W Boson Mass Measurements at the Tevatron

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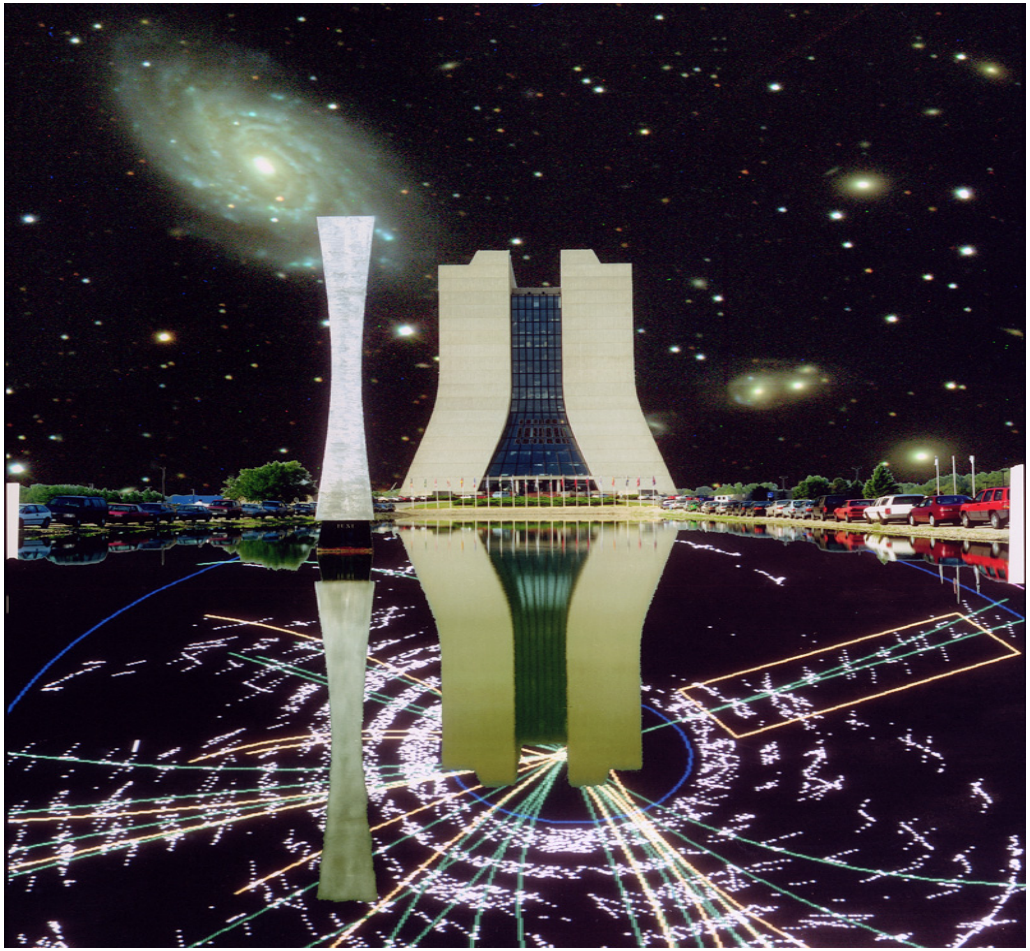
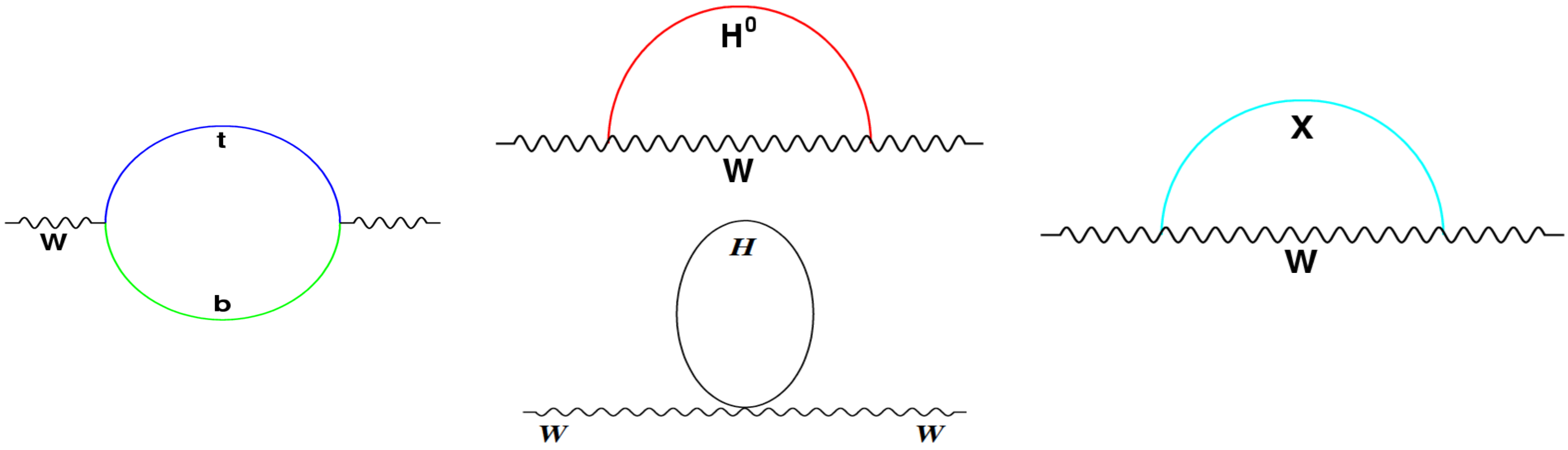
For the CDF and D0 Collaborations



Large Hadron Collider Physics Conference
Barcelona, May 17, 2013

Motivation for Precision Electroweak Measurements

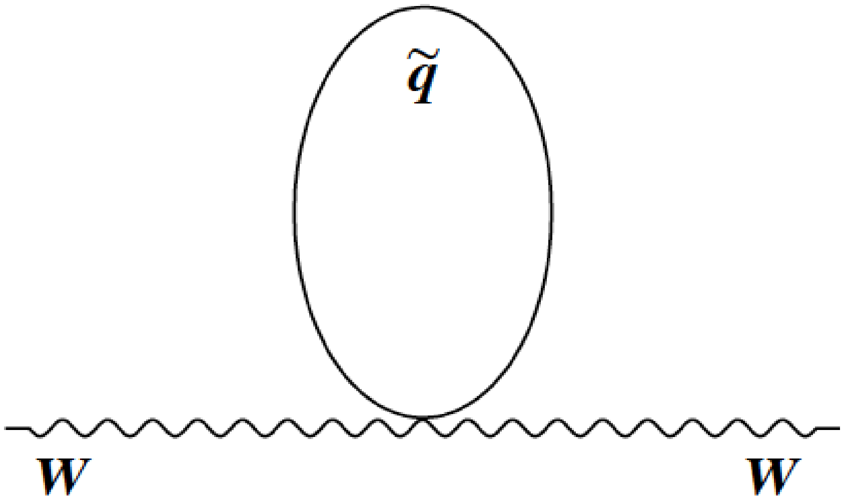
- Radiative corrections due to heavy quark and Higgs loops and exotica

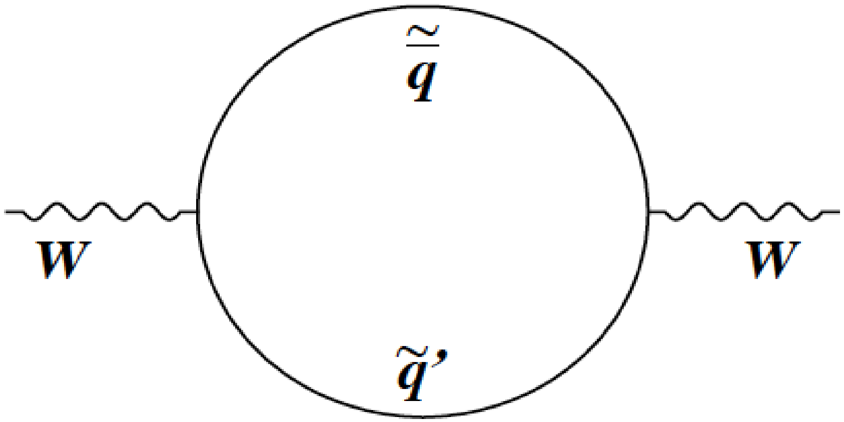


Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\mathrm{tree})]^2$
with the predictions $\Delta\rho = (\rho-1) \sim M_{top}^2$ and $\Delta\rho \sim \ln M_H$

- In conjunction with M_{top} and the Higgs boson mass, the W boson mass stringently tests the SM
- A discrepancy with the SM can be used to test new physics models

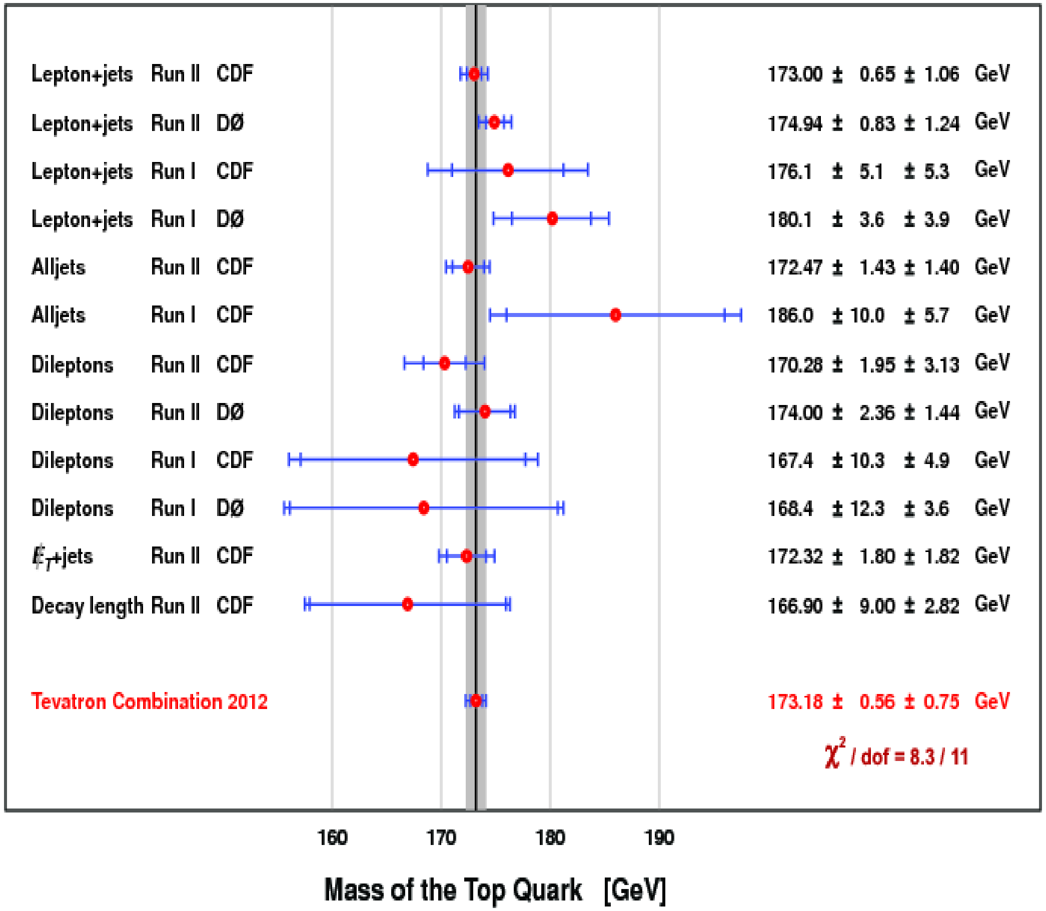
Contributions from Supersymmetric Particles





- Radiative correction depends on mass splitting (Δm^2) between squarks in SU(2) doublet
- After folding in limits on SUSY particles from direct searches, SUSY loops can contribute 100 MeV to M_W

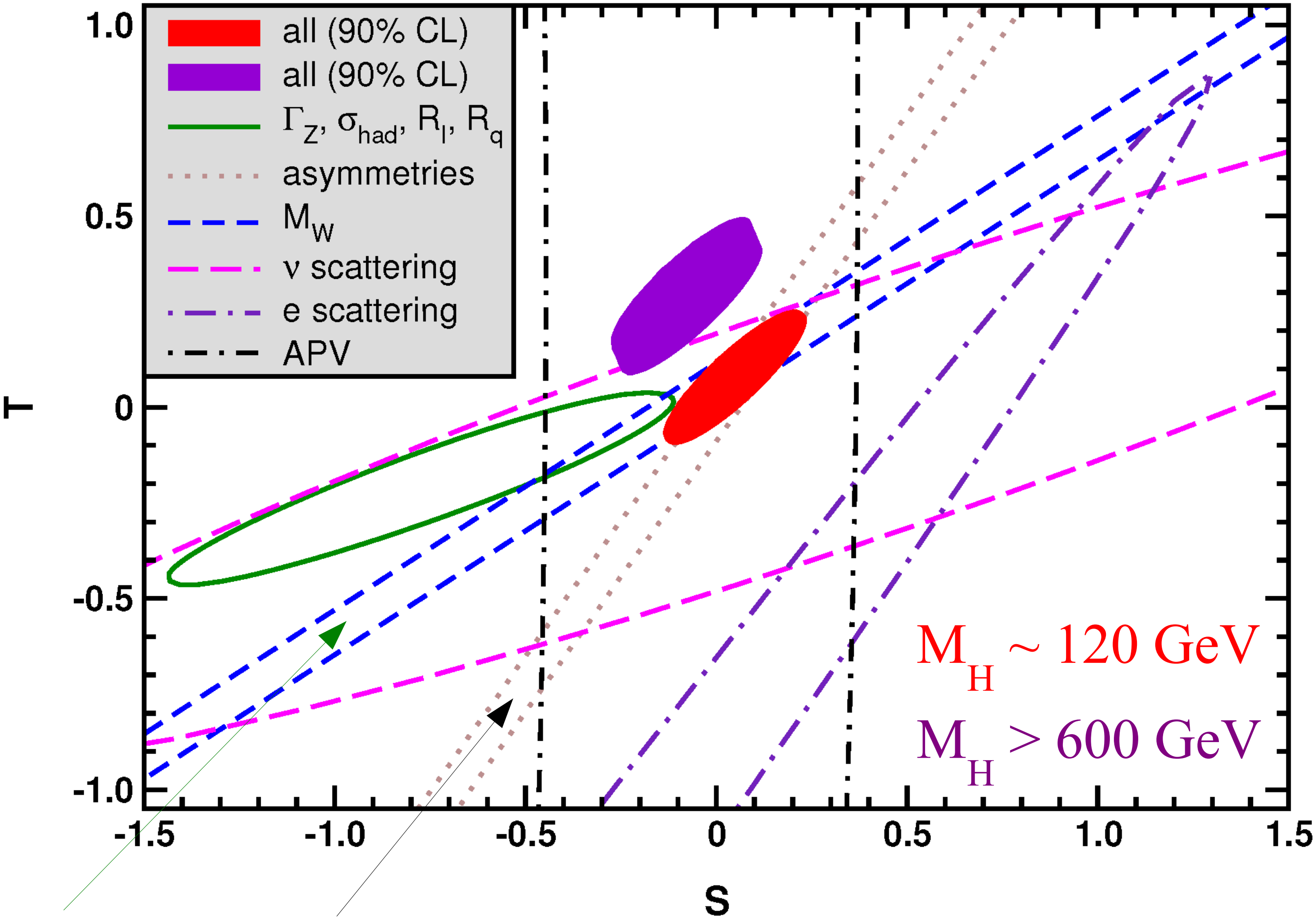
Progress on M_{top} at the Tevatron and LHC



- From the Tevatron and LHC (which is approaching Tevatron precision), $\Delta M_{top} < 0.9$ GeV => $\Delta M_H / M_H < 8\%$
- equivalent $\Delta M_W < 6$ MeV for the same Higgs mass constraint
- Current world average $\Delta M_W = 15$ MeV
  - progress on ΔM_W has the biggest impact on precision electroweak fit

Motivation

- Generic parameterization of new physics contributing to W and Z boson self-energies: *S, T, U* parameters (Peskin & Takeuchi)

