Measurement of the W Boson Mass at the Tevatron and LHC

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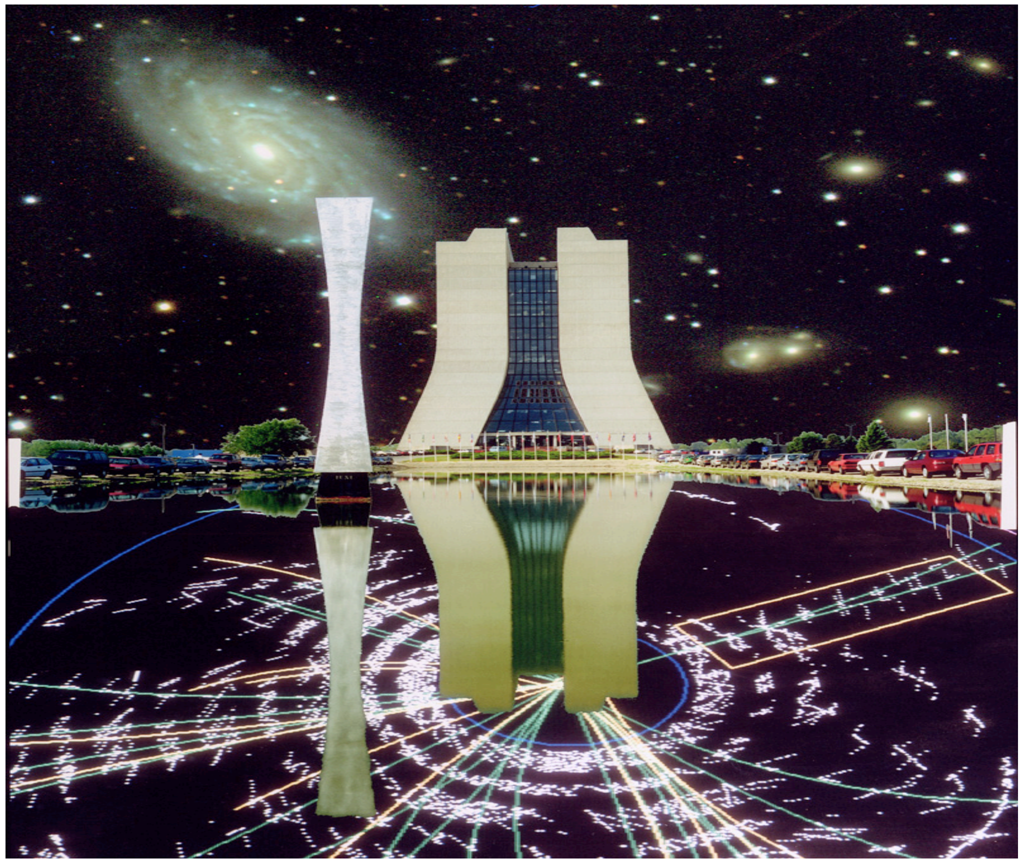


High Energy Physics Seminar
University of Maryland / Johns Hopkins University
December 2, 2009

Spontaneous Symmetry Breaking

- 2008 Nobel Prize in Physics

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

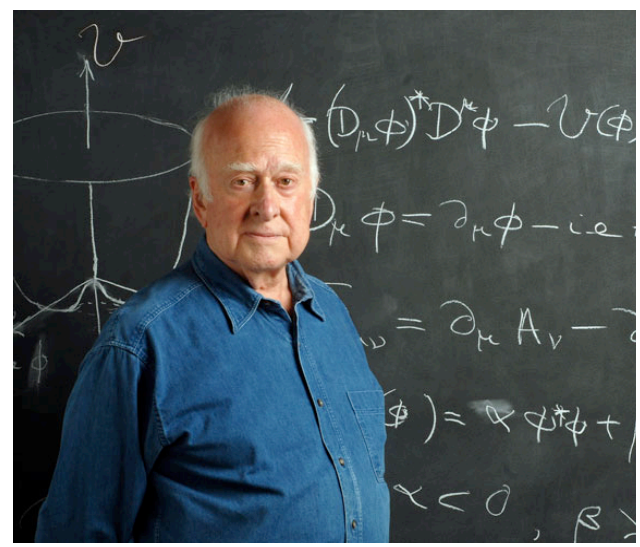
Yoichiro Nambu

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

Outline

- Importance of precision electroweak observables in the gauge and Higgs sectors of the Standard Model
- Current and future measurements of the W boson mass at the Tevatron
- W boson mass measurement at the LHC
  - potential for high precision
  - issues to address
- Summary

Peter Higgs



Motivation

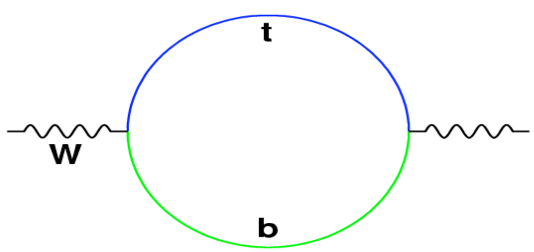
- The electroweak gauge sector of the standard model is constrained by three precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\ (1) \times 10^{-5}\ \text{GeV}^{-2}$

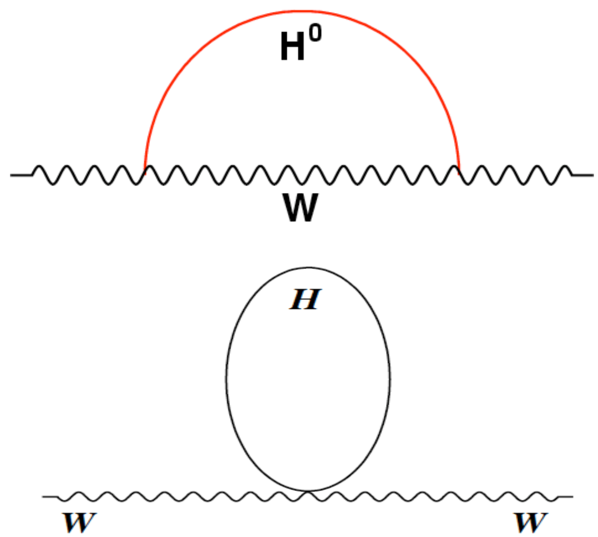
    $M_Z = 91.1876\ (21)\ \text{GeV}$
- At tree-level, these parameters are related to M_W by
  - $M_W{}^2 = \pi\alpha_{EM} / \sqrt{2}G_F \sin^2\vartheta_W$
    - Where ϑ_W is the weak mixing angle, defined by (in the on-shell scheme)

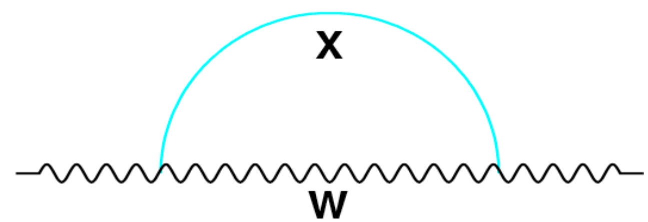
      $$\cos\vartheta_W = M_W/M_Z$$

Motivation

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



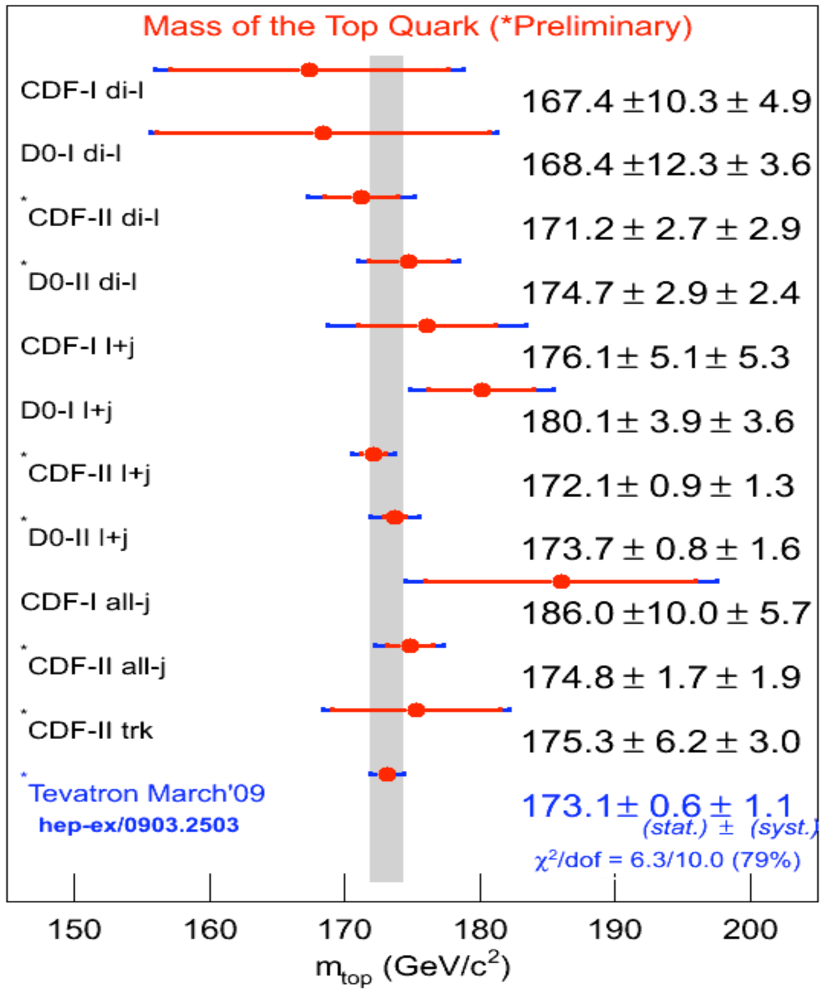




Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\text{tree})]^2$
with the predictions $(\rho - 1) \sim M_{top}^2$ and $(\rho - 1) \sim \ln M_H$

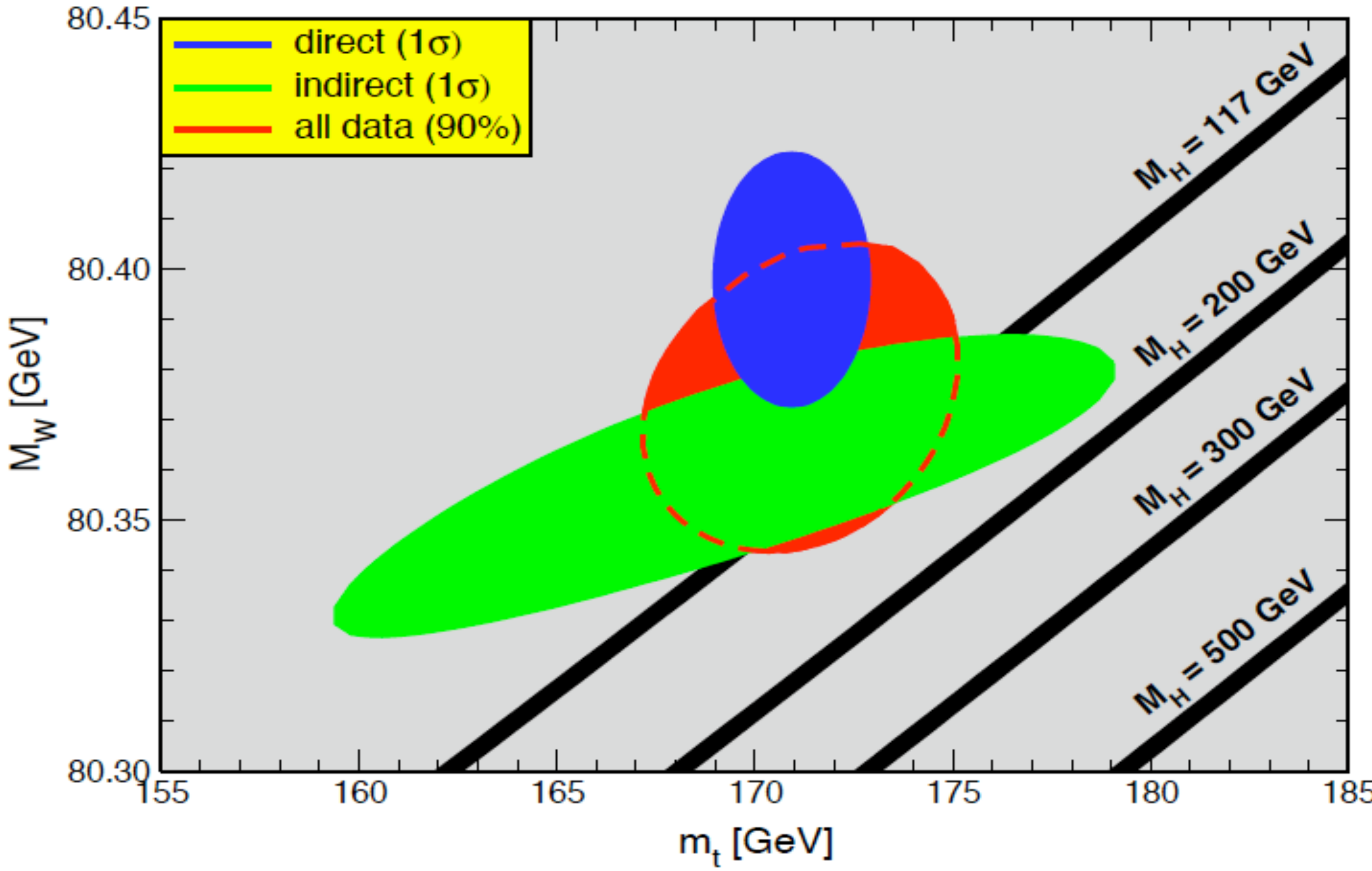
- In conjunction with M_{top}, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

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!

Uncertainty from $\alpha_{EM}(M_Z)$

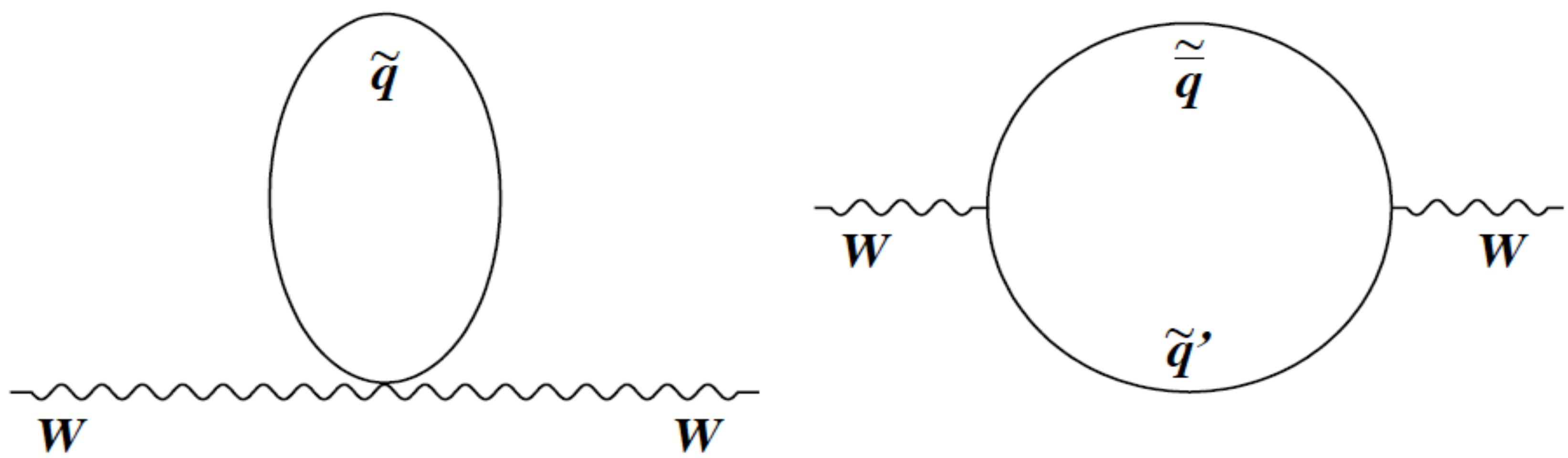


Line thickness due to $\delta\alpha_{EM}$

- $\delta\alpha_{EM}$ dominated by uncertainty from non-perturbative contributions: hadronic loops in photon propagator at low Q^2
- equivalent $\delta M_W \approx 4$ MeV for the same Higgs mass constraint
  - Was equivalent $\delta M_W \approx 15$ MeV a decade ago !

