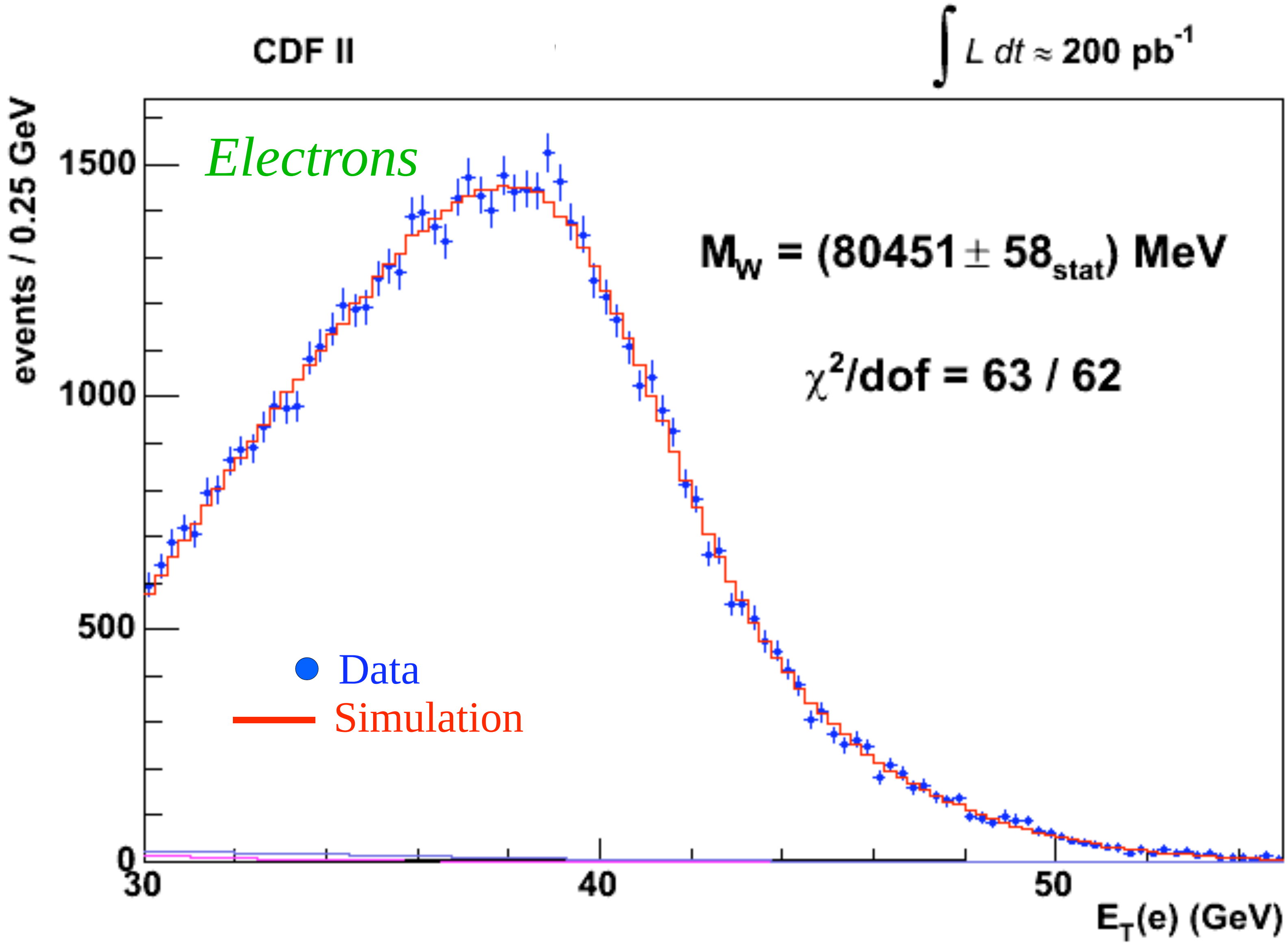


W Mass Fits

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
production dynamics	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)

