# Measuring the Mass of the W Boson

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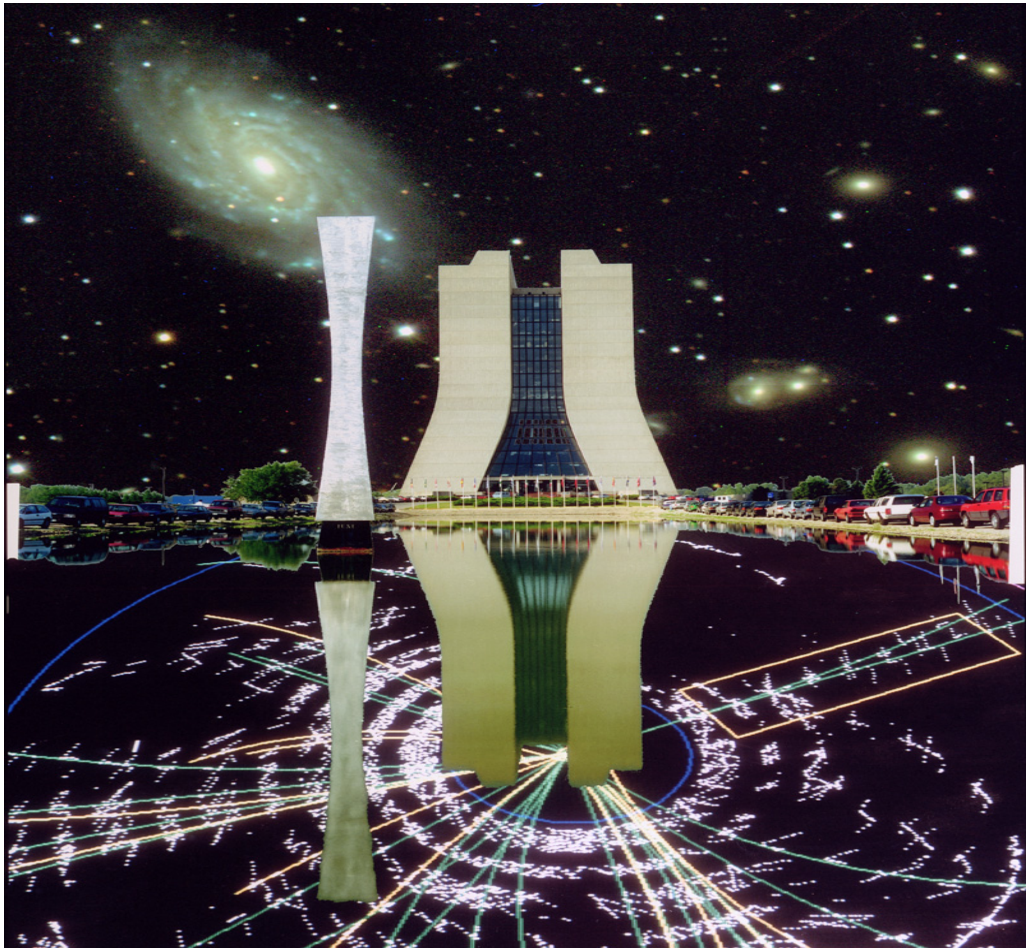

Hadron Collider Physics Summer School
Fermilab
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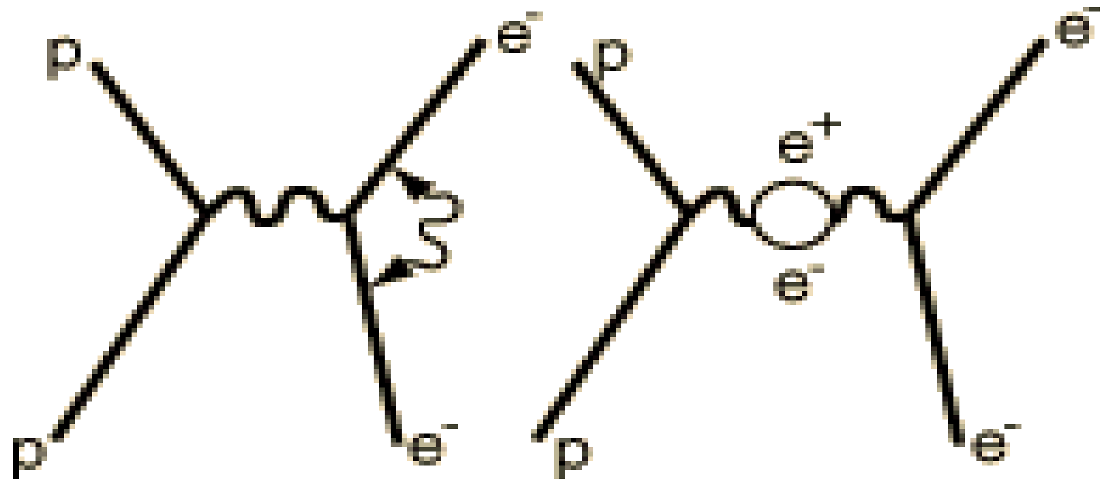
# Detecting New Physics through Precision Measurements

- Willis Lamb (Nobel Prize 1955) measured the difference between energies of $^2S_{1/2}$ and $^2P_{1/2}$ states of hydrogen atom
  - 4 micro electron volts difference compared to few electron volts binding energy
  - States should be degenerate in energy according to tree-level calculation
- Harbinger of vacuum fluctuations to be calculated by Feynman diagrams containing quantum loops
  - Modern quantum field theory of electrodynamics followed ( Nobel Prize 1965 for Schwinger, Feynman, Tomonaga)



# Parameters of Electro-Weak Interactions

- Gauge symmetries related to the electromagnetic and weak forces in the standard model, extension of QED
  - U(1) gauge group with gauge coupling $g$
  - SU(2) gauge group with gauge coupling $g'$

- And gauge symmetry-breaking via vacuum expectation value of Higgs field $v \neq 0$

- Another interesting phenomenon in nature: the U(1) generator and the neutral generator of SU(2) get mixed (linear combination) to yield the observed gauge bosons
  - Photon for electromagnetism
  - Z boson as one of the three gauge bosons of weak interaction
- Linear combination is given by Weinberg mixing angle $\vartheta_W$

# Parameters of Electro-Weak Interactions

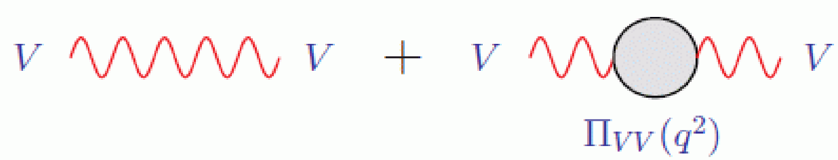
At tree level, all of the observables can be expressed in terms of *three* parameters of the SM Lagrangian: $v,\ g,\ g'$ or, equivalently, $v,\ e,\ s \equiv \sin\theta_W$ (also $c \equiv \cos\theta_W$)

$$\alpha = \frac{e^2}{4\pi}, \qquad G_F = \frac{1}{2\sqrt{2}v^2}, \qquad m_Z = \frac{e\,v}{\sqrt{2}sc}, \qquad m_W = \frac{e\,v}{\sqrt{2}s}, \qquad s^2_{\rm eff} = s^2,$$

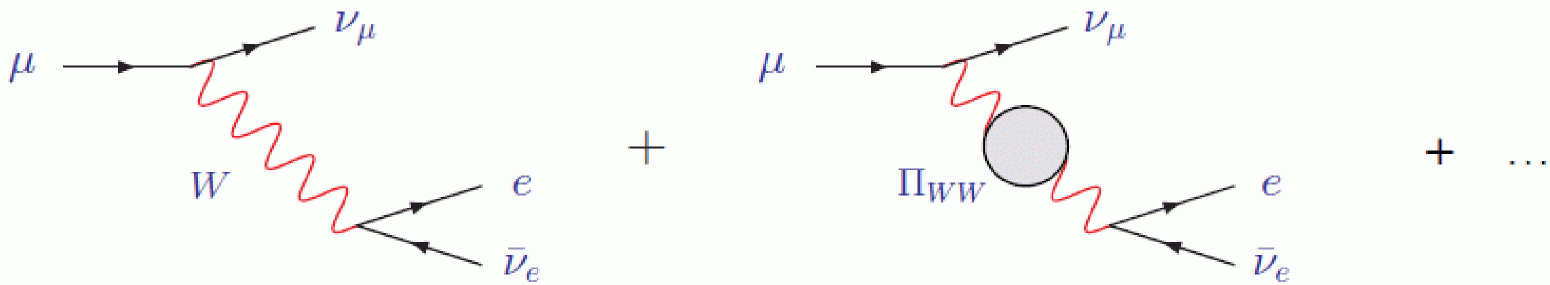
Radiative corrections to the relations between physical observables and Lagrangian params:

$$m_Z^2 = \frac{e^2v^2}{2\,s^2c^2} + \Pi_{ZZ}(m_Z^2)$$

$$m_W^2 = \frac{e^2v^2}{2\,s^2} + \Pi_{WW}(m_W^2)$$

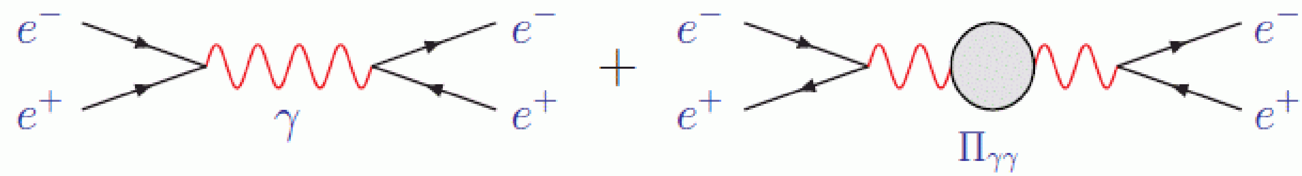



$$G_F = \frac{1}{2\sqrt{2}v^2}\left[1 - \frac{\Pi_{WW}(0)}{m_W^2} + \delta_{\rm VB}\right]$$



# Radiative Corrections to Electromagnetic Coupling

$$\alpha = \frac{e^2}{4\pi}\left[1 + \lim_{q^2 -> 0} \frac{\Pi_{\gamma\gamma}(q^2)}{q^2}\right]$$




this one is tricky: the hadronic contribution to $\Pi'_{\gamma\gamma}(0)$ cannot be computed perturbatively

We can however trade it for another experimental observable: $R_{\text{had}}(q^2) = \dfrac{\sigma_{\text{had}}(q^2)}{\sigma_{\ell^+\ell^-}(q^2)}$

$$\alpha(m_Z) = \frac{e^2}{4\pi}\left[1 + \frac{\Pi_{\gamma\gamma}(m_Z)}{m_Z{}^2}\right] = \frac{\alpha}{1 - \Delta\alpha(m_Z)}$$

$$\Delta\alpha(m_Z) = \underbrace{\Delta\alpha_\ell(m_Z) + \Delta\alpha_{\text{top}}(m_Z)}_{\text{calculable}} + \Delta\alpha^{(5)}_{\text{had}}(m_Z)$$

$$\Delta\alpha^{(5)}_{\text{had}}(m_Z) = -\frac{m_Z^2}{3\pi}\int_{4m_\pi^2}^{\infty} \frac{R_{\text{had}}(q^2)\mathrm{d}q^2}{q^2\,(q^2 - m_Z^2)} \;=\; 0.02758 \pm 0.00035$$

(This hadronic contribution is one of the biggest sources of uncertainty in EW studies)

# Radiative Corrections to W Boson Mass

All these corrections can be combined into relations among physical observables, e.g.:

$$m_W^2 = m_Z^2 \left[ \frac{1}{2} + \frac{1}{2} \sqrt{1 - \frac{2\sqrt{2}\,\pi\alpha}{G_F\, m_Z^2}\,(1+\Delta r)} \right]$$

$\Delta r$ can be parametrized in terms of two universal corrections and a remainder:

$$\Delta r \;=\; \Delta\alpha(m_Z) \;-\; \frac{c^2}{s^2}\,\Delta\rho \;+\; \Delta r_{\rm rem}$$

The leading corrections depend quadratically on $m_t$ but only logarithmically on $m_H$ :

$$\Delta\rho \;=\; \frac{\Pi_{ZZ}(0)}{m_Z^2} - \frac{\Pi_{WW}(0)}{m_W^2} \;\approx\; \frac{3\,\alpha}{16\pi c^2}\left( \frac{m_t^2}{s^2 m_Z^2} \;+\; \log\frac{m_H^2}{m_W^2} \;+\; \ldots \right)$$

$$\frac{\delta m_W^2}{m_W^2} \;\approx\; \frac{c^2}{c^2 - s^2}\,\Delta\rho\;, \qquad \delta\,\sin^2\theta_{\rm eff} \;\approx\; -\,\frac{c^2\,s^2}{c^2 - s^2}\,\Delta\,\rho$$

# Motivation for Precision Measurements

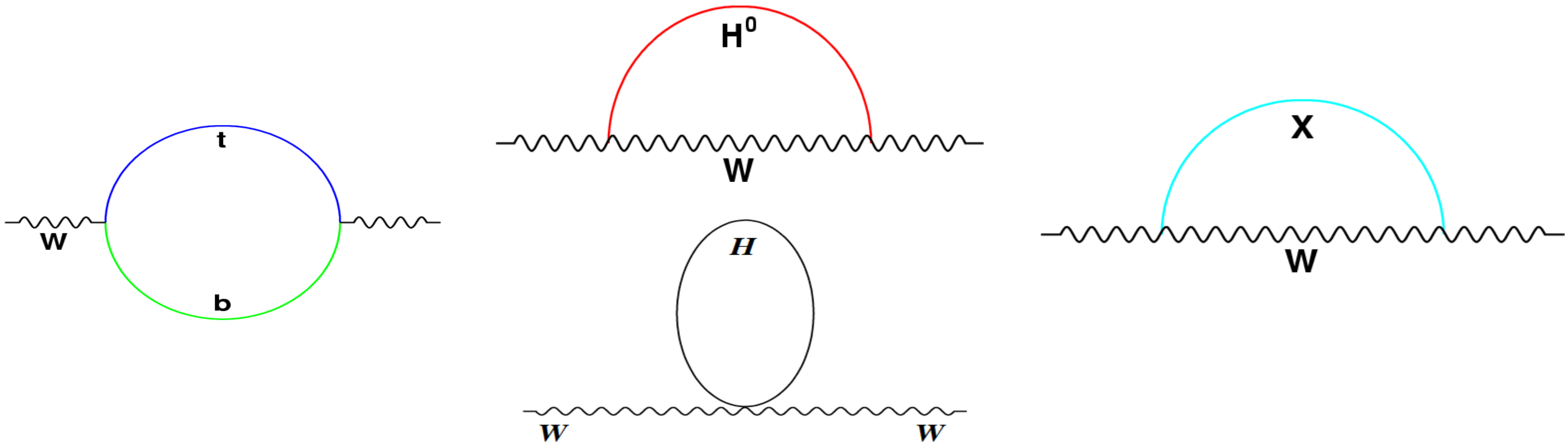
- The electroweak gauge sector of the standard model is constrained by three precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\,(1) \times 10^{-5}\ \text{GeV}^{-2}$

    $M_Z = 91.1876\,(21)\ \text{GeV}$
- At tree-level, these parameters are related to other electroweak observables, *e.g.* $M_W$
  - $M_W^{\,2} = \pi\alpha_{EM} / \sqrt{2}G_F \sin^2\vartheta_W$
    - Where $\vartheta_W$ is the Weinberg mixing angle, defined by

      $\cos\vartheta_W = M_W/M_Z$

# Motivation for Precision Measurements

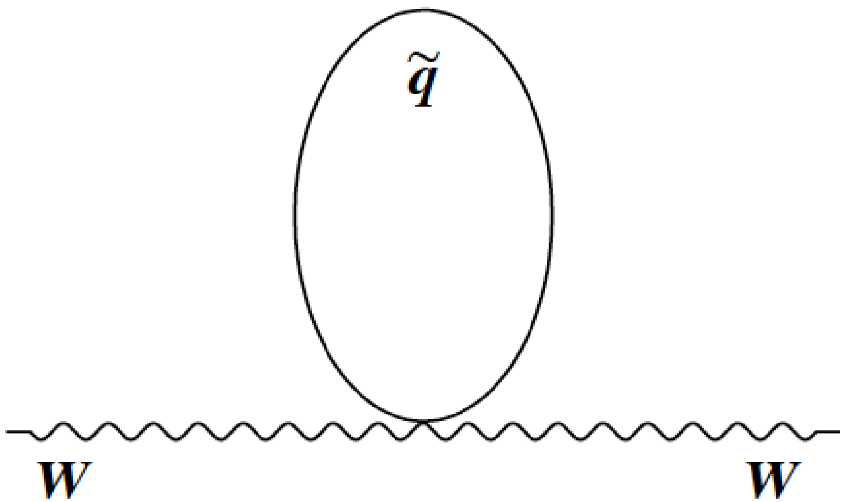
- Radiative corrections due to heavy quark and Higgs loops and exotica

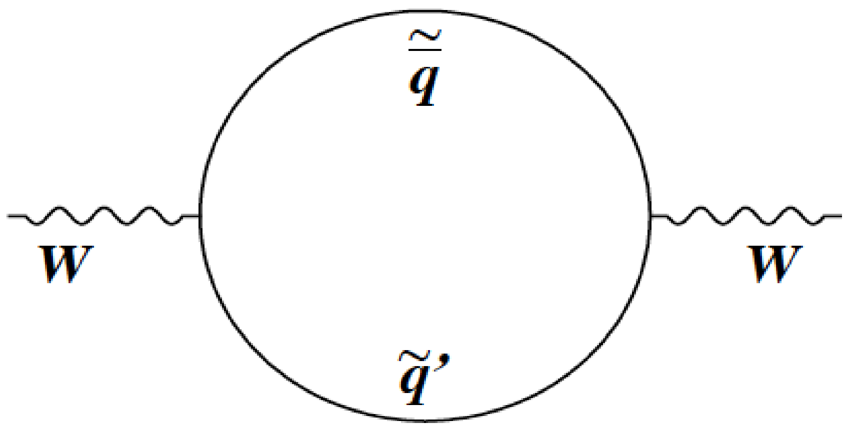



Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\text{tree})]^2$
with the predictions $\Delta\rho = (\rho - 1) \sim M_{top}^2$ and $\Delta\rho \sim \ln M_H$

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

# Contributions from Supersymmetric Particles

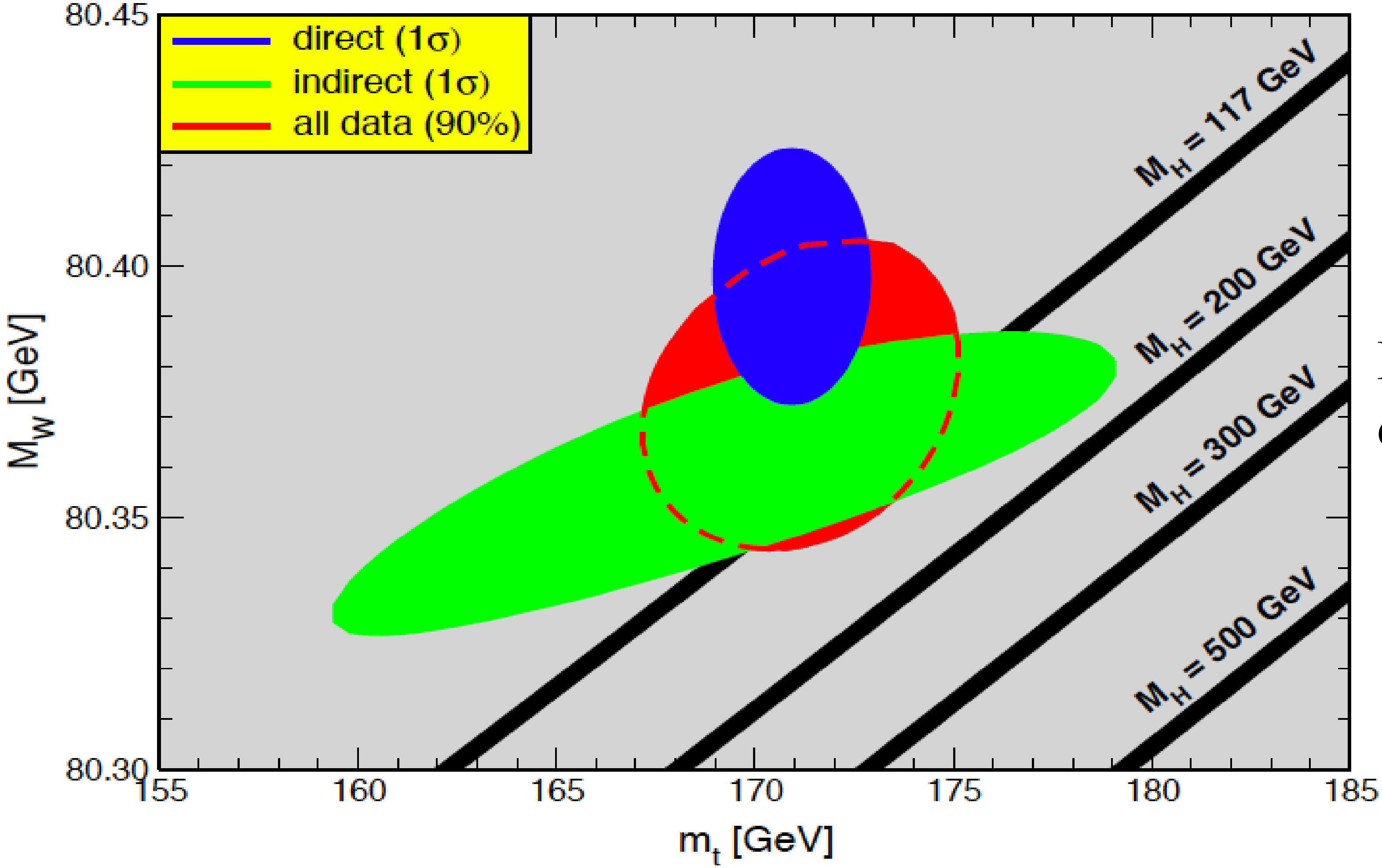



- Radiative correction depends on mass splitting ($\Delta m^2$) between squarks in SU(2) doublet

- After folding in limits on SUSY particles from direct searches, SUSY loops can contribute ~100 MeV to $M_W$

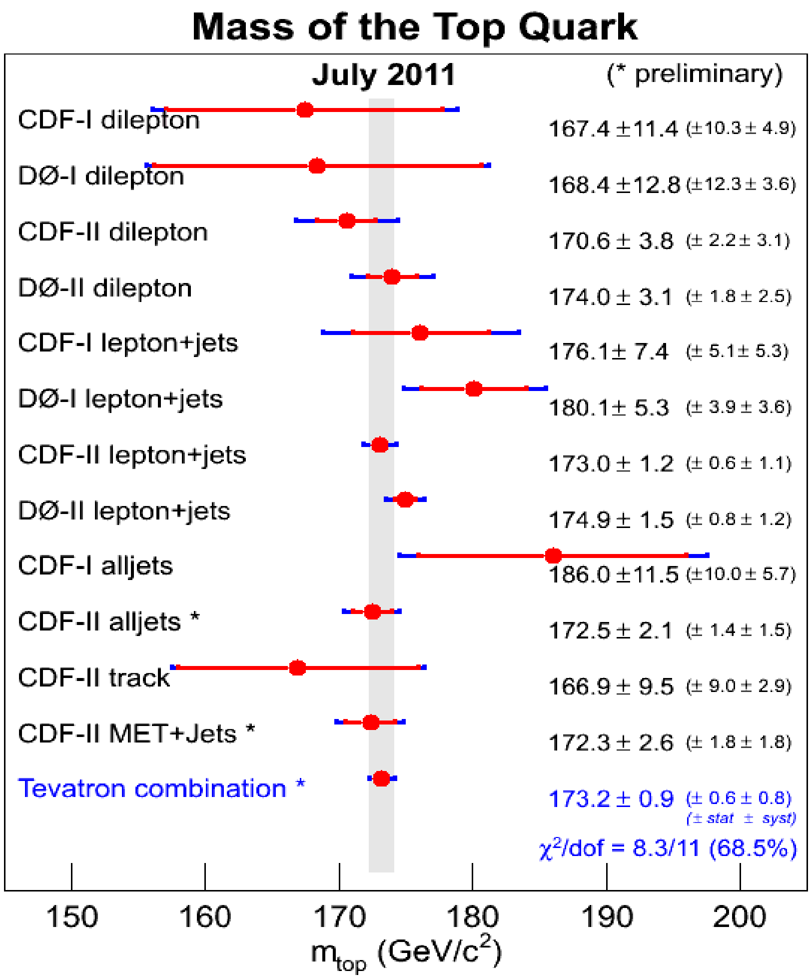
# Uncertainty from $\alpha_{EM}(M_Z)$




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

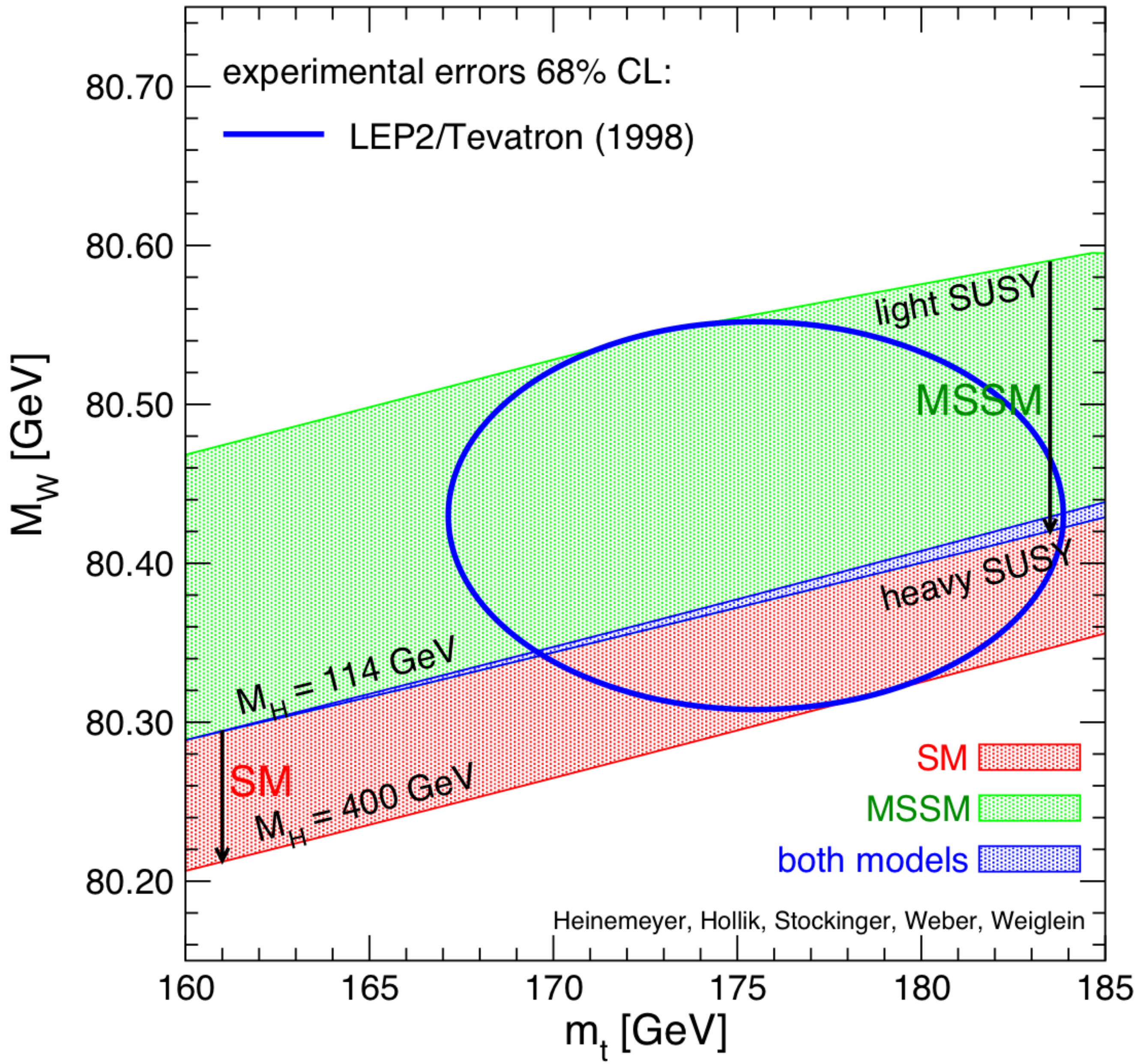
- $\delta\alpha_{EM}$ dominated by uncertainty from non-perturbative contributions: hadronic loops in photon propagator at low $Q^2$
- equivalent $\delta M_W \approx 4$ MeV for the same Higgs mass constraint
  - Was equivalent $\delta M_W \approx 15$ MeV a decade ago !