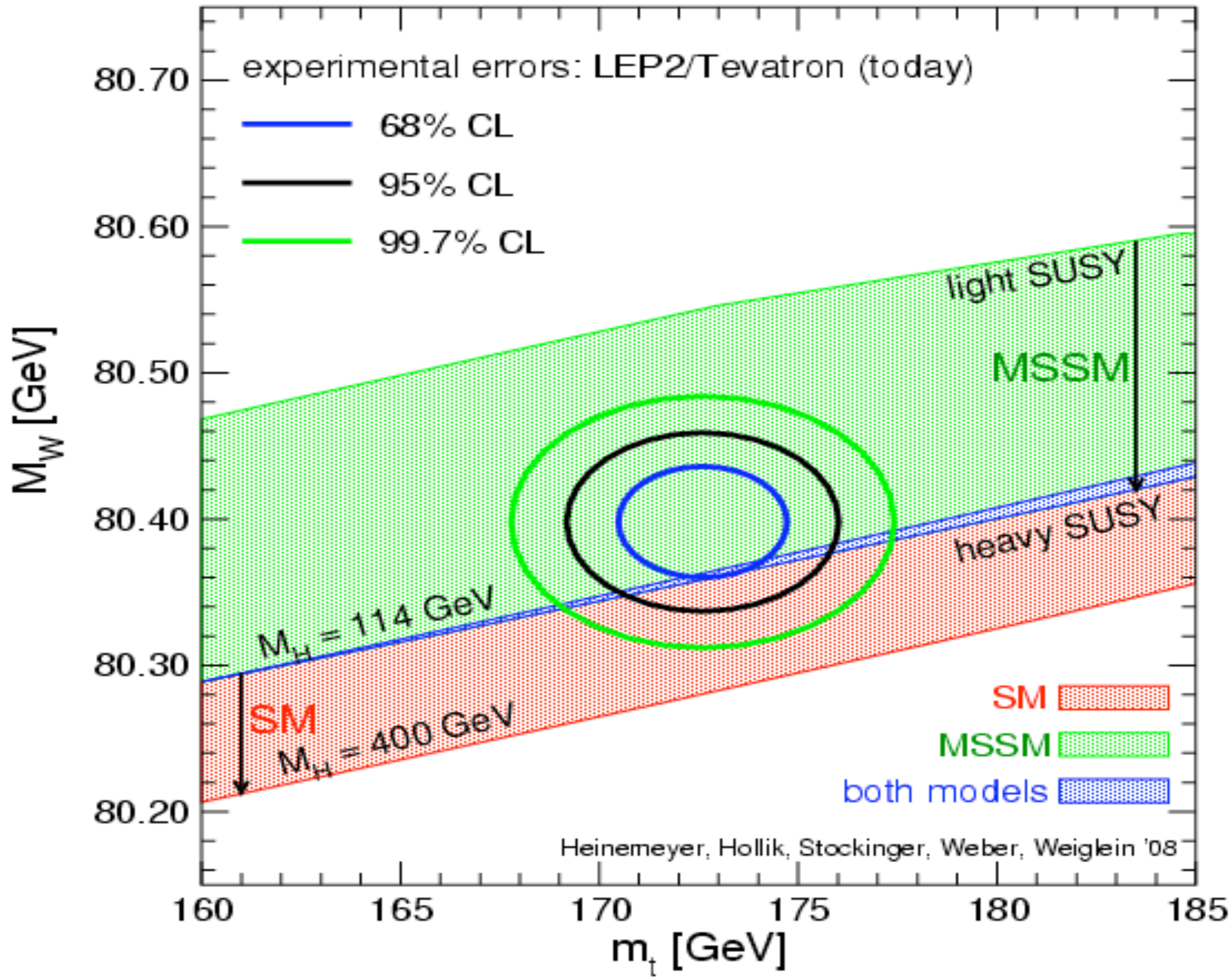
Contributions from Supersymmetric Particles

(or any other model of new physics with calculable radiative corrections)



- Radiative correction depends on mass splitting between squarks in SU(2) doublet
- After folding in limits on SUSY particles from direct searches, SUSY loops can contribute 100-200 MeV to M_W
- Ratio of squark masses > 2.5 already disfavored by precision electroweak measurements

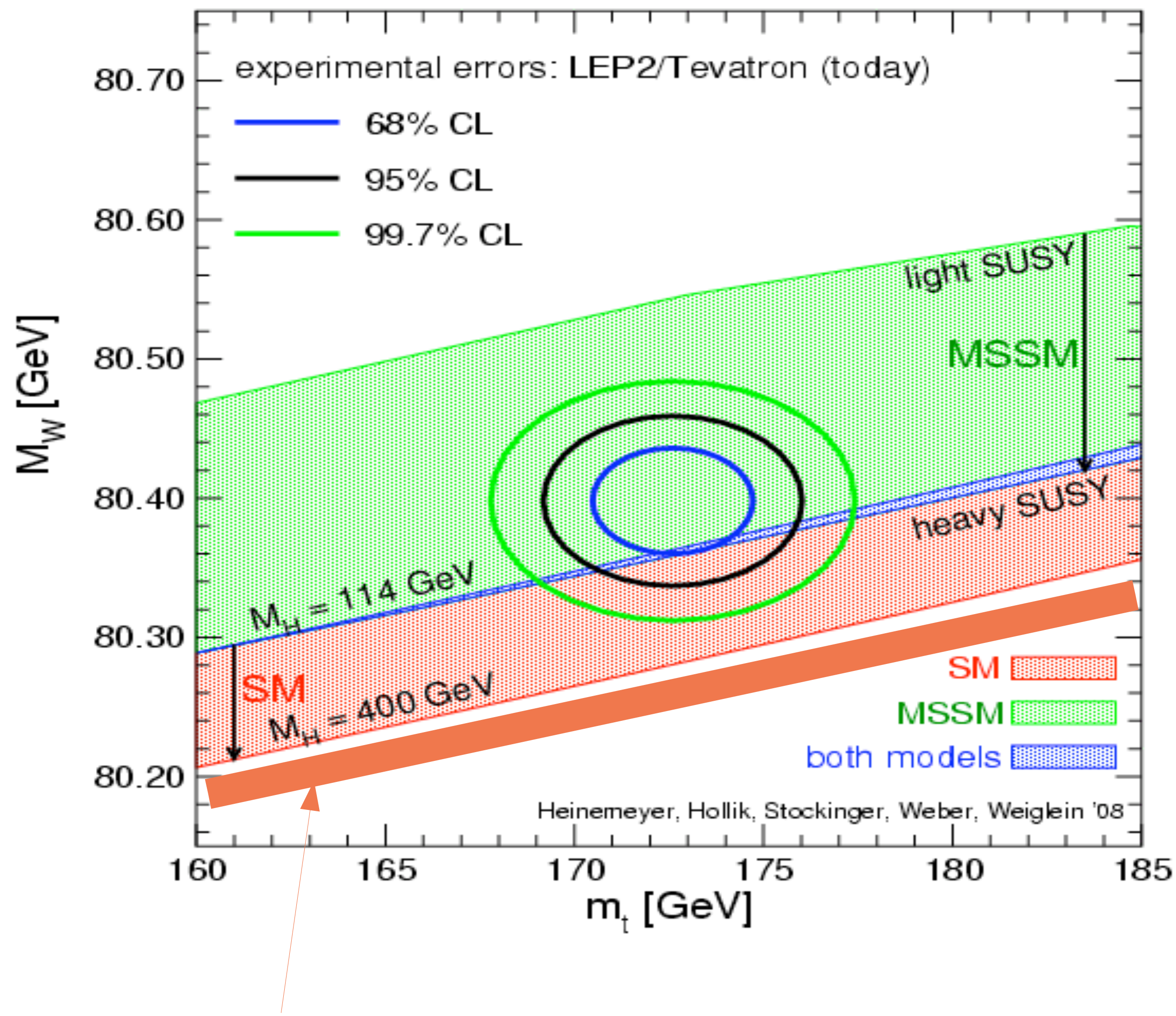
M_W *vs* M_{top}



How will this plot change after (if) LHC observes

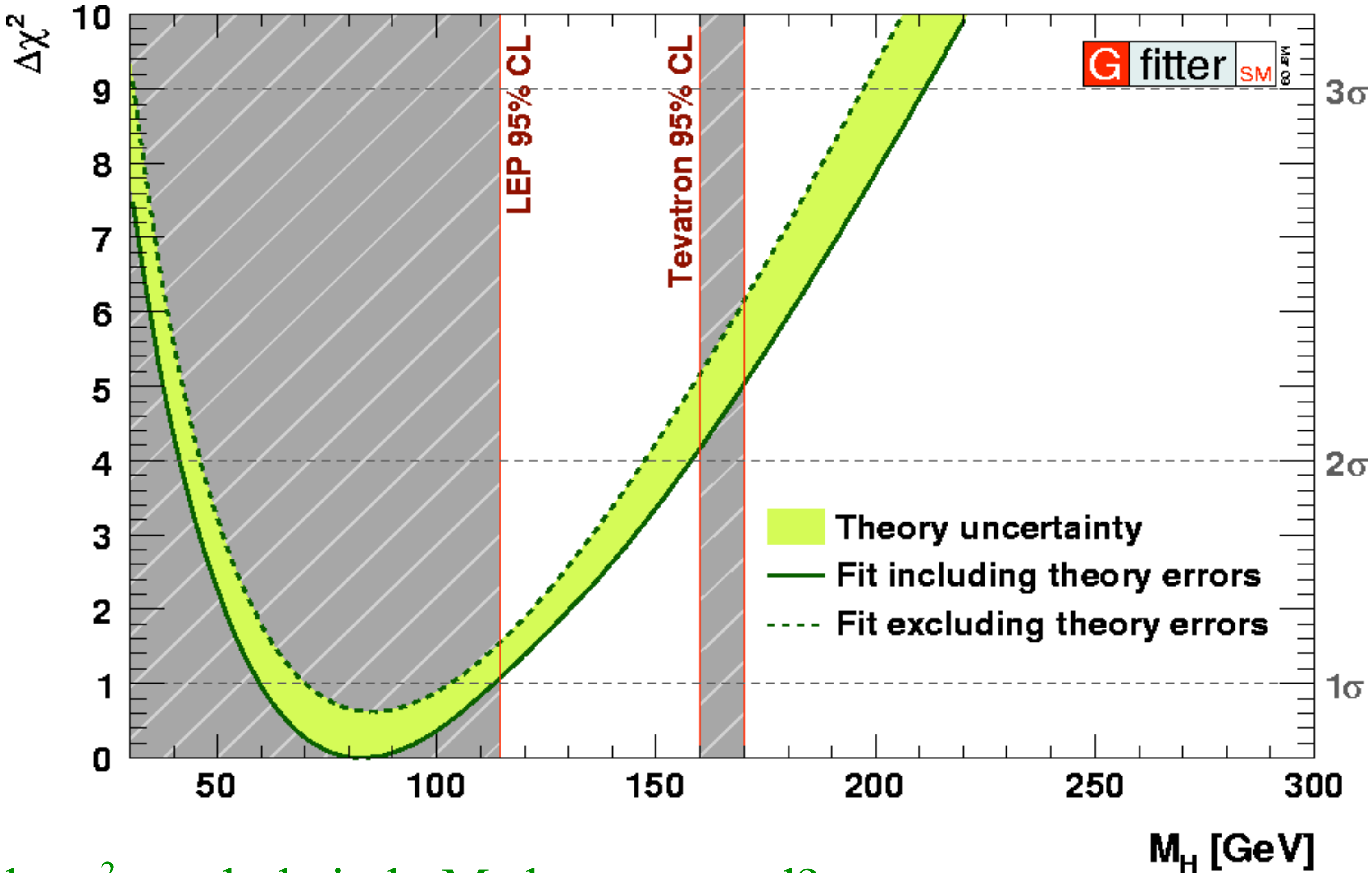
(I) the Higgs (ii) one or more SUSY particles (iii) something else ?

M_W *vs* M_{top}



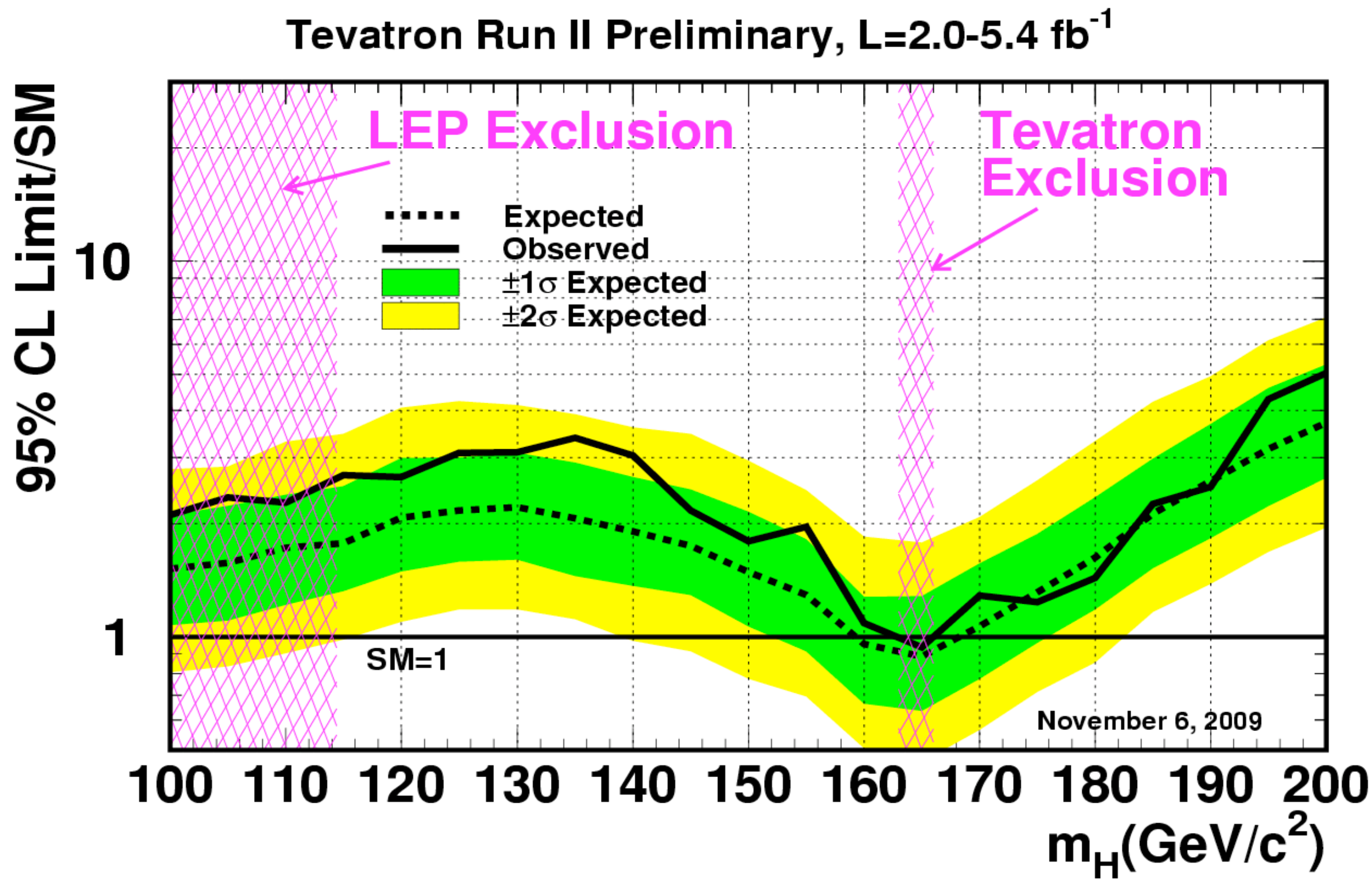
Higgs discovery with a large Higgs mass (measured with say 25% precision) would create an interesting landscape

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?
- Can 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?

