Electroweak Physics and Parton Distribution Functions

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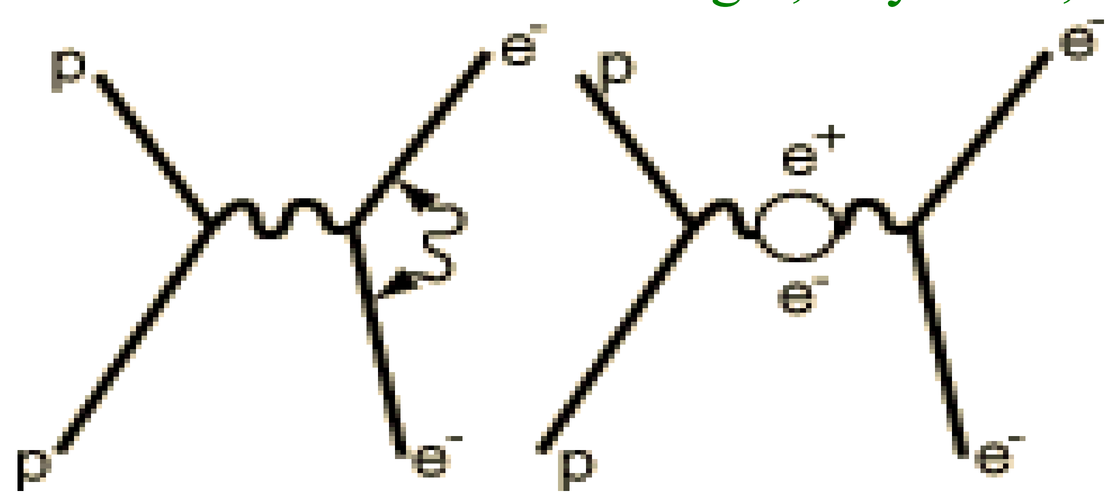
Detecting New Physics through Precision Measurements

- 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 ϑ_W

Parameters of Electro-Weak Interactions

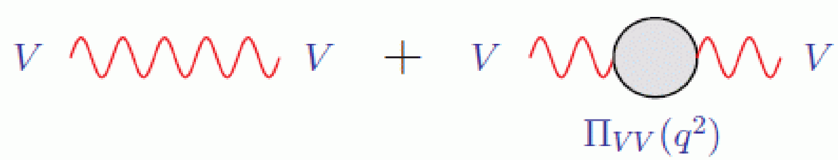
At tree level, all of the observables can be expressed in terms of *three* parameters of the SM Lagrangian: $v,\ g,\ g'$ or, equivalently, $v,\ e,\ s \equiv \sin\theta_W$ (also $c \equiv \cos\theta_W$)

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

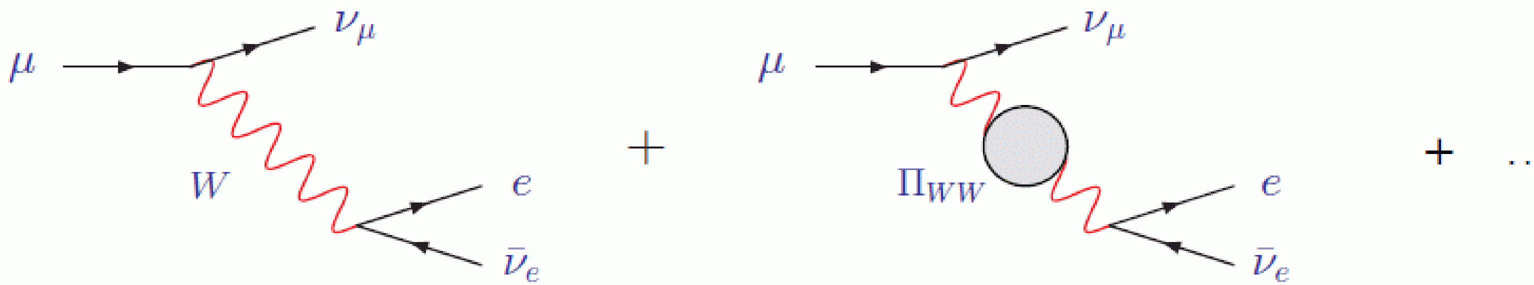
Radiative corrections to the relations between physical observables and Lagrangian params:

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

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

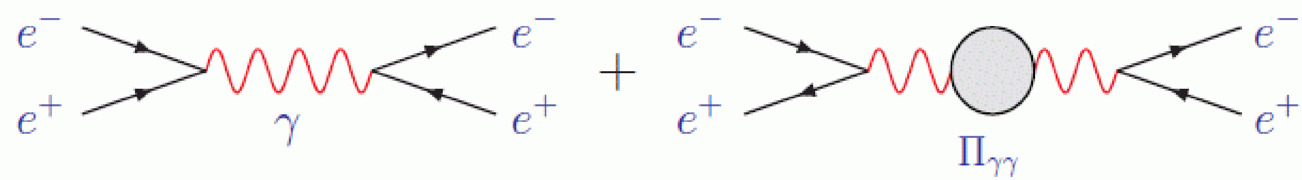


$$G_F = \frac{1}{2\sqrt{2}v^2}\left[1 - \frac{\Pi_{WW}(0)}{m_W^2} + \delta_{\rm VB}\right]$$



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

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

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

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

(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.:

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

Δr can be parametrized in terms of two universal corrections and a remainder:

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

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

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

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

Motivation for Precision Measurements

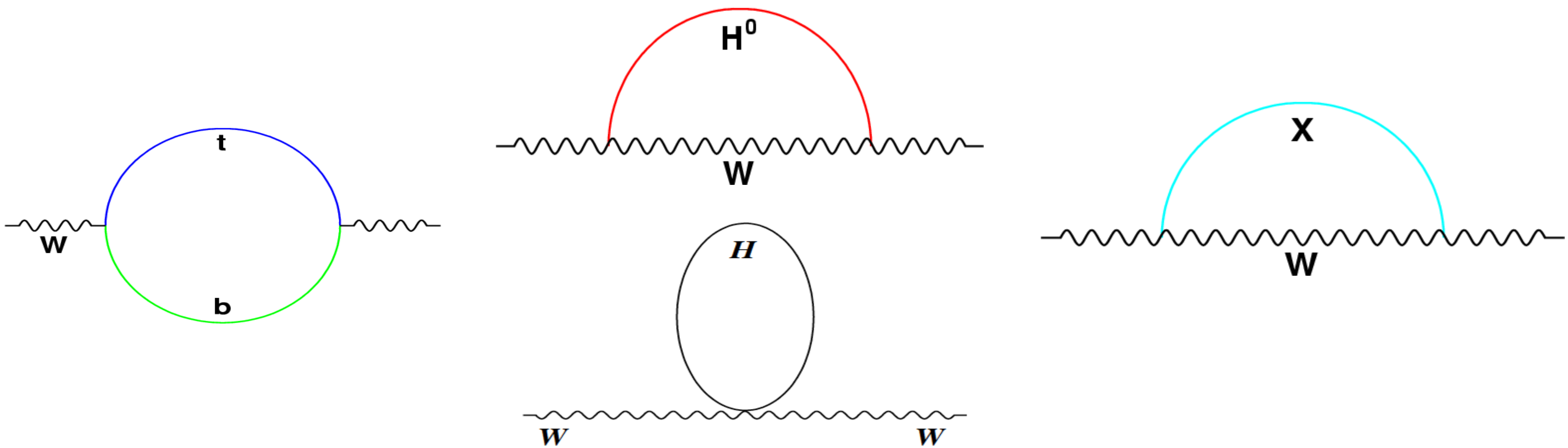
- The electroweak gauge sector of the standard model is constrained by three precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\ (1) \times 10^{-5}\ \mathrm{GeV}^{-2}$

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

      $\cos\vartheta_W = M_W/M_Z$

Motivation for Precision Measurements

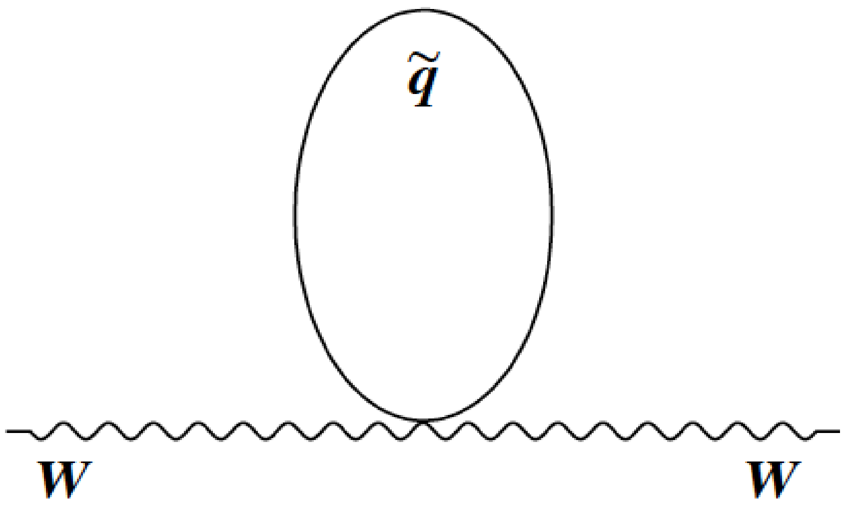
- Radiative corrections due to heavy quark and Higgs loops and exotica

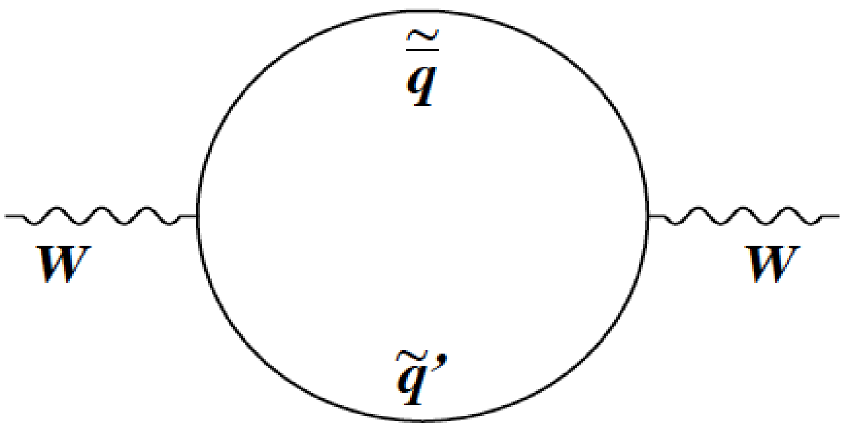


Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\text{tree})]^2$
with the predictions $\Delta\rho = (\rho\text{-}1) \sim M_{top}^2$ and $\Delta\rho \sim \ln M_H$

- 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

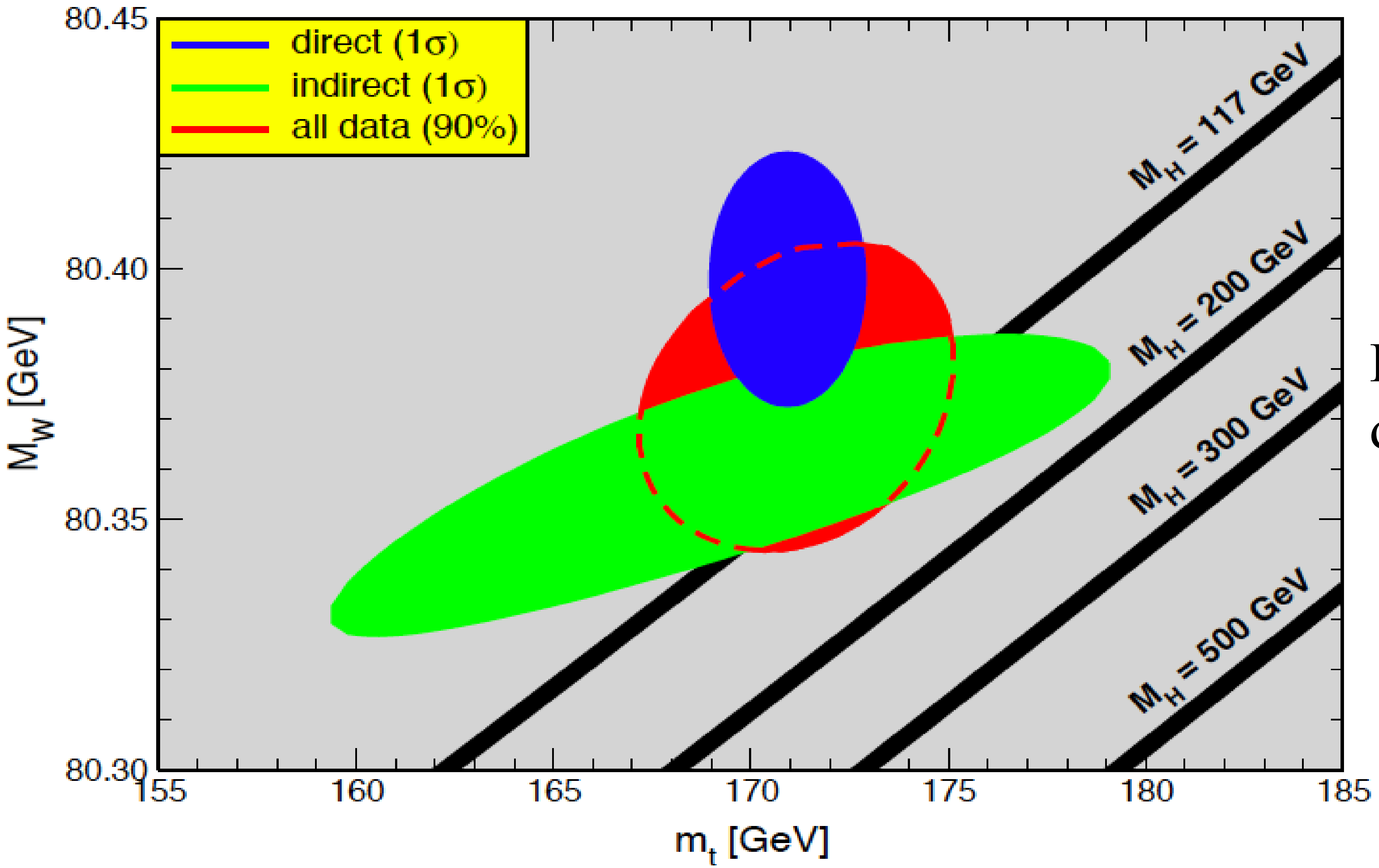




- Radiative correction depends on mass splitting (Δm^2) between squarks in SU(2) doublet