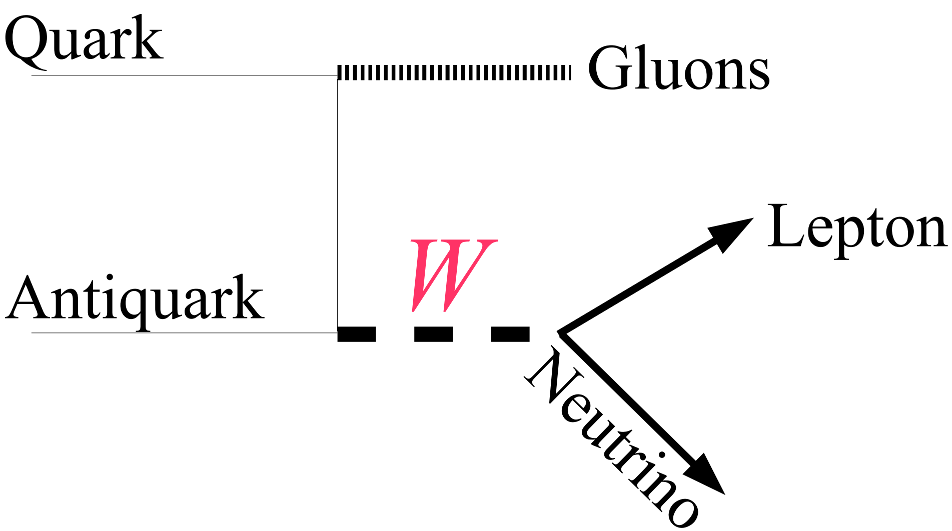


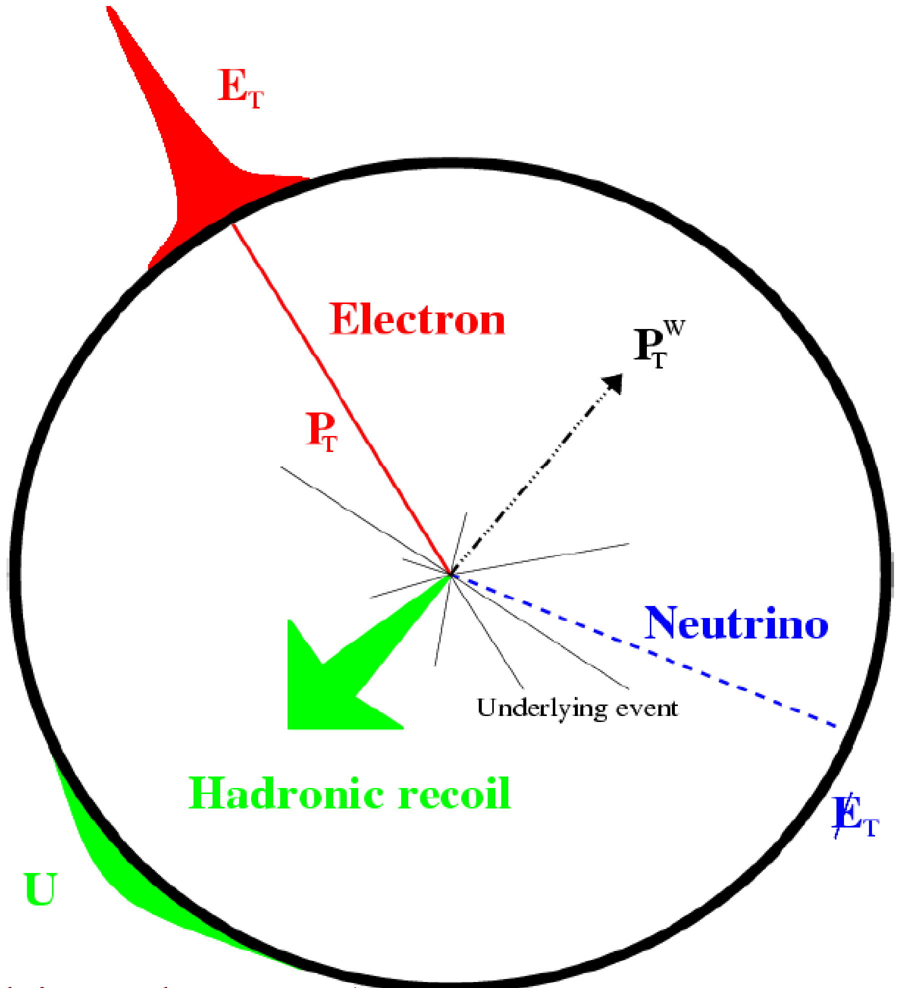
Additionally, M_W is the only measurement which constrains *U*

(from P. Langacker, 2012)

M_W and Asymmetries are the most powerful observables in this parameterization

W Boson Production at the Tevatron





Quark-antiquark annihilation dominates (80%)

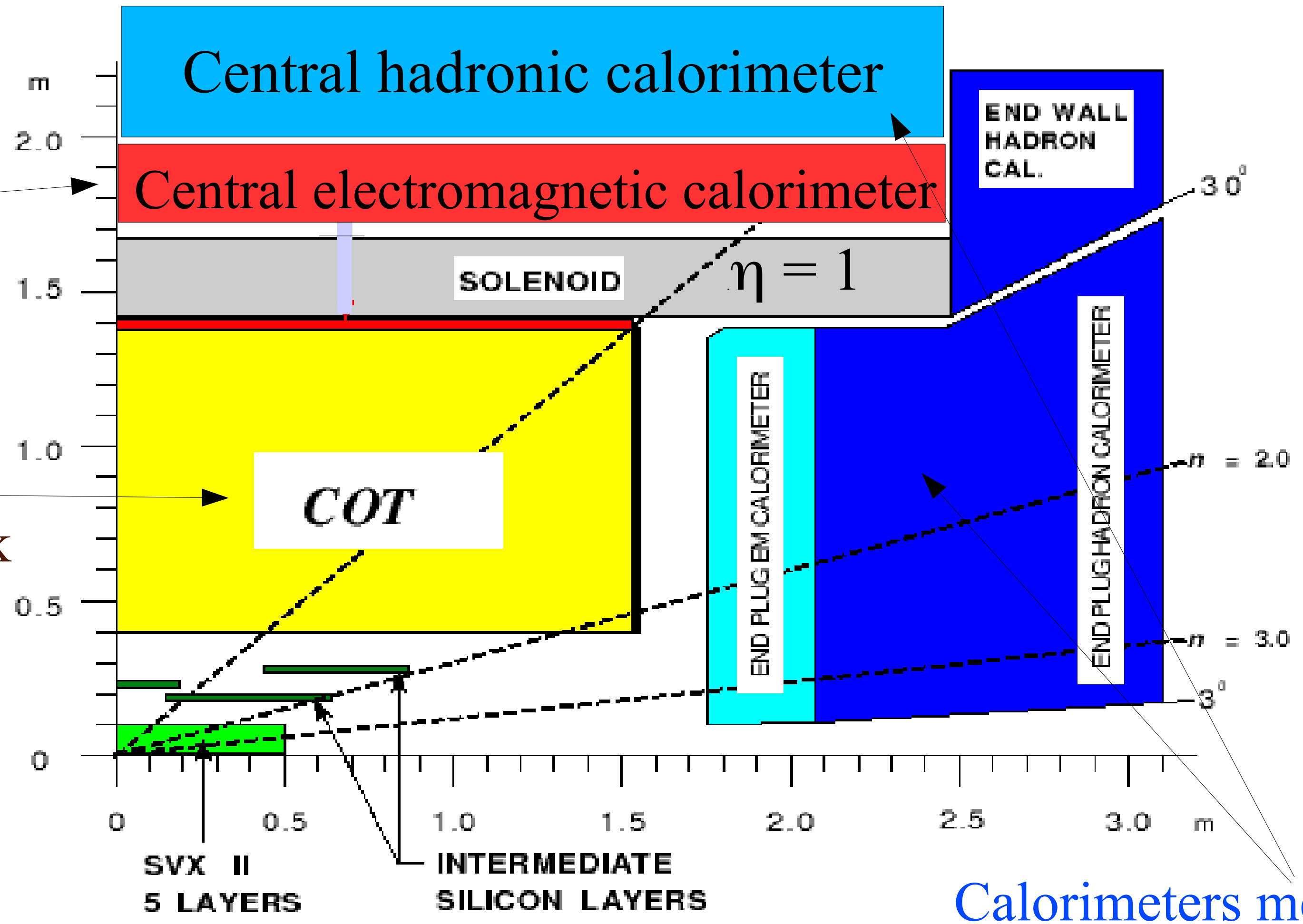
Lepton p_T carries most of *W* mass information, can be measured precisely (achieved 0.01%)

Initial state QCD radiation is *O*(10 GeV), measure as soft 'hadronic recoil' in calorimeter (calibrated to ~0.5%)

Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

Drift chamber provides precise lepton track momentum measurement



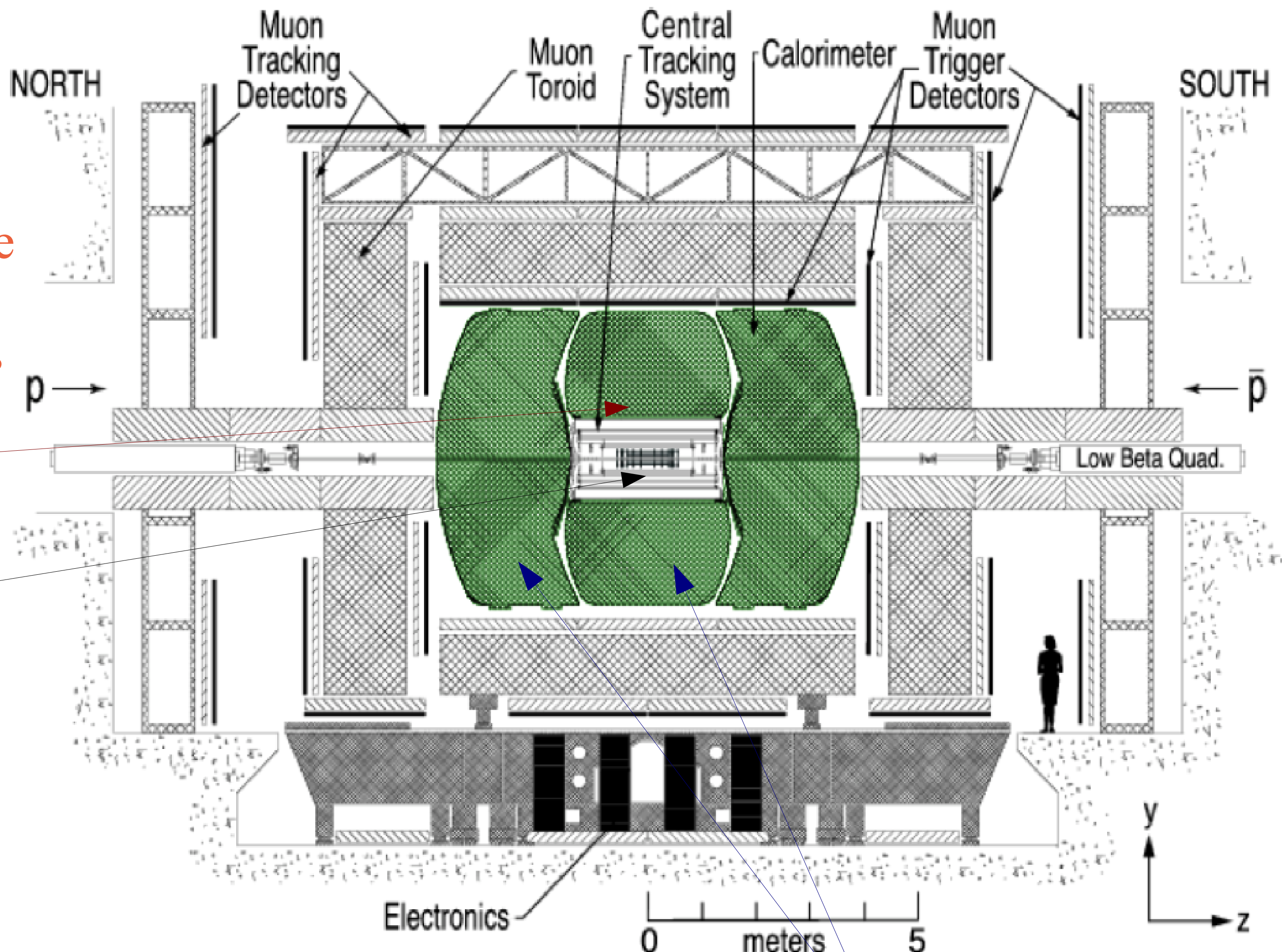
Calorimeters measure hadronic recoil particles

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

D0 Detector at Fermilab

Highly-segmented, stable Uranium+liquid Argon EM calorimeter provides precise electron energy measurement

Silicon and Scintillating fiber trackers provides precise lepton track position measurement



Calorimeters measure hadronic recoil particles

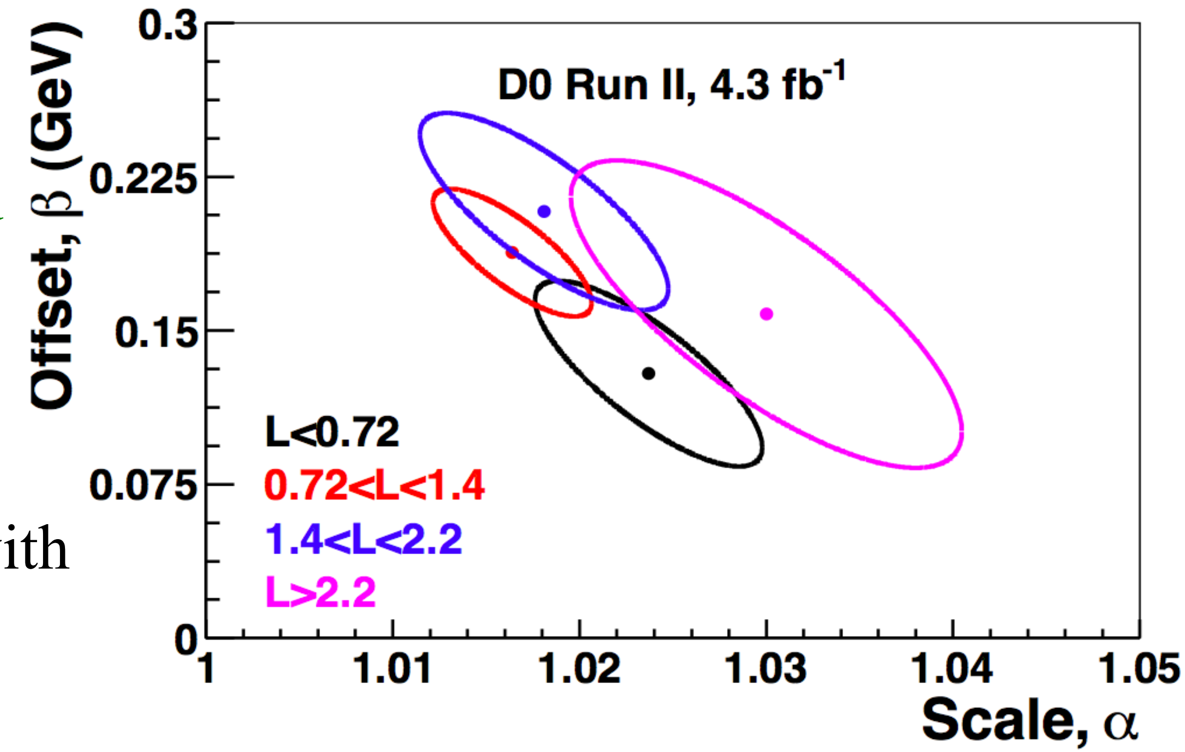
Electron Energy Scale at D0

- Correct for low-energy non-linearity
  - Energy loss due to upstream dead material (ionization, bremsstrahlung)
  - Modeling of underlying event energy flow in electron towers
  - Electronics noise and pileup
- Straight-line model for calorimeter response

$$R_{EM}(E_{true}) = \alpha \cdot (E_{true} - \bar{E}_{true}) + \beta + \bar{E}_{true}$$