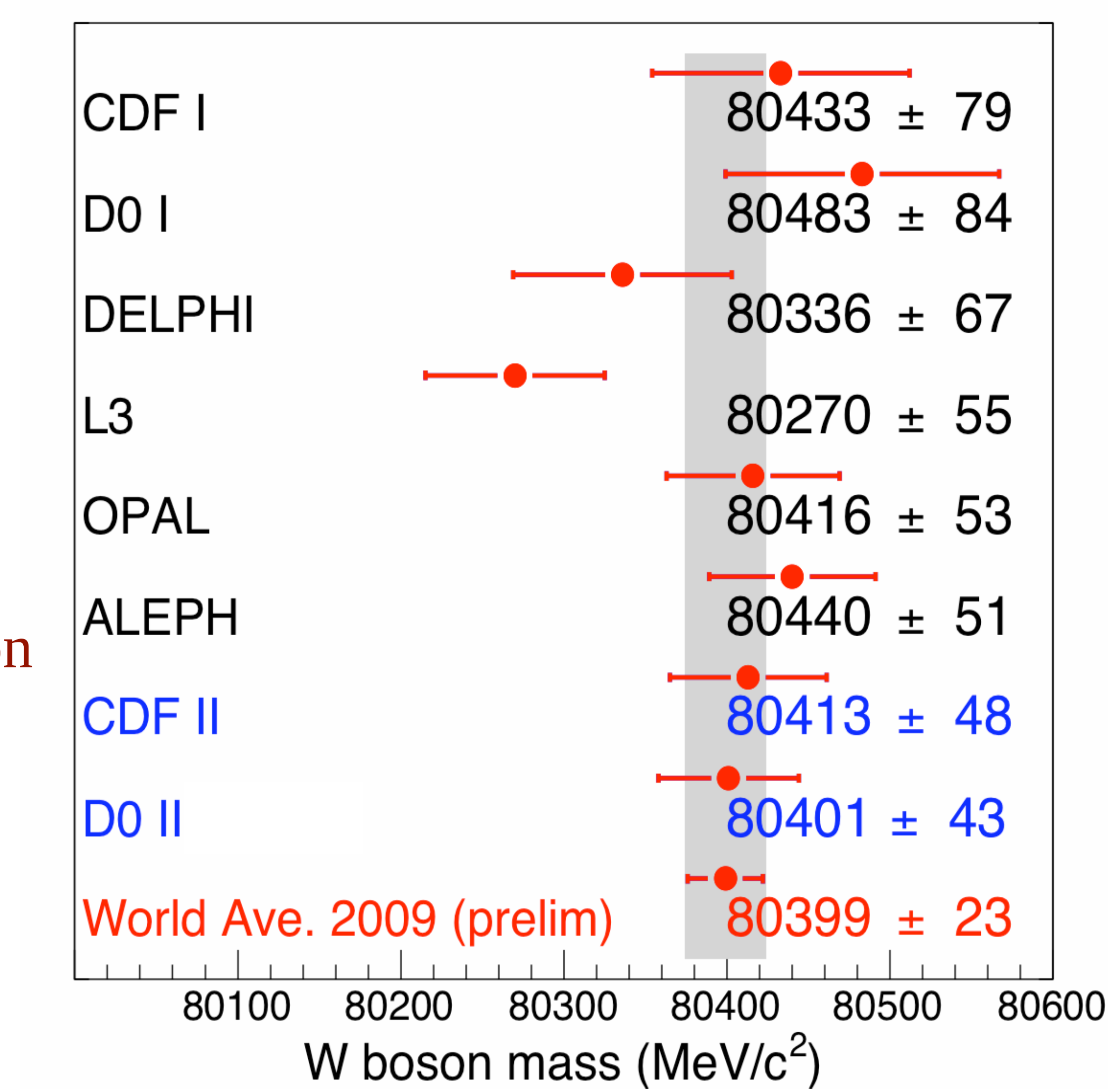
	CDF m	CDF *e*	D0 *e*
W statistics	100	65	60
Lepton energy scale	85	75	56
Lepton resolution	20	25	19
Recoil model	35	37	35
production dynamics	20	15	15
Selection bias	18	-	12
Backgrounds	25	5	9
Parton dist. Functions	15	15	8
QED rad. Corrections	11	11	12
$\Gamma(W)$	10	10	10
Total	144	113	84