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

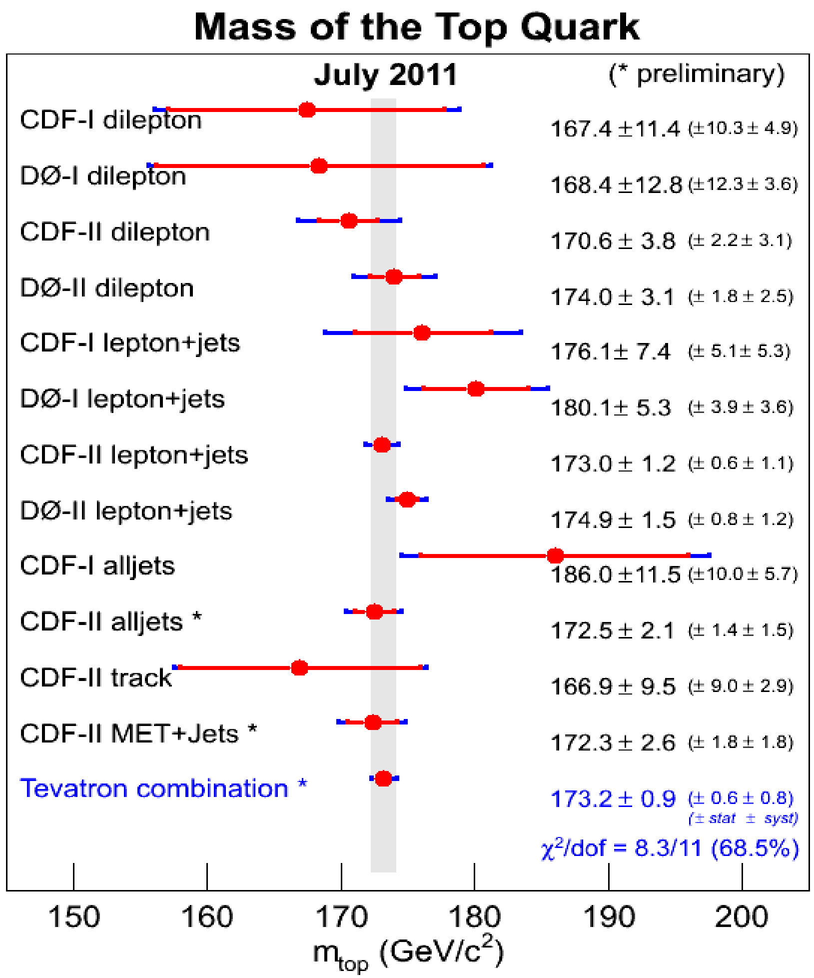
Uncertainty from $\alpha_{EM}(M_Z)$



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

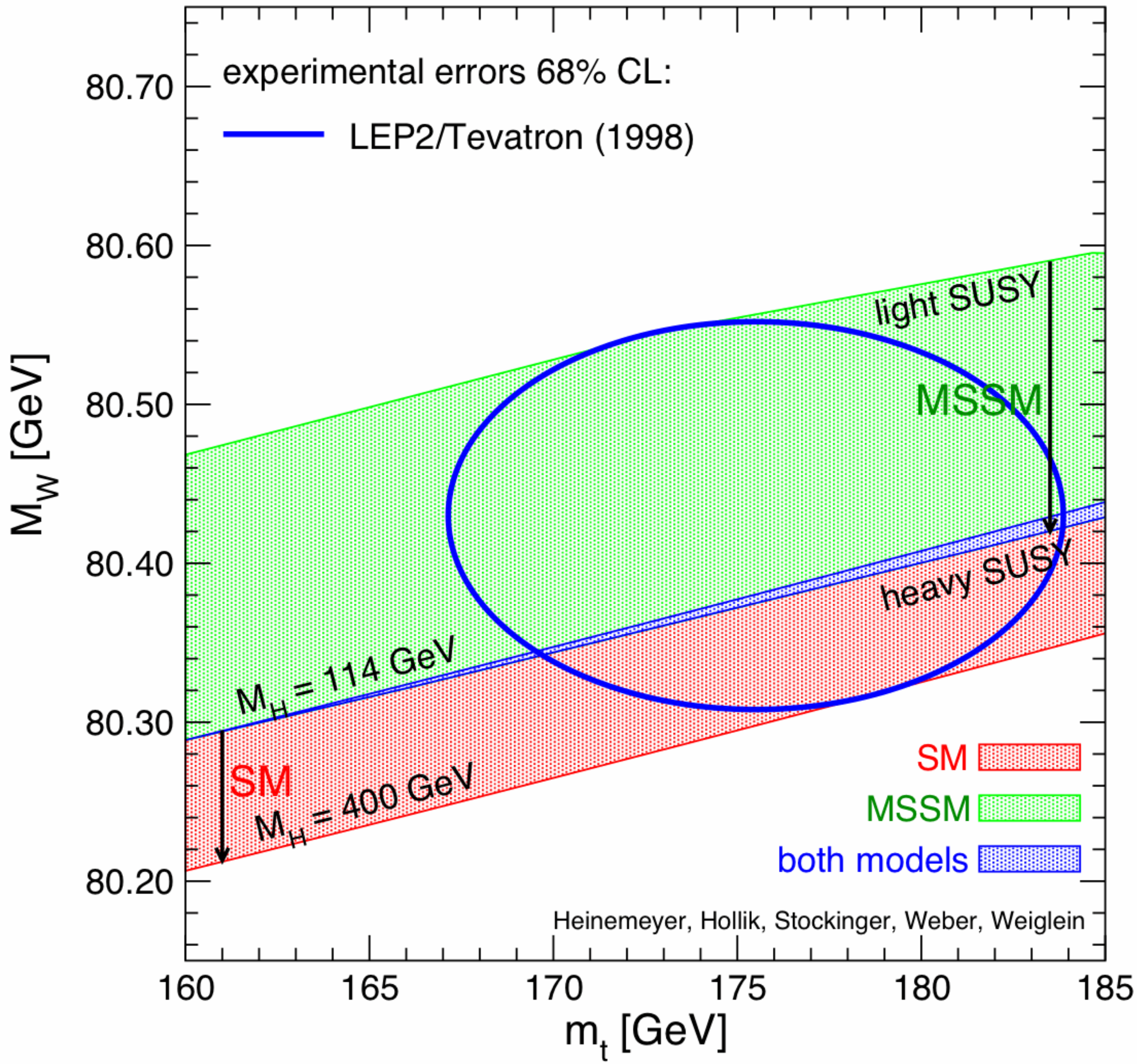
- $\delta\alpha_{EM}$ dominated by uncertainty from non-perturbative contributions: hadronic loops in photon propagator at low Q^2
- equivalent $\delta M_W \approx 4$ MeV for the same Higgs mass constraint
  - Was equivalent $\delta M_W \approx 15$ MeV a decade ago !

Progress on M_{top} at the Tevatron

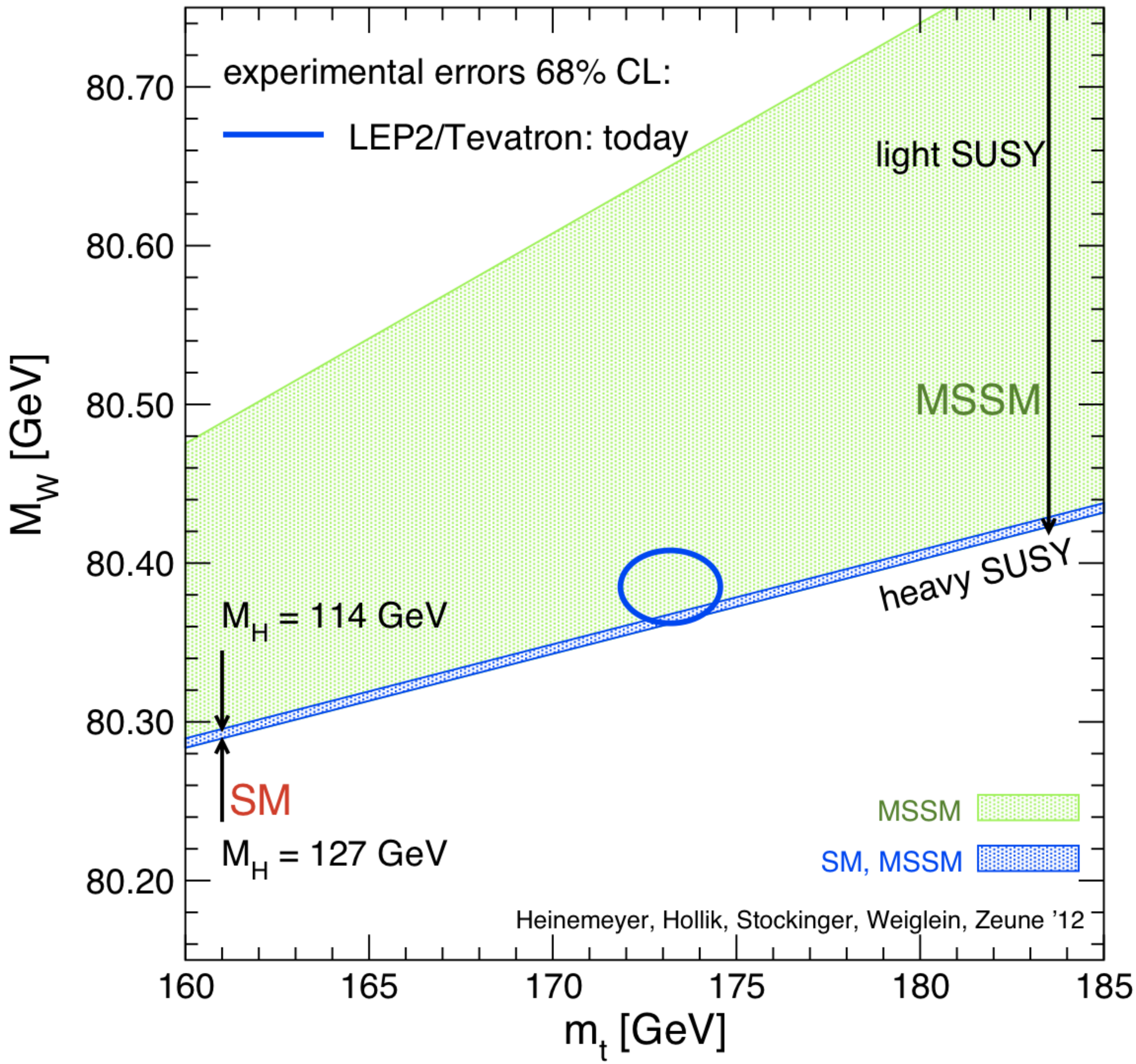


- From the Tevatron, ΔM_{top} = 0.9 GeV => $\Delta M_H / M_H$ = 8%
- equivalent ΔM_W = 6 MeV for the same Higgs mass constraint
- Current world average ΔM_W = 15 MeV
  - progress on ΔM_W has the biggest impact on Higgs constraint