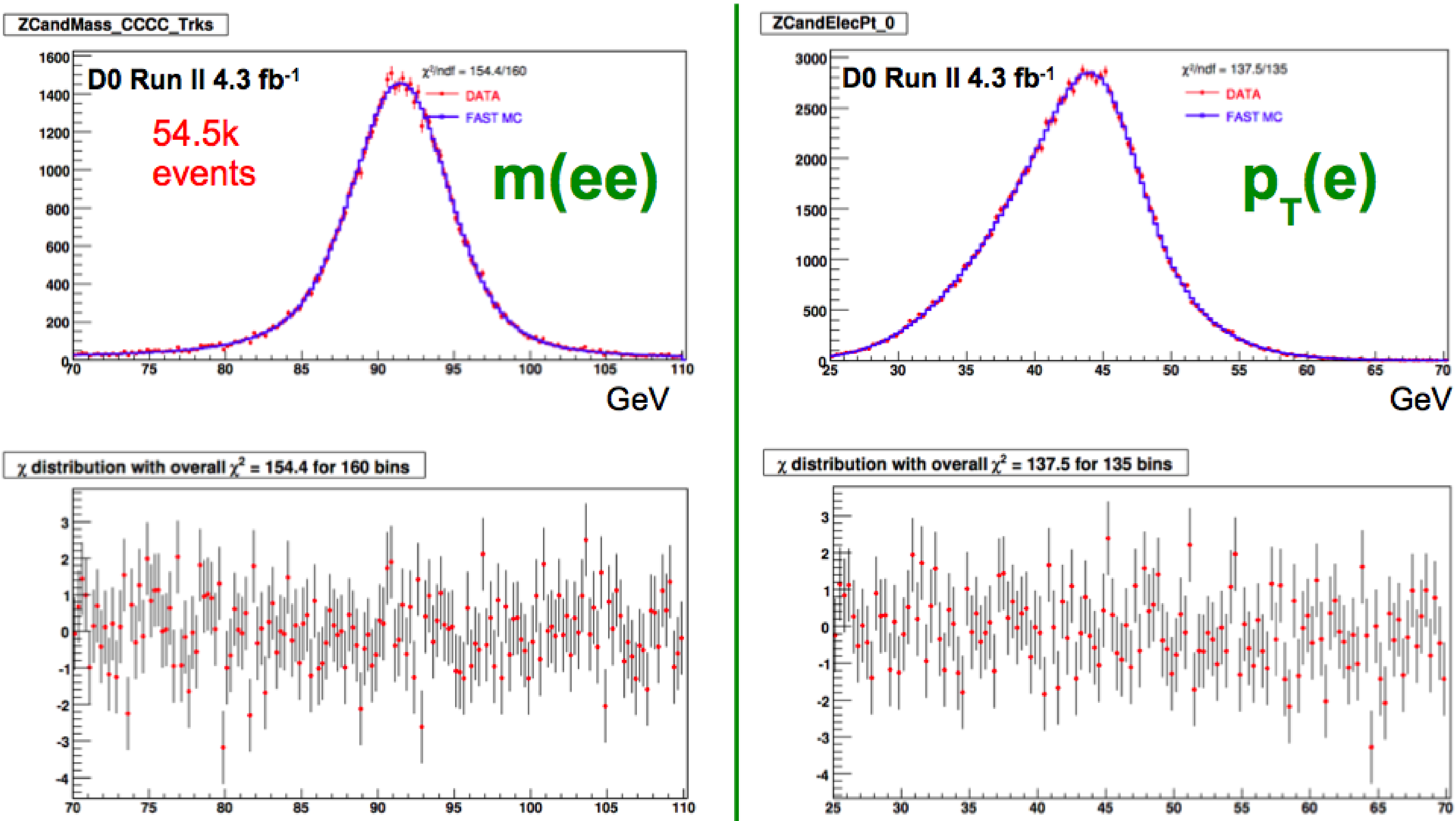
Tune on $Z \rightarrow ee$ mass exploiting electron energy spread

=> measure m_W/m_Z



Calibration procedure checked with closure test performed with GEANT pseudo-data

Z → *ee* data at D0

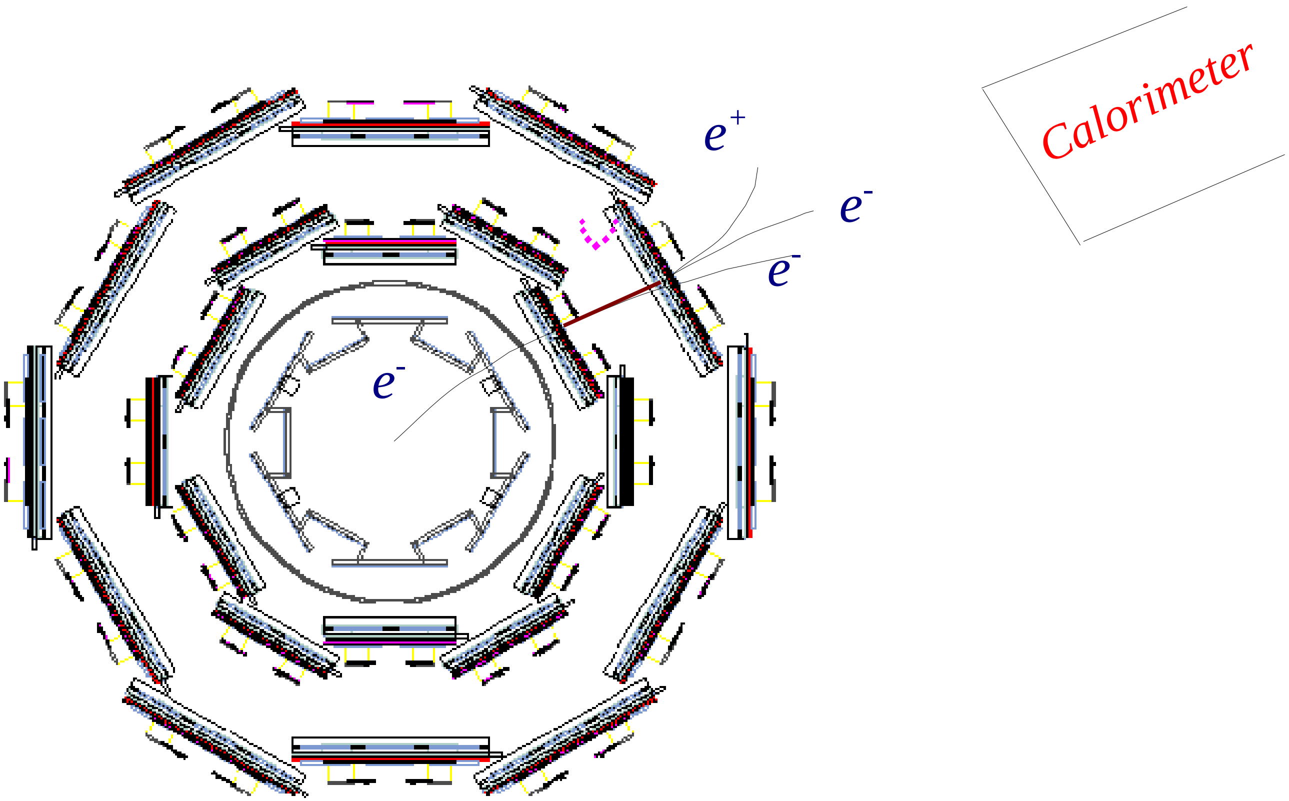


m(Z) = 91.193 ± 0.017 (stat) GeV

Good agreement between data and parameterised Monte Carlo.

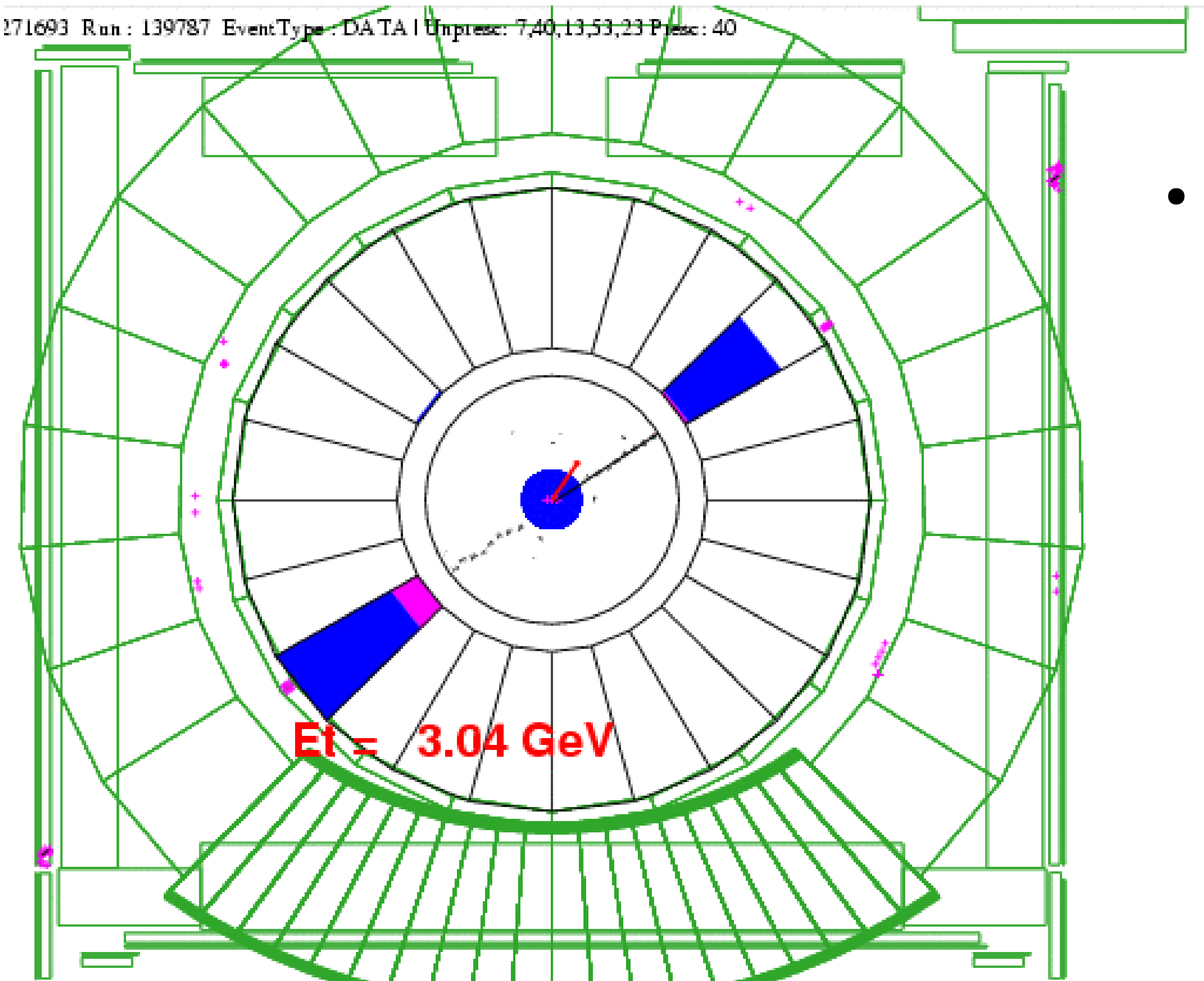
CDF Electron and Muon Measurement

- A complete detector simulation of all quantities measured in the data
- First-principles simulation of tracking
  - Tracks and photons propagated through a high-granularity 3-D lookup table of material properties for silicon detector and drift chamber



Internal Alignment of CDF Drift Chamber

- Use a clean sample of ~400*k* cosmic rays for cell-by-cell internal alignment

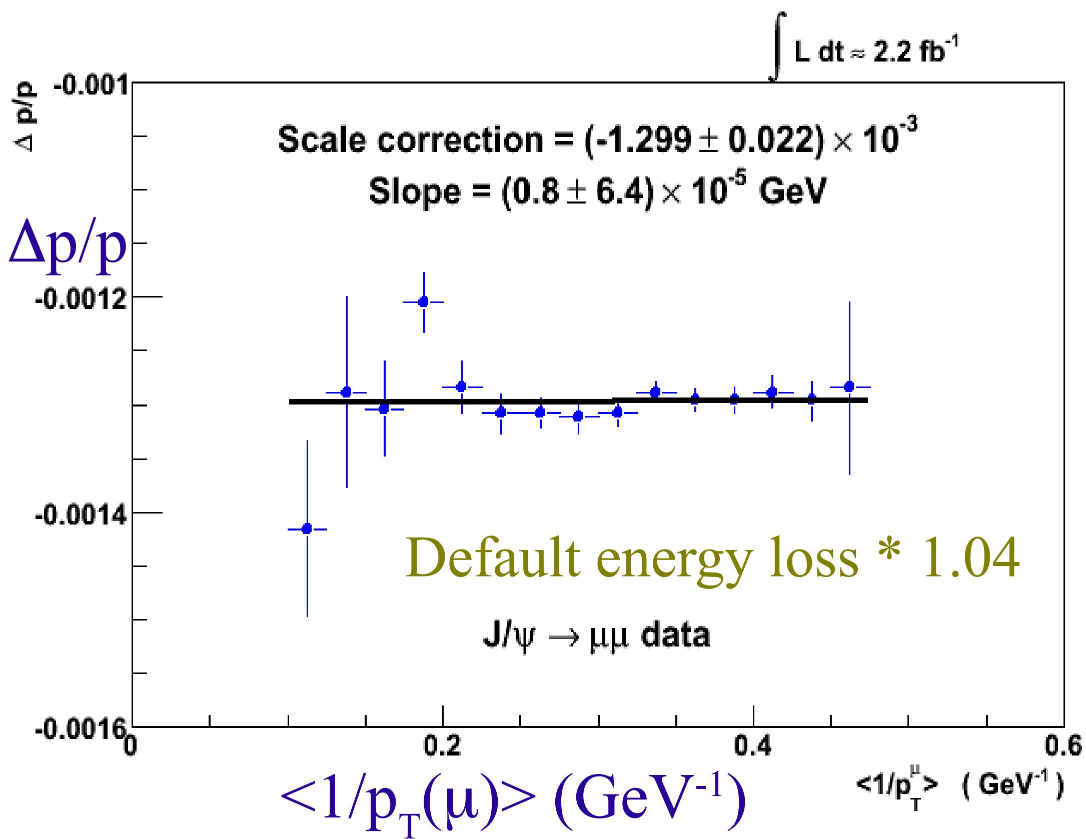


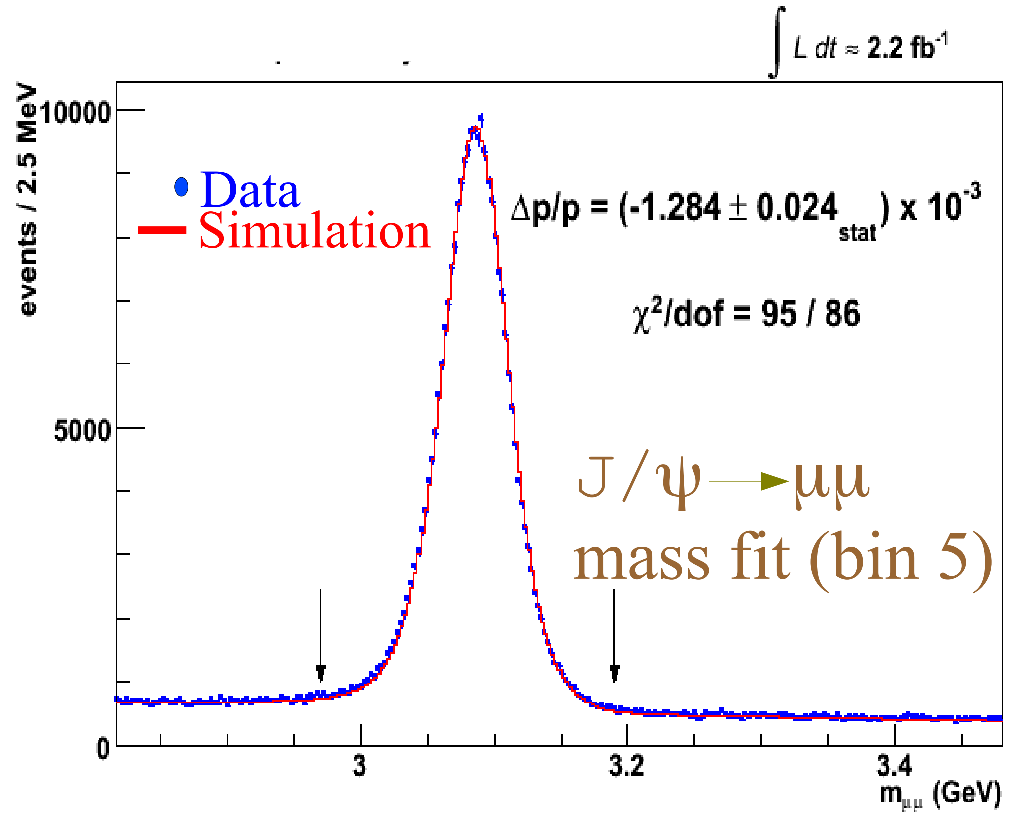
- Fit hits on both sides simultaneously to a single helix (A. Kotwal, H. Gerberich and C. Hays, NIMA 506, 110 (2003))
  - Time of incidence is a floated parameter in this 'dicosmic fit'

CDF Tracking Momentum Scale

Set using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ resonance and $Z \rightarrow \mu\mu$ masses

- Extracted by fitting J/ψ mass in bins of $1/p_T(\mu)$, and extrapolating momentum scale to zero curvature
- $J/\psi \rightarrow \mu\mu$ mass independent of $p_T(\mu)$ after 4% tuning of energy loss