For comparison to run 2 analysis

W Boson Mass Measurements

CDF: 200 pb^{-1}, electron and muon channels

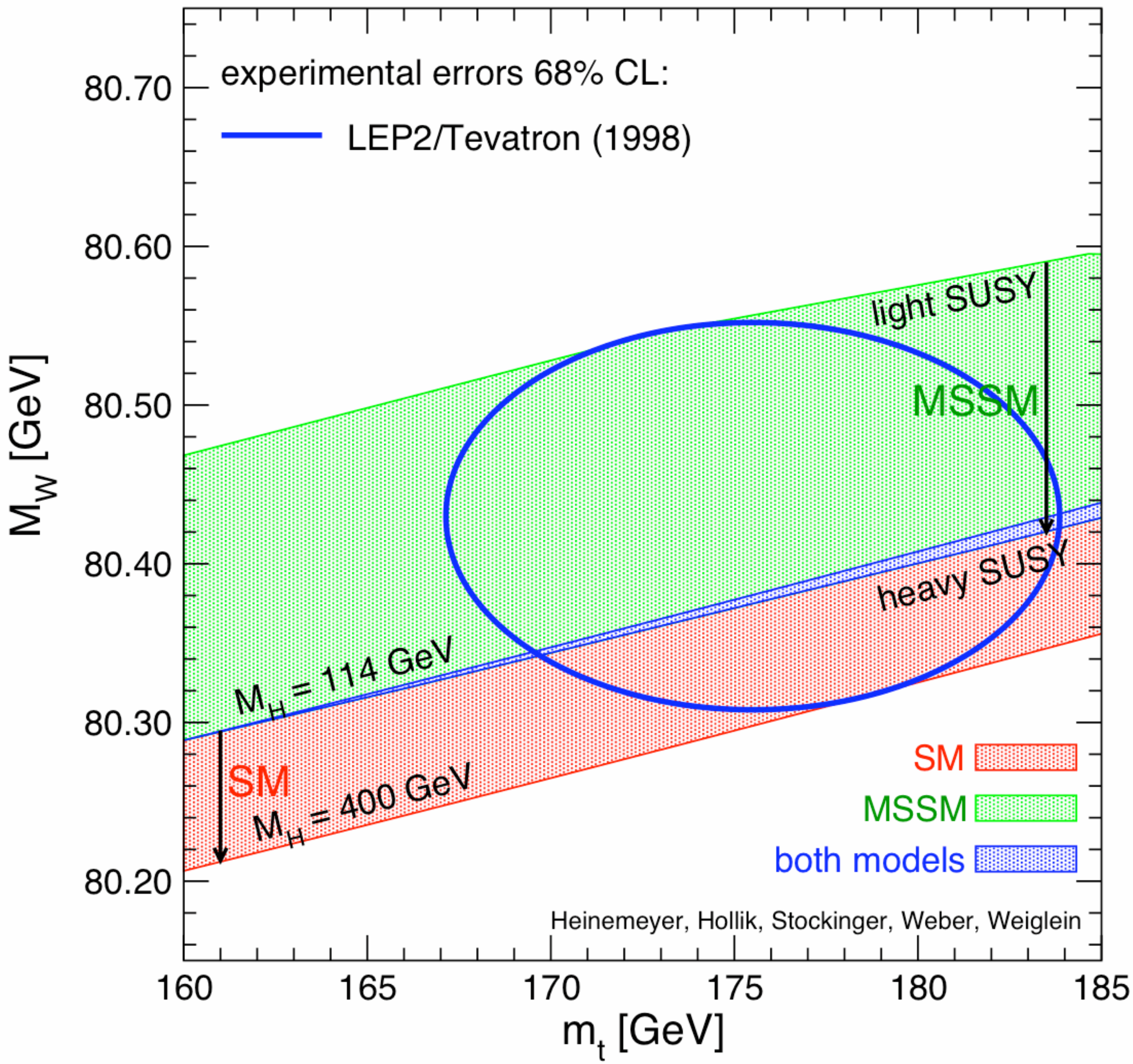
D0: 1 fb^{-1}, electron channel



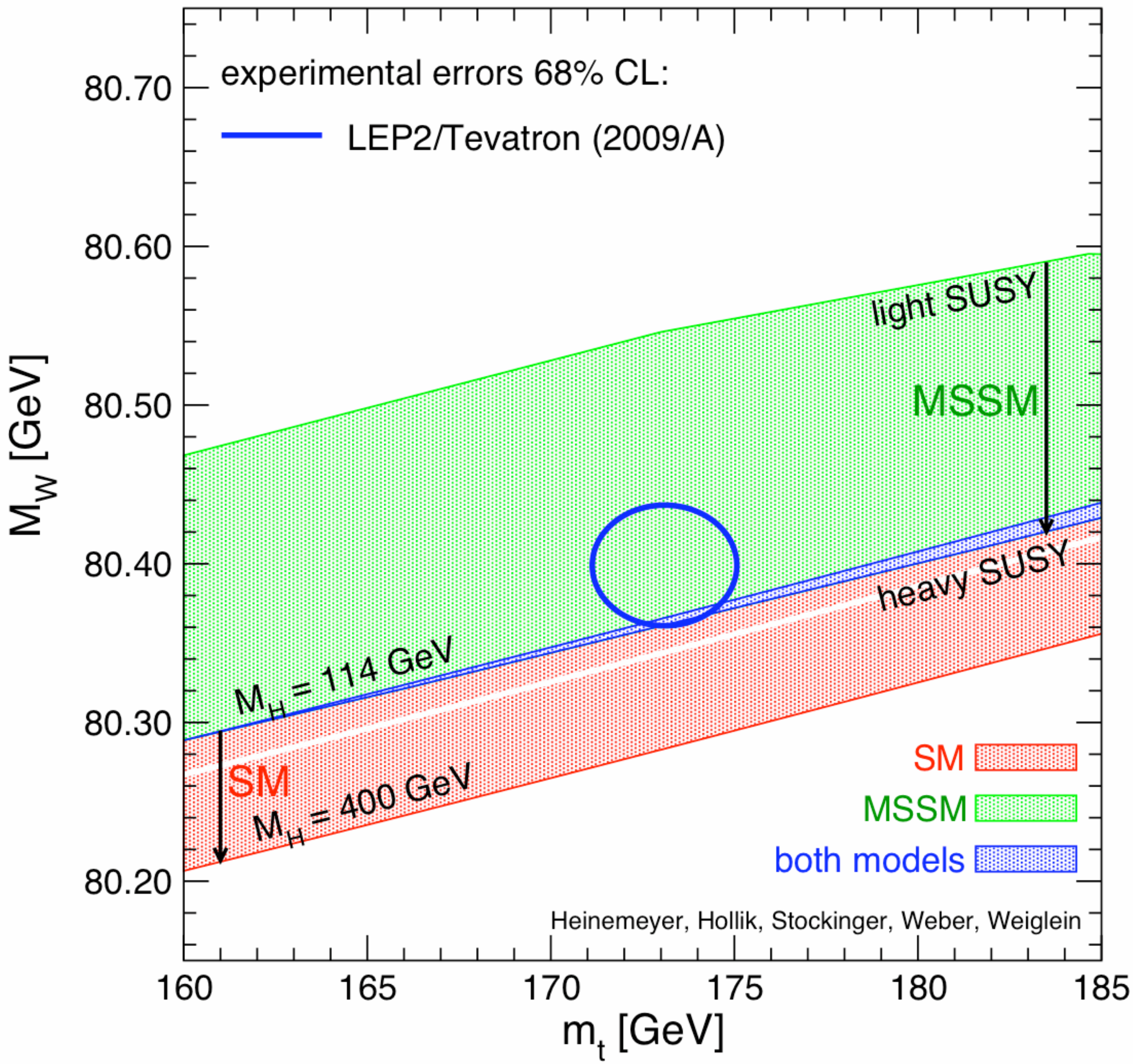
(D0 Run II: PRL 103:141801, 2009)