1998 Status of M_W *vs* M_{top}

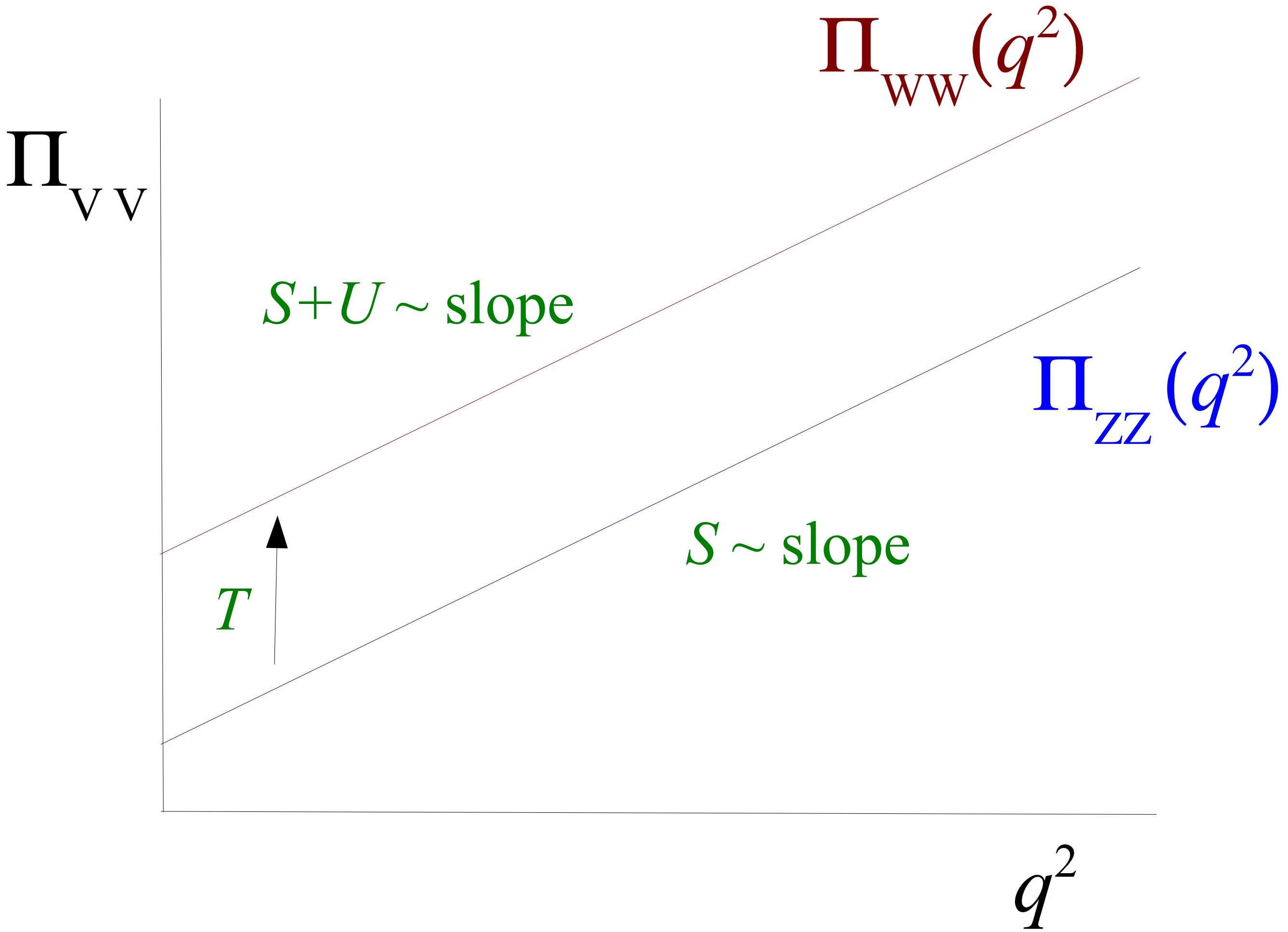


2012 Status of M_W *vs* M_{top}



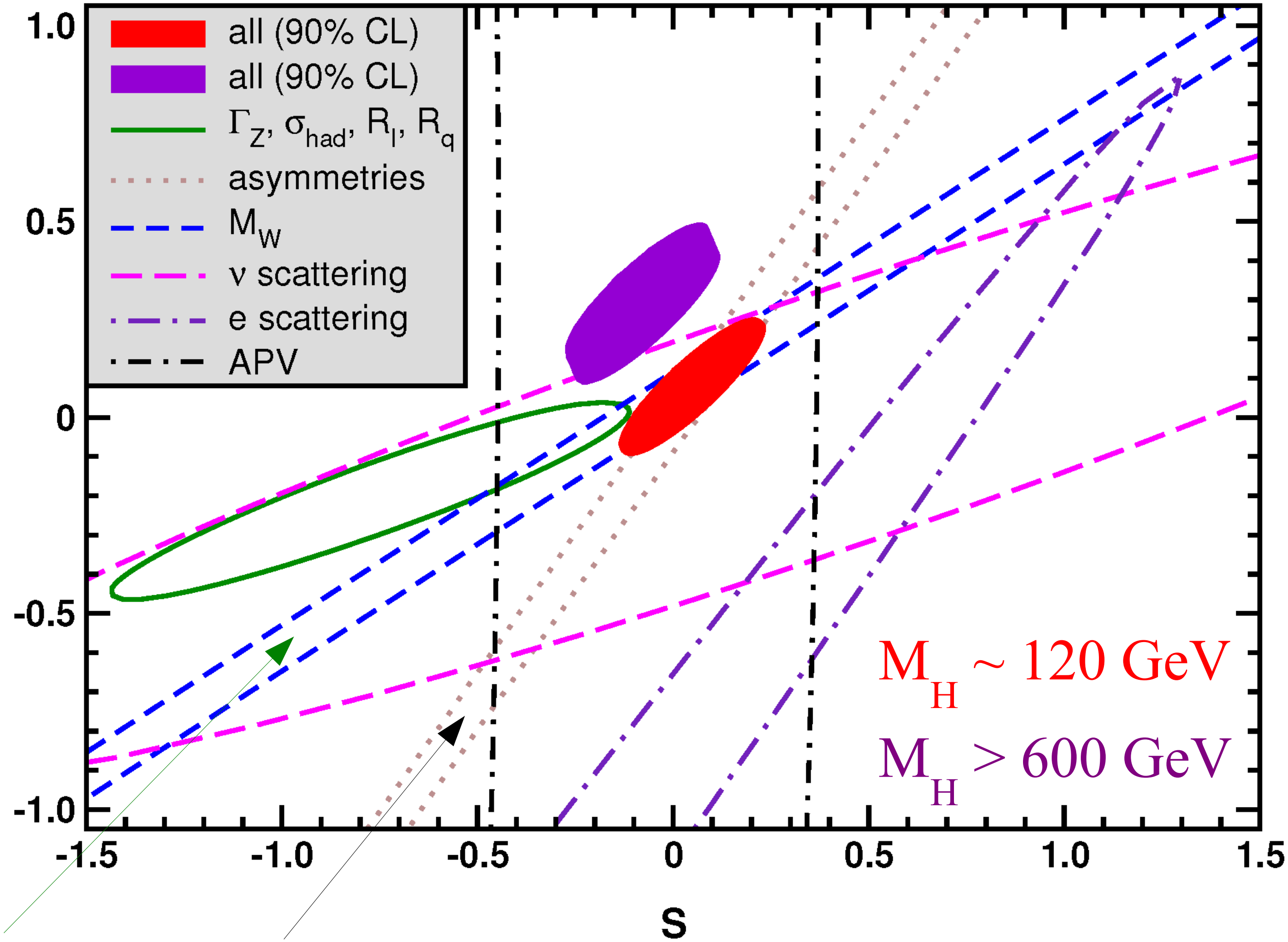
Motivation

- 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)



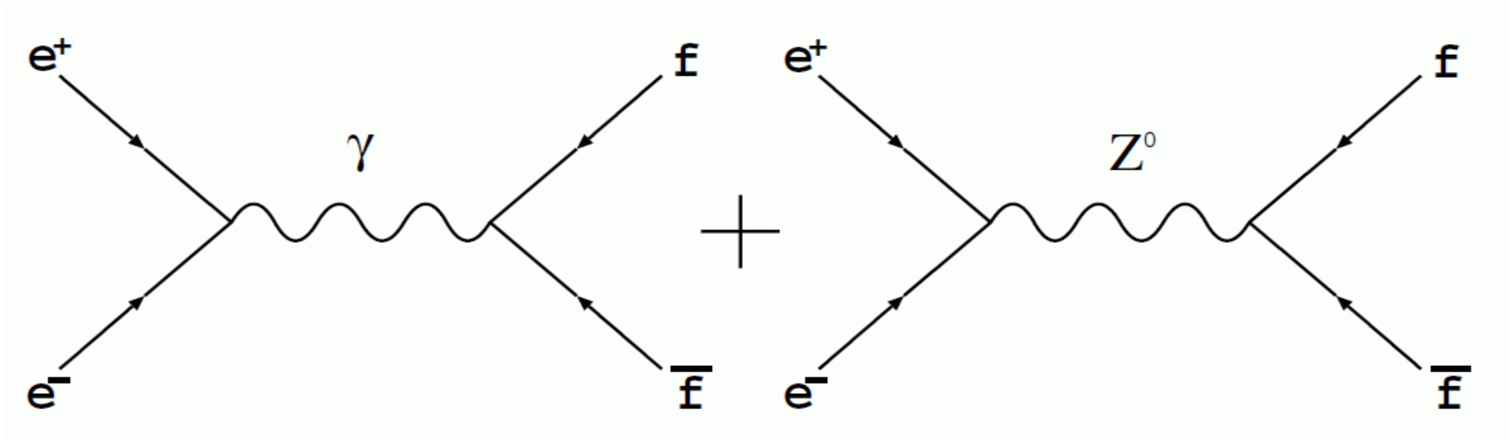
Additionally, M_W is the only measurement which constrains *U*

(from P. Langacker, 2012)

M_W and Asymmetries are the most powerful observables in this parameterization

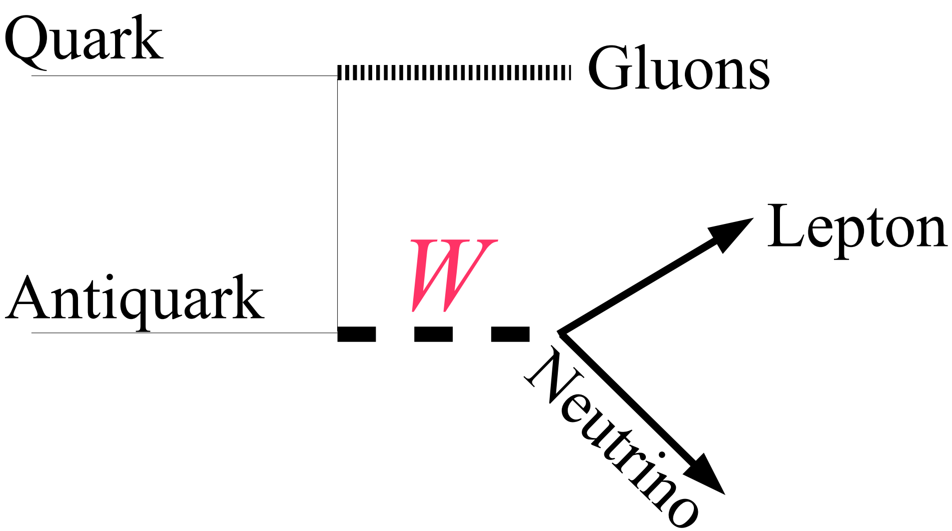
A_{FB} and A_{LR} Observables

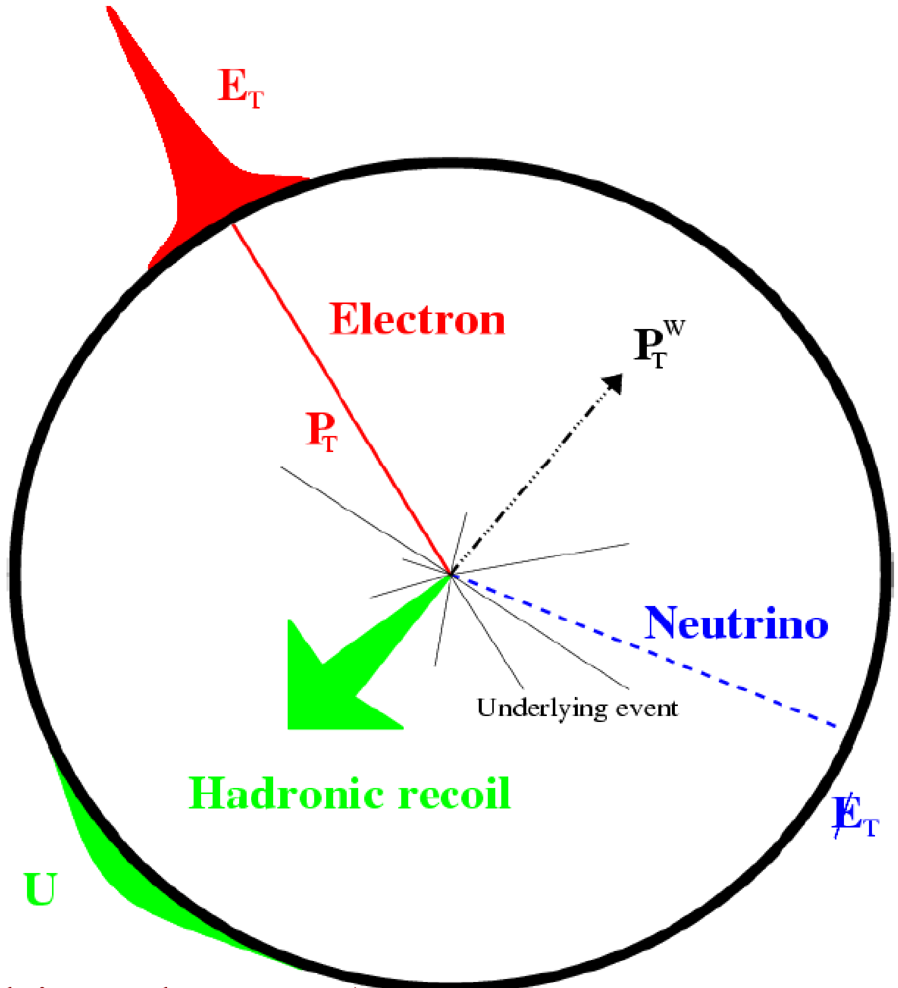
- Asymmetries definable in electron-positron scattering sensitive to Weinberg mixing angle ϑ_W



- Higgs and Supersymmetry also contribute radiative corrections to ϑ_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





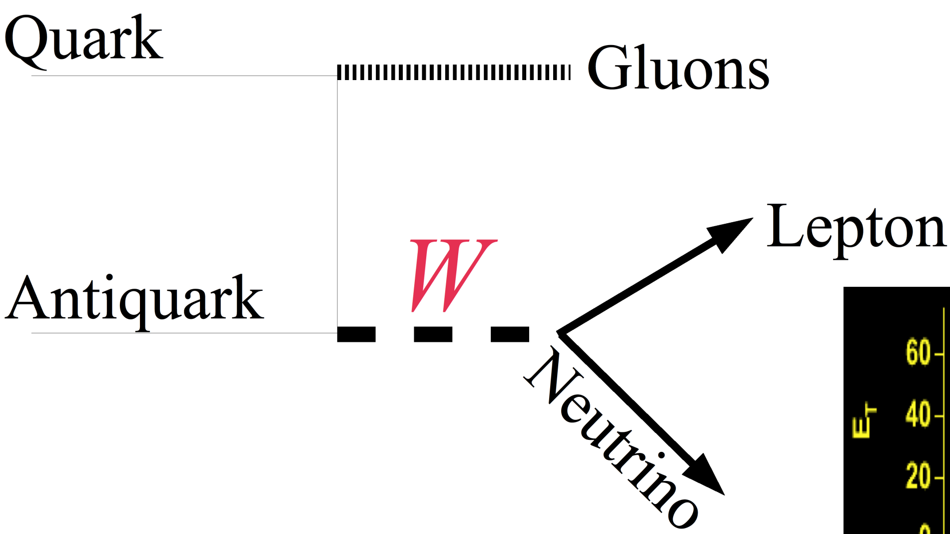
Quark-antiquark annihilation dominates (80%)

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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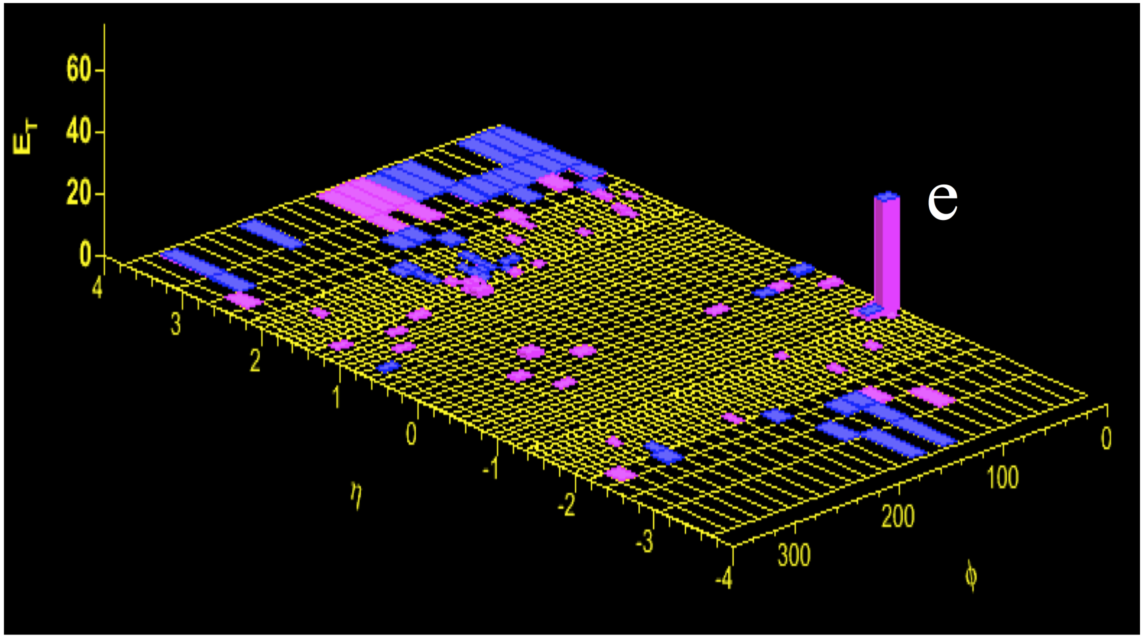