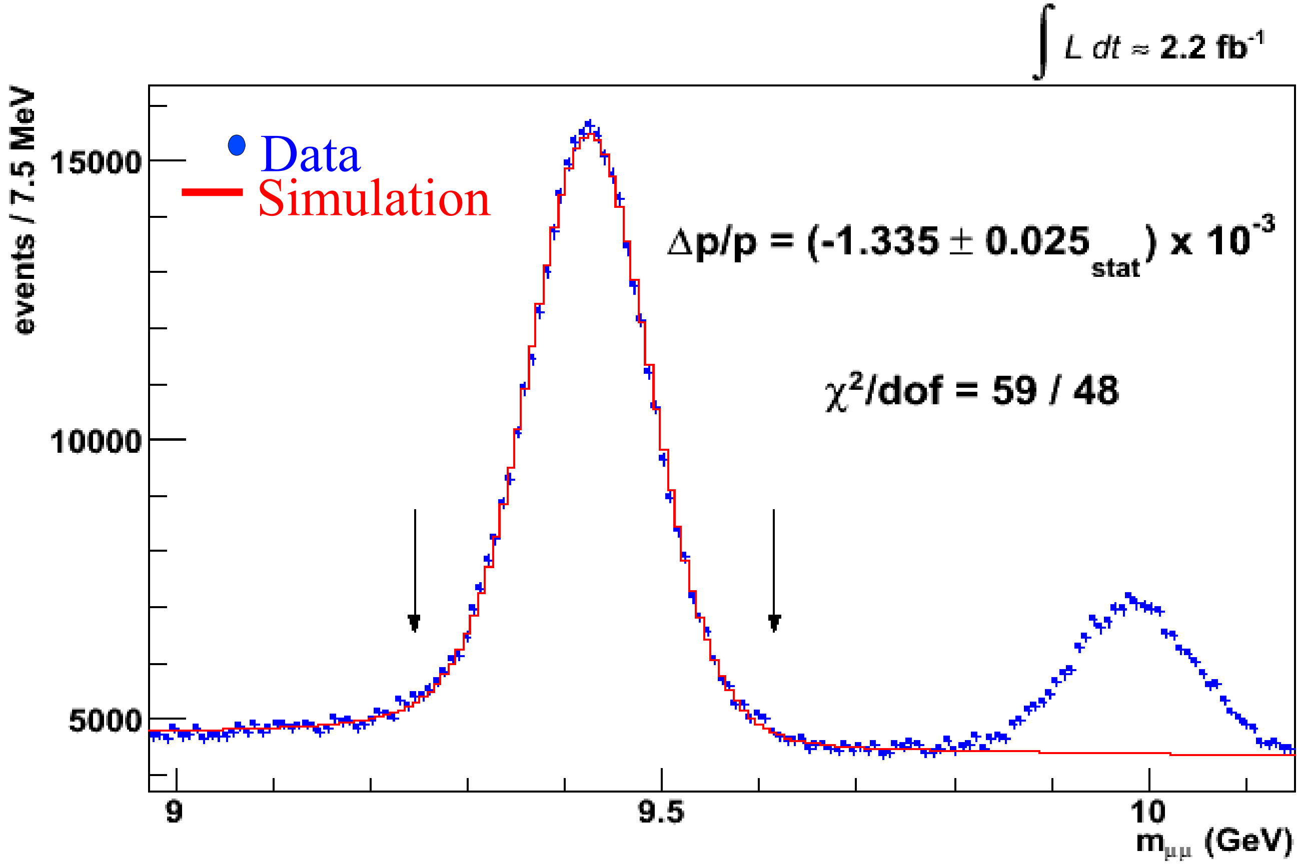




CDF Tracking Momentum Scale

$\Upsilon \rightarrow \mu\mu$ resonance provides

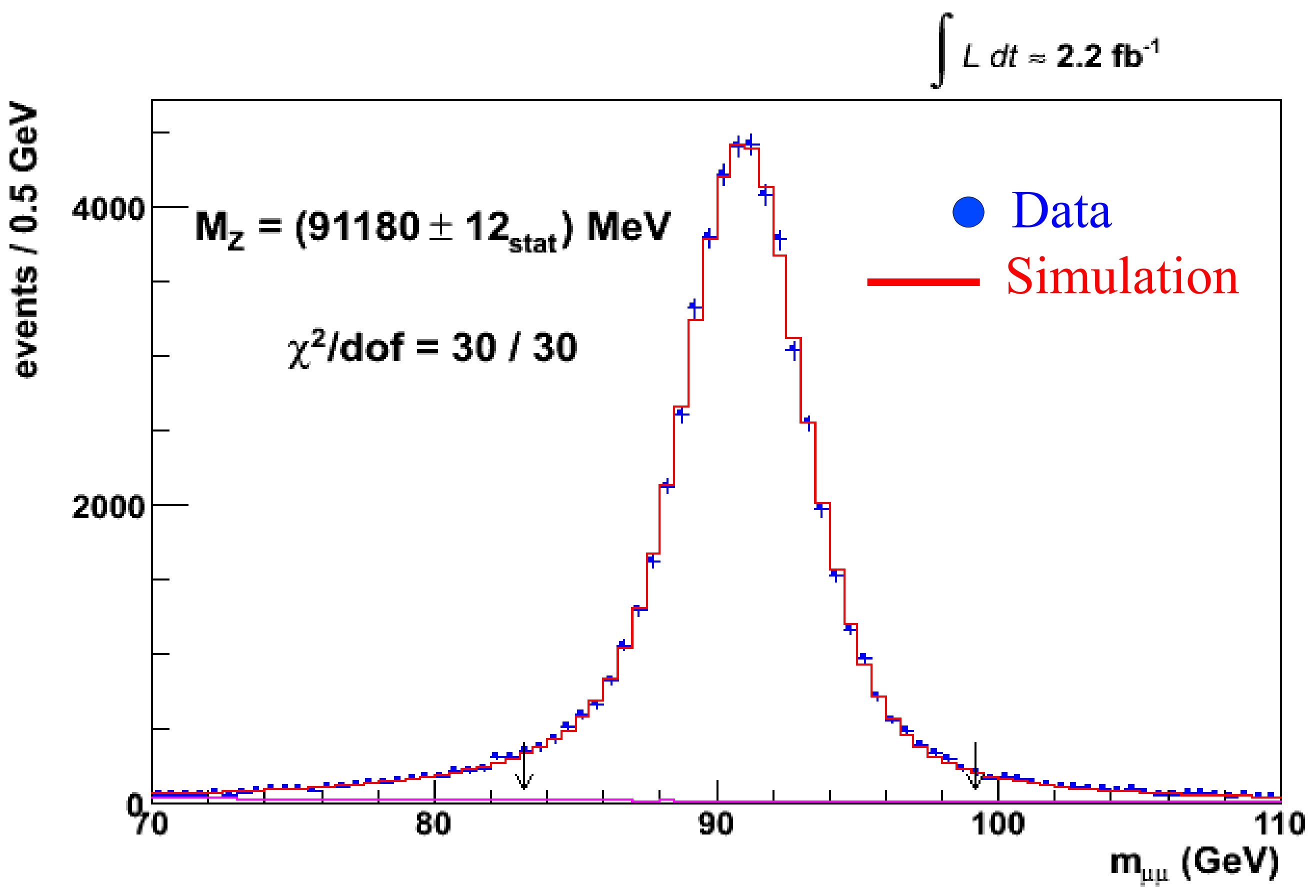
- Momentum scale measurement at higher p_T
- Validation of beam-constaining procedure (upsilons are promptly produced)
- Cross-check of non-beam-constrained (NBC) and beam-constrained (BC) fits



NBC $\Upsilon \rightarrow \mu\mu$ mass fit

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

- Using the J/ψ and ϒ momentum scale, performed "blinded" measurement of *Z* mass
  - *Z* mass consistent with PDG value (91188 MeV) (0.7σ statistical)
  - $M_Z = 91180 \pm 12_{stat} \pm 9_{momentum} \pm 5_{QED} \pm 2_{alignment}$ MeV

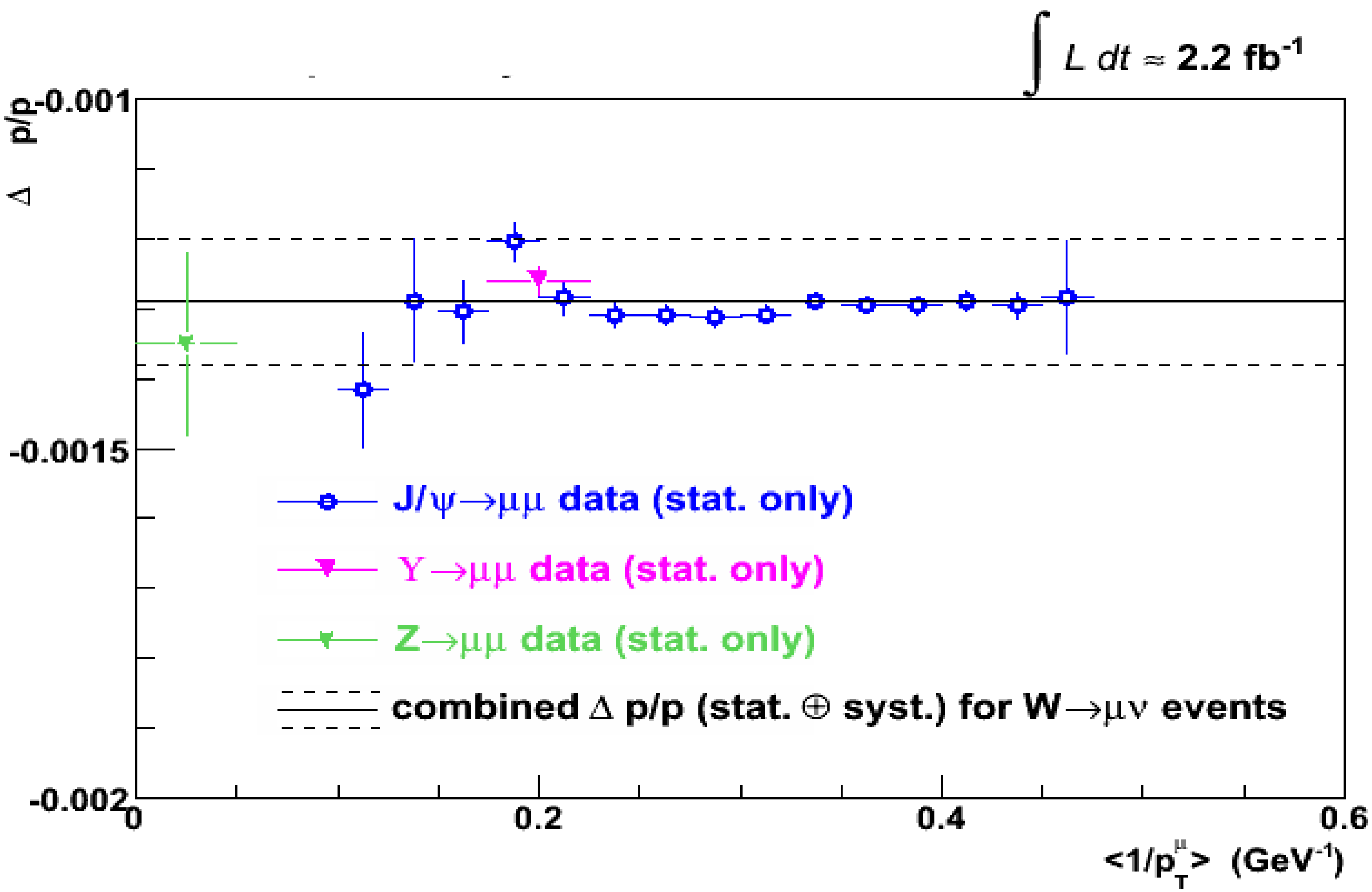


M(μμ) (GeV)

CDF Tracker Linearity Cross-check & Combination

- Final calibration using the J/ψ, ϒ and Z bosons for calibration
- Combined momentum scale correction :

$$\Delta p/p = (-1.29 \pm 0.07_{independent} \pm 0.05_{QED} \pm 0.02_{align}) \times 10^{-3}$$



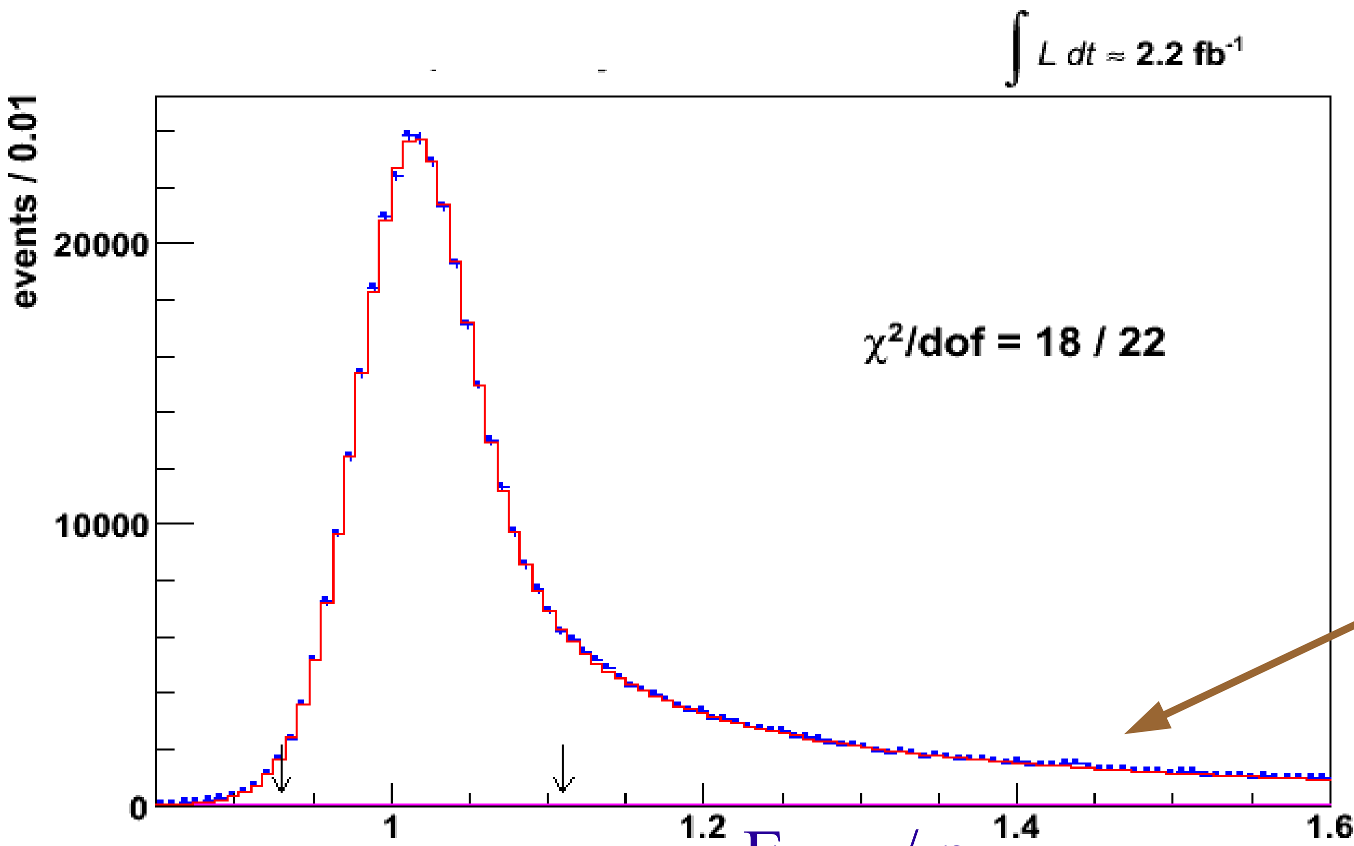
$\Delta M_W = 7$ MeV

EM Calorimeter Energy Calibration at CDF

- E/p peak from $W \rightarrow e\upsilon$ decays provides measurements of EM calorimeter scale and its (E_T-dependent) non-linearity

$$\Delta S_E = (9_{stat} \pm 5_{non-linearity} \pm 5_{X0} \pm 9_{Tracker}) \times 10^{-5}$$

Setting S_E to 1 using E/p calibration from combined $W \rightarrow e\upsilon$ and $Z \rightarrow ee$ samples



