# Electroweak Physics


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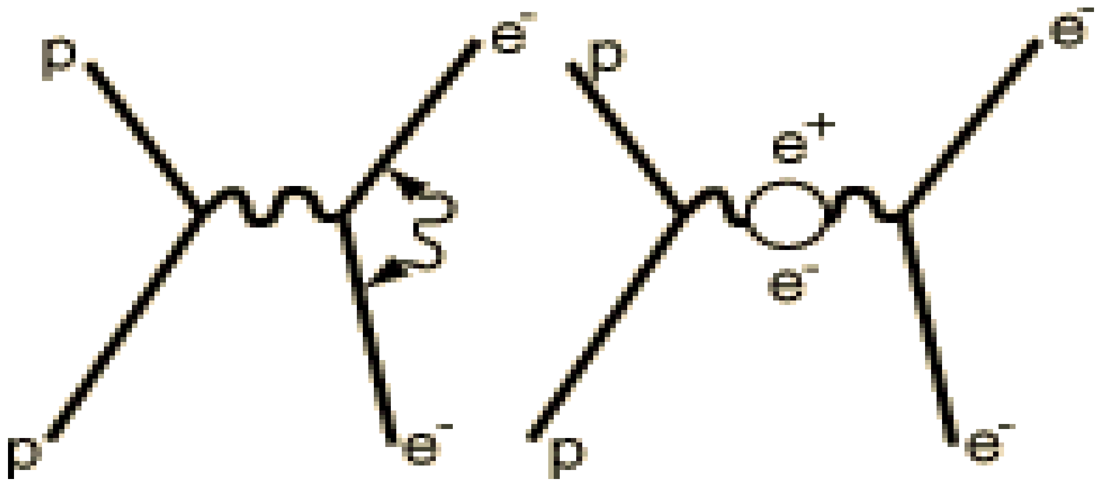
HEP 101
Duke University
March 27, 2017

# Detecting New Physics through Precision Measurements

- Willis Lamb (Nobel Prize 1955) measured the difference between energies of $^2S_{½}$ and $^2P_{½}$ 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

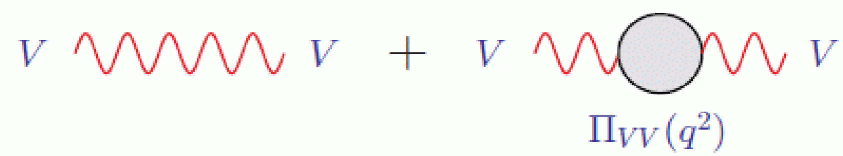
At tree level, all of the observables can be expressed in terms of *three* parameters of the SM Lagrangian: $v,\ g,\ g'$ or, equivalently, $v,\ e,\ s \equiv \sin\theta_W$ (also $c \equiv \cos\theta_W$)

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

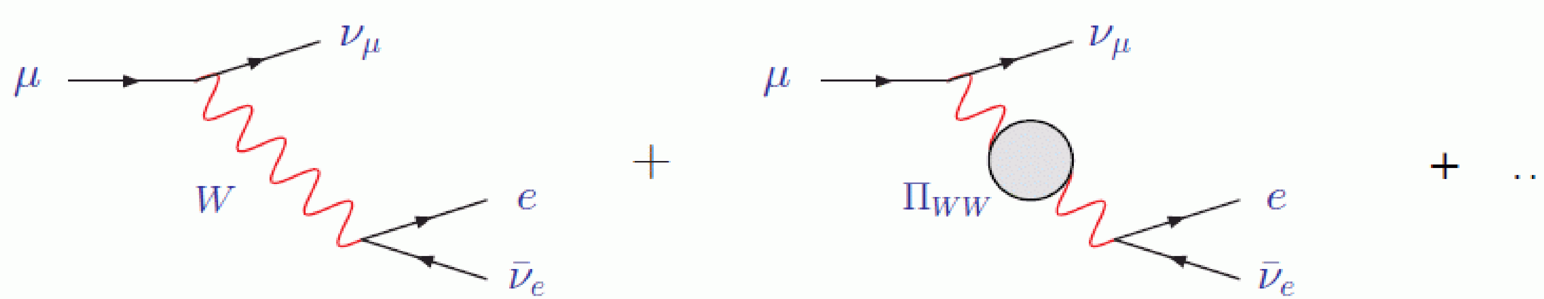
Radiative corrections to the relations between physical observables and Lagrangian params:

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

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

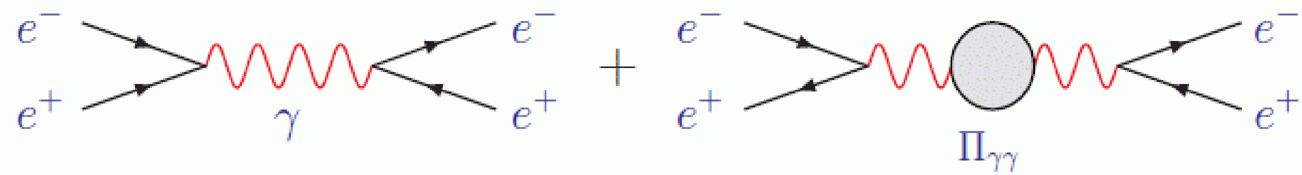



$$G_F = \frac{1}{2\sqrt{2}v^2}\left[1 - \frac{\Pi_{WW}(0)}{m_W^2} + \delta_{\rm VB}\right]$$



# 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: $R_{\rm had}(q^2) = \dfrac{\sigma_{\rm had}(q^2)}{\sigma_{\ell^+\ell^-}(q^2)}$

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

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

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

(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:

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

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

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

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

# Motivation for Precision Measurements

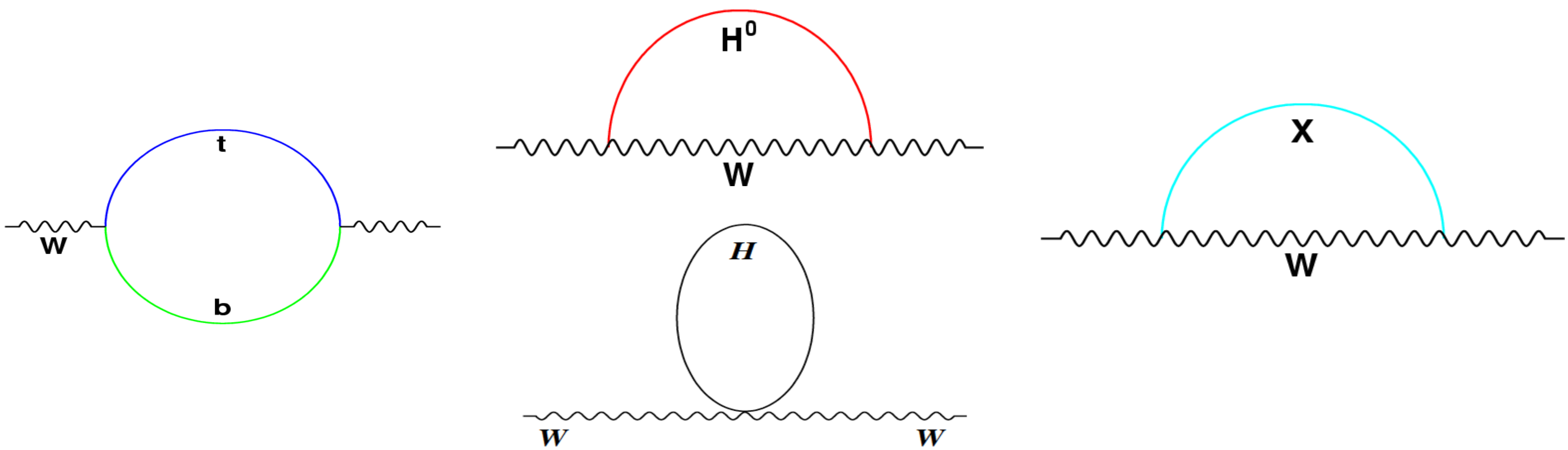
- The electroweak gauge sector of the standard model is constrained by three precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\ (1) \times 10^{-5}\ \mathrm{GeV}^{-2}$

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

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

# Motivation for Precision Measurements

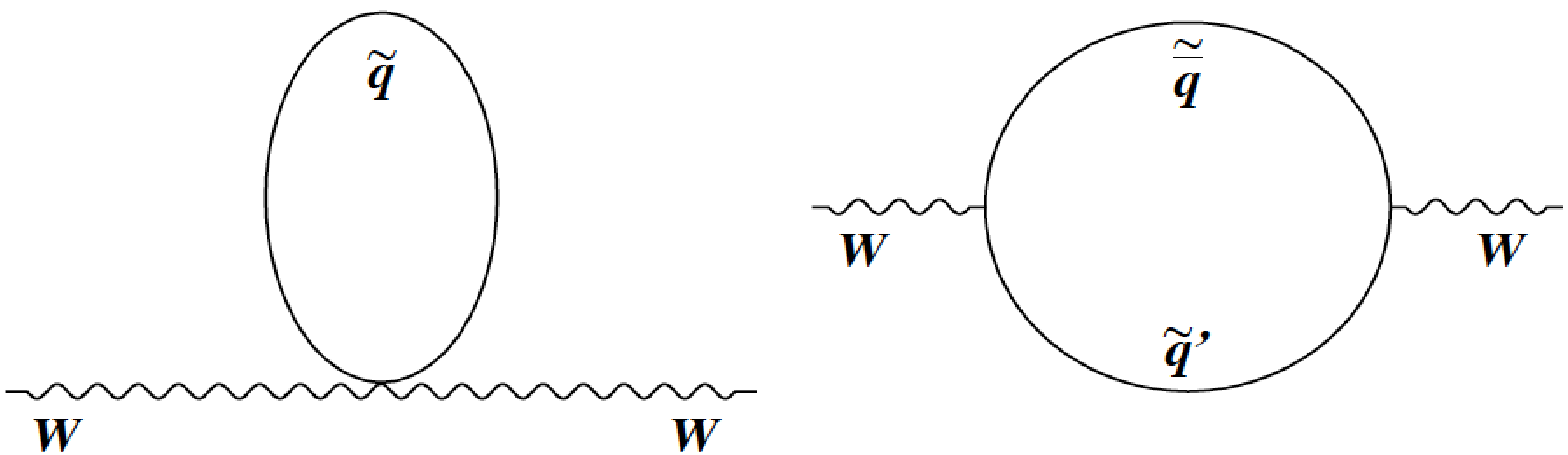
- Radiative corrections due to heavy quark and Higgs loops and exotica




Motivate the introduction of the ρ parameter: $M_W^2 = \rho\, [M_W(\text{tree})]^2$
with the predictions $\Delta\rho = (\rho 21)\ \gamma\ \int_{top}^{2}$ and $\Delta\rho\ \gamma\ \ln M_H$

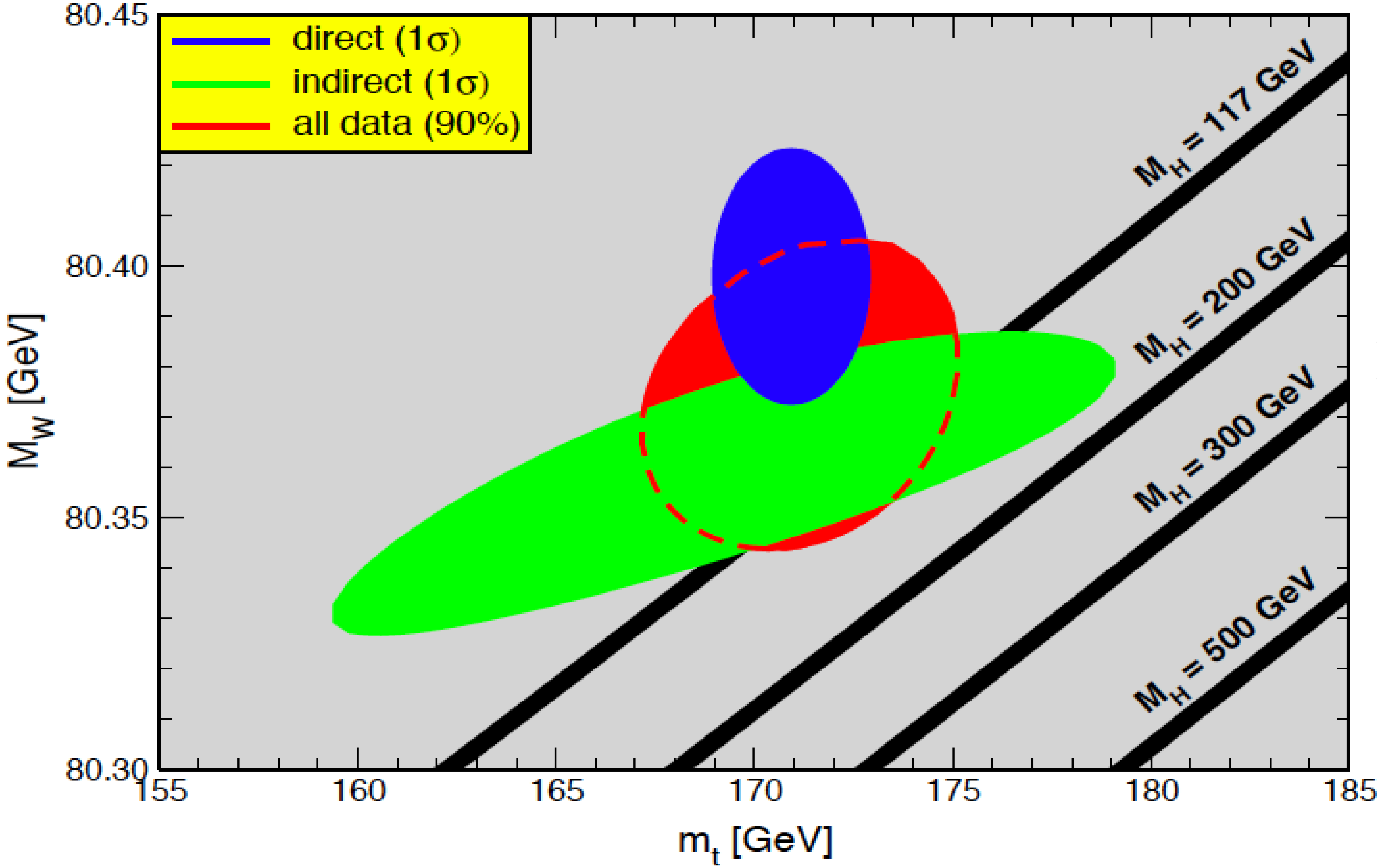
- In conjunction with $M_{top}$, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

# 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 $M_W$

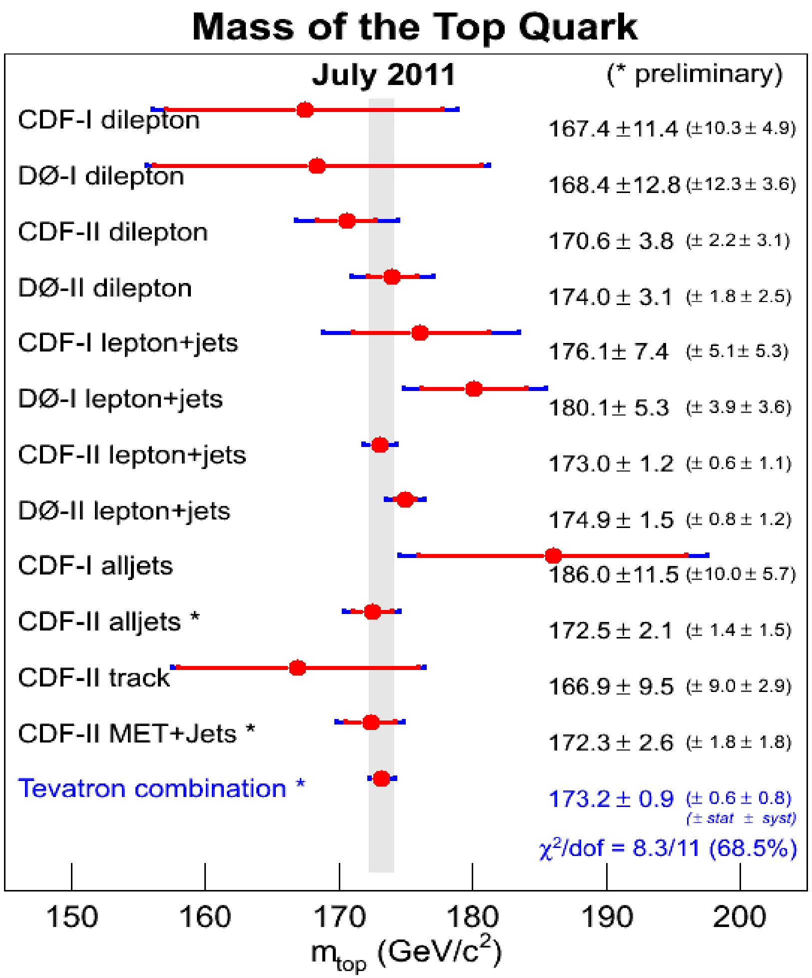
# Uncertainty from $\alpha_{EM}(M_Z)$




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

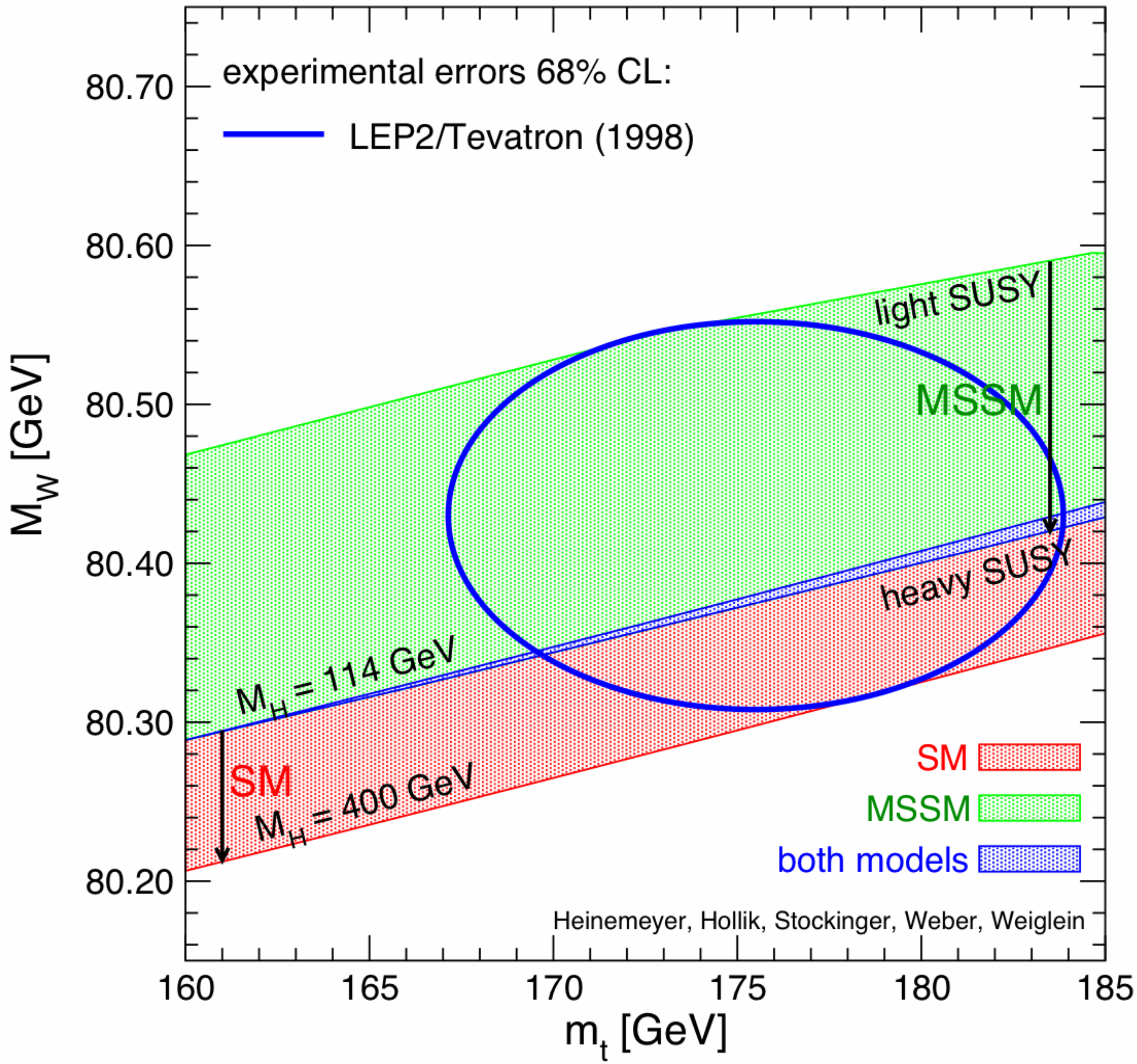
- $\delta\alpha_{EM}$ dominated by uncertainty from non-perturbative contributions: hadronic loops in photon propagator at low $Q^2$
- equivalent $\delta M_W \approx 4$ MeV for the same Higgs mass constraint
  - Was equivalent $\delta M_W \approx 15$ MeV a decade ago !

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

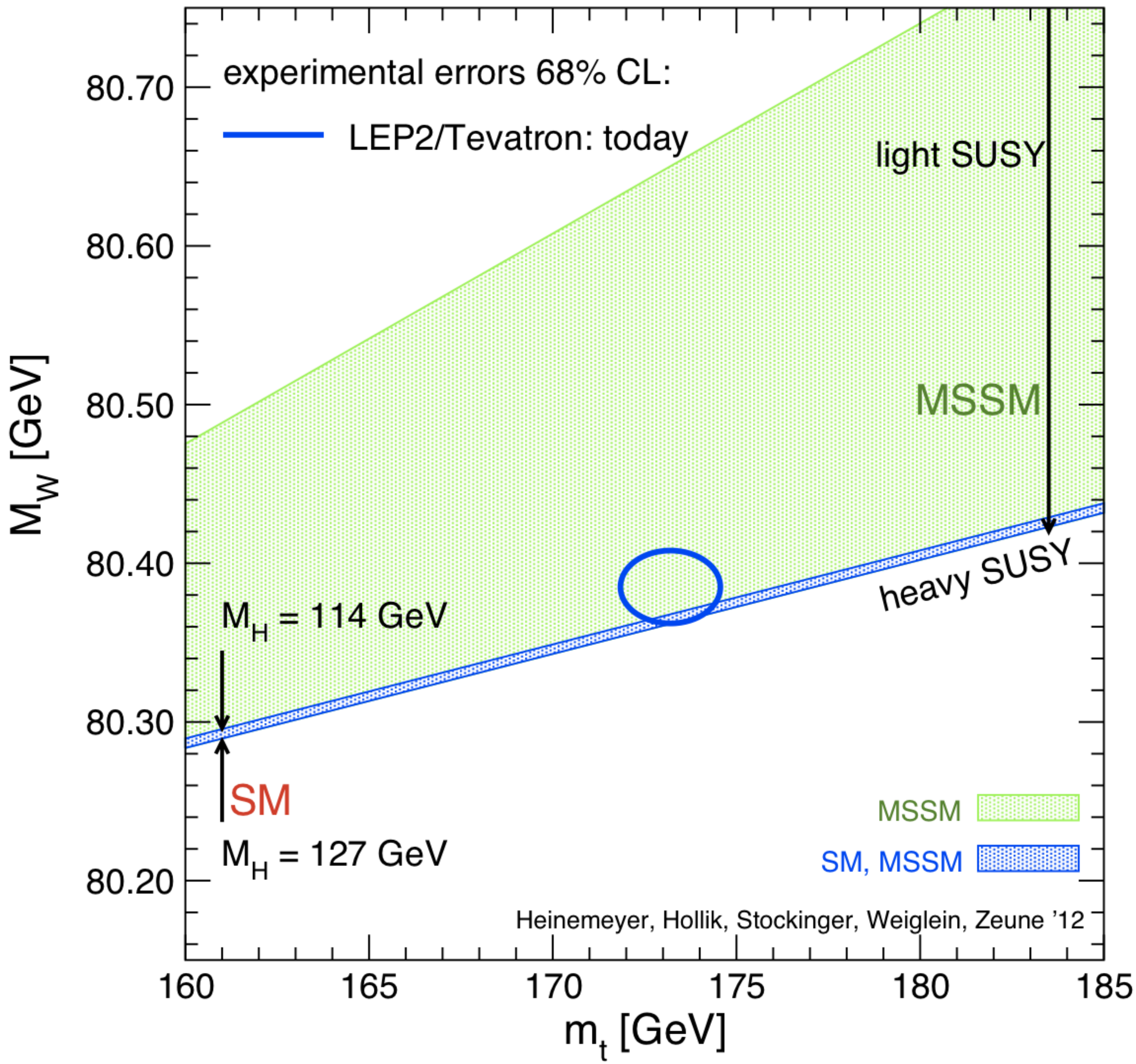



- From the Tevatron, $\Delta M_{top} = 0.9$ GeV => $\Delta M_H / M_H = 8\%$
- equivalent $\Delta M_W = 6$ MeV for the same Higgs mass constraint
- Current world average $\Delta M_W = 15$ MeV
  - progress on $\Delta M_W$ has the biggest impact on Higgs constraint

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

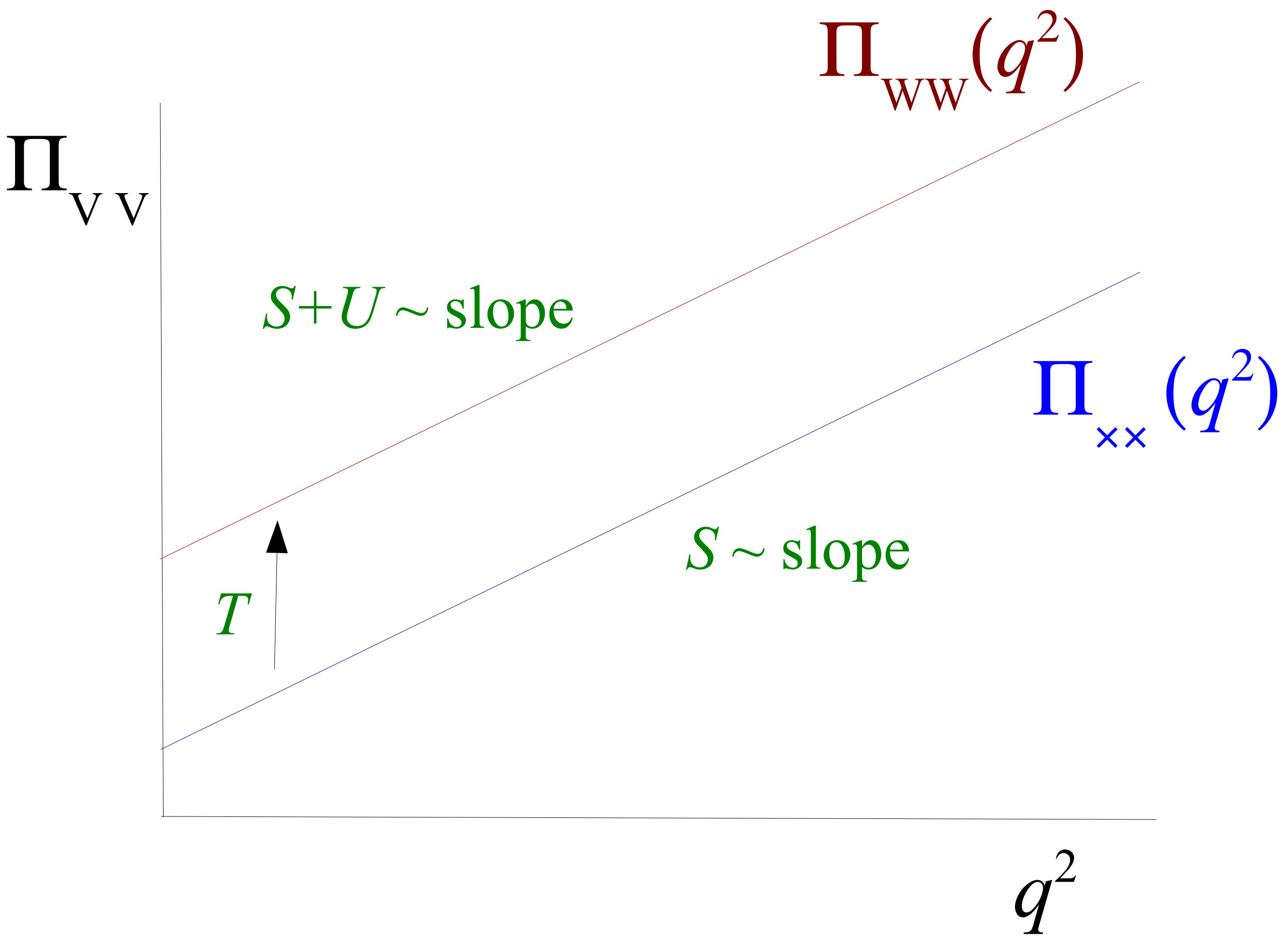


# 2012 Status of $M_W$ *vs* $M_{top}$



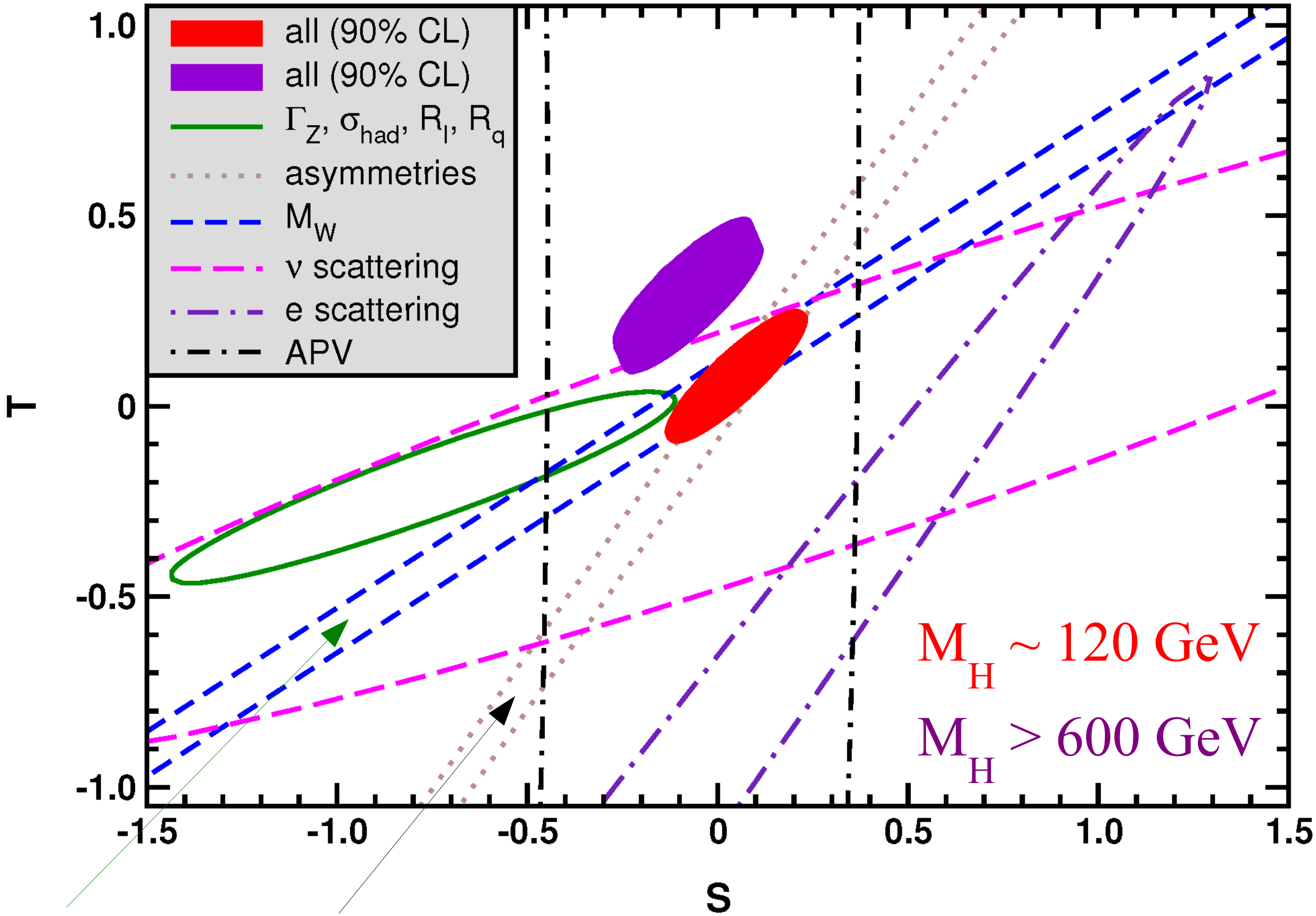
# Motivation

- 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)