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

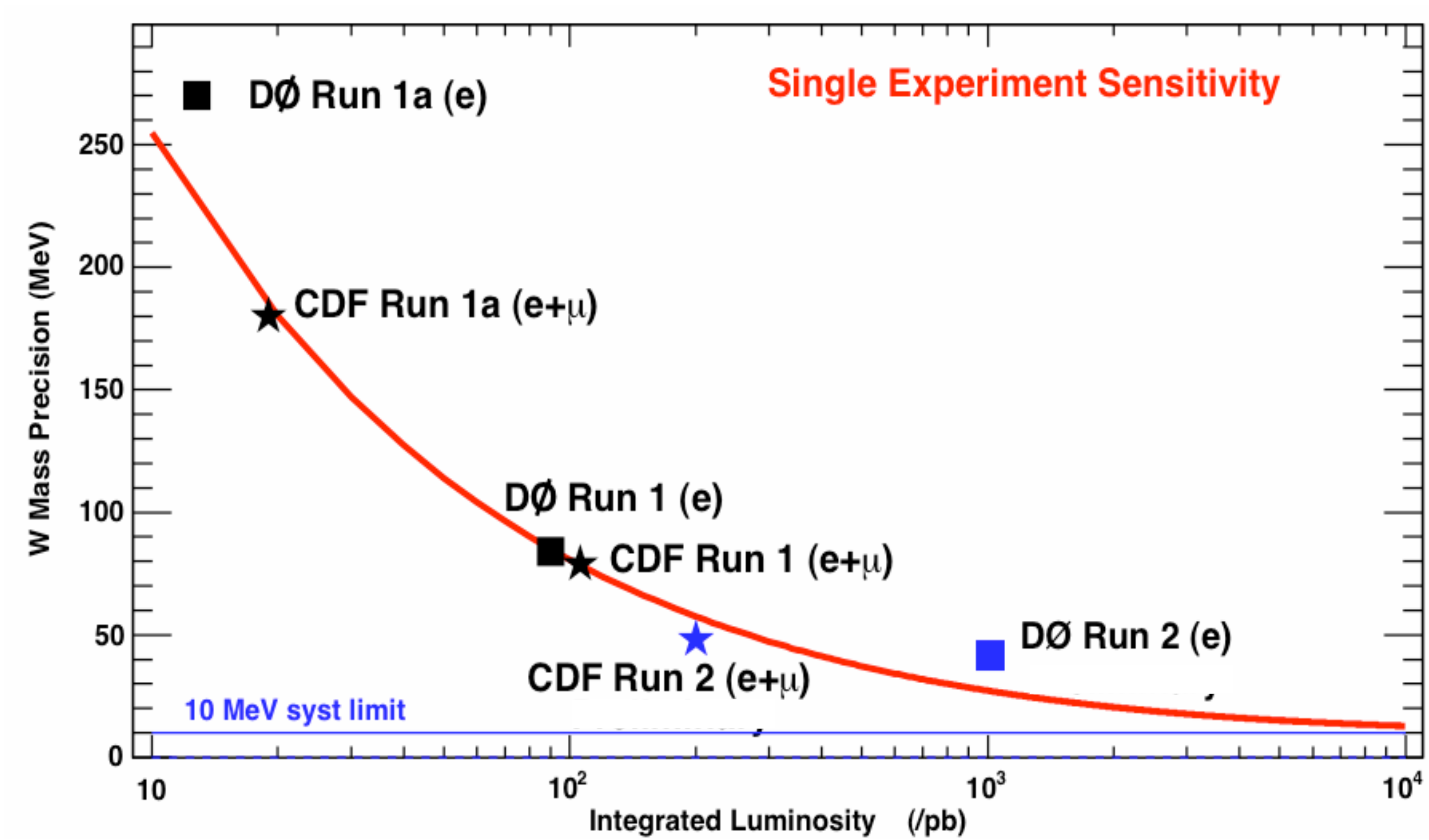
Pre-Run 2 M_W *vs* M_{top}



Post-Run 2 M_W *vs* M_{top}