E_{CAL} / p_{track}

$\Delta M_W = 13$ MeV

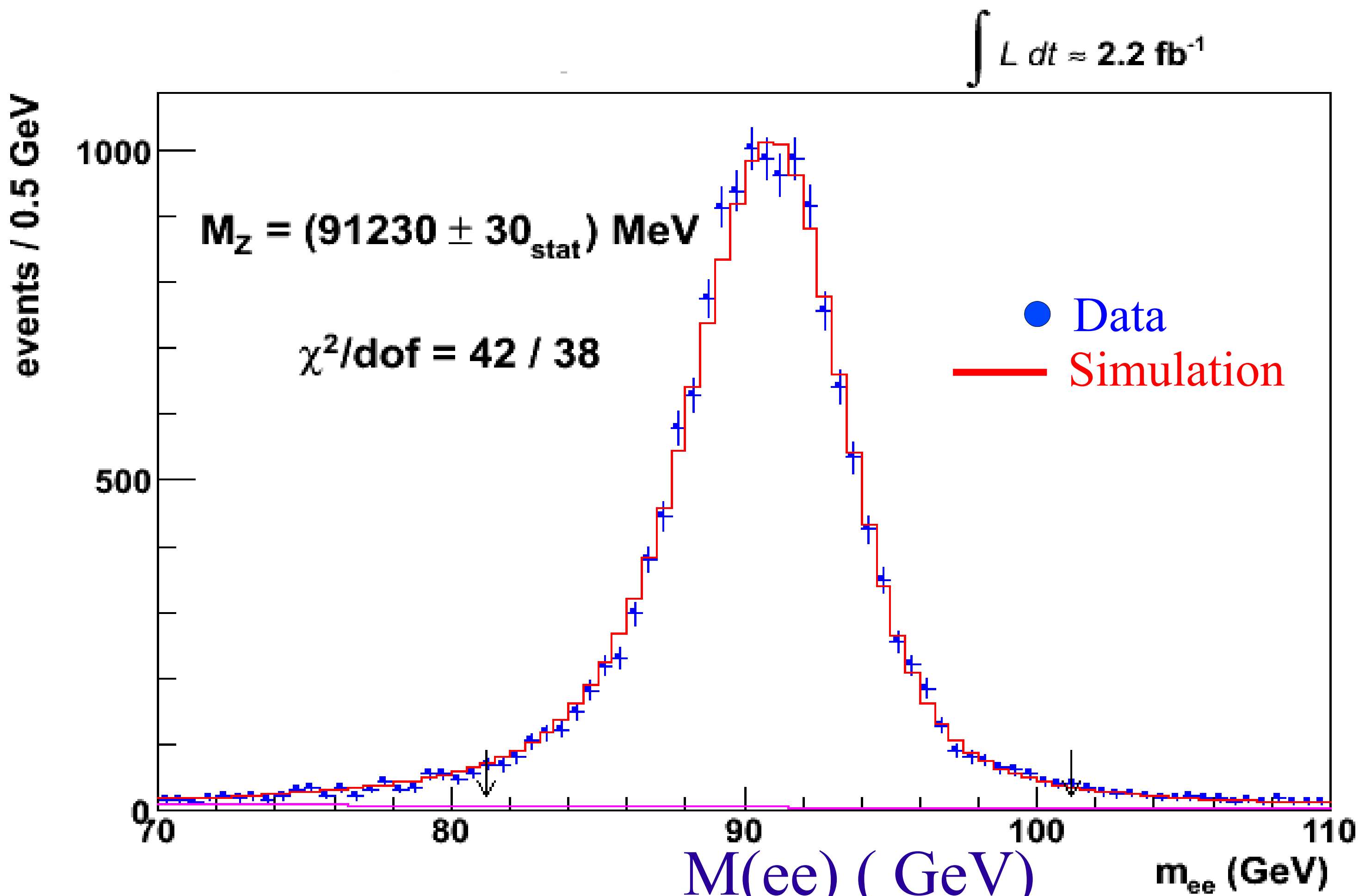
● Data

— Simulation

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

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

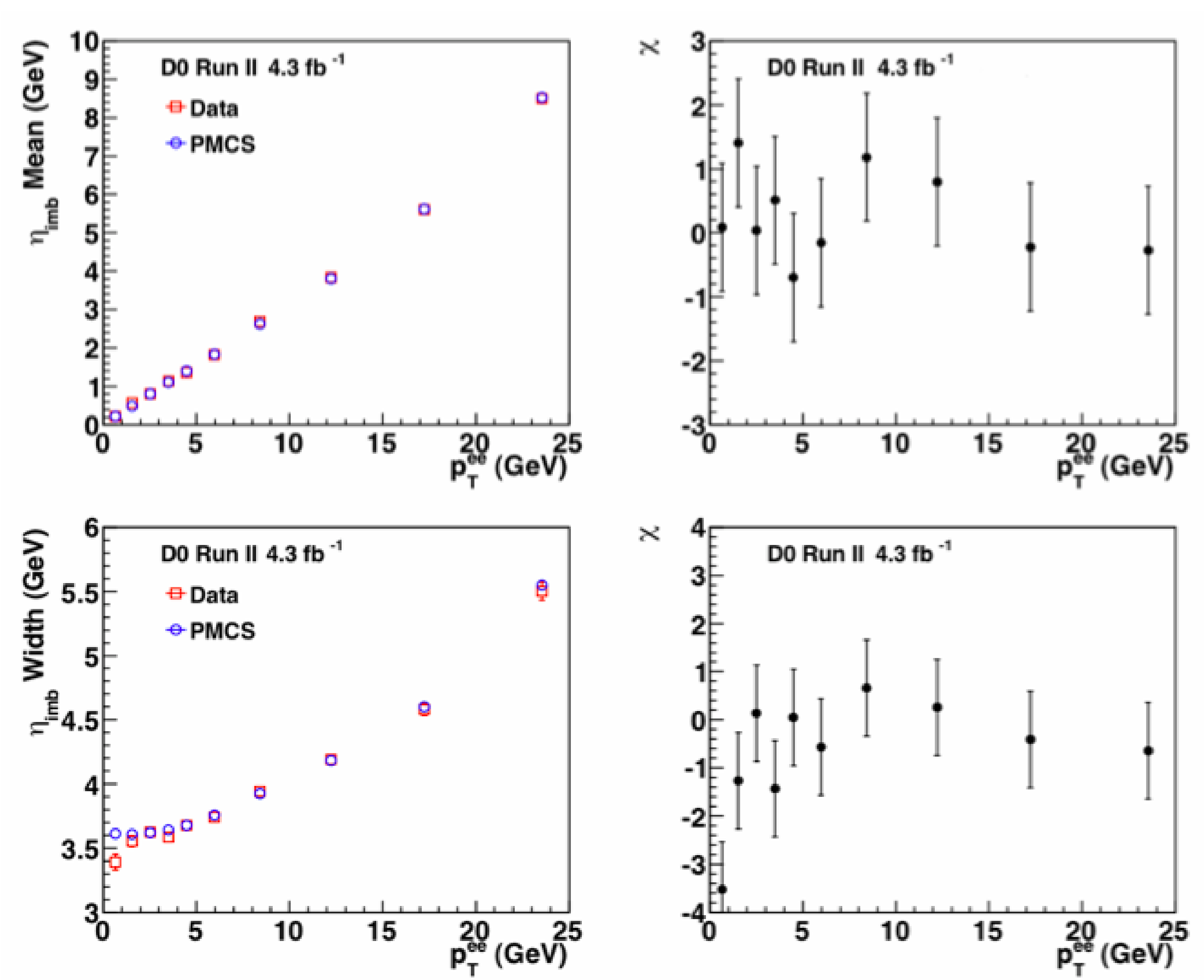
- Performed "blind" measurement of Z mass using E/p-based calibration
  - Consistent with PDG value (91188 MeV) within 1.4σ (statistical)
  - $M_Z = 91230 \pm 30_{stat} \pm 10_{calorimeter} \pm 8_{momentum} \pm 5_{QED} \pm 2_{alignment}$ MeV
- Combine E/p-based calibration with $Z \rightarrow ee$ mass for maximum precision

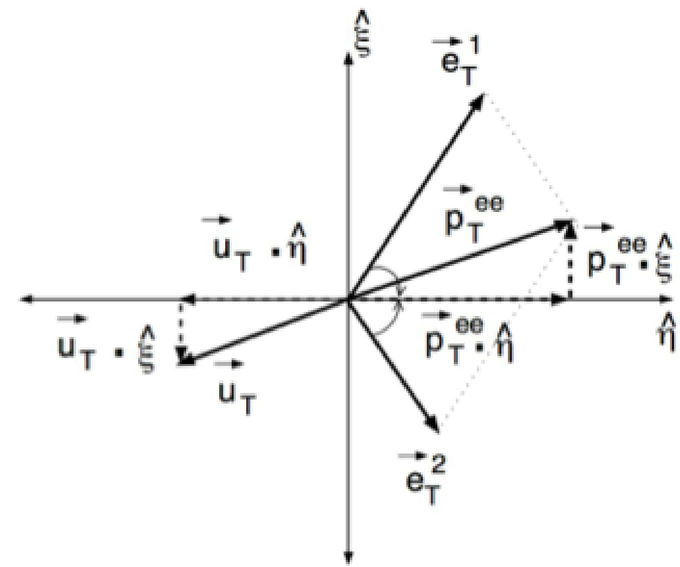


$\Delta M_W = 10$ MeV

Recoil Response Model at D0 (similar to CDF)

- Hadronic response model motivated from "first principles"
  - "jet response" + spectator interaction + additional interactions and noise