# Progress on $M_{top}$ at the Tevatron

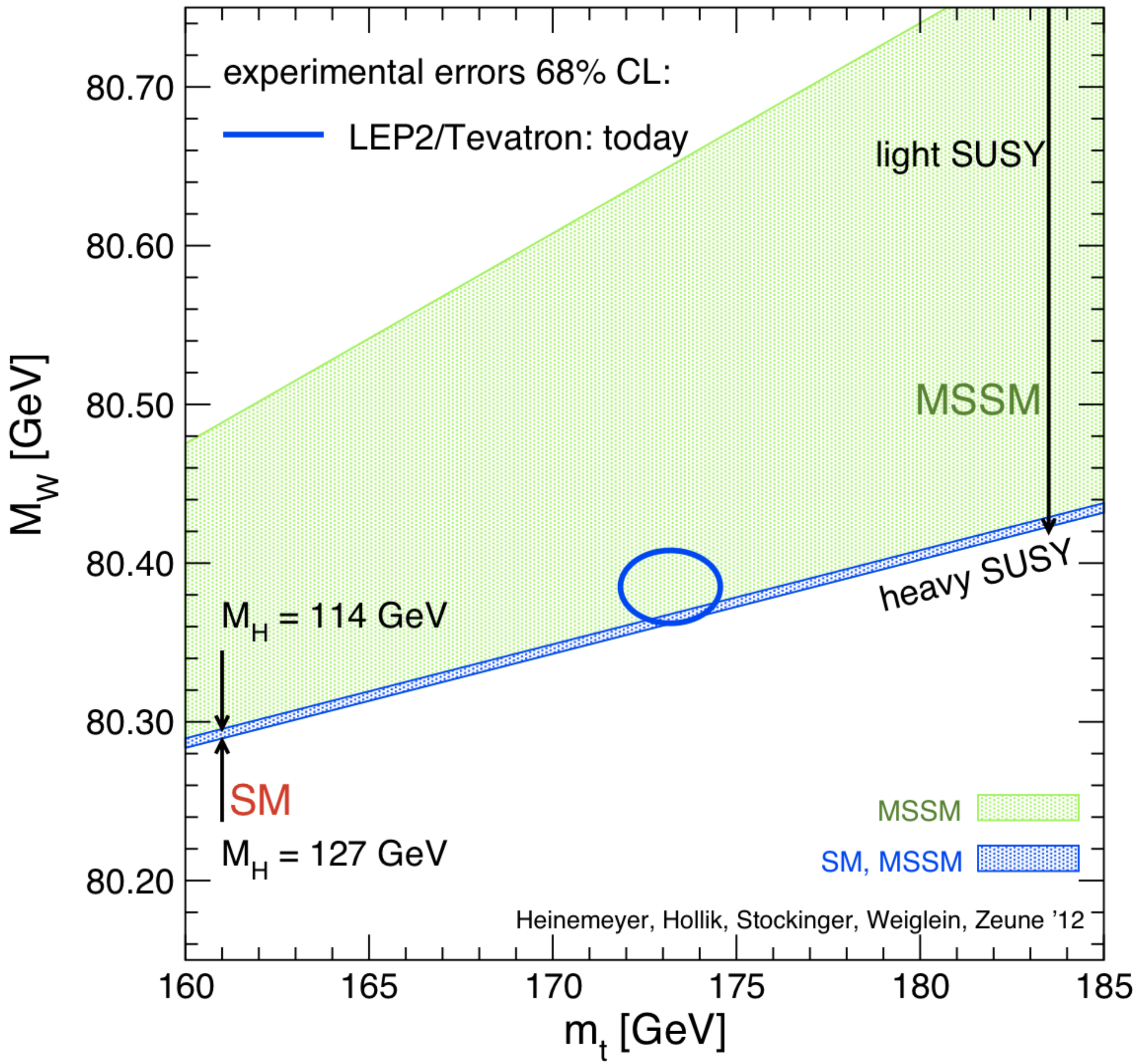



- From the Tevatron, $\Delta M_{top} = 0.9$ GeV => $\Delta M_H / M_H = 8\%$
- equivalent $\Delta M_W = 6$ MeV for the same Higgs mass constraint
- Current world average $\Delta M_W = 15$ MeV
  - progress on $\Delta M_W$ has the biggest impact on Higgs constraint

# 1998 Status of $M_W$ *vs* $M_{top}$

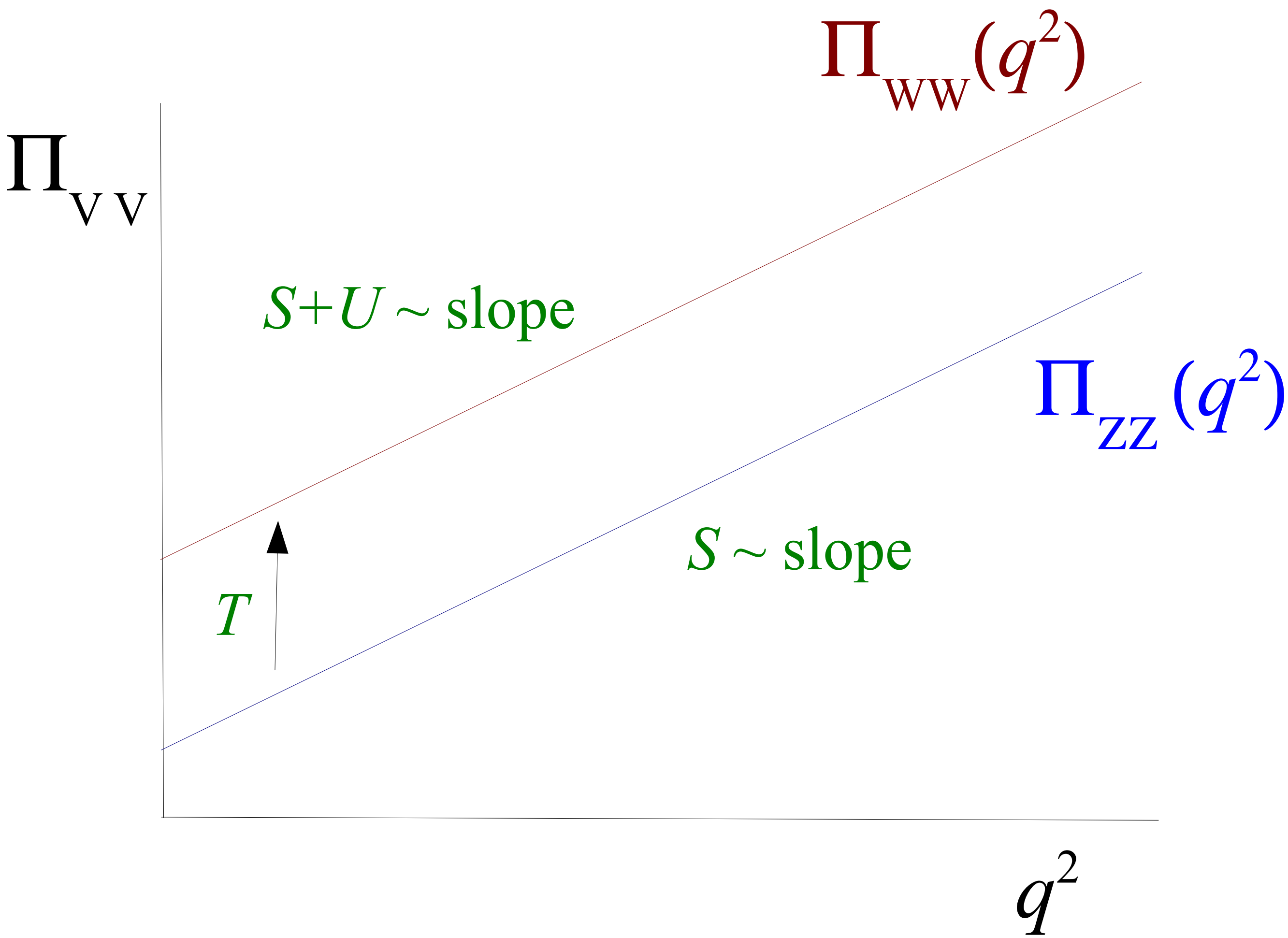


# 2012 Status of $M_W$ *vs* $M_{top}$



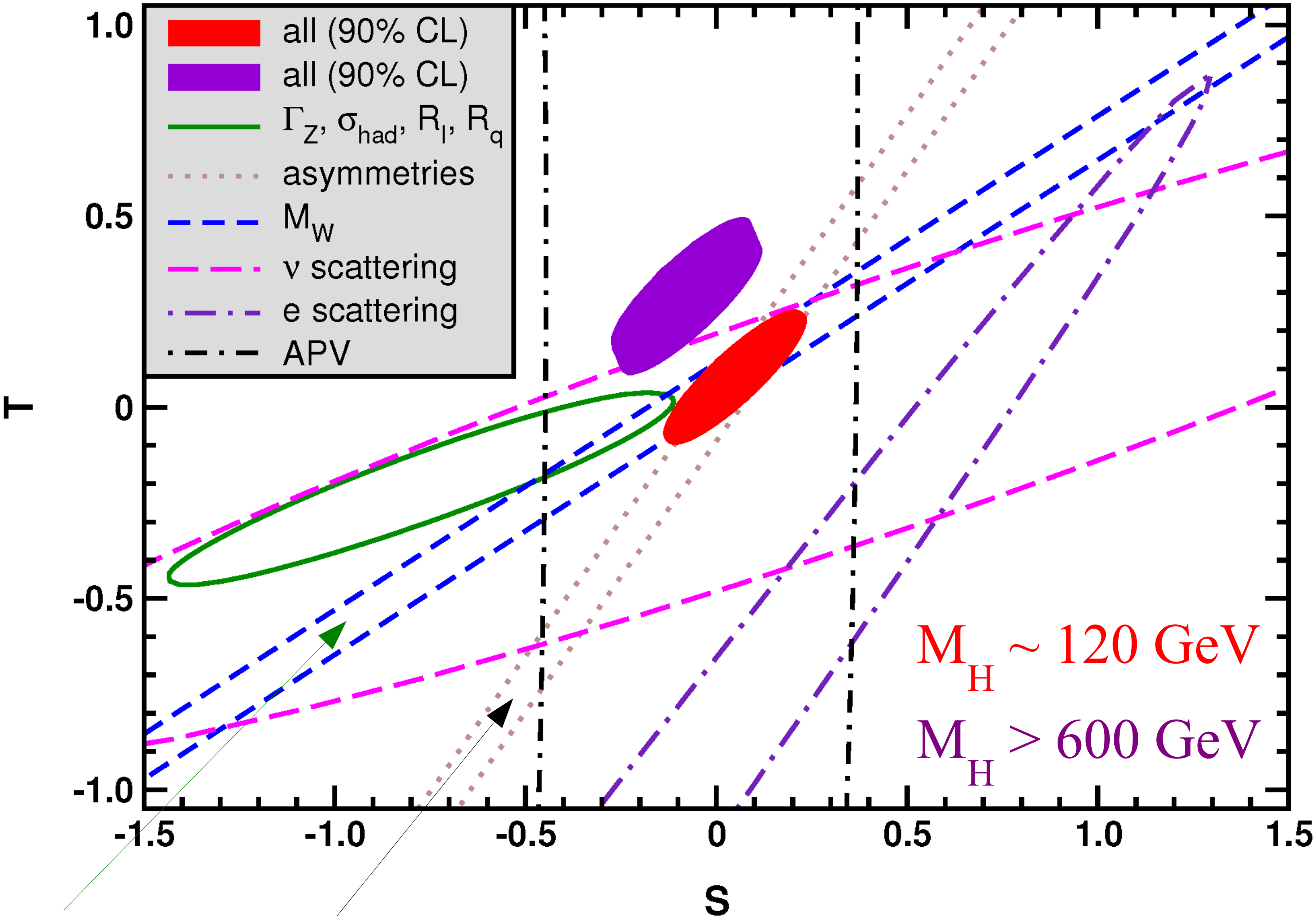
# Motivation

- Generic parameterization of new physics contributing to W and Z boson self-energies through radiative corrections in propagators
  - *S, T, U* parameters (Peskin & Takeuchi, Marciano & Rosner, Kennedy & Langacker, Kennedy & Lynn)



# Motivation

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



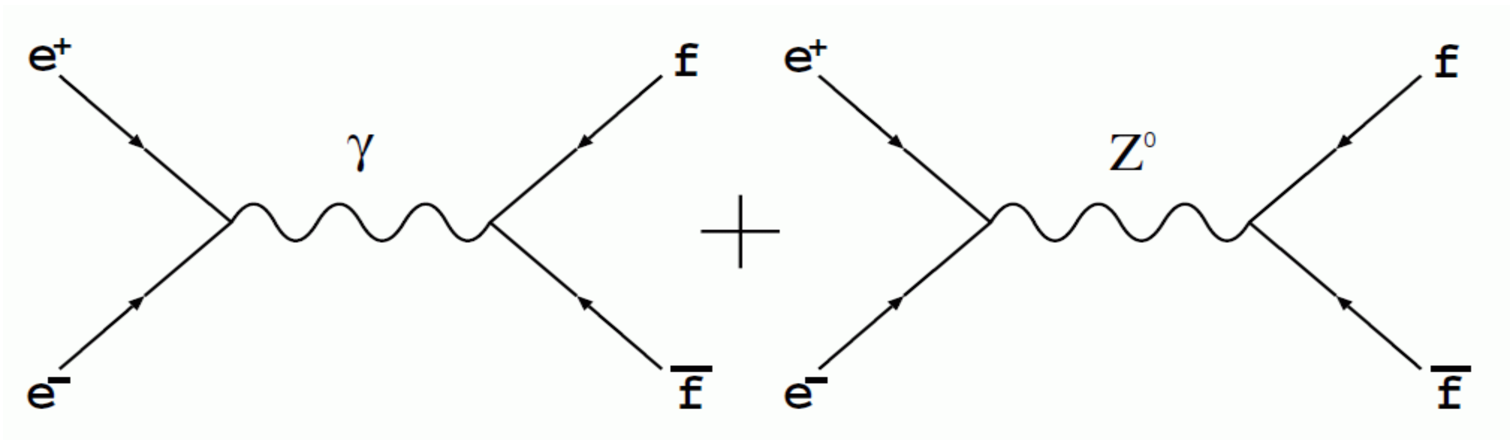

Additionally, $M_W$ is the only measurement which constrains *U*

(from P. Langacker, 2012)

$M_W$ and Asymmetries are the most powerful observables in this parameterization

# $A_{FB}$ and $A_{LR}$ Observables

- Asymmetries definable in electron-positron scattering sensitive to Weinberg mixing angle $\vartheta_W$

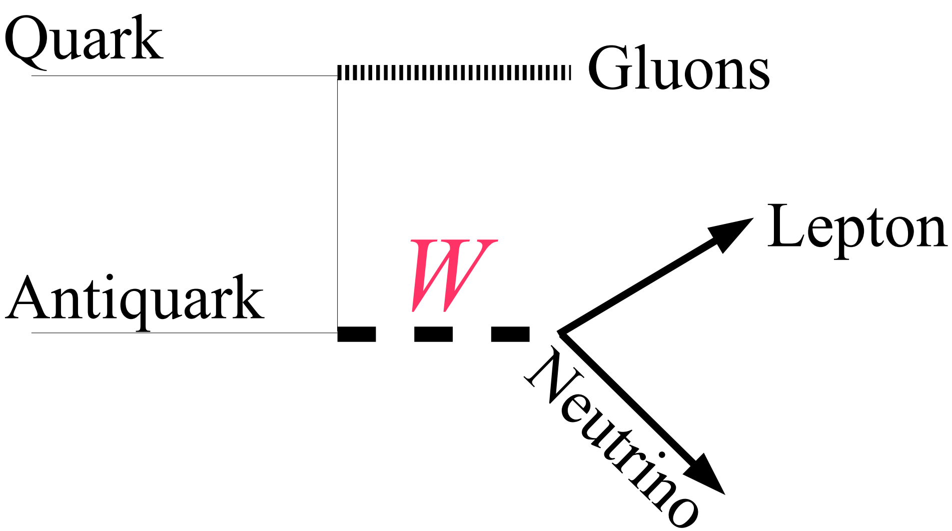


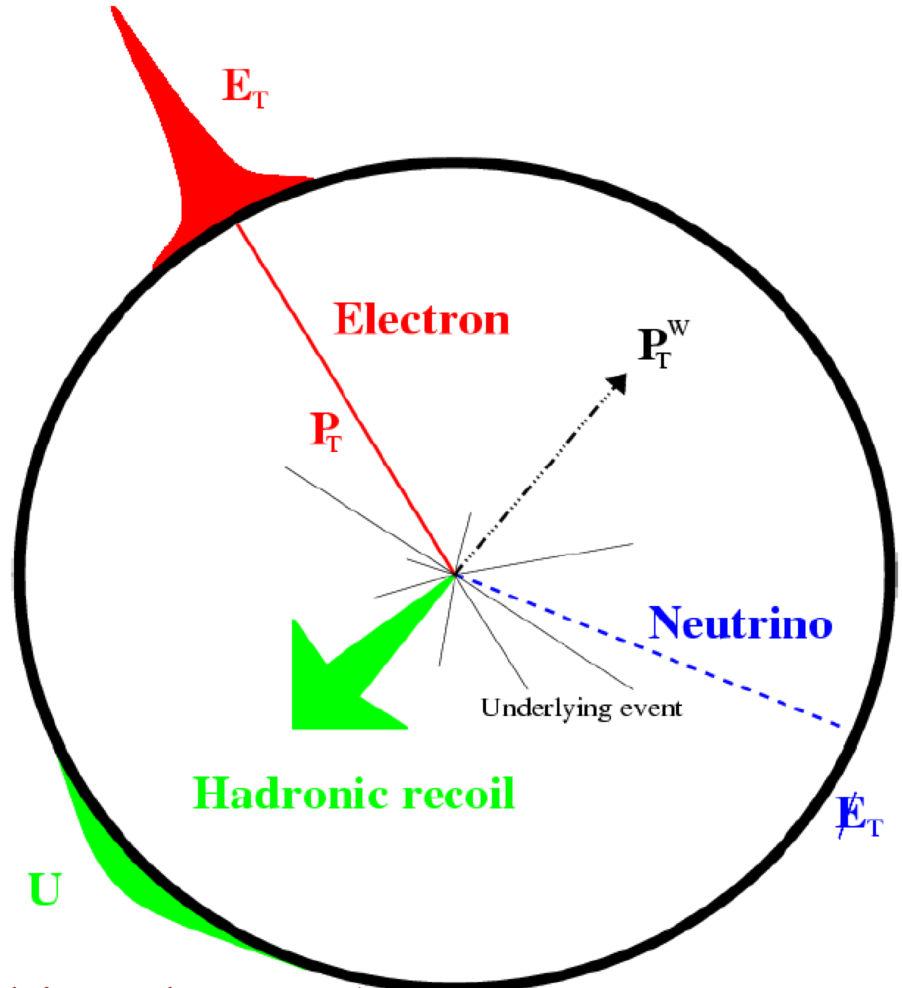

- Higgs and Supersymmetry also contribute radiative corrections to $\vartheta_W$ via quantum loops

- $A_{FB}$ is the angular (forward – backward) asymmetry of the final state

- $A_{LR}$ is the asymmetry in the total scattering probability for different polarizations of the initial state

# W Boson Production at the Tevatron



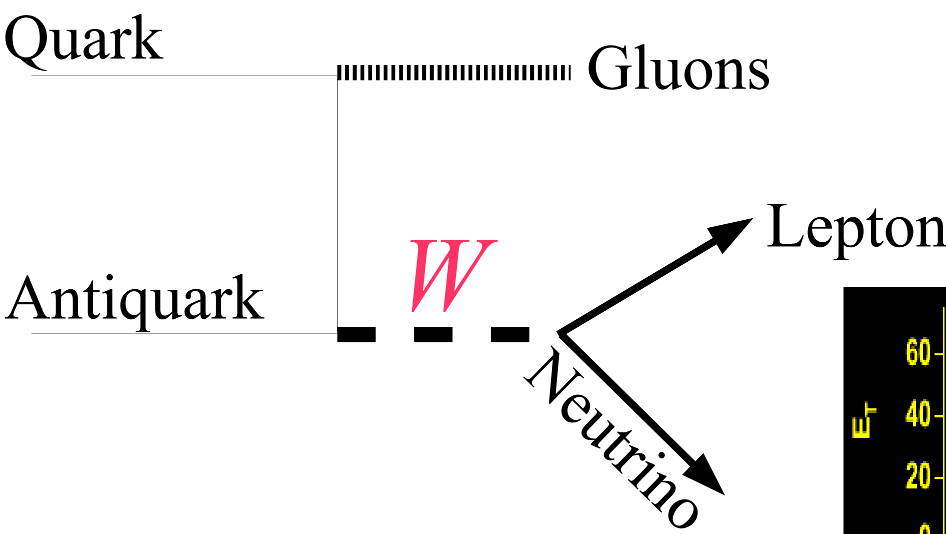

Quark-antiquark annihilation dominates (80%)

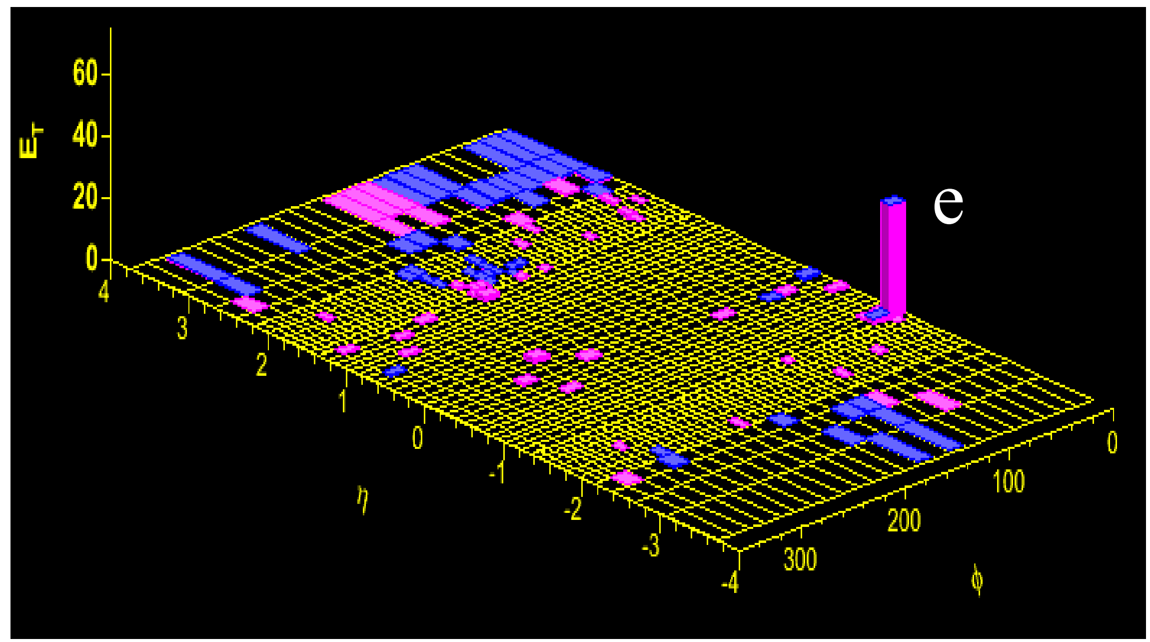
Lepton $p_T$ carries most of *W* mass information, can be measured precisely (achieved 0.01%)

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

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

# W Boson Production at the Tevatron

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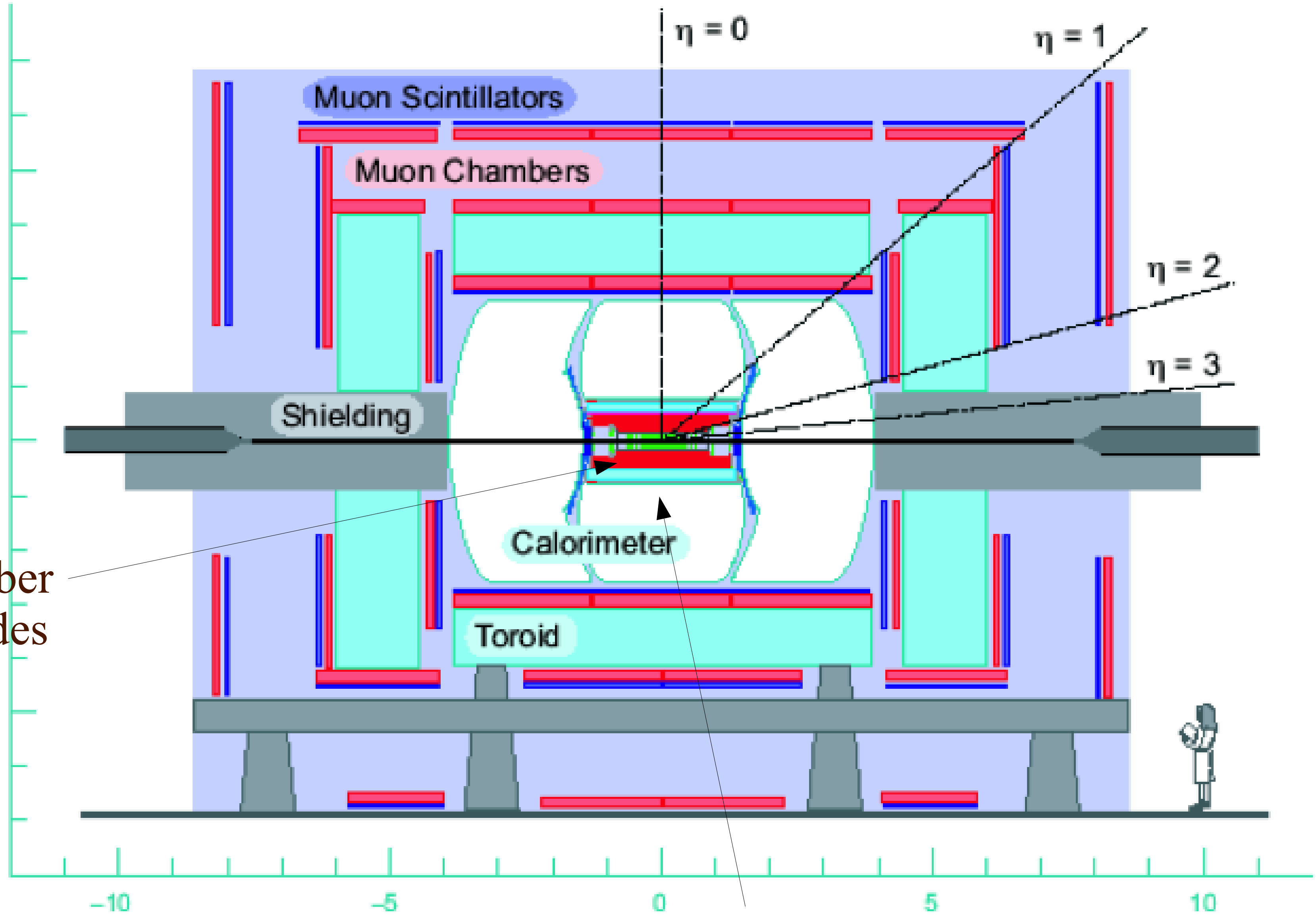
# D0 Detector at Fermilab