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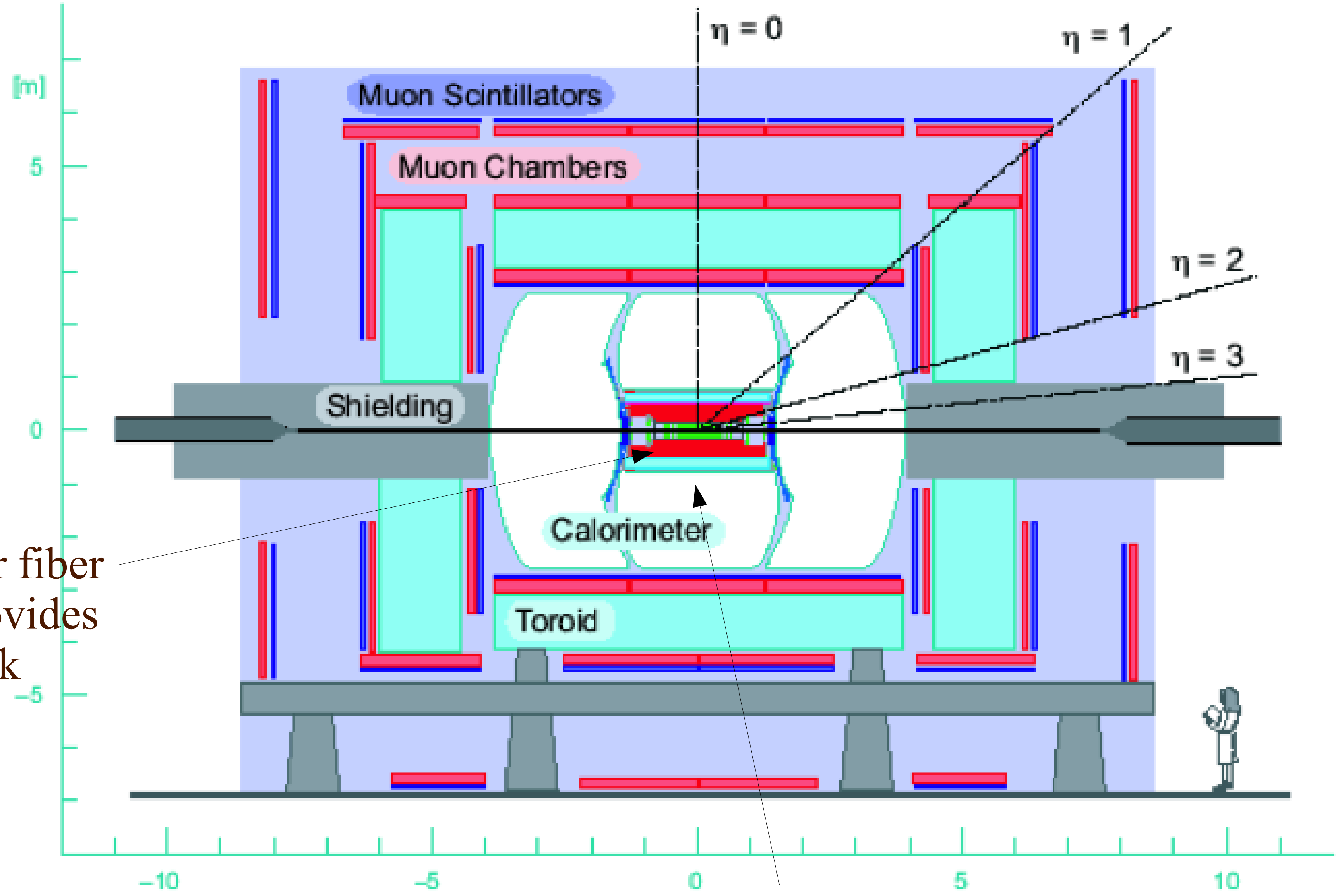
D0 Detector at Fermilab



Scintillator fiber tracker provides lepton track direction

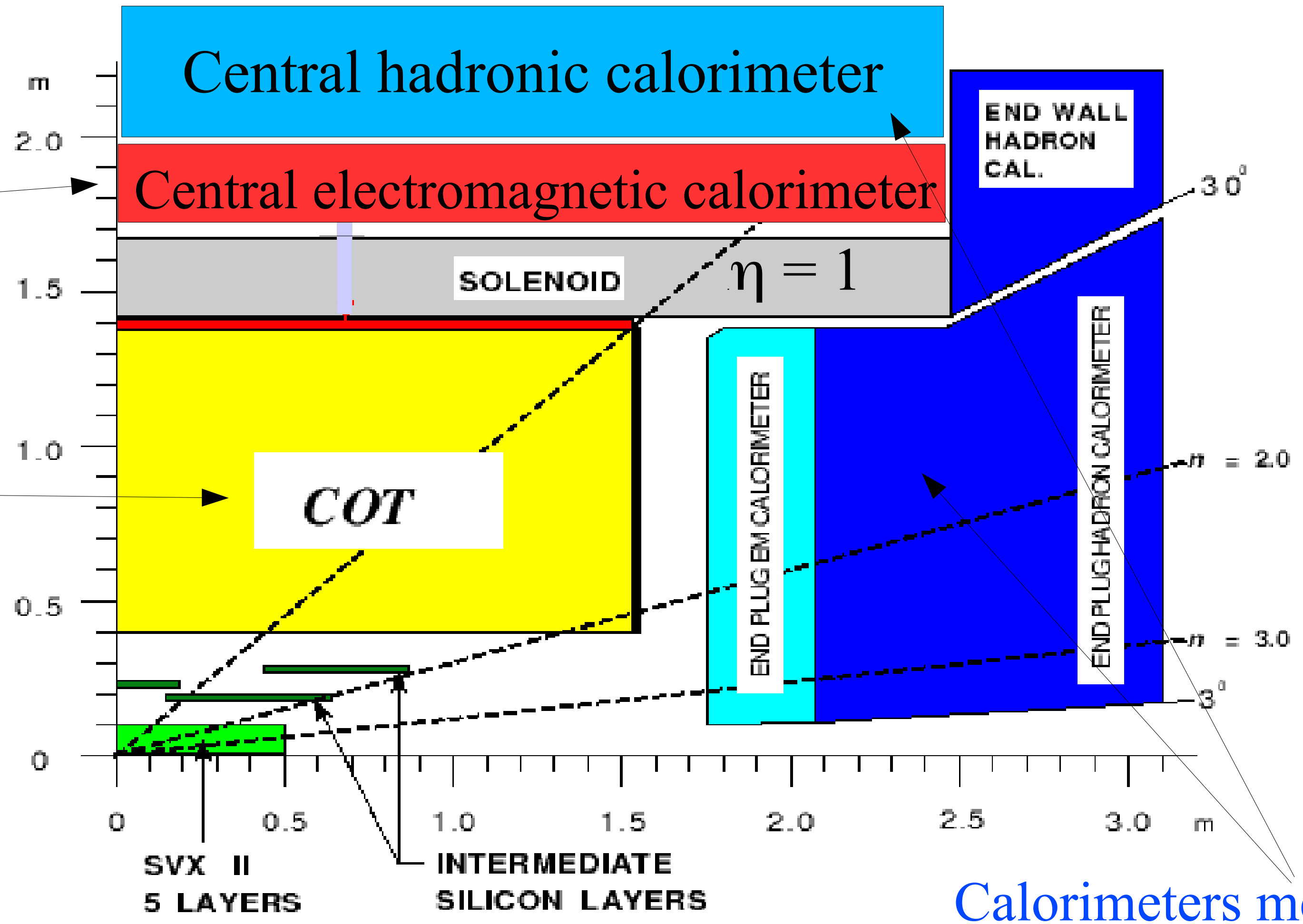
Electromagnetic Calorimeter measures electron energy

Hadronic calorimeters measure recoil particles

Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

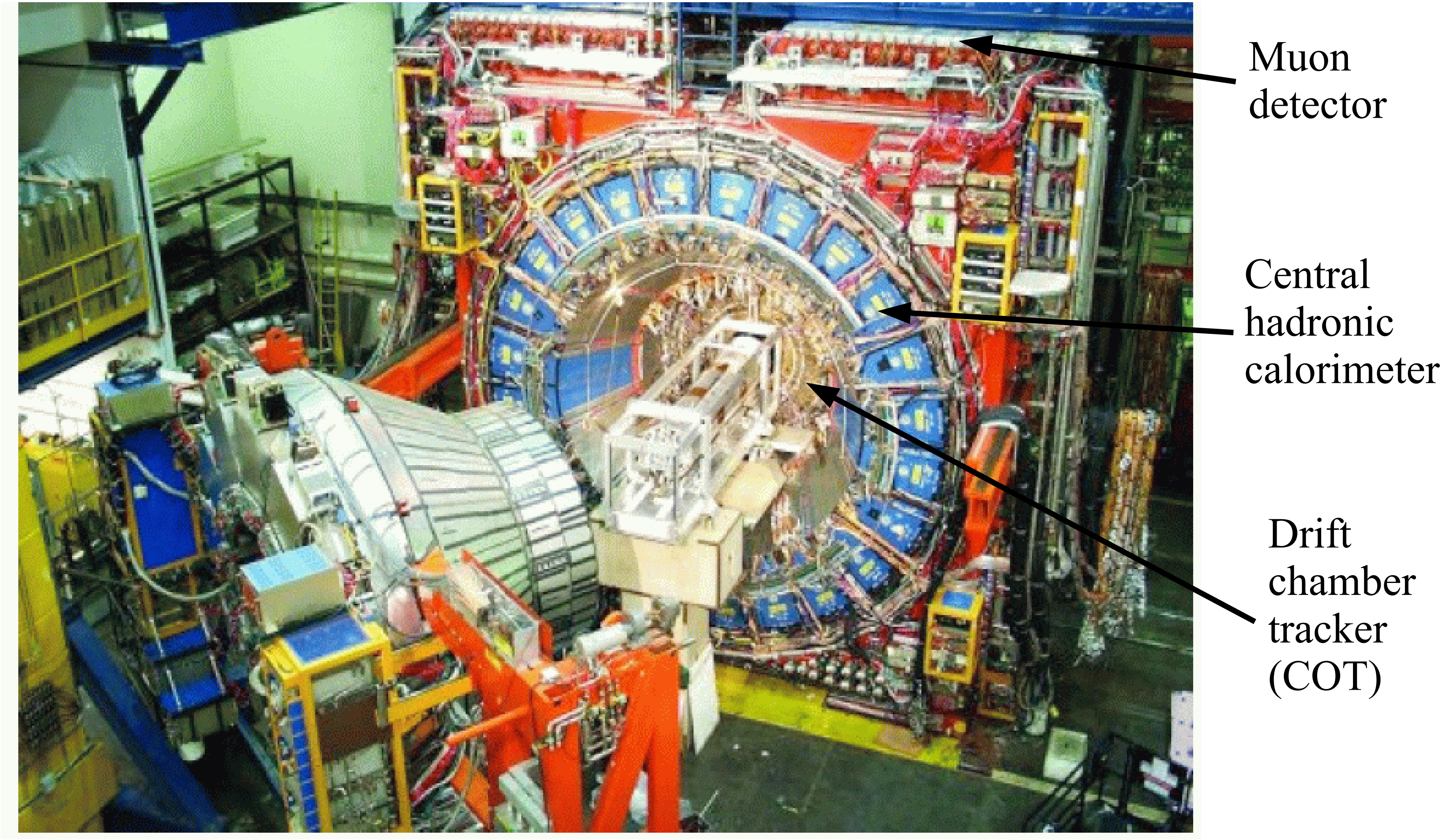
Drift chamber provides precise lepton track momentum measurement



Calorimeters measure hadronic recoil particles

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

Collider Detector at Fermilab (CDF)