Improvement of M_W Uncertainty with Sample Statistics

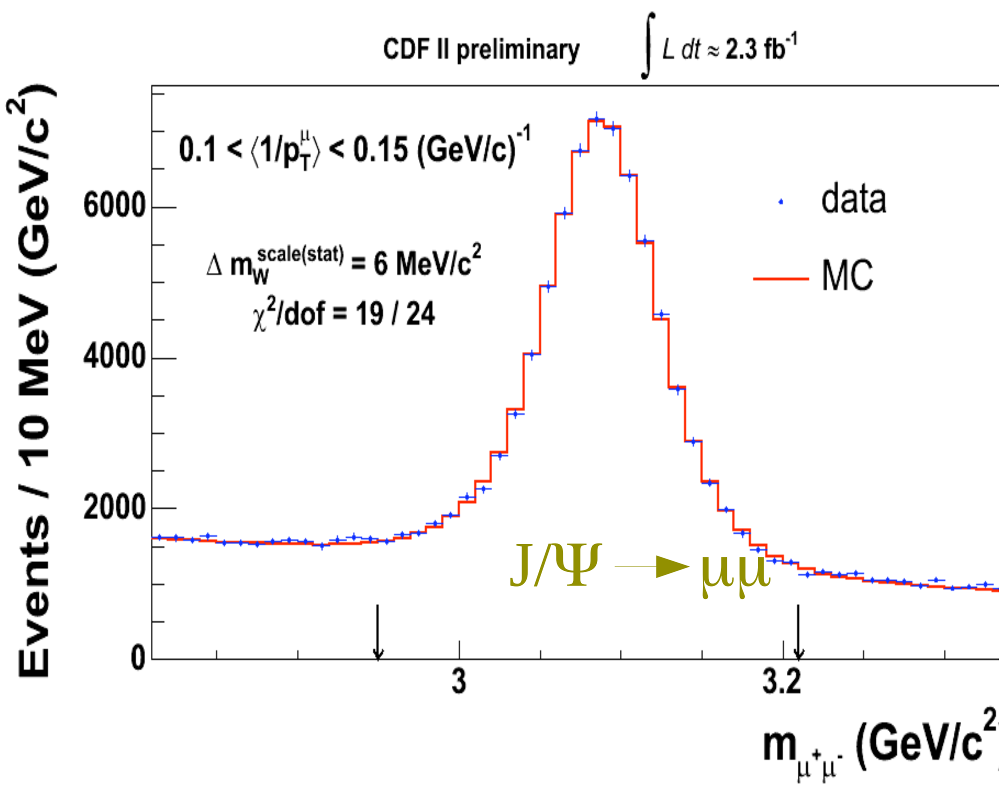


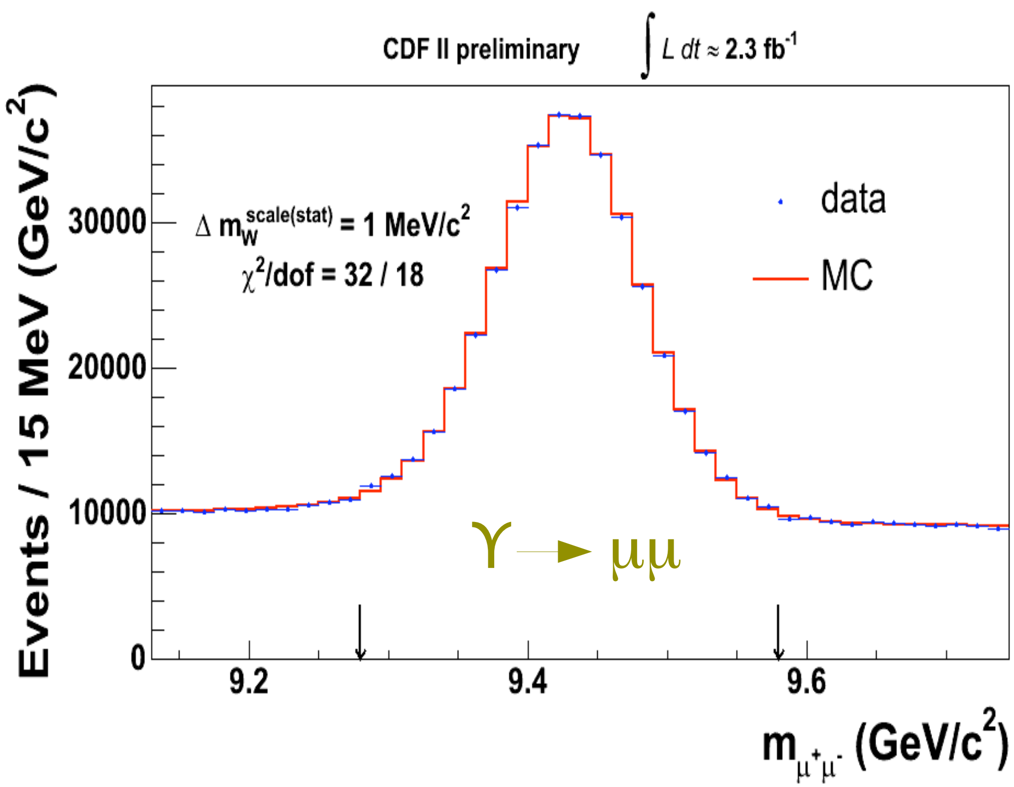
Next target: 15-20 MeV measurement of M_W from the Tevatron