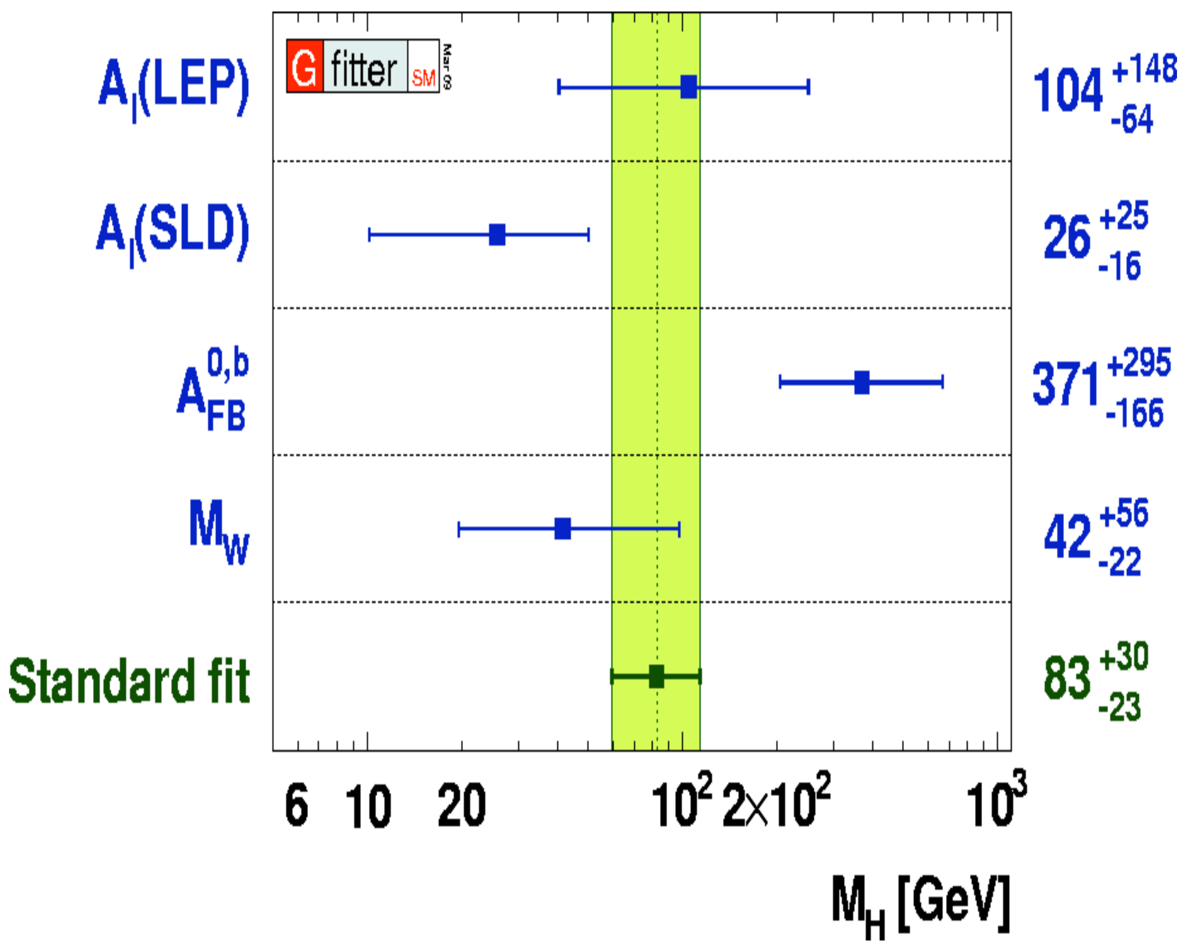
Current Tevatron SM Higgs Limits



- Tevatron sensitivity within factor of 2 of standard model for $M_H < 185$ GeV
- Doubling of dataset (10 fb^{-1} per experiment) quite likely by 2011
- Analysis improvements have contributed as much as luminosity increases
- More analysis improvements being developed

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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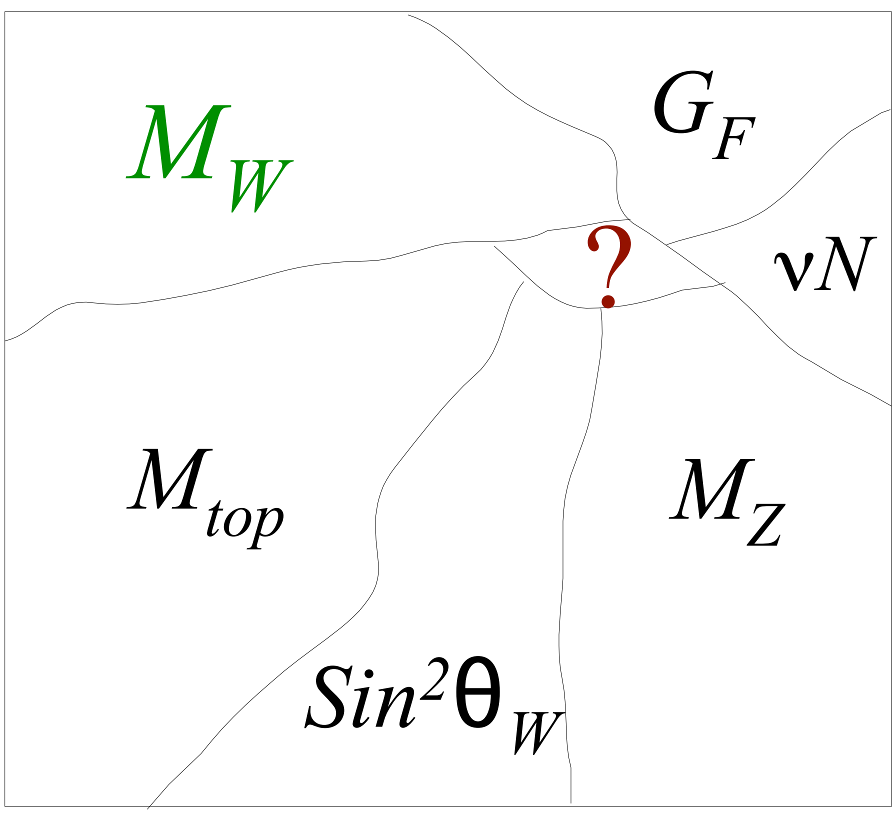

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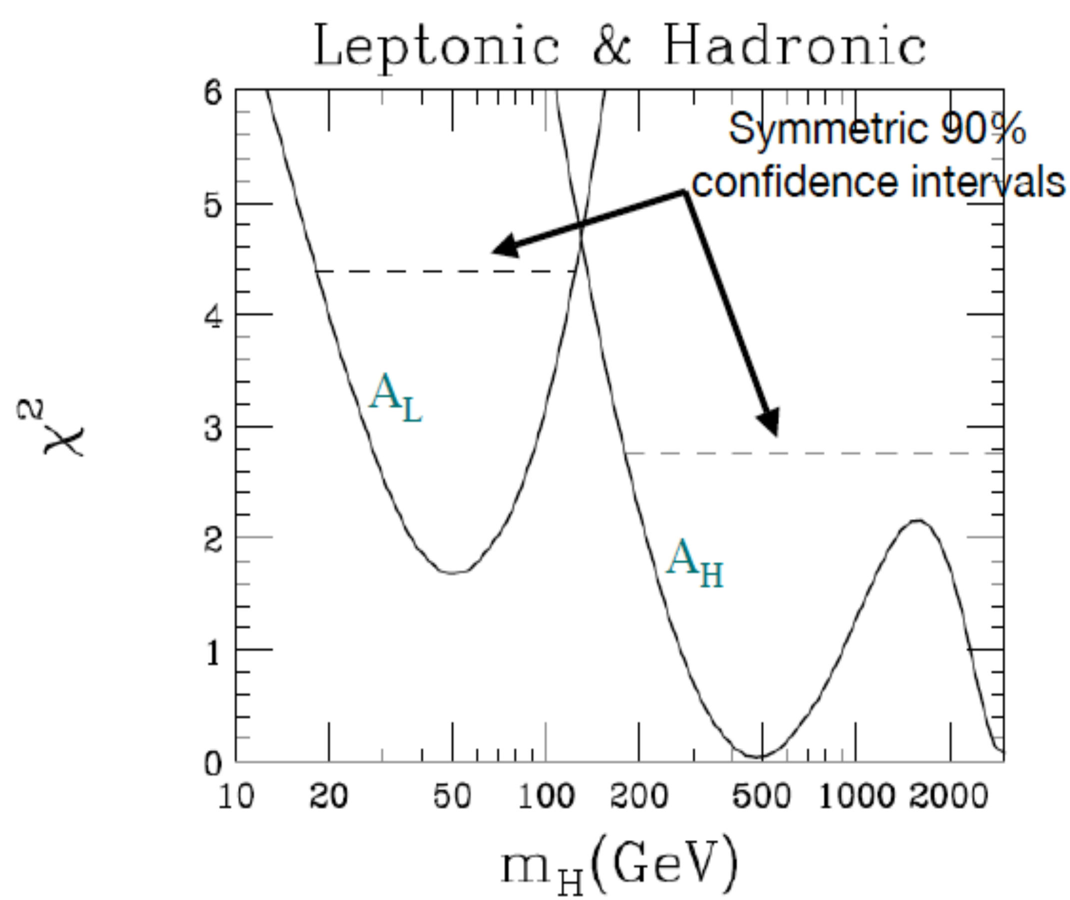
Motivation II

- Separate fits for M_H using only leptonic and only hadronic measurements of asymmetries: marginal difference in preferred Higgs mass (from M. Chanowitz, February 2007 Seminar, Fermilab)

χ^2 Distributions: Leptonic vs. Hadronic



Possible explanations:

Statistical fluctuation

Systematic experimental bias

New physics contributions:

MSSM — Altarelli *et. al.*

4th family — Okun *et. al.*

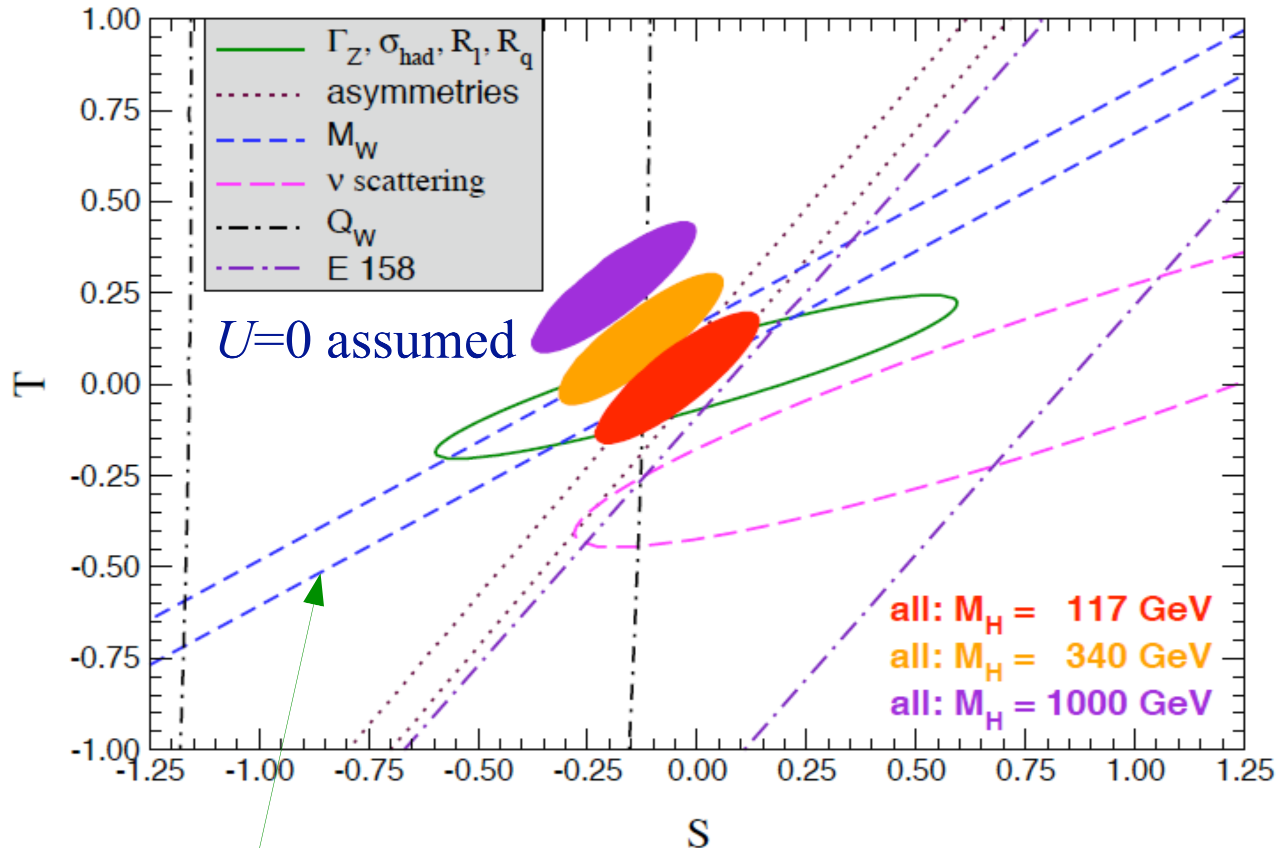
Opaque branes — Carena *et. al.*

To raise M_H prediction of leptonic asymmetries

New physics in b-quark asymmetry requires large modification to Zbb vertex

Motivation III

- Generic parameterization of new physics contributing to W and Z boson self-energies: *S, T, U* parameters
  - Does not parameterize new physics in boson-fermion vertices



(From PDG 2009)

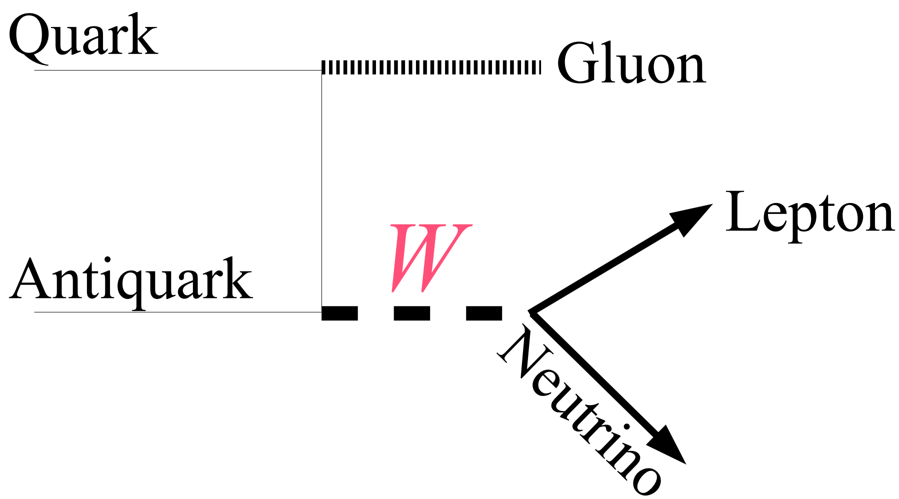
Asymmetries and M_W are the most powerful observables in this parameterization

Motivational Summary

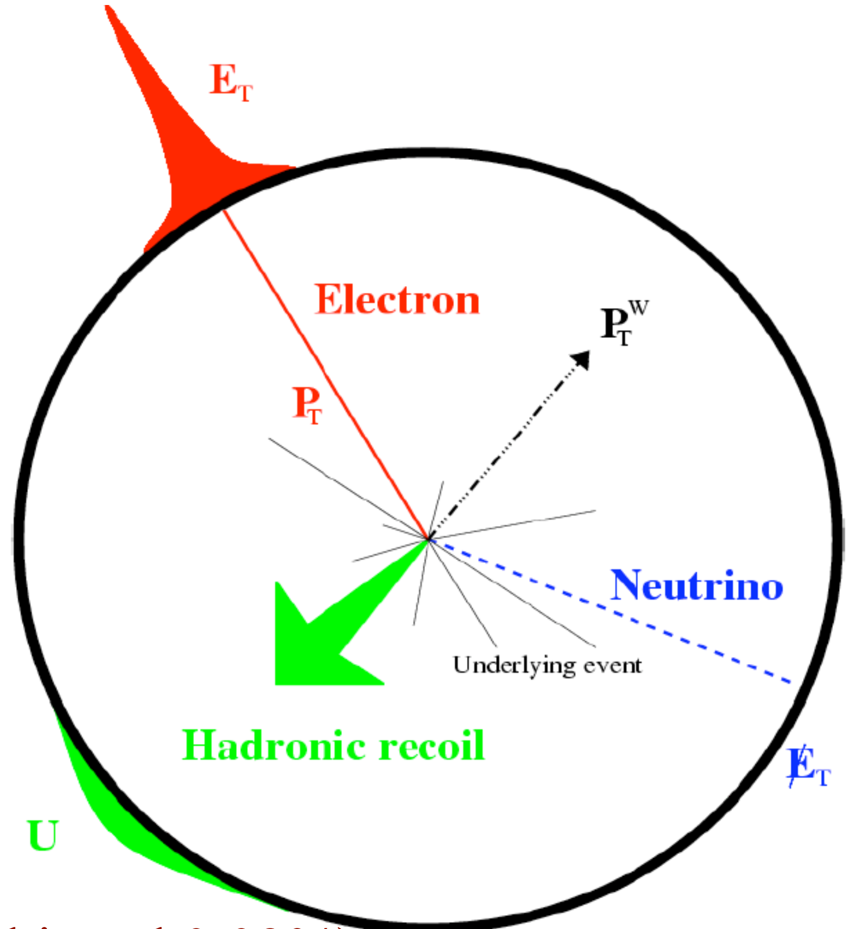
- At the dawn of the LHC era, we don't know
  - Mechanism of electroweak symmetry breaking
  - Solution to electroweak scale *vs* Planck scale hierarchy
  - …
- If there is new physics, there is a large range of models
- Precision electroweak measurements have provided much guidance
  - But some intriguing tension in electroweak fits already
- Will LHC discoveries decrease or increase this tension?
- Higher precision on electroweak observables makes LHC discoveries *even* more interesting:
  - Guide interpretation of what we see
  - Triangulate for what is not yet seen
  - M_W has become a major player, and becomes more powerful as precision keeps improving

W Boson Mass
Analysis Strategy

W Boson Production at the Tevatron



Quark-antiquark annihilation dominates (80%)