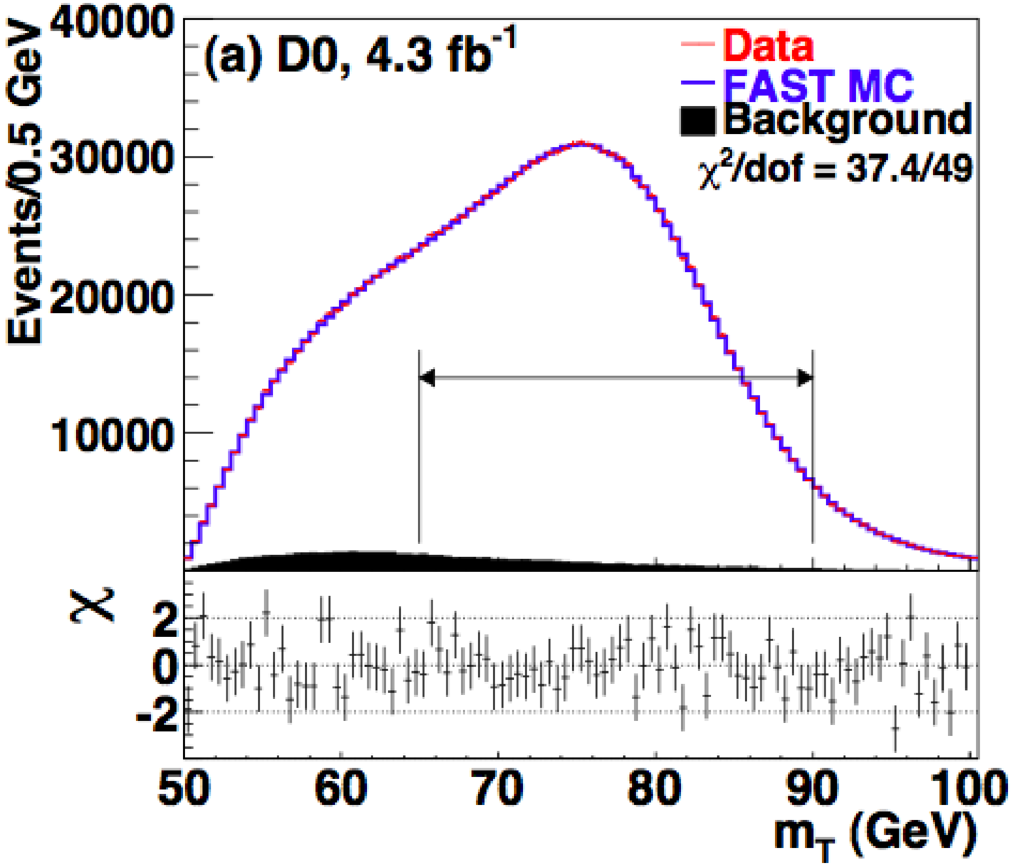


Tuned on p_T balance in Z boson events

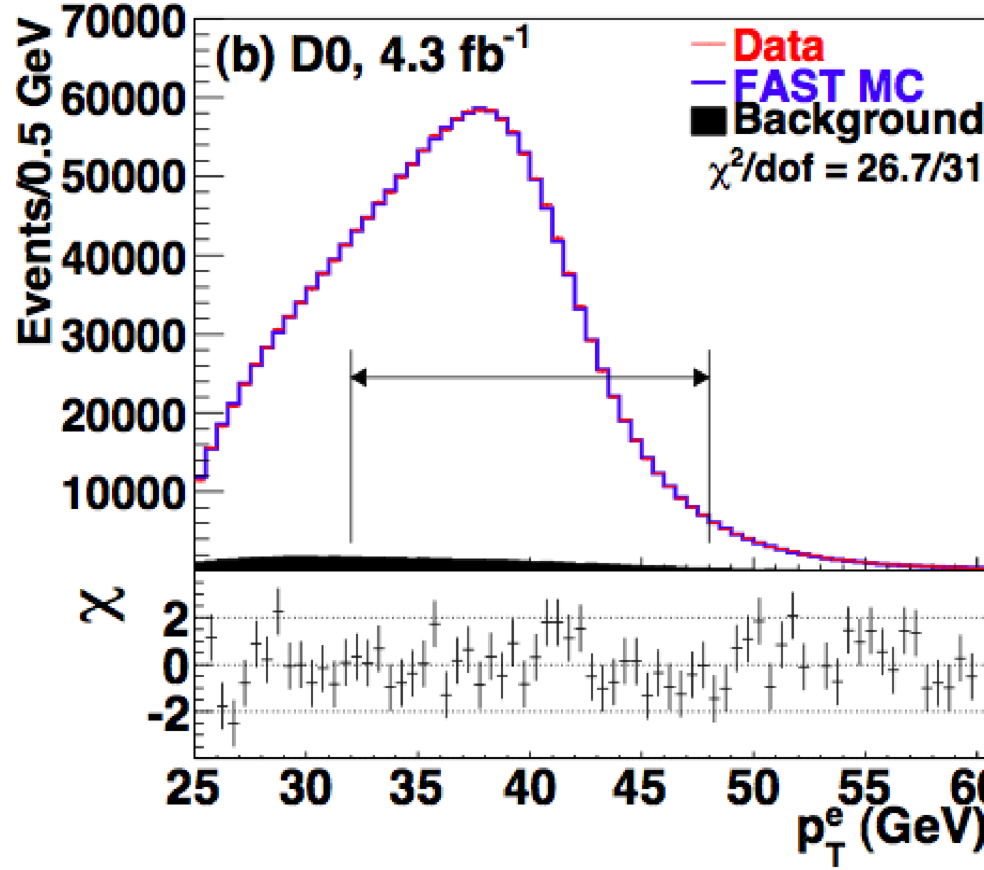
W Mass Fits at D0

1.677M W events

M_T



$p_T(e)$

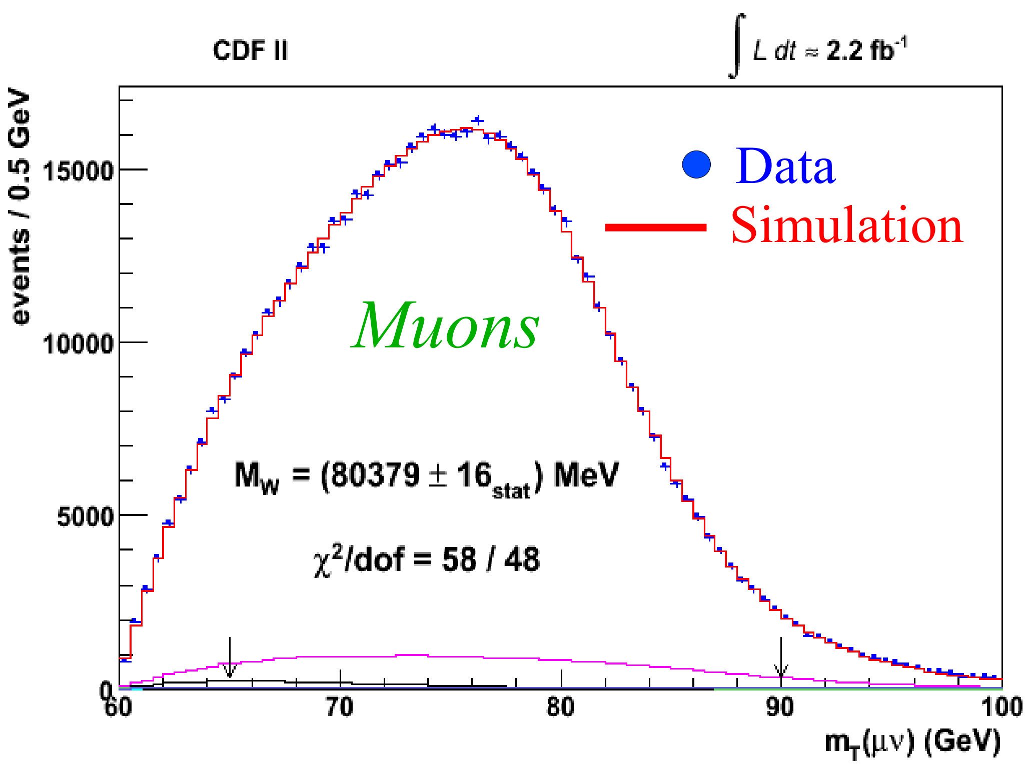


Fitted result:
m_W = 80371 ± 13 (stat) MeV

Fitted result:
m_W = 80343 ± 14 (stat) MeV

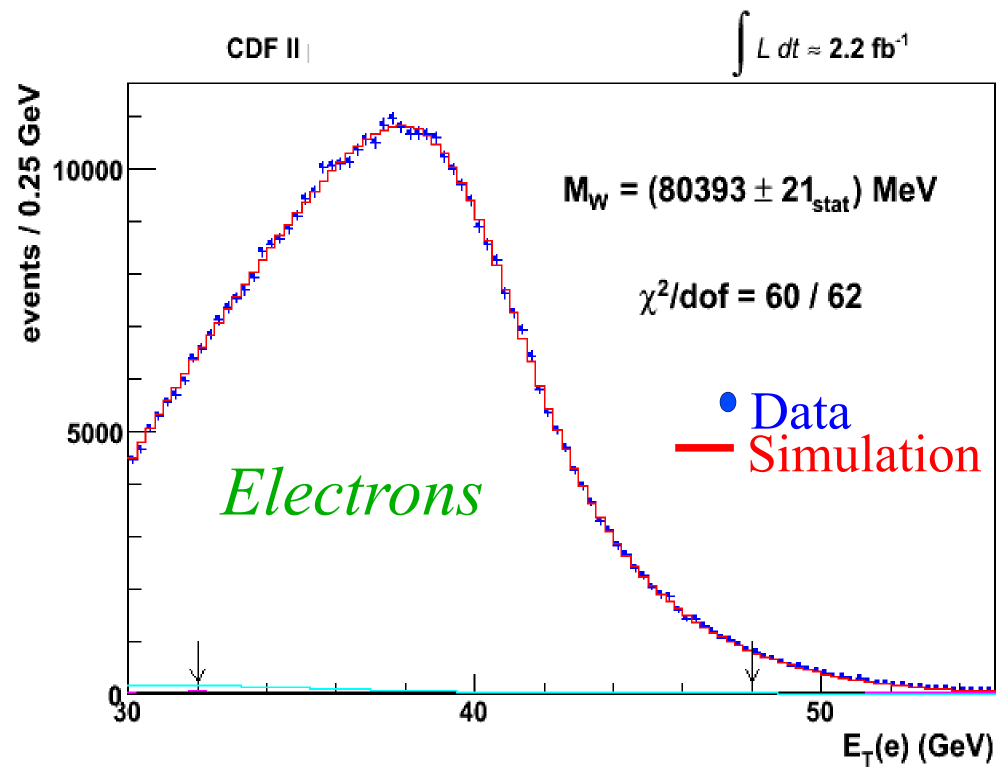
W Mass Fits at CDF

625k events



Muon-channel transverse mass fit

470k events



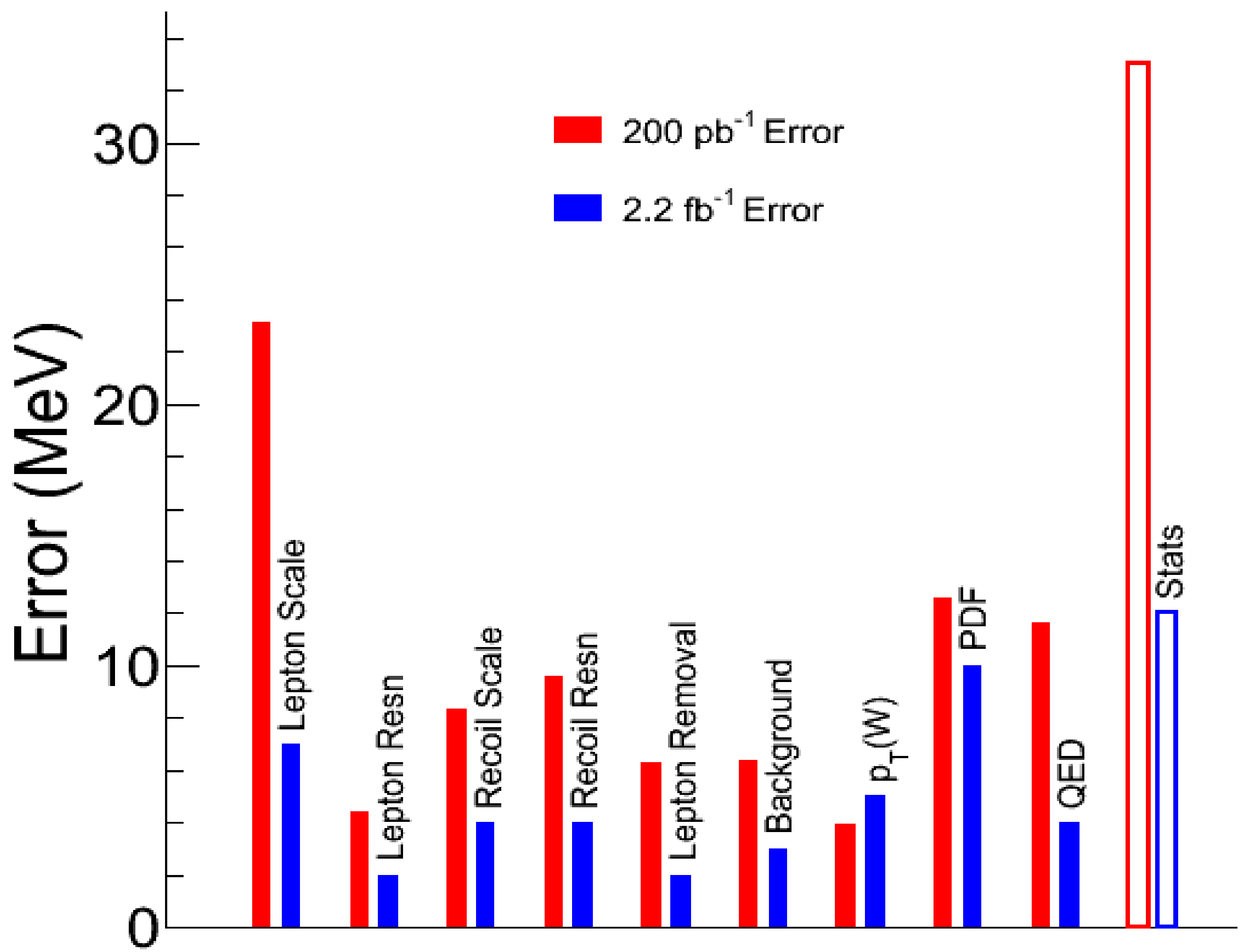
electron-channel lepton p_T fit

Neutrino p_T fits also performed by both experiments to check consistency

Transverse Mass Fit Uncertainties (MeV)

Source	CDF $m_T(\mu,\nu)$	CDF $m_T(e,\nu)$	DØ $m_T(e,\nu)$
Experimental – Statistical power of the calibration sample.			
Lepton Energy Scale	7	10	16
Lepton Energy Resolution	1	4	2
Lepton Energy Non-Linearity			4
Lepton Energy Loss			4
Recoil Energy Scale	5	5	
Recoil Energy Resolution	7	7	
Lepton Removal	2	3	
Recoil Model			5
Efficiency Model			1
Background	3	4	2
W production and decay model – Not statistically driven.			
PDF	10	10	11
QED	4	4	7
Boson p_T	3	3	2

Combined W Mass Result, Error Scaling (CDF)

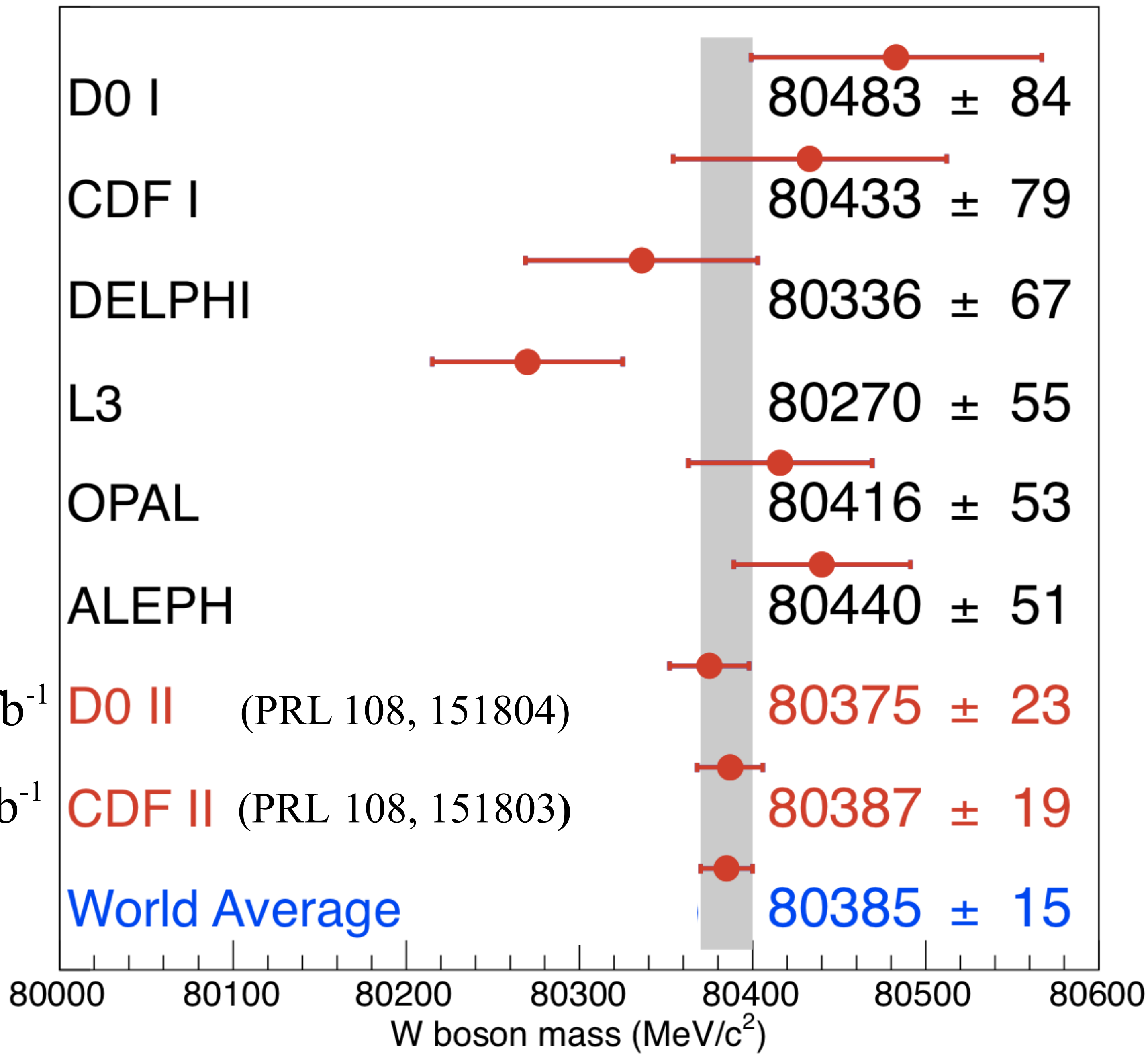


W Boson Mass Measurements from Different Experiments

World average
computed by TeVEWWG
ArXiv: 1204.0042

5.3 fb^{-1}

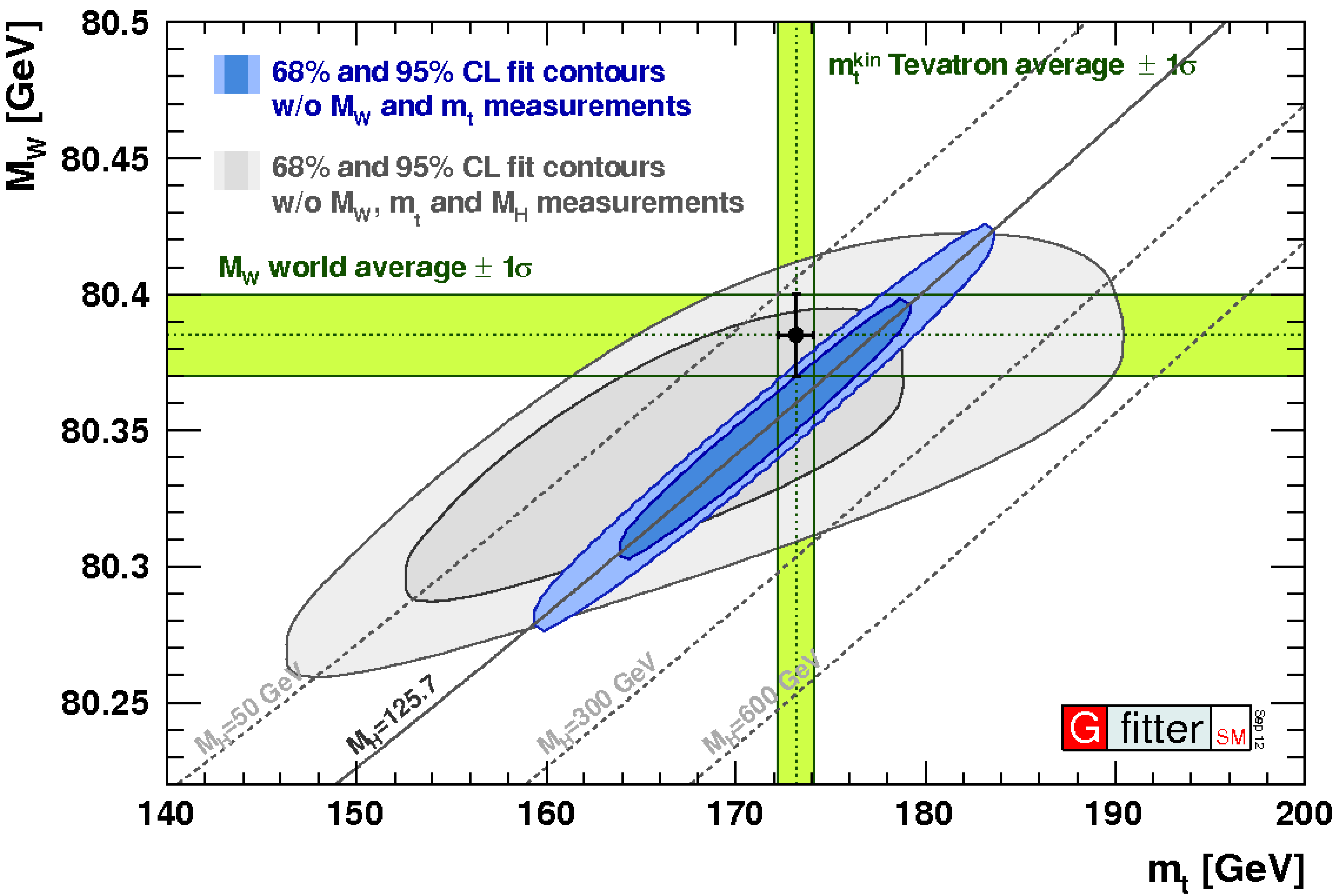
2.2 fb^{-1}



PDF Uncertainties – scope for improvement

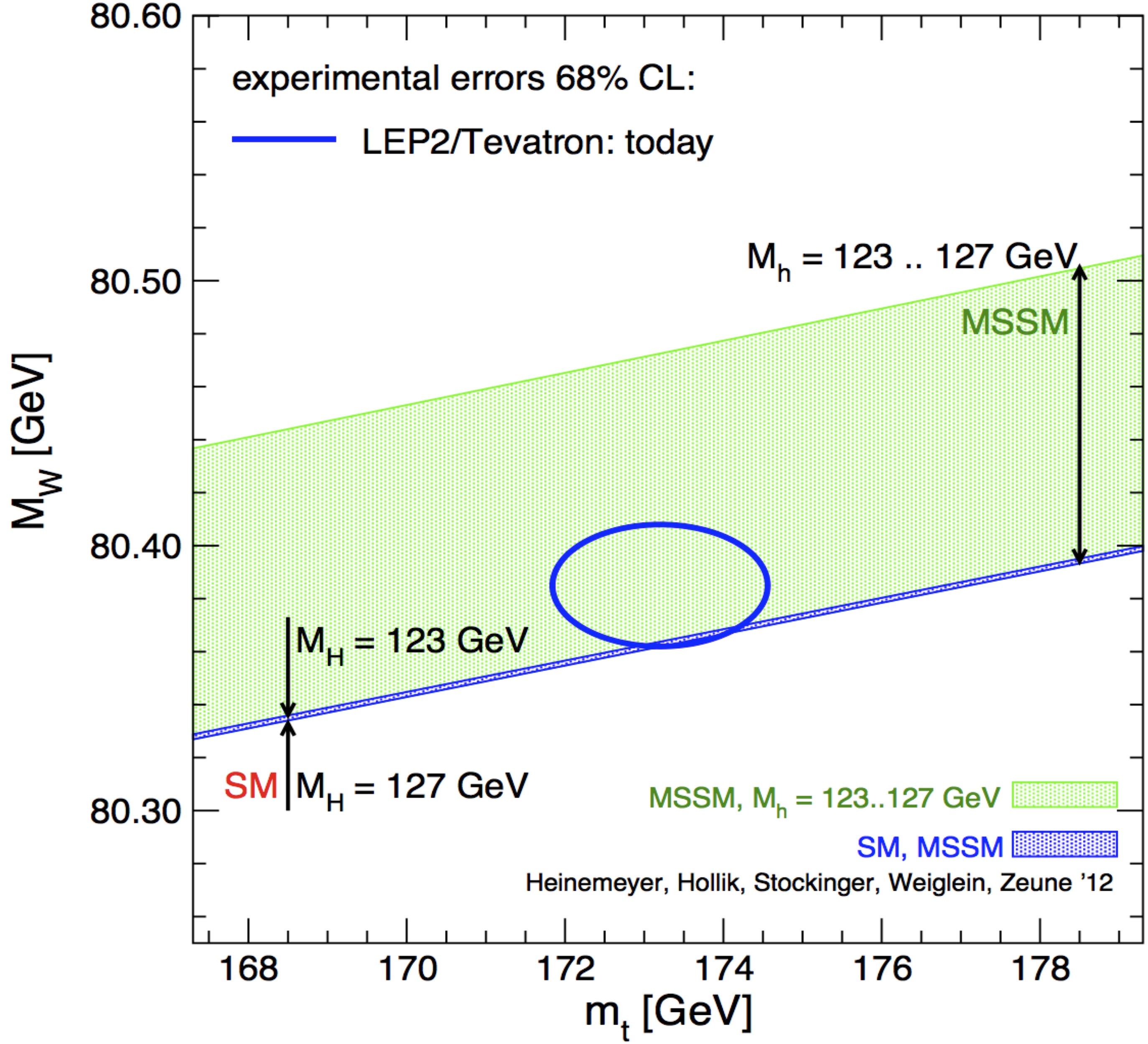
- Factor of 5 bigger samples of W and Z bosons available at Tevatron
- Newer PDF sets, *e.g.* CT10W include more recent data, such as Tevatron W charge asymmetry data
- Dominant sources of W mass uncertainty are the d_{valence} and $\bar{d}$-$\bar{u}$ degrees of freedom
  - Understand consistency of data constraining these d.o.f.
  - PDF fitters increase tolerance to accommodate inconsistent datasets
- Tevatron and LHC measurements that can further constrain PDFs:
  - Z boson rapidity distribution
  - W → $l\nu$ lepton rapidity distribution
  - W boson charge asymmetry