Scintillator fiber tracker provides lepton track direction

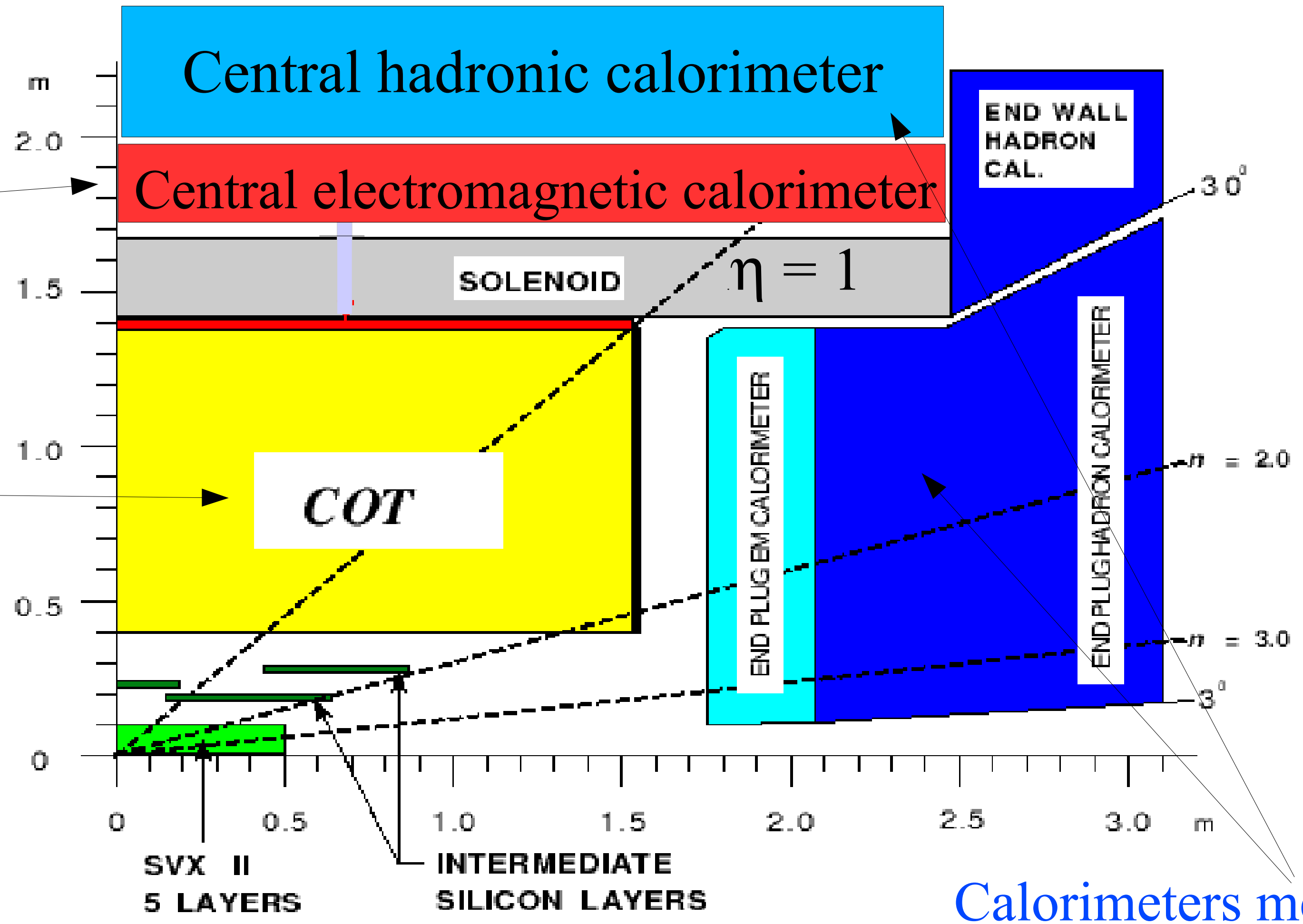
Electromagnetic Calorimeter measures electron energy

Hadronic calorimeters measure recoil particles

# Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

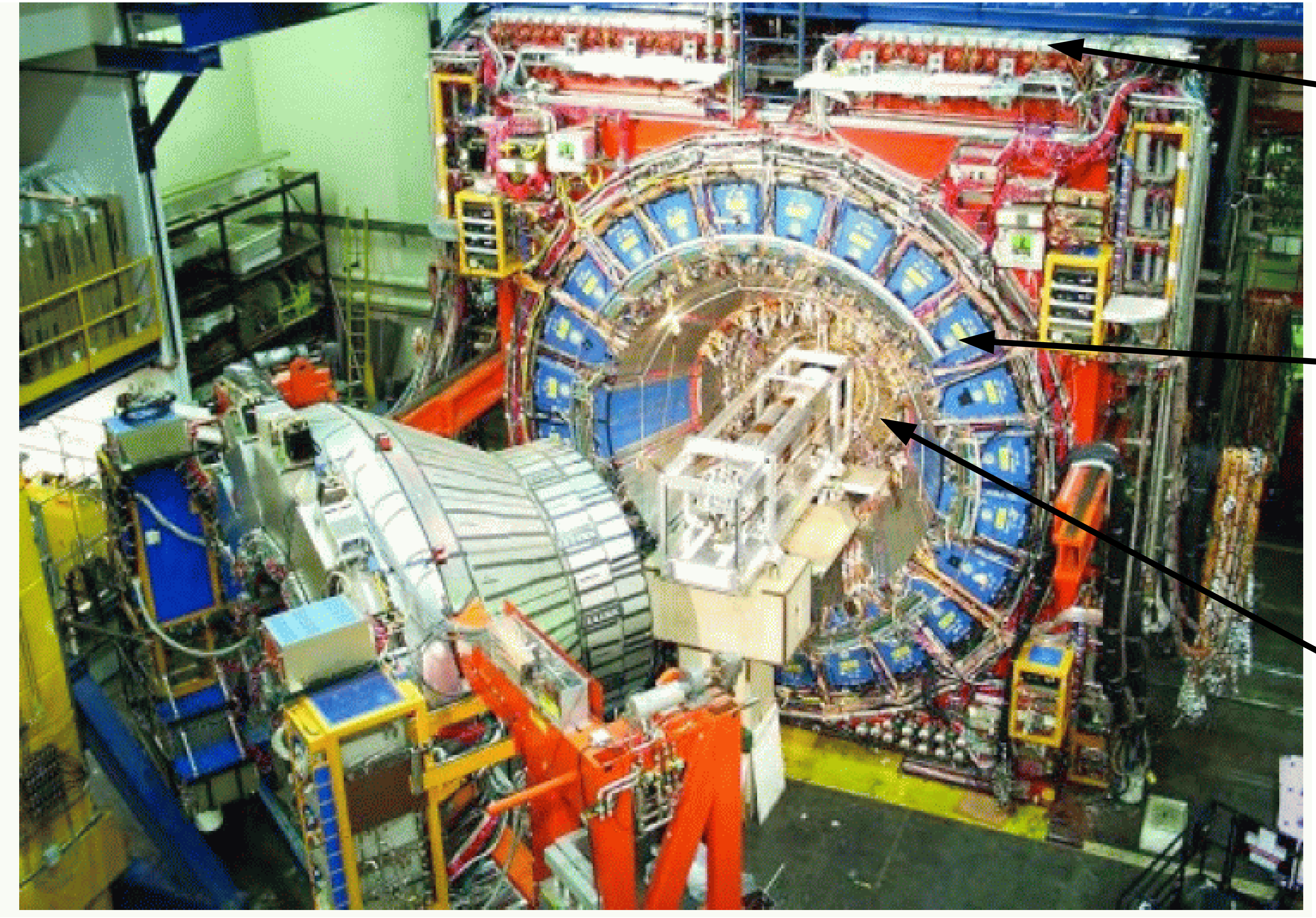
Drift chamber provides precise lepton track momentum measurement




Calorimeters measure hadronic recoil particles

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

# Collider Detector at Fermilab (CDF)



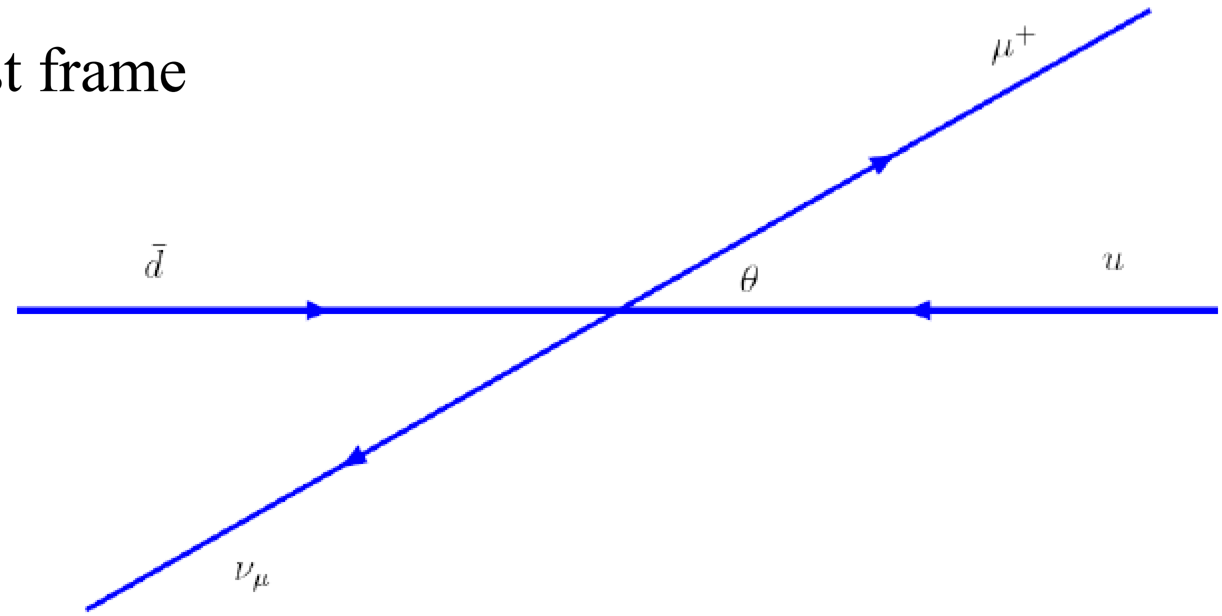
# W mass measurement – decay kinematics

- Main complication: invariant mass cannot be reconstructed from 2-body leptonic decay mode
  - Because neutrino is not detectable directly
- Exploit the "Jacobian edge" in lepton transverse momentum spectrum

$$\frac{d\sigma}{d\cos\hat{\theta}} = \sigma_0(\hat{s})\left[\frac{1}{2}(1+\cos\hat{\theta})^2 + \frac{1}{2}(1-\cos\hat{\theta})^2\right]$$

$$= \sigma_0(\hat{s})(1+\cos^2\hat{\theta})$$

W boson rest frame



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- Main complication: invariant mass cannot be reconstructed from 2-body leptonic decay mode
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- Exploit the "Jacobian edge" in lepton transverse momentum spectrum

$$
\begin{aligned}
\frac{d\sigma}{dp_T} &= \frac{d\sigma}{d((m_W/2)\sin\hat{\theta})} \\
&= \frac{2}{m_W}\frac{d\sigma}{d\sin\hat{\theta}} \\
&= \frac{2}{m_W}\frac{d\sigma}{d\cos\hat{\theta}}\left|\frac{d\cos\hat{\theta}}{d\sin\hat{\theta}}\right| \\
&= \frac{2}{m_W}\sigma_0(\hat{s})(1+\cos^2\theta)|\tan\hat{\theta}| \\
&= \sigma_0(\hat{s})\frac{4p_T}{m_W^2}(2-4p_T^2/m_W^2)\left(\frac{1}{\sqrt{1-4p_T^2/m_W^2}}\right)
\end{aligned}
$$

Invariant under longitudinal boost

# W mass measurement – decay kinematics

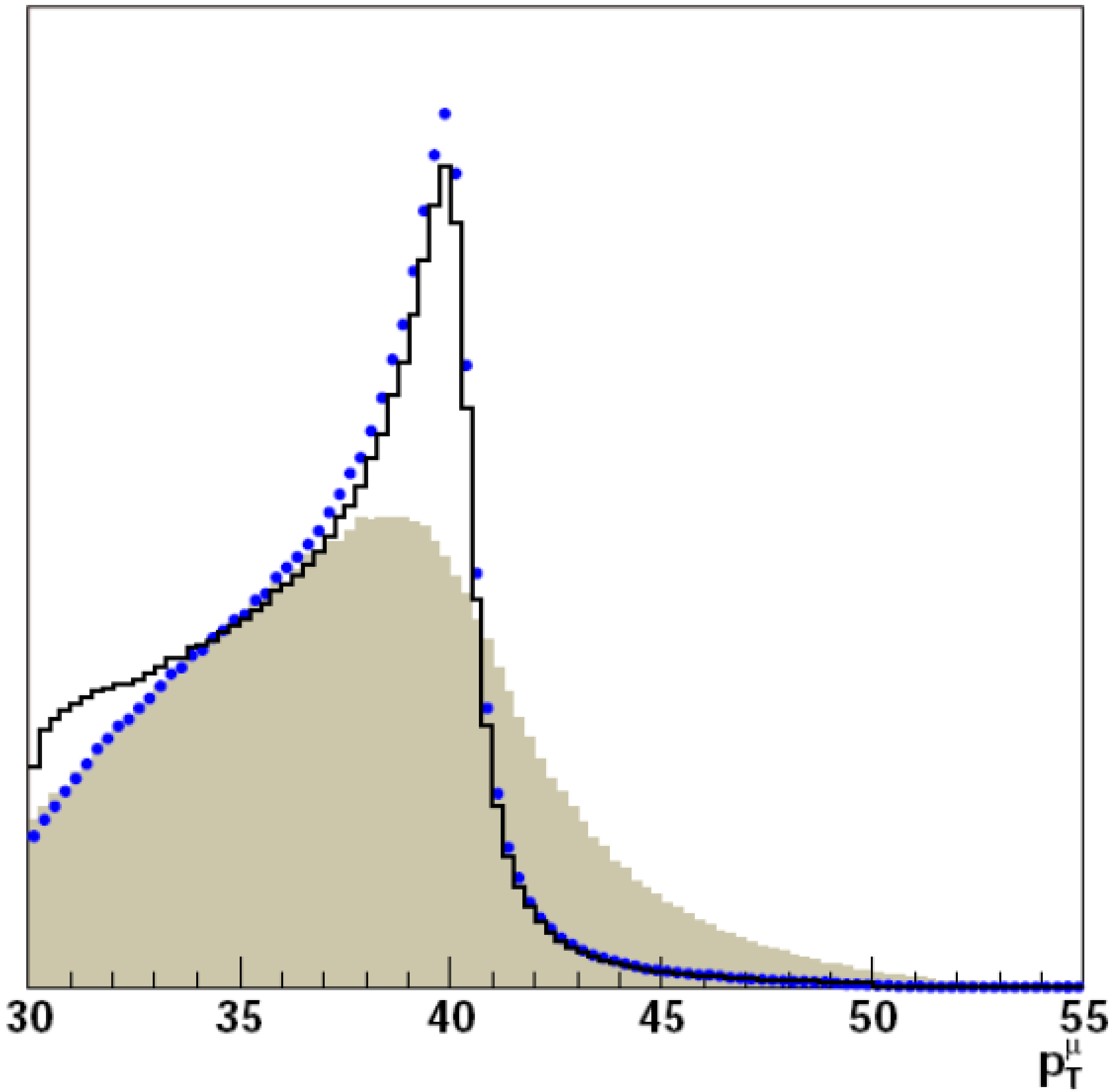
- Main complication: invariant mass cannot be reconstructed from 2-body leptonic decay mode
  - Because neutrino is not detectable directly
- Exploit the "Jacobian edge" in lepton transverse momentum spectrum

We can transfer $\frac{d\sigma}{dp_T}$ to $\frac{d\sigma}{dm_T}$ by using $m_T = 2p_T$:

$$\begin{aligned}\frac{d\sigma}{dm_T} &= \frac{1}{2}\frac{d\sigma}{dp_T} \\ &= \sigma_0(\hat{s})\frac{m_T}{m_W}\left(2 - \frac{m_T^2}{m_W^2}\right)\left(\frac{1}{\sqrt{1 - m_T^2/m_W^2}}\right)\end{aligned}$$

# W mass measurement – decay kinematics

- Lepton transverse momentum not invariant under transverse boost
- But measurement resolution on leptons is good



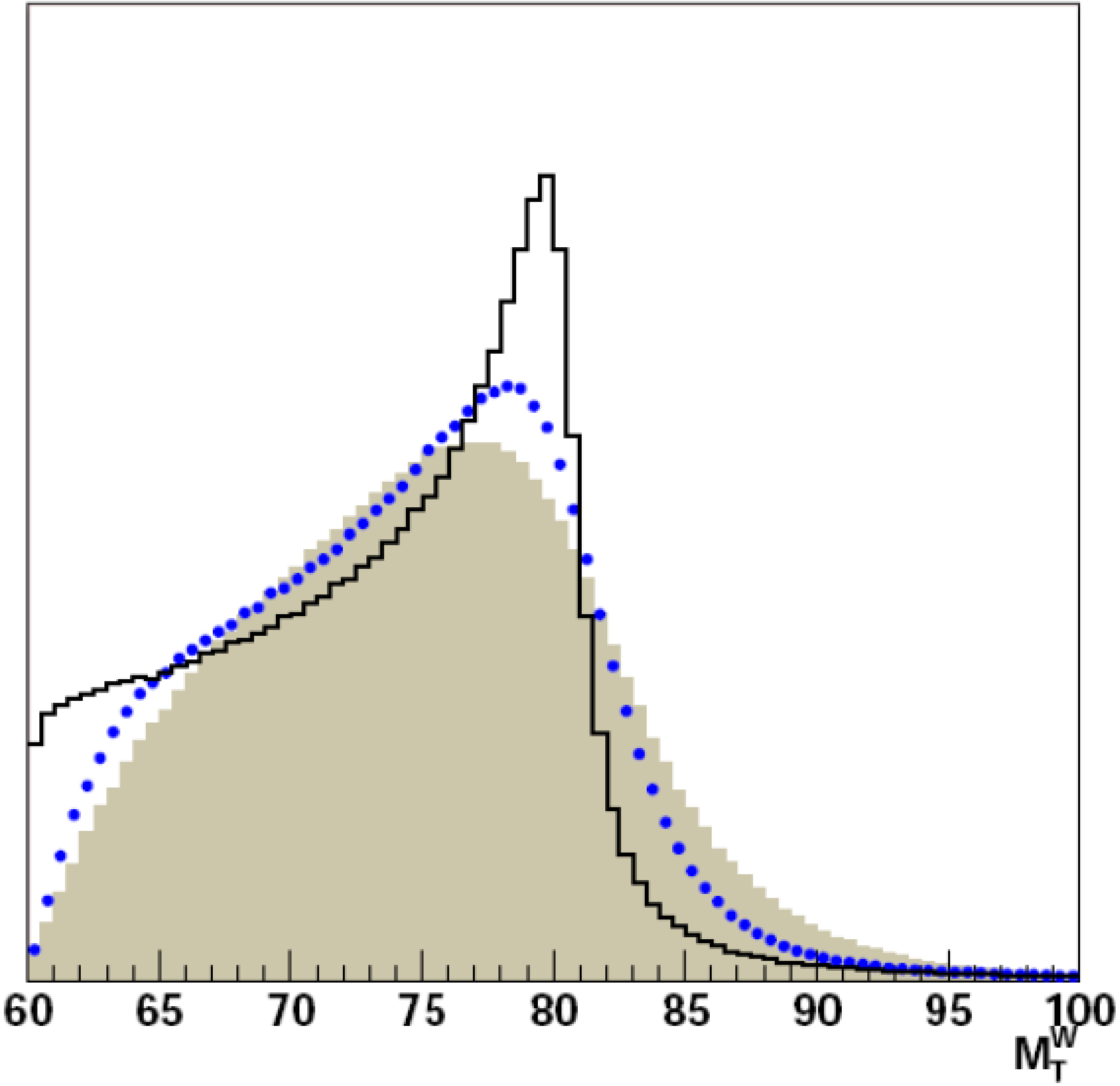

Black curve: truth level, no $p_T(W)$

Blue points: detector-level with lepton resolution and selection, But no $p_T(W)$

Shaded histogram: with $p_T(W)$

# W mass measurement – decay kinematics

- Define "transverse mass" → approximately invariant under transverse boost
- But measurement resolution of "neutrino" is not as good due to recoil

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Blue points: detector-level with lepton resolution and selection, But no $p_T(W)$

Shaded histogram: with $p_T(W)$

$$m_T = \sqrt{\left(E_T^l + E_T^\nu\right)^2 - \left(\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu}\right)^2}$$

$$= \sqrt{2 p_T^\mu p_T^\nu (1 - \cos\Delta\phi)}$$

# CDF Event Selection

- Goal: Select events with high $p_T$ leptons and small hadronic recoil activity
  - to maximize W mass information content and minimize backgrounds
- Inclusive lepton triggers: loose lepton track and muon stub / calorimeter cluster requirements, with lepton $p_T > 18$ GeV
  - Kinematic efficiency of trigger ~100% for offline selection
- Offline selection requirements:
  - Electron cluster $E_T > 30$ GeV, track $p_T > 18$ GeV
  - Muon track $p_T > 30$ GeV
  - Loose identification requirements to minimize selection bias
- W boson event selection: one selected lepton, $|\boldsymbol{u}| < 15$ GeV & $p_T(\nu) > 30$ GeV
  - Z boson event selection: two selected leptons

# CDF W & Z Data Samples

| Sample | Candidates |
|---|---|
| $W \to e\nu$ | 470126 |
| $W \to \mu\nu$ | 624708 |
| $Z \to e^+e^-$ | 16134 |
| $Z \to \mu^+\mu^-$ | 59738 |

- Integrated Luminosity (collected between February 2002 – August 2007):
  - Electron and muon channels: $\mathcal{L} = 2.2\ \mathrm{fb}^{-1}$
  - Identical running conditions for both channels, guarantees cross-calibration
- Event selection gives fairly clean samples
  - Mis-identification backgrounds ~ 0.5%

# Analysis Strategy

# Strategy

*Maximize the number of internal constraints and cross-checks*

*Driven by two goals:*

*1) Robustness: constrain the same parameters in as many different ways as possible*

*2) Precision: combine independent measurements after showing consistency*

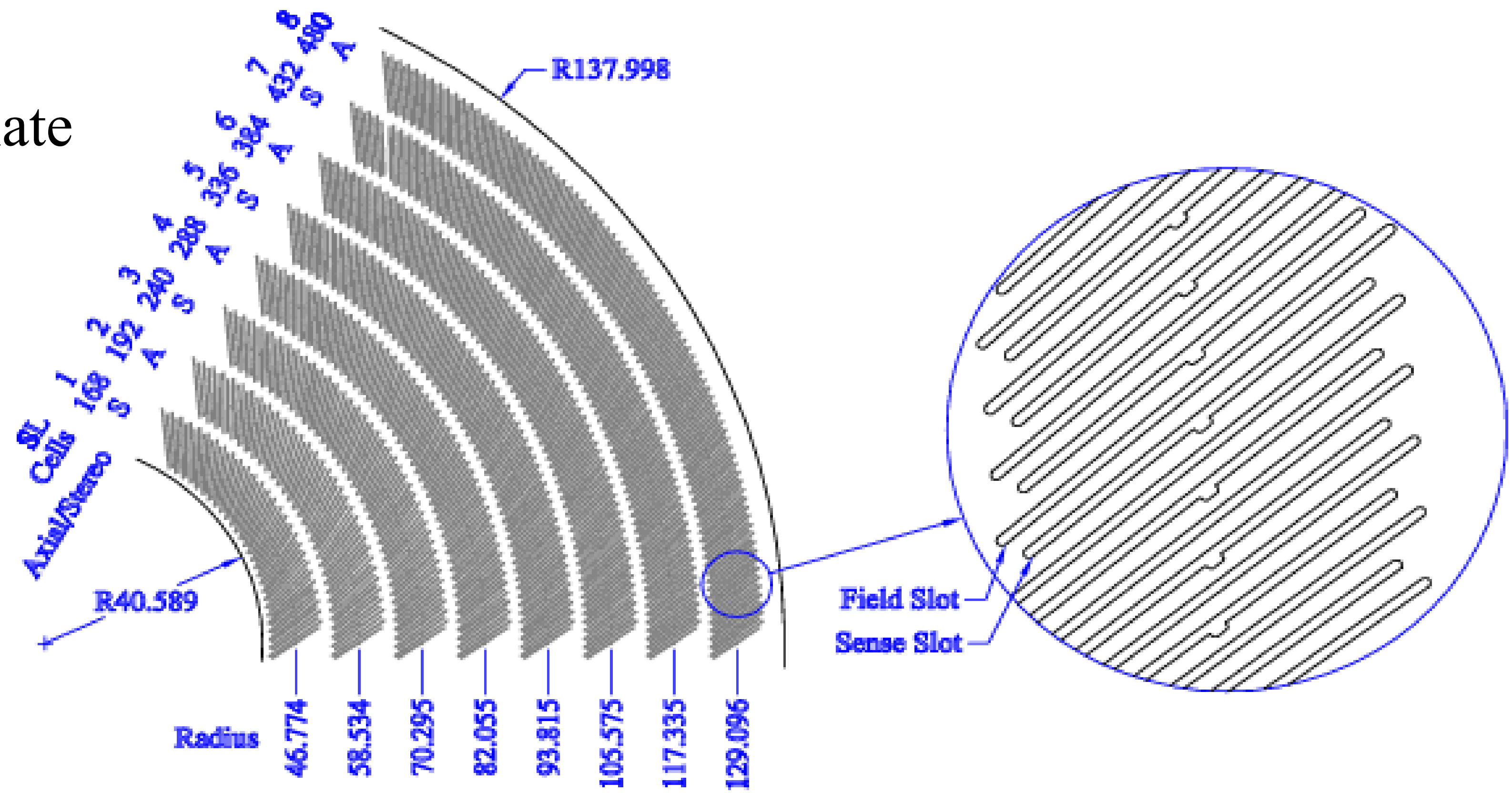
# Outline of Analysis

*Energy scale measurements drive the W mass measurement*

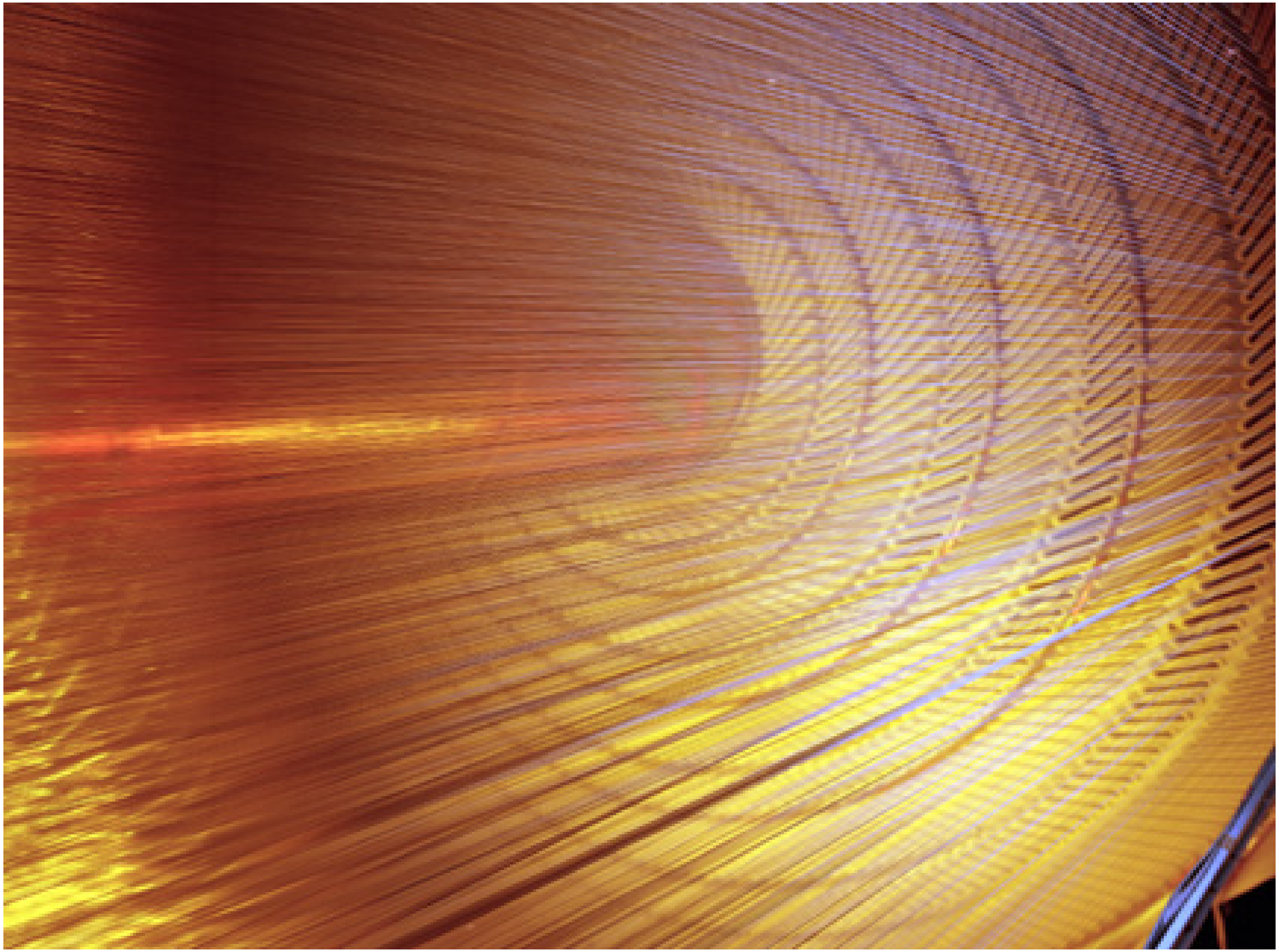
- Tracker Calibration
  - alignment of the COT (~2400 cells) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \to \mu\mu$ and $\Upsilon \to \mu\mu$ mass fits
  - Confirmed using $Z \to \mu\mu$ mass fit
- EM Calorimeter Calibration
  - COT momentum scale transferred 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