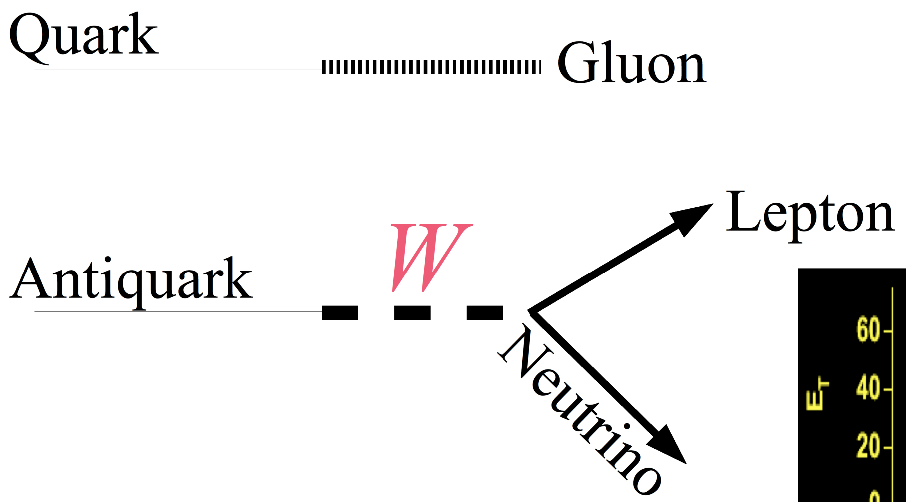


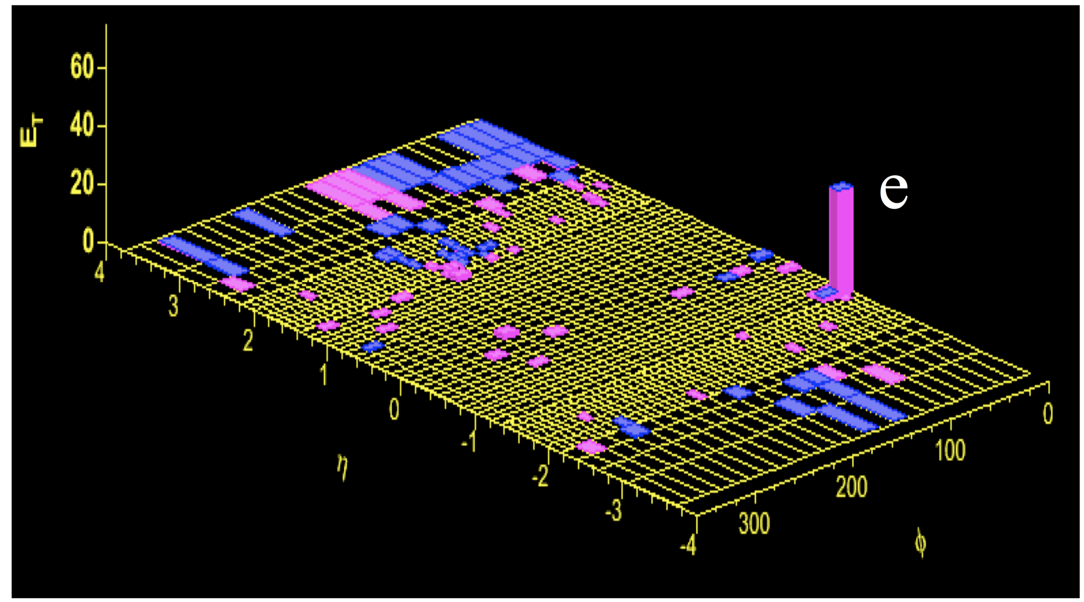
Lepton p_T carries most of W mass information, can be measured precisely (achieved 0.03%)

Initial state QCD radiation is $O(10 \text{ GeV})$, 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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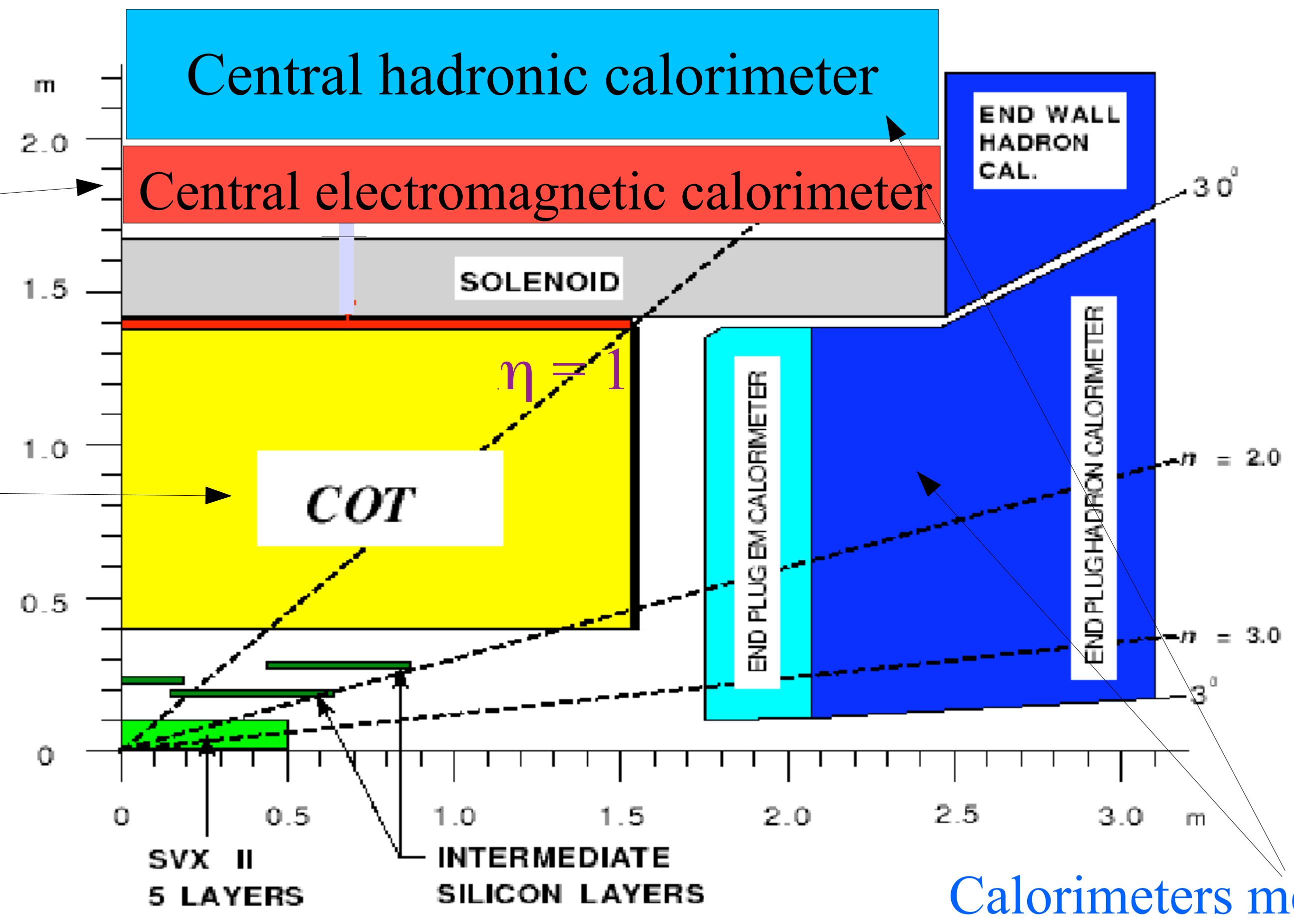
Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

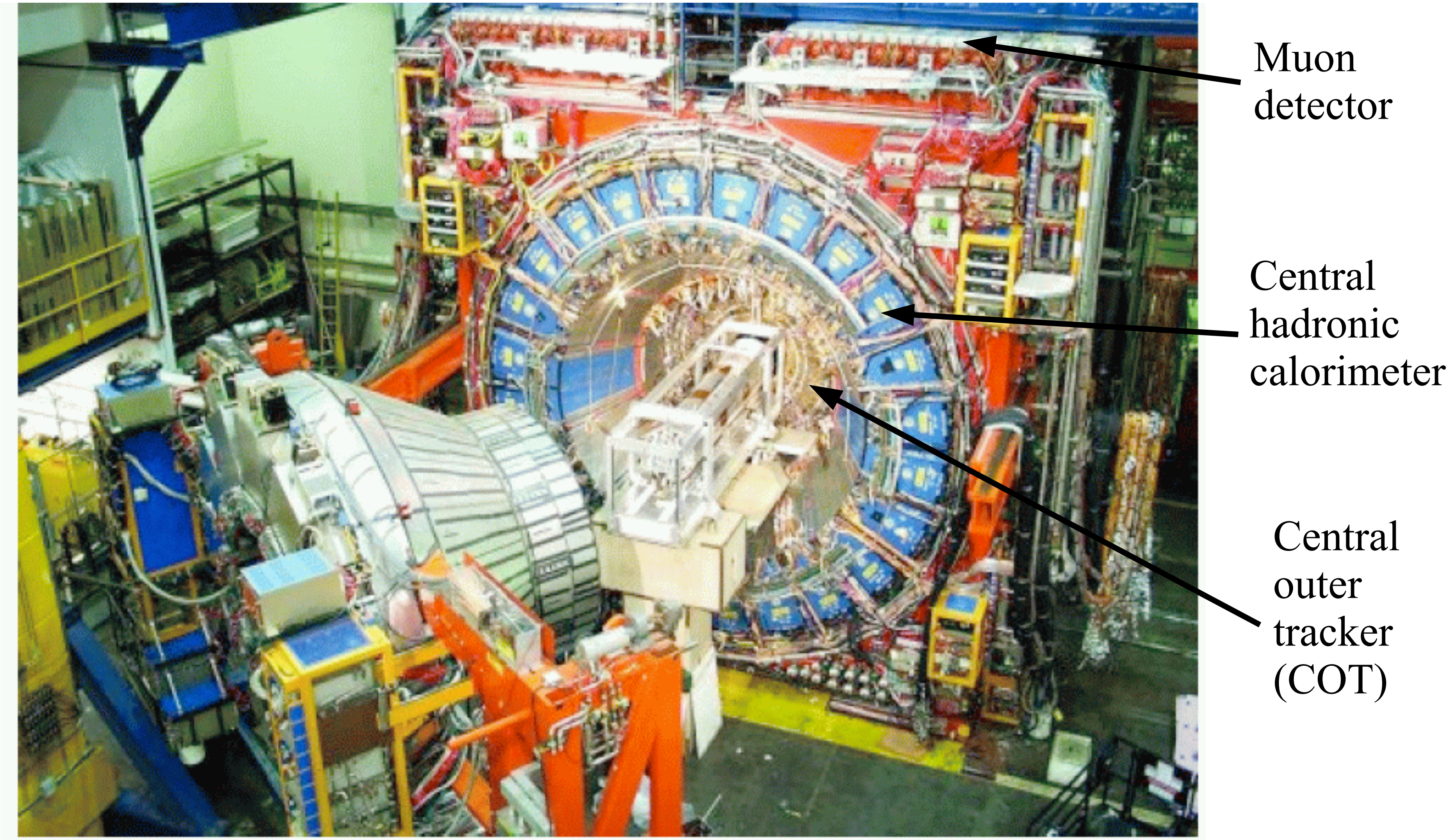
COT provides precise lepton track momentum measurement

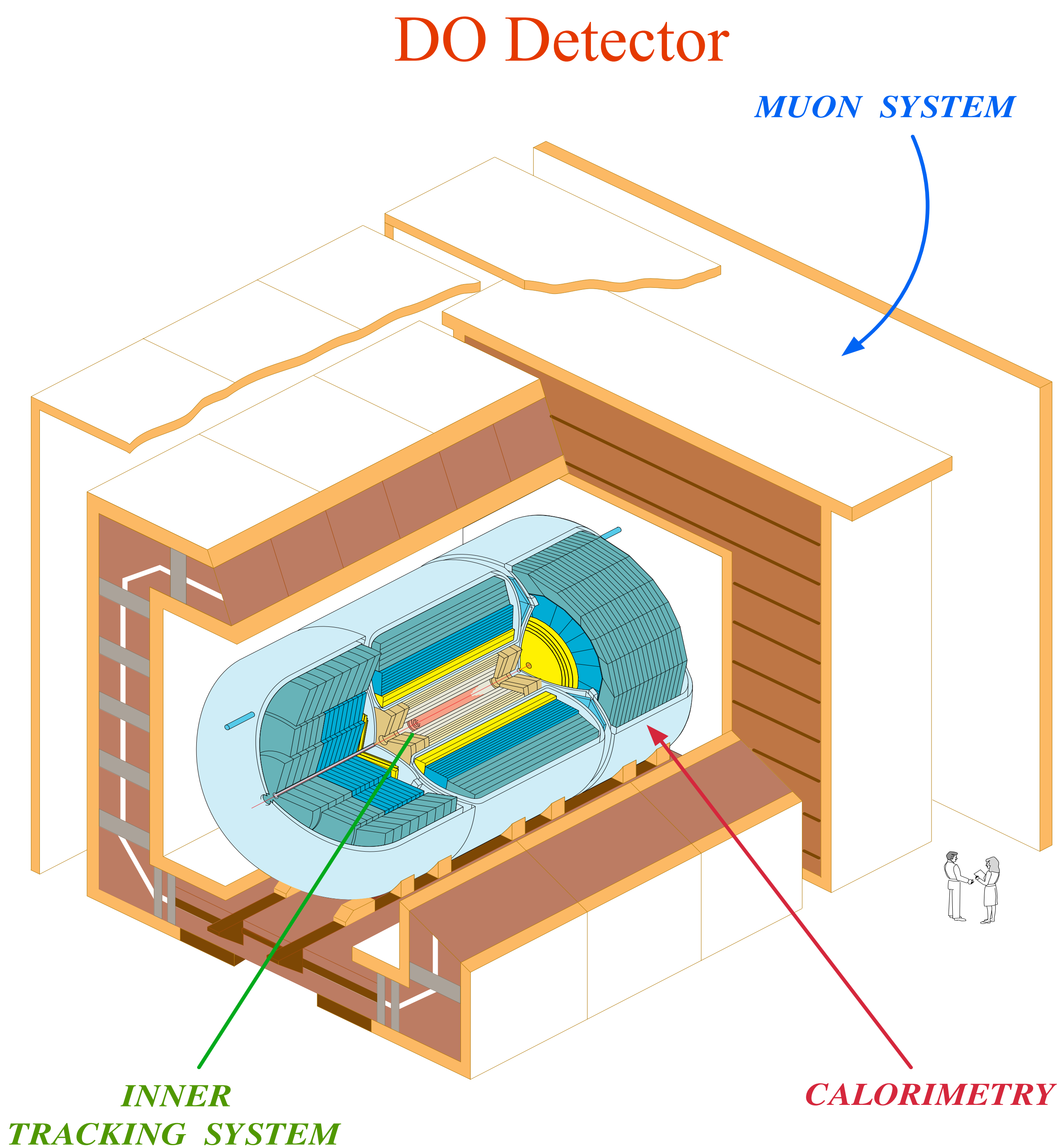


Calorimeters measure hadronic recoil particles

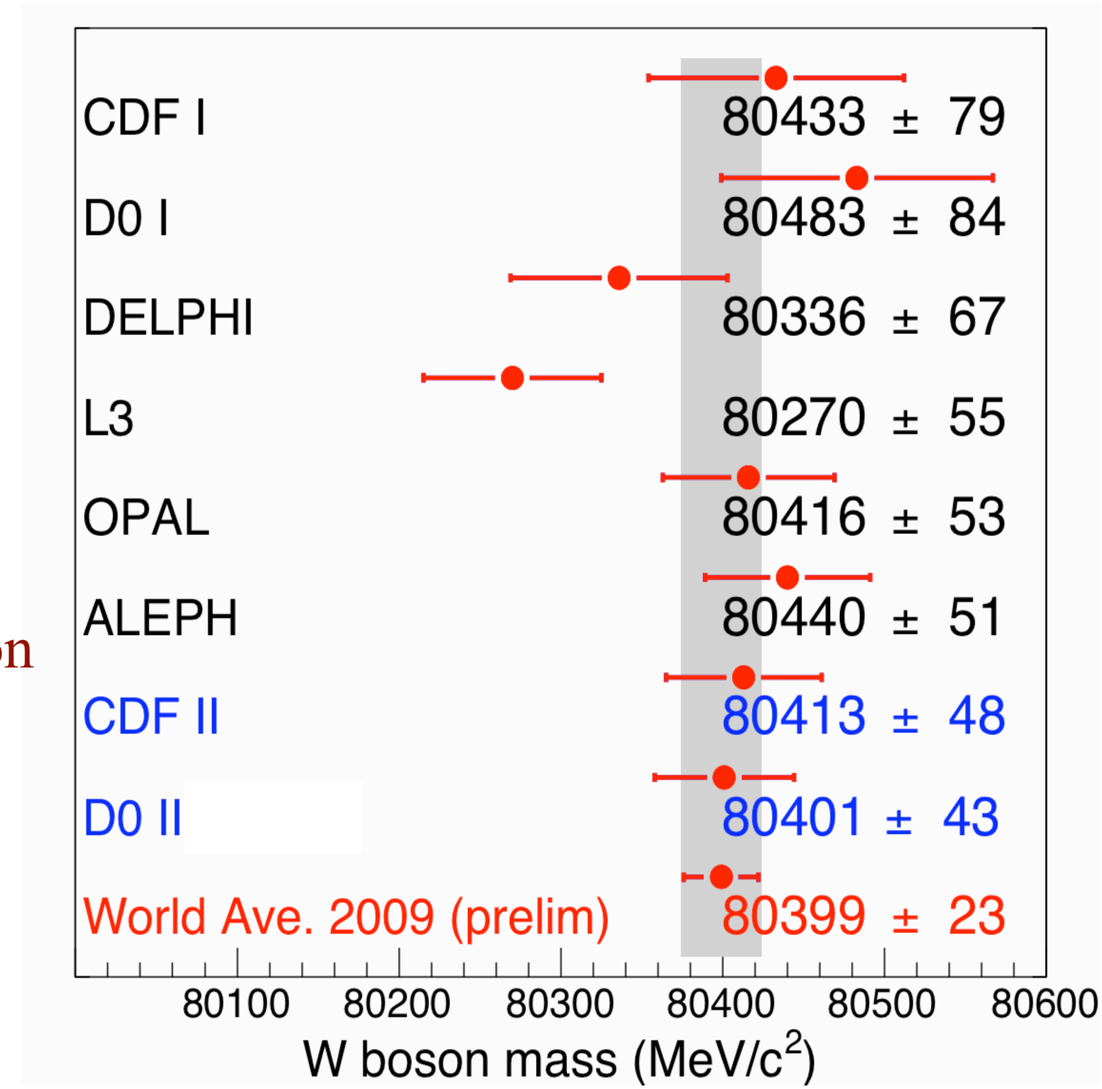
Select W and Z bosons with central (| **η** | < 1) leptons