Test of Electroweak Quantum Loops at High Energy



The top quark mass, the W boson mass and the mass of the Higgs boson provides a stringent test of the standard model at loop level

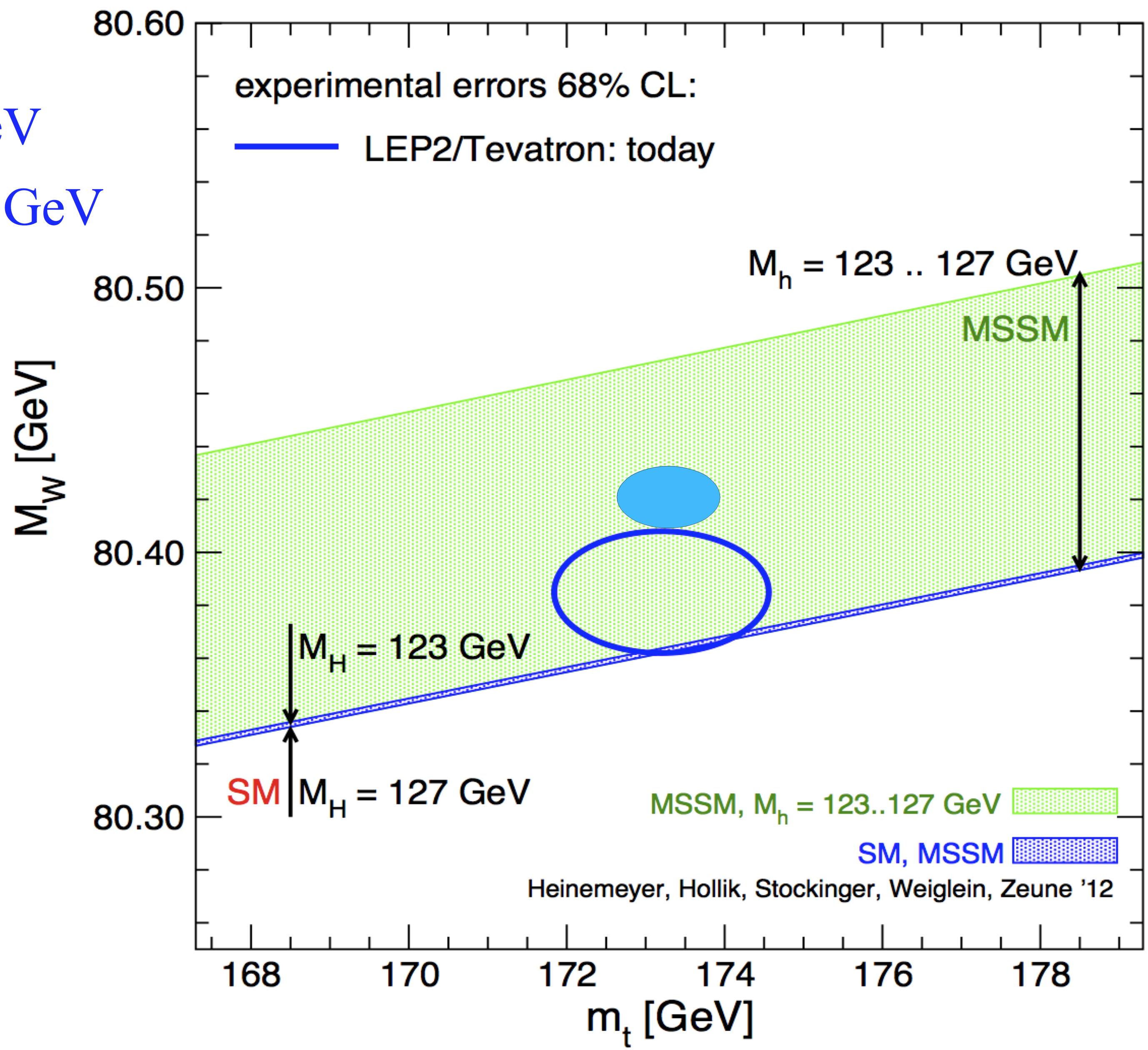
Current M_W *vs* M_{top}



Improved M_W *vs* M_{top} (half the current uncertainties)

$\delta M_W \sim 7$ MeV

$\delta m_{top} \sim 0.5$ GeV



Summary

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

- New Tevatron W mass result from 2.2 fb^{-1} - 5.3 fb^{-1} (PRL 108, 151803 & 151804)
  - $M_W = 80385 \pm 15$ MeV

- New global electroweak fit $M_H = 94^{+29}_{-24}$ GeV @ 68% CL (LEPEWWG)
  - Consistent with directly measured $M_H \sim 125$ GeV

- Looking forward to $\Delta M_W < 10$ MeV from 10 fb^{-1} of Tevatron data
  - Could LHC achieve $\Delta M_W \sim 5$ MeV given huge statistics ?

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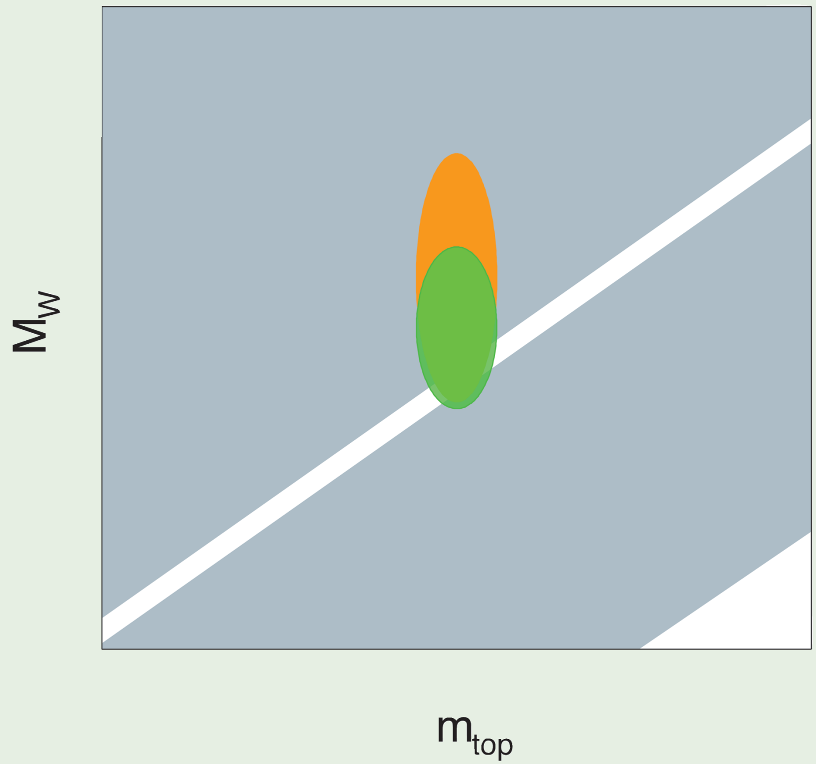

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Backup

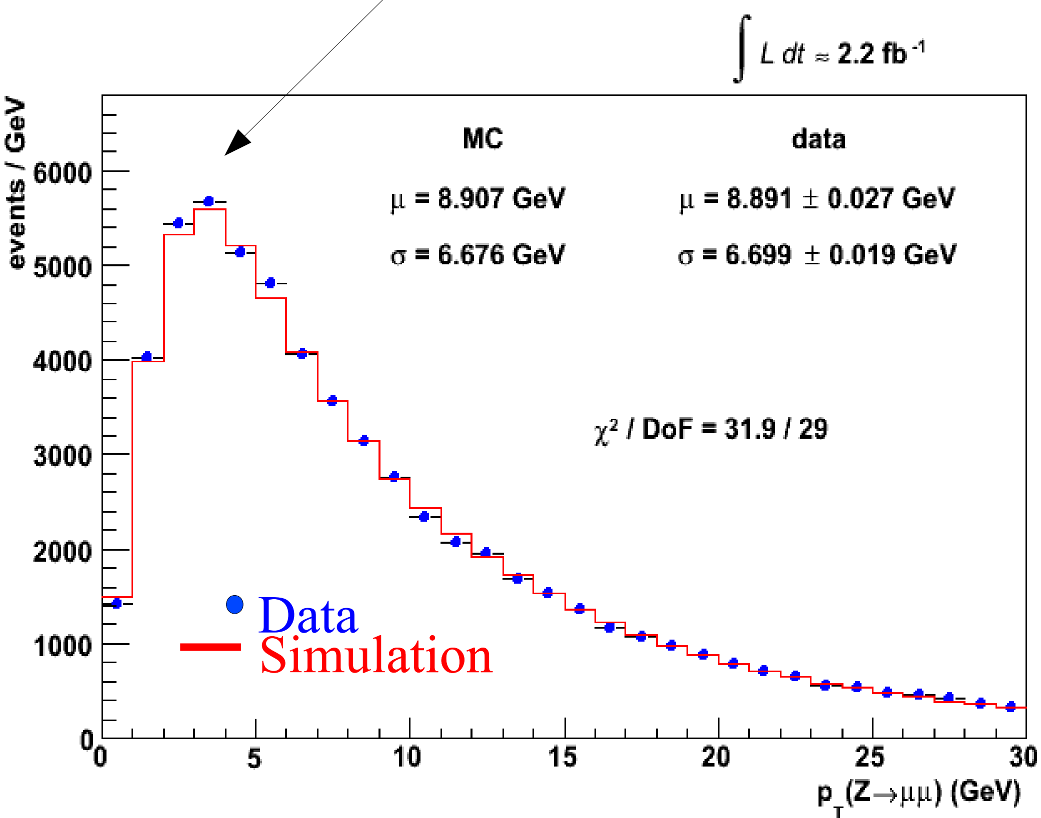
Constraining Boson p_T Spectrum

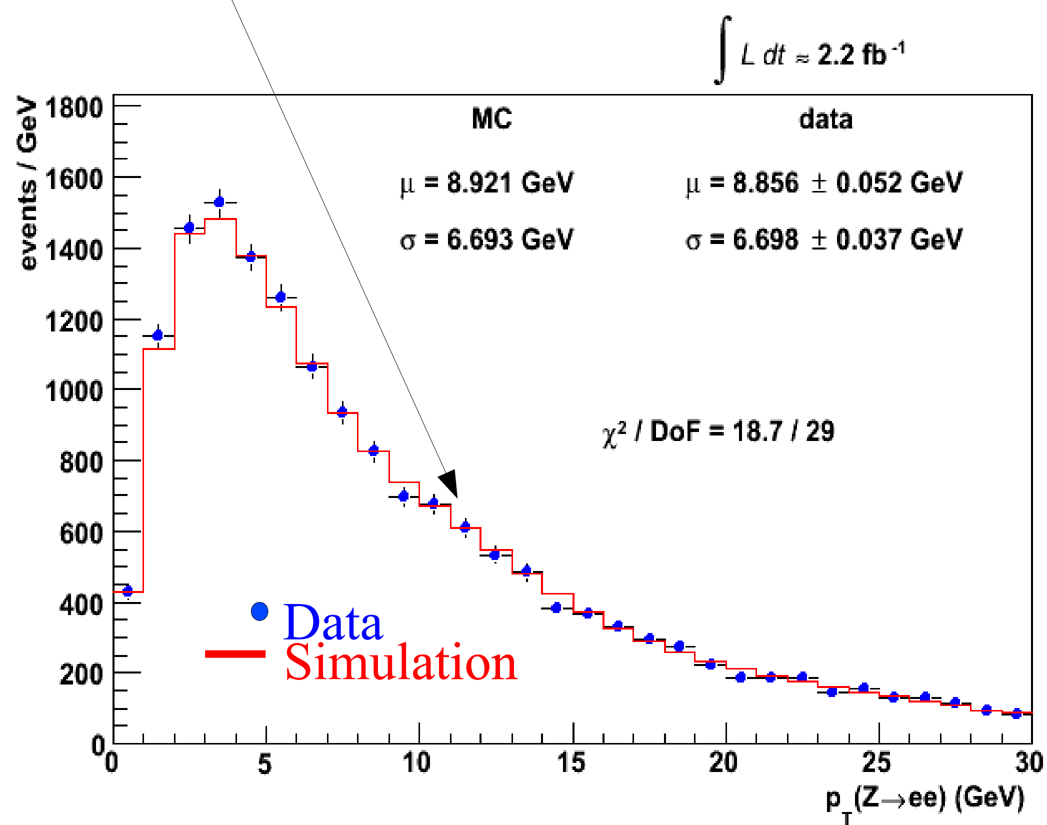
- Fit the non-perturbative parameter g_2 and QCD coupling α_s in RESBOS to $p_T(ll)$ spectra:

$\Delta M_W = 5$ MeV

Position of peak in boson p_T spectrum depends on g_2

Tail to peak ratio depends on α_s





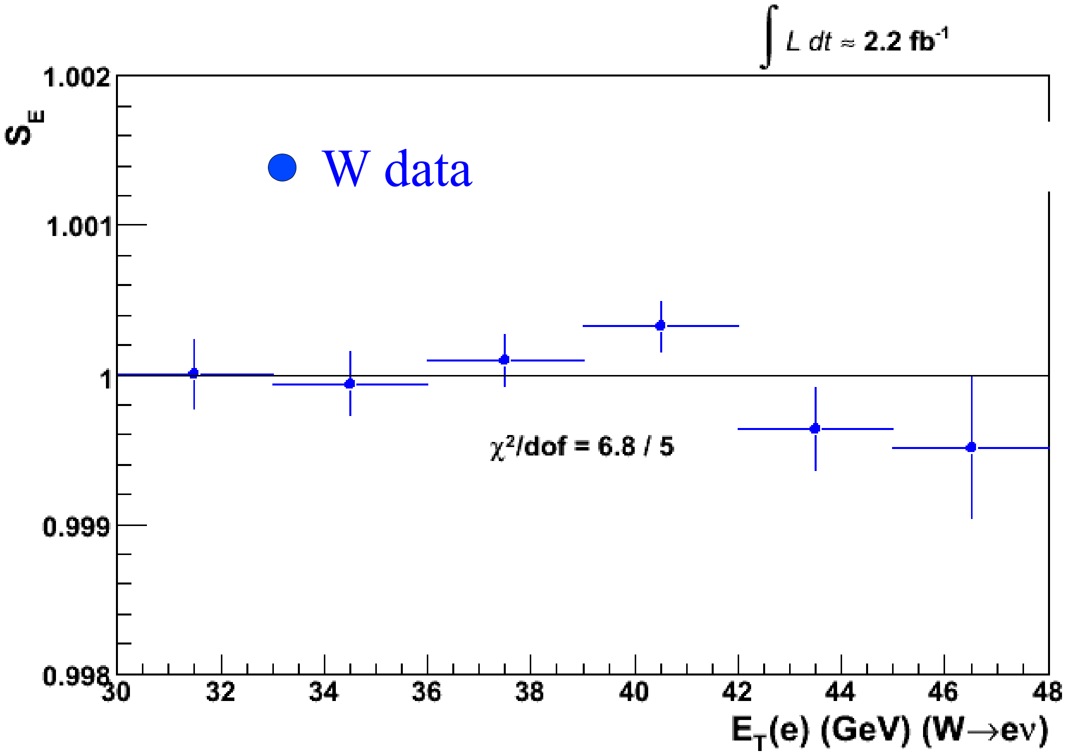
Measurement of EM Calorimeter Non-linearity