# Drift Chamber (COT) Alignment

COT endplate geometry



# CDF Particle Tracking Chamber



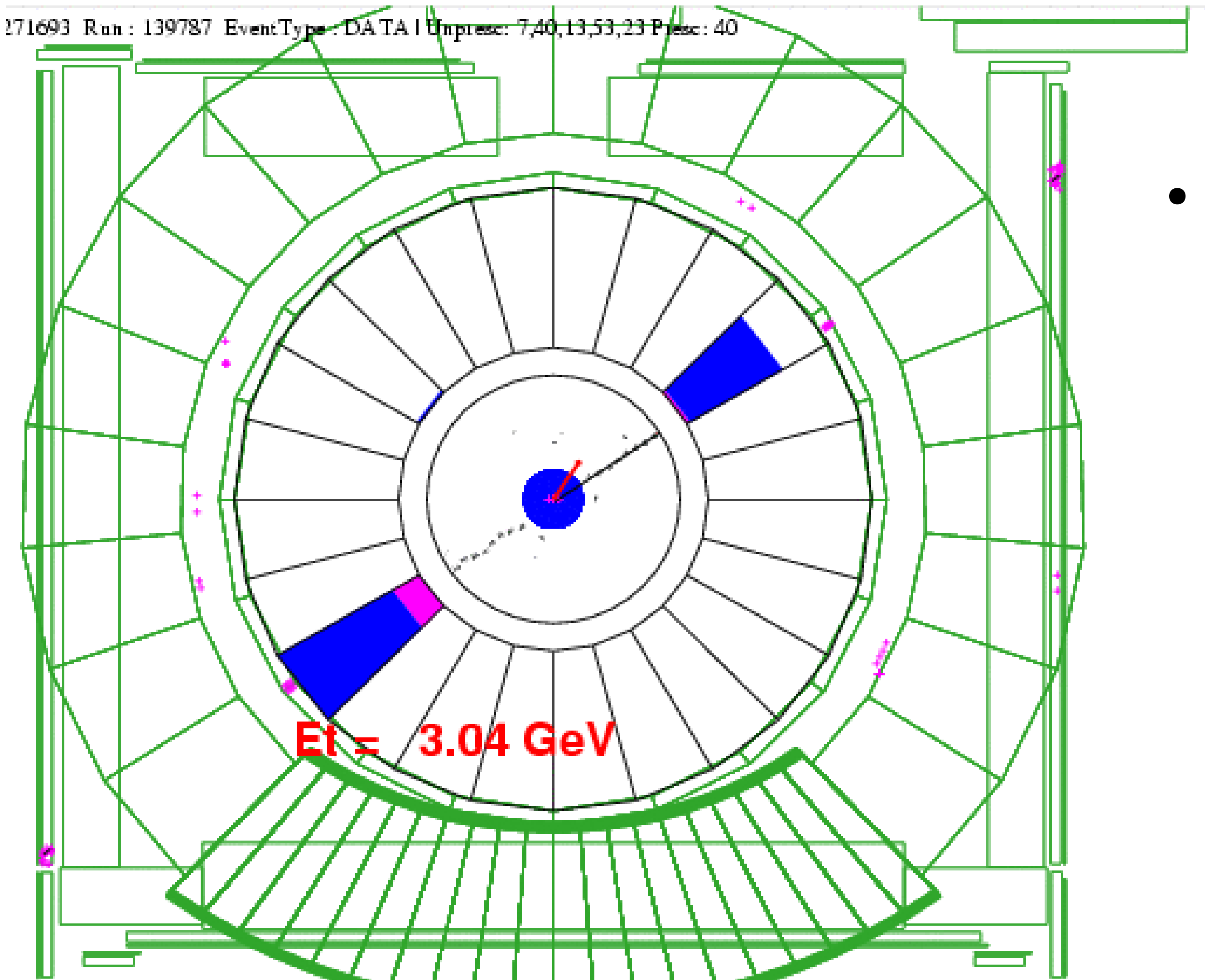
Reconstruction of particle trajectories, calibration to ~2 μm accuracy:

A. Kotwal, H. Gerberich and C. Hays, NIM A506, 110 (2003)

C. Hays et al, NIM A538, 249 (2005)

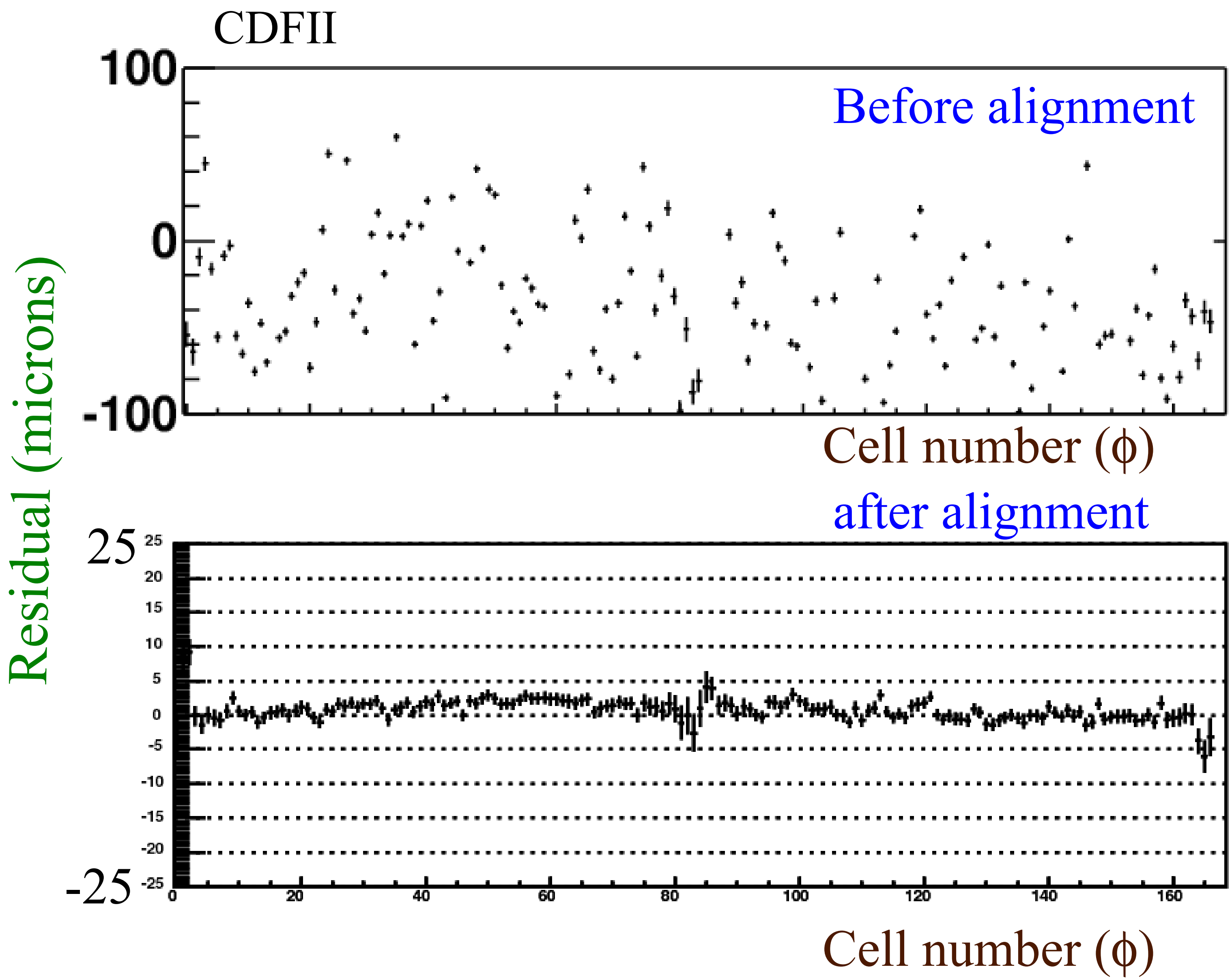
# Internal Alignment of COT

- Use a clean sample of ~400*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'

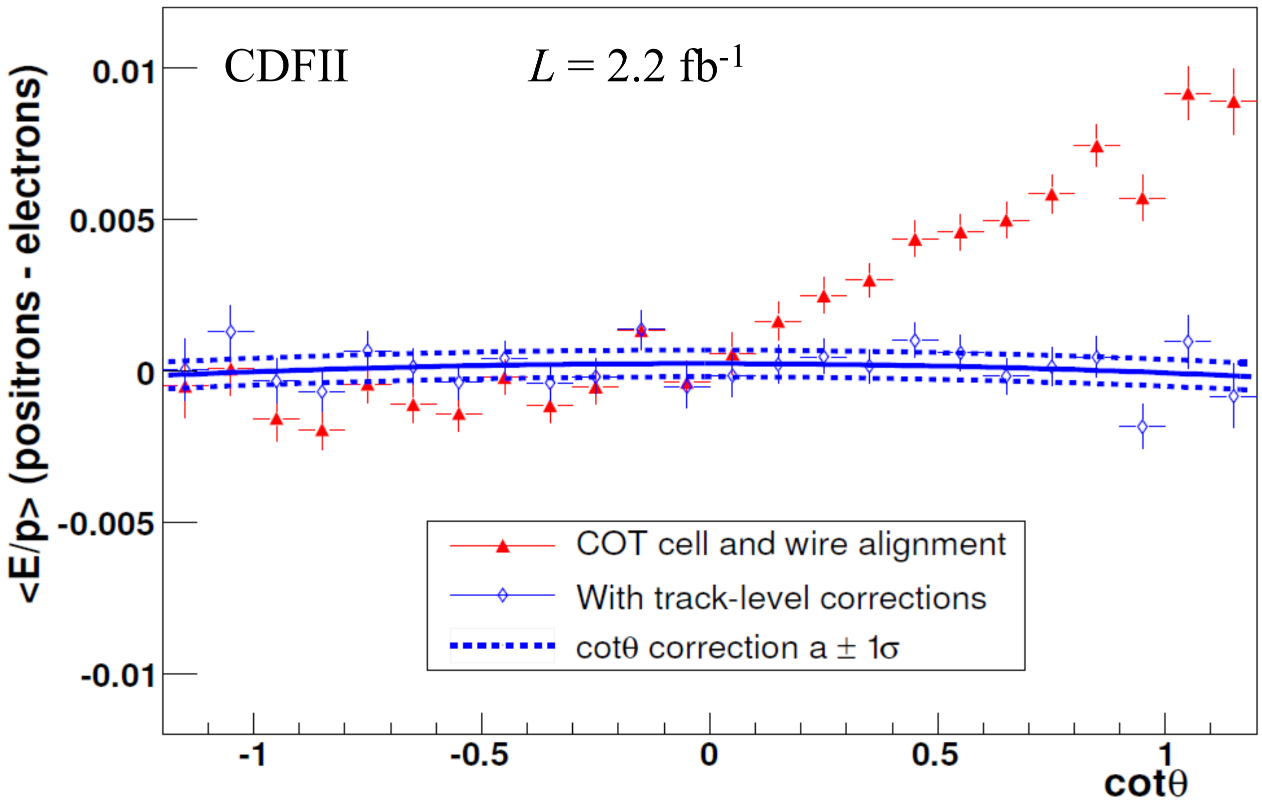
# Residuals of COT cells after alignment




Final relative alignment of cells ~2 μm (initial alignment ~50 μm)

# Cross-check of COT alignment

- Cosmic ray alignment removes most deformation degrees of freedom, but "weakly constrained modes" remain
- 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 as a function of polar and azimuthal angle: statistical errors => $\Delta M_W = 2$ MeV

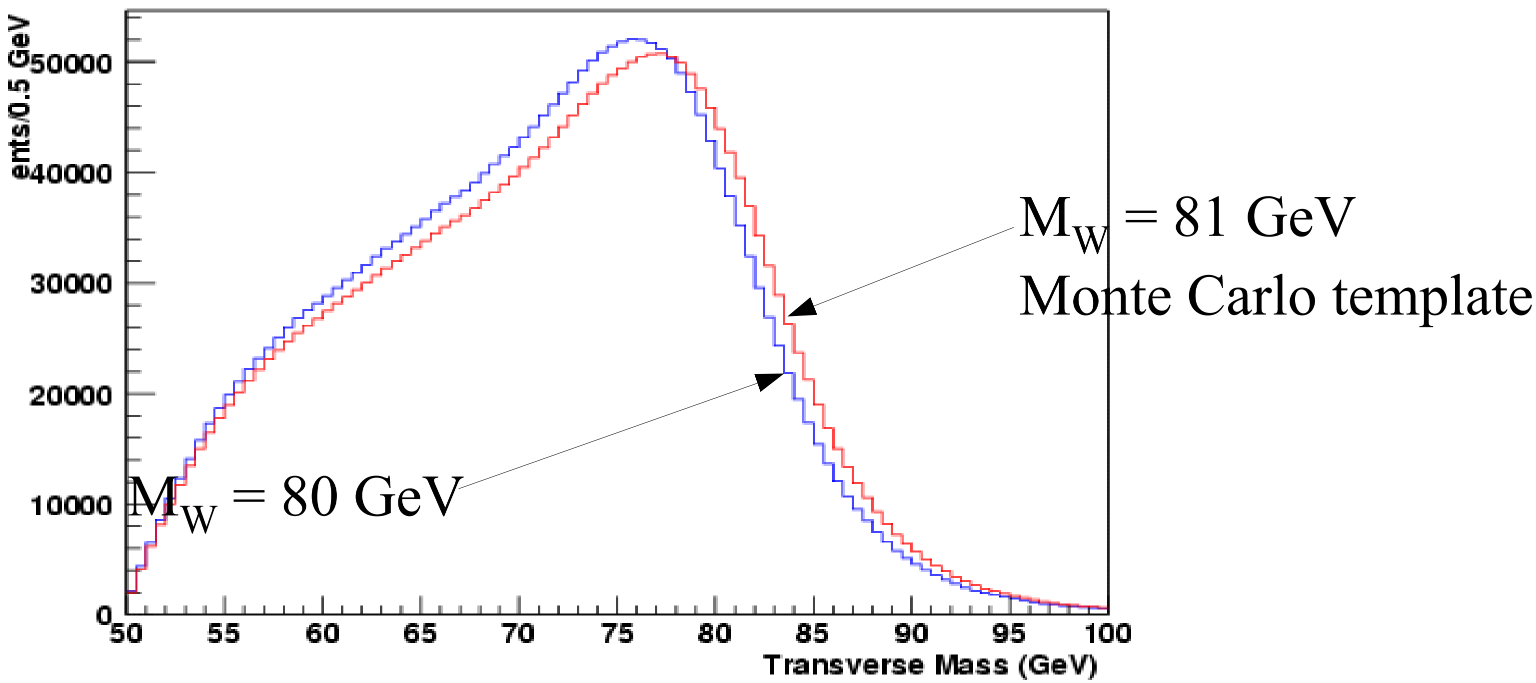


# Signal Simulation and Fitting

# Signal Simulation and Template Fitting

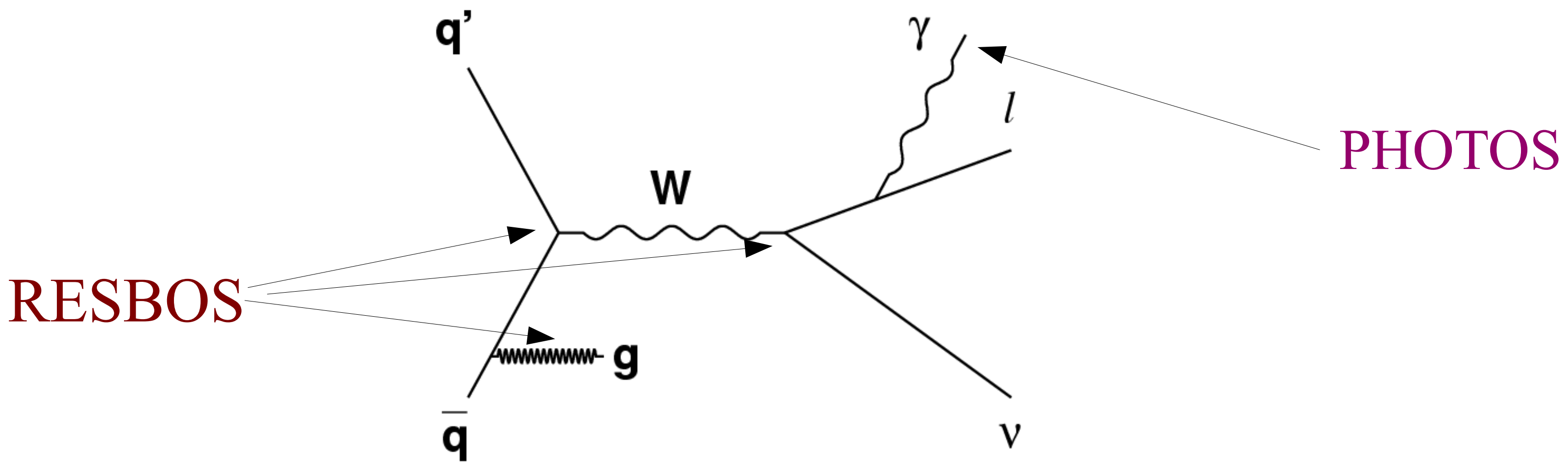
- All signals simulated using a Custom Monte Carlo
  - Generate finely-spaced templates as a function of the fit variable
  - perform binned maximum-likelihood fits to the data
- Custom fast Monte Carlo makes smooth, high statistics templates
  - And provides analysis control over key components of the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

$$L = \prod_{i=1}^{N} \frac{e^{-m_i} {m_i}^{n_i}}{n_i!}$$




- We will extract the W mass from six kinematic distributions: Transverse mass, charged lepton $p_T$ and missing $E_T$ 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 $p_T$
- Multiple radiative photons generated according to PHOTOS (P. Golonka and Z. Was, Eur. J. Phys. C 45, 97 (2006) and references therein)

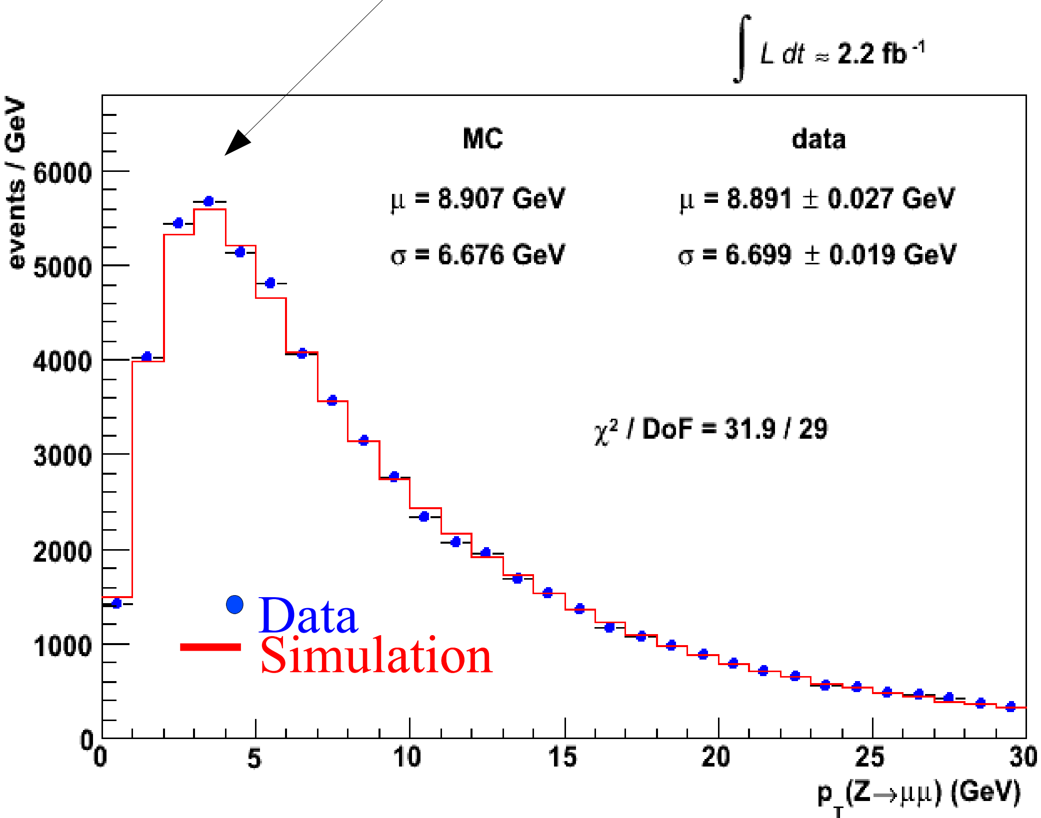
# Constraining Boson $p_T$ Spectrum

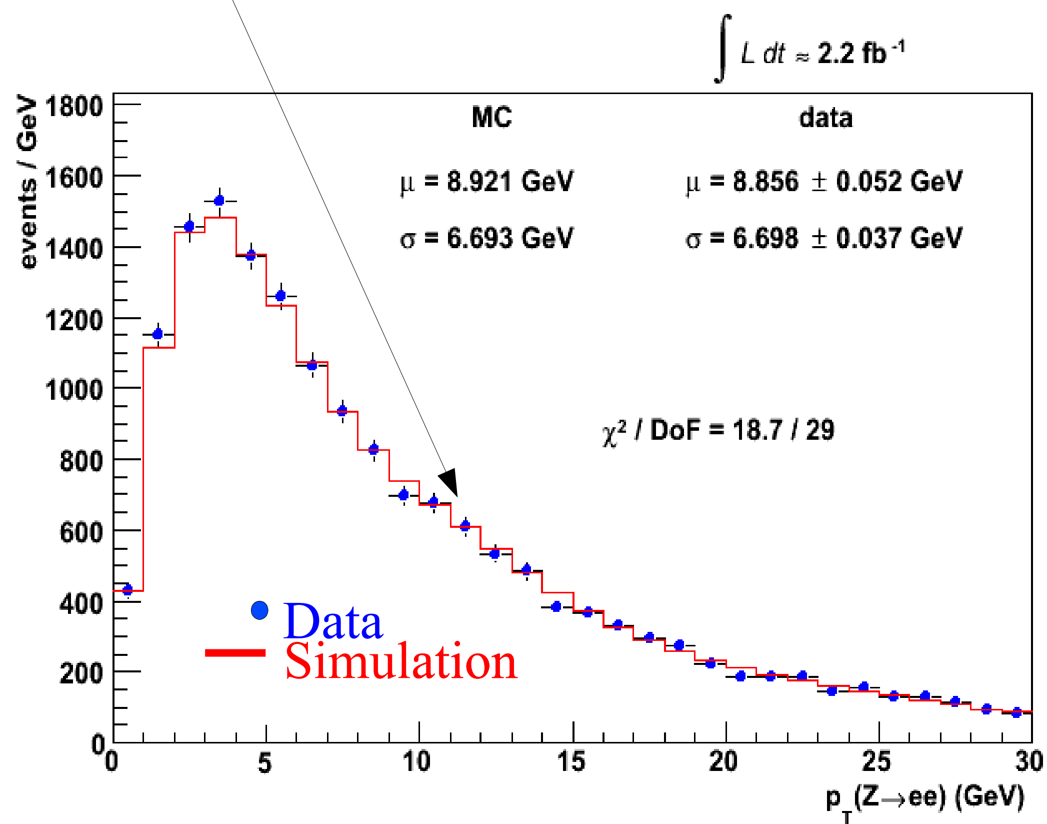
- Fit the non-perturbative parameter $g_2$ and QCD coupling $\alpha_s$ in RESBOS to $p_T(ll)$ spectra:

$\Delta M_W = 5$ MeV

Position of peak in boson $p_T$ spectrum depends on $g_2$

Tail to peak ratio depends on $\alpha_s$



# Outline of Analysis

*Energy scale measurements drive the W mass measurement*

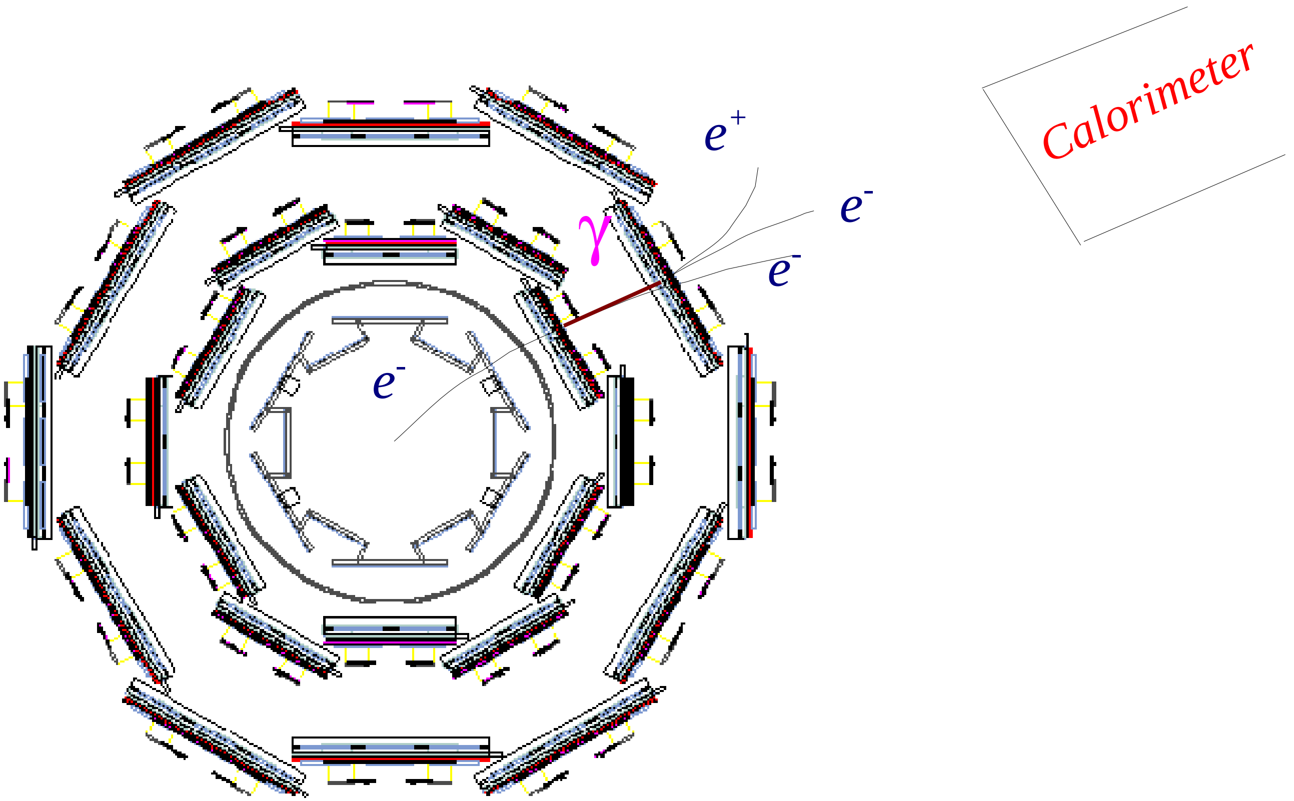
- Tracker Calibration
  - alignment of the COT (~2400 cells) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
  - Confirmed using $Z \rightarrow \mu\mu$ mass fit
- EM Calorimeter Calibration
  - COT momentum scale transferred to EM calorimeter using a fit to the peak of the E/p spectrum, around $E/p \sim 1$
  - 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

# Custom 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 detailed formulae and Landau distribution
    - Generate bremsstrahlung photons down to 0.4 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

# Custom 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

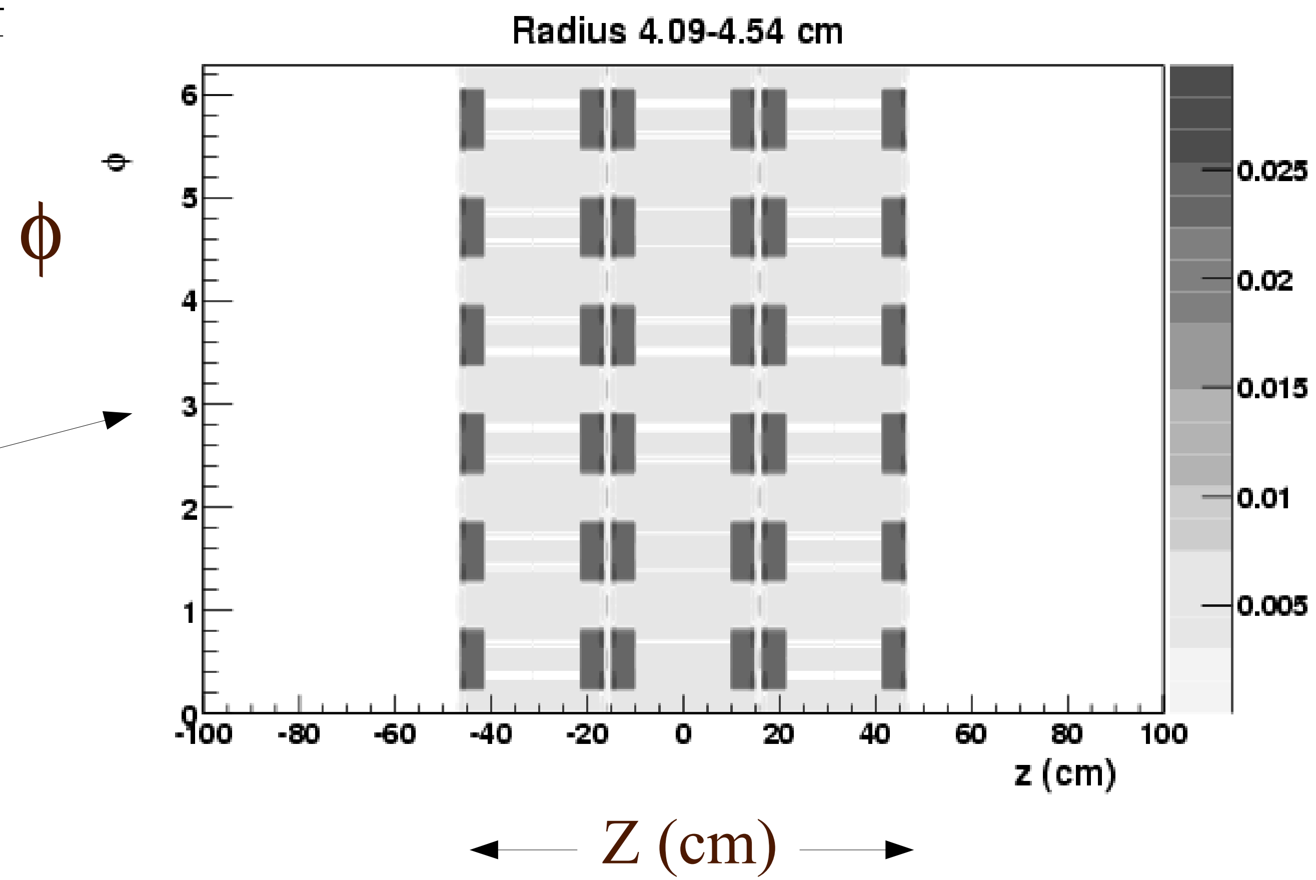


# 3-D Material Map in Simulation

- Built from detailed construction-level knowledge of inner tracker: silicon ladders, bulkheads, port-cards etc.