Collider Detector at Fermilab (CDF)




DO Detector
MUON SYSTEM
INNER
TRACKING SYSTEM
CALORIMETRY

W Boson Mass Measurements



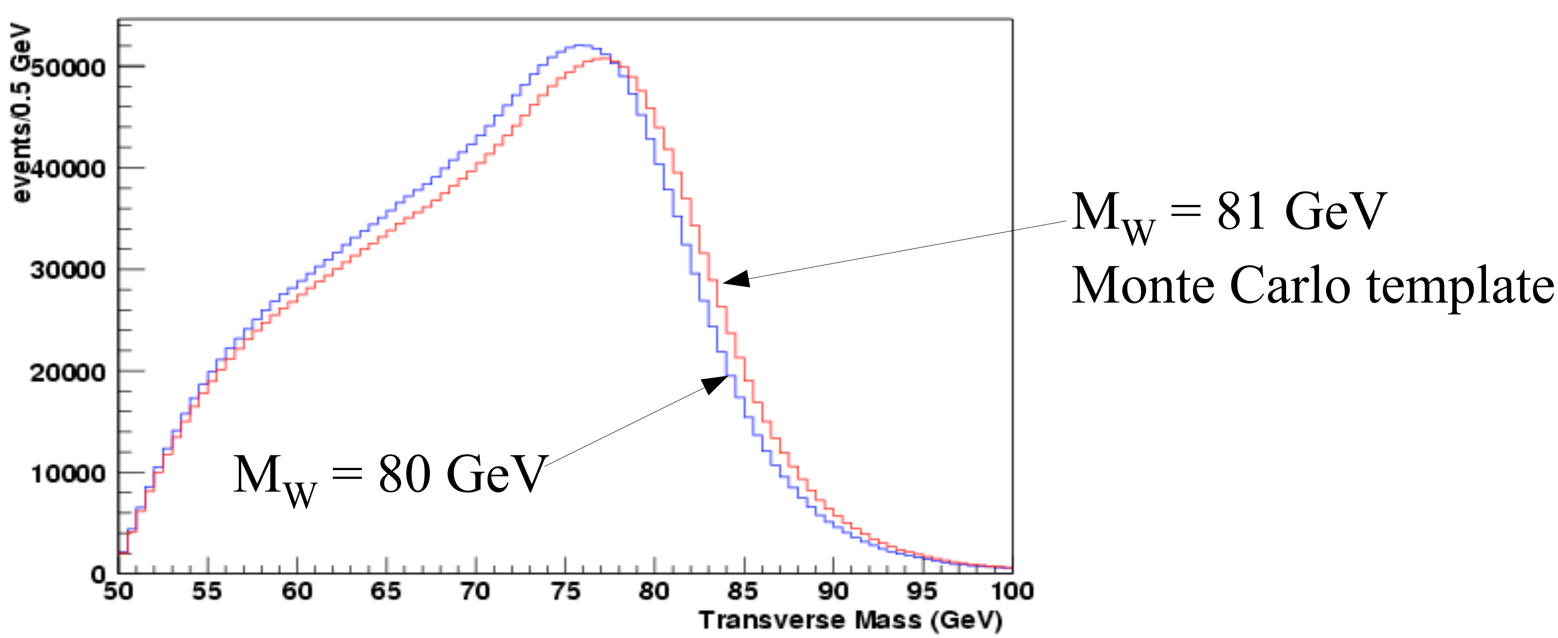
CDF: 200 pb^{-1}, electron and muon channels

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

(D0 Run II: PRL 103:141801, 2009)
(CDF Run II: PRL 99:151801, 2007; PRD 77:112001, 2008)

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



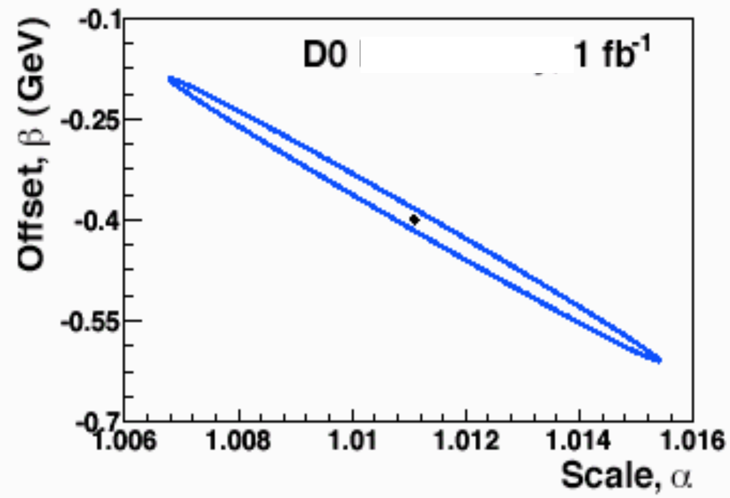
- CDF and D0 extract the W mass from three kinematic distributions: Transverse mass, charged lepton p_T and neutrino p_T

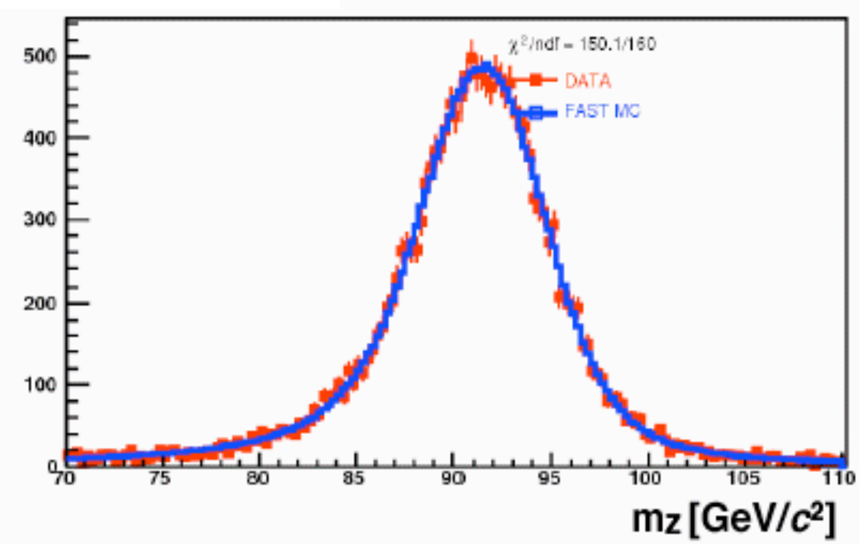
Energy scale and resolution at DØ

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

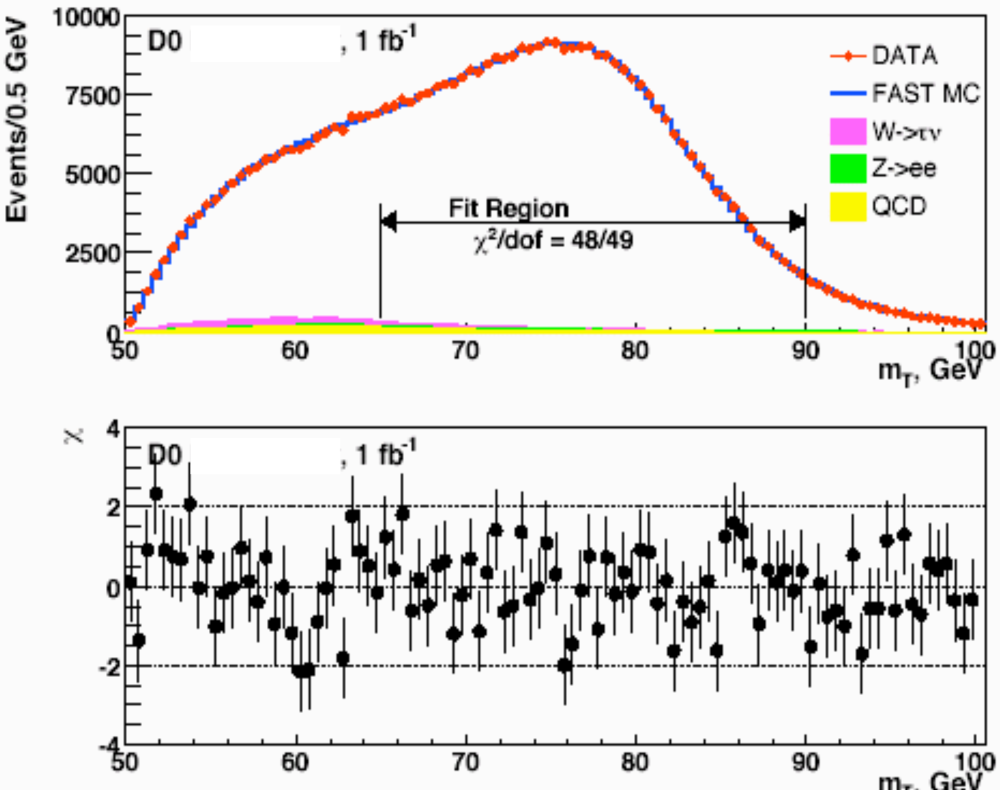
$$R_{EM}(R_0) = \alpha \times E_0 + \beta$$

  - 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





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

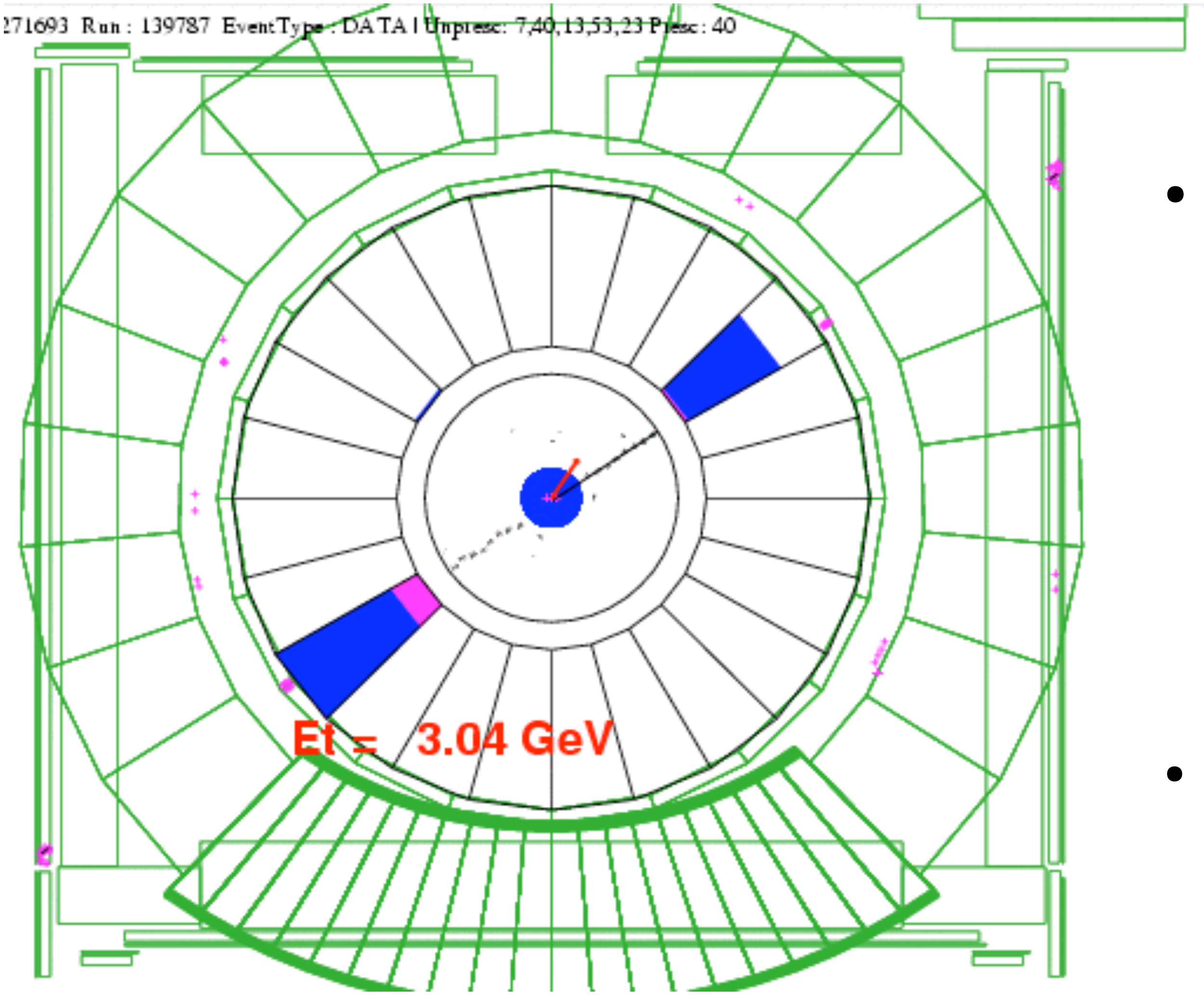
Outline of CDF Analysis

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 $J/\psi \to \mu\mu$ and $\Upsilon \to \mu\mu$ mass fits
    - Confirmed using $Z \to \mu\mu$ 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 $Z \to ee$ mass fit
- Tracker and EM Calorimeter resolutions
- Hadronic recoil modelling
  - Characterized using p_T-balance in $Z \to ll$ events

Internal Alignment of COT

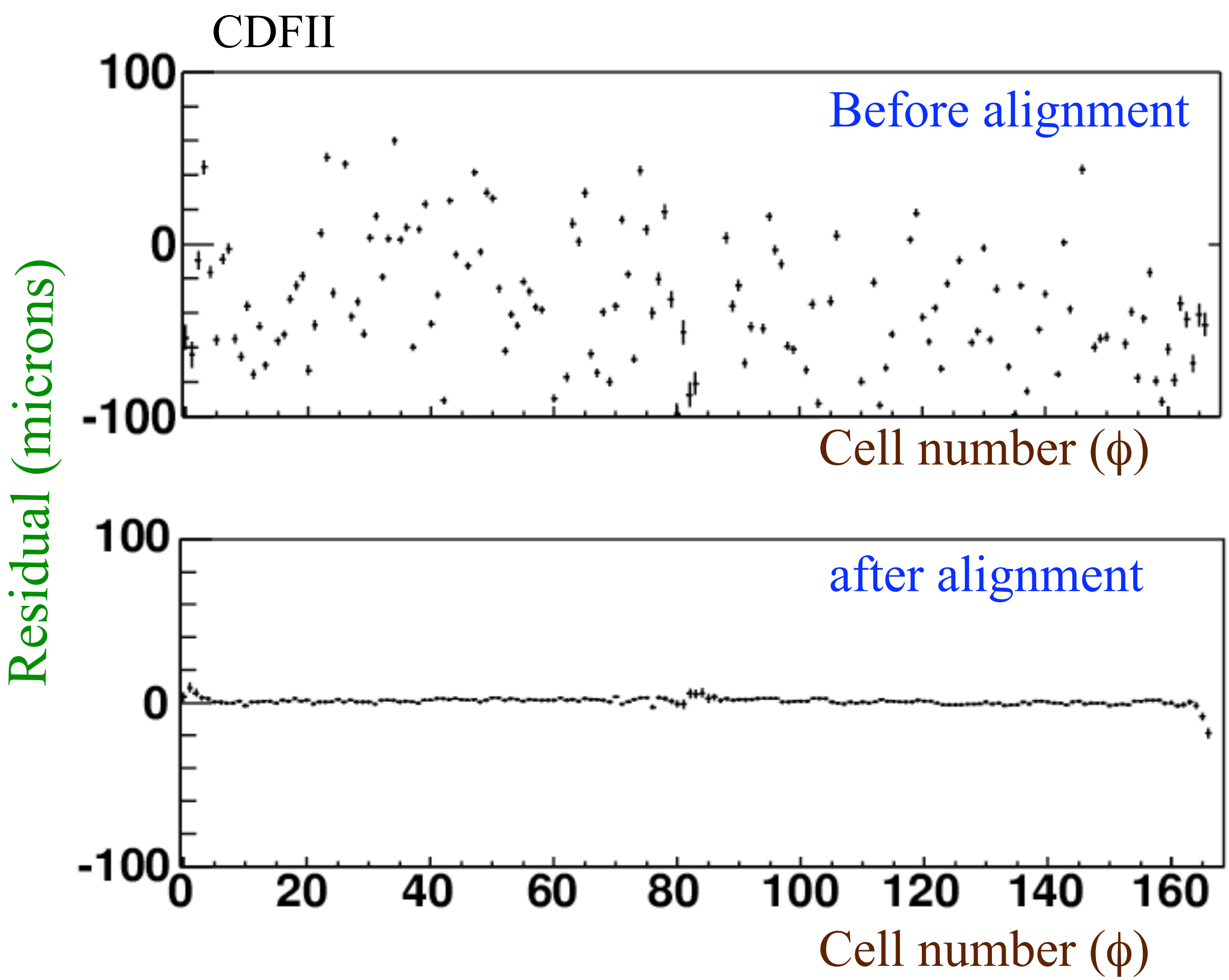
- Use a clean sample of ~200k cosmic rays for cell-by-cell internal alignment