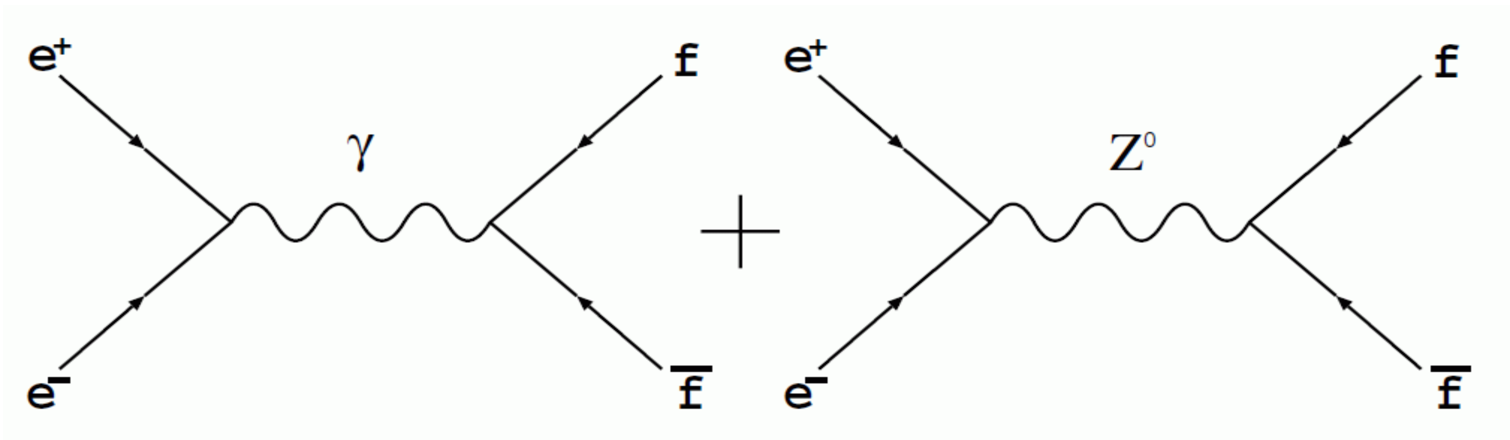

Additionally, $M_W$ is the only measurement which constrains *U*

(from P. Langacker, 2012)

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

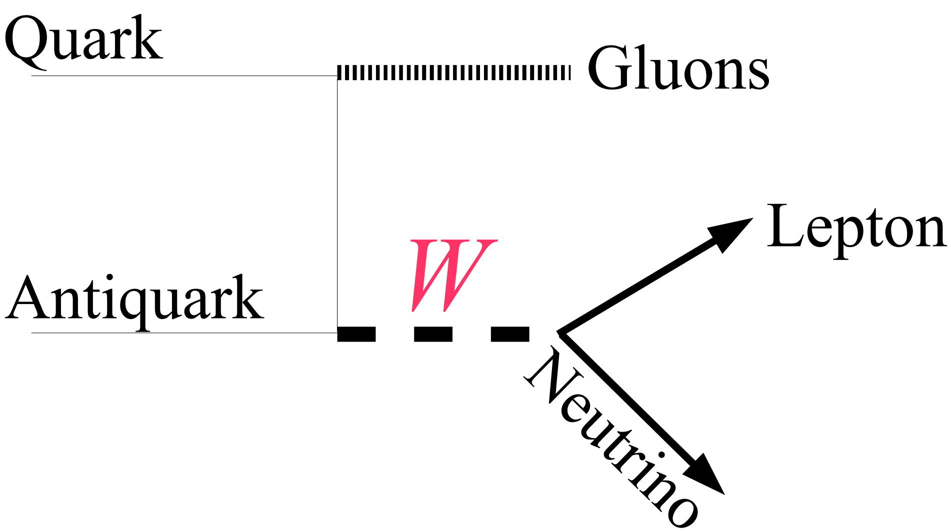
# $A_{FB}$ and $A_{LR}$ Observables

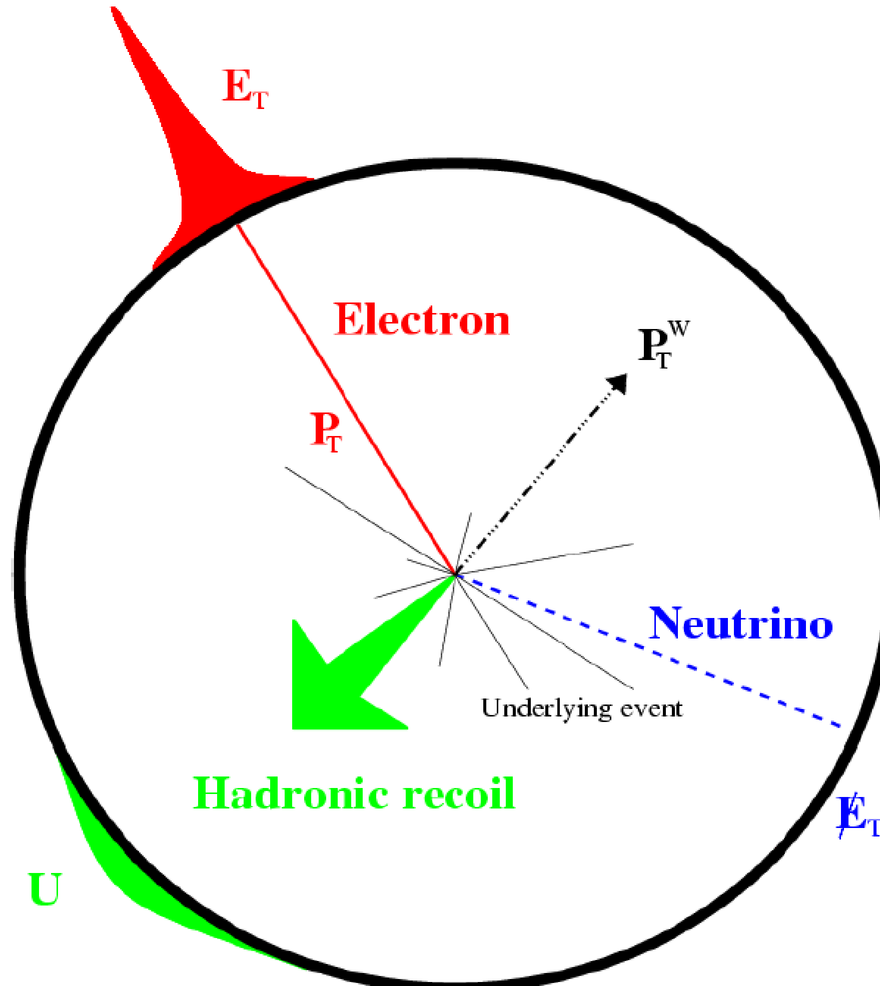
- Asymmetries definable in electron-positron scattering sensitive to Weinberg mixing angle $\vartheta_W$




- 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



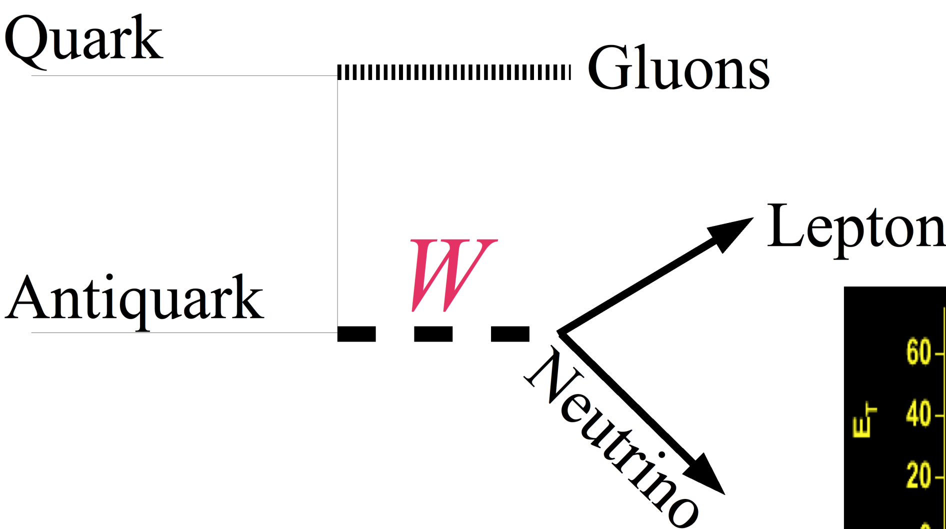

Quark-antiquark annihilation dominates (80%)

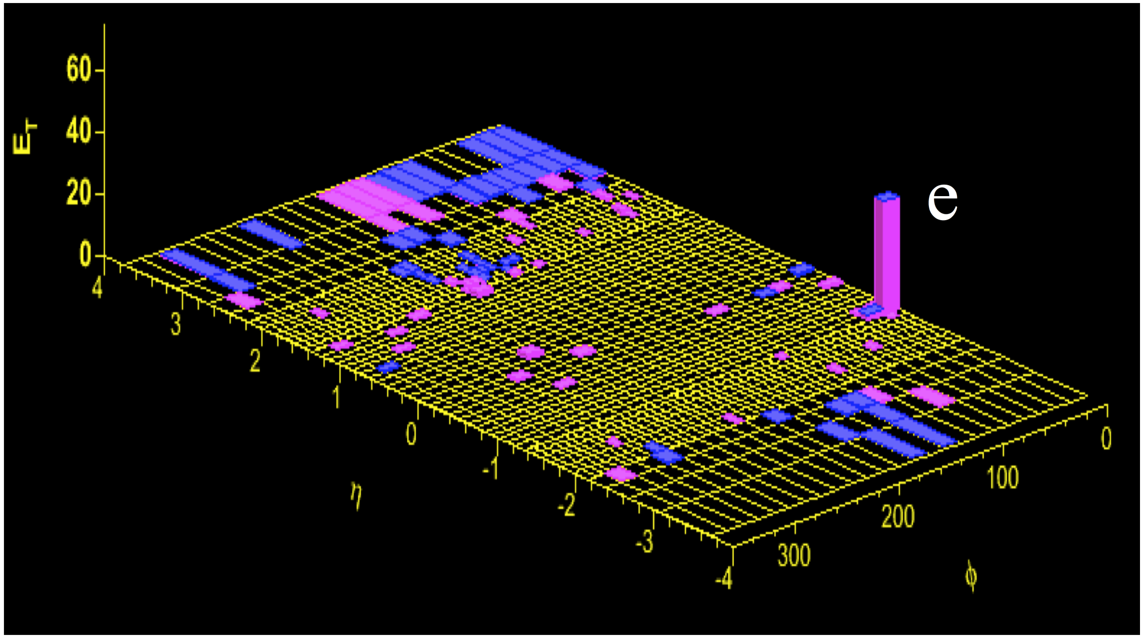
Lepton $p_T$ carries most of *W* mass information, can be measured precisely (achieved 0.01%)

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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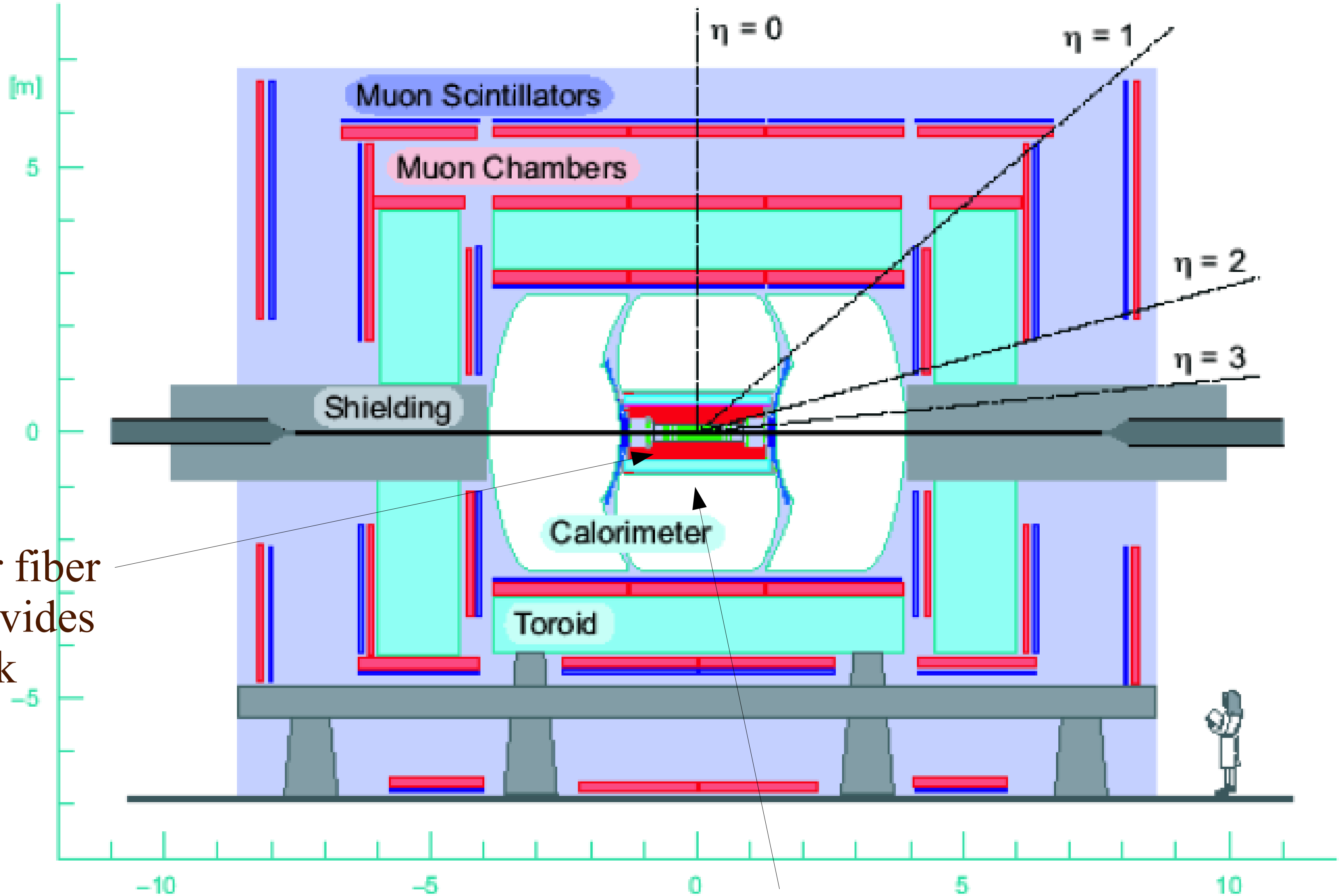
# D0 Detector at Fermilab



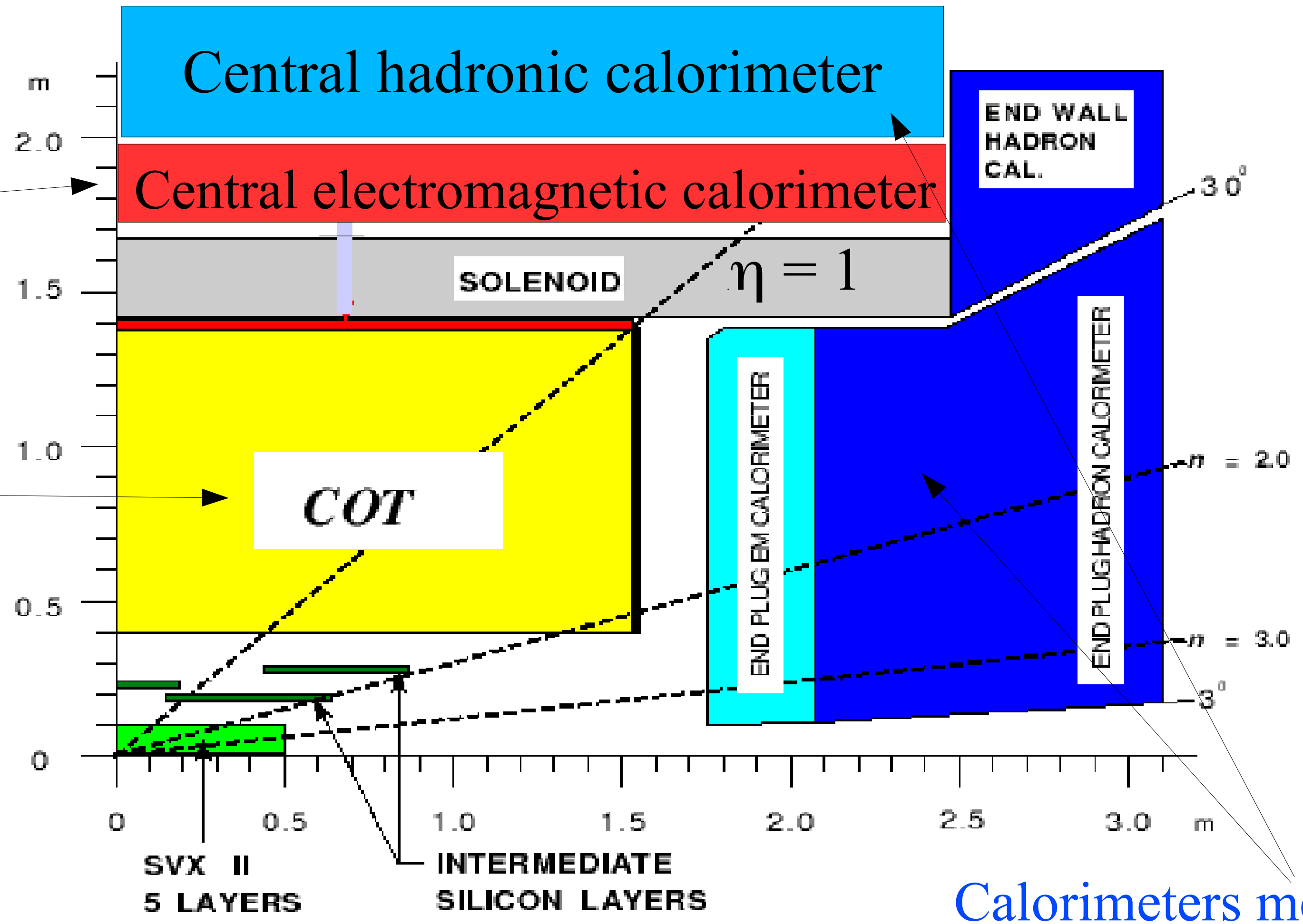

Scintillator fiber tracker provides lepton track direction

Electromagnetic Calorimeter measures electron energy
Hadronic calorimeters measure recoil particles

# Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

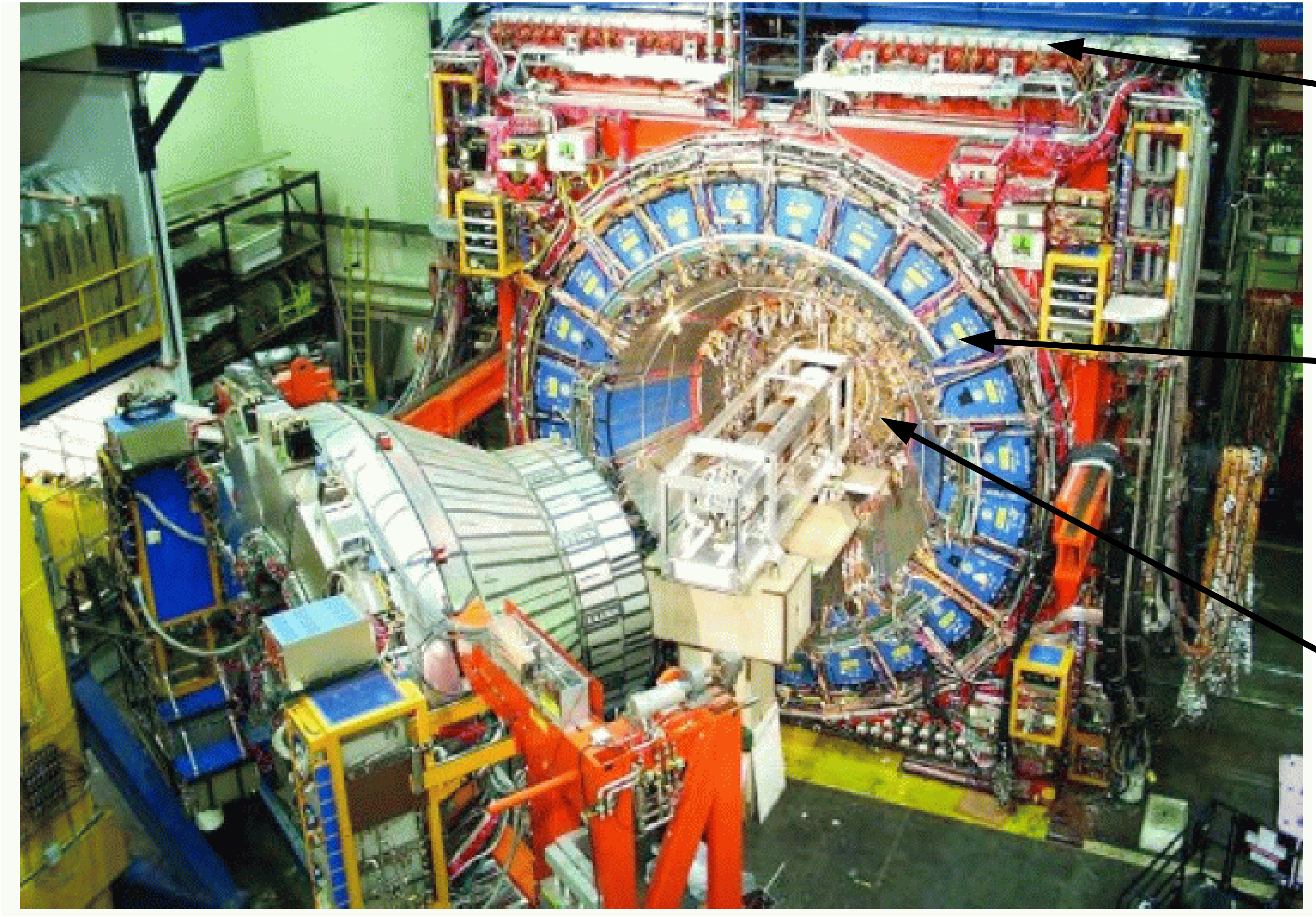
Drift chamber provides precise lepton track momentum measurement




Calorimeters measure hadronic recoil particles

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

# Collider Detector at Fermilab (CDF)

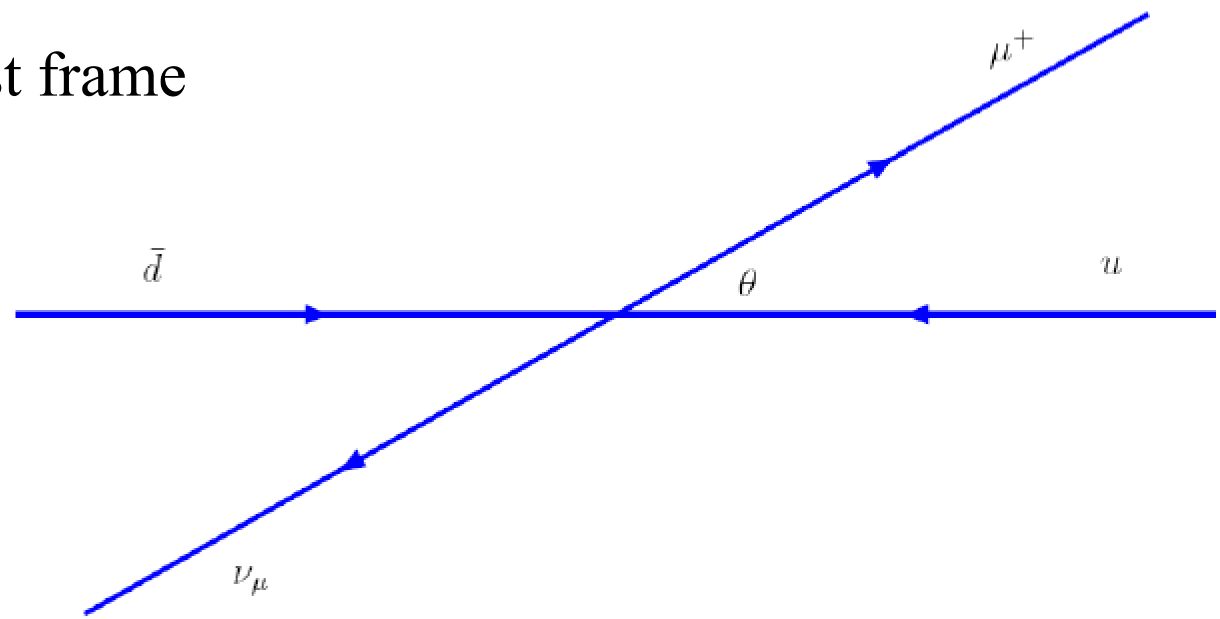


# W mass measurement – decay kinematics

- 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

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

W boson rest frame



# W mass measurement – decay kinematics

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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

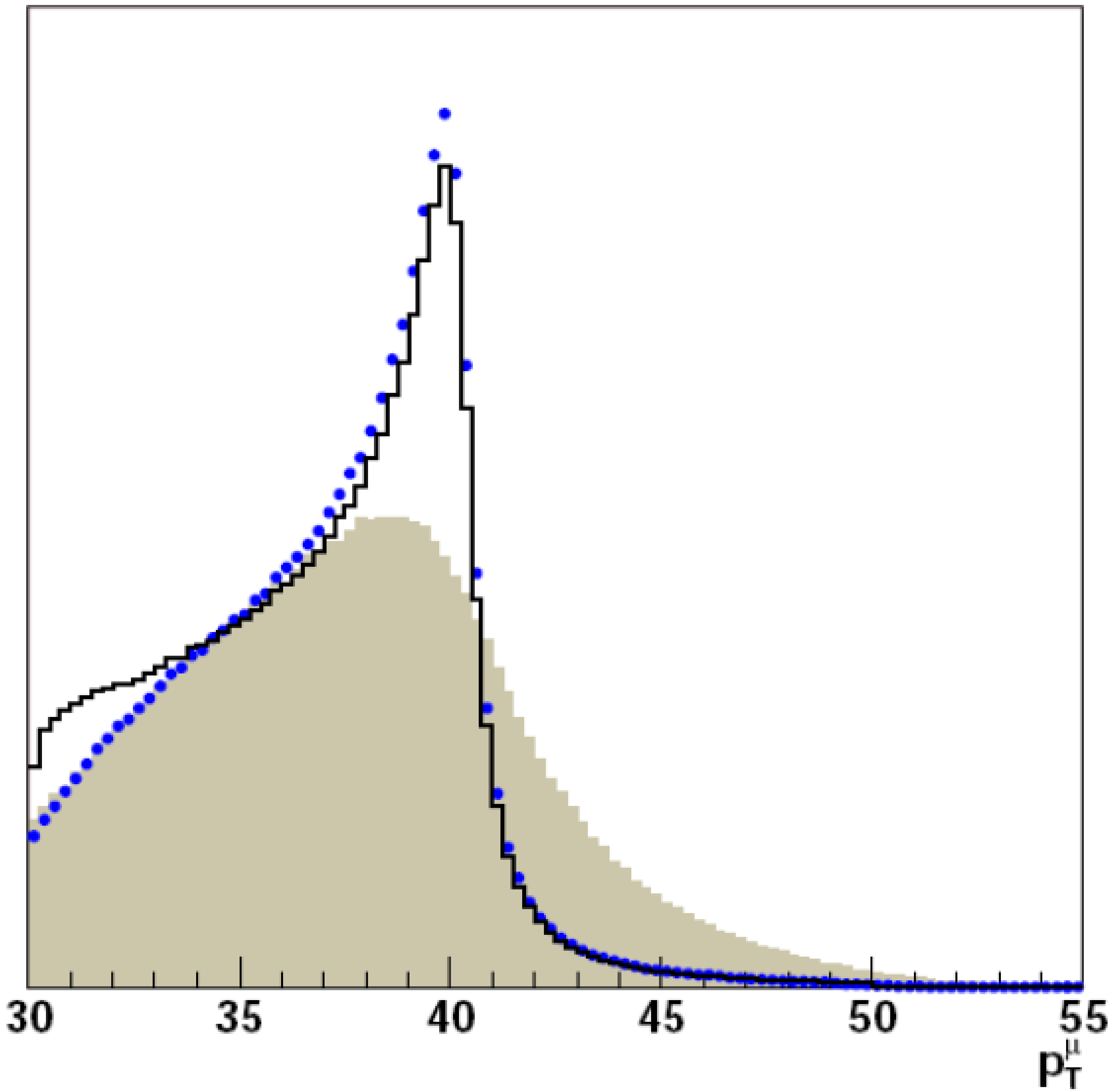
- Main complication: invariant mass cannot be reconstructed from 2-body leptonic decay mode
  - Because neutrino is not detectable directly
- Exploit the "Jacobian edge" in lepton transverse momentum spectrum