- Tuned based on studies of inclusive photon conversions

- Radiation lengths *vs* ($\phi$,$z$) at different radii shows localized nature of material distribution



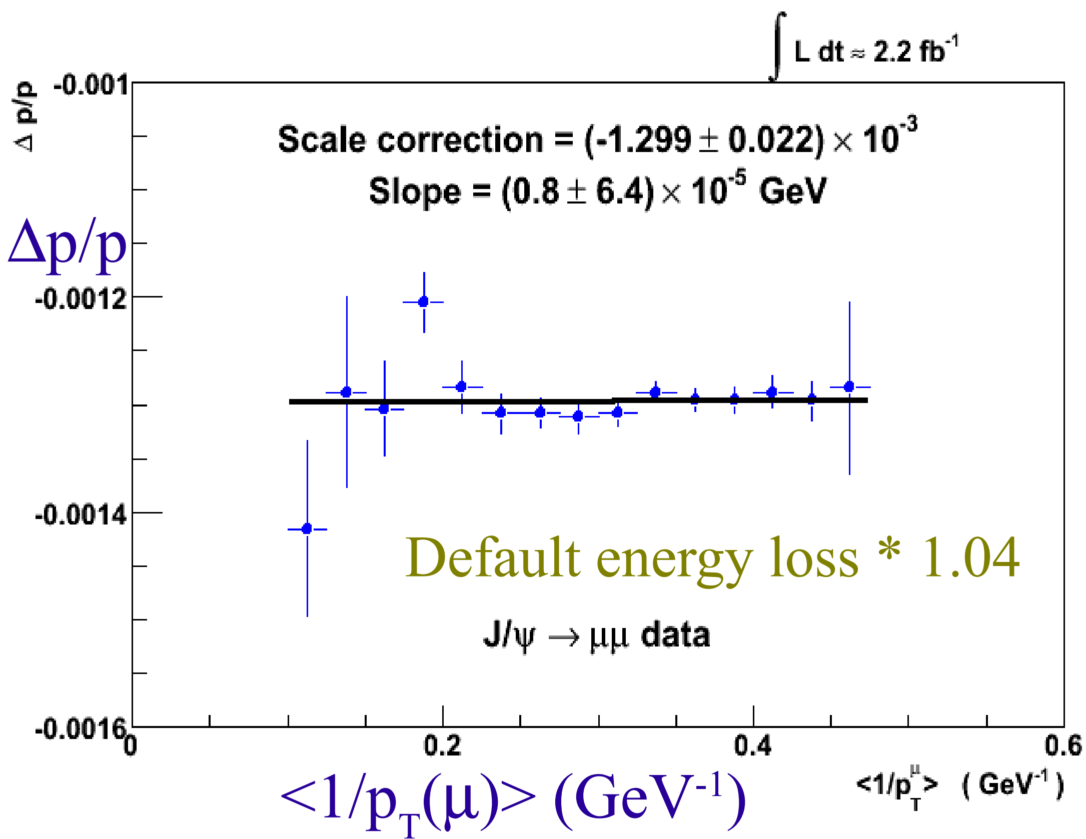

- Include dependence on type of material via Landau-Pomeranchuk-Migdal suppression of soft bremsstrahlung

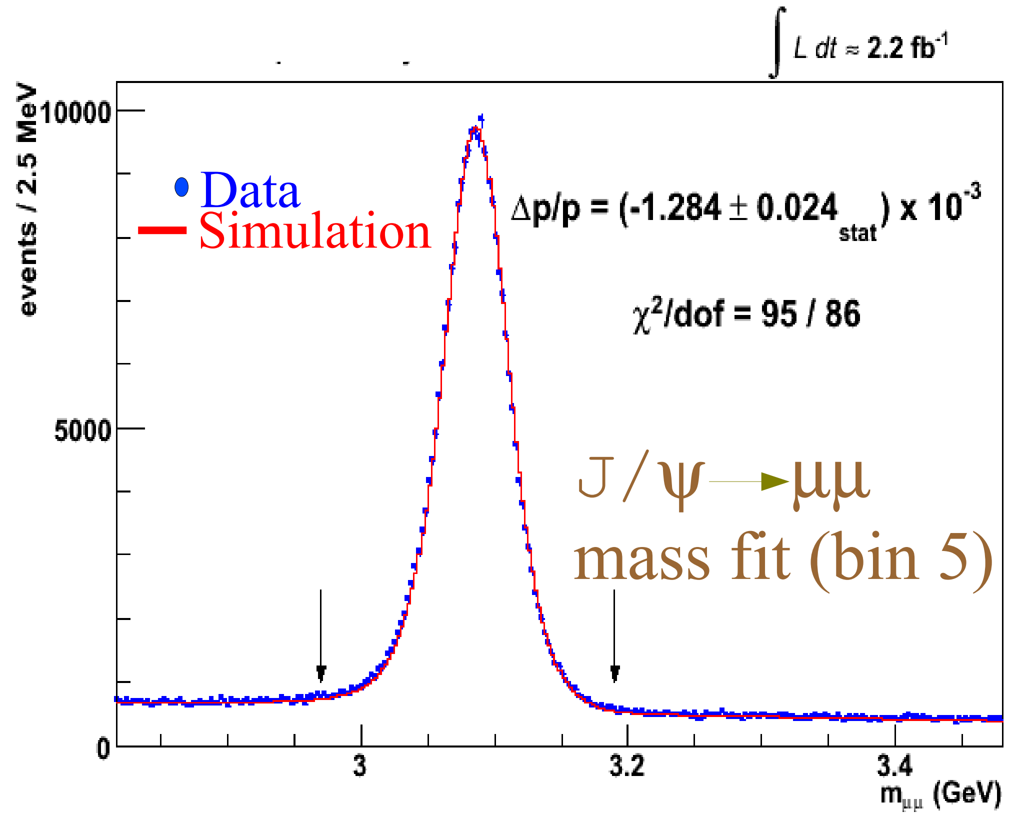
# Tracking Momentum Scale

# Tracking Momentum Scale

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

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

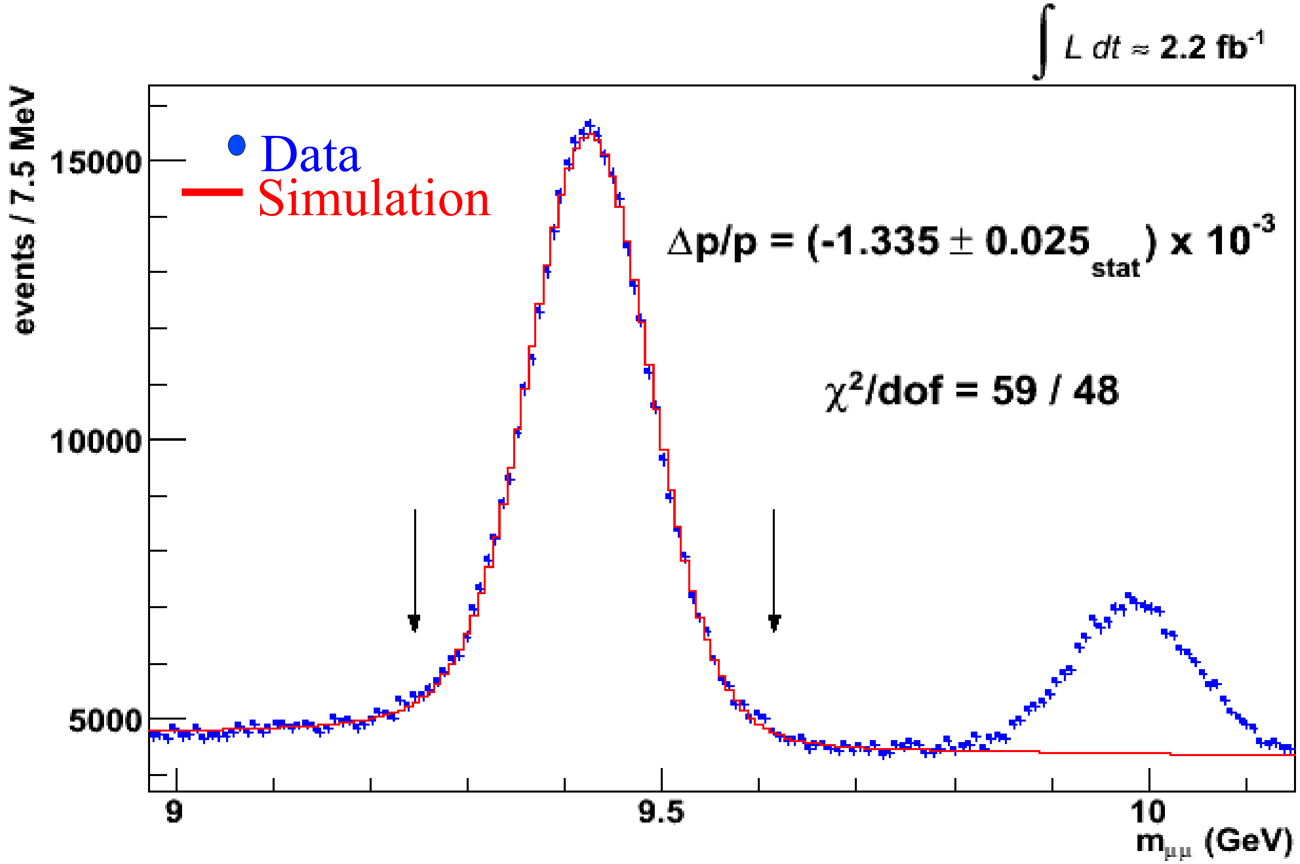


# Tracking Momentum Scale

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

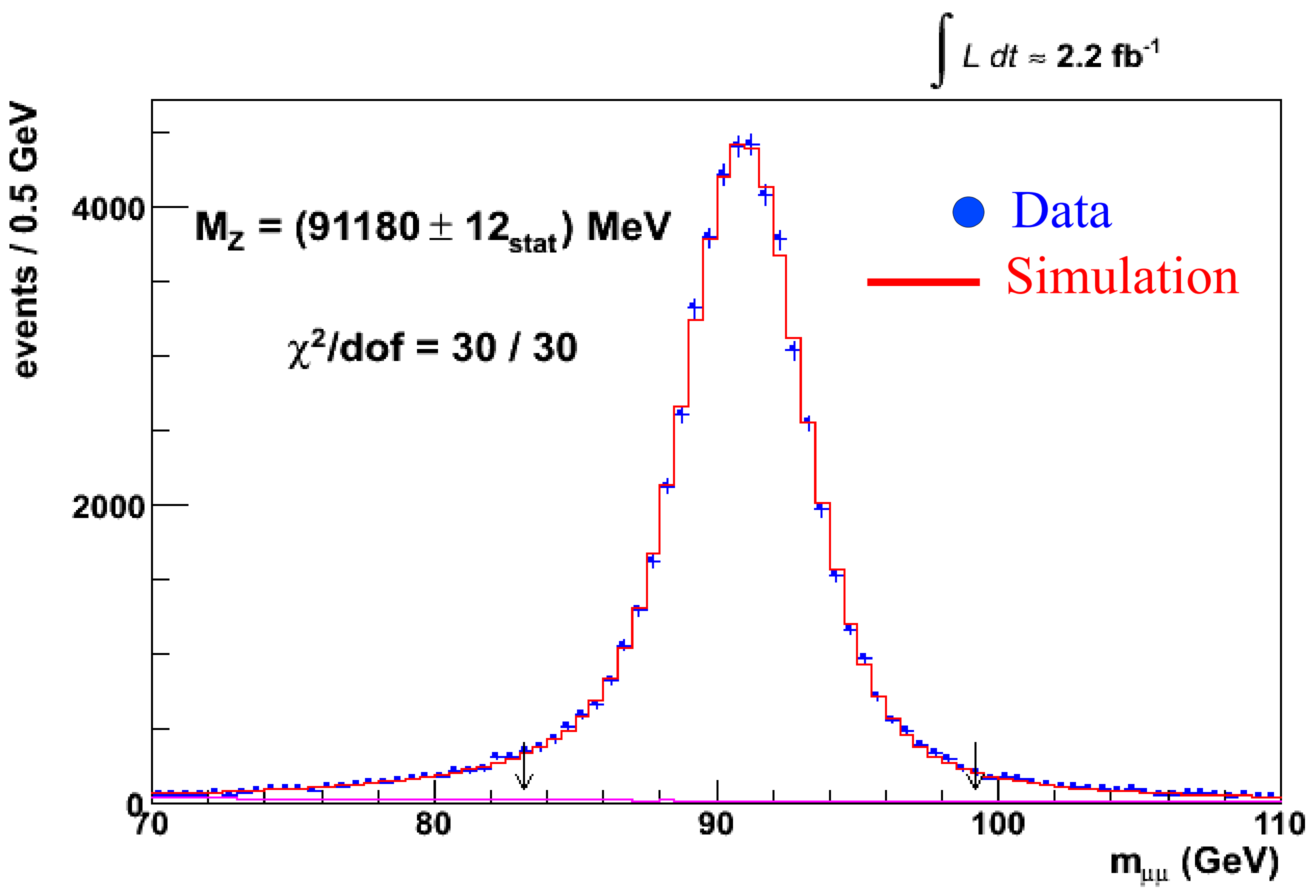
- Momentum scale measurement at higher $p_T$




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

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

- 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

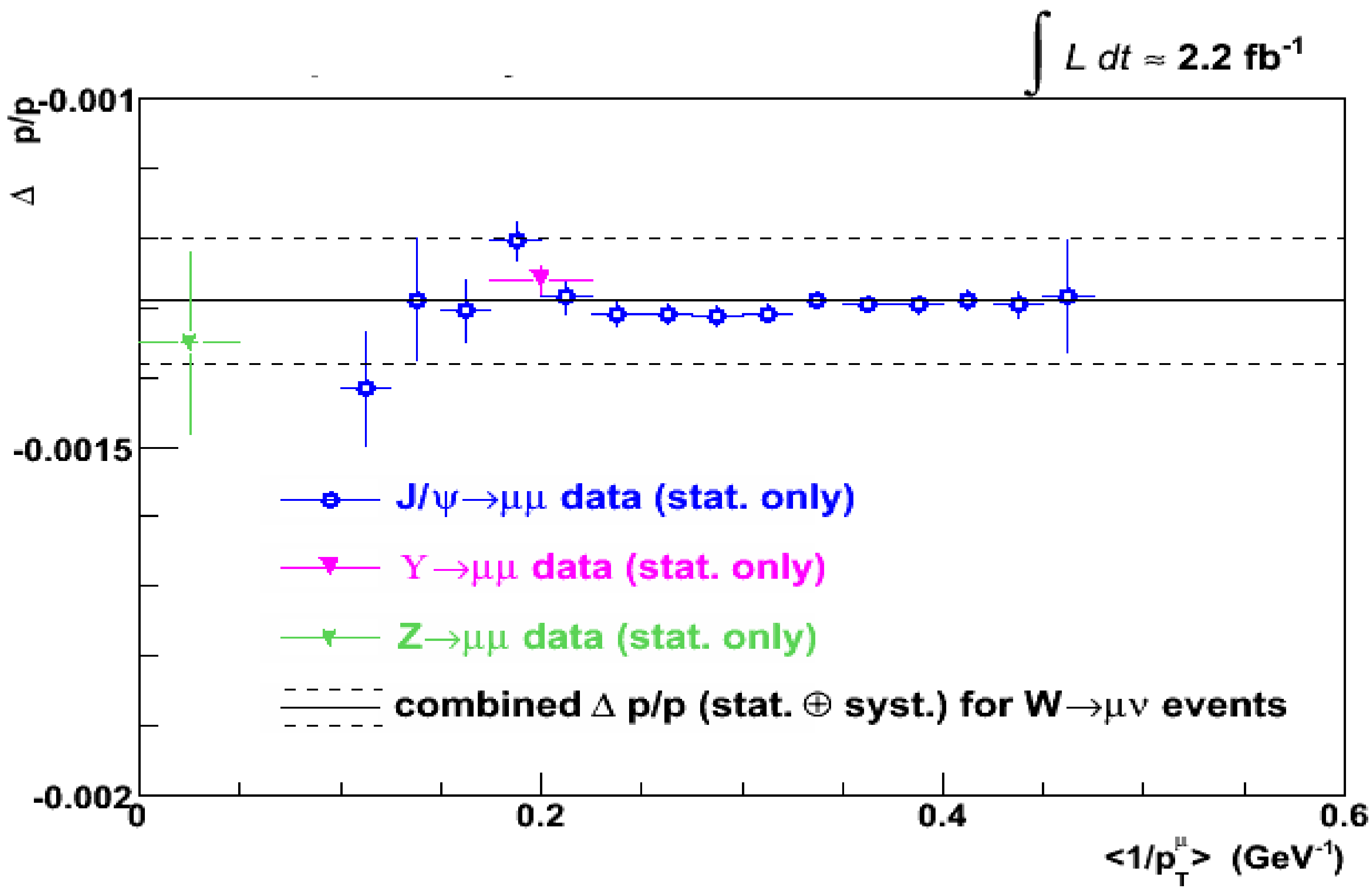



M(μμ) (GeV)

# Tracker Linearity Cross-check & Combination

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

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

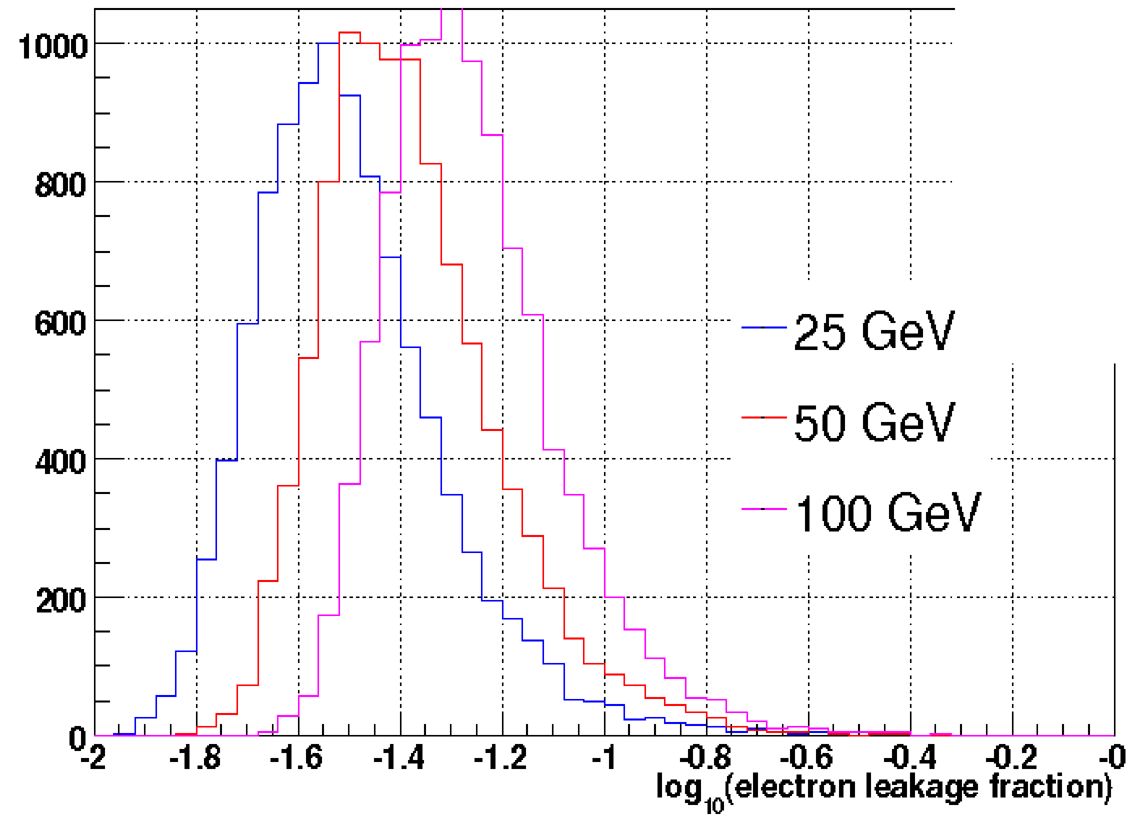



$\Delta M_W$ = 7 MeV

# EM Calorimeter Response

# Calorimeter Simulation for Electrons and Photons

- Distributions of lost energy calculated using detailed GEANT4 simulation of calorimeter
  - Leakage into hadronic calorimeter
  - Absorption in the coil
  - Dependence on incident angle and $E_T$




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

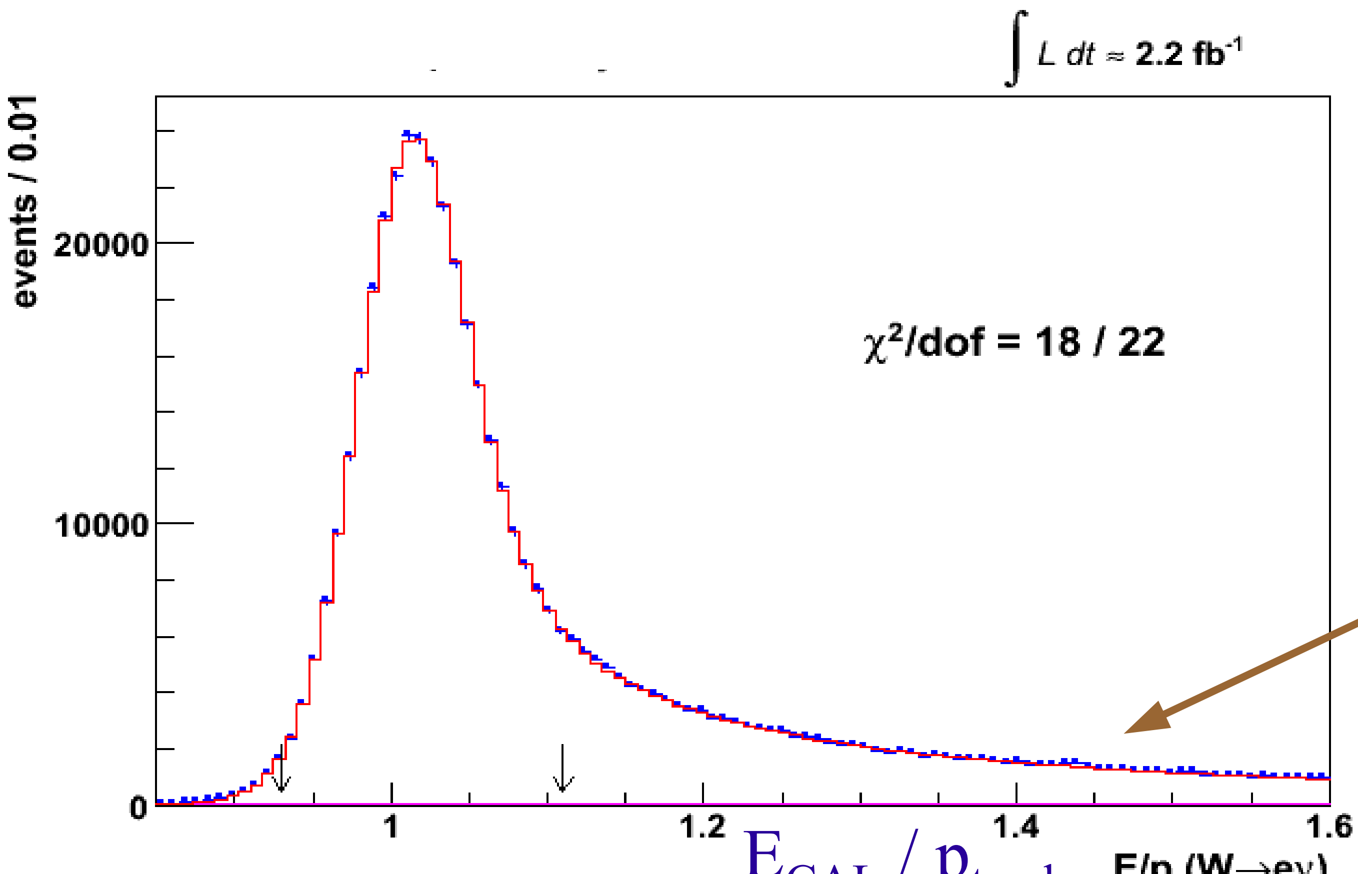
# EM Calorimeter Scale

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

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

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

$\Delta M_W = 13$ MeV




$E_{CAL} / p_{track}$

Data

Simulation

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

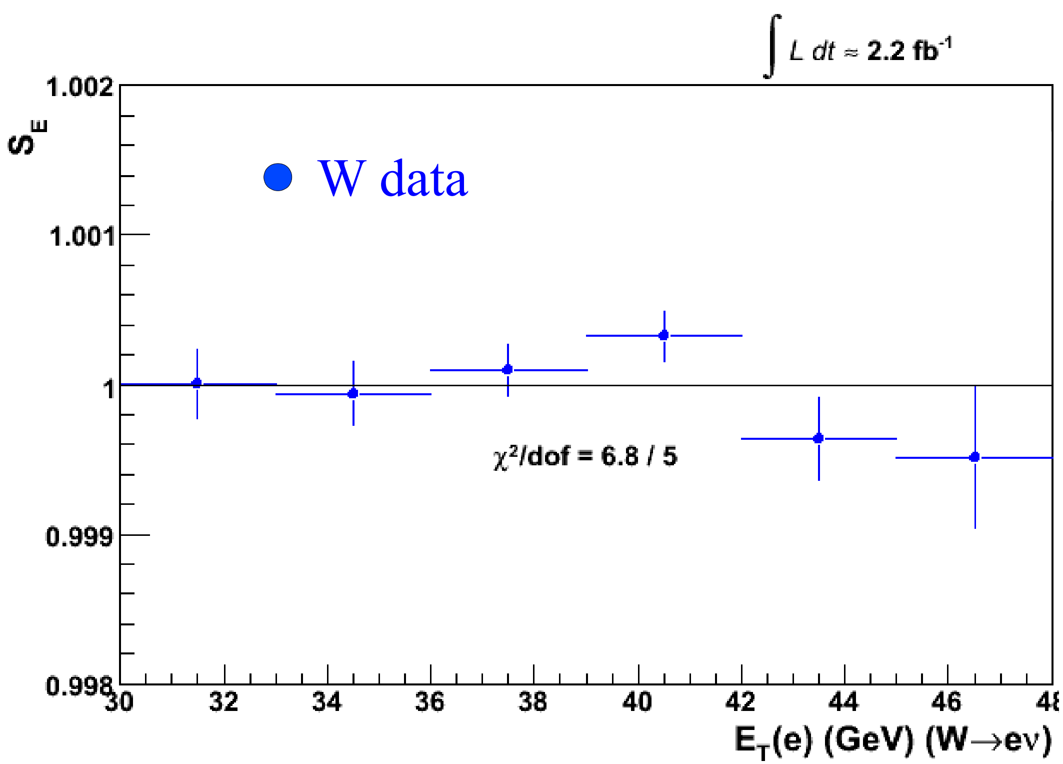
# Measurement of EM Calorimeter Non-linearity