- 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

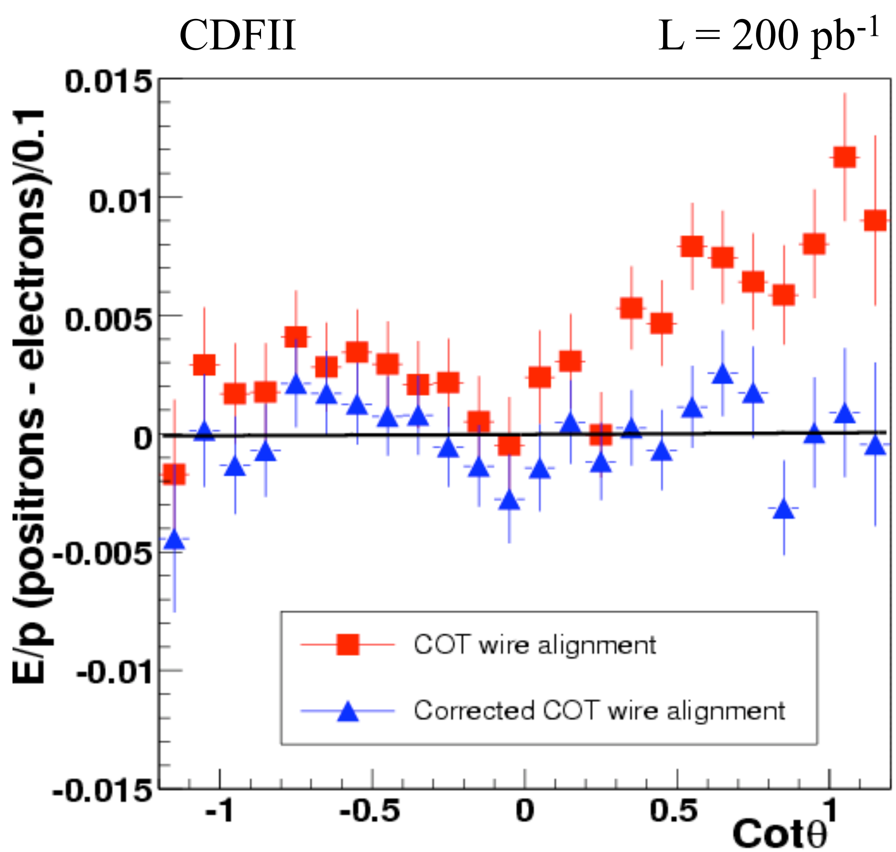
Residuals of COT cells after alignment



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

Cross-check of COT alignment

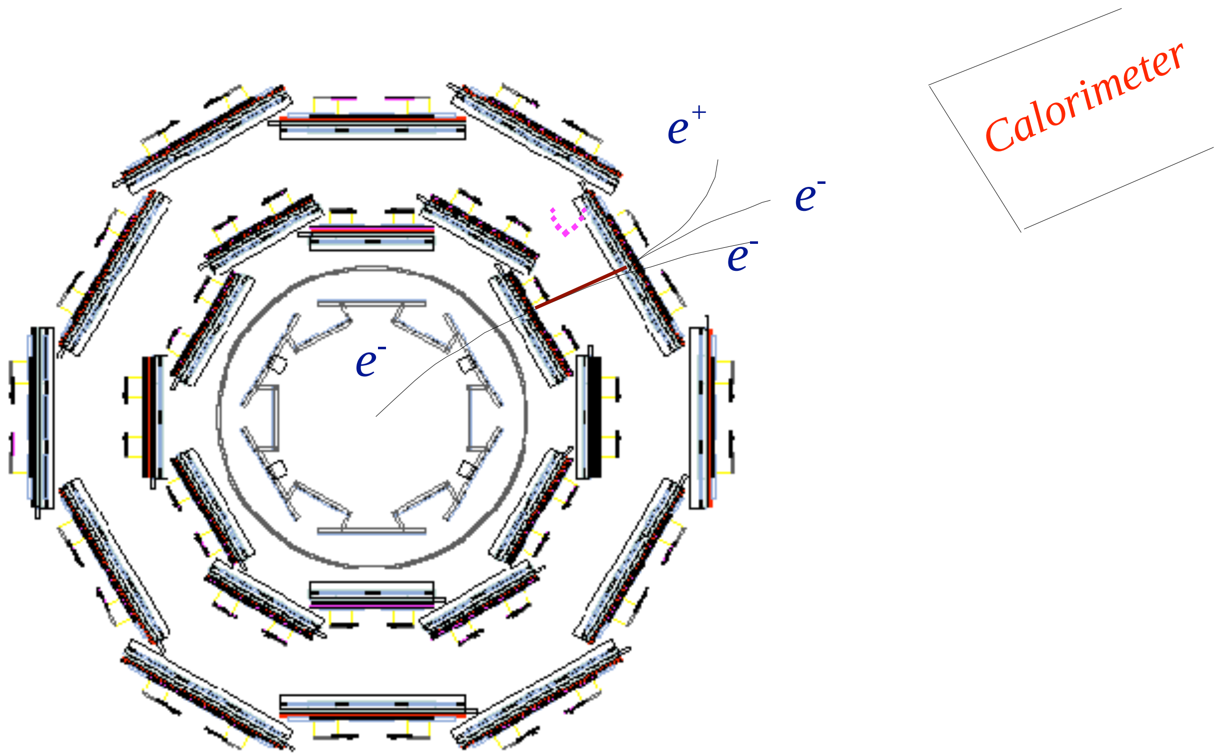
- Final cross-check and correction to track curvature based on difference of <E/p> for positrons *vs* electrons (red points)
- Smooth ad-hoc curvature corrections applied => $\delta M_W = 6$ MeV
- Systematic effects also relevant for LHC trackers



Signal Simulation and Fitting

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 detector geometry

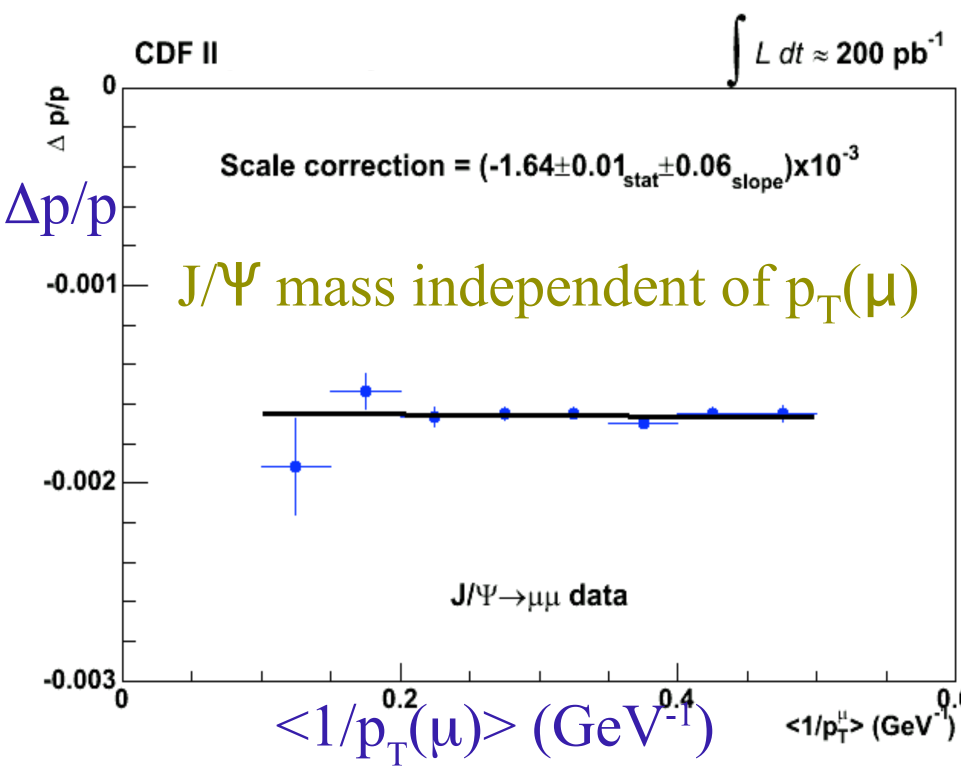


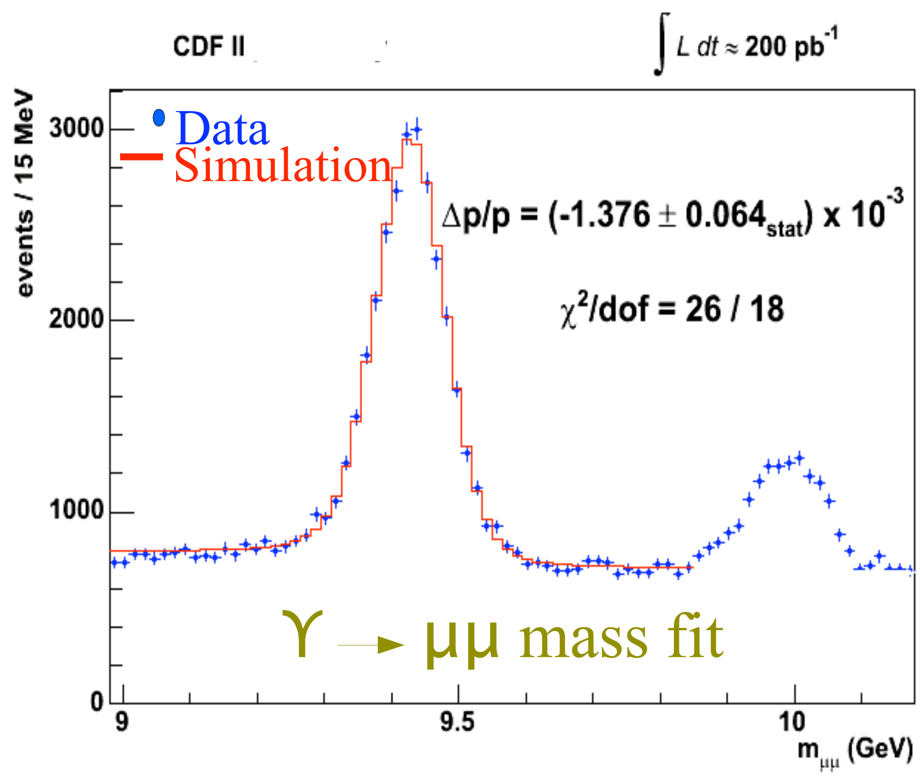
Tracking Momentum Calibration

- 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

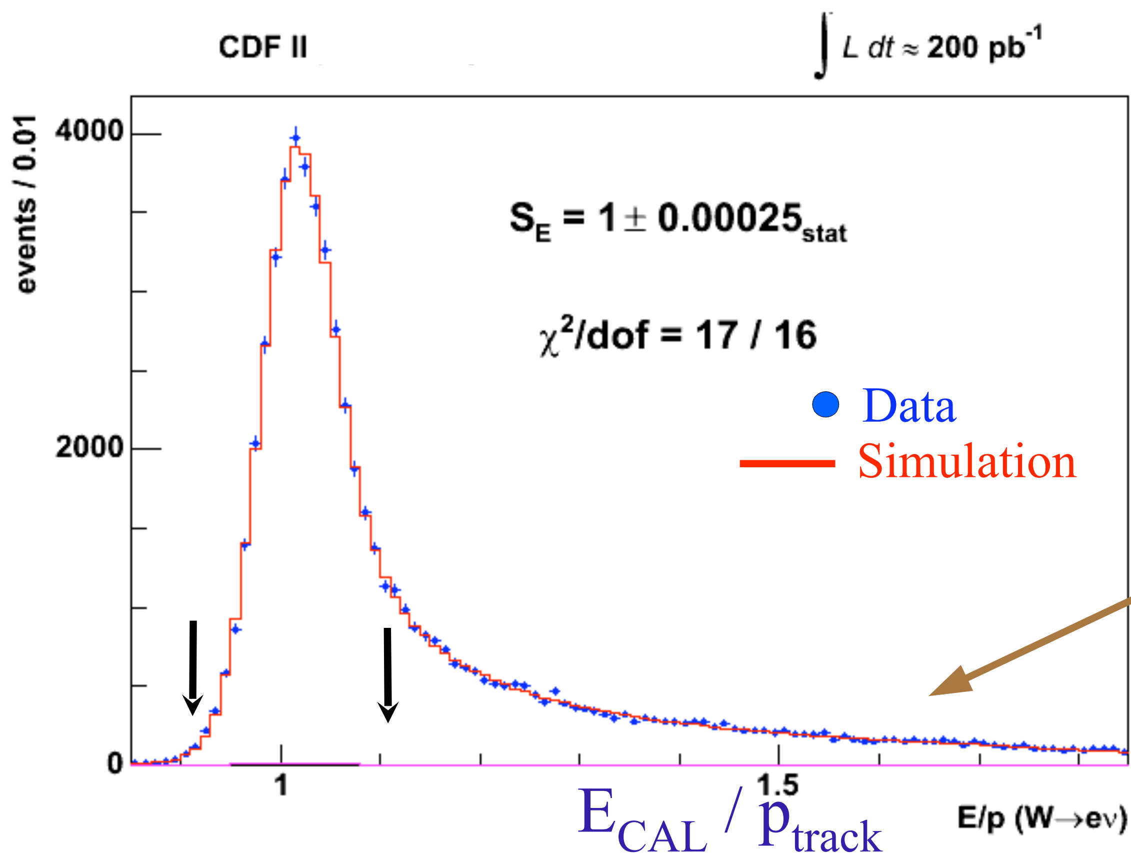
- Systematics-dominated, improved detector modelling required





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

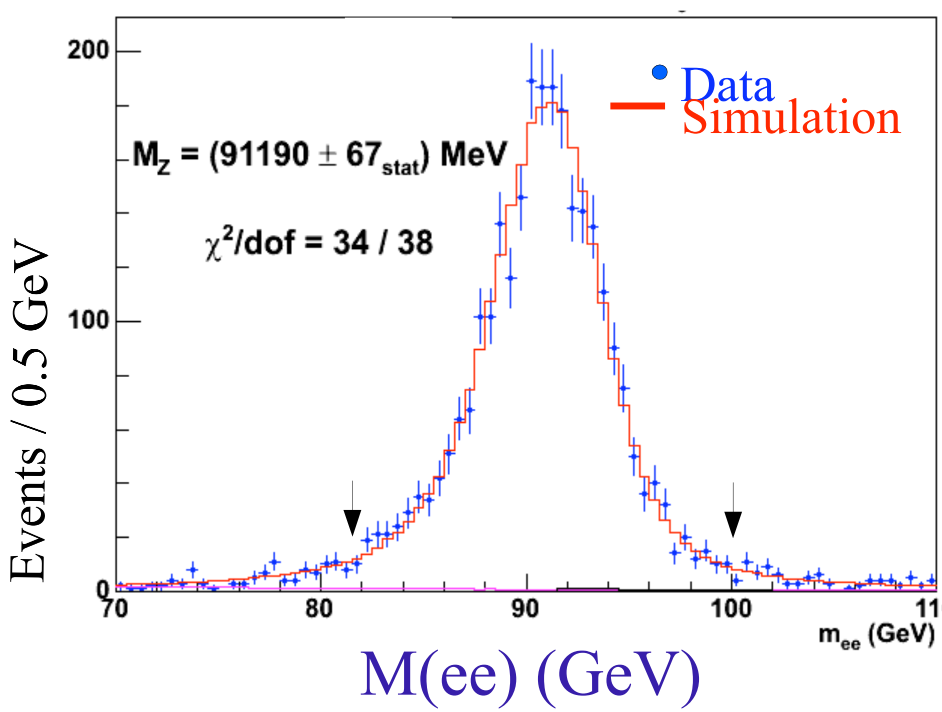


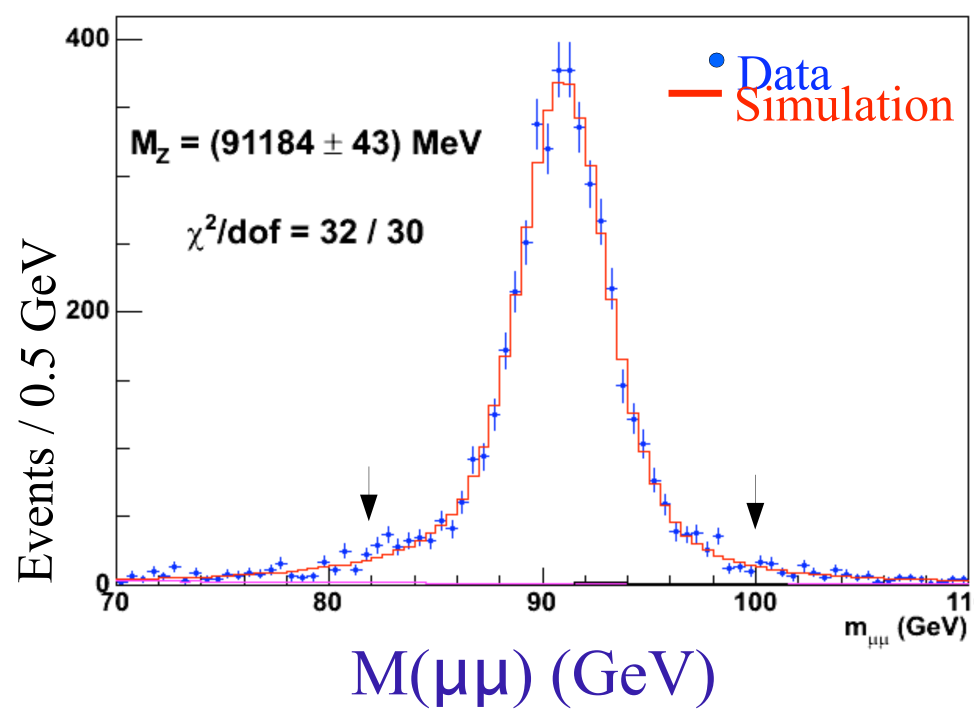
Tail region of E/p spectrum used for tuning model of radiative material