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

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

# W mass measurement – decay kinematics

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



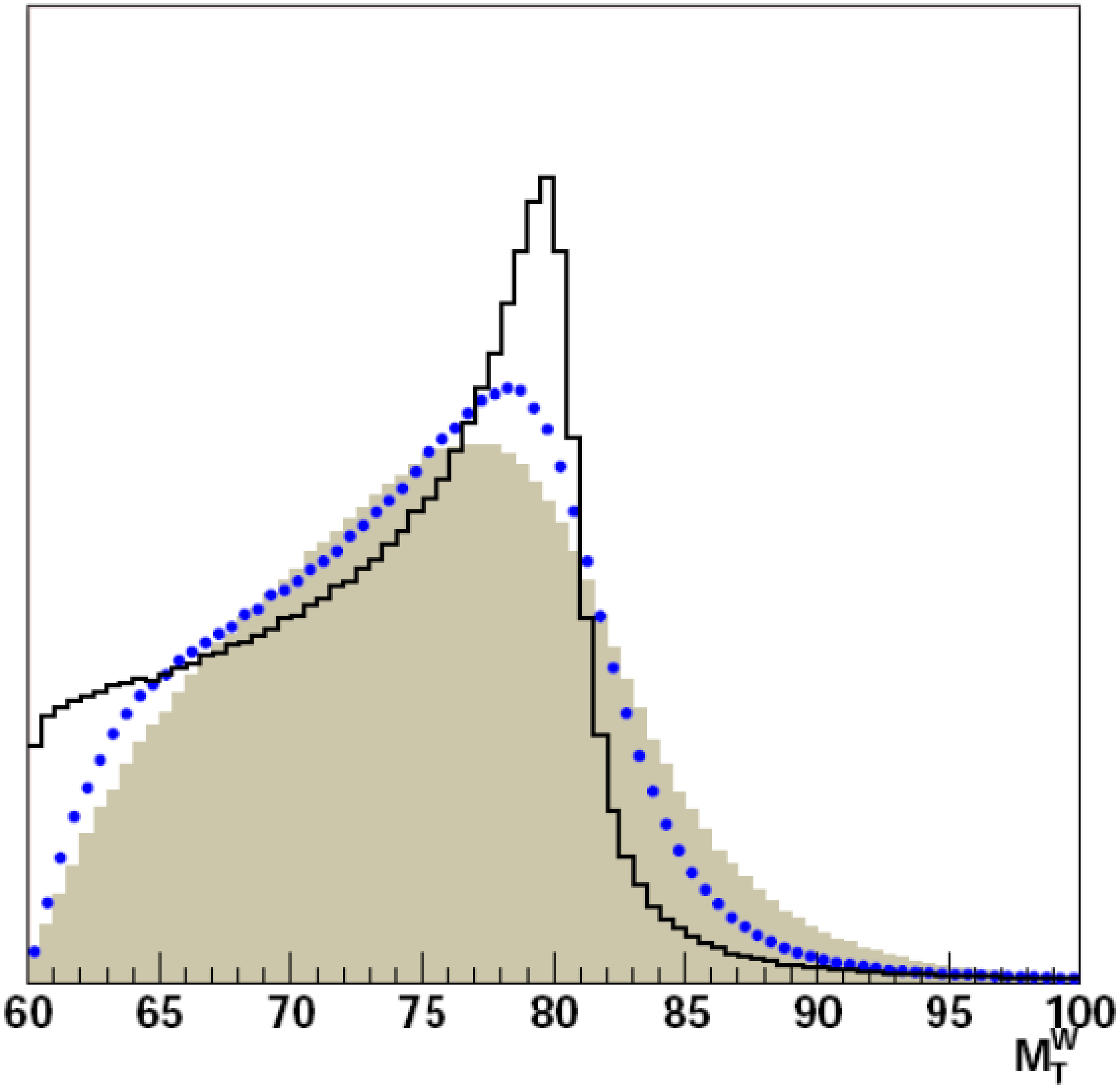

Black curve: truth level, no $p_T(W)$

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




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 $p_T(W)$

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

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

# 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 |
|---|---|
| $W \rightarrow e\nu$ | 470126 |
| $W \rightarrow \mu\nu$ | 624708 |
| $Z \rightarrow e^+e^-$ | 16134 |
| $Z \rightarrow \mu^+\mu^-$ | 59738 |

- Integrated Luminosity (collected between February 2002 – August 2007):
  - Electron and muon channels: $\mathcal{L}$ = 2.2 $fb^{-1}$
  - 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*

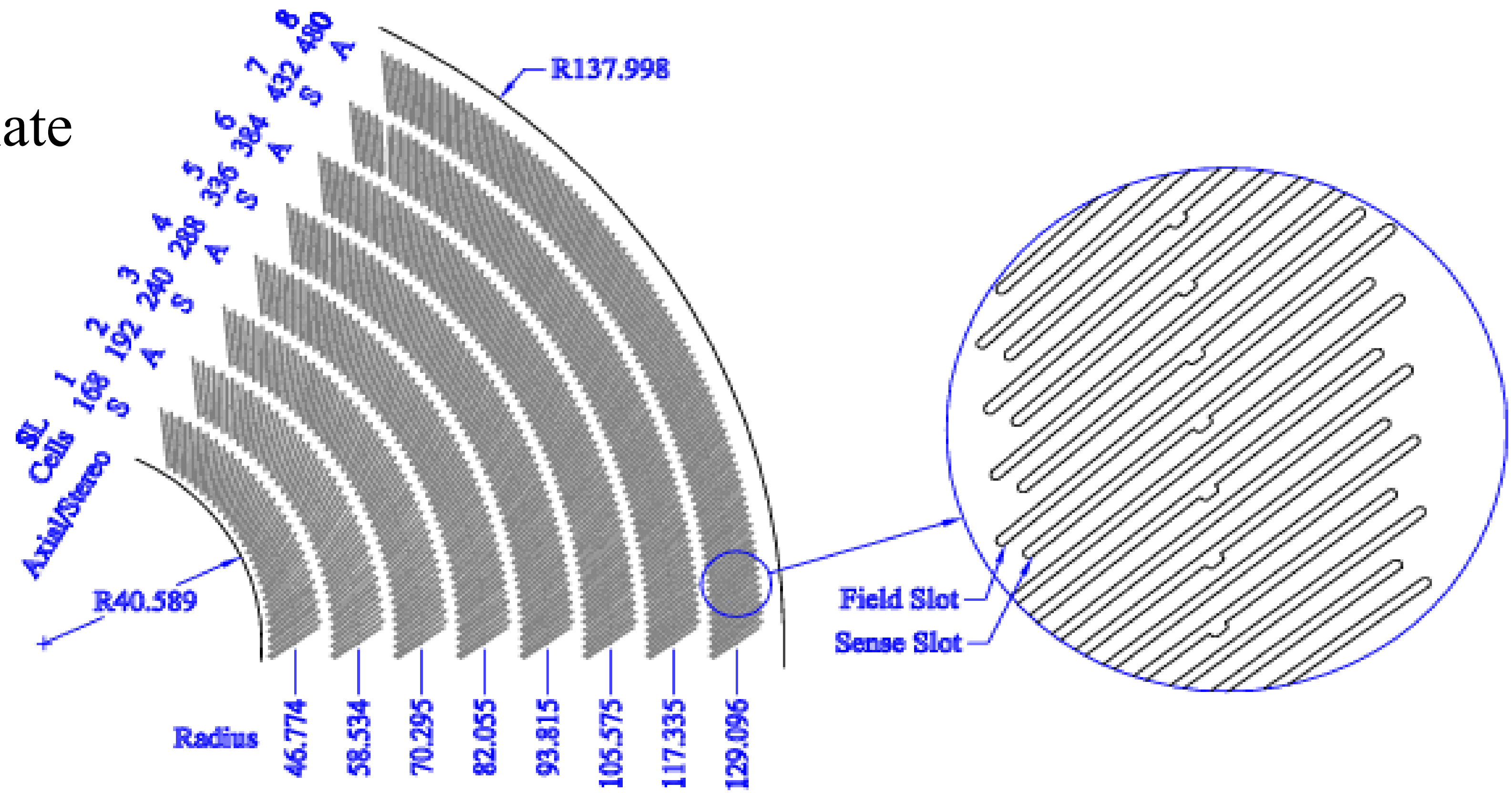
# Outline of Analysis

*Energy scale measurements drive the W mass measurement*

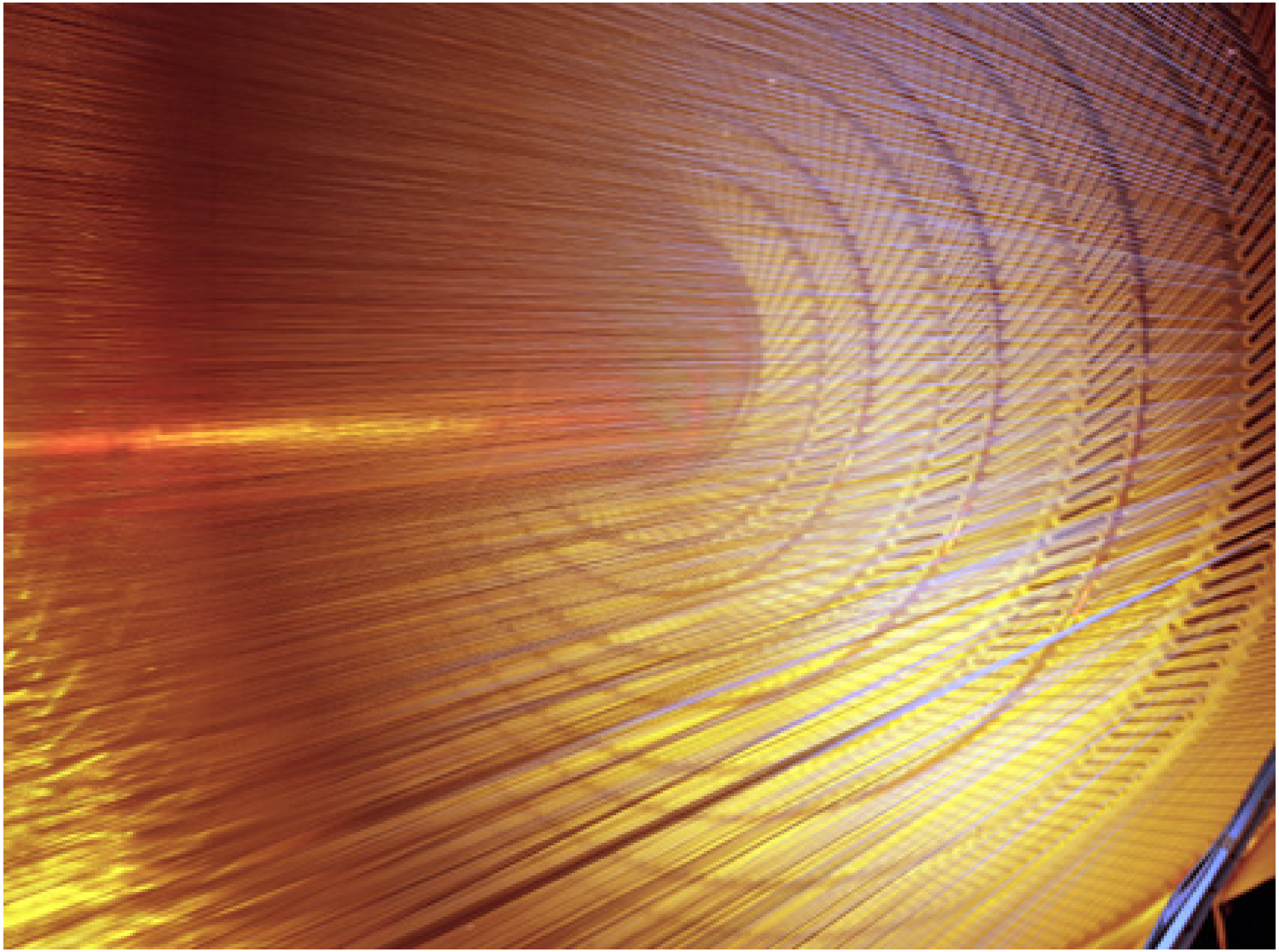
- Tracker Calibration
  - alignment of the COT (~2400 cells) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
  - Confirmed using $Z \rightarrow \mu\mu$ mass fit
- EM Calorimeter Calibration
 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

# Drift Chamber (COT) Alignment

COT endplate geometry



# CDF Particle Tracking Chamber



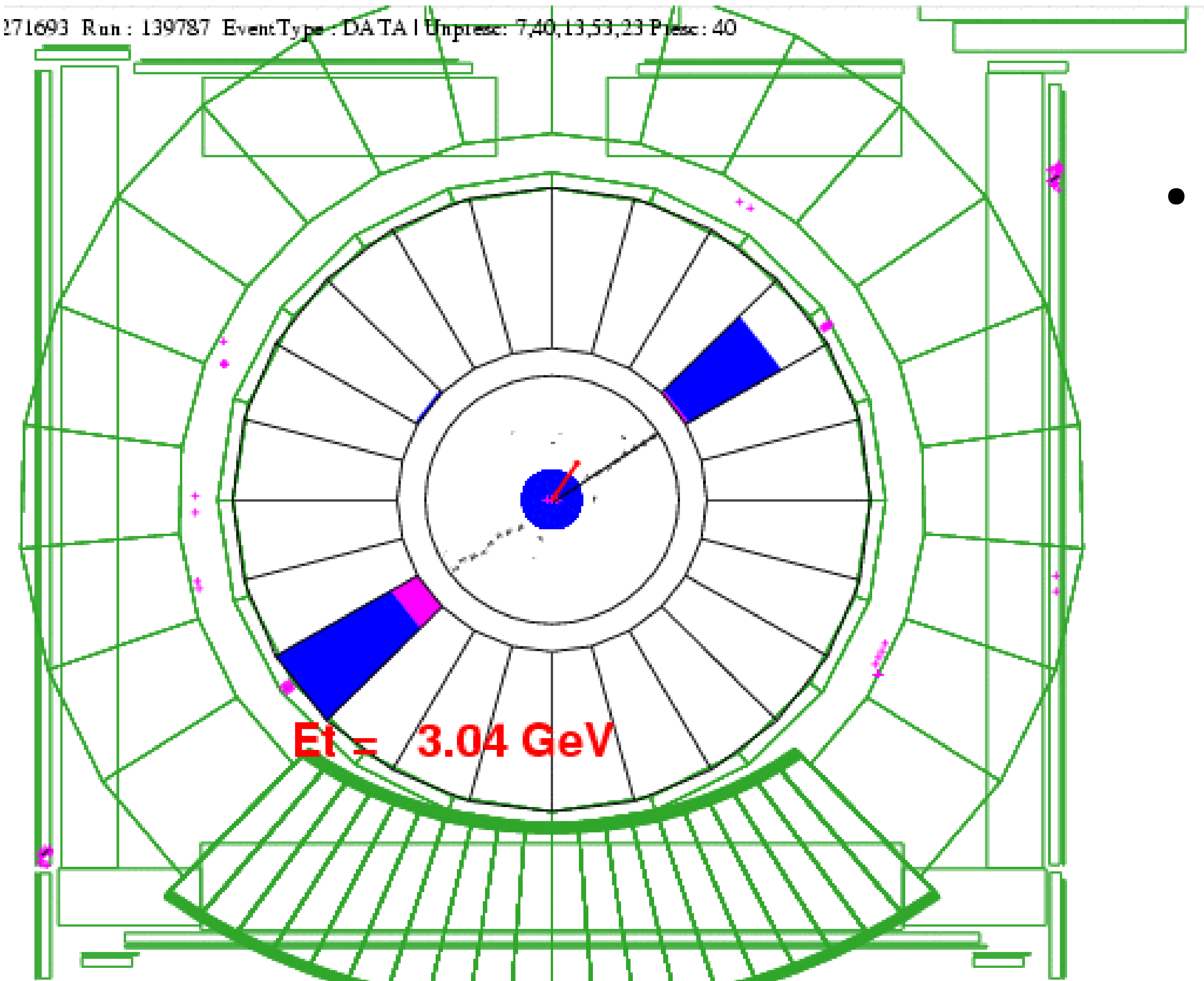
Reconstruction of particle trajectories, calibration to ~2 μm accuracy:

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

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

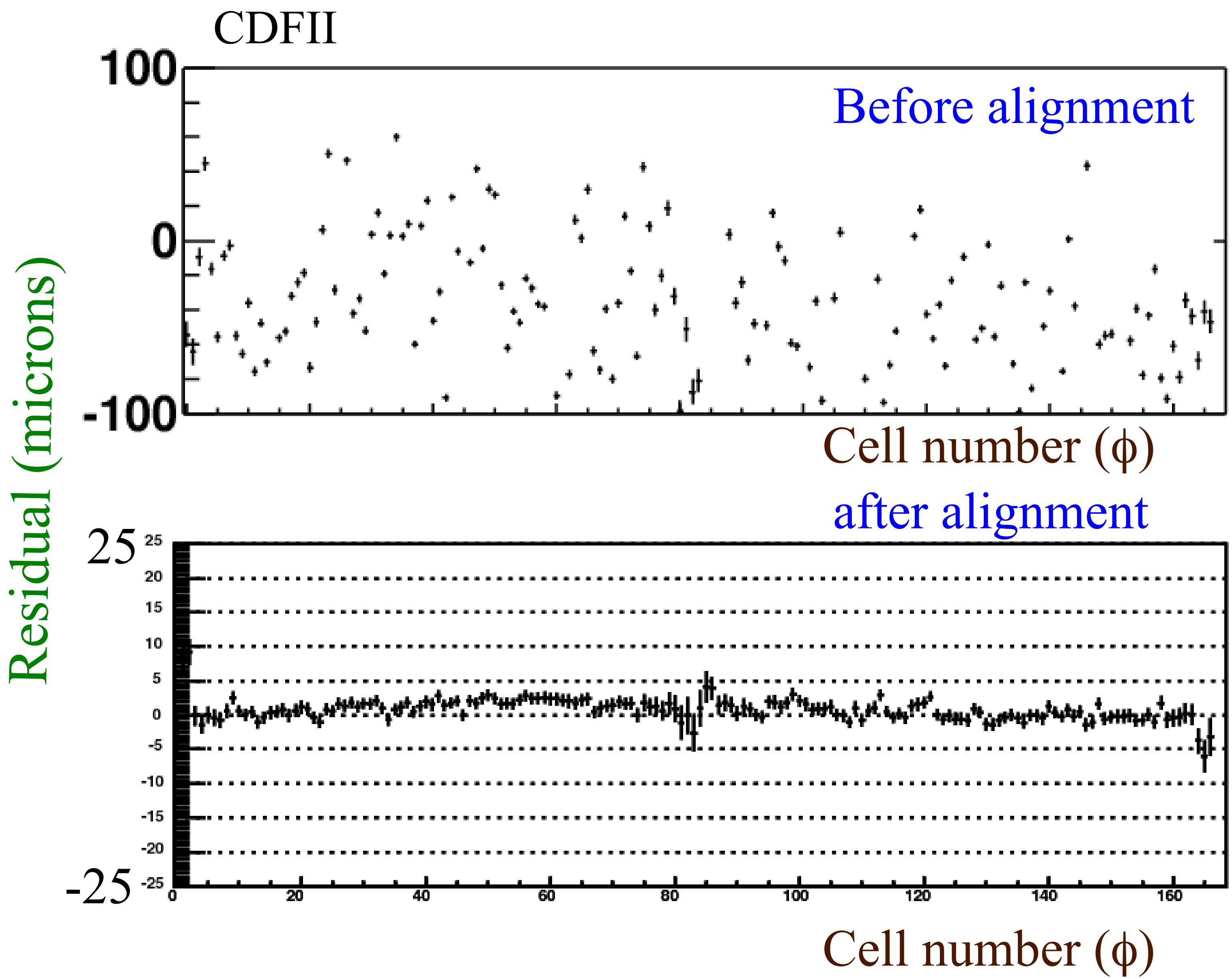
# Internal Alignment of COT

- 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'

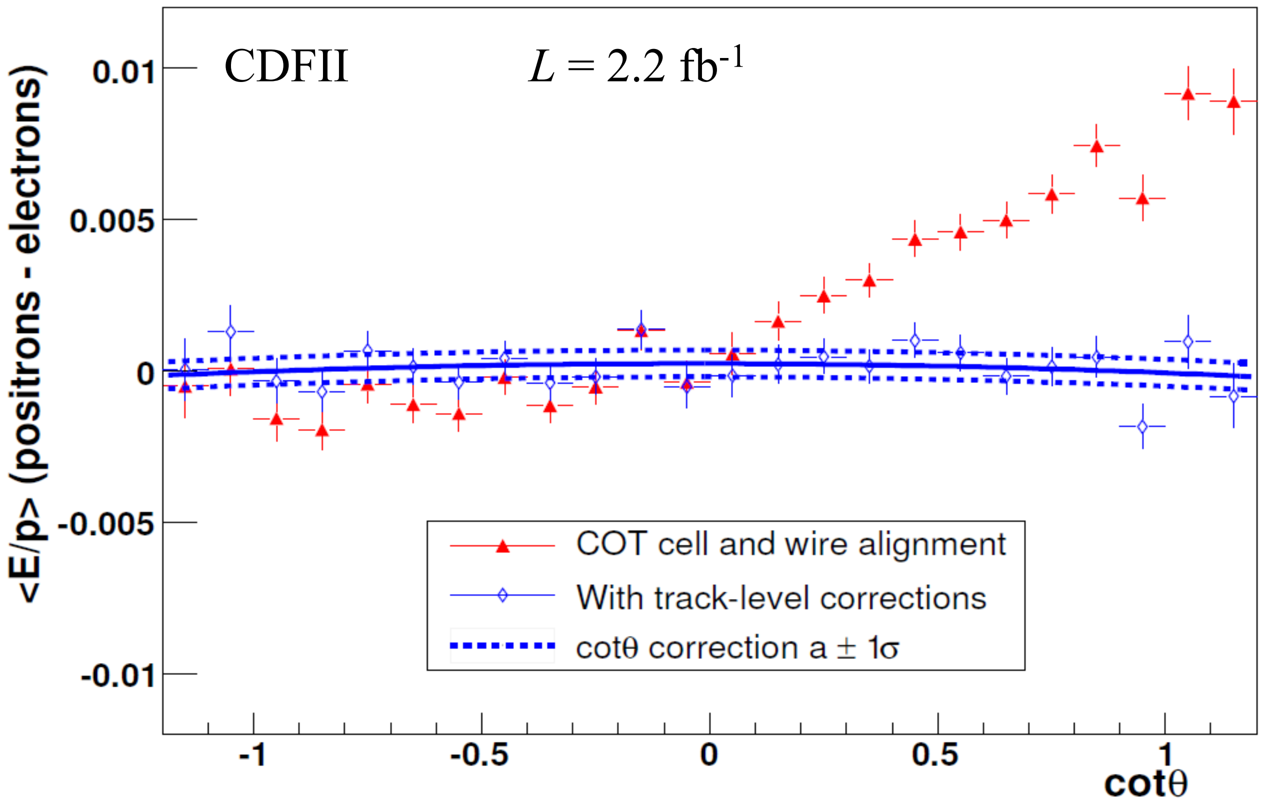
# Residuals of COT cells after alignment




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

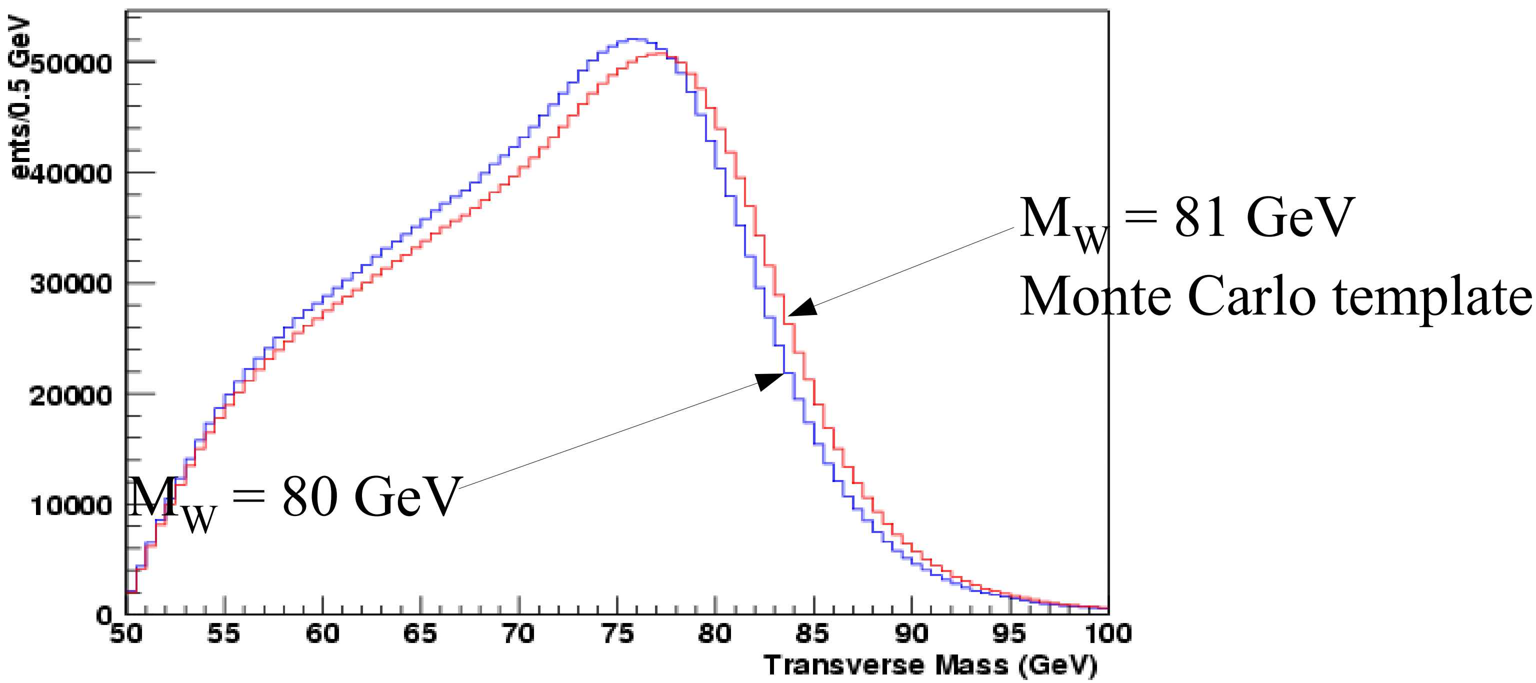


# Signal Simulation and Fitting

# Signal Simulation and Template Fitting

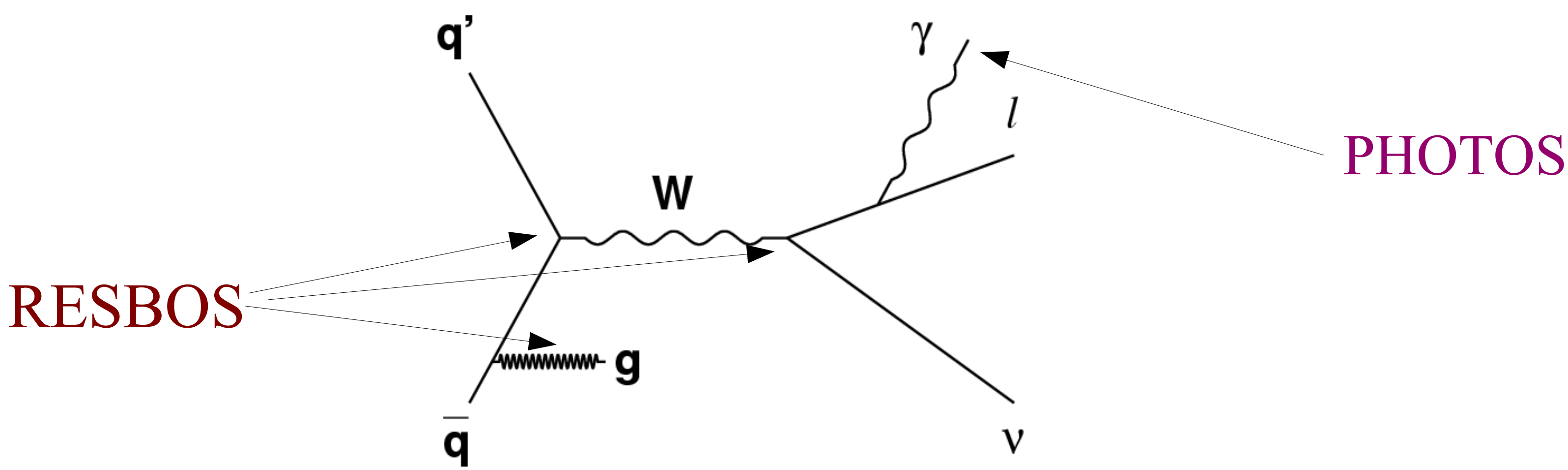
- All signals simulated using a Custom Monte Carlo
  - Generate finely-spaced templates as a function of the fit variable
  - perform binned maximum-likelihood fits to the data
- Custom fast Monte Carlo makes smooth, high statistics templates
  - And provides analysis control over key components of the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