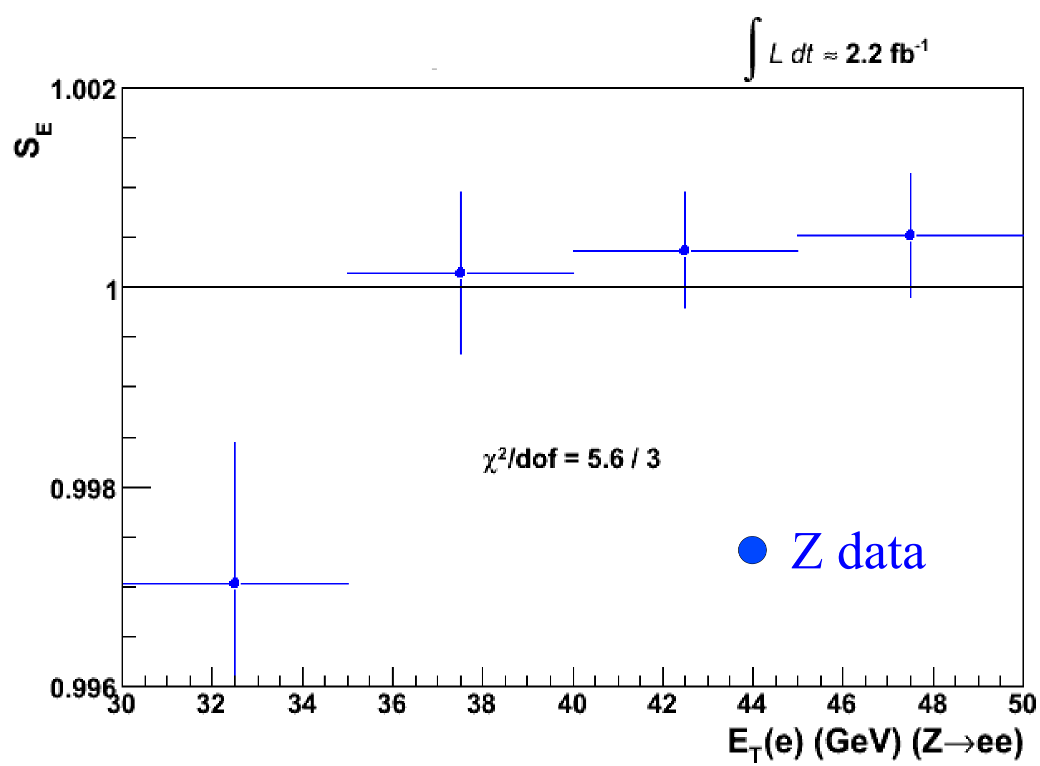
- Perform E/p fit-based calibration in bins of electron $E_T$
- GEANT-motivated parameterization of non-linear response:

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

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

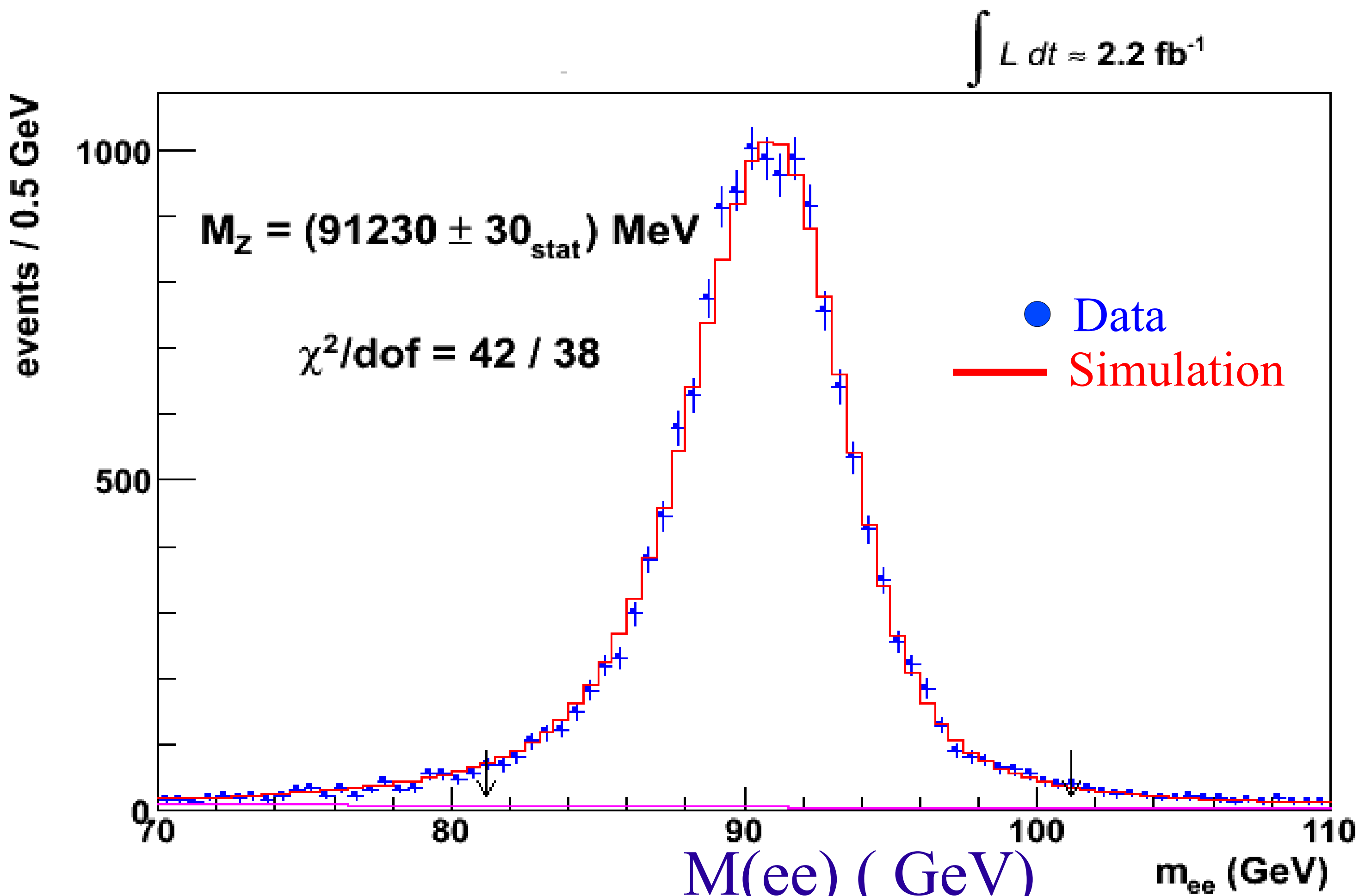
$\Rightarrow \Delta M_W = 4$ MeV



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

- 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

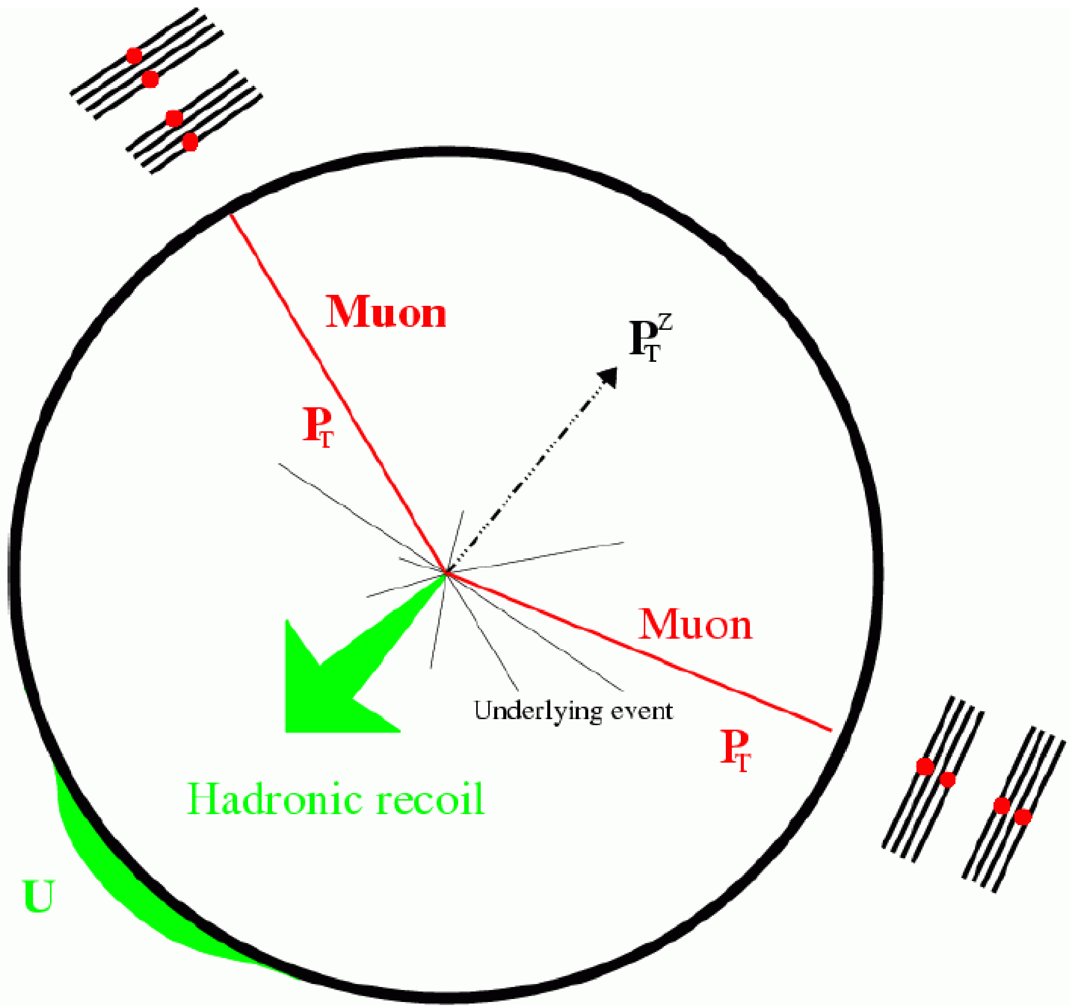



$\Delta M_W = 10$ MeV

# Hadronic Recoil Model

# Constraining the Hadronic Recoil Model

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



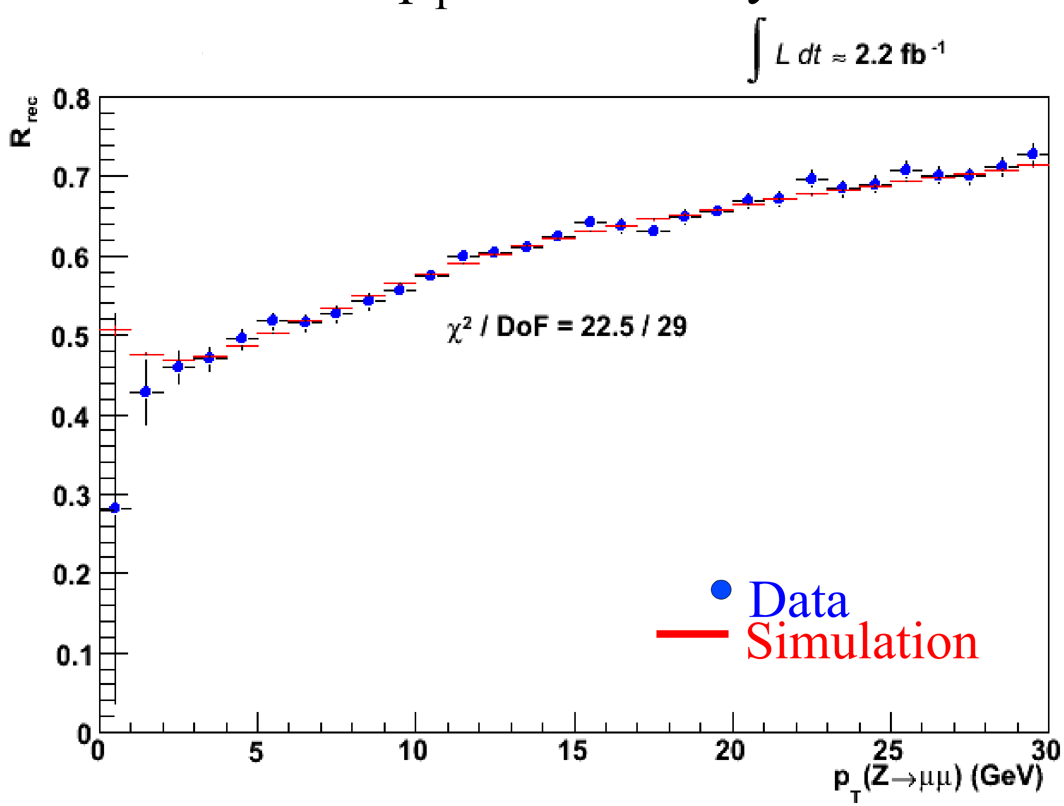

Detector response model for hadronic recoil tuned using $p_T$-balance in $Z \rightarrow ll$ events

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

# Hadronic Recoil Simulation

Recoil momentum 2-vector ***u*** has

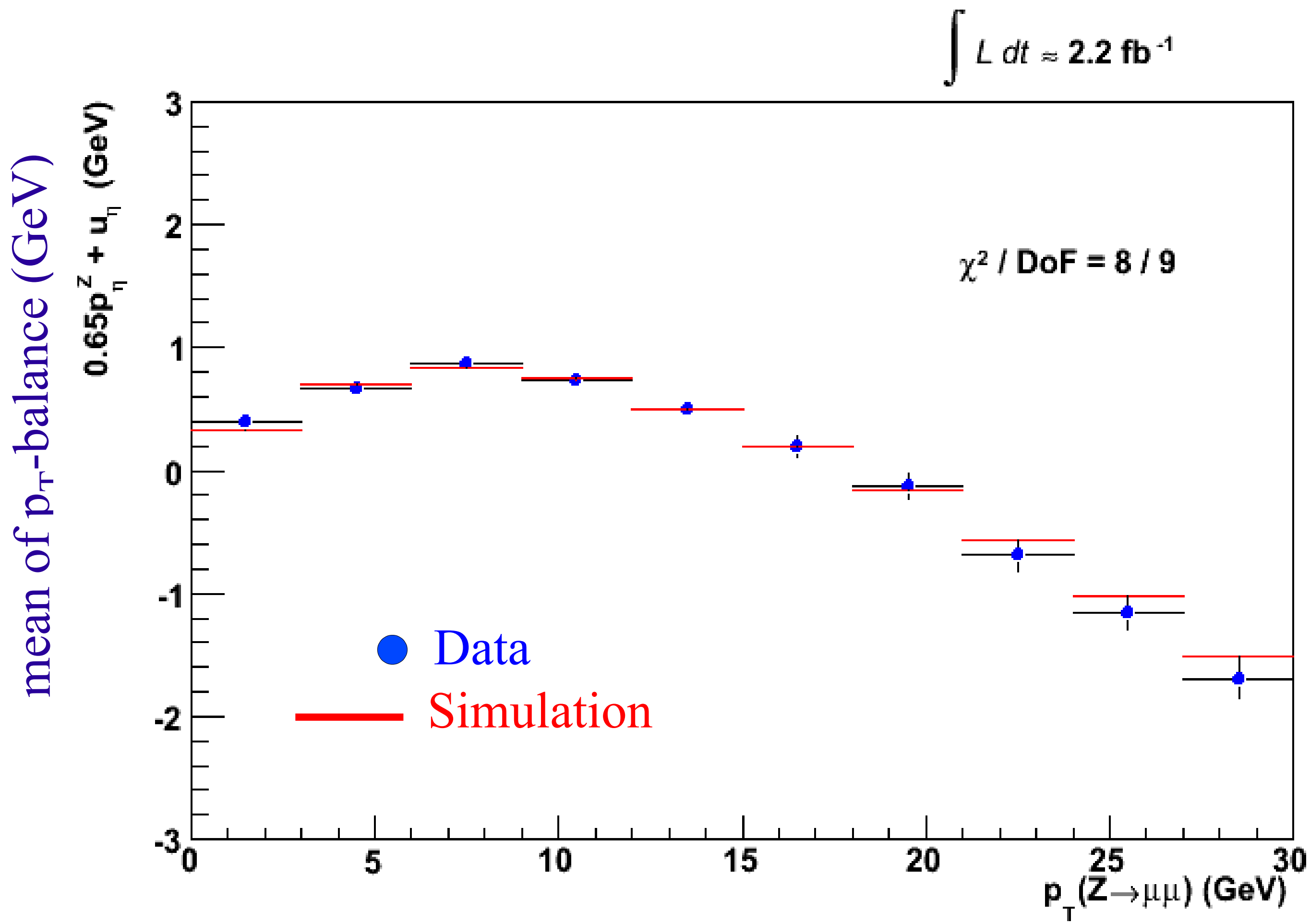
- a soft 'spectator interaction' component, randomly oriented
  - Modelled using minimum-bias data with tunable magnitude
- A hard 'jet' component, directed opposite the boson $p_T$
  - $P_T$-dependent response and resolution parameterizations
  - Hadronic response $R = \boldsymbol{u}_{reconstructed} / \boldsymbol{u}_{true}$ parameterized as a logarithmically increasing function of boson $p_T$ motivated by Z boson data

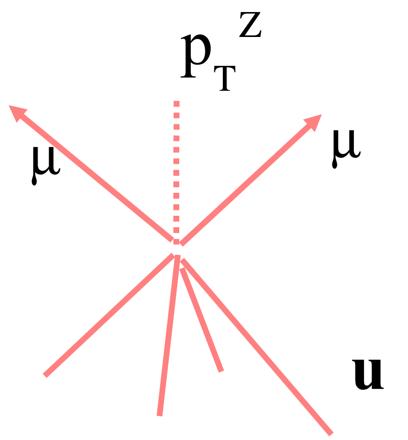


# Tuning Recoil Response Model with *Z* events

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

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



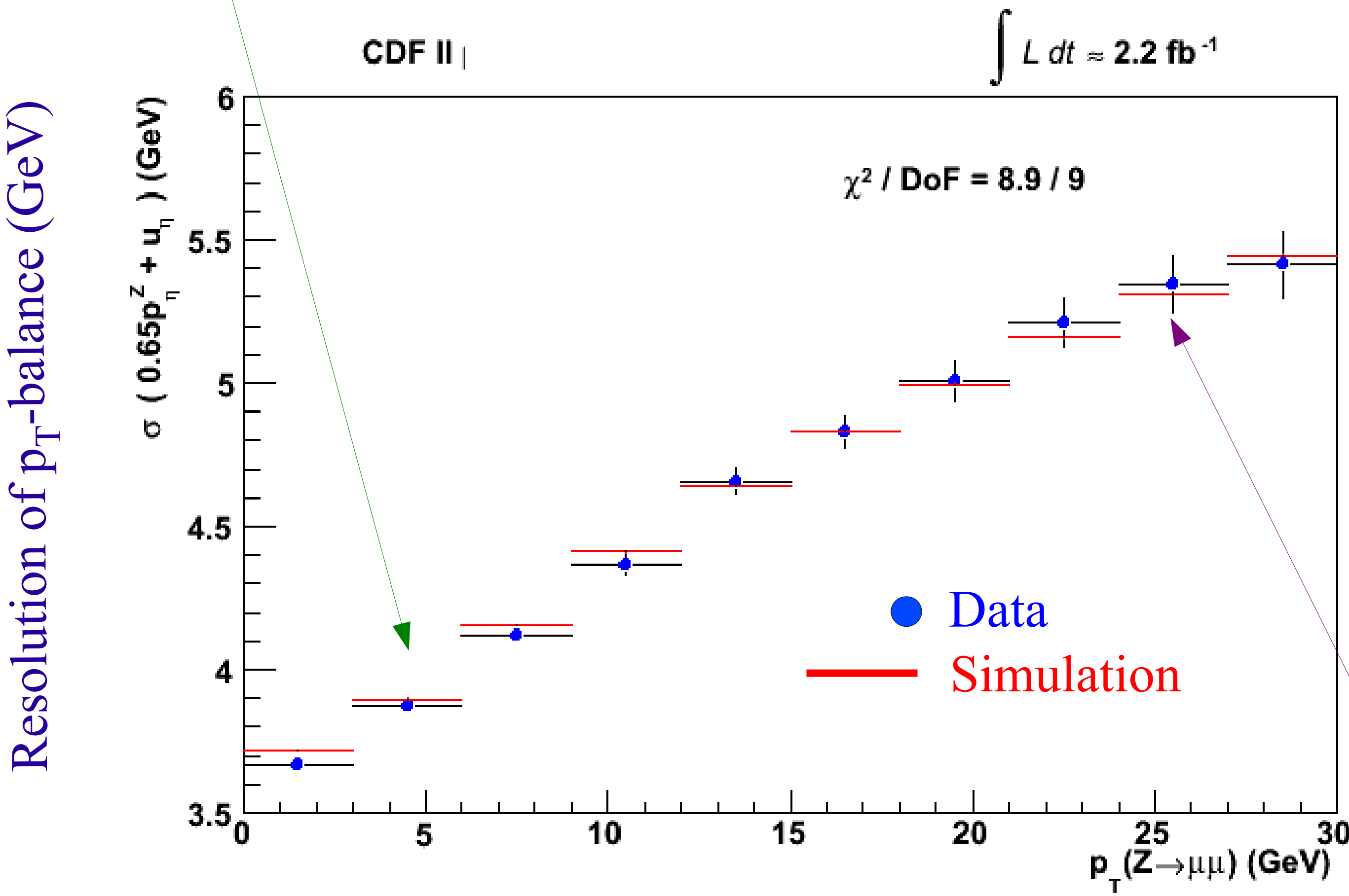



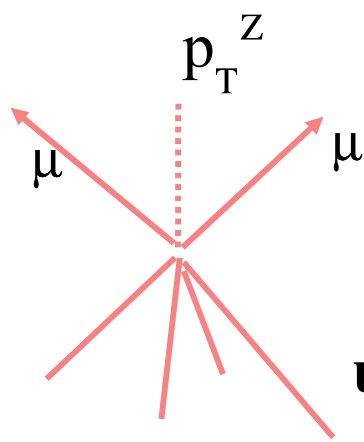

Hadronic model parameters tuned by minimizing $\chi^2$ between data and simulation

$\Delta M_W = 4$ MeV

# Tuning Recoil Resolution Model with *Z* events

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



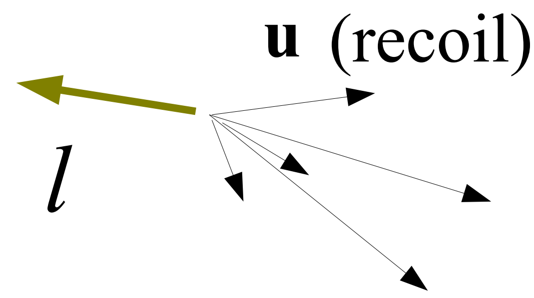



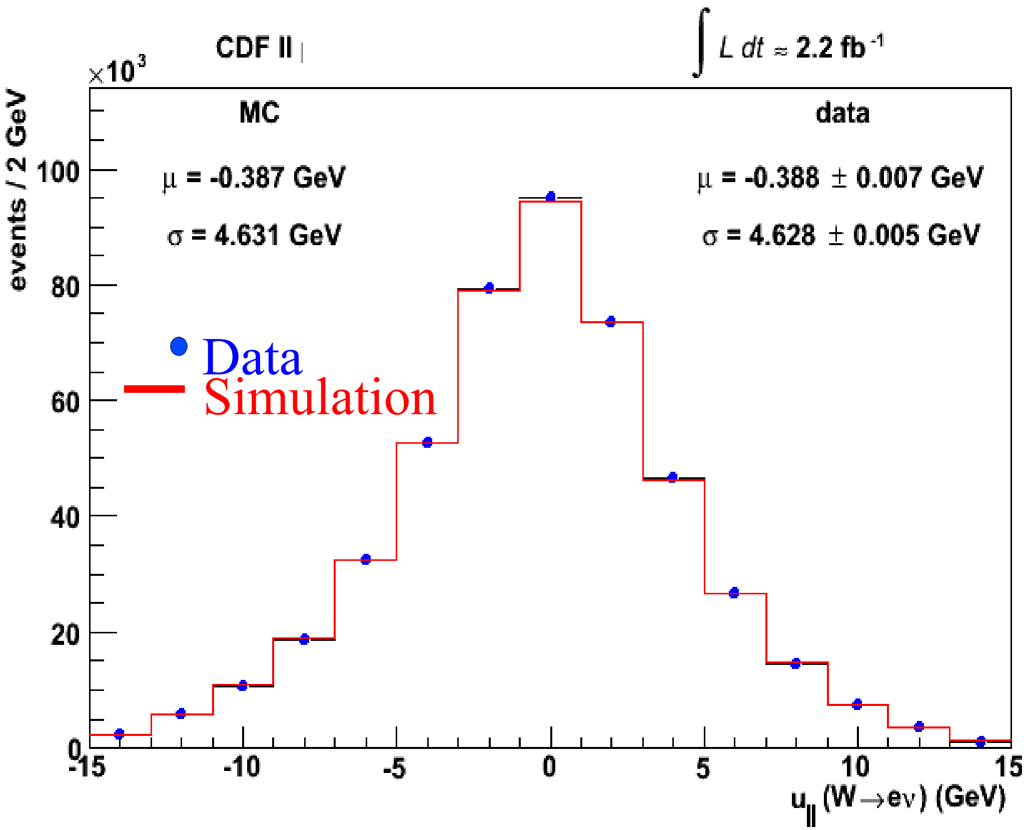

$\Delta M_W$ = 4 MeV

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

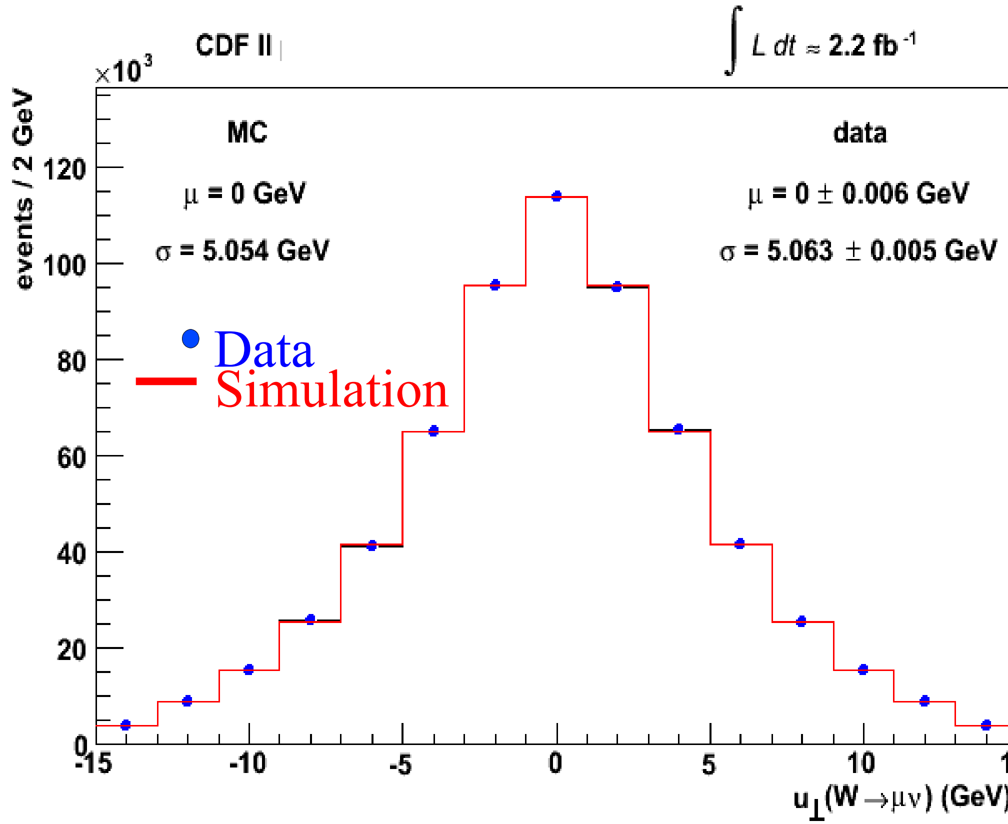
# Testing Hadronic Recoil Model with *W* events