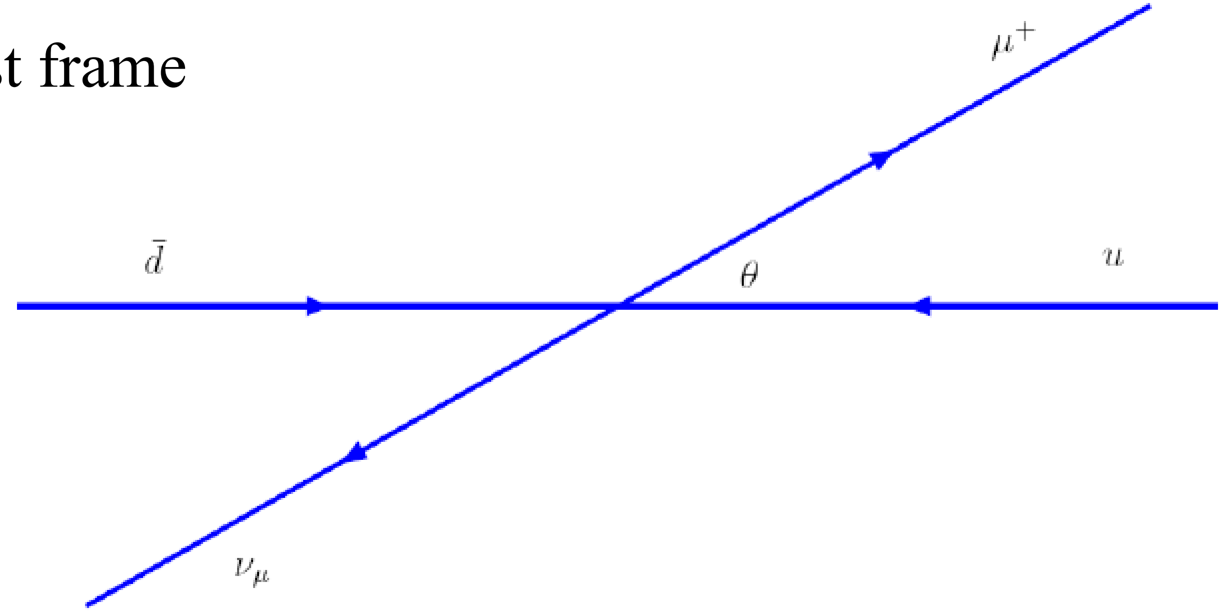


W mass measurement – decay kinematics

- 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

- 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

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

Invariant under longitudinal boost

W mass measurement – decay kinematics

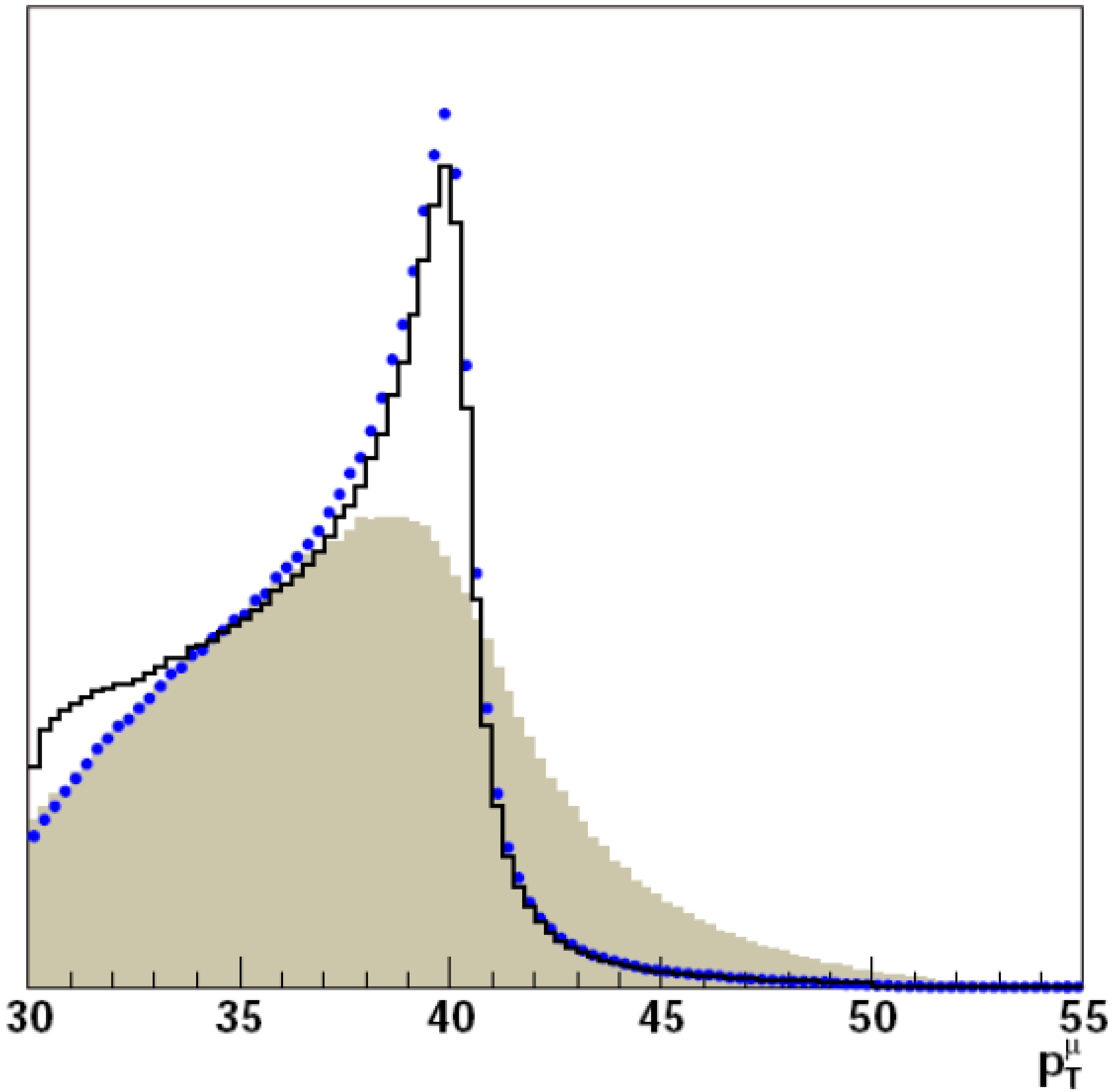
- Main complication: invariant mass cannot be reconstructed from 2-body leptonic decay mode
    - Because neutrino is not detectable directly
- Exploit the "Jacobian edge" in lepton transverse momentum spectrum

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



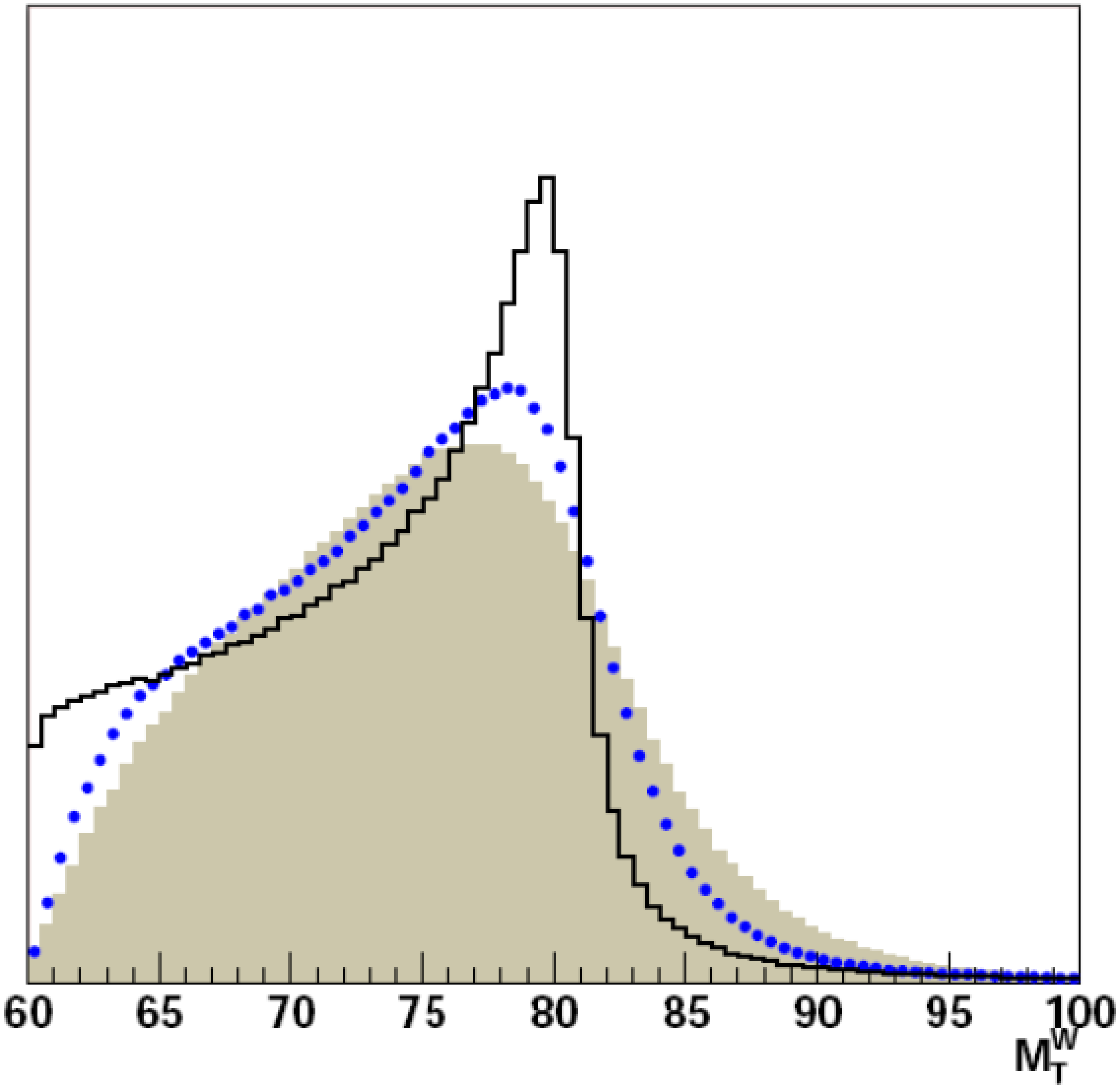
Black curve: truth level, no $p_T(W)$

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



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
$W \to e\nu$	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: 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

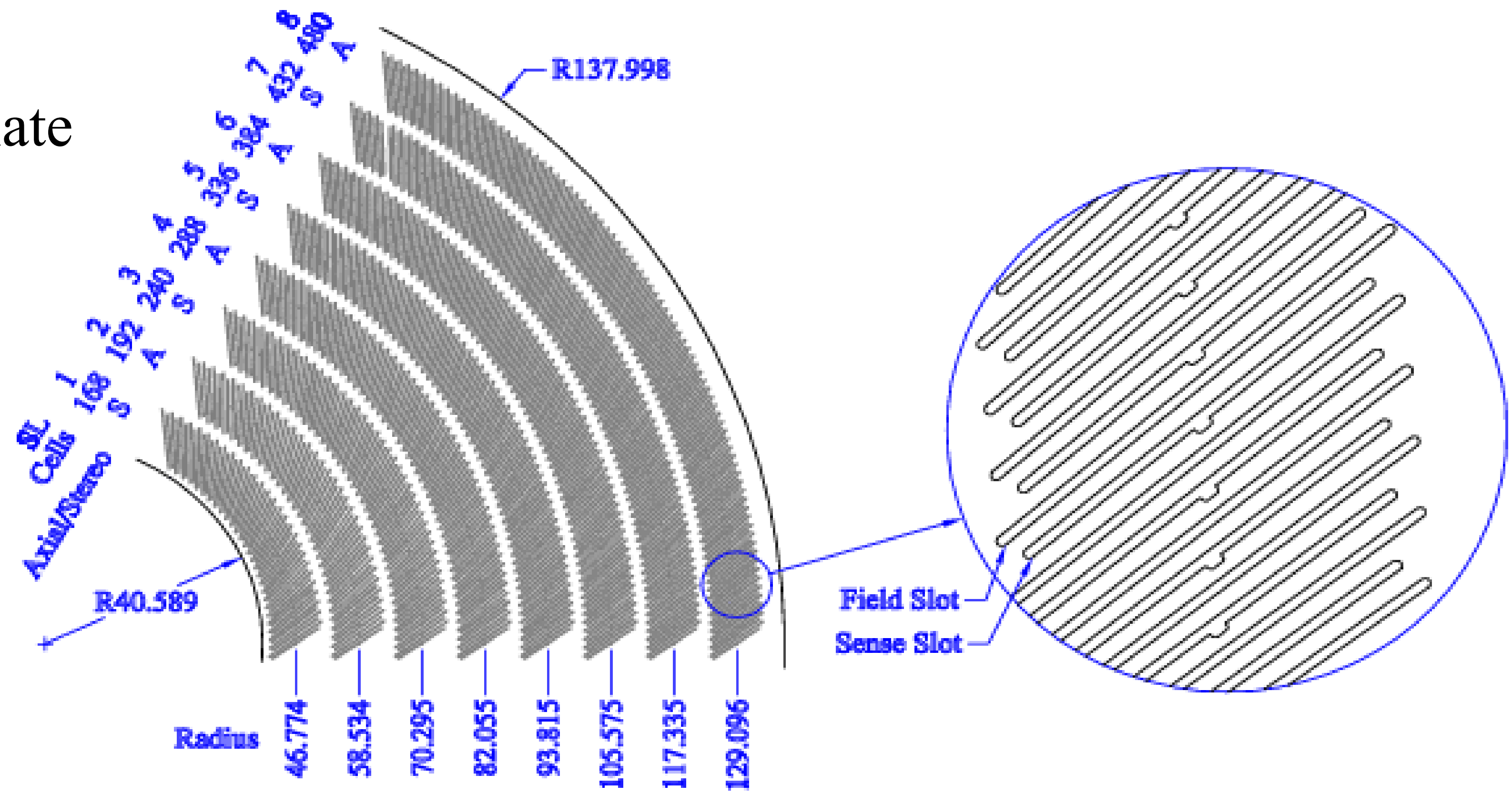
Outline of Analysis

Energy scale measurements drive the W mass measurement

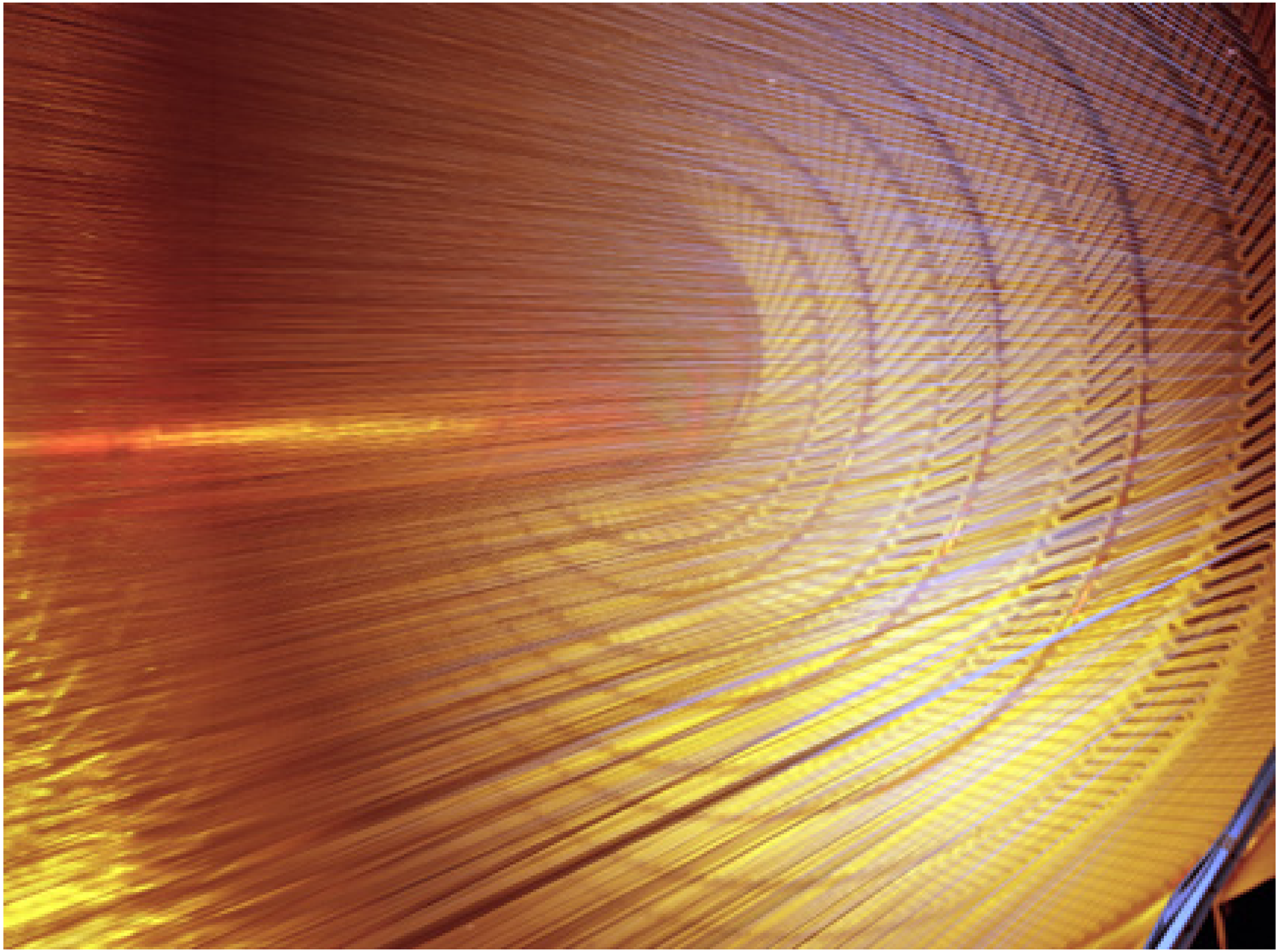
- Tracker Calibration
  - alignment of the COT (~2400 cells) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
  - Confirmed using $Z \rightarrow \mu\mu$ mass fit
- EM Calorimeter Calibration
 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