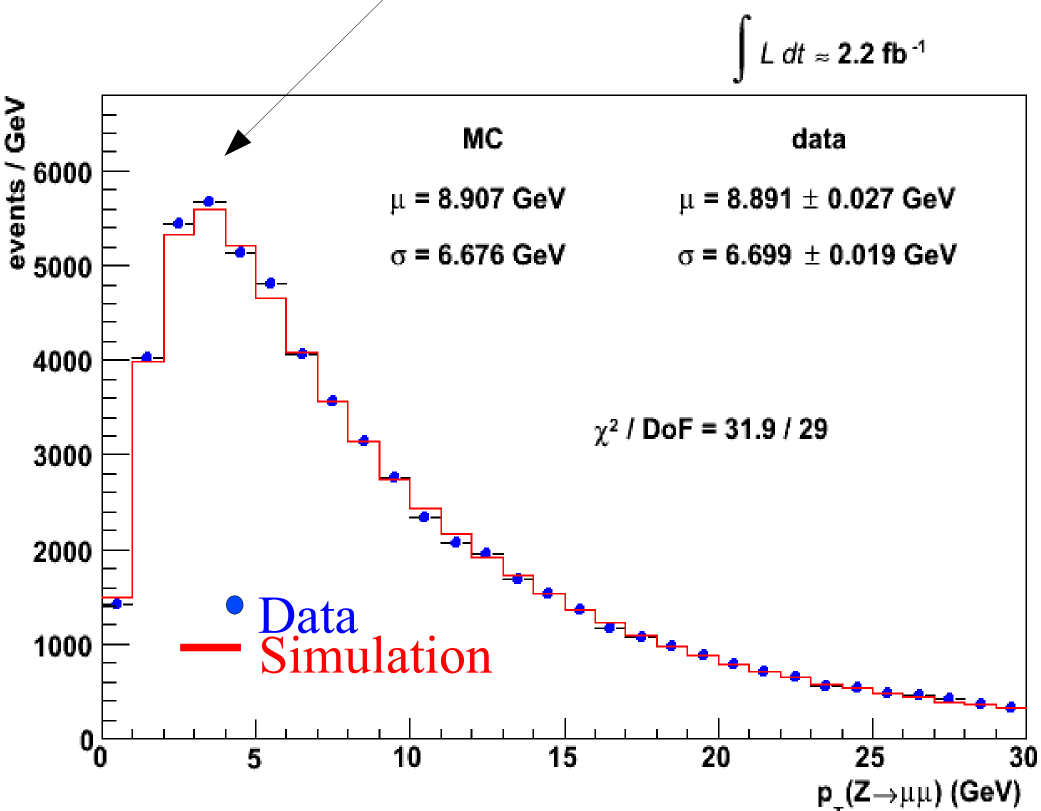
# Constraining Boson $p_T$ Spectrum

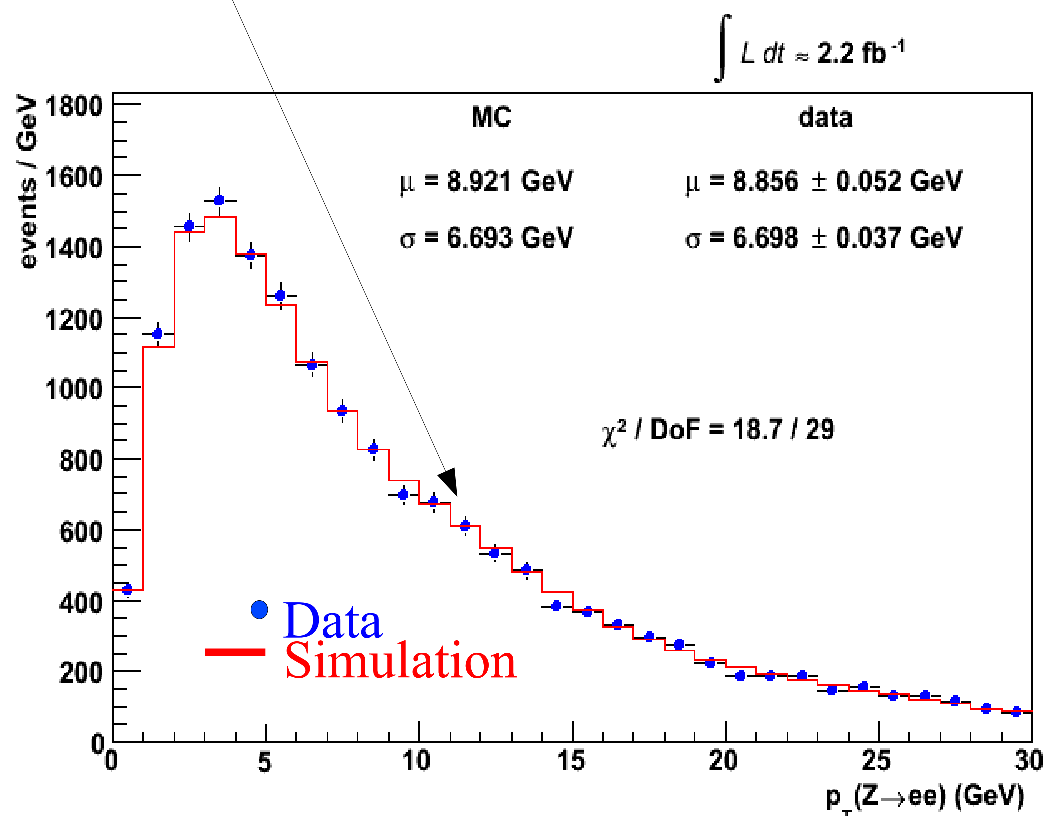
- Fit the non-perturbative parameter $g_2$ and QCD coupling $\alpha_s$ in RESBOS to $p_T(ll)$ spectra:

$\Delta M_W = 5$ 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*

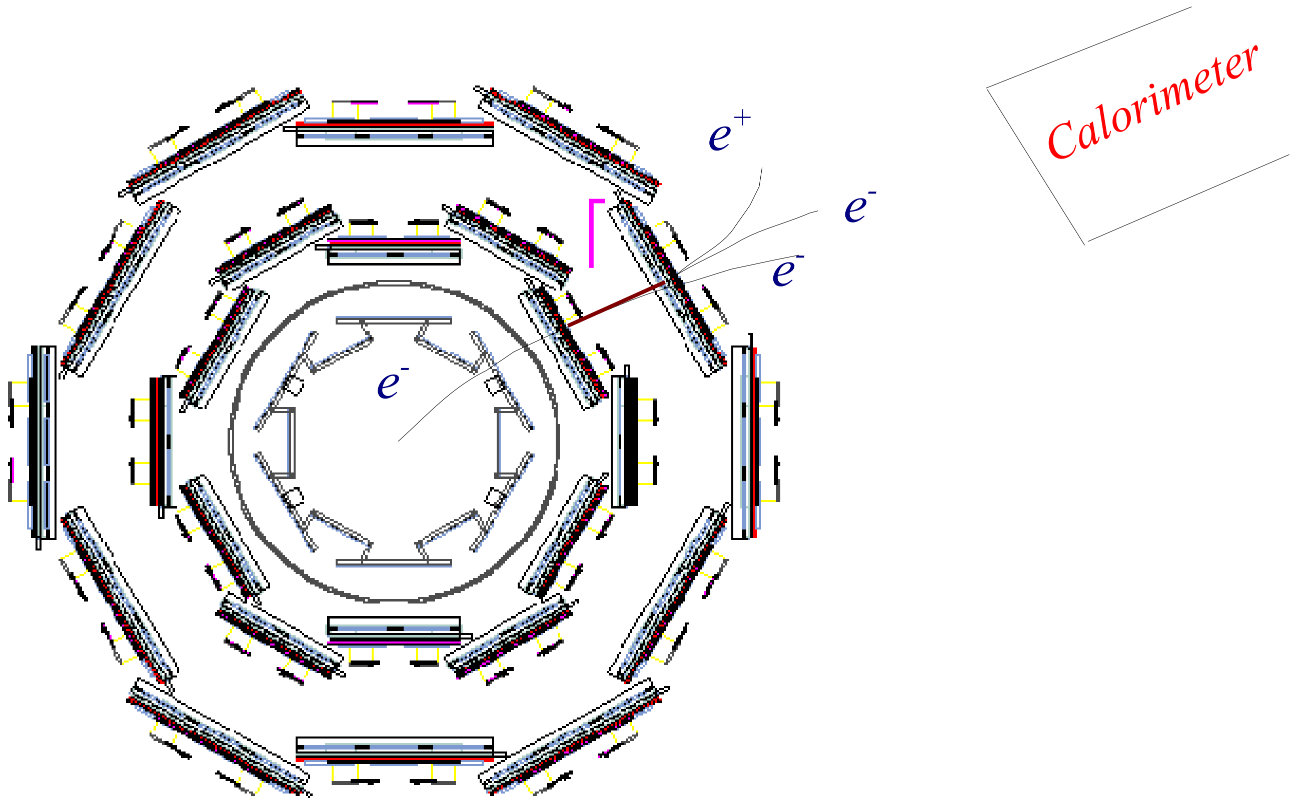
- Tracker Calibration
  - alignment of the COT (~2400 cells) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
  - Confirmed using $Z \rightarrow \mu\mu$ mass fit
- EM Calorimeter Calibration
 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

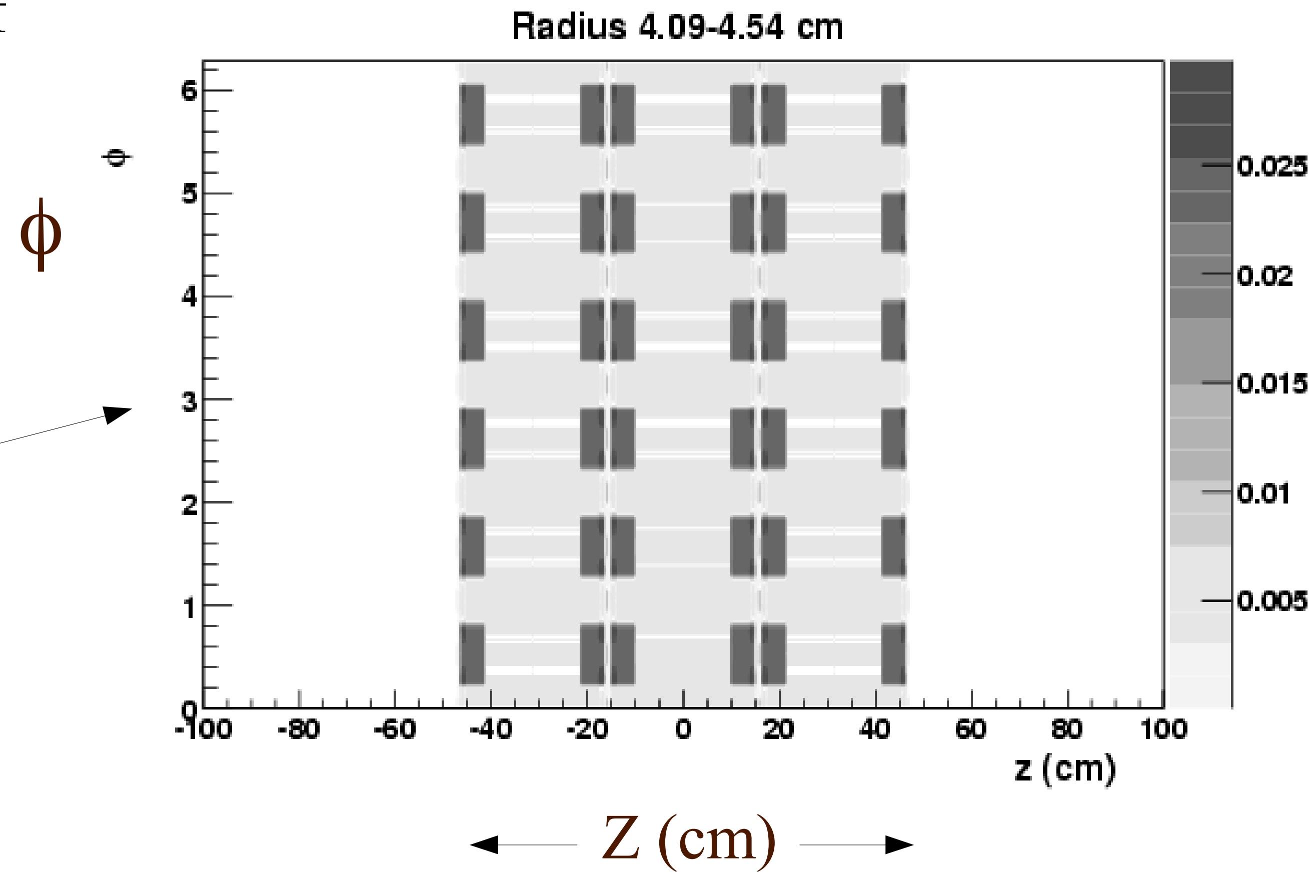


# 3-D Material Map in Simulation

- 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



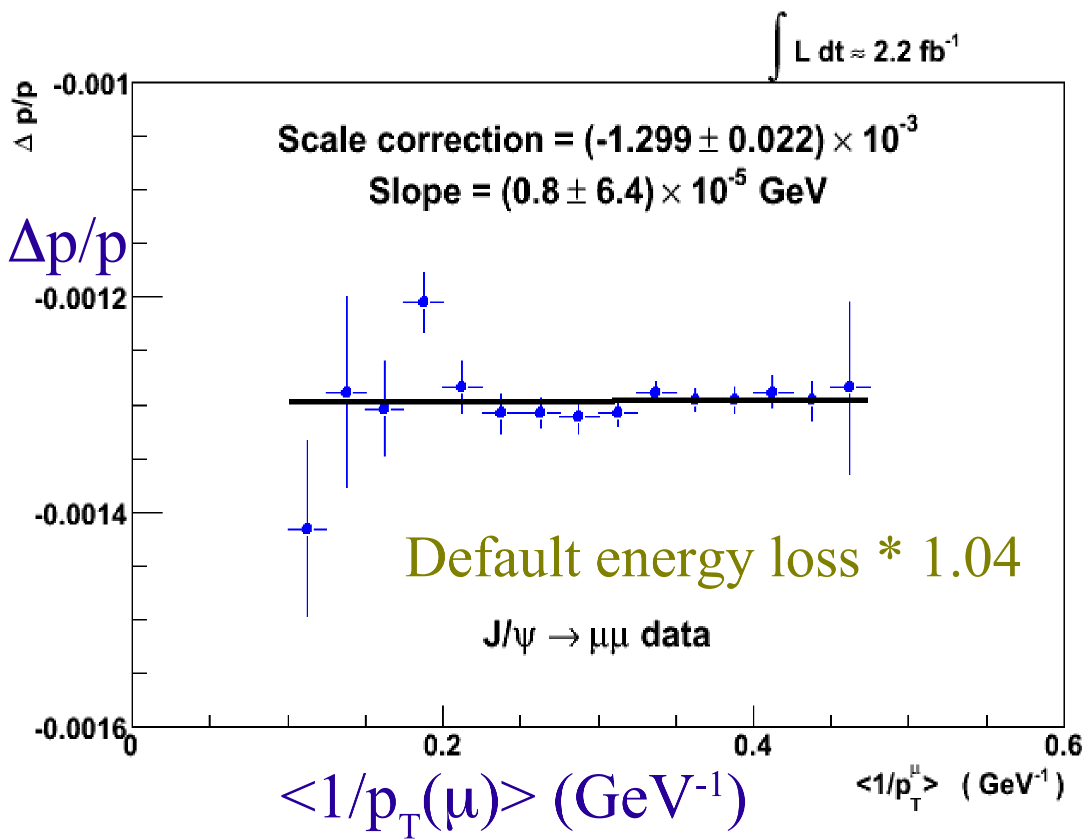

- Include dependence on type of material via Landau-Pomeranchuk-Migdal suppression of soft bremsstrahlung

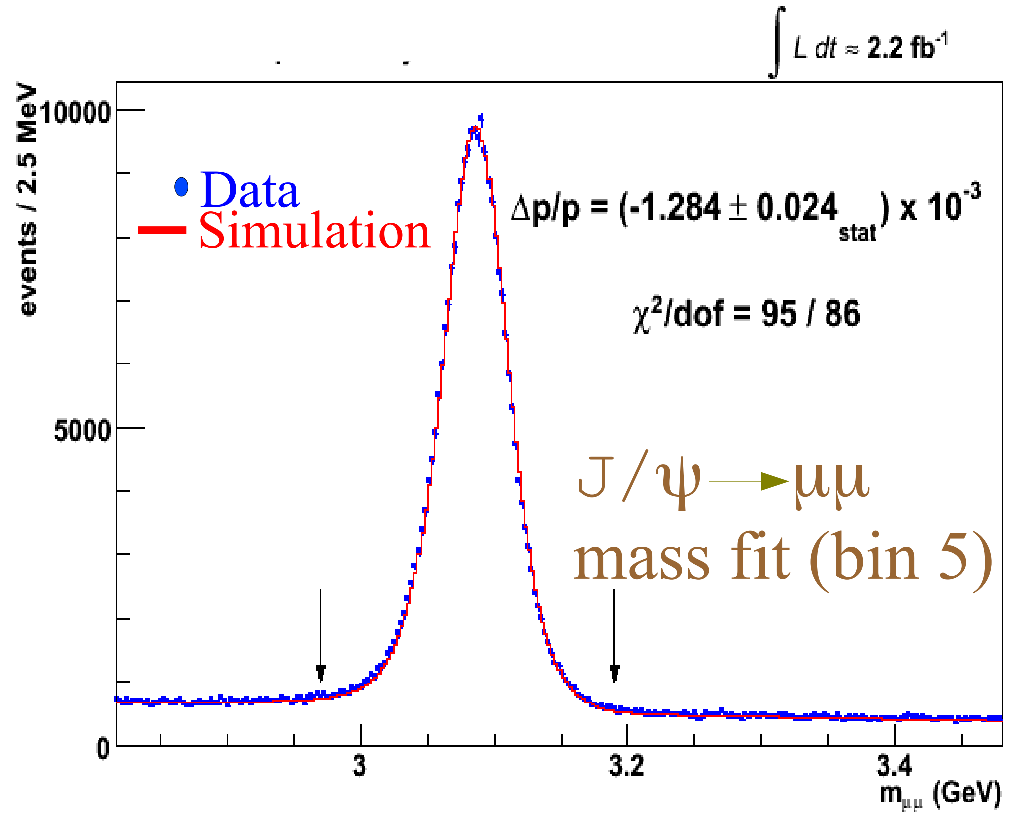
# Tracking Momentum Scale

# 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

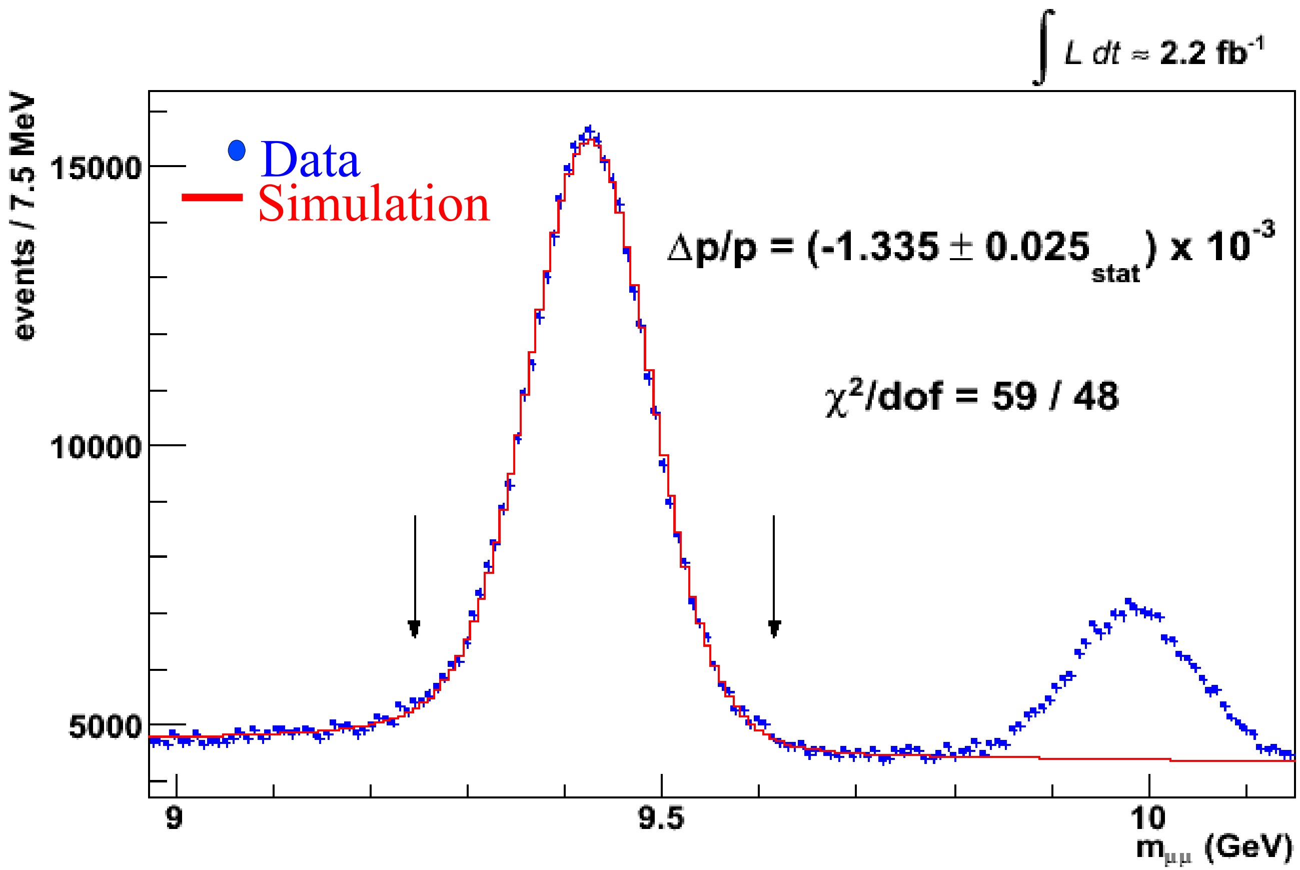


# Tracking Momentum Scale

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

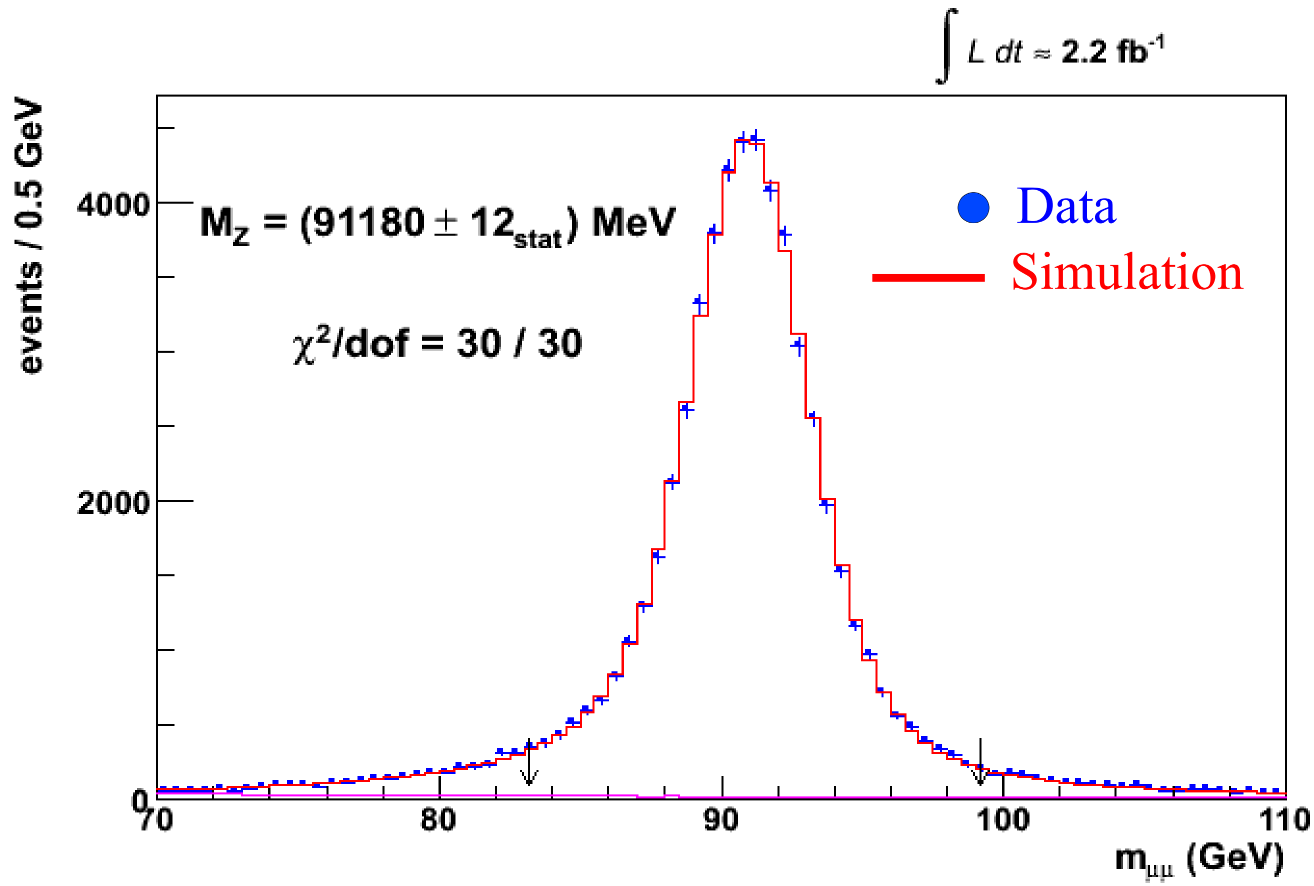
- Momentum scale measurement at higher $p_T$




$\Upsilon \rightarrow \mu\mu$ 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

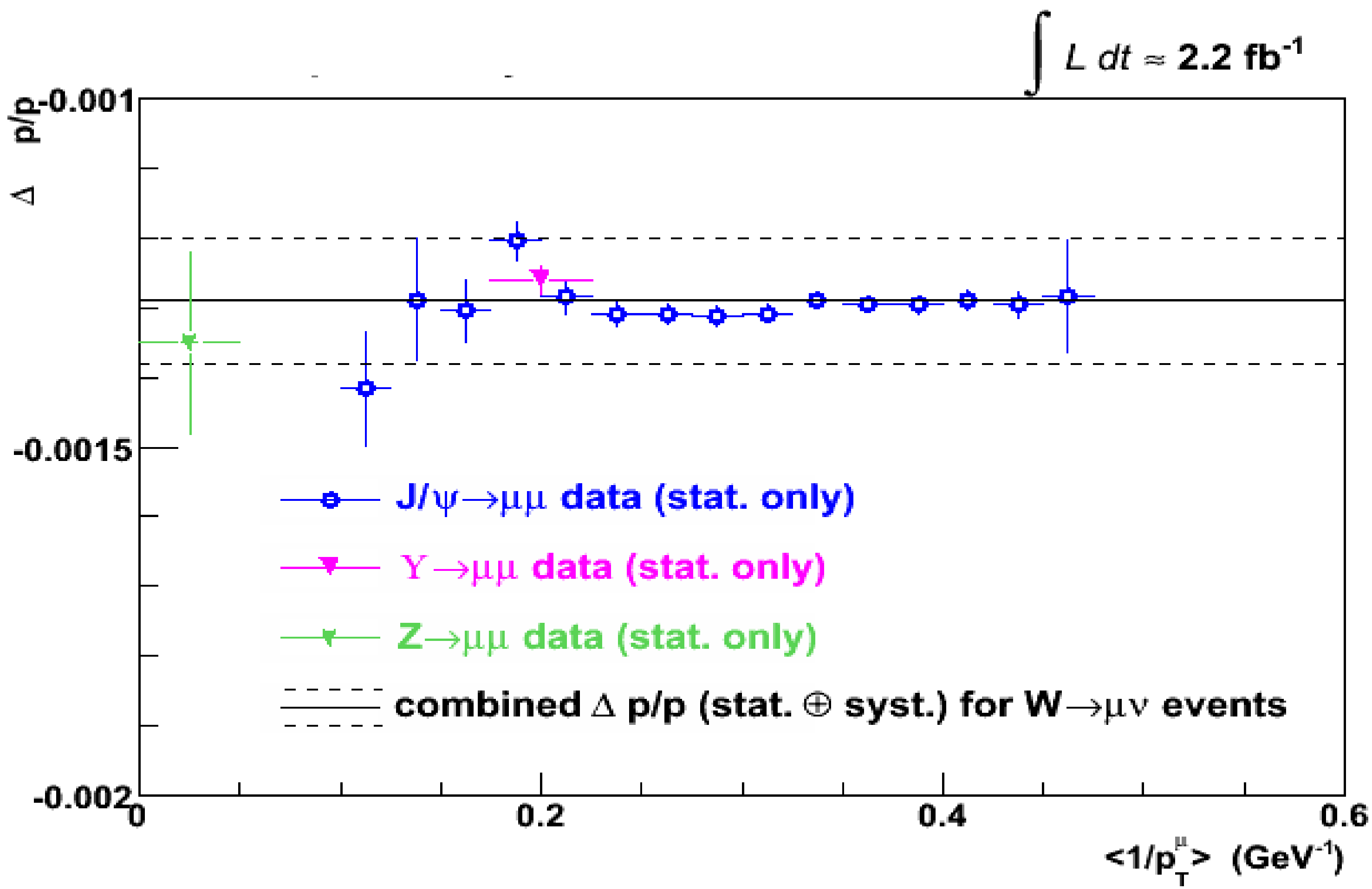



M(μμ) (GeV)