Compare recoil distributions between simulation and data



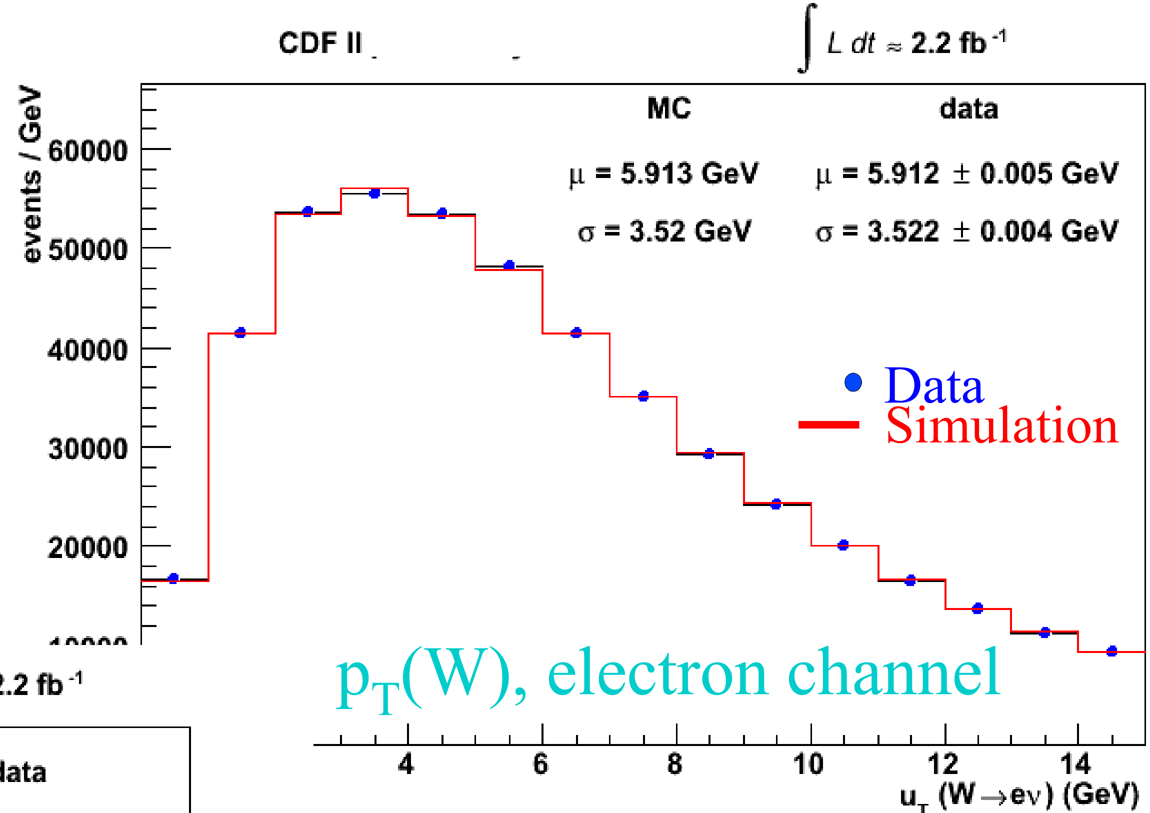

Recoil projection (GeV) on lepton direction

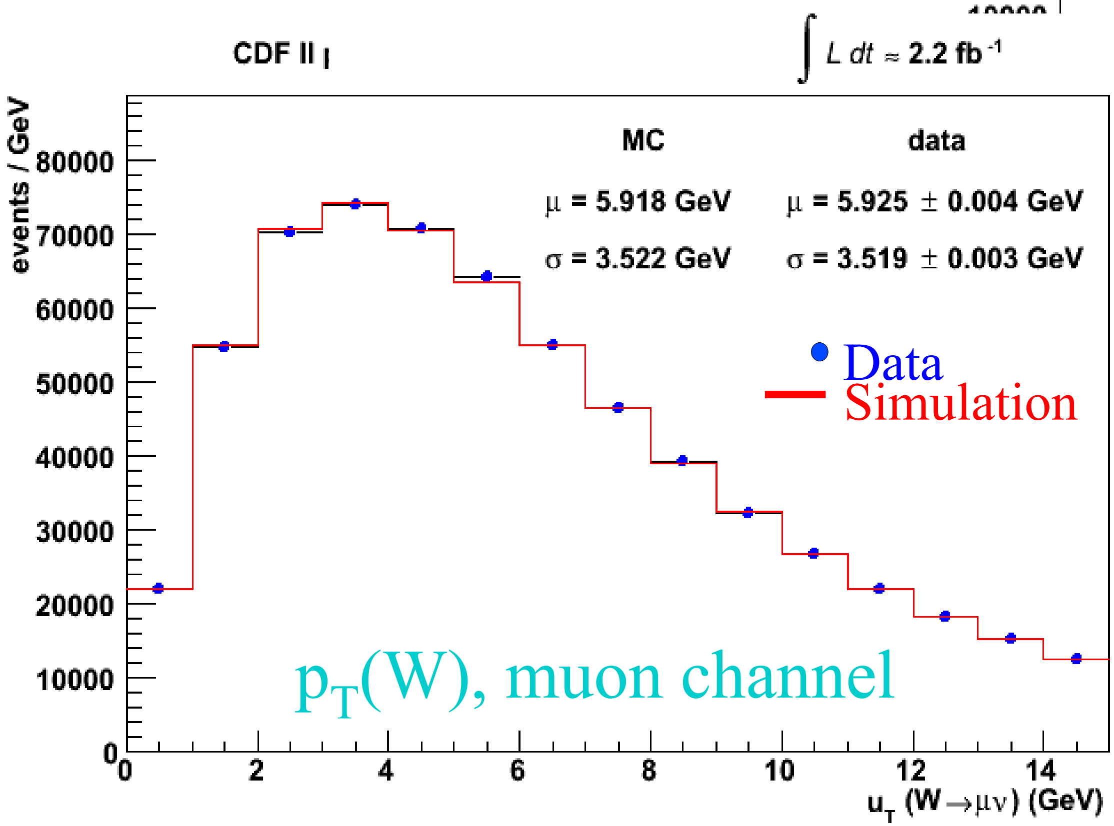


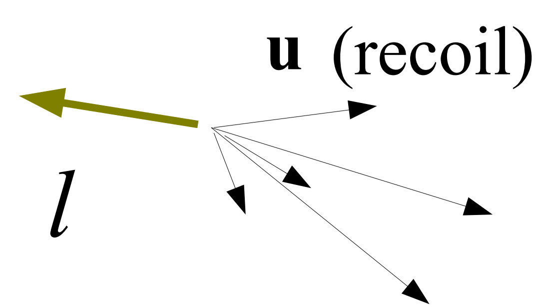

Recoil projection (GeV) perpendicular to lepton

# Testing Hadronic Recoil Model with *W* events

Recoil model validation plots confirm the consistency of the model



# Parton Distribution Functions

- Affect W kinematic lineshapes through acceptance cuts
- In the rest frame, $p_T = m \sin \theta^* / 2$
- Longitudinal cuts on lepton in the lab frame sculpt the distribution of $\theta^*$, hence biases the distribution of lepton $p_T$
  - Relationship between lab frame and rest frame depends on the boost of the W boson along the beam axis
- Parton distribution functions control the longitudinal boost
- Uncertainty due to parton distribution functions evaluated by fitting pseudo-experiments (simulated samples with the same statistics and selection as data) with varied parton distribution functions
  - Current uncertainty 10 MeV
  - Largest source of systematic uncertainty
  - Expected to reduce with lepton and boson rapidity measurements at Tevatron and LHC

# W Mass Fits

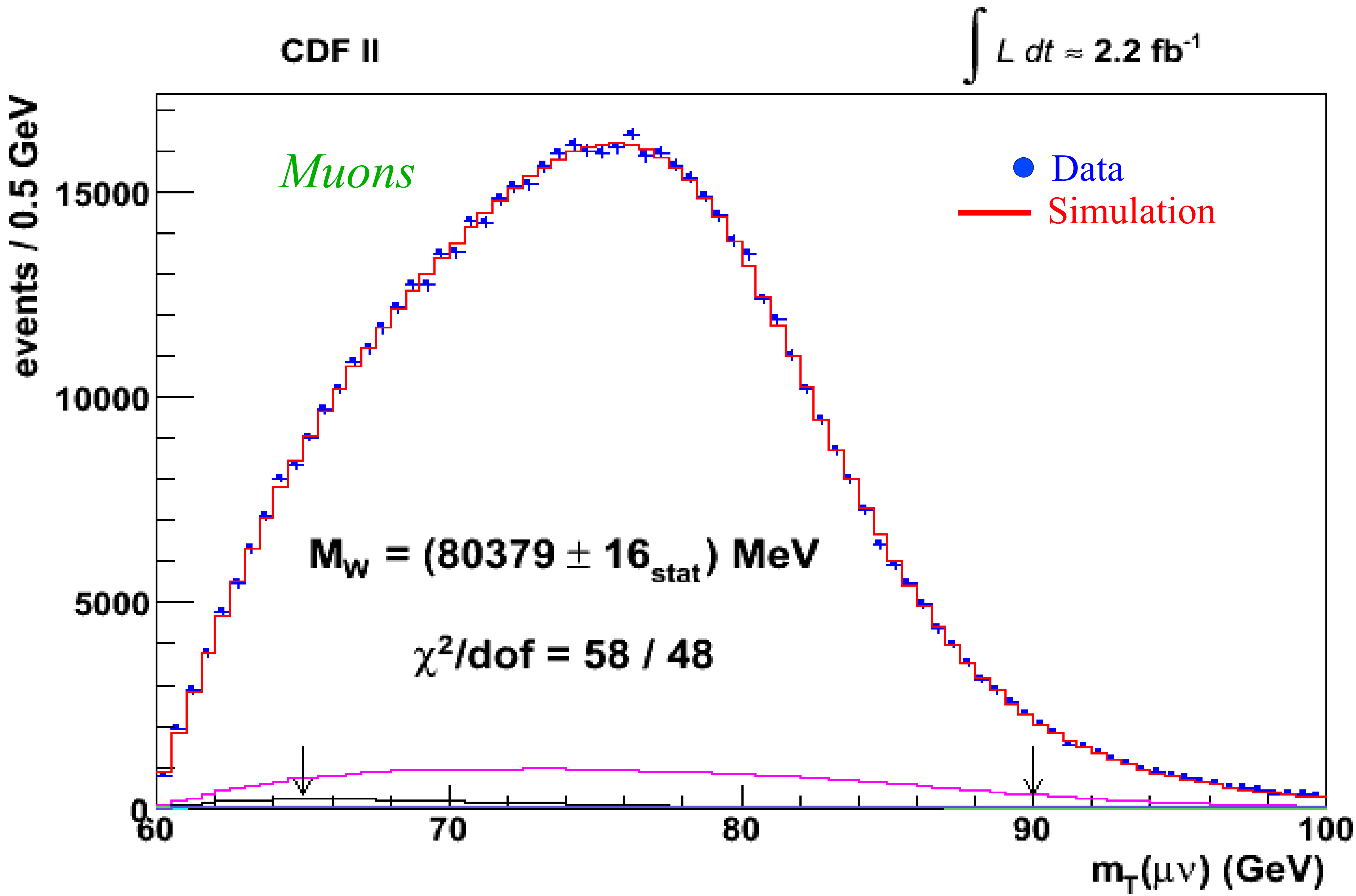
# Blind Analysis Technique

- All W and Z mass fit results were blinded with a random [-75,75] MeV offset hidden in the likelihood fitter

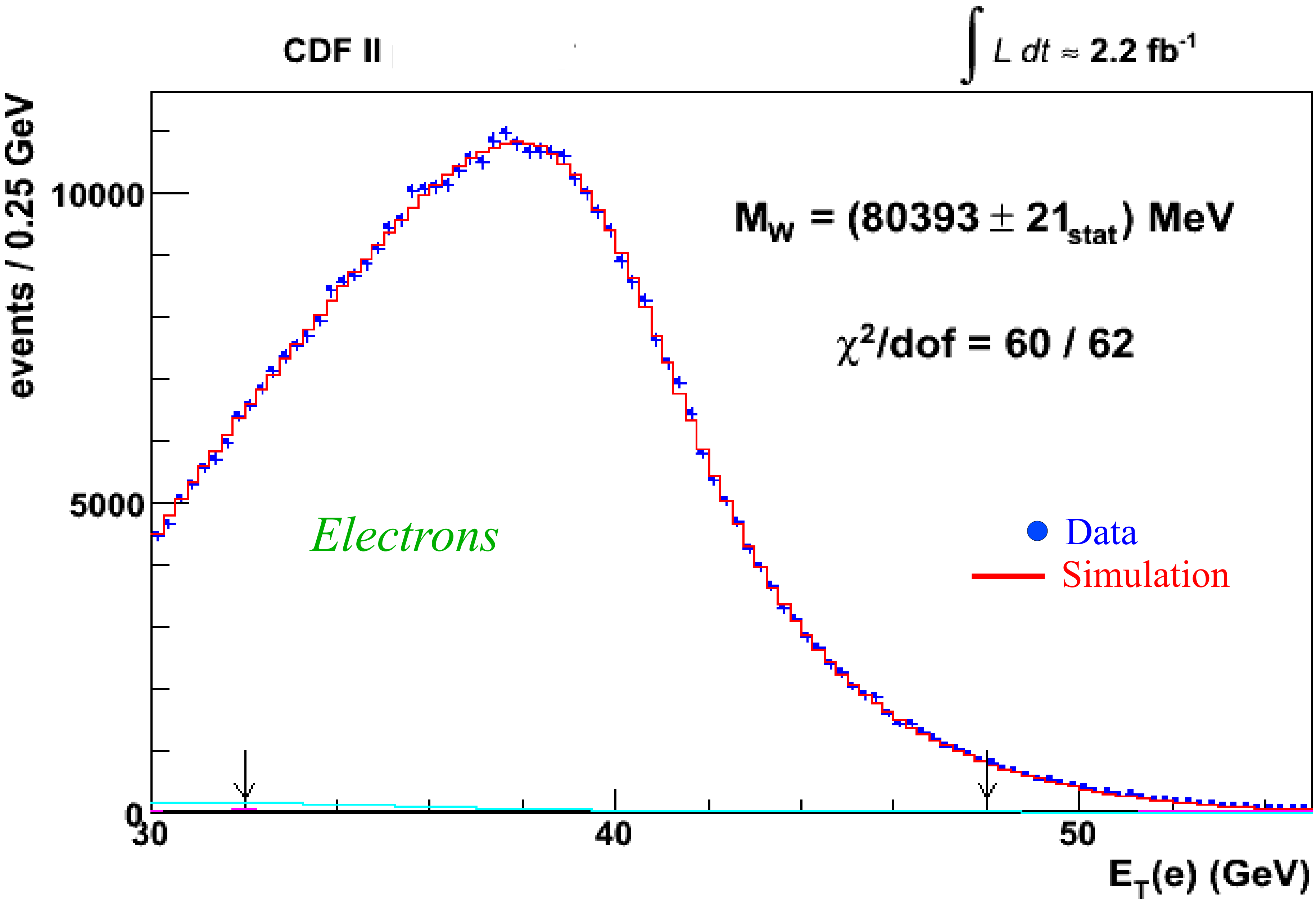
- Blinding offset removed after the analysis was declared frozen

- Technique allows to study all aspects of data while keeping Z mass and W mass result unknown within 75 MeV

# *W* Transverse Mass Fit

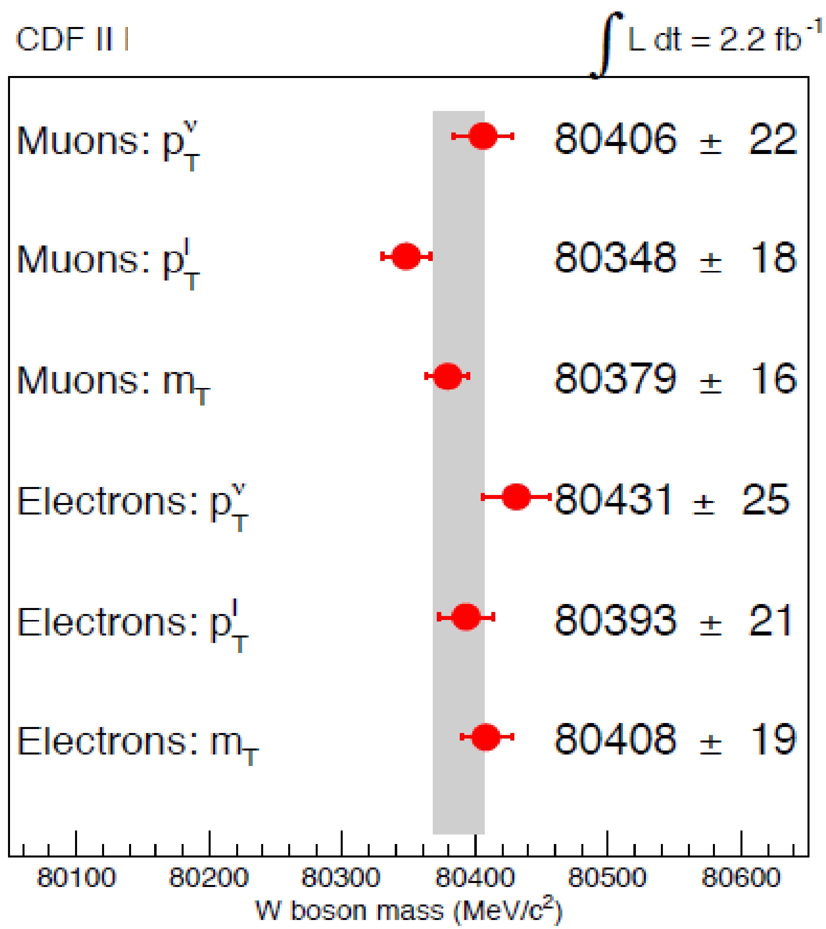


# *W* Mass Fit using Lepton $p_T$



# Summary of *W* Mass Fits

| Charged Lepton | Kinematic Distribution | Fit Result (MeV) | $\chi^2$/DoF |
|---|---|---|---|
| Electron | Transverse mass | $80408 \pm 19$ | 52/48 |
| Electron | Charged lepton $p_T$ | $80393 \pm 21$ | 60/62 |
| Electron | Neutrino $p_T$ | $80431 \pm 25$ | 71/62 |
| Muon | Transverse mass | $80379 \pm 16$ | 57/48 |
| Muon | Charged lepton $p_T$ | $80348 \pm 18$ | 58/62 |
| Muon | Neutrino $p_T$ | $80406 \pm 22$ | 82/62 |

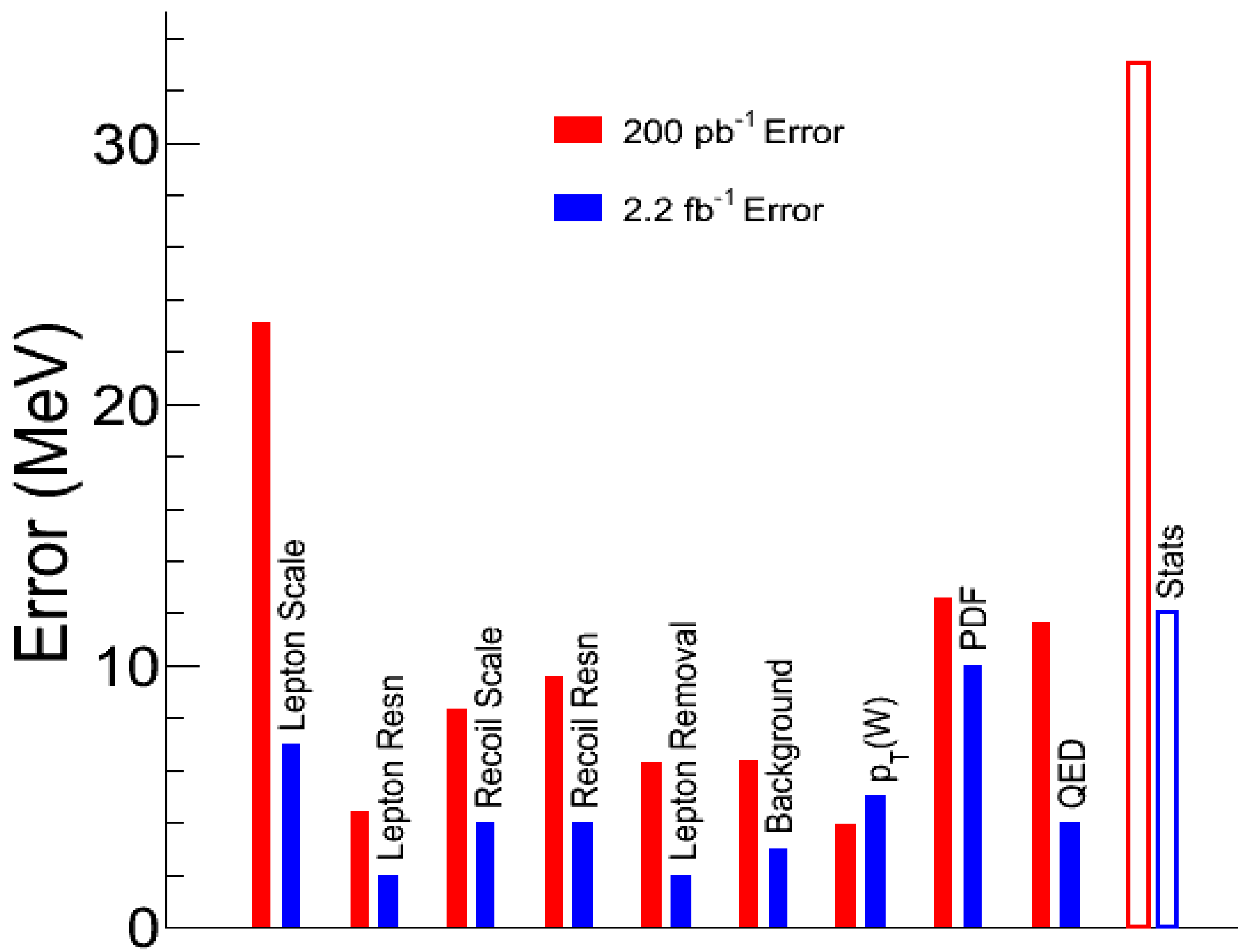


# CDF Result (2.2 $fb^{-1}$)
# Transverse Mass Fit Uncertainties (MeV)

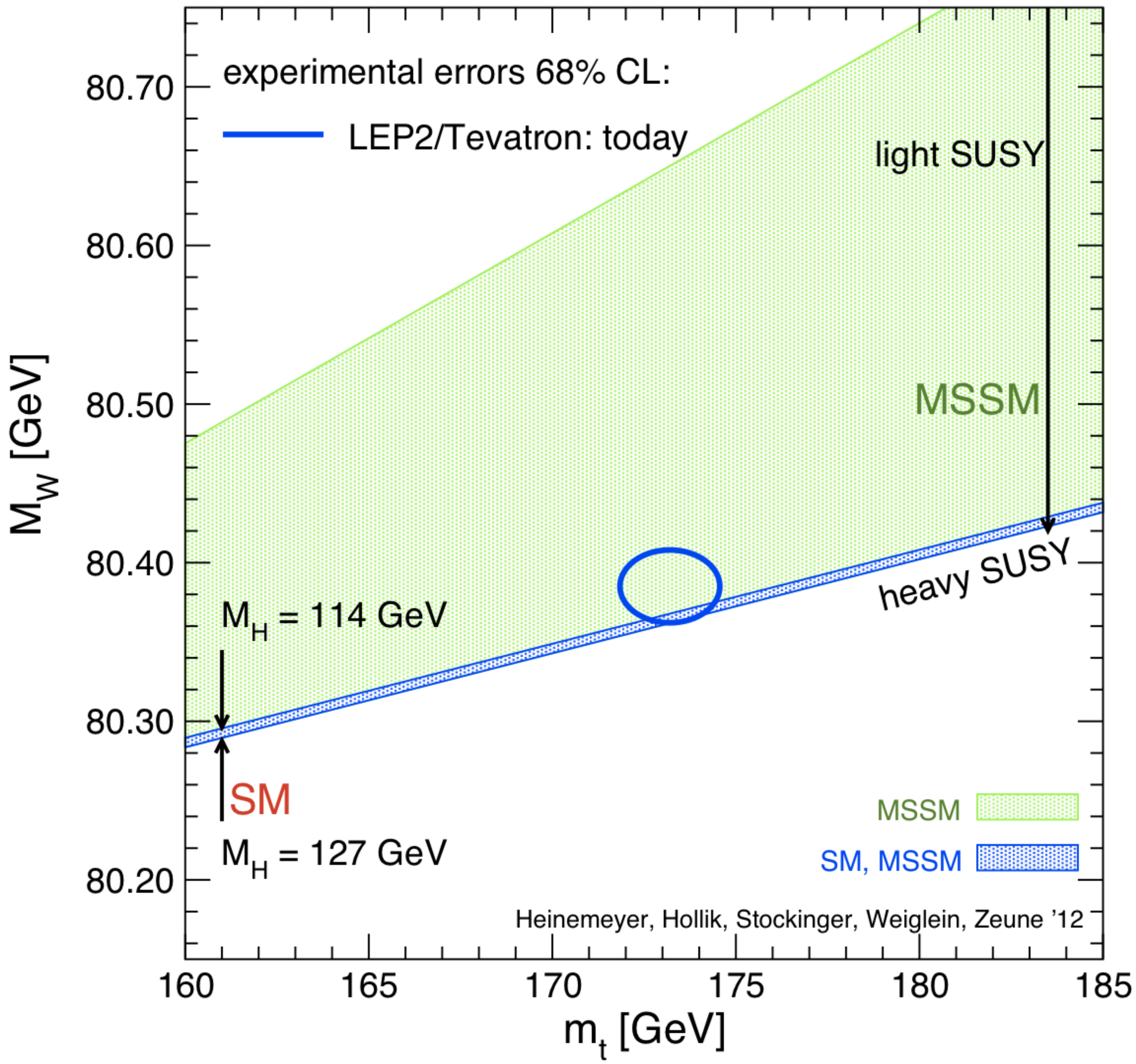
| | *electrons* | *muons* | *common* |
|---|---|---|---|
| W statistics | 19 | 16 | 0 |
| Lepton energy scale | 10 | 7 | 5 |
| Lepton resolution | 4 | 1 | 0 |
| Recoil energy scale | 5 | 5 | 5 |
| Recoil energy resolution | 7 | 7 | 7 |
| Selection bias | 0 | 0 | 0 |
| Lepton removal | 3 | 2 | 2 |
| Backgrounds | 4 | 3 | 0 |
| pT(W) model | 3 | 3 | 3 |
| Parton dist. Functions | 10 | 10 | 10 |
| QED rad. Corrections | 4 | 4 | 4 |
| Total systematic | 18 | 16 | 15 |
| Total | 26 | 23 | |