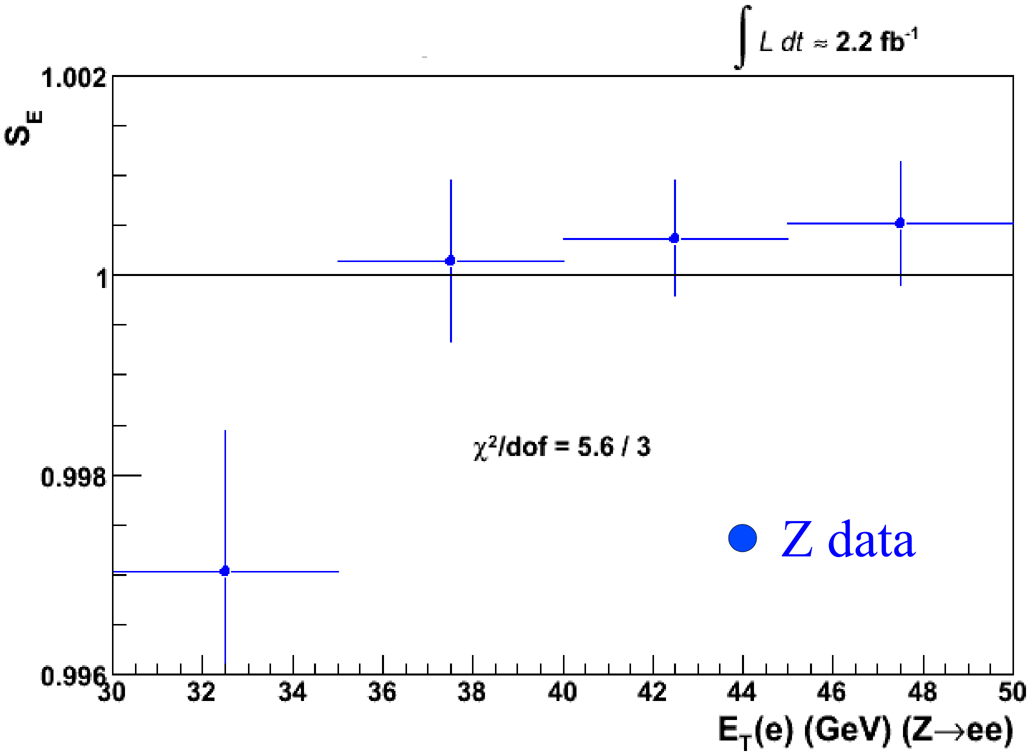
- Perform E/p fit-based calibration in bins of electron E_T
- GEANT-motivated parameterization of non-linear response:

$$S_E = 1 + \beta \log(E_T / 39 \text{ GeV})$$

- Tune on W and Z data: $\beta = (5.2 \pm 0.7_{stat}) \times 10^{-3}$

  $\Rightarrow \Delta M_W = 4$ MeV

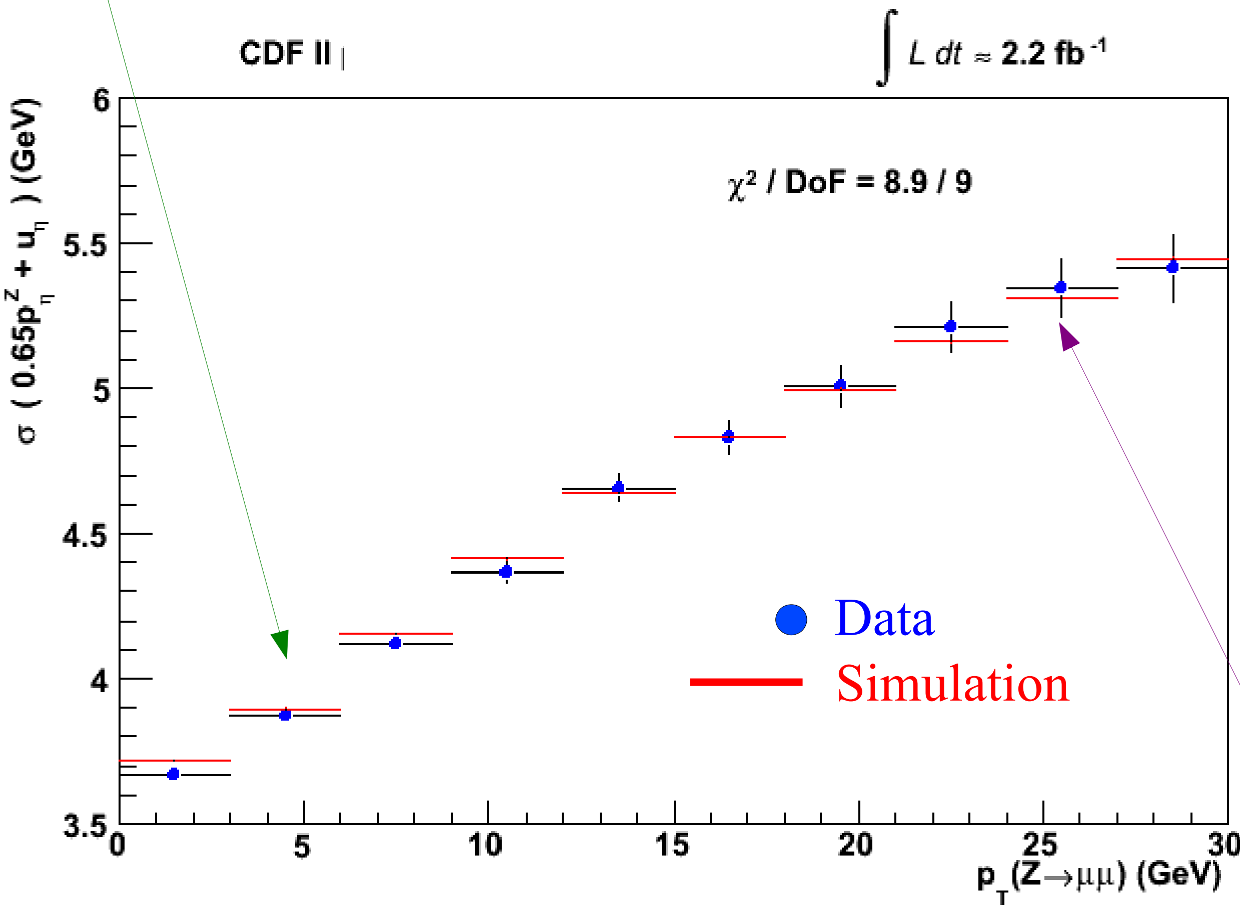


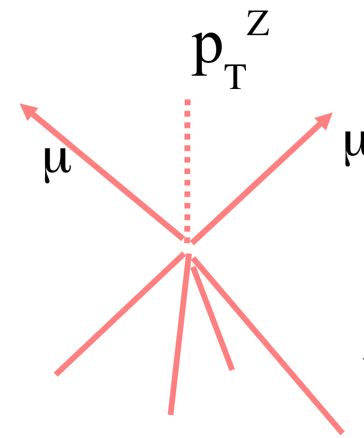


Tuning Recoil Resolution Model with *Z* events

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

Resolution of p_T-balance (GeV)



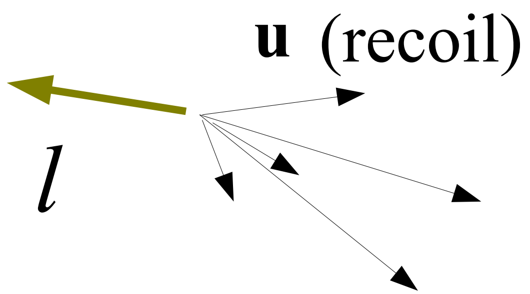


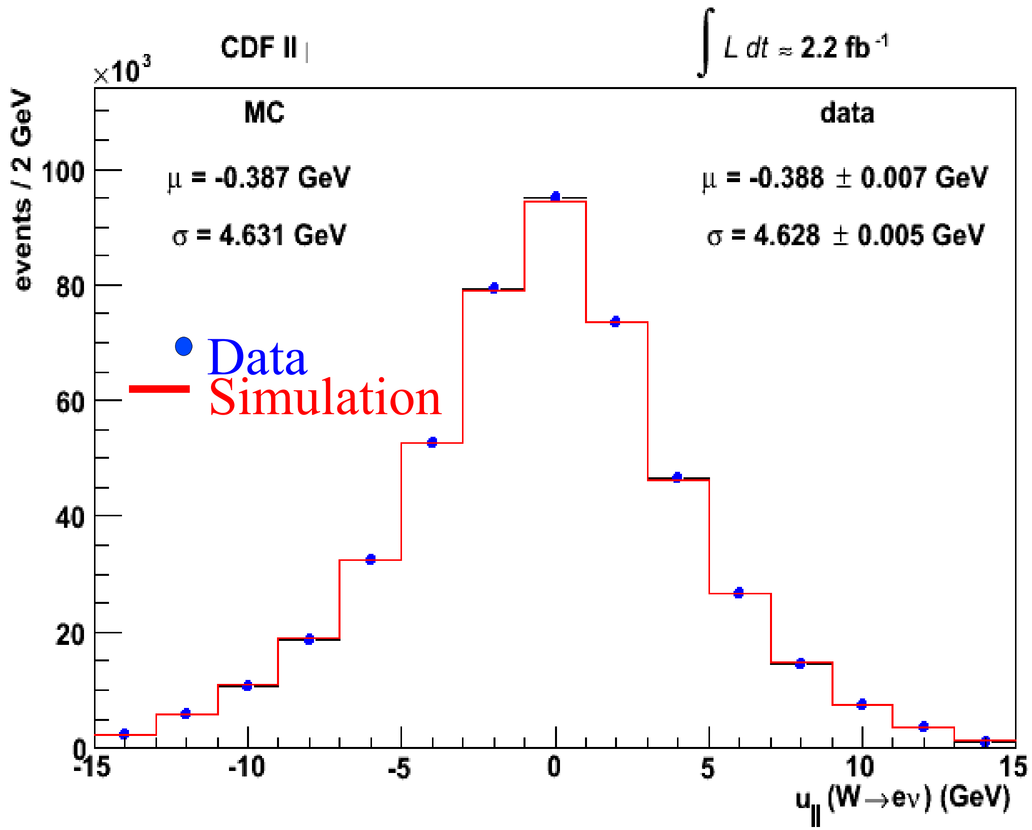
$\Delta M_W = 4\ \mathrm{MeV}$

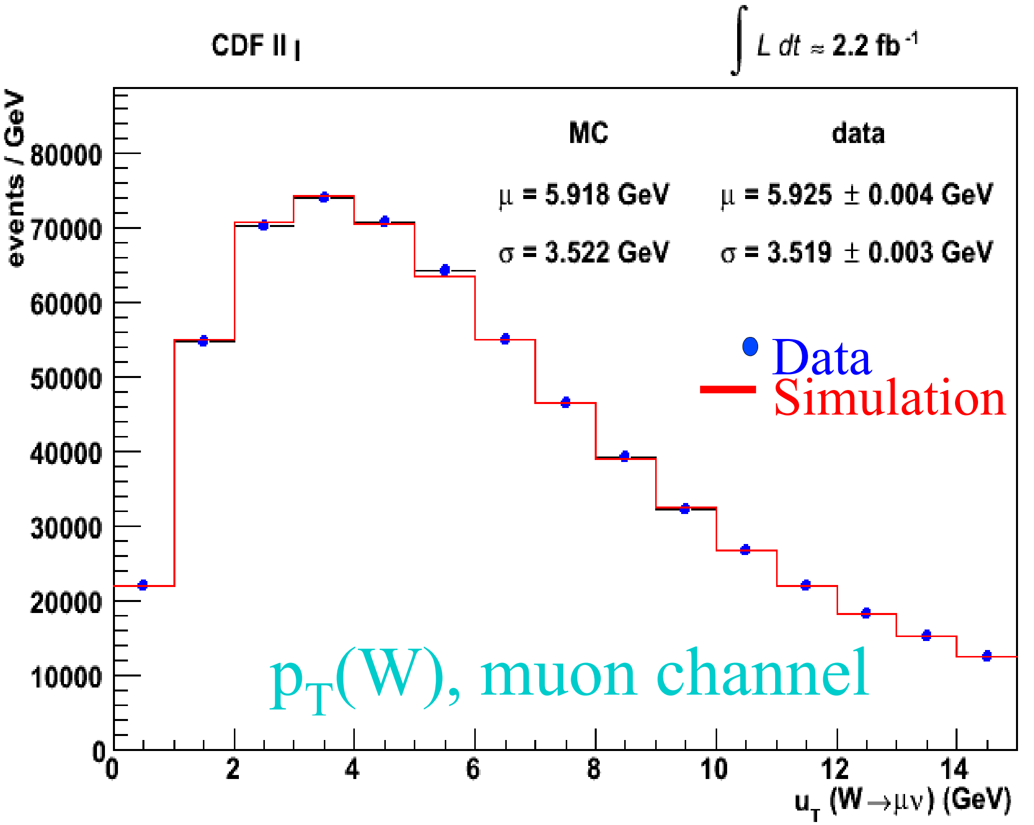
At high $p_T(Z)$, p_T-balance constrains jet resolution

Testing Hadronic Recoil Model with *W* events

Compare recoil distributions between simulation and data







Recoil projection (GeV) on lepton direction

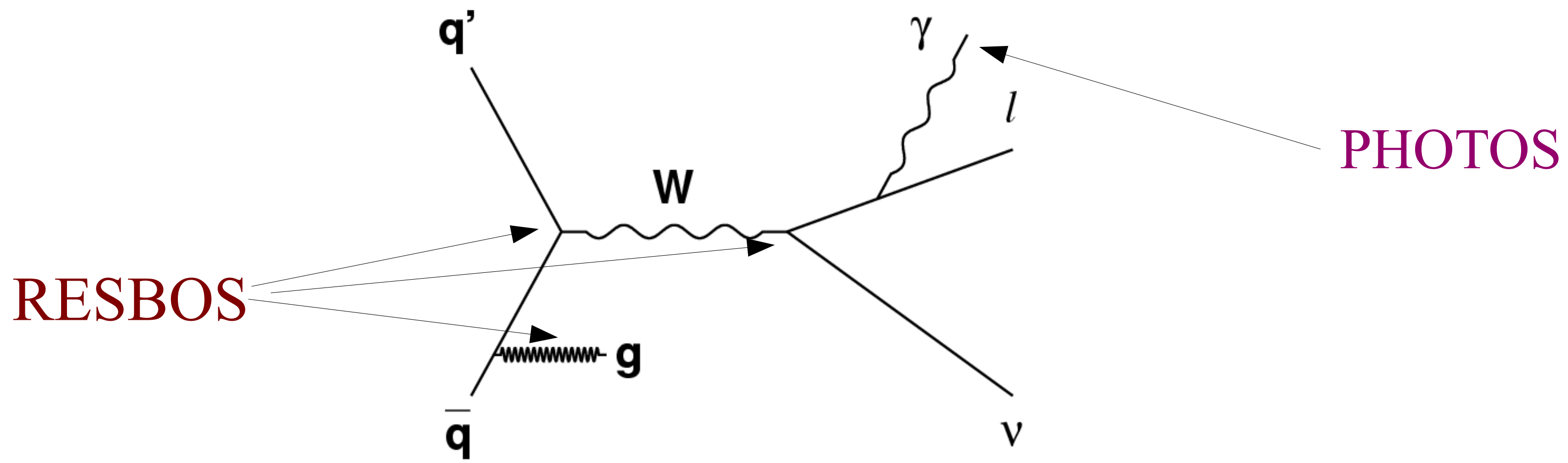
Systematic Uncertainties in QED Radiative Corrections

	CDF0	CDFIa	CDFIb	CDFII 200pb^{-1}	CDFII 2.3fb^{-1}	DØ 1fb^{-1}
effects:						
single photon	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
exact $\mathcal{O}(\alpha)$	–	–	–	$\surd$	$\surd$	–
multi-photon	–	–	–	–	$\surd$	$\surd$
ISR	–	–	–	–	$\surd$	–
uncertainties:						
2γ emission	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
ISR	–	–	$\surd$	$\surd$	$\surd$	$\surd$
$\alpha\alpha_s$	–	–	–	$\surd$	$\surd$	–
SV cut-off	–	–	–	$\surd$	$\surd$	$\surd$
Z/W correl.	–	–	–	$\surd$	$\surd$	$\surd$
beyond 2γ	–	–	–	–	$\surd$	–
H.O. SV corr.	–	–	–	–	$\surd$	–
pair creation	–	–	–	–	$\surd$	–
Breit-Wigner	–	–	–	–	$\surd$	–
EWK scheme	–	–	–	–	$\surd$	–

Parton Distribution Functions

- Affect W kinematic lineshapes through acceptance cuts
- We use CTEQ6 as the default PDF
- Use ensemble of 'uncertainty' PDFs
  - Represent variations of eigenvectors in the PDF parameter space
  - compute δM_W contribution from each error PDF
- Using MSTW2008 PDF ensemble defined for 68% CL, obtain systematic uncertainty of 10 MeV
- Comparing CTEQ and MSTW at 90% CL, yield similar uncertainty (CTEQ is 10% larger)
  - Cross-check: default MSTW2008 relative to default CTEQ6 yields 6 MeV shift in W mass

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
- Multiple radiative photons generated according to PHOTOS (P. Golonka and Z. Was, Eur. J. Phys. C 45, 97 (2006) and references therein)