Preliminary Studies of 2.3 fb^{-1} Data from CDF

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

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



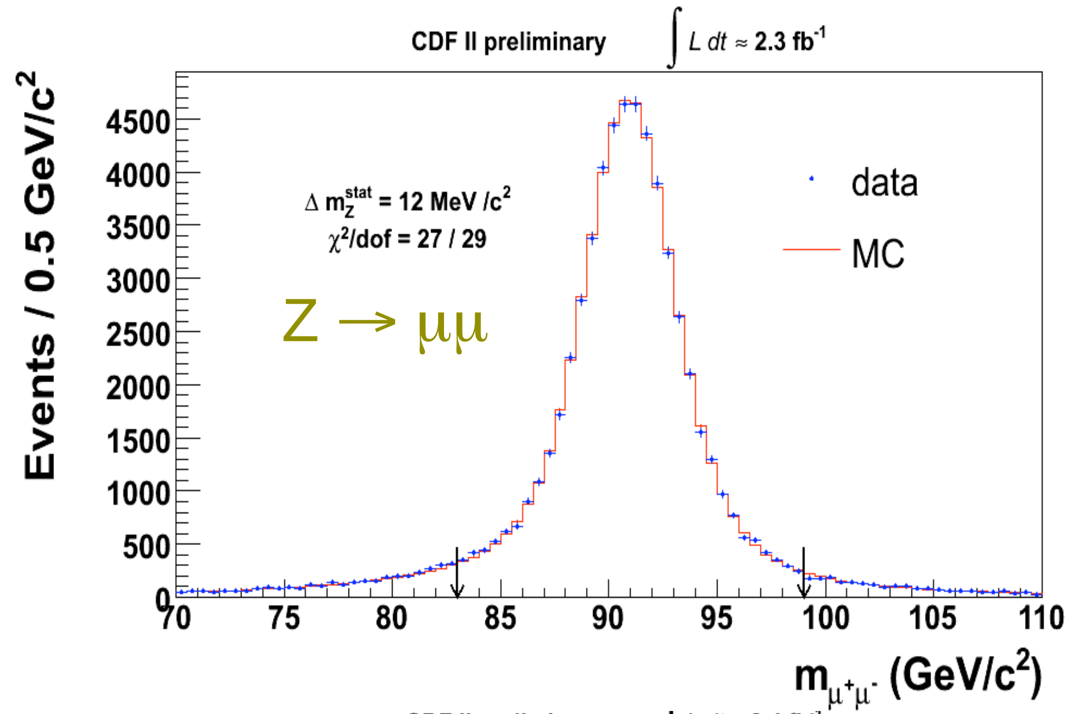


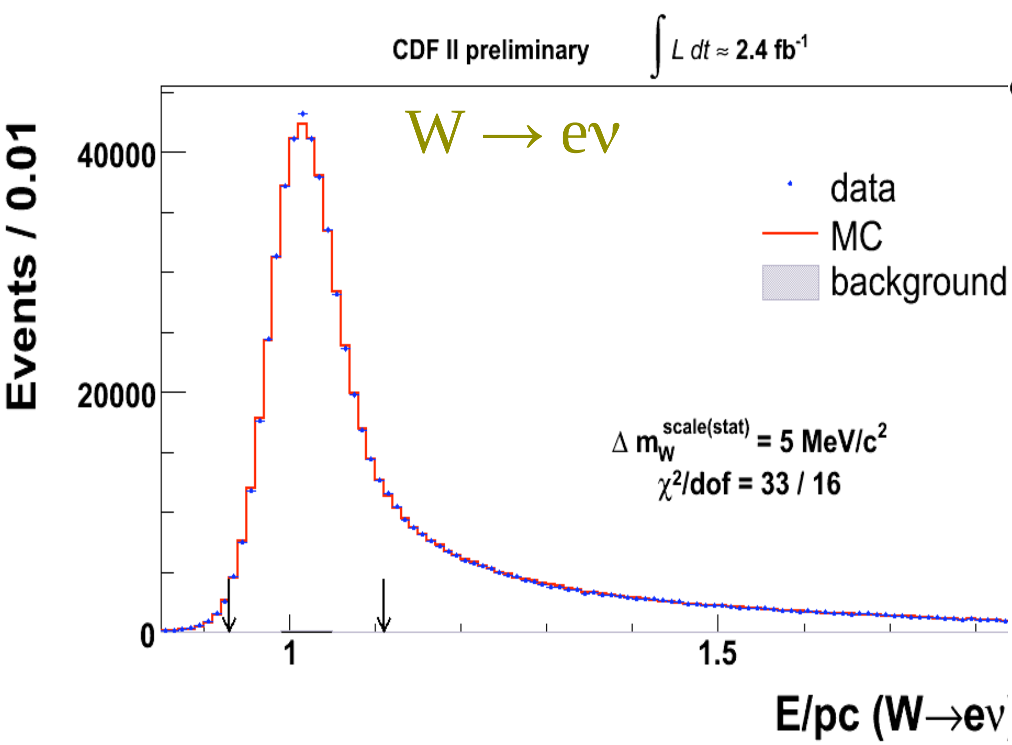
Preliminary Studies of 2.3 fb^{-1} Data

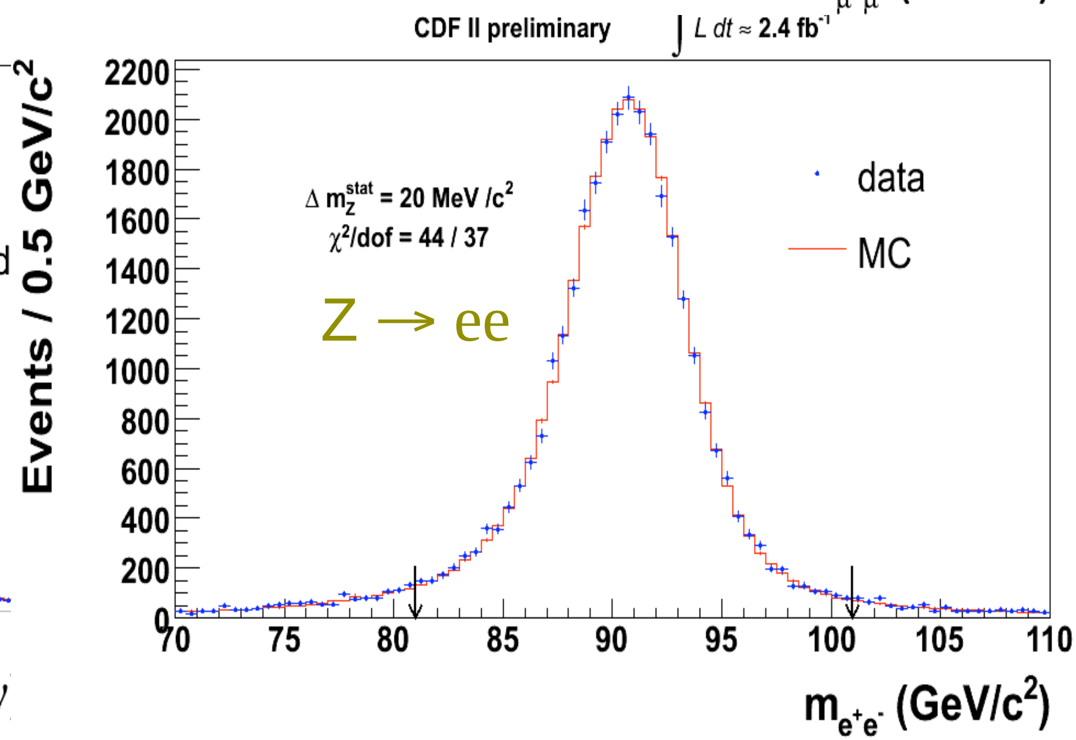
Statistical errors on all lepton calibration fits have scaled with statistics