# Tracker Linearity Cross-check & Combination

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

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

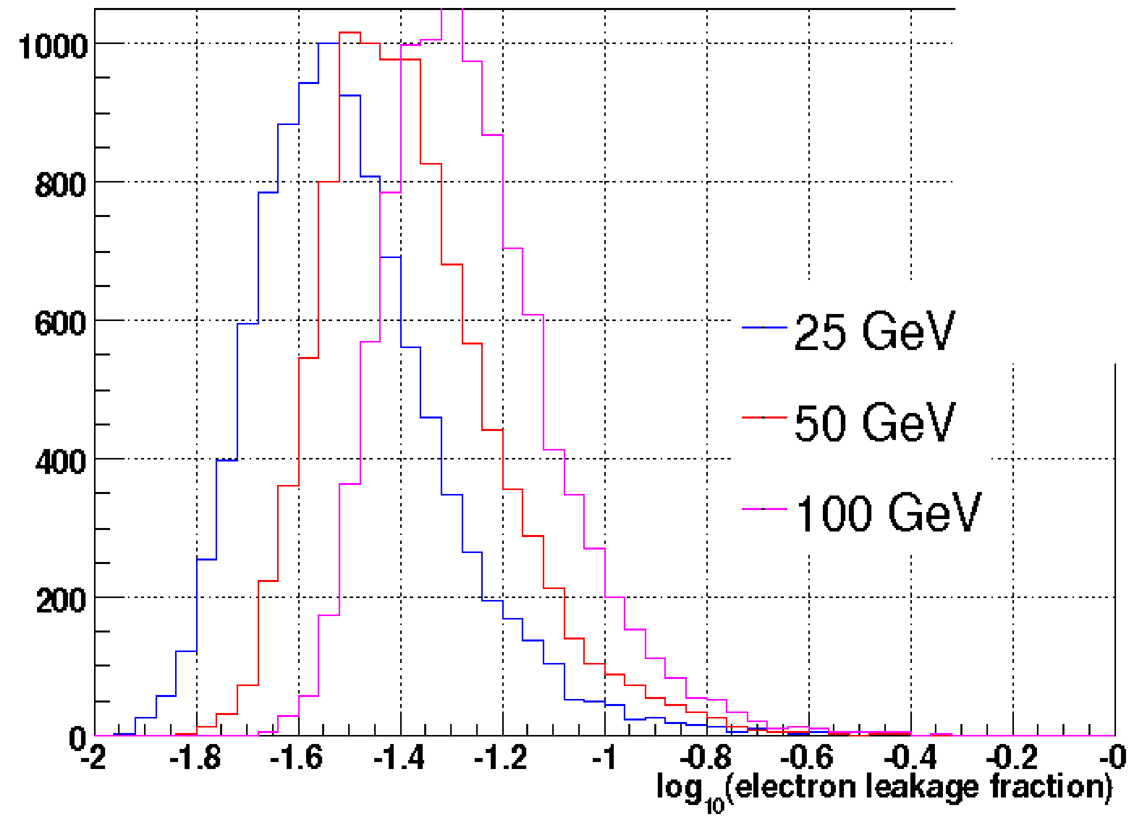



$\Delta M_W = 7$ MeV

# 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 $E_T$



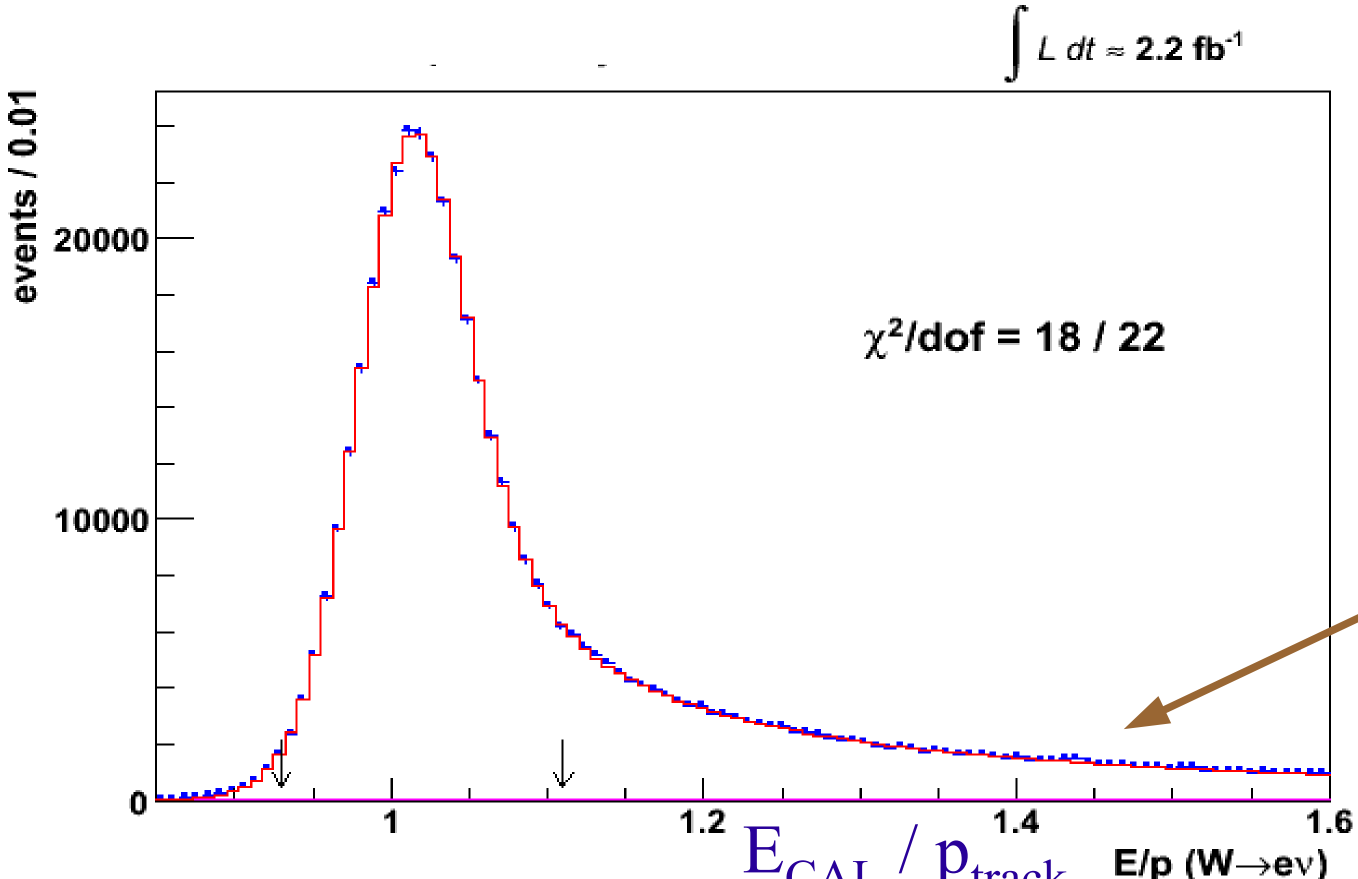

- Energy-dependent gain (non-linearity) parameterized and fit from data
- Energy resolution parameterized as fixed sampling term and tunable constant term
  - Constant terms are fit from the width of E/p peak and $Z\rightarrow ee$ mass peak

# EM Calorimeter Scale

- E/p peak from $W \rightarrow e\upsilon$ 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 $W \rightarrow e\upsilon$ 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

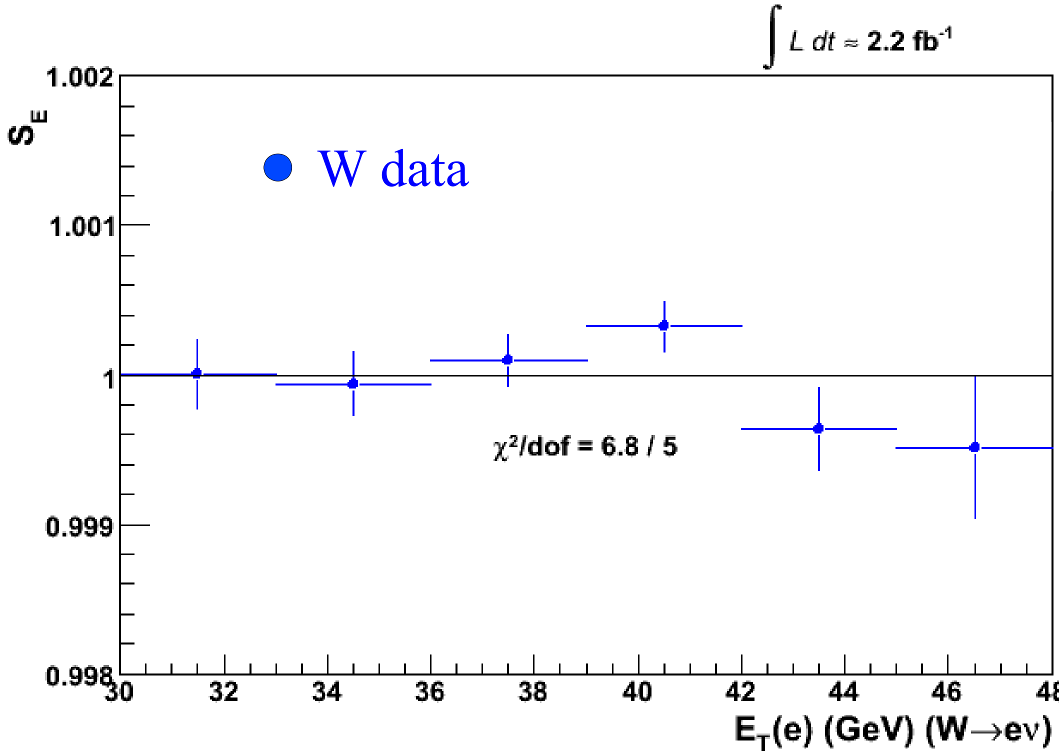
# Measurement of EM Calorimeter Non-linearity

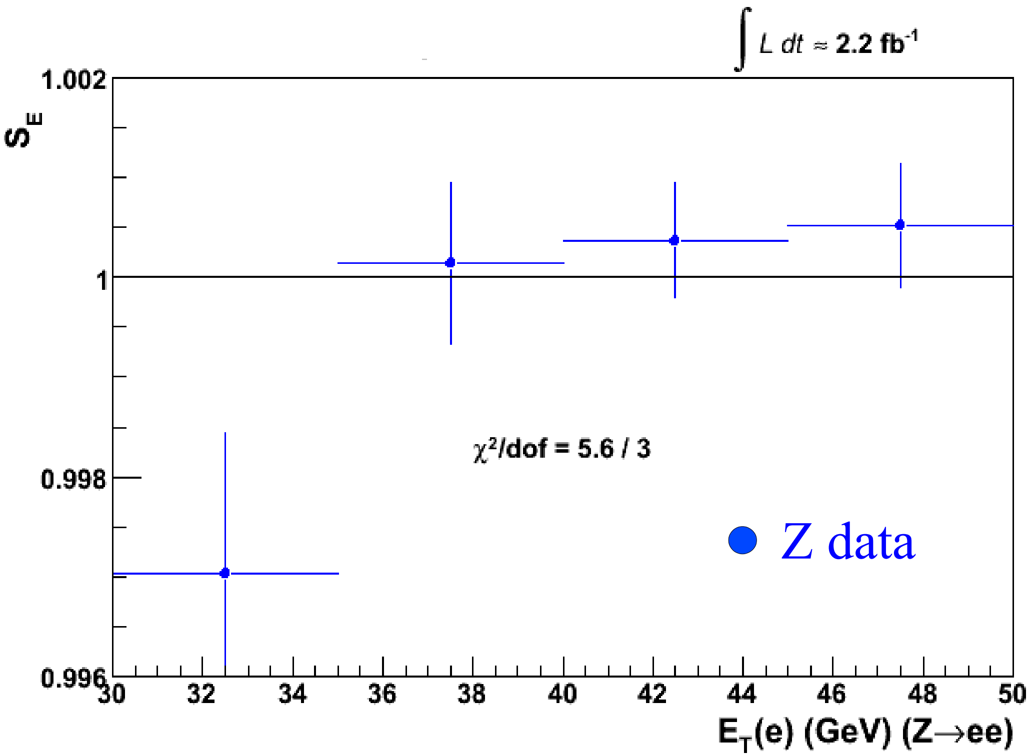
- Perform E/p fit-based calibration in bins of electron $E_T$
- GEANT-motivated parameterization of non-linear response:

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

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

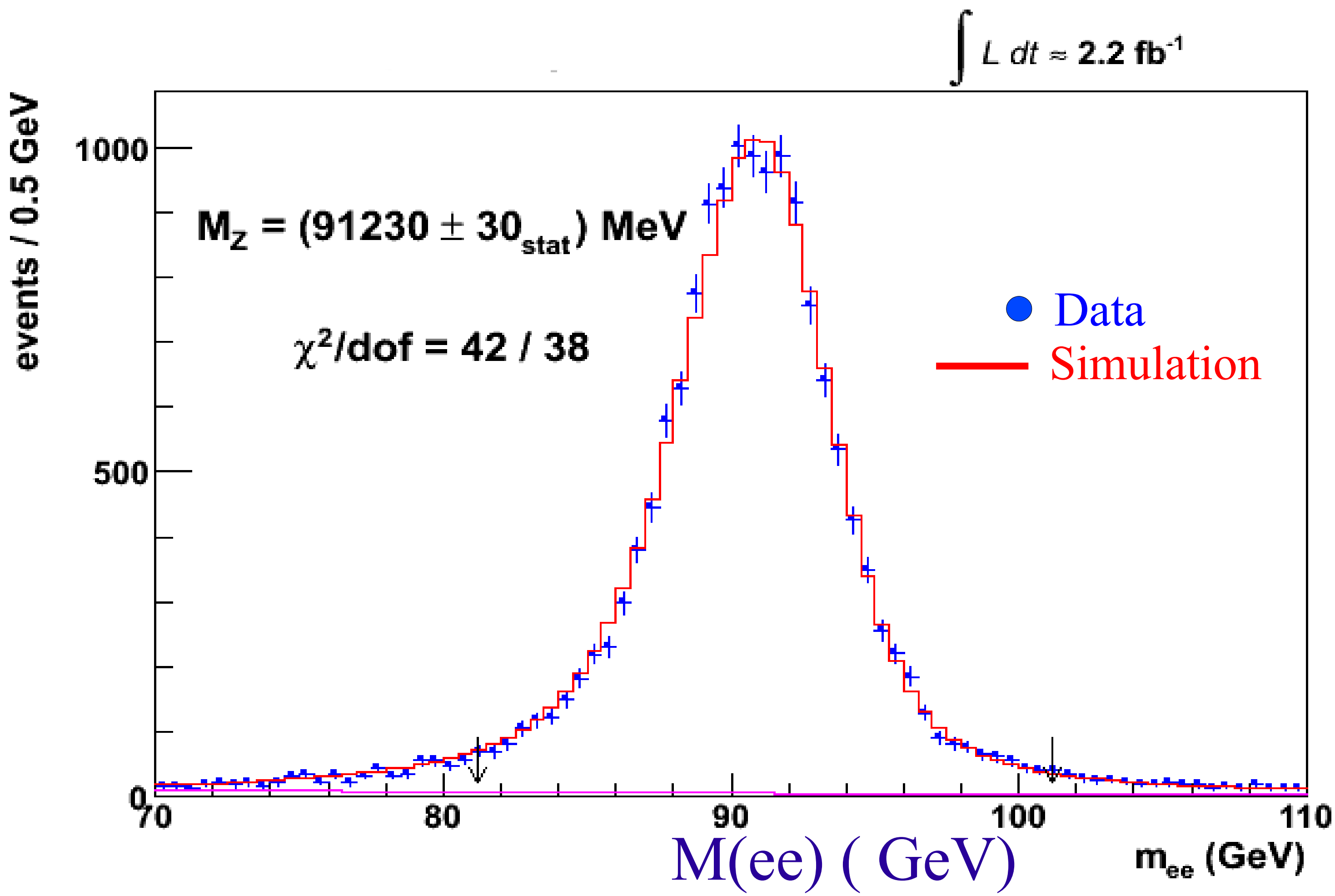
  $\Rightarrow \Delta M_W = 4$ MeV



# $Z \rightarrow ee$ 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



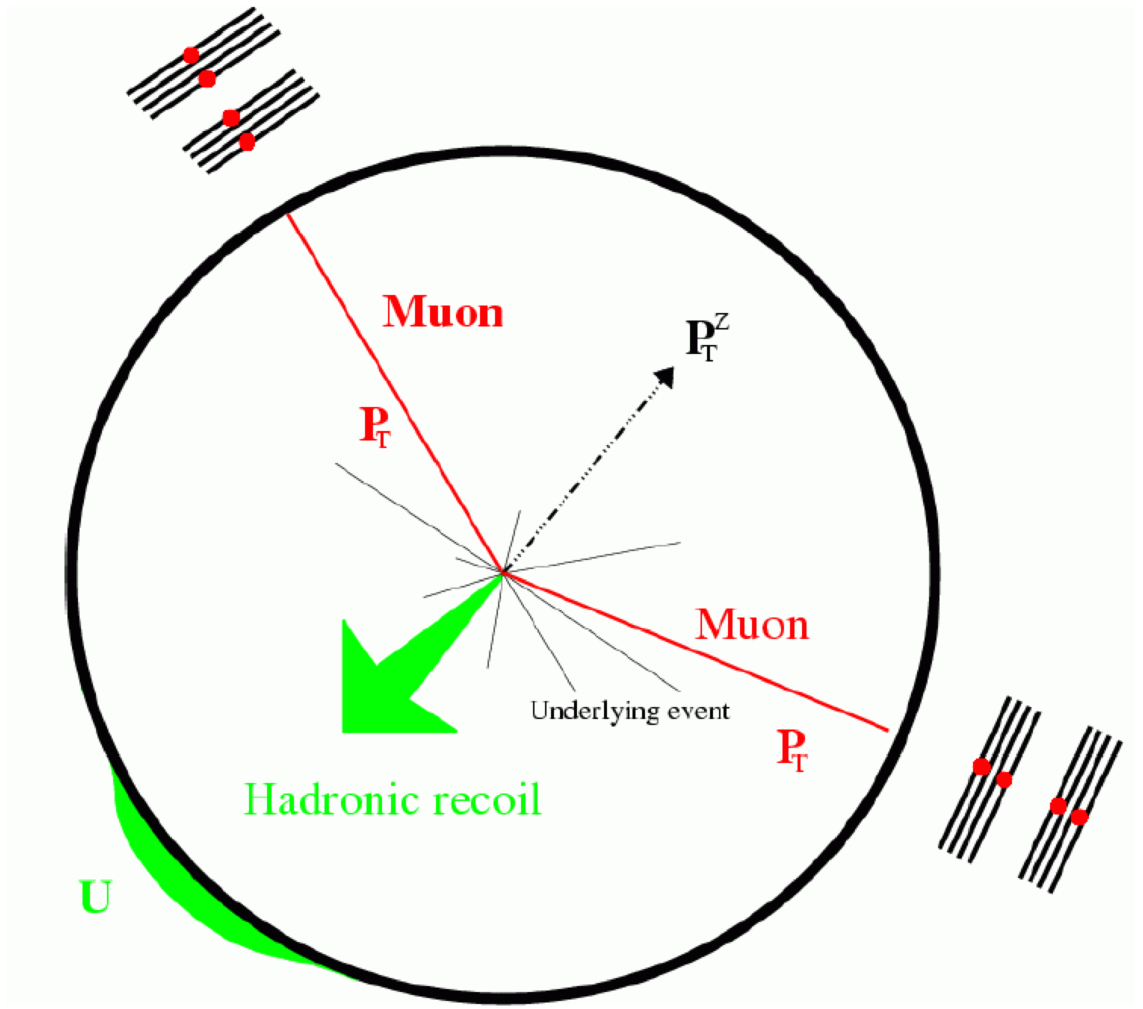

$\Delta M_W = 10$ MeV

# 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→*ll* events

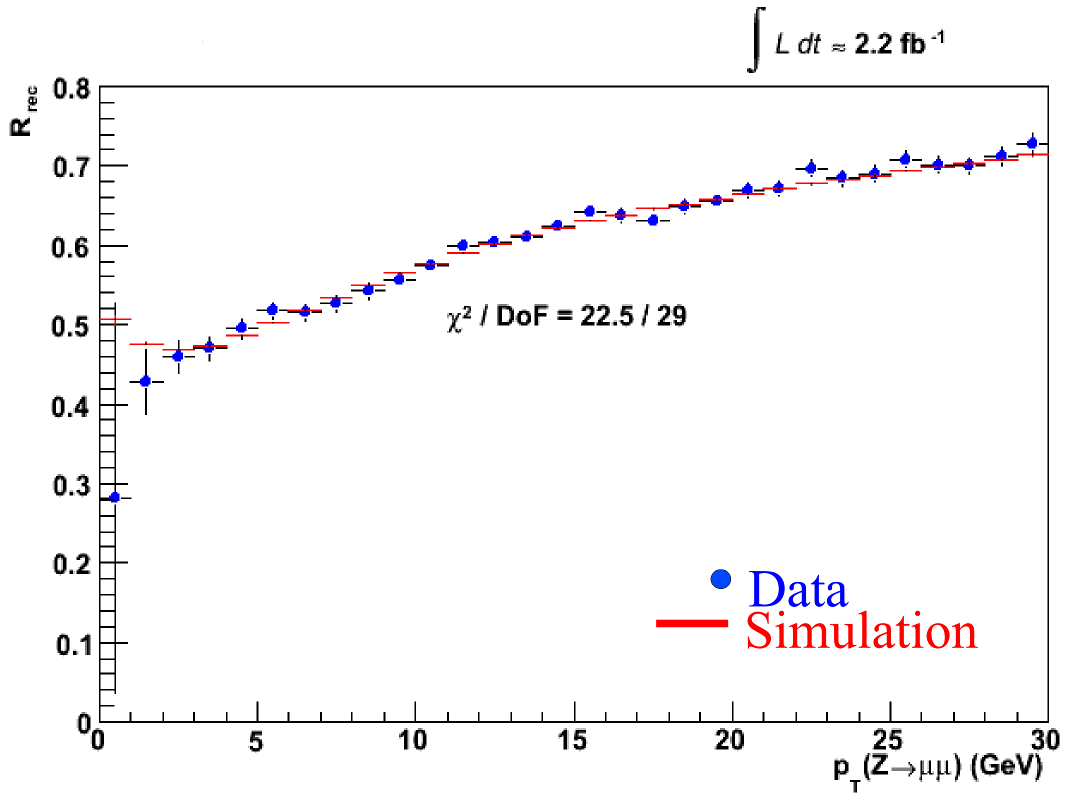



Transverse momentum of Hadronic recoil (***u***) calculated as 2-vector-sum over calorimeter towers

# Hadronic Recoil Simulation

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

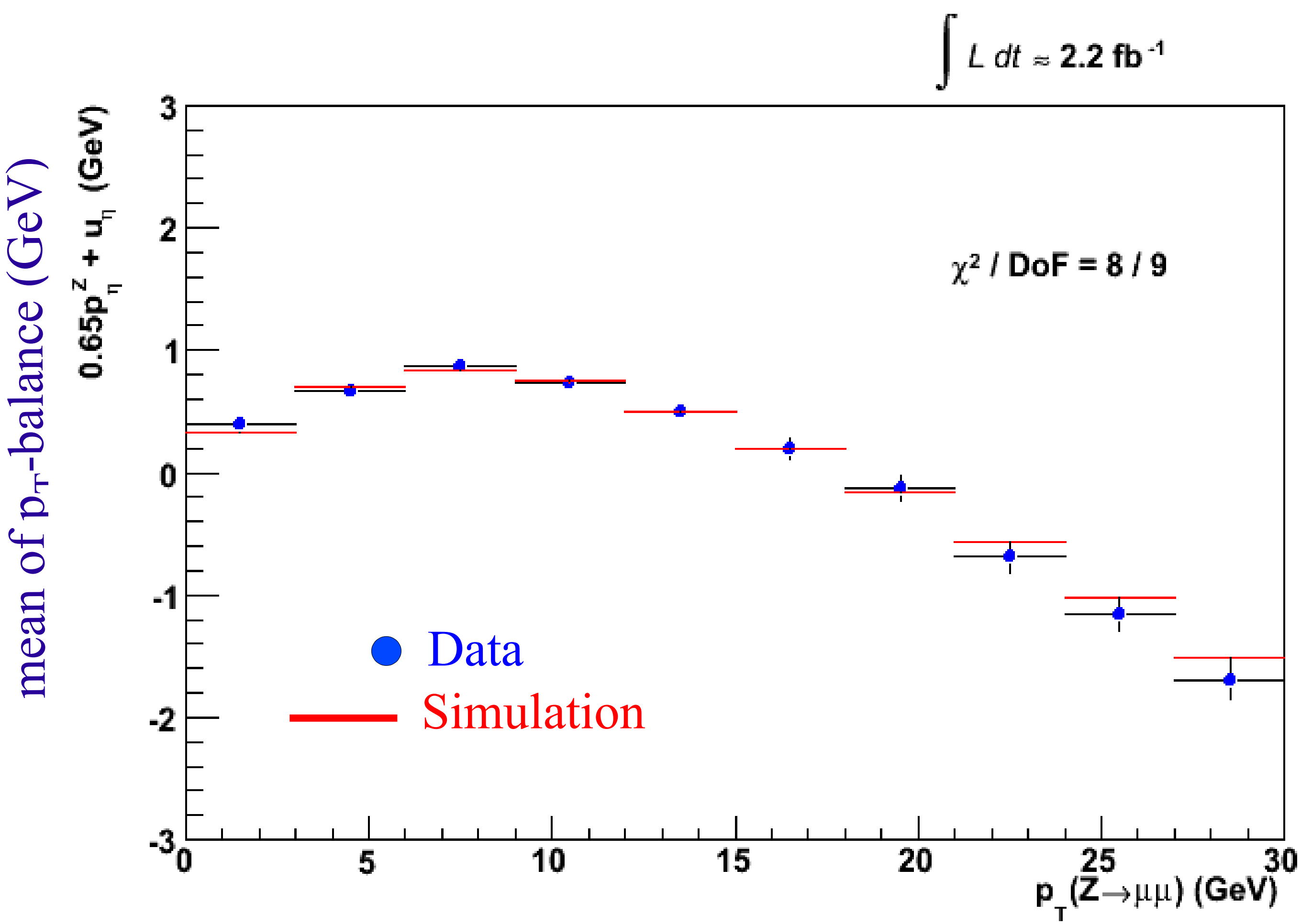
- a soft 'spectator interaction' component, randomly oriented
  - Modelled using minimum-bias data with tunable magnitude
- A hard 'jet' component, directed opposite the boson $p_T$
  - $P_T$-dependent response and resolution parameterizations
  - Hadronic response $R = \boldsymbol{u}_{reconstructed}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

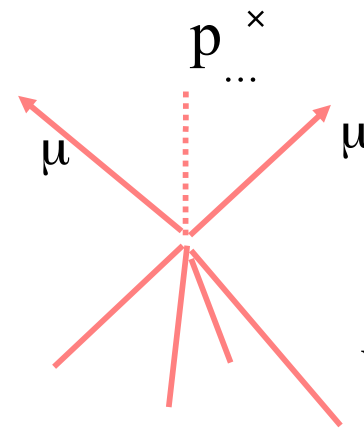


# Tuning Recoil Response Model with *Z* events

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



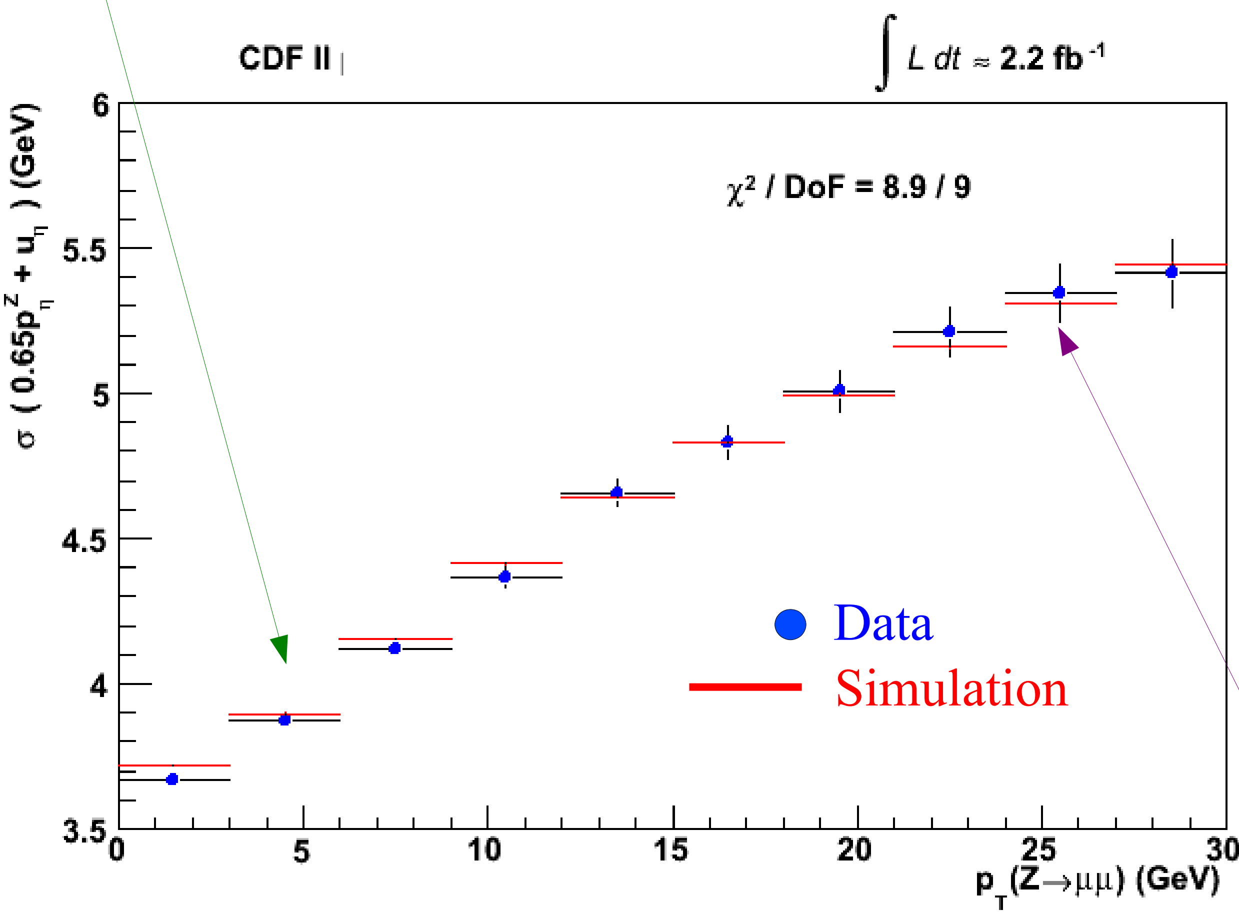

Hadronic model parameters tuned by minimizing $\chi^2$ between data and simulation