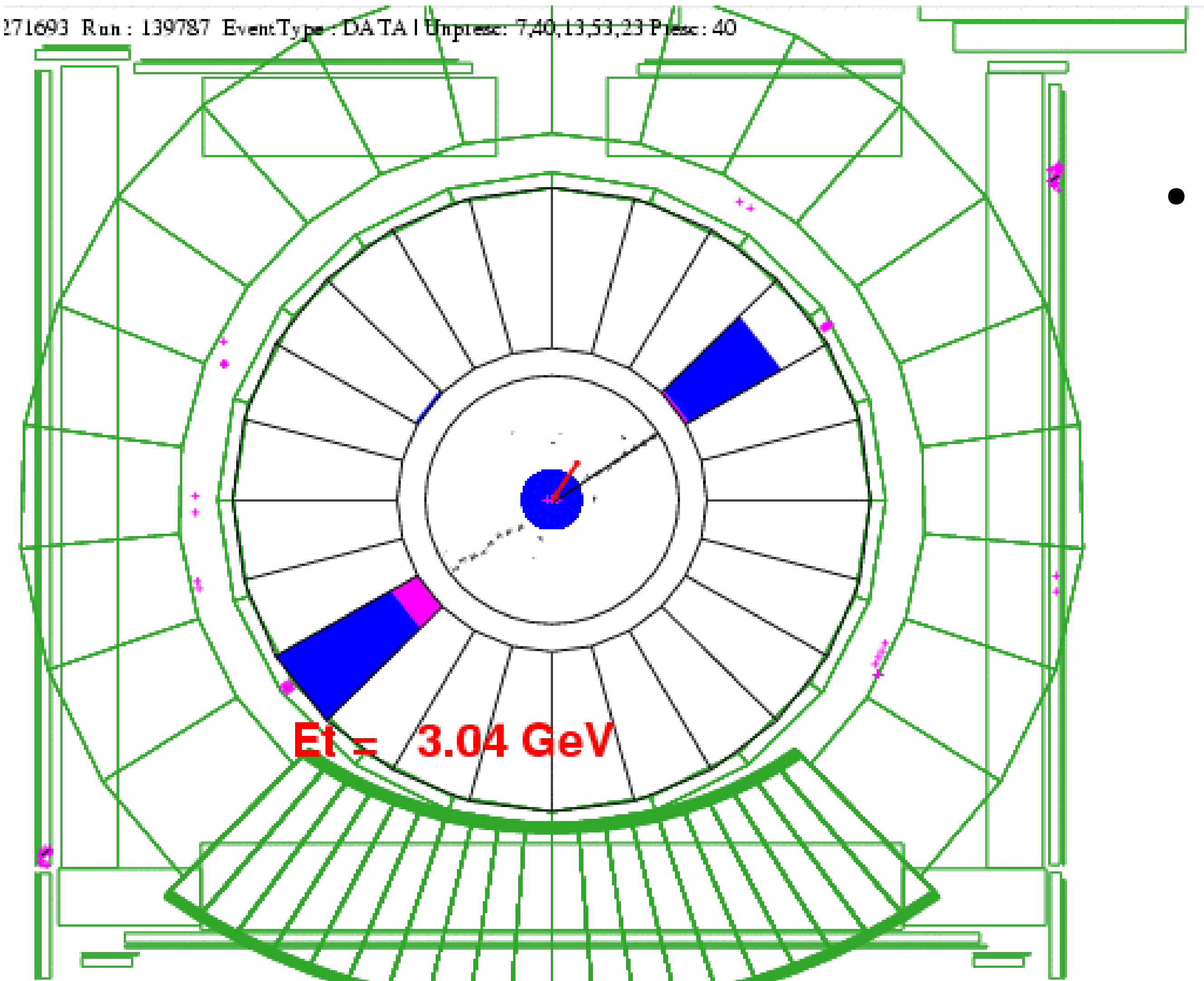
Reconstruction of particle trajectories, calibration to ~2 μm accuracy:

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

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

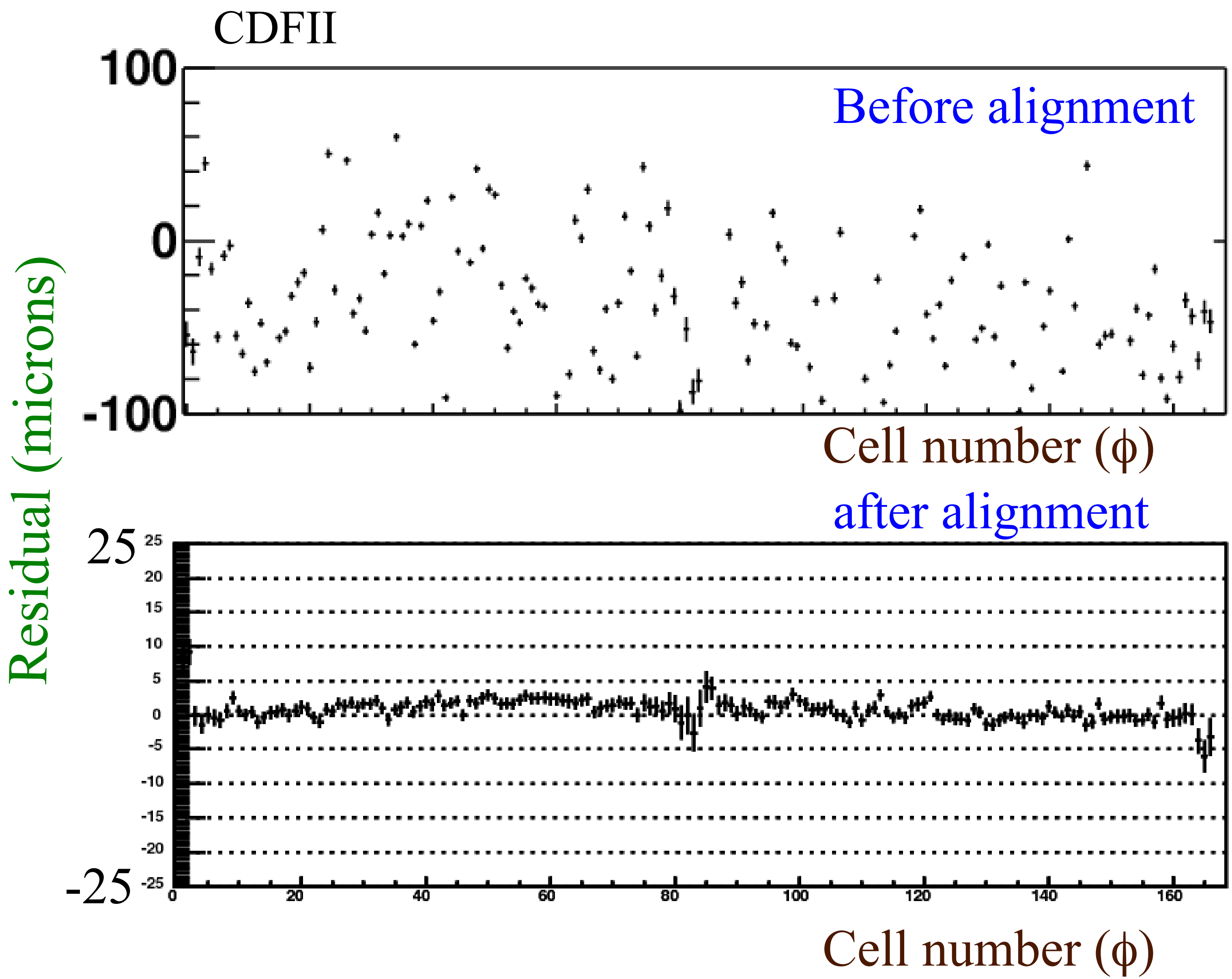
Internal Alignment of COT

- 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'