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

# Combined W Mass Result, Error Scaling

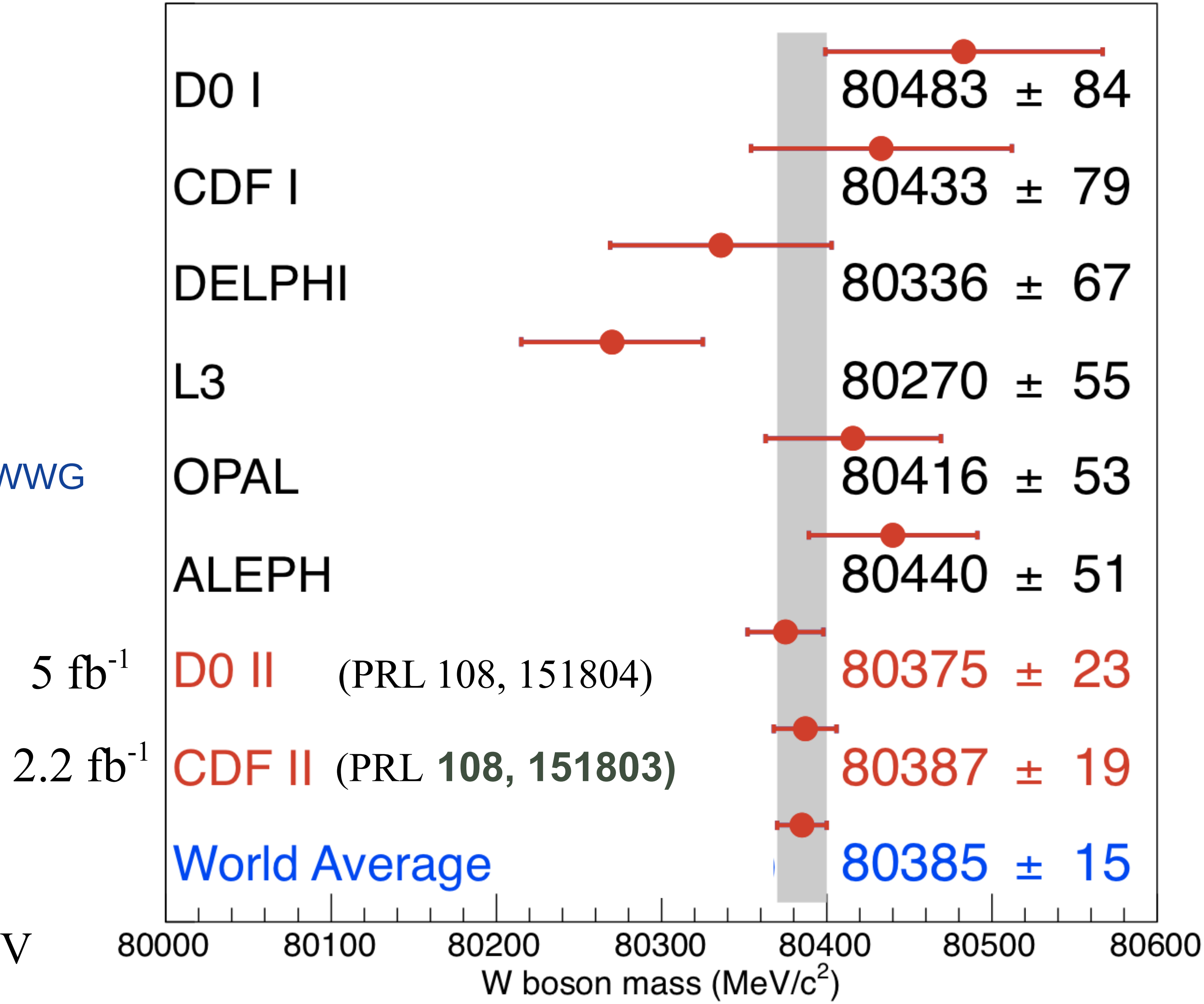


# 2012 Status of $M_W$ *vs* $M_{top}$



# W Boson Mass Measurements from Different Experiments

World average computed by TeVEWWG ArXiv: 1204.0042




Previous world average = 80399 ± 23 MeV

# Future $M_W$ Measurements at Tevatron and LHC

- Factor of 2-5 bigger samples of W and Z bosons available at Tevatron
- Huge samples at LHC
- For most of the sources of systematic uncertainties, we have demonstrated that we can find ways to constrain them with data and scale systematic uncertainties with data statistics
- Exception is the PDF uncertainty, where we have not made a dedicated effort to constrain the PDFs within the analysis
- We need to address specific PDF degrees of freedom to answer the question:
  - Can we approach total uncertainty on $M_W \sim 10$ MeV at the Tevatron?
- (A.V. Kotwal and J. Stark, Ann. Rev. Nucl. Part. Sci., vol. 58, Nov 2008)

# PDF Uncertainties – scope for improvement

- 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 $d_{\text{valence}}$ 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 $\rightarrow l\nu$ lepton rapidity distribution
  - W boson charge asymmetry

# Summary

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

- New Tevatron W mass results are very precise:
  - $M_W = 80387 \pm 19$ MeV (CDF)
    $= 80375 \pm 23$ MeV (D0)
    $= 80385 \pm 15$ MeV (world average)

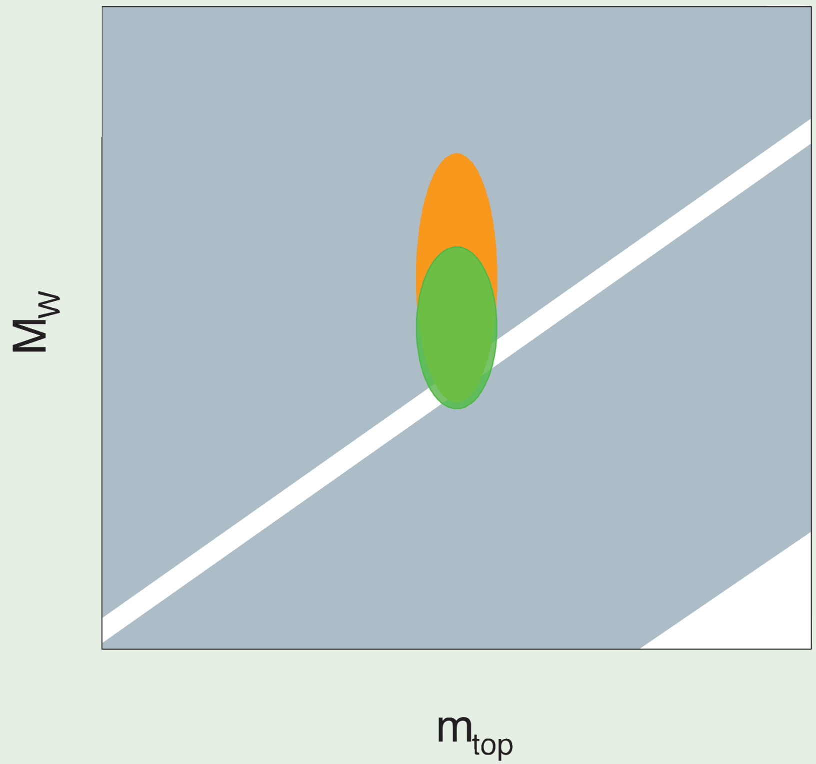
- New global electroweak fit $M_H = 94^{+29}_{-24}$ GeV @ 68% CL (LEPEWWG)
  - SM Higgs prediction is pinned in the low-mass range
  - confront mass of new particle from direct search result ~ 125 GeV

- Looking forward to $\Delta M_W < 10$ MeV from full Tevatron dataset
  goal of $\Delta M_W < 5$ MeV from LHC data

# PHYSICAL REVIEW LETTERS™

Articles published week ending 13 APRIL 2012





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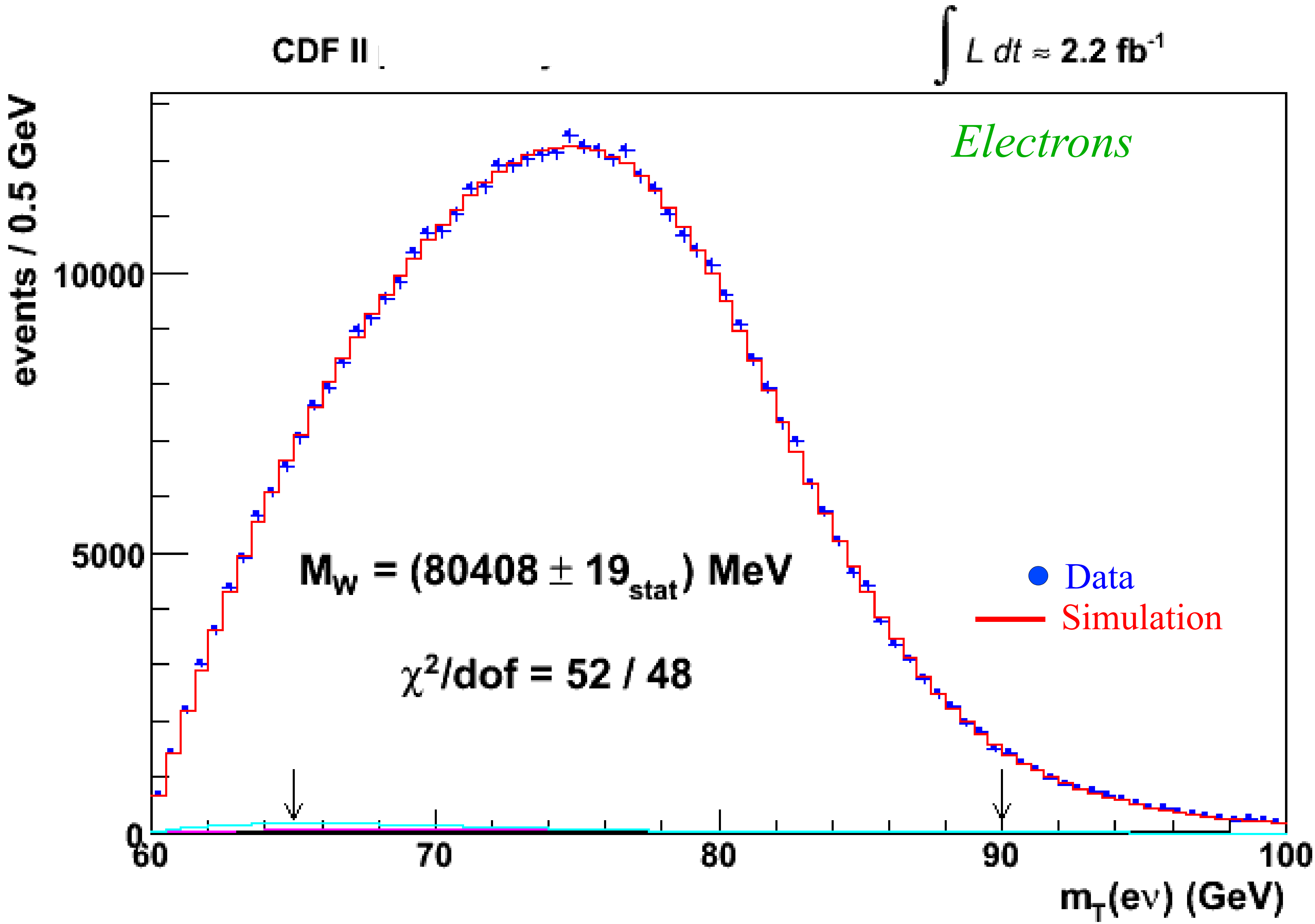
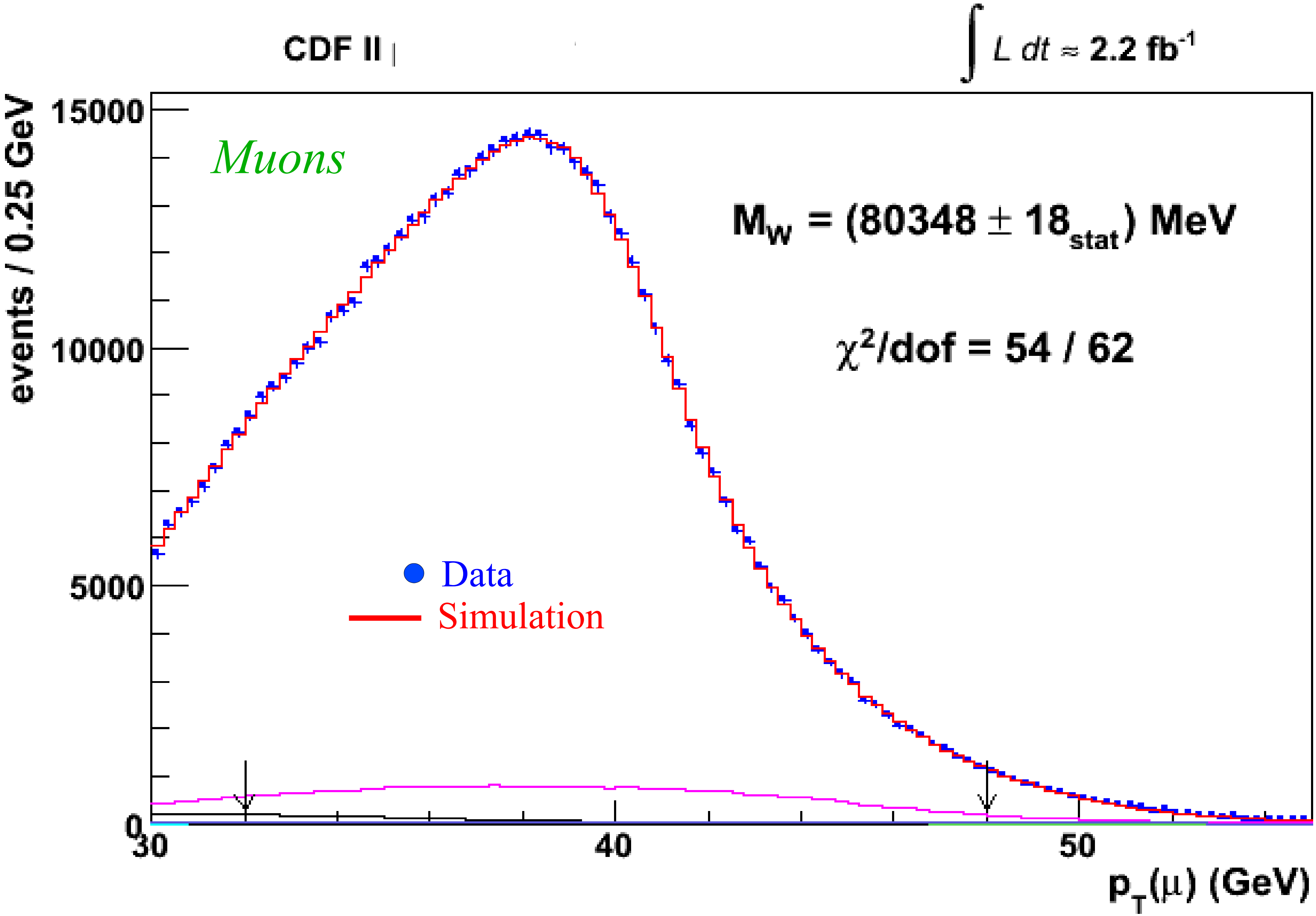
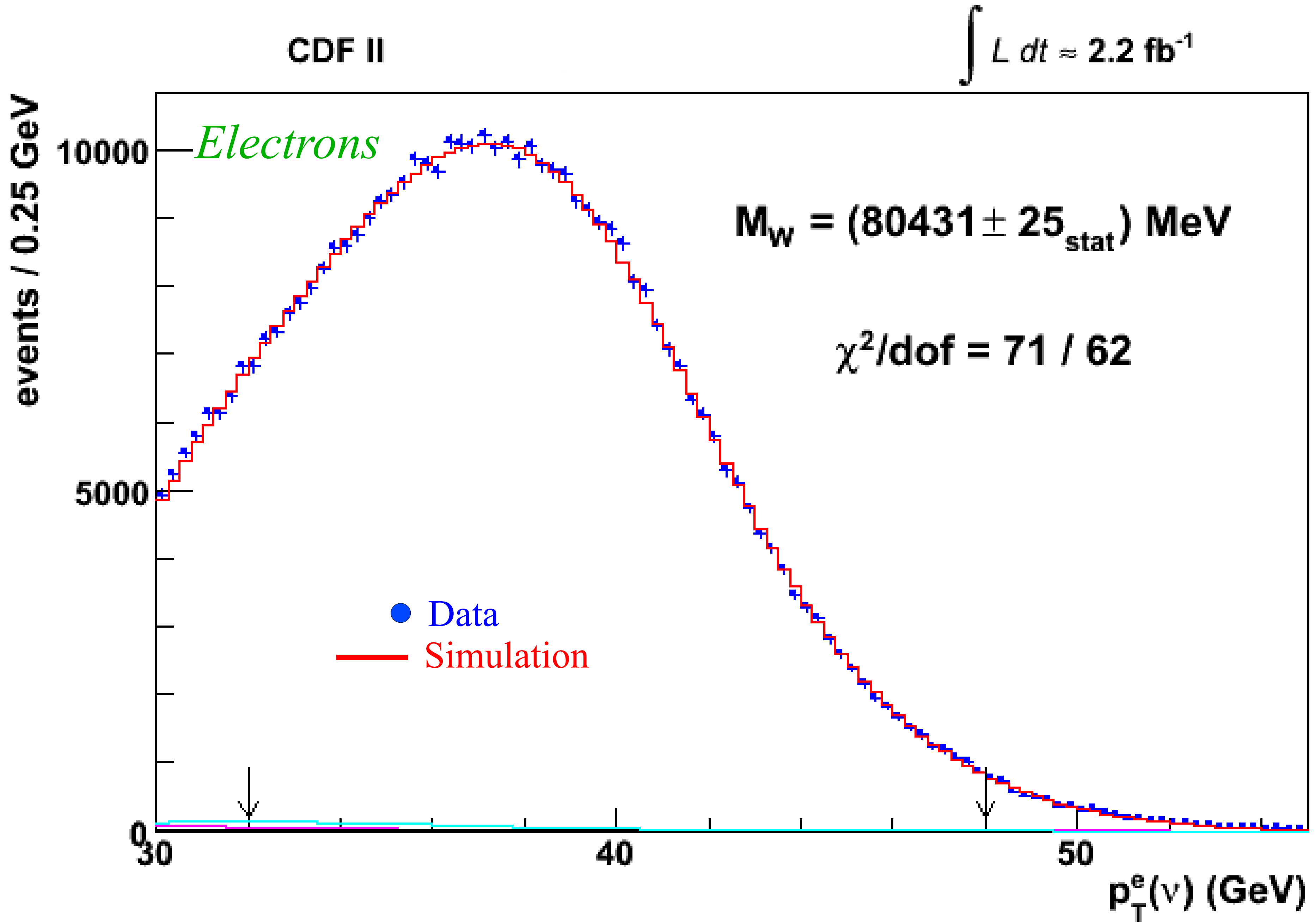
# *W* Transverse Mass Fit



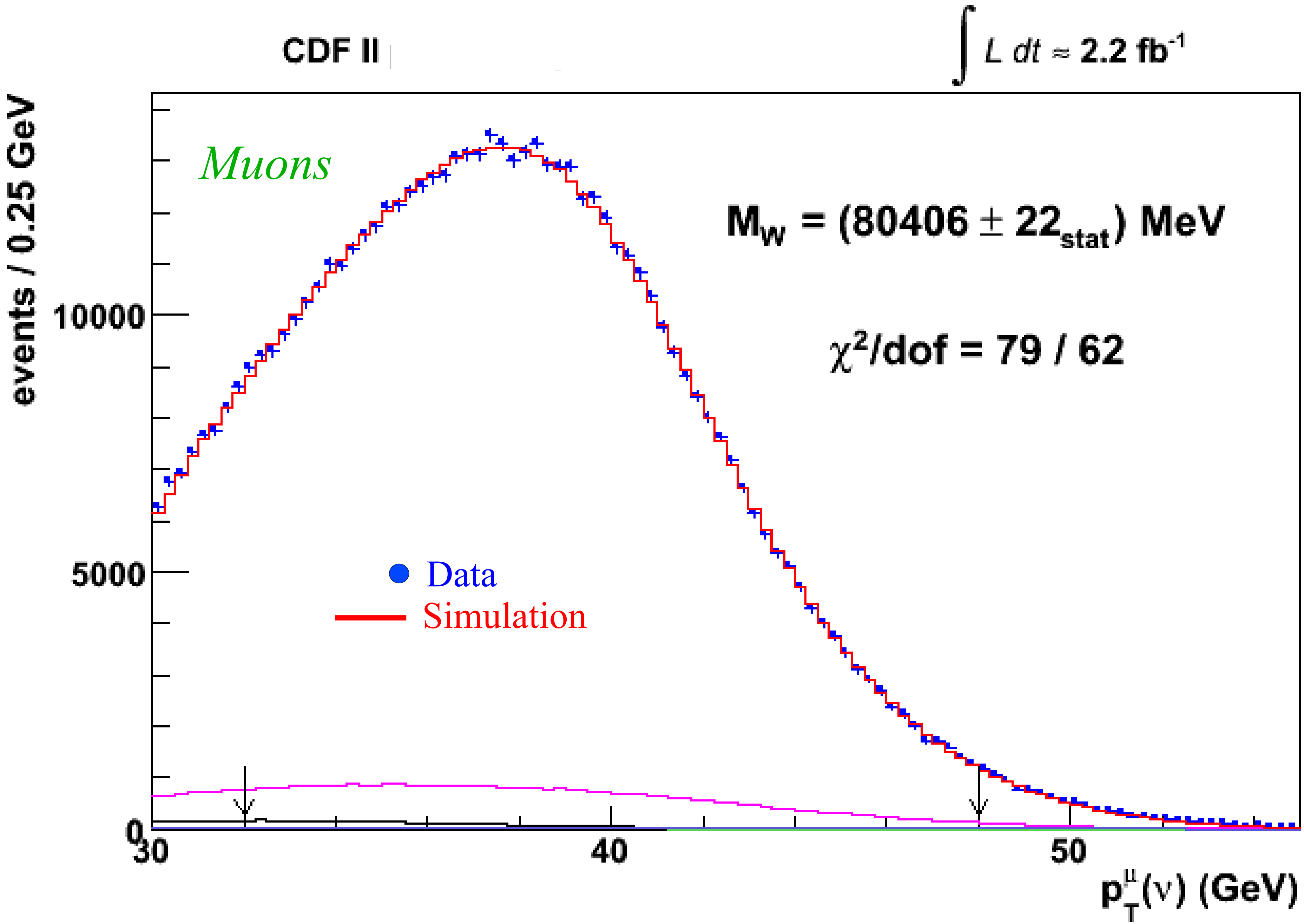
# *W* Lepton $p_T$ Fit



# *W* Missing $E_T$ Fit



# *W* Missing $E_T$ Fit



# Lepton Resolutions

- Tracking resolution parameterized in the custom simulation by
  - Radius-dependent drift chamber hit resolution $\sigma_h \sim (150 \pm 1_{stat})\ \mu m$
  - Beamspot size $\sigma_b = (35 \pm 1_{stat})\ \mu m$
  - 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

=> $\Delta M_W = 1$ MeV (muons)

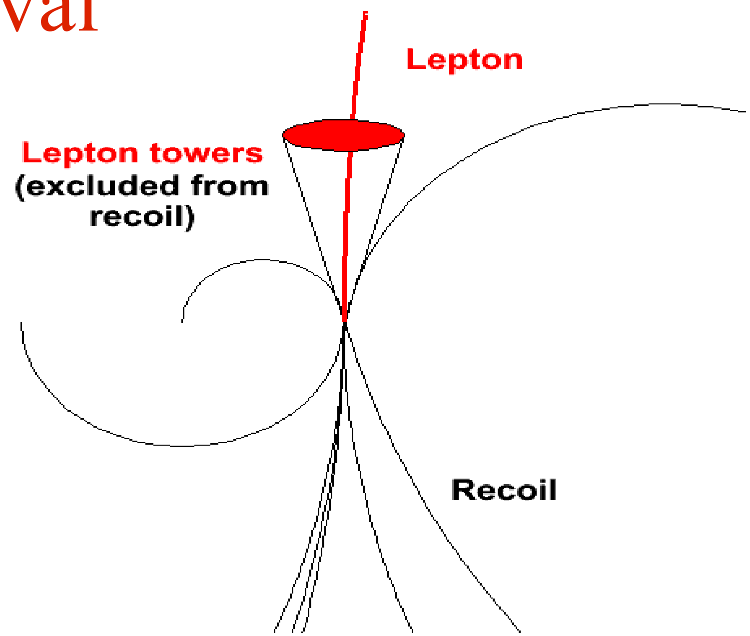
- Electron cluster resolution parameterized in the custom simulation by
  - $12.6\% / \sqrt{E_T}$ (sampling term)
  - Primary constant term $\kappa = (0.68 \pm 0.05_{stat})\ \%$
  - Secondary photon resolution $\kappa_\gamma = (7.4 \pm 1.8_{stat})\ \%$
  - Tuned on the widths of the E/p peak and the $Z \rightarrow ee$ peak (selecting radiative electrons)

=> $\Delta M_W = 4$ 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 $\phi$-rotated windows

$$\Delta M_W = 2\ \text{MeV}$$




## Electron channel W data

Electron Electromagnetic $E_T$(MeV)

| Tower $\Delta\eta$ ($\eta$) \ Tower $\Delta\phi$ ($\phi$) | -3 | -2 | -1 | 0 | 1 | 2 | 3 |
|---|---|---|---|---|---|---|---|
| 3 | 46 | 46 | 46 | 47 | 47 | 46 | 46 |
| 2 | 46 | 46 | 47 | 53 | 48 | 47 | 46 |
| 1 | 47 | 47 | 50 | 1219 | 73 | 48 | 47 |
| 0 | 47 | 50 | 63 | 38443 | 161 | 53 | 48 |
| -1 | 46 | 46 | 47 | 164 | 51 | 47 | 46 |
| -2 | 46 | 46 | 47 | 47 | 47 | 45 | 46 |
| -3 | 45 | 46 | 46 | 46 | 46 | 45 | 45 |

## Muon channel W data

Muon Hadronic $E_T$ (MeV)

| Tower $\Delta\eta$ ($\eta$) \ Tower $\Delta\phi$ ($\phi$) | -3 | -2 | -1 | 0 | 1 | 2 | 3 |
|---|---|---|---|---|---|---|---|
| 3 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| 2 | 12 | 12 | 12 | 13 | 12 | 11 | 12 |
| 1 | 12 | 12 | 12 | 406 | 13 | 12 | 12 |
| 0 | 12 | 12 | 12 | 1282 | 14 | 12 | 12 |
| -1 | 12 | 12 | 12 | 75 | 12 | 12 | 12 |
| -2 | 12 | 12 | 11 | 12 | 12 | 11 | 11 |
| -3 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |

# Backgrounds in the W sample

## Muons

| Background | % of $W \to \mu\nu$ data | $\delta m_W$ (MeV) | | |
|---|---|---|---|---|
| | | $m_T$ fit | $p_T^\mu$ fit | $p_T^\nu$ fit |
| $Z \to \mu\mu$ | $7.35 \pm 0.09$ | 2 | 4 | 5 |
| $W \to \tau\nu$ | $0.880 \pm 0.004$ | 0 | 0 | 0 |
| QCD | $0.035 \pm 0.025$ | 1 | 1 | 1 |
| DIF | $0.24 \pm 0.08$ | 1 | 3 | 1 |
| Cosmic rays | $0.02 \pm 0.02$ | 1 | 1 | 1 |
| Total | | 3 | 5 | 6 |

## Electrons

| Background | % of $W \to e\nu$ data | $\delta m_W$ (MeV) | | |
|---|---|---|---|---|
| | | $m_T$ fit | $p_T^e$ fit | $p_T^\nu$ fit |
| $Z \to ee$ | $0.139 \pm 0.014$ | 1 | 2 | 1 |
| $W \to \tau\nu$ | $0.93 \pm 0.01$ | 1 | 1 | 1 |
| QCD | $0.39 \pm 0.14$ | 4 | 2 | 4 |
| Total | | 4 | 3 | 4 |

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

# *W* Mass Fit Results

- Electron and muon $m_T$ fits combined

  **$m_W$ = 80390 ± 20 MeV,** $\chi^2$/dof = 1.2/1 (28%)

- Electron and muon $p_T$ fits combined

  **$m_W$ = 80366 ± 22 MeV,** $\chi^2$/dof = 2.3/1 (13%)

- Electron and muon MET fits combined

  **$m_W$ = 80416 ± 25 MeV,** $\chi^2$/dof = 0.5/1 (49%)

- All electron fits combined

  **$m_W$ = 80406 ± 25 MeV,** $\chi^2$/dof = 1.4/2 (49%)

- All muon fits combined

  **$m_W$ = 80374 ± 22 MeV,** $\chi^2$/dof = 4/2 (12%)

- All fits combined

  **$m_W$ = 80387 ± 19 MeV,** $\chi^2$/dof = 6.6/5 (25%)

# $p_T(l)$ Fit Systematic Uncertainties

| Systematic (MeV/$c^2$) | Electrons | Muons | Common |
|---|---|---|---|
| Lepton Energy Scale | 10 | 7 | 5 |
| Lepton Energy Resolution | 4 | 1 | 0 |
| Recoil Energy Scale | 6 | 6 | 6 |
| Recoil Energy Resolution | 5 | 5 | 5 |
| $u_{\|\|}$ efficiency | 2 | 1 | 0 |
| Lepton Removal | 0 | 0 | 0 |
| Backgrounds | 3 | 5 | 0 |
| $p_T(W)$ model | 9 | 9 | 9 |
| Parton Distributions | 9 | 9 | 9 |
| QED radiation | 4 | 4 | 4 |
| Total | 19 | 18 | 16 |