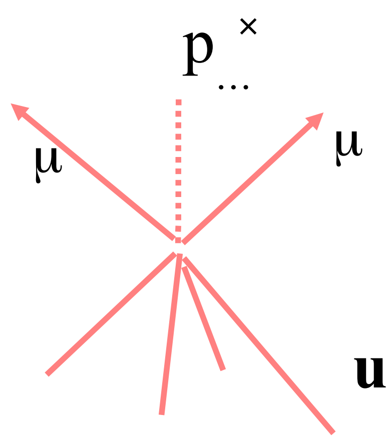
$\Delta M_W$ = 4 MeV

# Tuning Recoil Resolution Model with *Z* events

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

Resolution of $p_T$-balance (GeV)



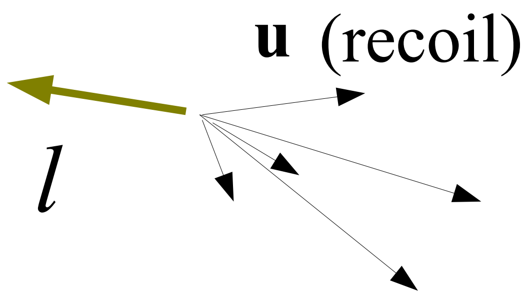



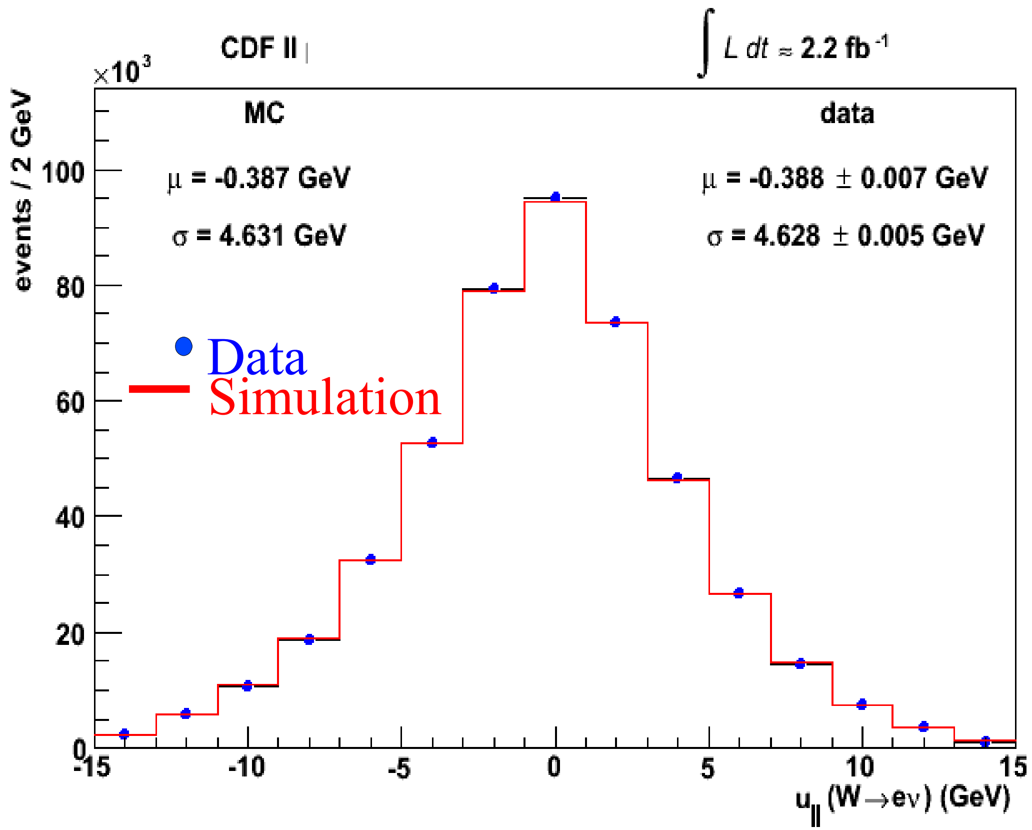

$\Delta M_W = 4$ MeV

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

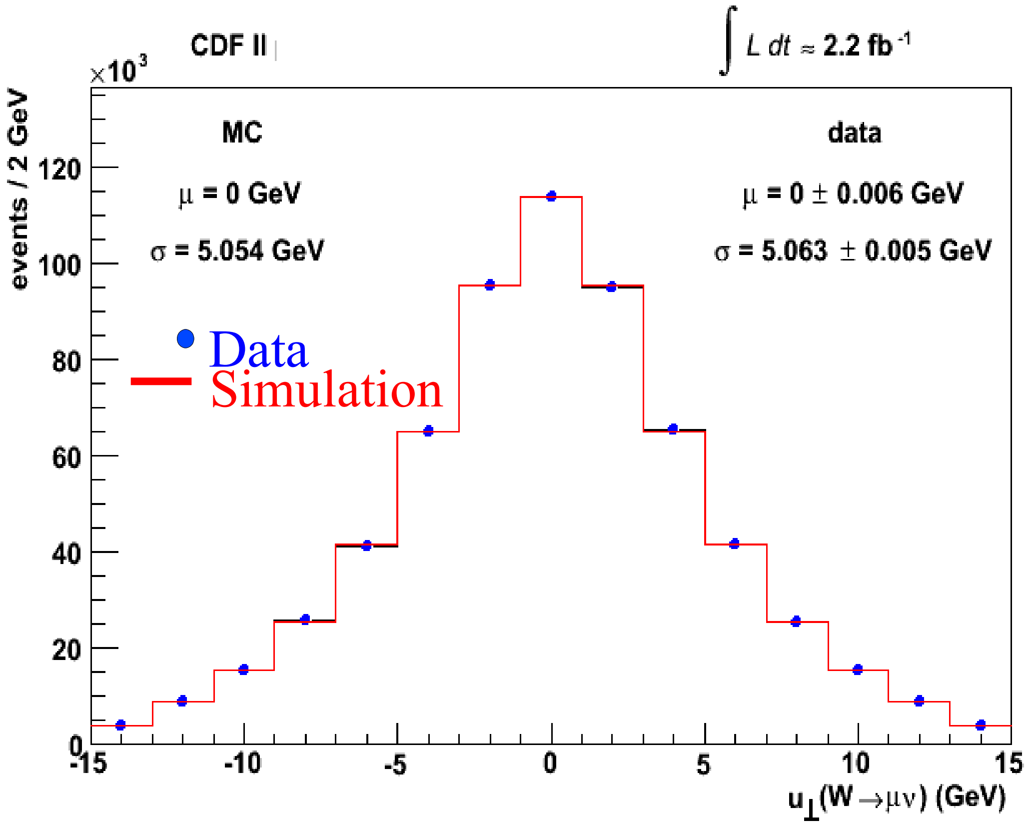
# Testing Hadronic Recoil Model with *W* events

Compare recoil distributions between simulation and data



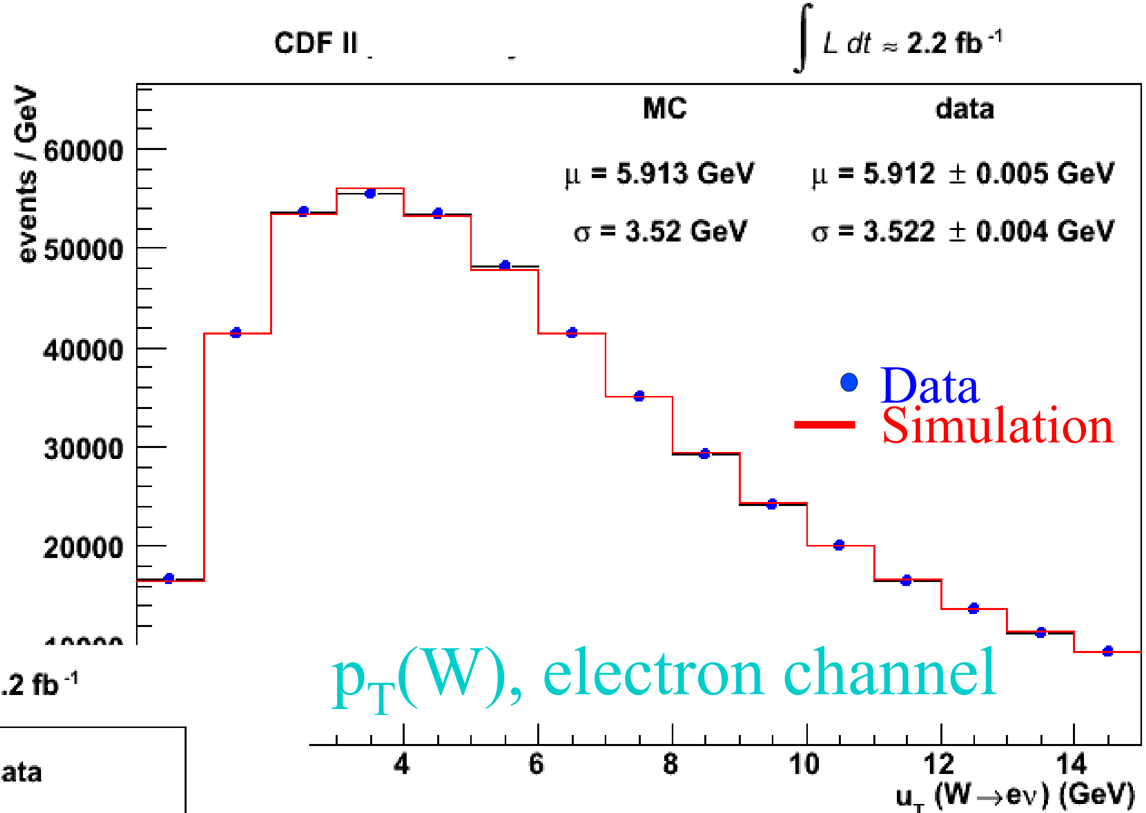

Recoil projection (GeV) on lepton direction

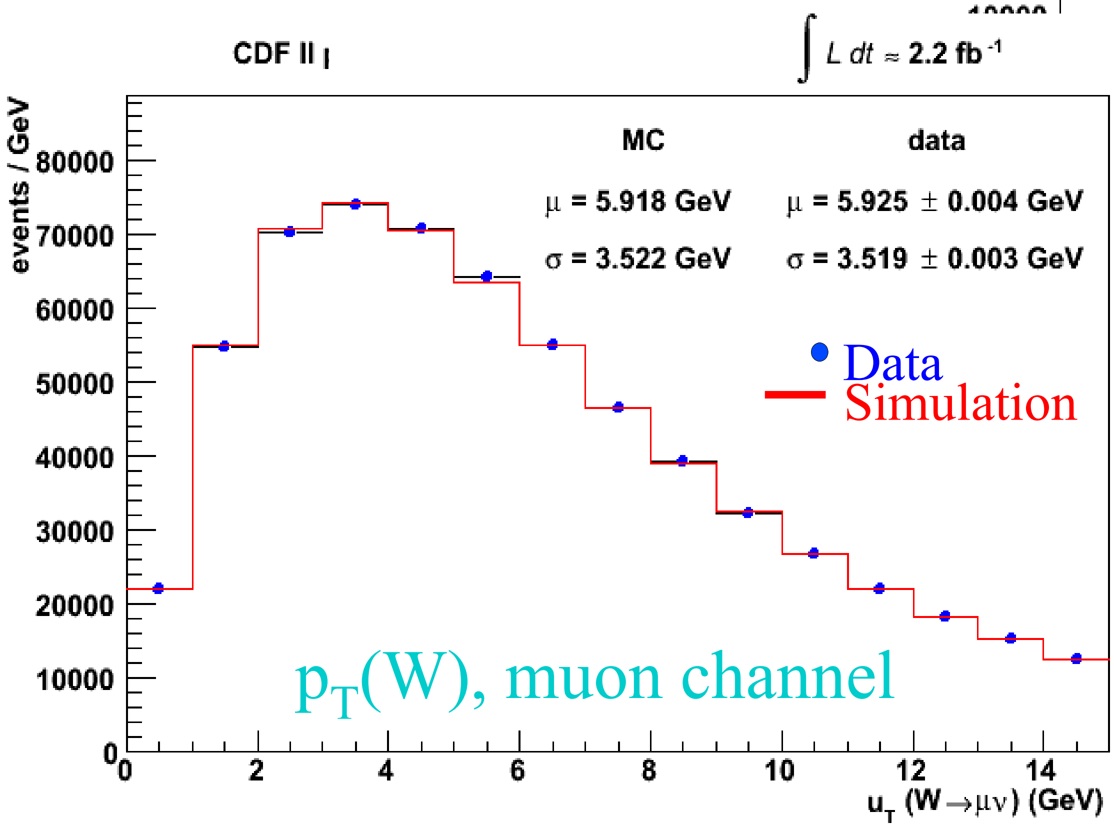


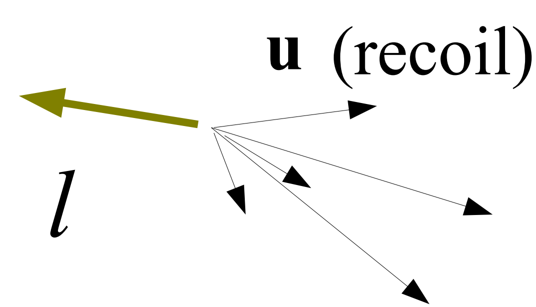

Recoil projection (GeV) perpendicular to lepton

# Testing Hadronic Recoil Model with *W* events

Recoil model validation plots confirm the consistency of the model



# Parton Distribution Functions

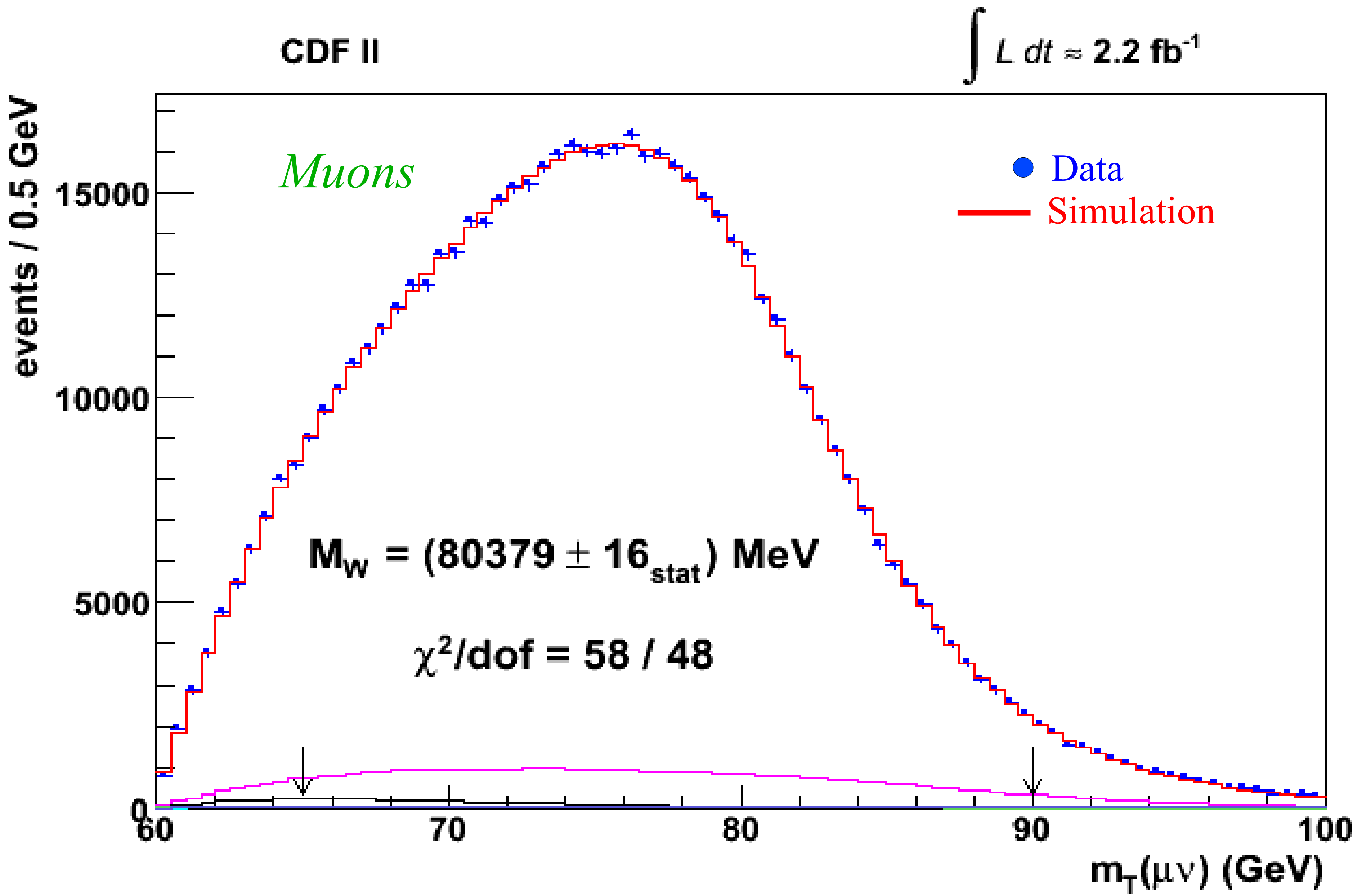
- Affect W kinematic lineshapes through acceptance cuts
- In the rest frame, $p_T = m \sin \theta^* / 2$
- Longitudinal cuts on lepton in the lab frame sculpt the distribution of $\theta^*$, hence biases the distribution of lepton $p_T$
  - Relationship between lab frame and rest frame depends on the 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

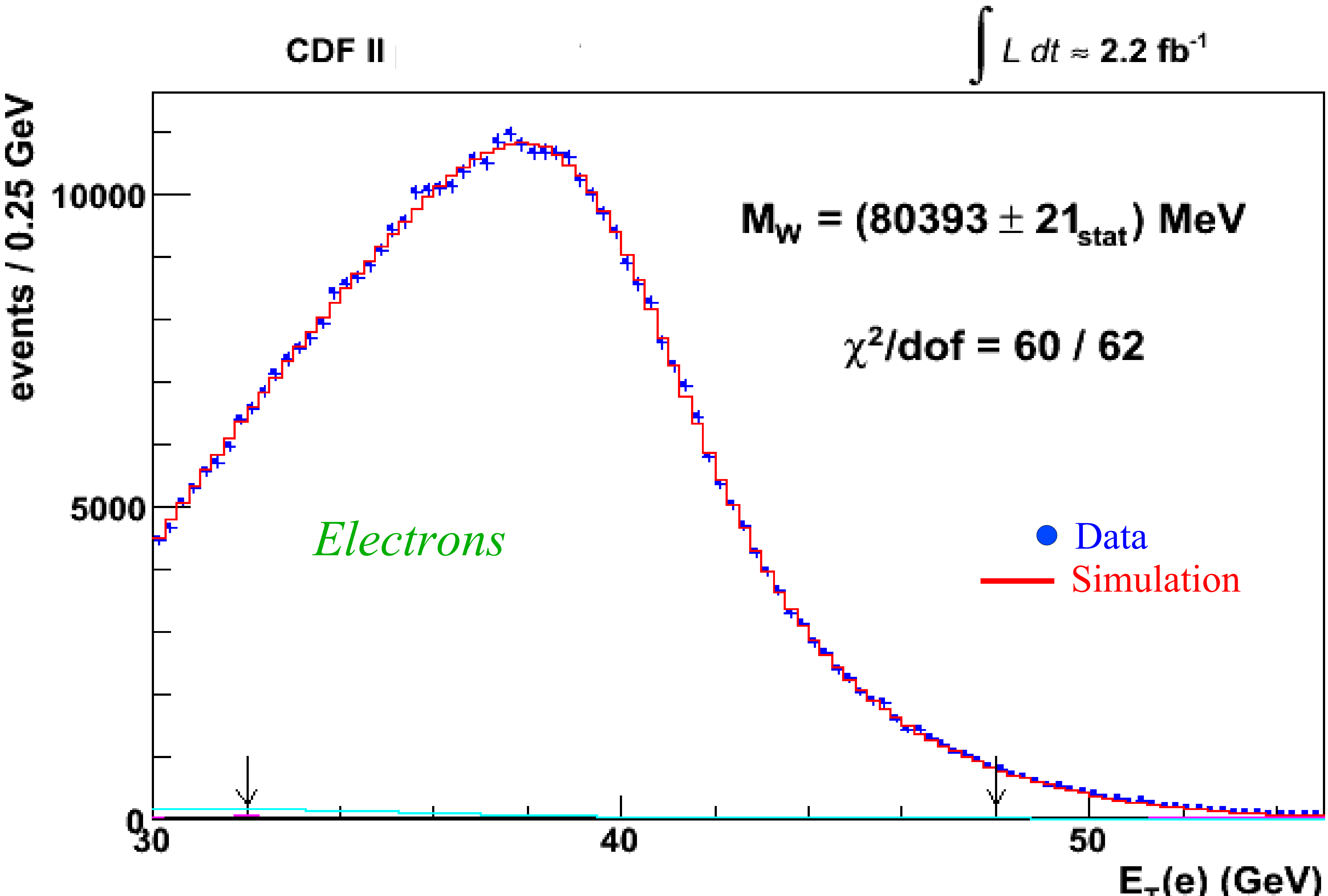
# Blind Analysis Technique

- 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

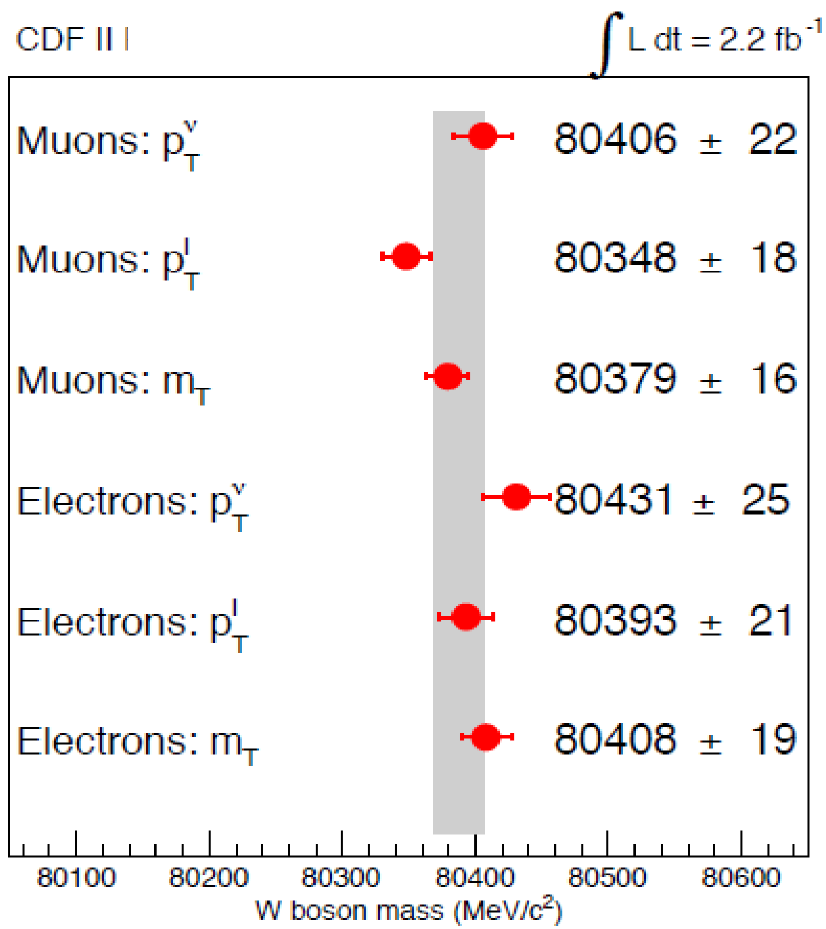


# *W* Mass Fit using Lepton $p_T$



# 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 |

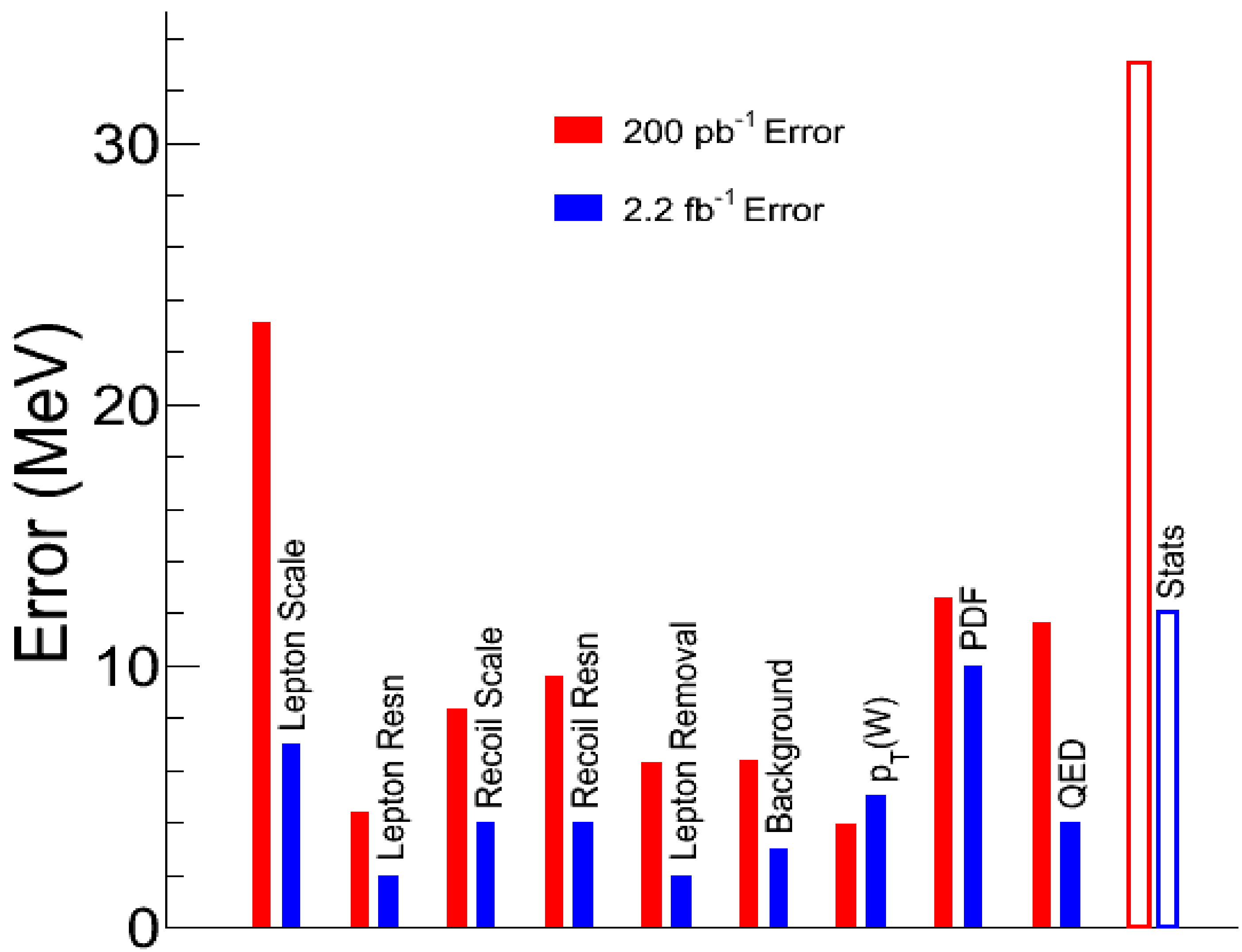


# CDF Result (2.2 $fb^{-1}$)
# Transverse Mass Fit Uncertainties (MeV)

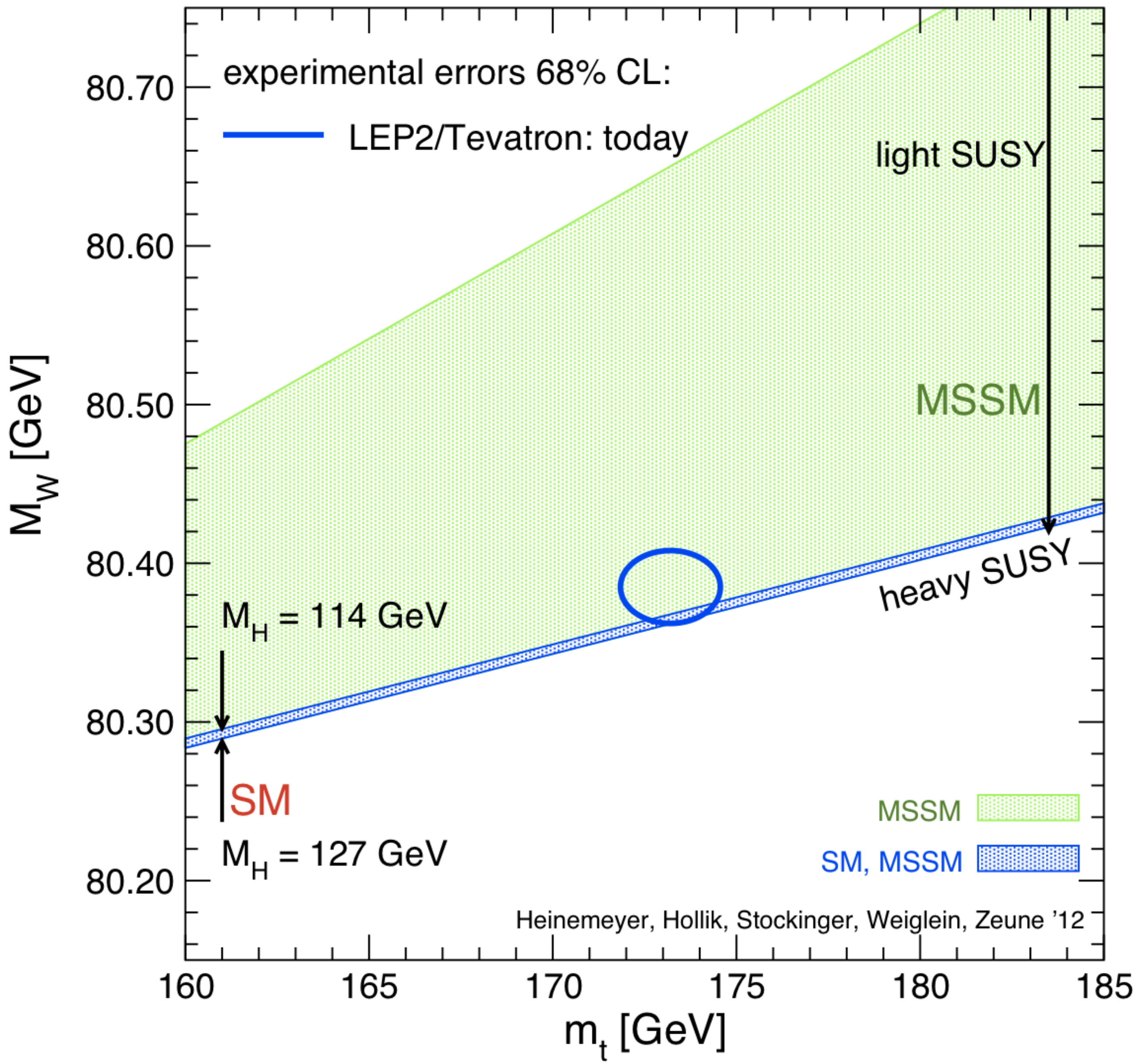
| | *electrons* | *muons* | *common* |
|---|---|---|---|
| W statistics | 19 | 16 | 0 |
| Lepton energy scale | 10 | 7 | 5 |
| Lepton resolution | 4 | 1 | 0 |
| Recoil energy scale | 5 | 5 | 5 |
| Recoil energy resolution | 7 | 7 | 7 |
| Selection bias | 0 | 0 | 0 |
| Lepton removal | 3 | 2 | 2 |
| Backgrounds | 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* $M_{top}$