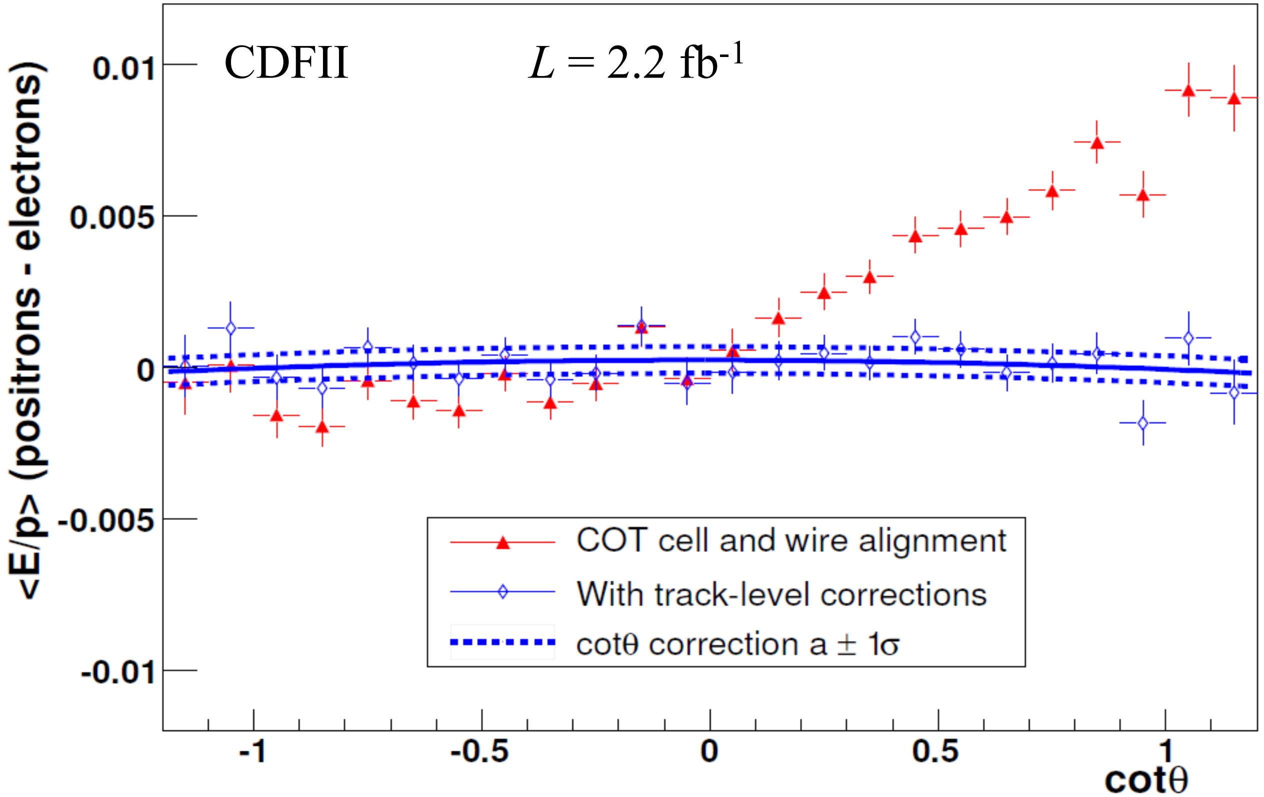
Residuals of COT cells after alignment



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

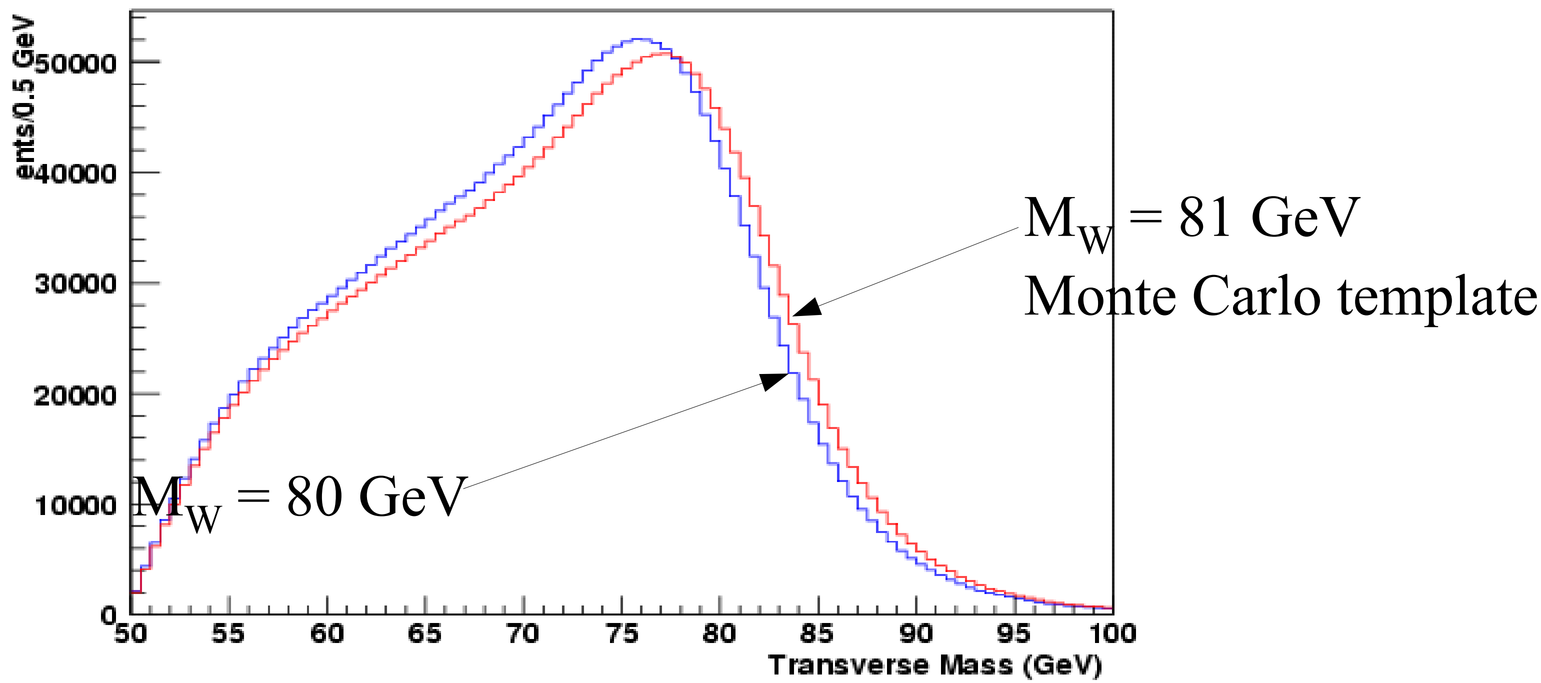


Signal Simulation and Fitting

Signal Simulation and Template Fitting

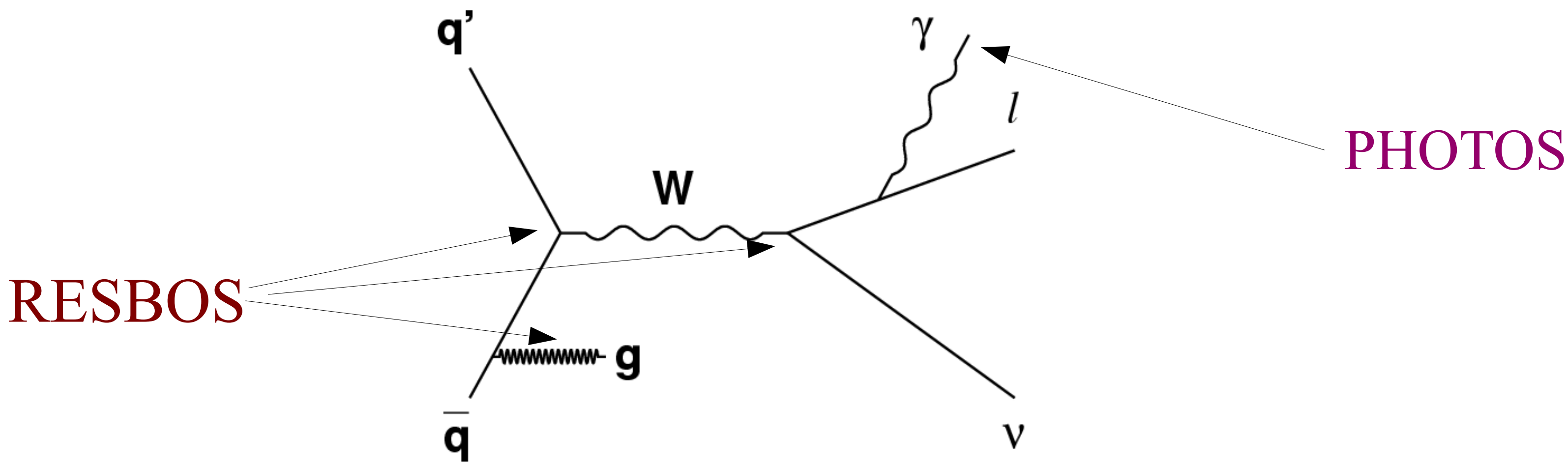
- All signals simulated using a Custom Monte Carlo
  - Generate finely-spaced templates as a function of the fit variable
  - perform binned maximum-likelihood fits to the data
- Custom fast Monte Carlo makes smooth, high statistics templates
  - And provides analysis control over key components of the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

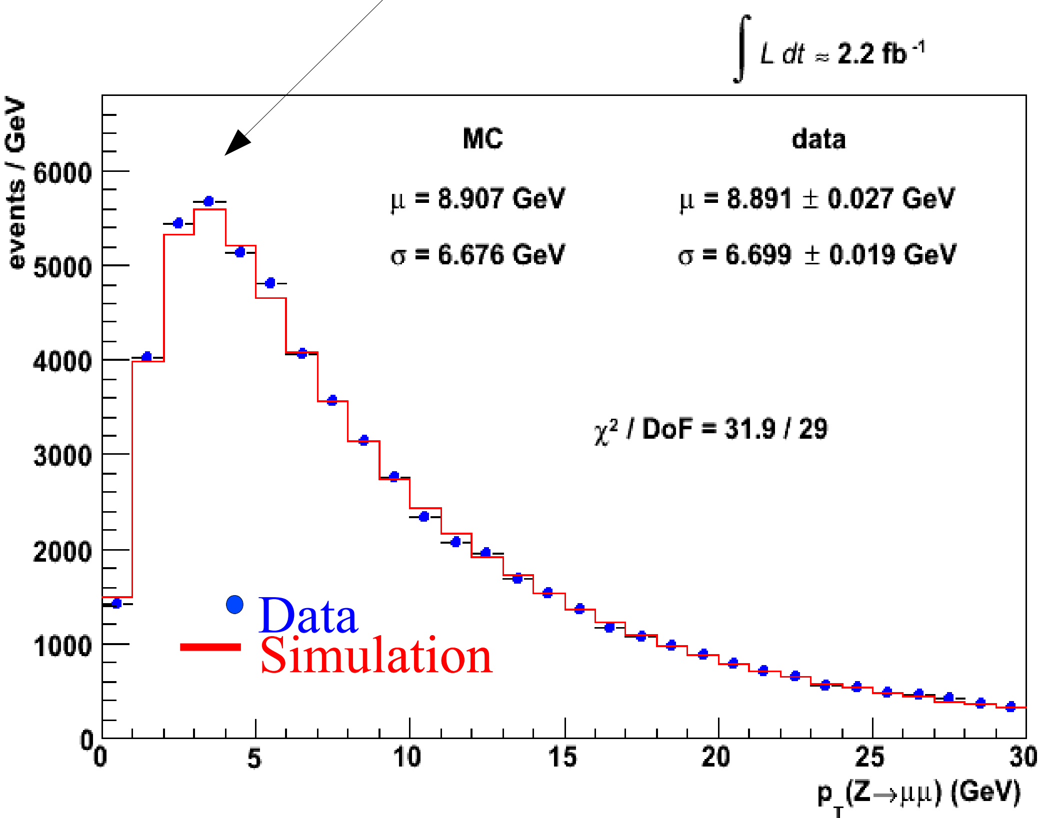
Constraining Boson p_T Spectrum

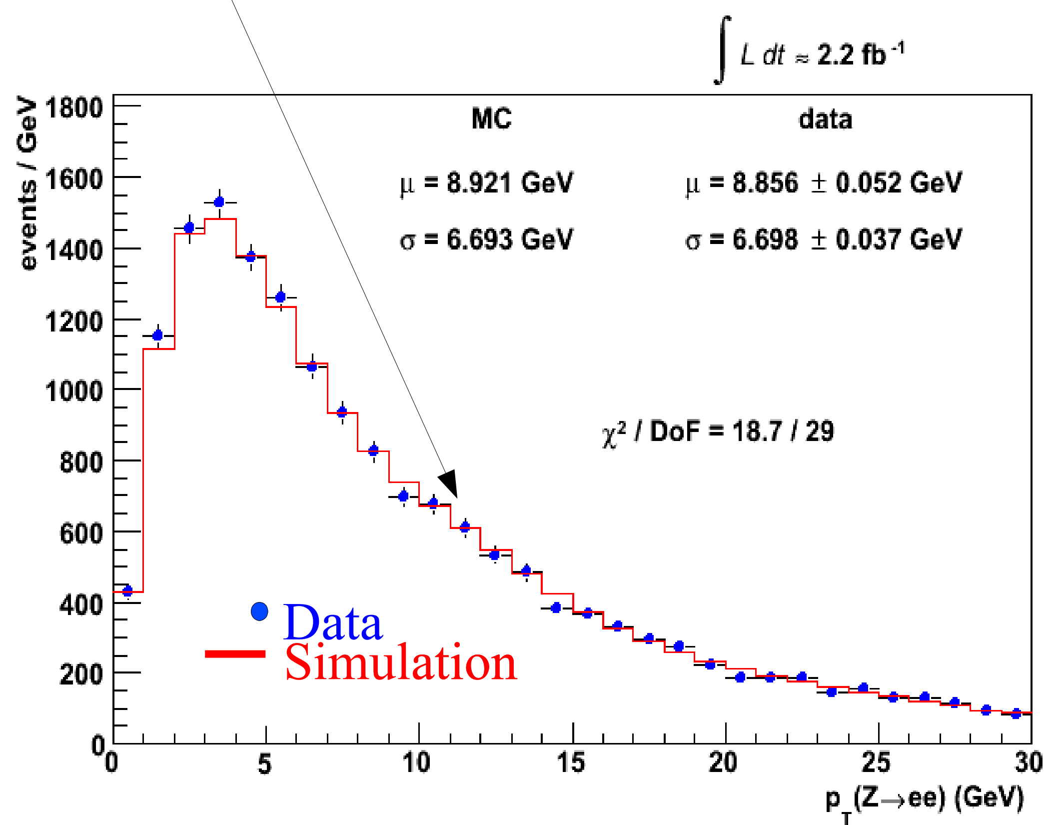
- Fit the non-perturbative parameter g_2 and QCD coupling α_s in RESBOS to $p_T(ll)$ spectra:

$\Delta M_W = 5$ MeV

Position of peak in boson p_T spectrum depends on g_2

Tail to peak ratio depends on α_s





Outline of Analysis

Energy scale measurements drive the W mass measurement

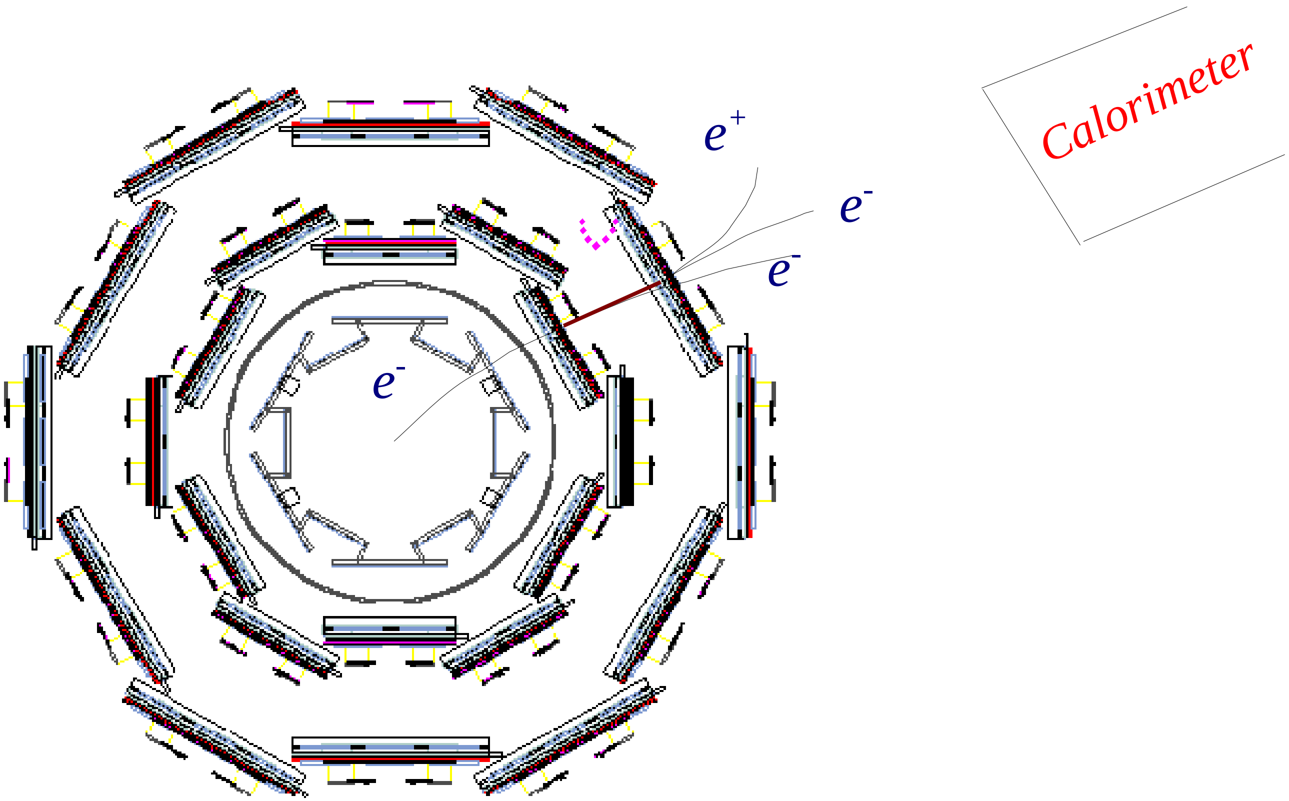
- Tracker Calibration
  - alignment of the COT (~2400 cells) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
  - Confirmed using $Z \rightarrow \mu\mu$ mass fit
- EM Calorimeter Calibration
 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

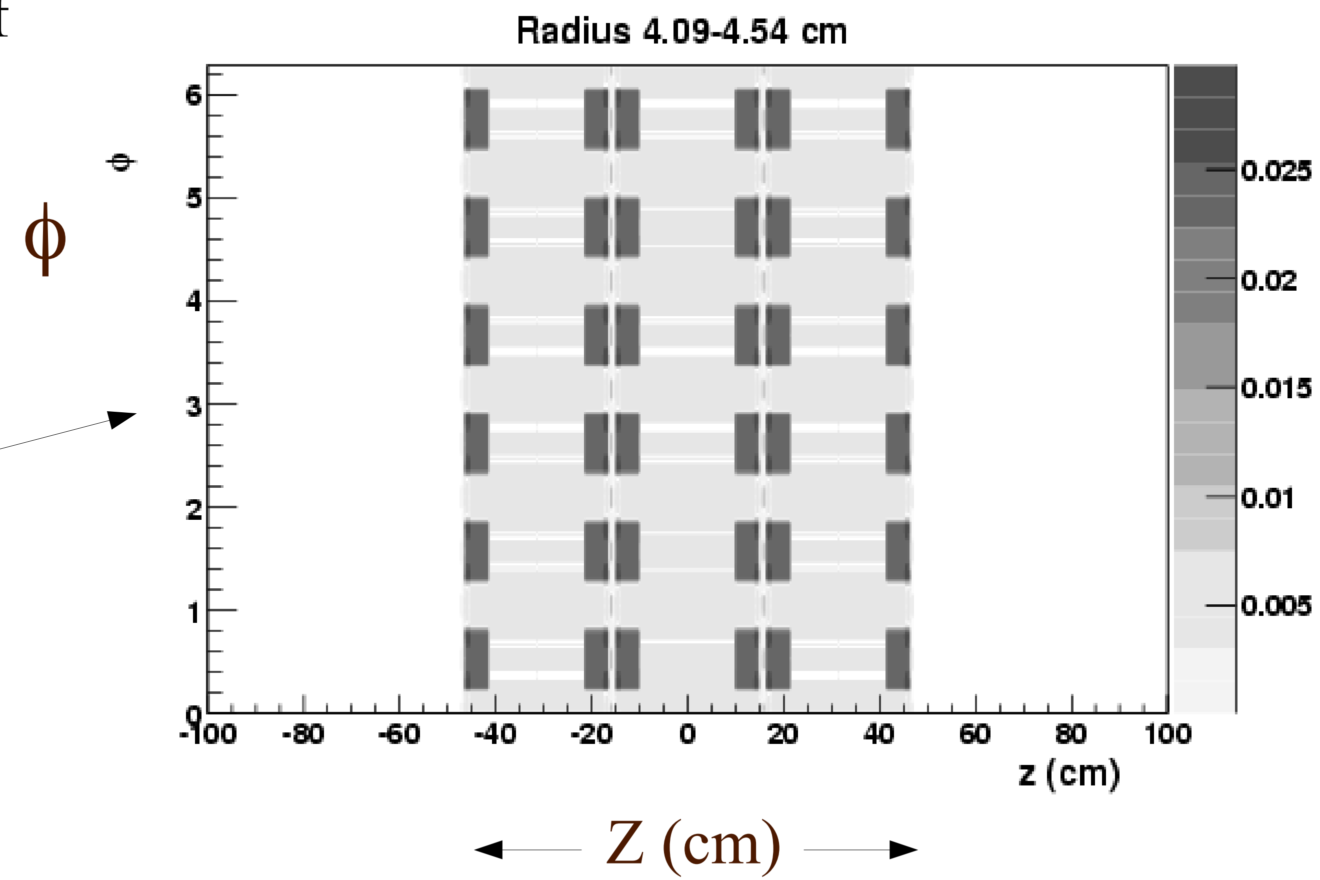


3-D Material Map in Simulation

- 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* (ϕ,*z*) at different radii shows localized nature of material distribution