$Z \rightarrow ll$ Mass Cross-checks

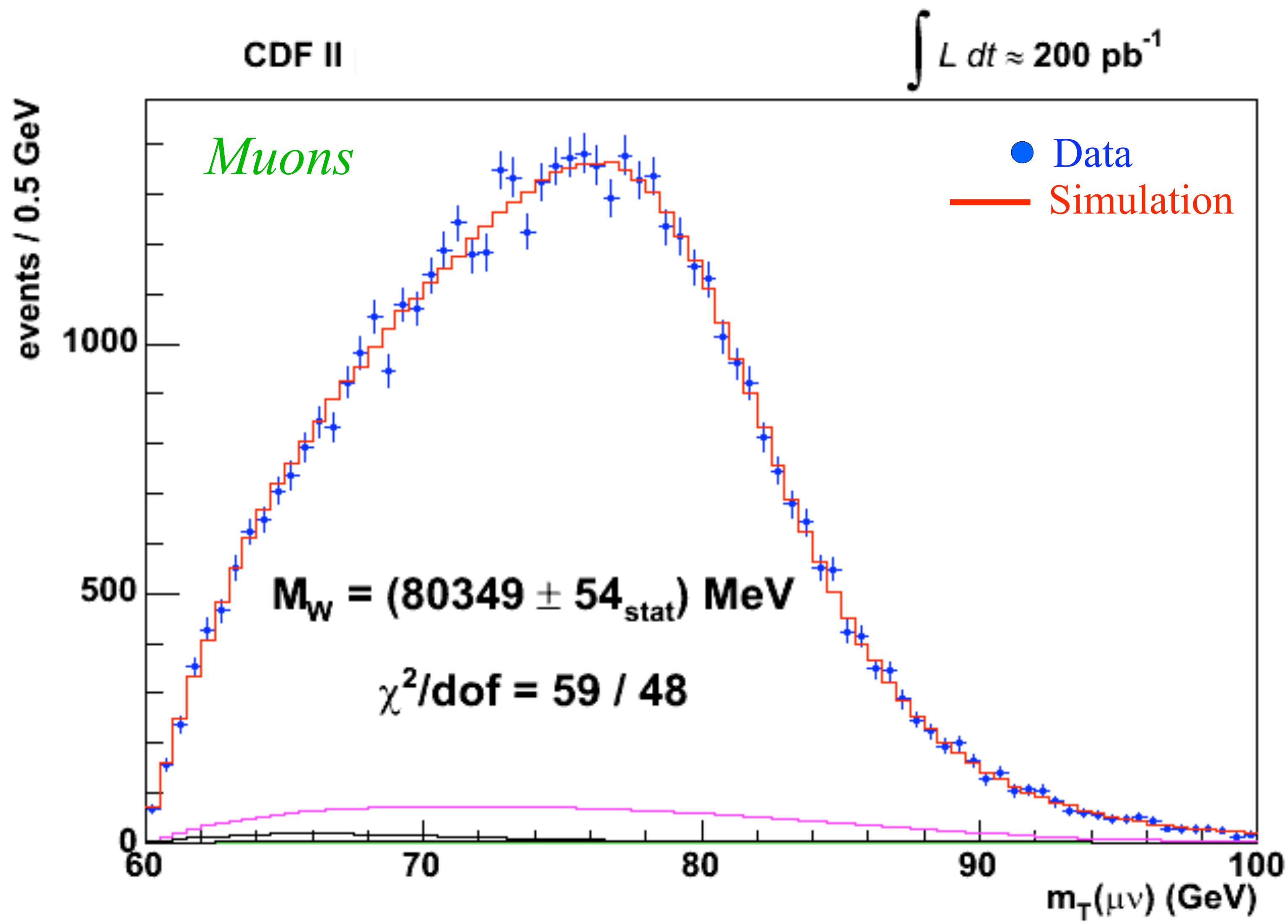
- Z boson mass fits consistent with tracking and E/p-based calibrations

CDF II $L \sim 200/pb$

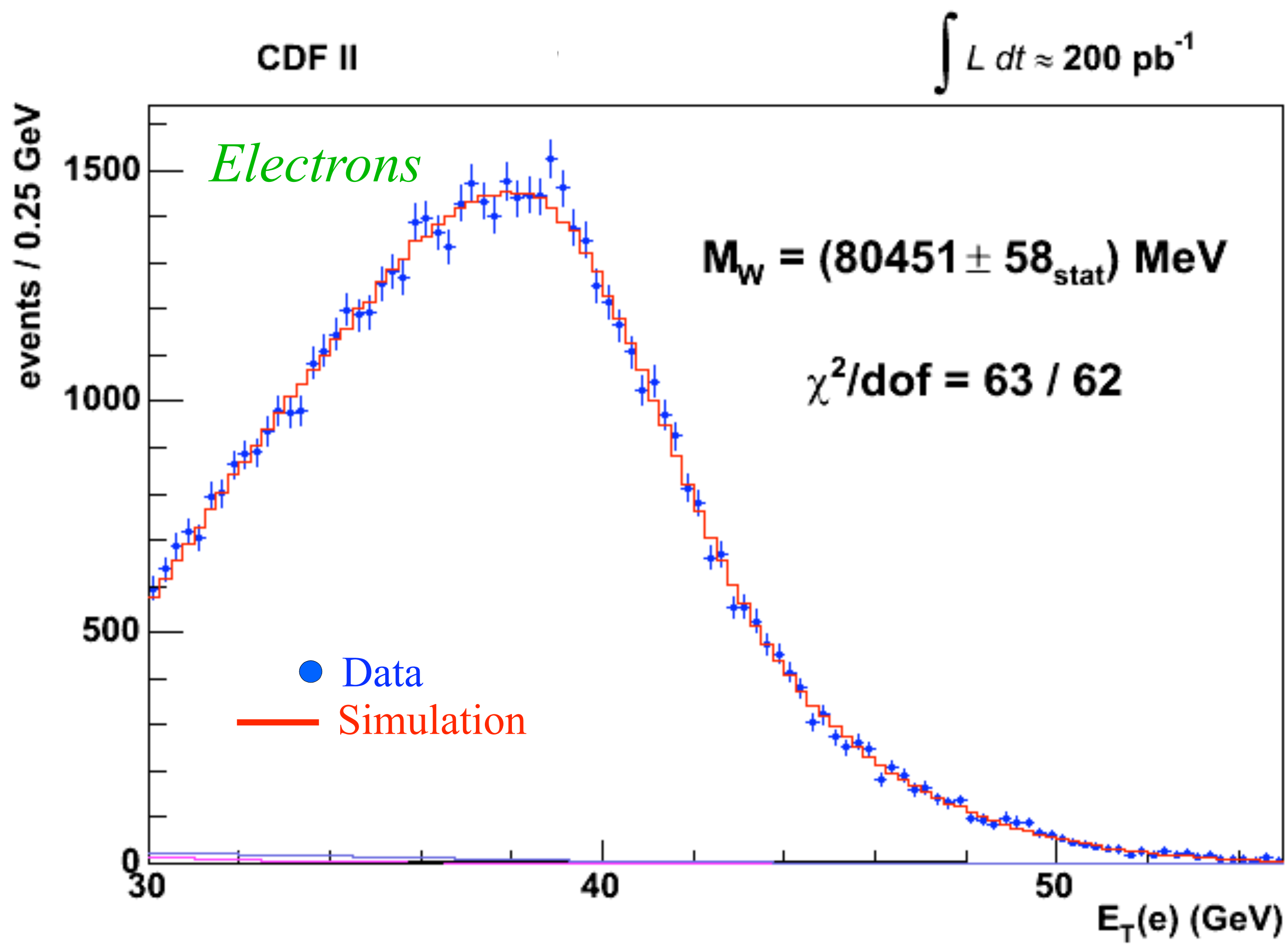




W Transverse Mass Fits



W Lepton p_T Fits



Transverse Mass Fit Uncertainties (MeV)

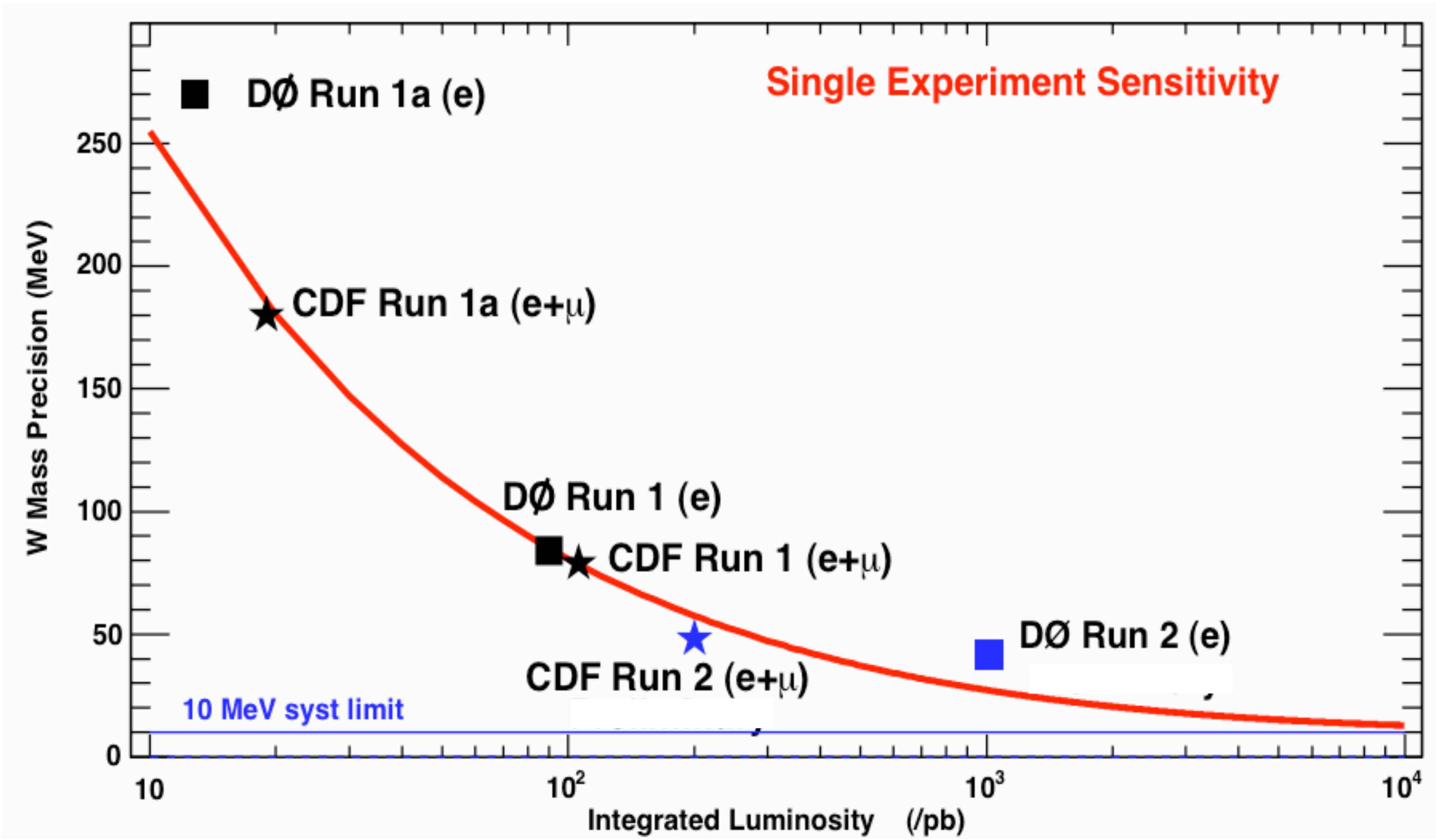
(CDF, PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)

	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

Improvement of M_W Uncertainty with Sample Statistics

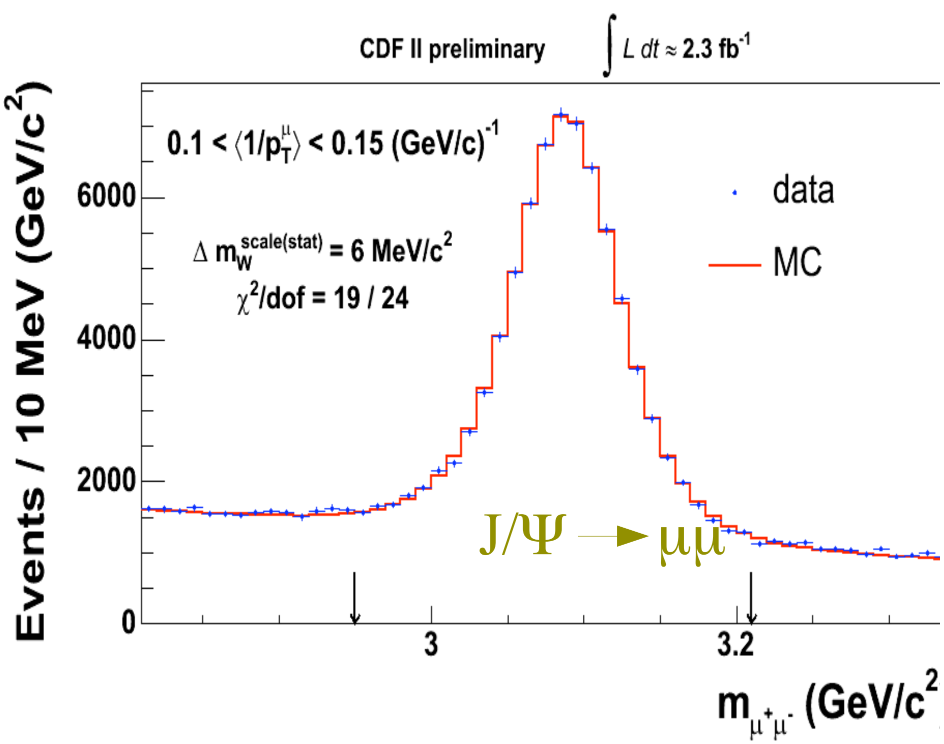


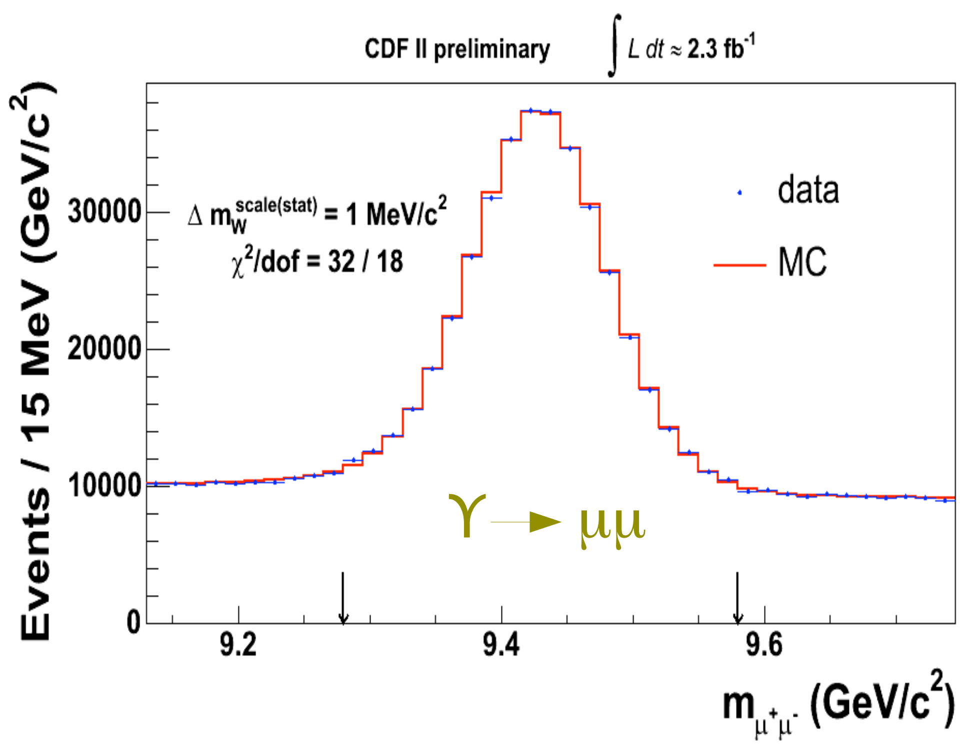
Next target: 15-20 MeV measurement of M_W from the Tevatron