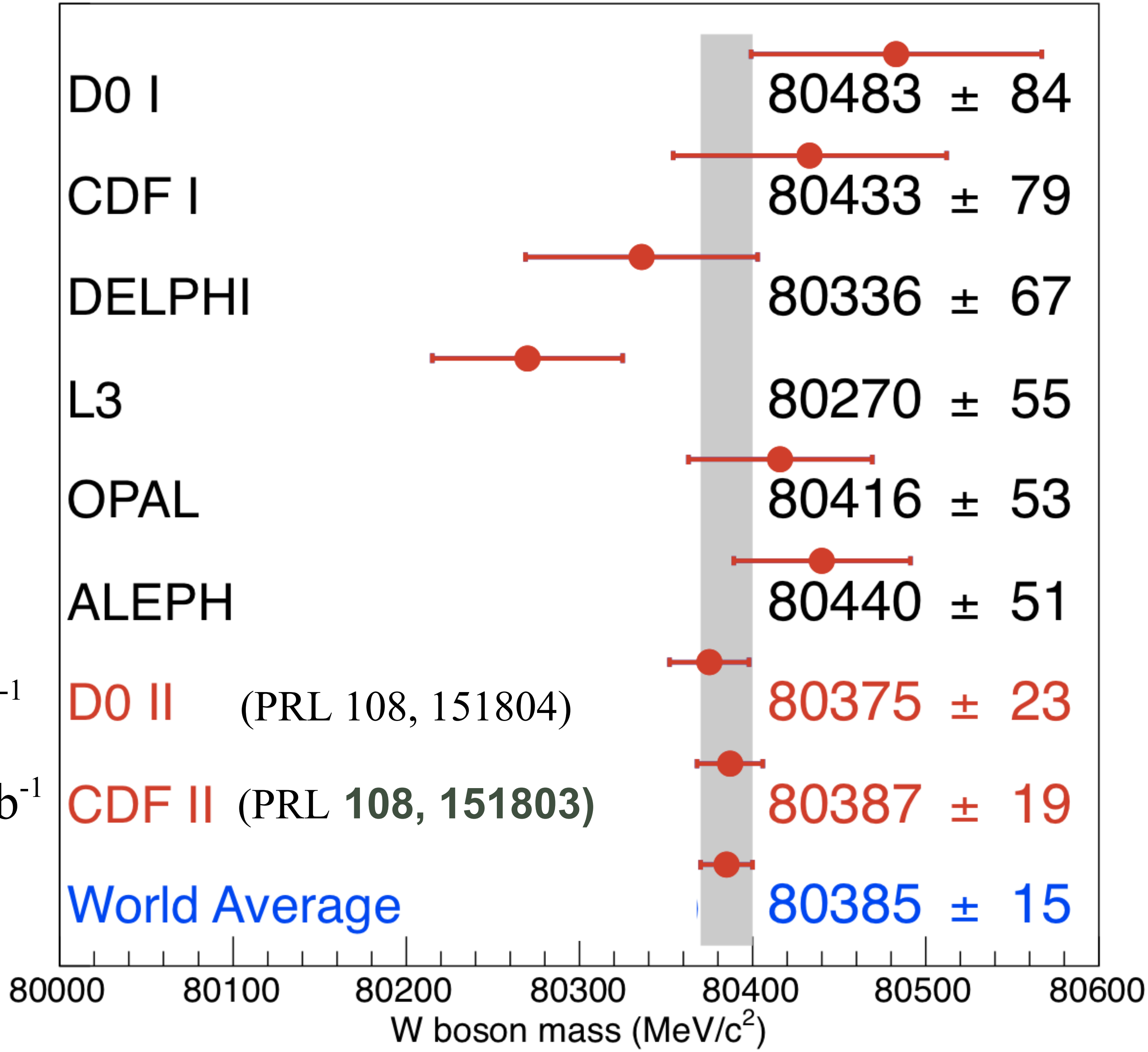
# W Boson Mass Measurements from Different Experiments

World average
computed by TeVEWWG
ArXiv: 1204.0042

5 $fb^{-1}$

2.2 $fb^{-1}$

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 → $l\nu$ lepton rapidity distribution
  - W boson charge asymmetry

# PDF Constraint – *W* Charge Asymmetry

- Measurement of the electron charge asymmetry in inclusive *W* production at CMS: http://arxiv.org/pdf/1206.2598v2.pdf

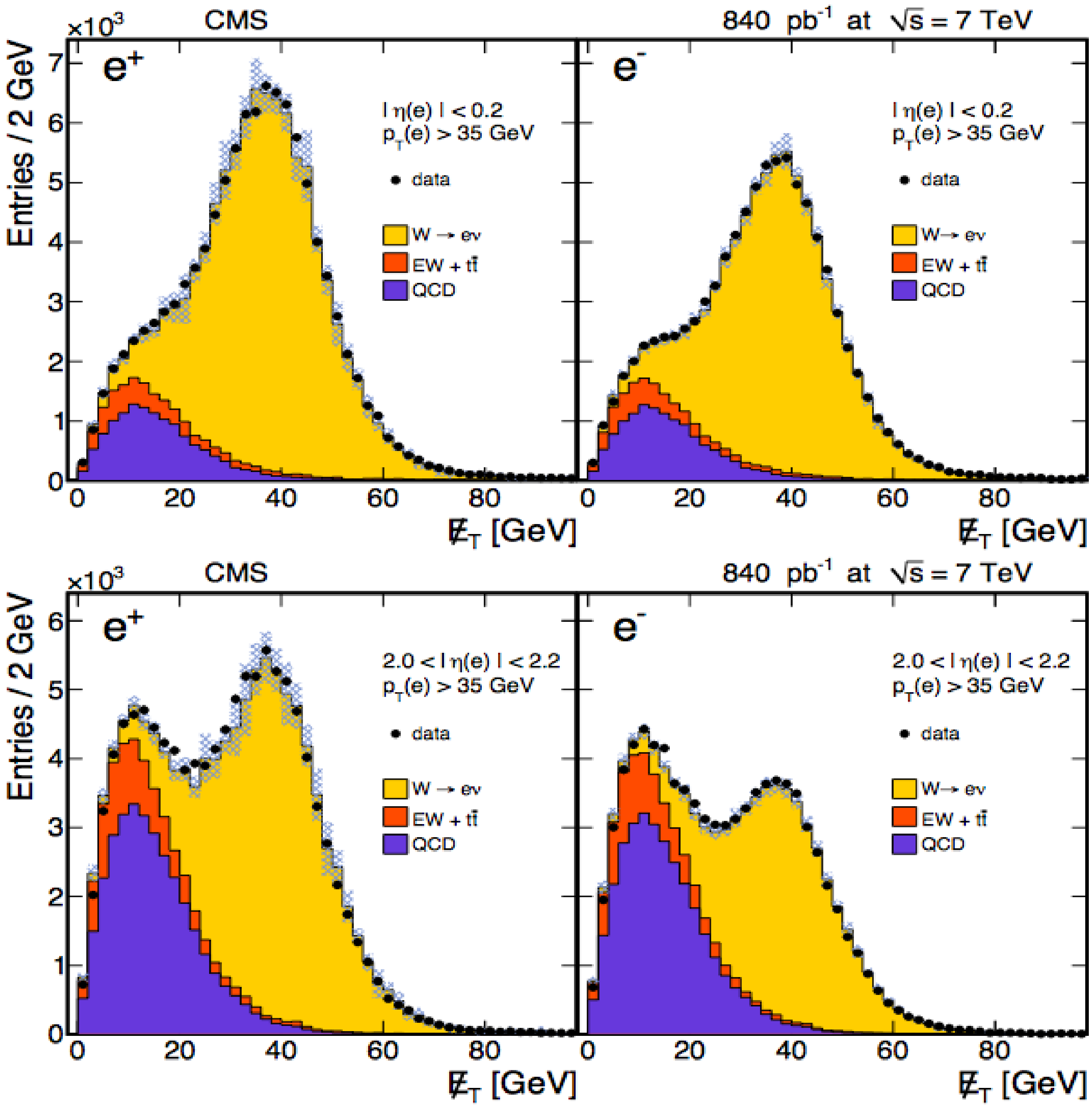
$$\mathcal{A}(\eta) = \frac{d\sigma/d\eta(W^+ \to e^+\nu) - d\sigma/d\eta(W^- \to e^-\bar{\nu})}{d\sigma/d\eta(W^+ \to e^+\nu) + d\sigma/d\eta(W^- \to e^-\bar{\nu})}$$

ő $$\frac{u(x_1)D(x_2) - U(x_1)d(x_2)}{u(x_1)D(x_2) + U(x_1)d(x_2)}$$

where q(*x*) [Q(*x*)] denotes the quark (antiquark) density at momentum faction *x*

$x_1 x_2$ ö $M_W^2/s$ & $ln(x_1/x_2) \propto \eta$

# Missing $E_T$ in Inclusive W Boson Events (CMS)



# Systematic Uncertainties in Electron Asymmetry (CMS)

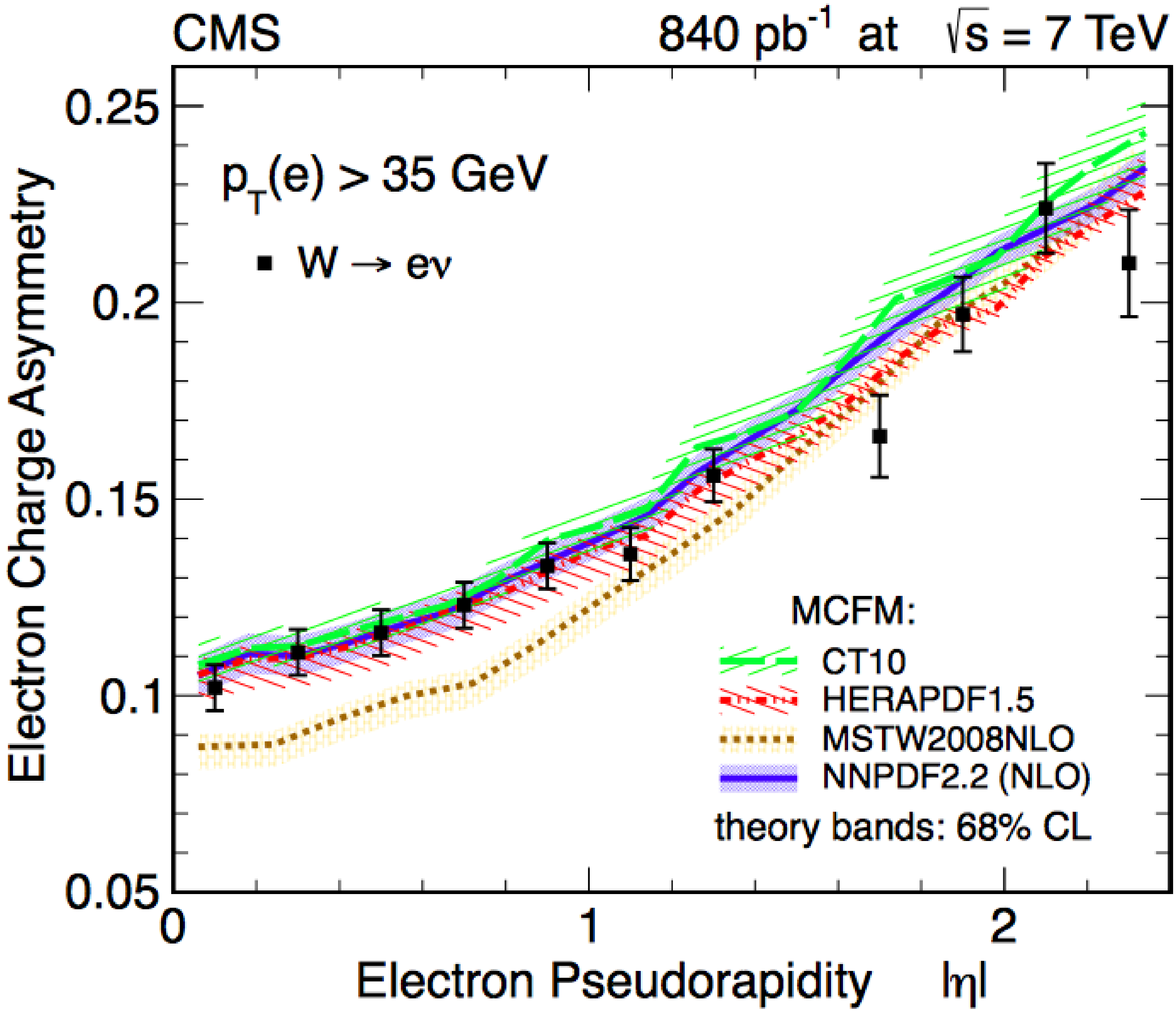
Table 1: Summary of the systematic uncertainties on the asymmetry. All values are given in units of $10^{-3}$.

| $\lvert\eta\rvert$ bin | Signal Yield | Energy Scale & Res. | Charge MisId. | Efficiency Ratio |
|---|---|---|---|---|
| $0.0 < \lvert\eta\rvert < 0.2$ | 1.8 | 0.6 | <0.1 | 4.5 |
| $0.2 < \lvert\eta\rvert < 0.4$ | 2.5 | 0.6 | <0.1 | 4.4 |
| $0.4 < \lvert\eta\rvert < 0.6$ | 2.7 | 0.3 | <0.1 | 4.4 |
| $0.6 < \lvert\eta\rvert < 0.8$ | 2.5 | 0.3 | <0.1 | 4.4 |
| $0.8 < \lvert\eta\rvert < 1.0$ | 1.9 | 0.6 | 0.1 | 4.4 |
| $1.0 < \lvert\eta\rvert < 1.2$ | 2.4 | 1.0 | 0.1 | 4.9 |
| $1.2 < \lvert\eta\rvert < 1.4$ | 2.6 | 0.8 | 0.1 | 5.4 |
| $1.6 < \lvert\eta\rvert < 1.8$ | 3.1 | 0.8 | 0.1 | 9.2 |
| $1.8 < \lvert\eta\rvert < 2.0$ | 2.0 | 1.6 | 0.2 | 8.7 |
| $2.0 < \lvert\eta\rvert < 2.2$ | 2.0 | 2.6 | 0.3 | 10.0 |
| $2.2 < \lvert\eta\rvert < 2.4$ | 2.9 | 2.4 | 0.3 | 12.5 |

Correction for backgrounds

Measured using $Z \longrightarrow ee$ events

# Systematic Uncertainties in Electron Asymmetry (CMS)



# Trilinear and Quartic Gauge Couplings

- Prediction of "forces" based on the idea of gauge invariance in Quantum Field Theory
  - Ψ → ∫^EBξ(Y) Ψ (B∈PB∫ ΓΞ∈ΚΟΛΛΞ ∈ΓΞΛΚ ΛΑ
    Α∫Ξ ΞΛΚ□ ∫Θ∫)
- ∂ΚΓΞΛ ∫PUΓΞΛΚ ΛΑ∈Σ∫UΓΛΞΜΛΠ∫ΚΓΞΘΑ$_\mu$ (∈Η.∈ Β∈PB∫
  □ ∫Θ∫),
  - $\partial_\mu \Psi \rightarrow D_\mu \Psi = (\partial_\mu - i\, g A_\mu)\,\Psi$
  - $A_\mu \rightarrow A_\mu + \partial_\mu \xi$
- Gauge-invariant Field Strength tensor $F_{\mu\nu}$
  - $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
  - For gauge transformation in the internal space described by the (Abelian) U(1) group
- Kinetic energy associated with e.g. "electromagnetic field"

# Trilinear and Quartic Gauge Couplings

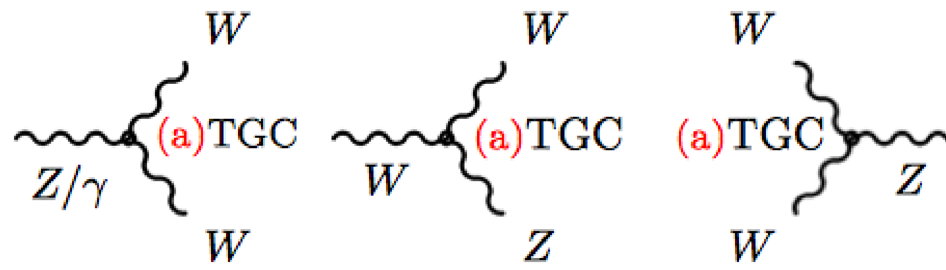
- For non-Abelian Gauge group, Gauge-invariant Field Strength tensor $F_{\mu\nu}$
  - $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu, A_\nu]$
- (gauge and Lorentz-invariant) kinetic energy term $F_{\mu\nu} F^{\mu\nu}$ ΦΕϑΘςΟ
  - ΠϑΞ ΟΤΓΕΙΓ ∈Ξϑ ΝΡ∈∫ΞΞΠΕ∪ΕΚ Β∈ΡΒϑ ϑΘς (ΠΓ ϑΟϑ ΦΕϑΘς ΠΓ ϑ Β∈ΡΒϑ ∩ΛΟΛΚ ΜΕΛΜΕΒ∈ΠΛΞ)
  - ≠Ρ∩Ε∪Πϑ Ξ Ο
  - ƒ Ρ∈ΞΠΕ∪Πϑ Ξ Ο
- π∈ΠΠϑΞΙΤ Λ ΠΦΜϑΟΛΑΠϑΞ ΟΦΕϑΘς ΠΕΦΚϑ∈Ξ∈Κ∫ ΝΡ∈ΞΠΕ∪ Β∈ΡΒϑ ∪ΛΡΜΦΚΒΟ

# Anomalous Trilinear Gauge Coupling

$V = Z, \gamma$

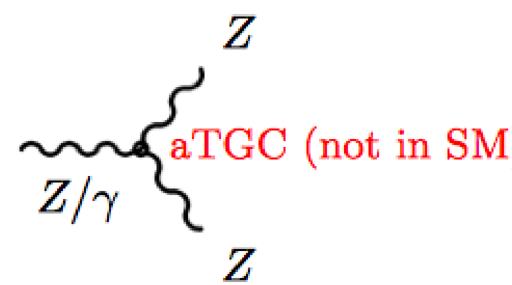
- effective parametrizations for anomalous couplings:
  - $WWV$ vertex: $\Delta g_1^Z, \Delta\kappa_Z, \Delta\kappa_\gamma, \lambda_Z, \lambda_\gamma$

    → constraints from $WW$, $WZ$, $W\gamma$, and EW $Zjj$ measurements




  - $ZZV$ vertex (not in SM): $h_3^V$, $h_4^V$, $f_4^V$, $f_5^V$

    → constraints from $ZZ$ and $Z\gamma$ measurements

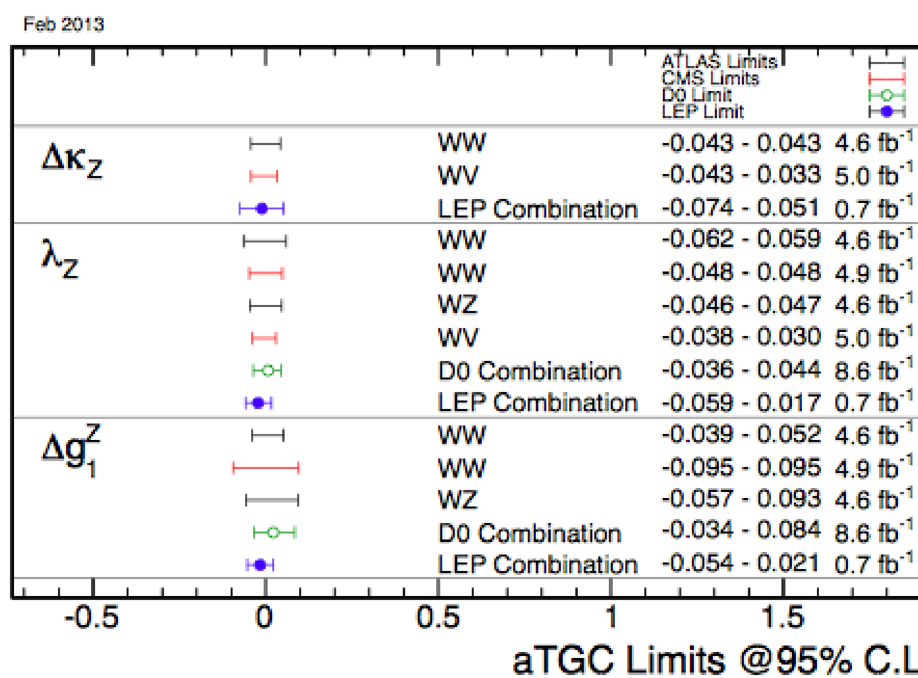



- 1- and 2-dimensional 95% confidence intervals for aTGC from 7 TeV data, e.g.

  → without and with form factors to avoid unitarity violation

  $$\mathcal{F}(s) = \frac{1}{(1+\hat{s}/\Lambda_{\rm FF}{}^2)^n}$$

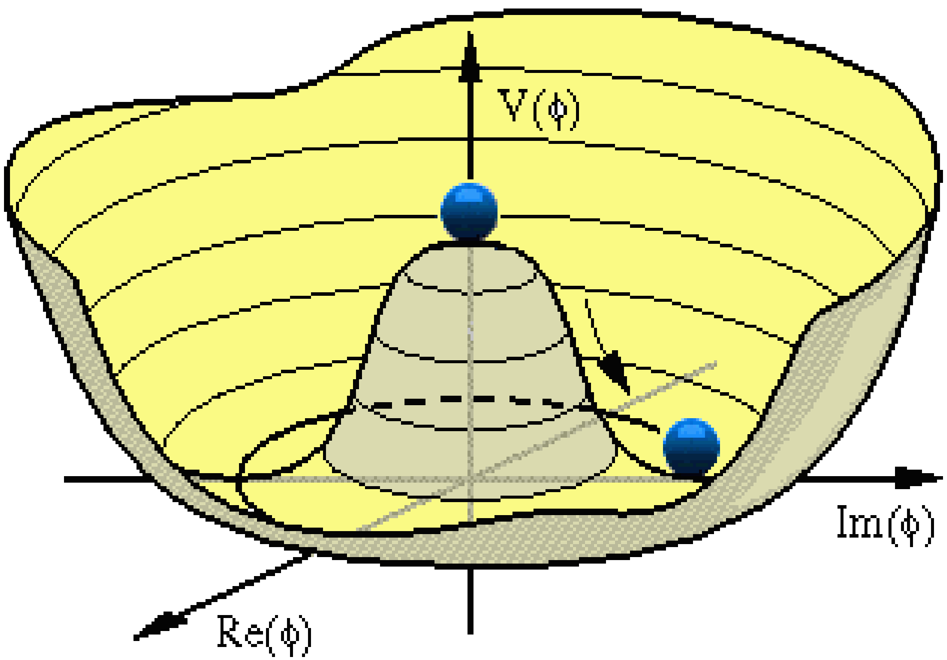
  ($\Lambda_{\rm FF}$: form factor scale)




(from A. Vest, TU-Dresden)

# Spontaneous Symmetry Breaking of Gauge Symmetry

- postulate of scalar Higgs field which develops a vacuum expectation value via spontaneous symmetry breaking (SSB)




- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state
- Radial (Higgs boson) and azimuthal (longitudinal gauge boson) excitations are related !!

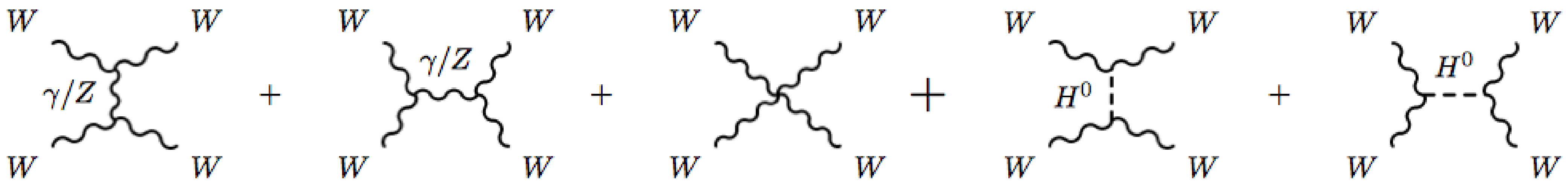
# Quartic Gauge Couplings

$V = W, Z$

- the mechanism responsible for EWSB must regulate $\sigma(V_L V_L \to V_L V_L)$ to restore unitarity above $\sim 1 - 2$ TeV

  $\rightarrow$ a light SM Higgs boson exactly cancels increase for large $s$ (for $HWW$ coupling)

$$\mathcal{A}(W_L W_L \to W_L W_L) \propto \frac{g_W^2}{v^2}\left[-s - t + \frac{s^2}{s-m_H^2} + \frac{t^2}{t-m_H^2}\right]$$




- unitarity preservation only visible in $VV$ scattering

  $\Rightarrow$ $VV$ scattering is a key process to probe the SM nature of EWSB!

- at the LHC: measure $VVjj$ final states $\rightarrow$ same-sign $W^\pm W^\pm jj$ most promising

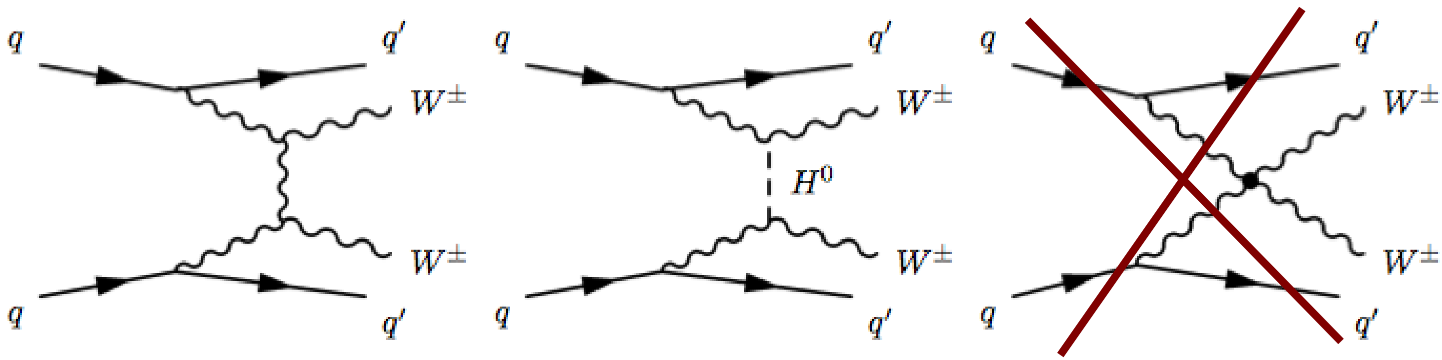
(from A. Vest, TU-Dresden)

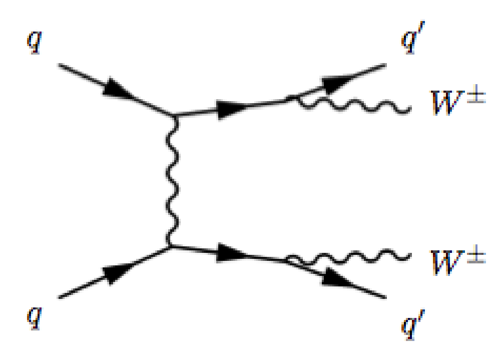
# Same-Sign Boson-boson Scattering

- electroweak $W^{\pm}W^{\pm}jj$ production:

  $W^{\pm}W^{\pm}jj$-EW VBS: no s-channel diagrams

  non-VBS diagrams, e.g.

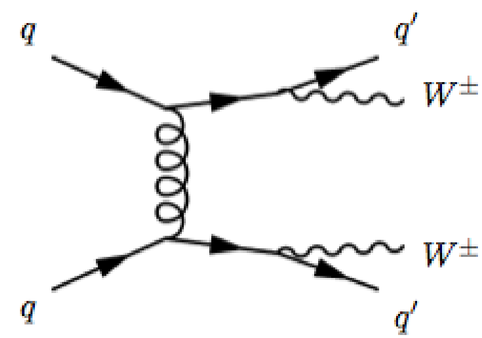



  → lowest order: $W^{\pm}W^{\pm} + 2$ jets, there is no SM inclusive $W^{\pm}W^{\pm}$ production!