Detector and data quality maintained over time

detailed calibrations in progress

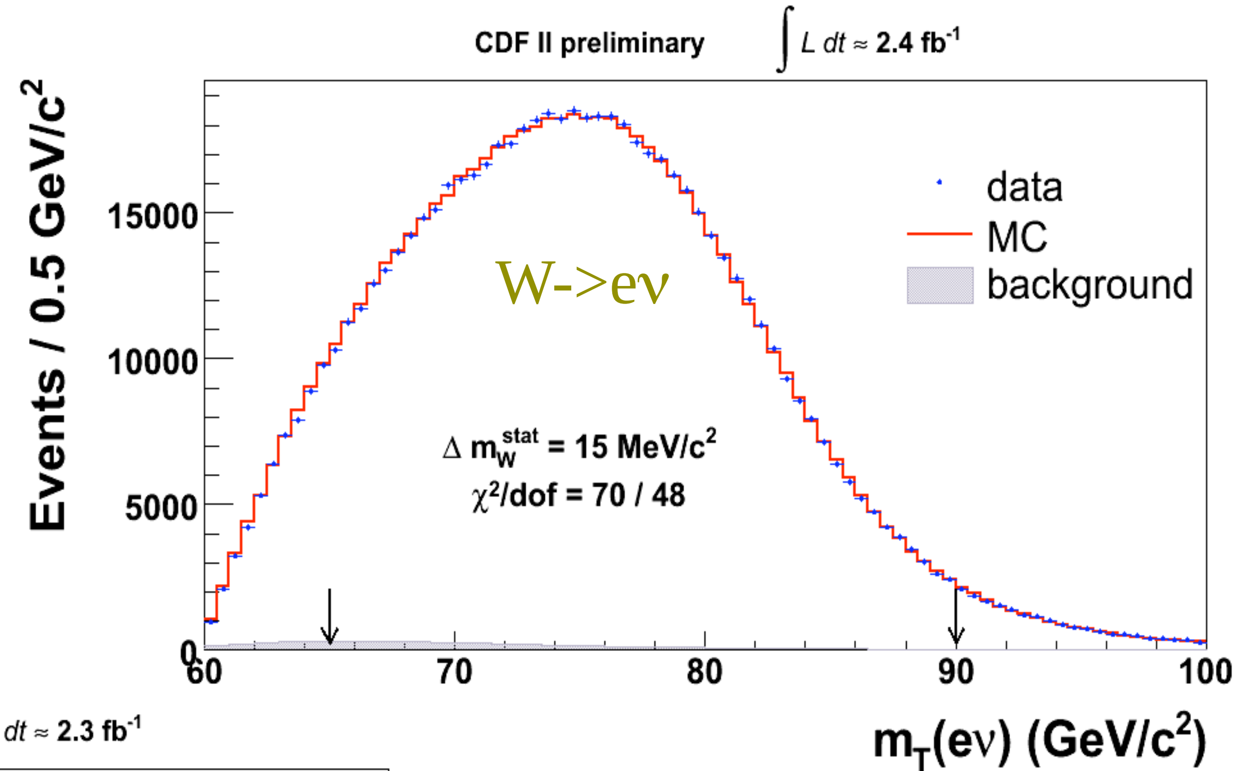


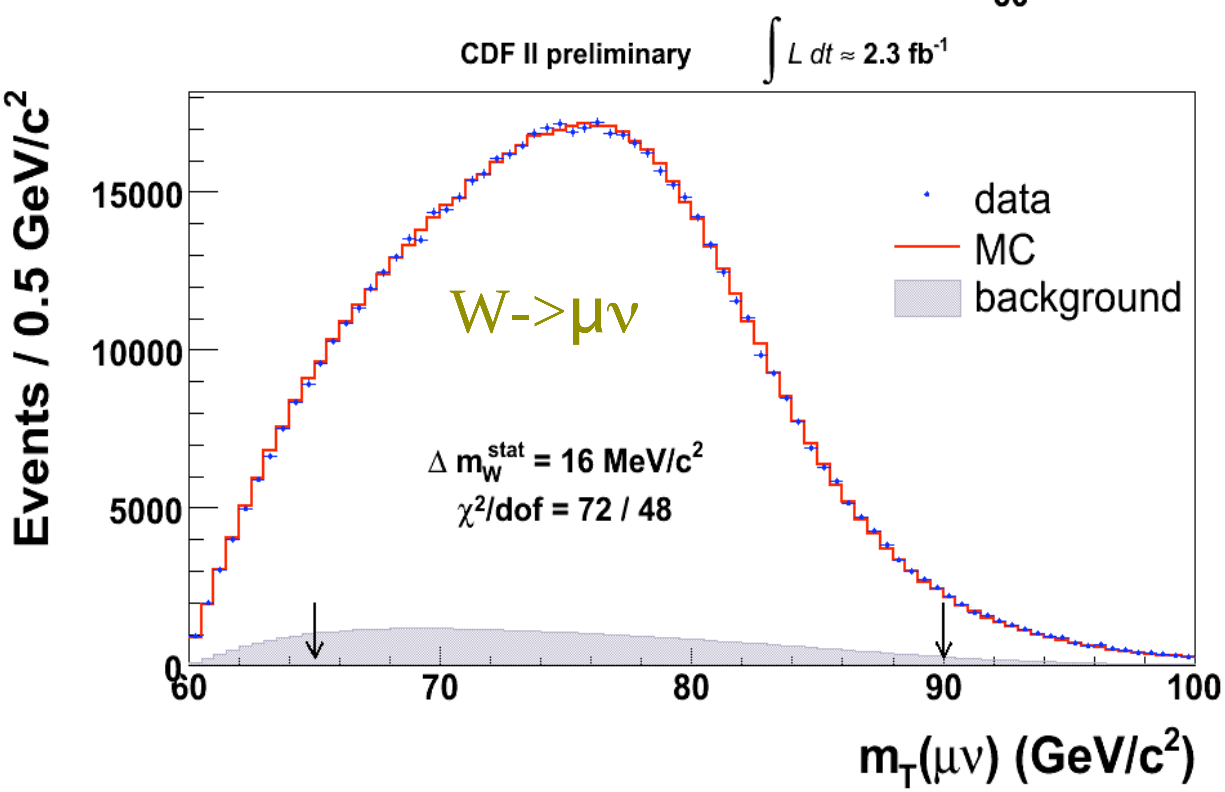




Preliminary Studies of 2.3 fb^{-1} Data

Recoil resolution not significantly degraded at higher instantaneous luminosity





statistical errors on transverse mass fits are scaling with statistics

M_W Measurement at LHC

- Very high statistics samples of W and Z bosons
  - 10 fb^{-1} at 14 TeV: 40 million W boson and 4 million Z boson candidates per decay channel per experiment
- Statistical uncertainty on W mass fit ~ 2 MeV
- Calibrating lepton energy response using the Z → *ll* mass resonance, best-case scenario of statistical limit ~ 5 MeV precision on calibrations
- Calibration of the hadronic calorimeter based on transverse momentum balance in Z → *ll* events also ~ 2 MeV statistical limit
- Total uncertainty on M_W ~ 5 MeV if Z → *ll* data can measure all the W boson systematics