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



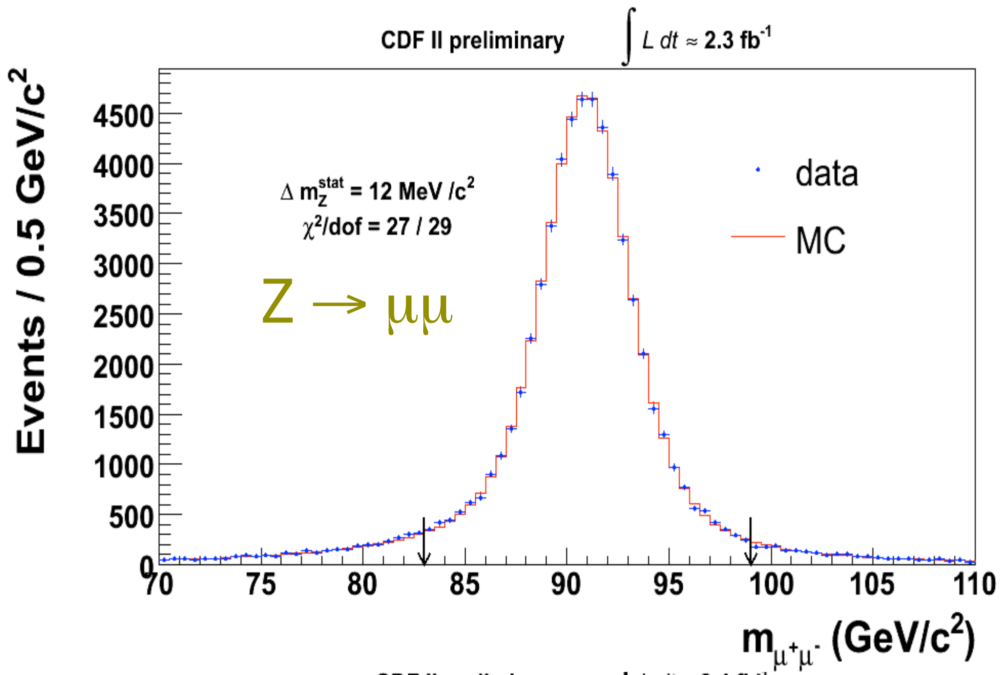


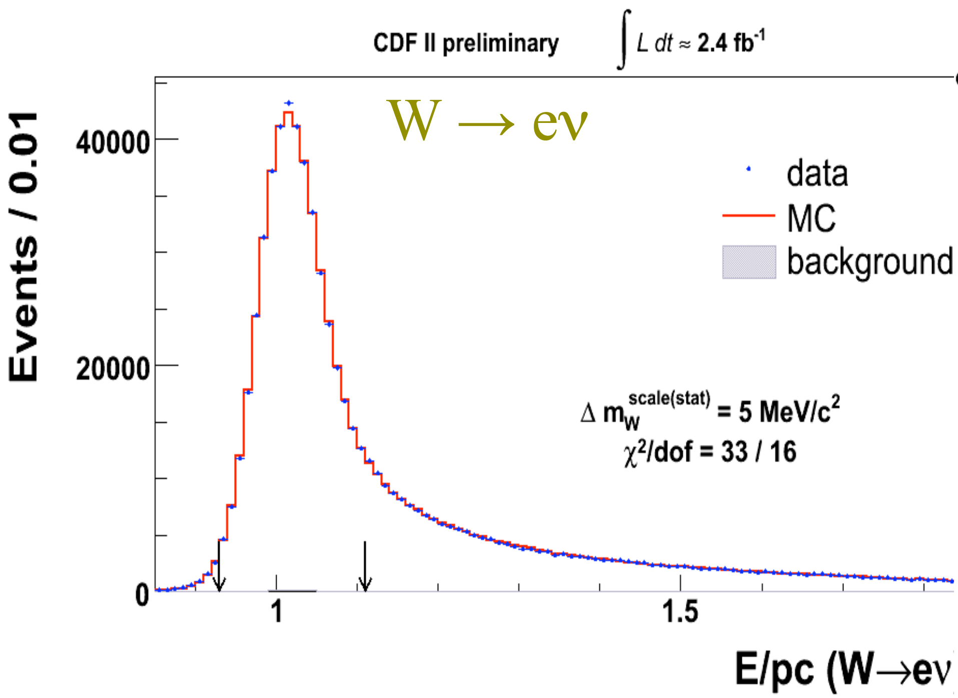
Preliminary Studies of 2.3 fb^{-1} Data

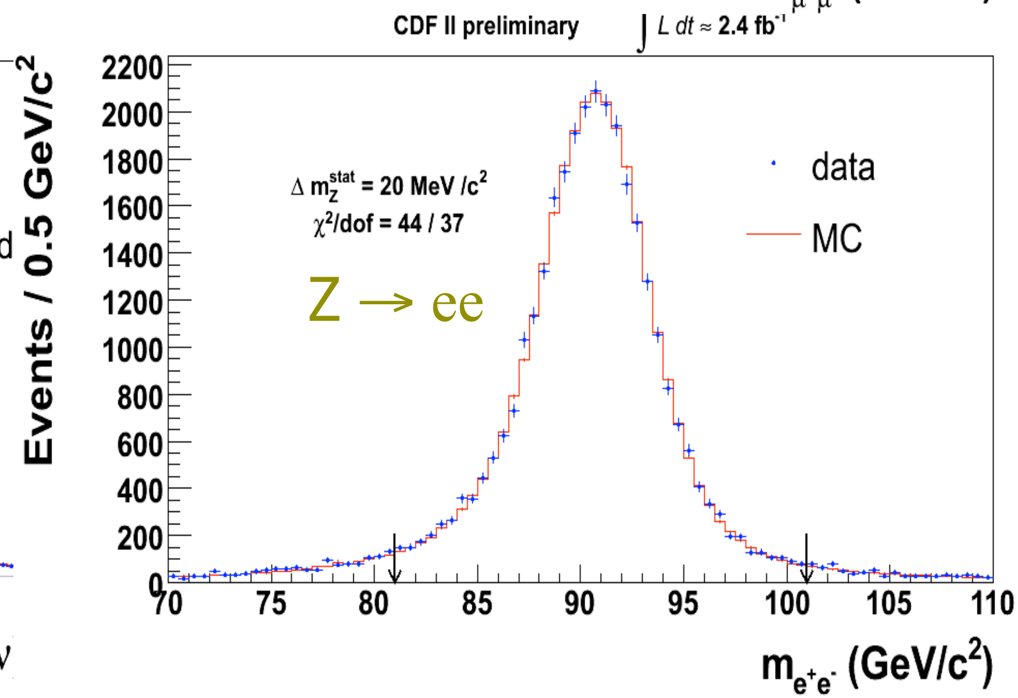
Statistical errors on all lepton calibration fits have scaled with statistics

Detector and data quality maintained over time

detailed calibrations in progress

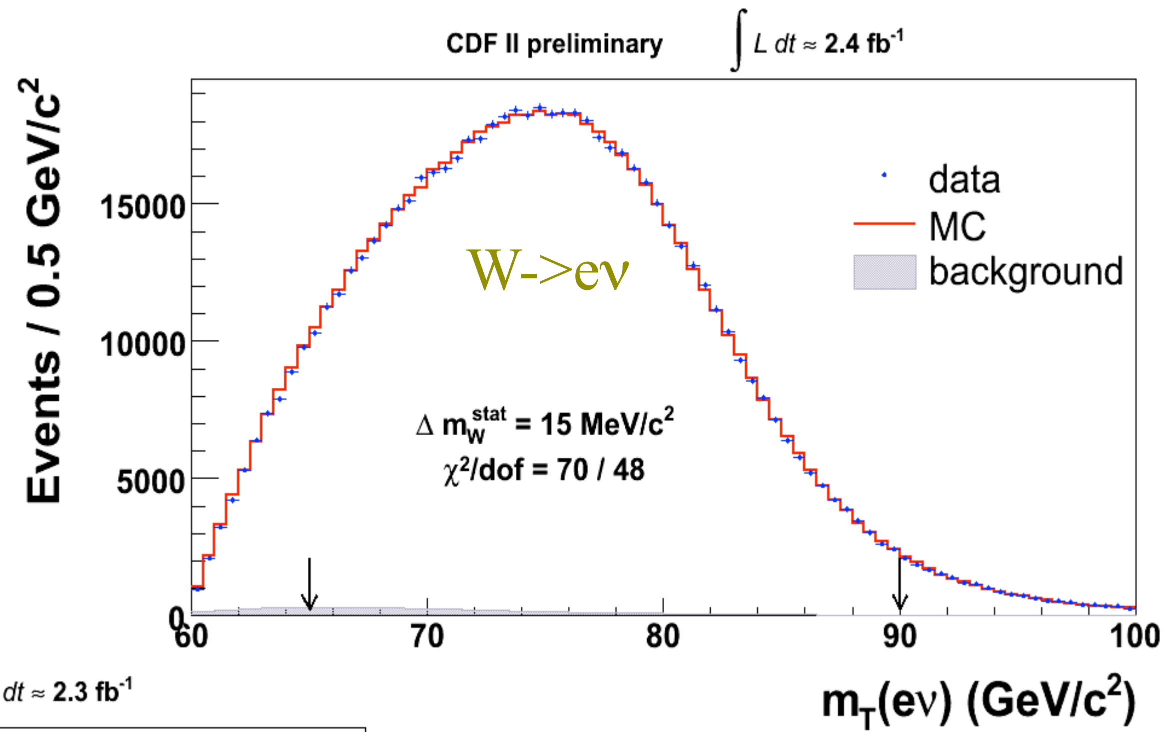


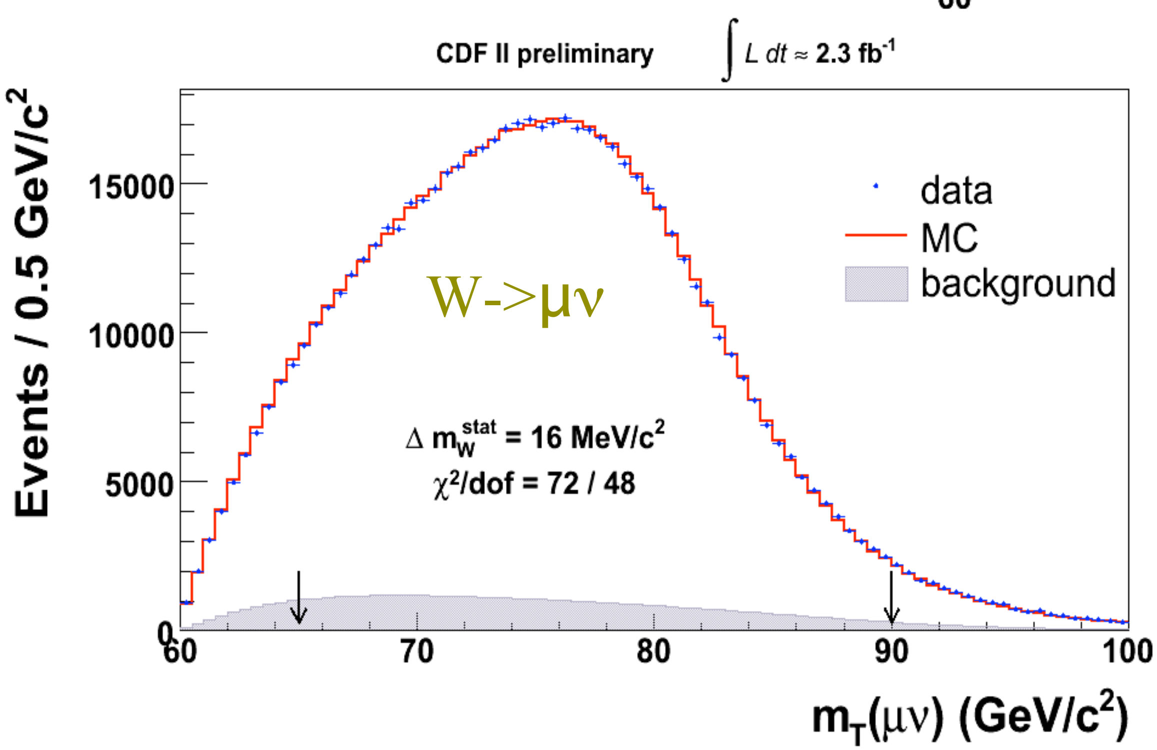




Preliminary Studies of 2.3 fb^{-1} Data

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 $Z \rightarrow ll$ mass resonance, best-case scenario of statistical limit ~ 5 MeV precision on calibrations
- Calibration of the hadronic calorimeter based on transverse momentum balance in $Z \rightarrow ll$ events also ~ 2 MeV statistical limit
- Total uncertainty on M_W ~ 5 MeV if $Z \rightarrow ll$ 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 $Z \rightarrow ll$ data constrain all the relevant W boson systematics?
- Can we add other constraints from other mass resonances and tracking detectors ?

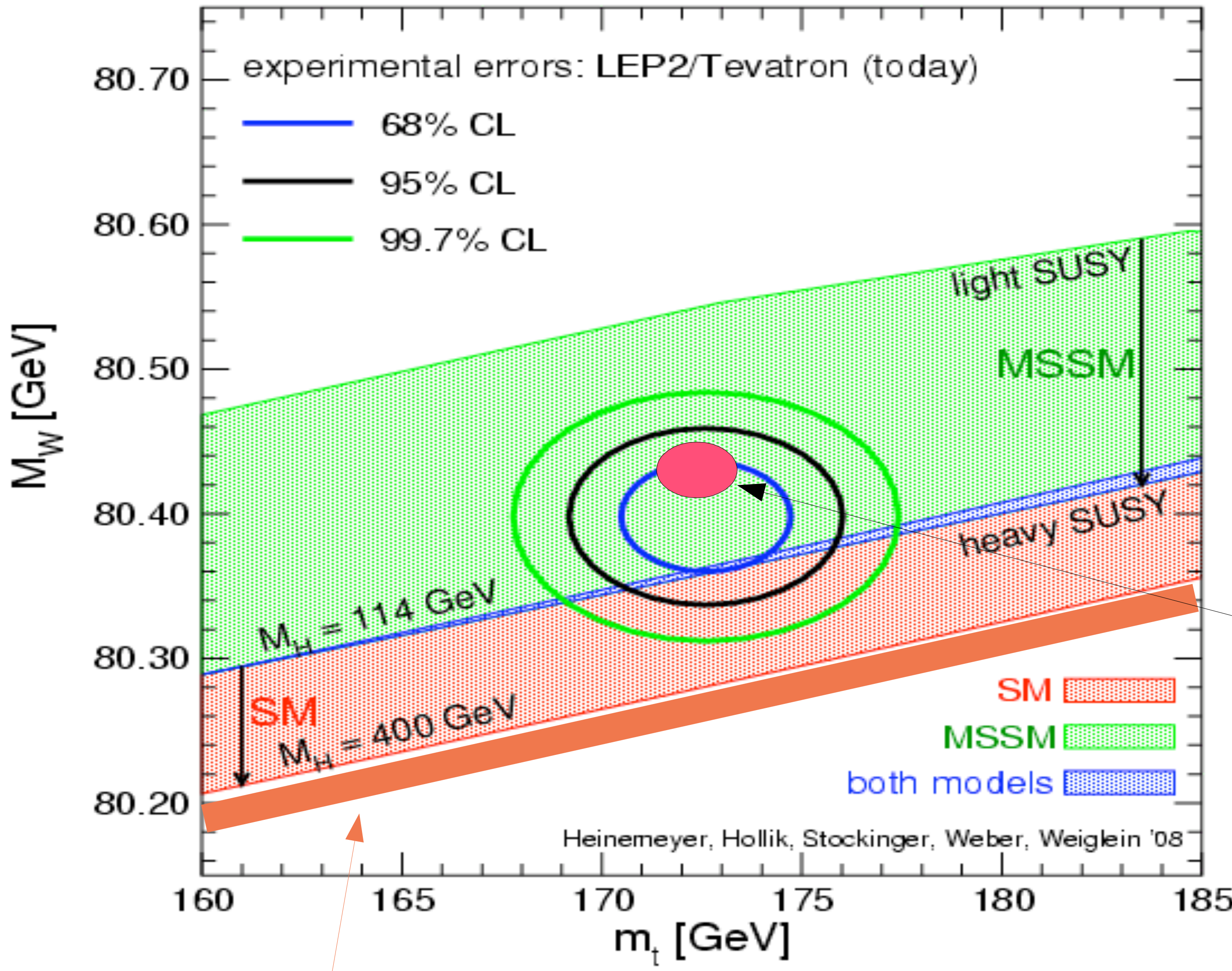
- With every increase in statistics of the data samples, we climb a new learning curve on the systematic effects
  - Improved calculations of QED radiative corrections available
  - Better understanding of parton distributions from global fitting groups (CTEQ, MSTW, Giele *et al*)

- 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 $\delta M_W \sim$ 5-10 MeV

A possible Future Scenario



$\delta M_W = 10$ MeV

$\delta m_{top} = 0.5$ GeV

Higgs discovery with a large Higgs mass