  → VBS: “tagging” jets well separated in $y$ with large $m_{jj}$ (similar to EW $Zjj$ production)

- strong $W^{\pm}W^{\pm}jj$ production:




  → no LO $gg$ or $qg$ initial state → strong $W^{\pm}W^{\pm}jj$ contributions comparably small

(from A. Vest, TU-Dresden)

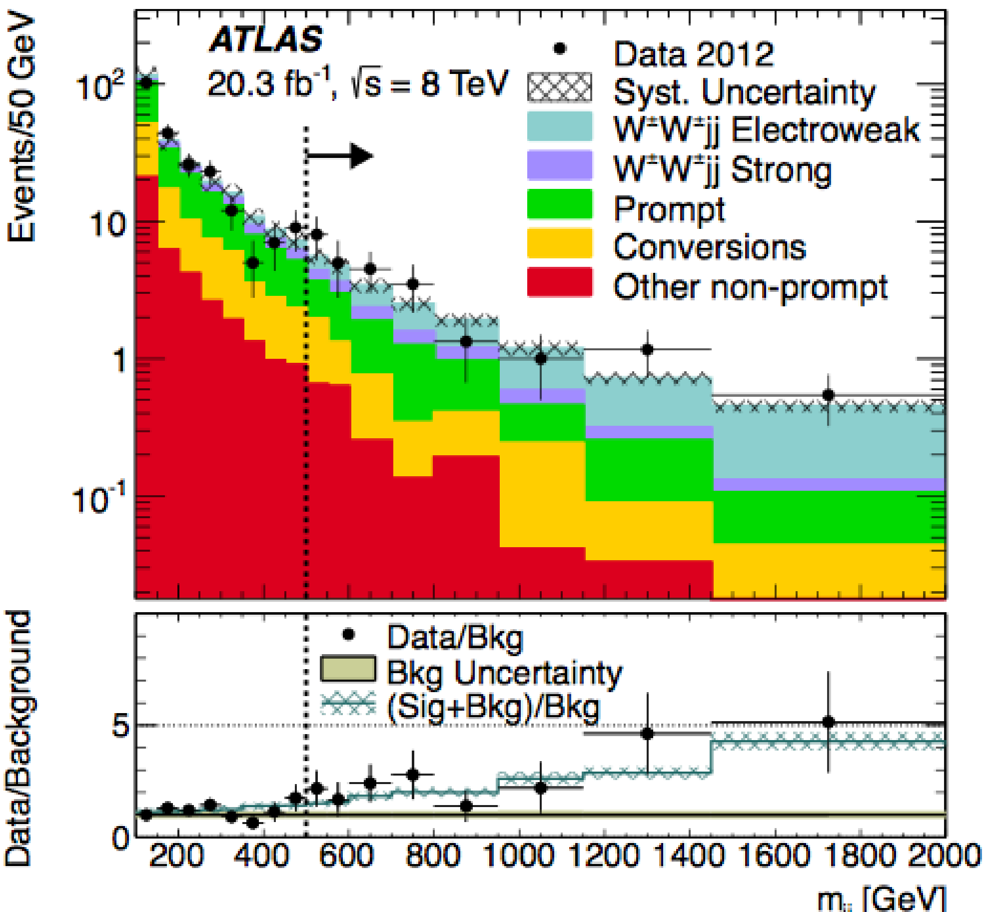
# $W^{\pm}W^{\pm}$ Scattering

**for EW+strong measurement**

("inclusive signal region")

→ $m_{jj} > 500$ GeV (jets with largest $p_T$)

invariant mass of the 2 tagging jets

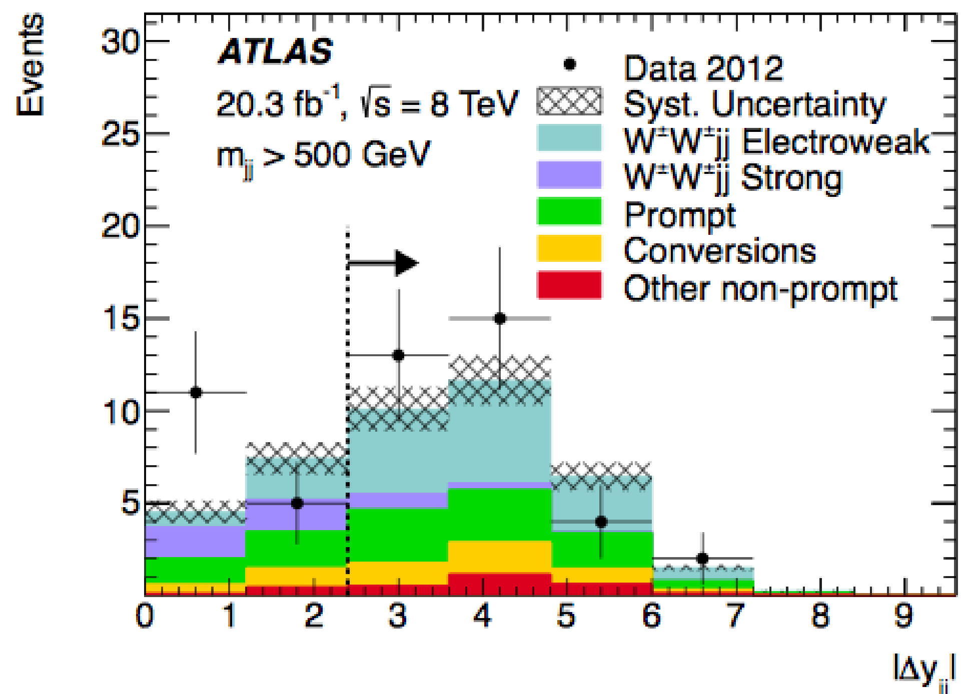



**for EW measurement**

("VBS signal region")

→ additional cut on $|\Delta y_{jj}| > 2.4$

$|\Delta y_{jj}|$ between the 2 tagging jets

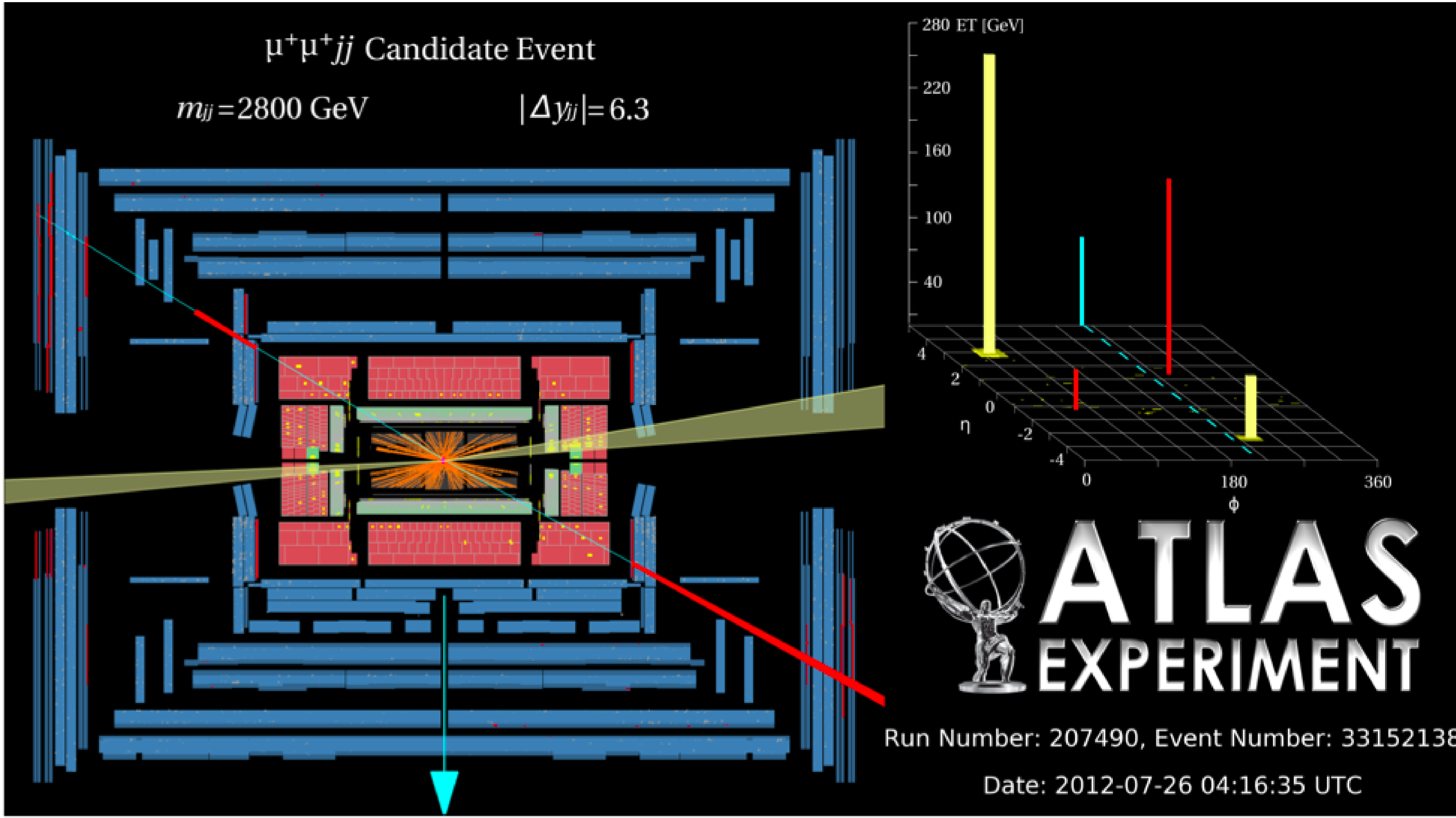



EW and strong $W^{\pm}W^{\pm}jj$ from SHERPA, normalized with POWHEG

(from A. Vest, TU-Dresden)

ATLAS: arXiv:1405.6241, submitted to PRL
CMS: PAS SMP-13-015

# $W^{\pm}W^{\pm}$ Scattering




jets: $p_T^{j1} = 271$ GeV, $p_T^{j2} = 54$ GeV, $\eta^{j1} = 2.9$, $\eta^{j2} = -3.4$ $E_T^{\mathrm{miss}} = 75$ GeV

muons: $p_T^{\mu 1} = 180$ GeV, $p_T^{\mu 2} = 38$ GeV, $\eta^{\mu 1} = 1.4$, $\eta^{\mu 2} = -1.3$

(from A. Vest, TU-Dresden)

# 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 directly measured mass of Higgs Boson ~ 125 GeV

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

# Summary

- Collider measurements can help to improve our knowledge of PDFs which are needed for making precision measurements

- For the first time, LHC is creating the opportunity to test a key prediction of the SM:

    - The unitarization of longitudinal boson scattering at high energy

- Same-sign WW scattering signal observed

    - Ongoing searches for other channels: WZ and Wγ ΕΚ Σ⌡∪ΠΛΞ∩ΛΟΛΚ ΟυΕΠ⌡ΞΚΒ Ι Λ⌠⌡

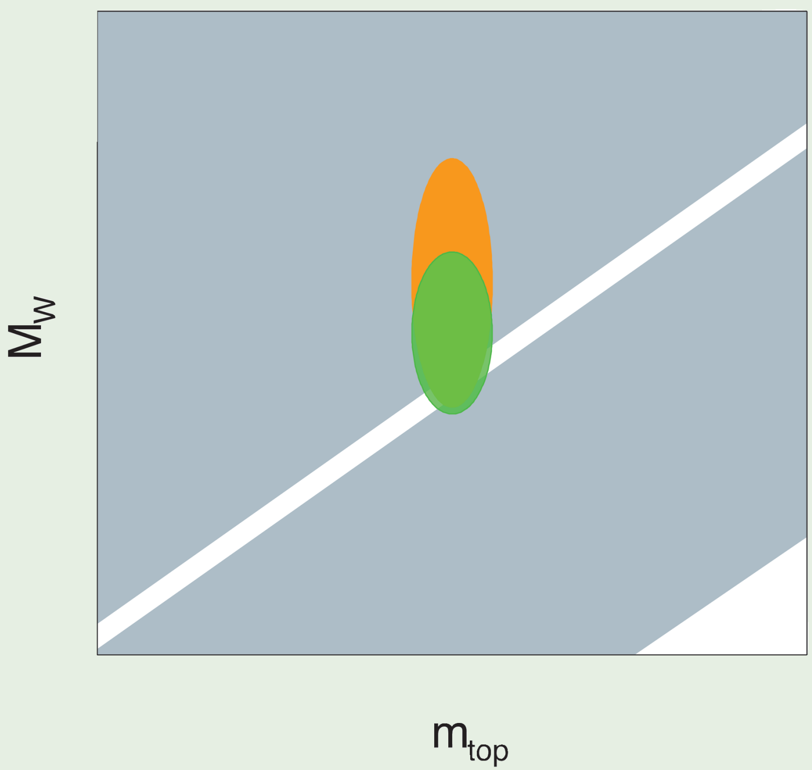
    - Opposite-sign WW scattering has largest signal yield, but overwhelmed by top-antitop production background

- High-Luminosity LHC will provide opportunity to test composite Higgs models

# PHYSICAL REVIEW LETTERS™



Articles published week ending 13 APRIL 2012

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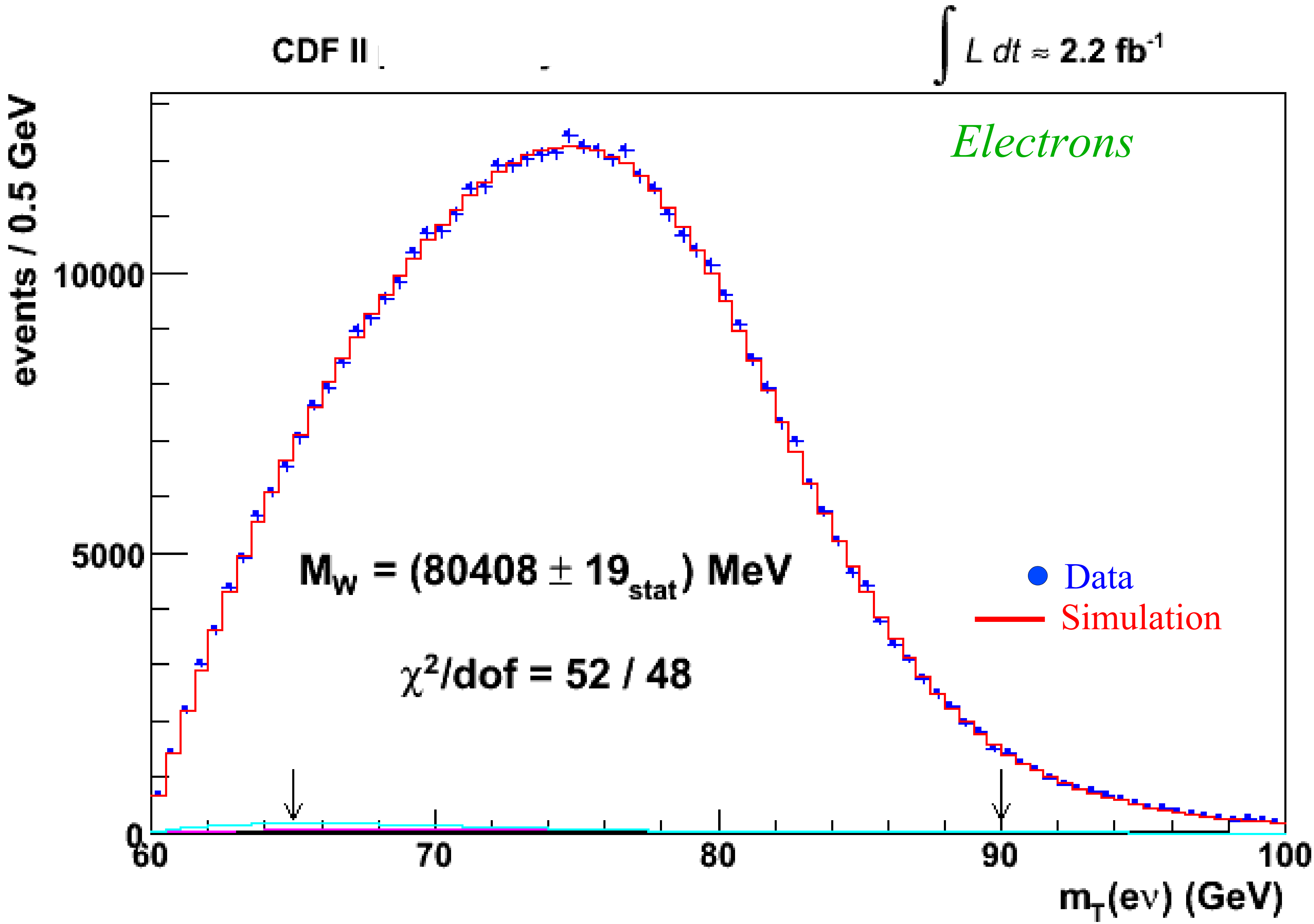
**American Physical Society**™

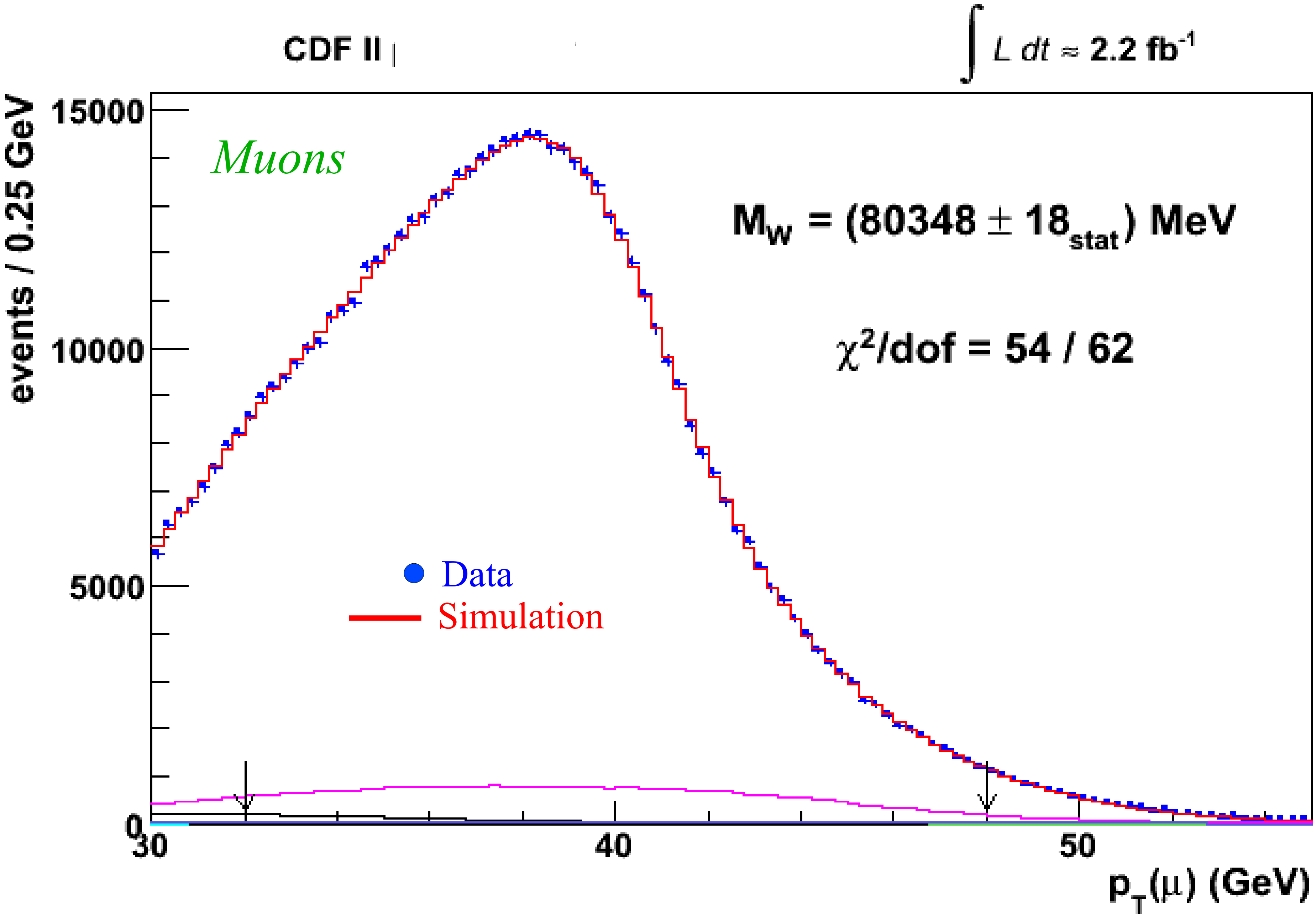
APS physics™

Volume 108, Number 15

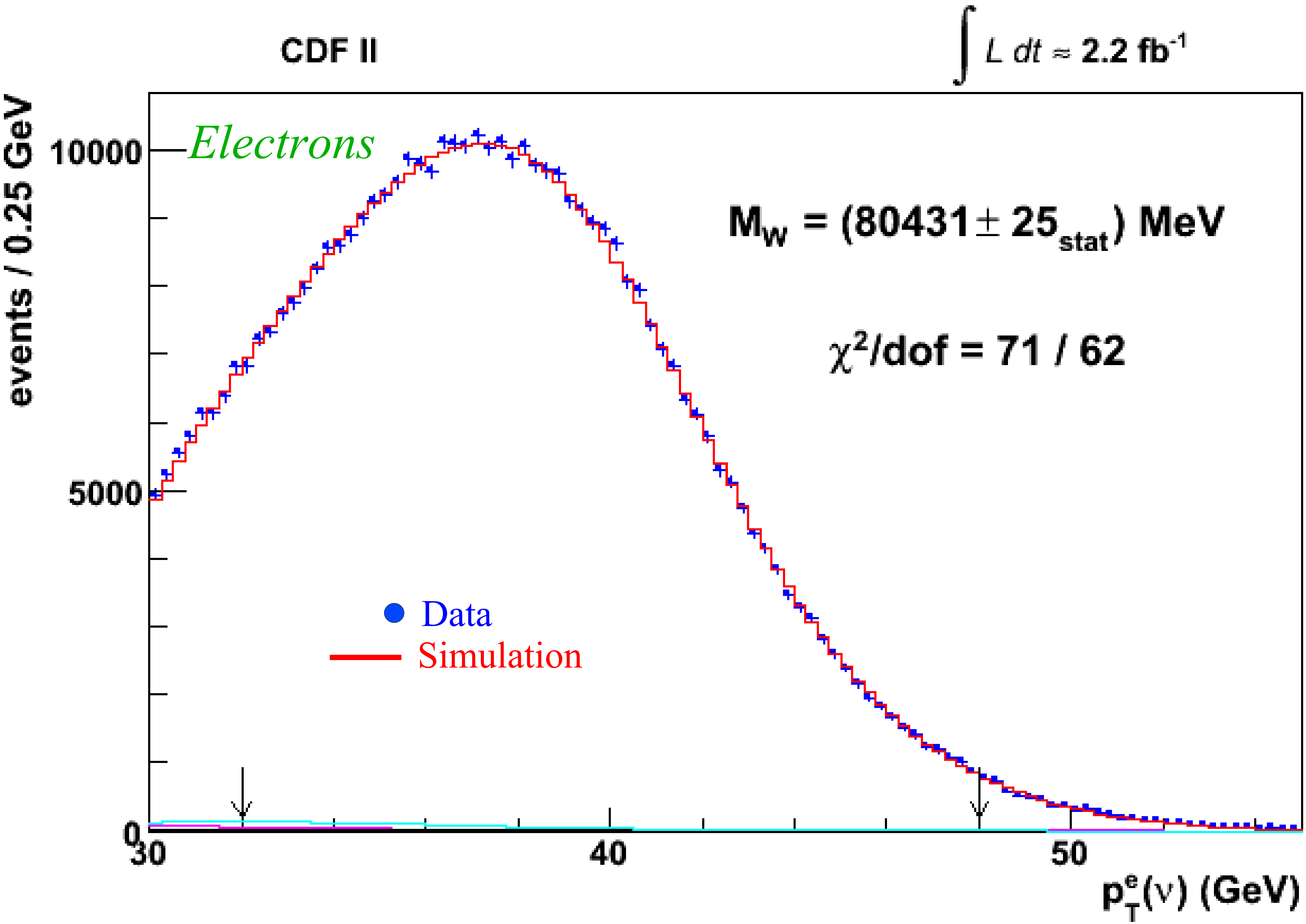
# *W* Transverse Mass Fit



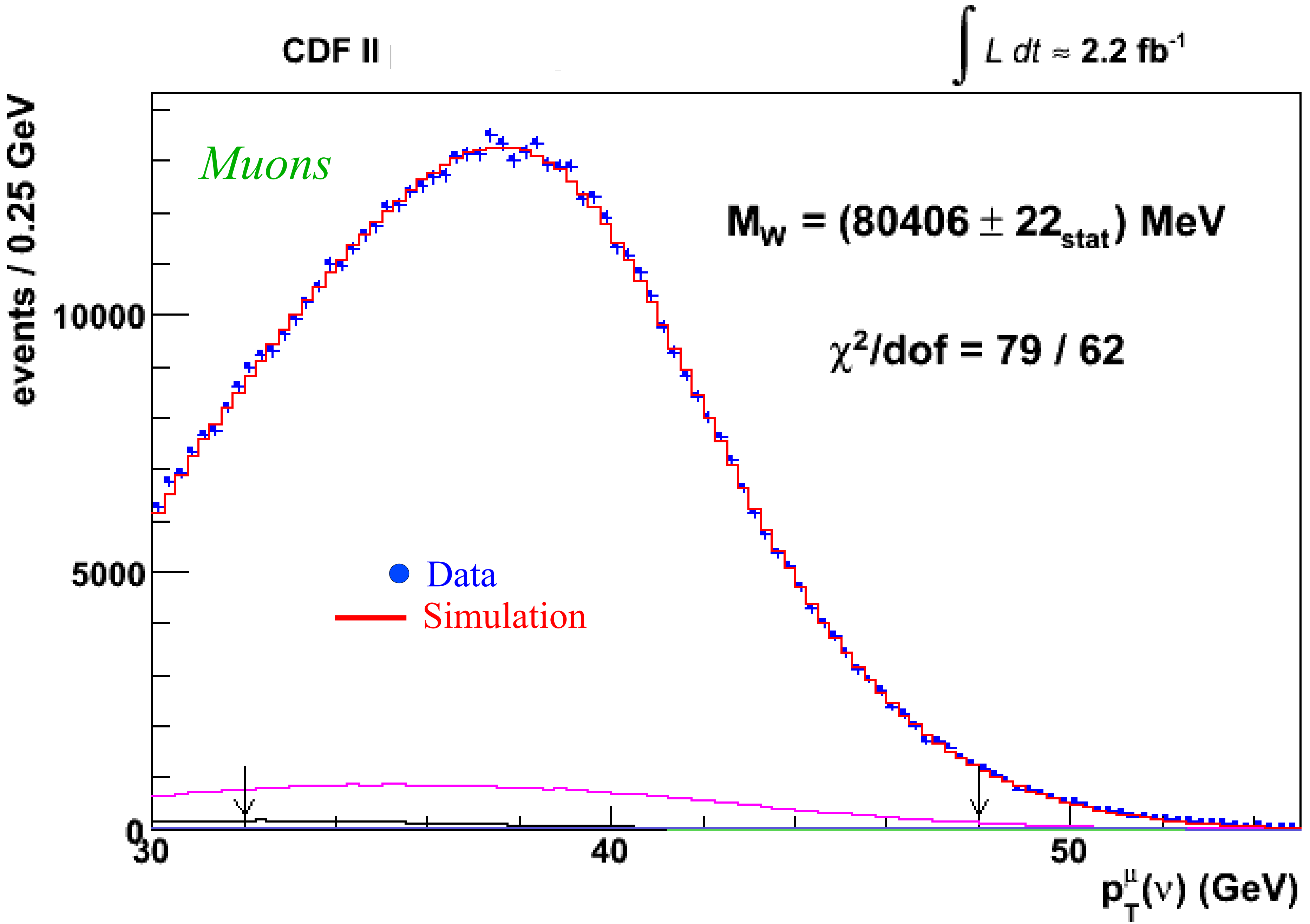
# *W* Lepton $p_T$ Fit



# $W$ 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 $\sigma_h$ $\gamma$ $(150 \pm 1_{stat})$ μm
  - Beamspot size $\sigma_b = (35 \pm 1_{stat})$ μm
  - Tuned on the widths of the $Z \rightarrow \mu\mu$ (beam-constrained) and $\Upsilon \rightarrow \mu\mu$ (both beam constrained and non-beam constrained) mass peaks

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

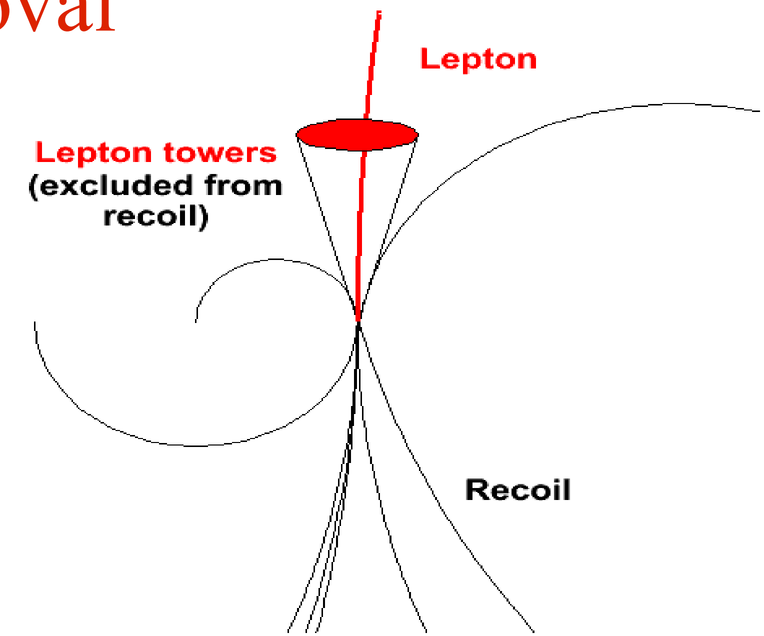
- Electron cluster resolution parameterized in the custom simulation by
  - 12.6% / $\sqrt{E_T}$ (sampling term)
  - Primary constant term $\kappa = (0.68 \pm 0.05_{stat})$ %
  - Secondary photon resolution $\kappa_\gamma = (7.4 \pm 1.8_{stat})$ %
  - Tuned on the widths of the E/p peak and the $Z \rightarrow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