M_W Measurement at LHC

- Can the $Z \rightarrow ll$ data constrain all the relevant W boson systematics?
- Production and decay dynamics are slightly different
  - Different quark parton distribution functions
  - Non-perturbative (e.g. charm mass effects in $cs \rightarrow W$) effects
  - QCD effects on polarization of W *vs* Z affects decay kinematics
- Lepton energies different by ~10% in W *vs* Z events
- Presence of second lepton influences the Z boson event relative to W
- Reconstructed kinematic quantity different (invariant vs transverse mass)
- Subtle differences in QED radiative corrections
- ....
- .... (A.V. Kotwal and J. Stark, Ann. Rev. Nucl. Part. Sci., vol. 58, Nov 2008)

M_W Measurement at LHC

- Can the Z → *ll* data constrain all the relevant W boson systematics?
- Can we add other constraints from other mass resonances and tracking detectors ?

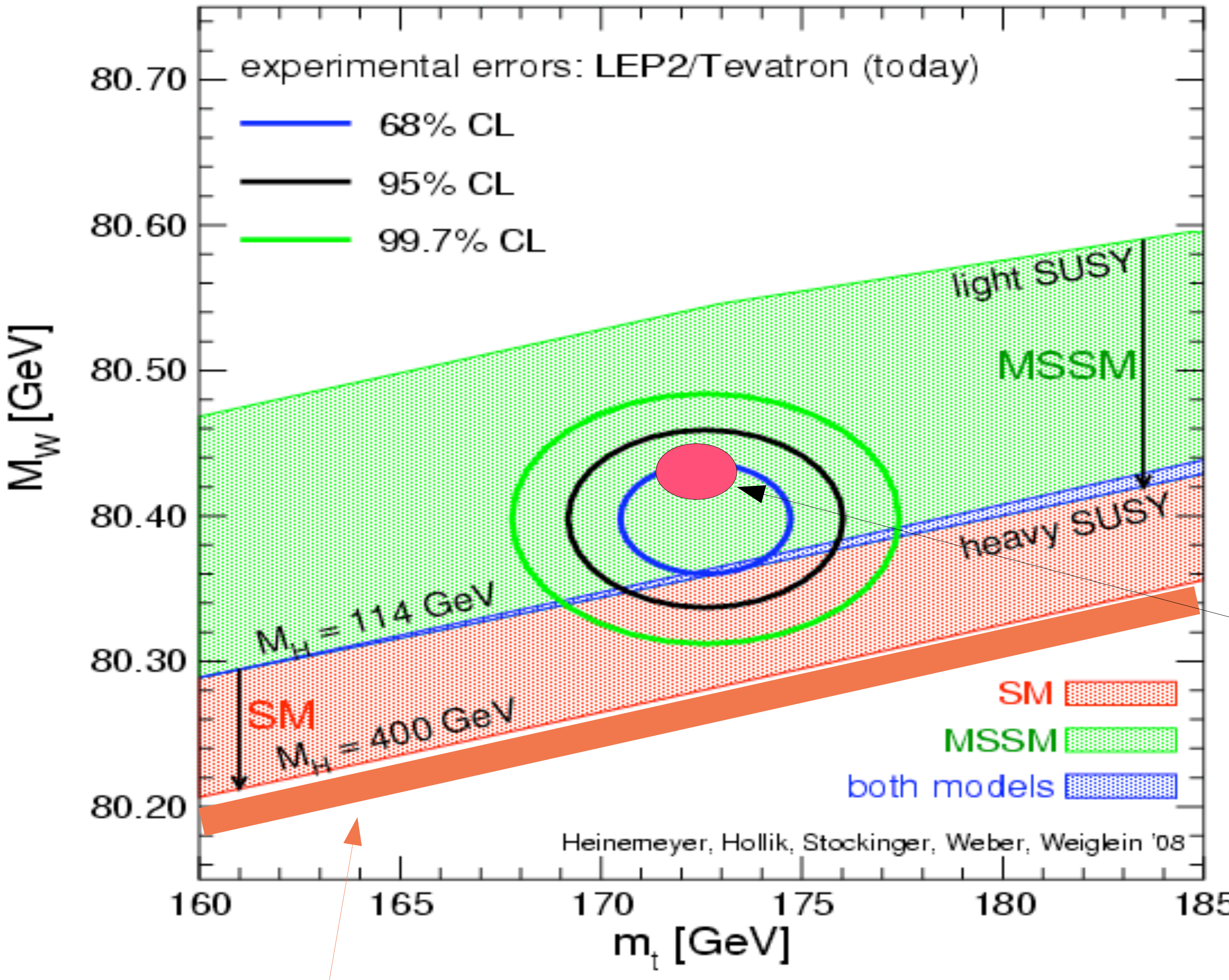
- With every increase in statistics of the data samples, we climb a new learning curve on the systematic effects
  - Improved calculations of QED radiative corrections available
  - Better understanding of parton distributions from global fitting groups (CTEQ, MSTW, Giele *et al*)

- large sample statistics at the LHC imply the potential is there for 5-10 MeV precision on M_W

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:
  - $M_W = 80413 \pm 48$ MeV
- D0 Run 2 W mass result with 1 fb^{-1} data:
  - $M_W = 80401 \pm 43$ 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)
- Learning as we go: Tevatron → LHC may produce $\delta M_W \sim 5\text{-}10$ MeV

A possible Future Scenario



$\delta M_W = 10$ MeV

$\delta m_{top} = 0.5$ GeV

Higgs discovery with a large Higgs mass

Combined Results

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