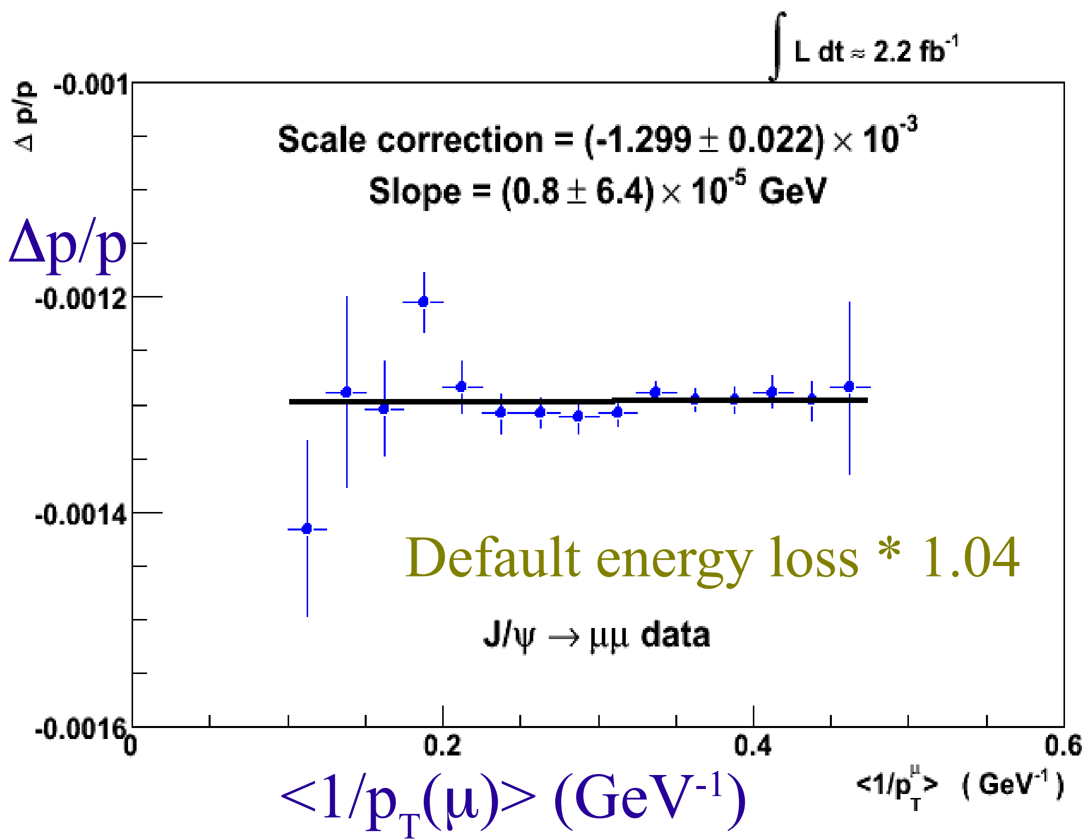
- Include dependence on type of material via Landau-Pomeranchuk-Migdal suppression of soft bremsstrahlung

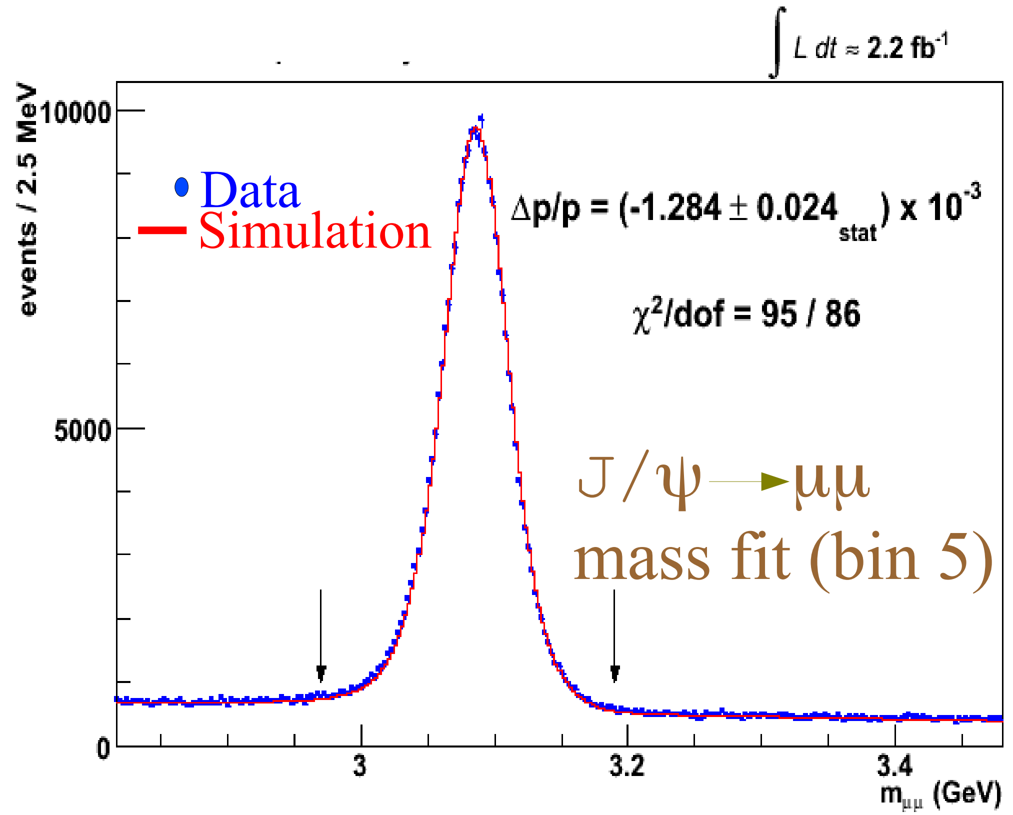
Tracking Momentum Scale

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/ψ 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

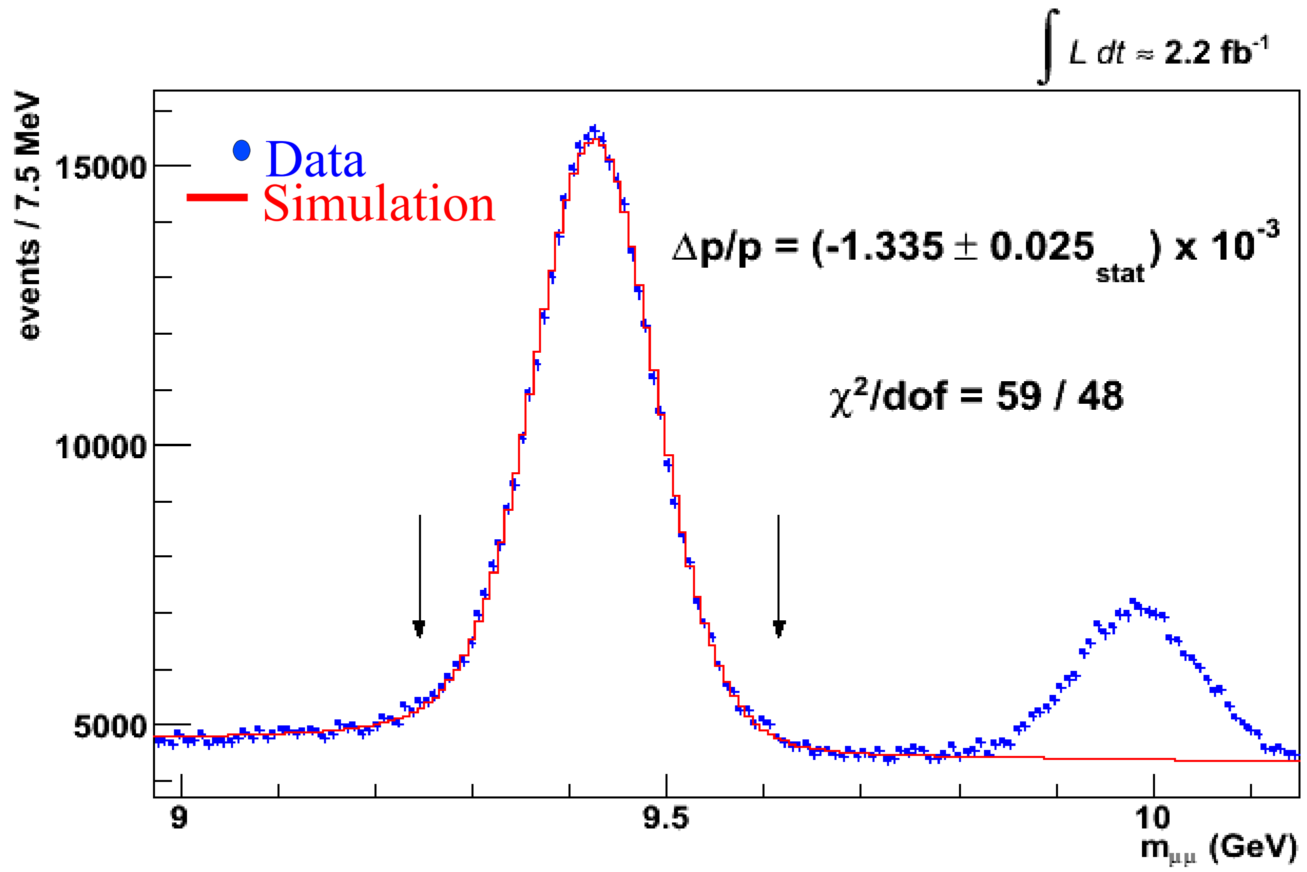




Tracking Momentum Scale

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

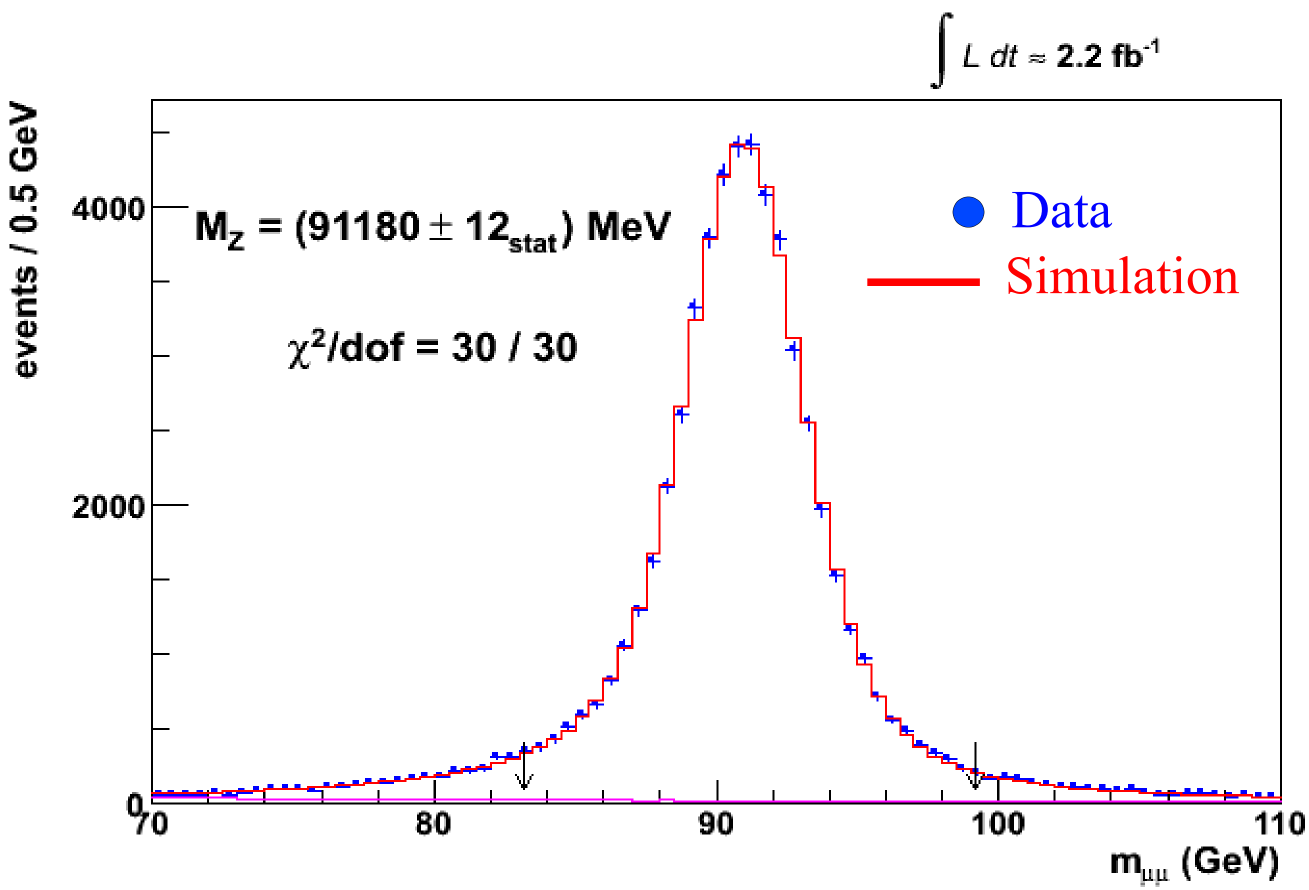
- Momentum scale measurement at higher p_T



$\Upsilon \rightarrow \mu\mu$
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

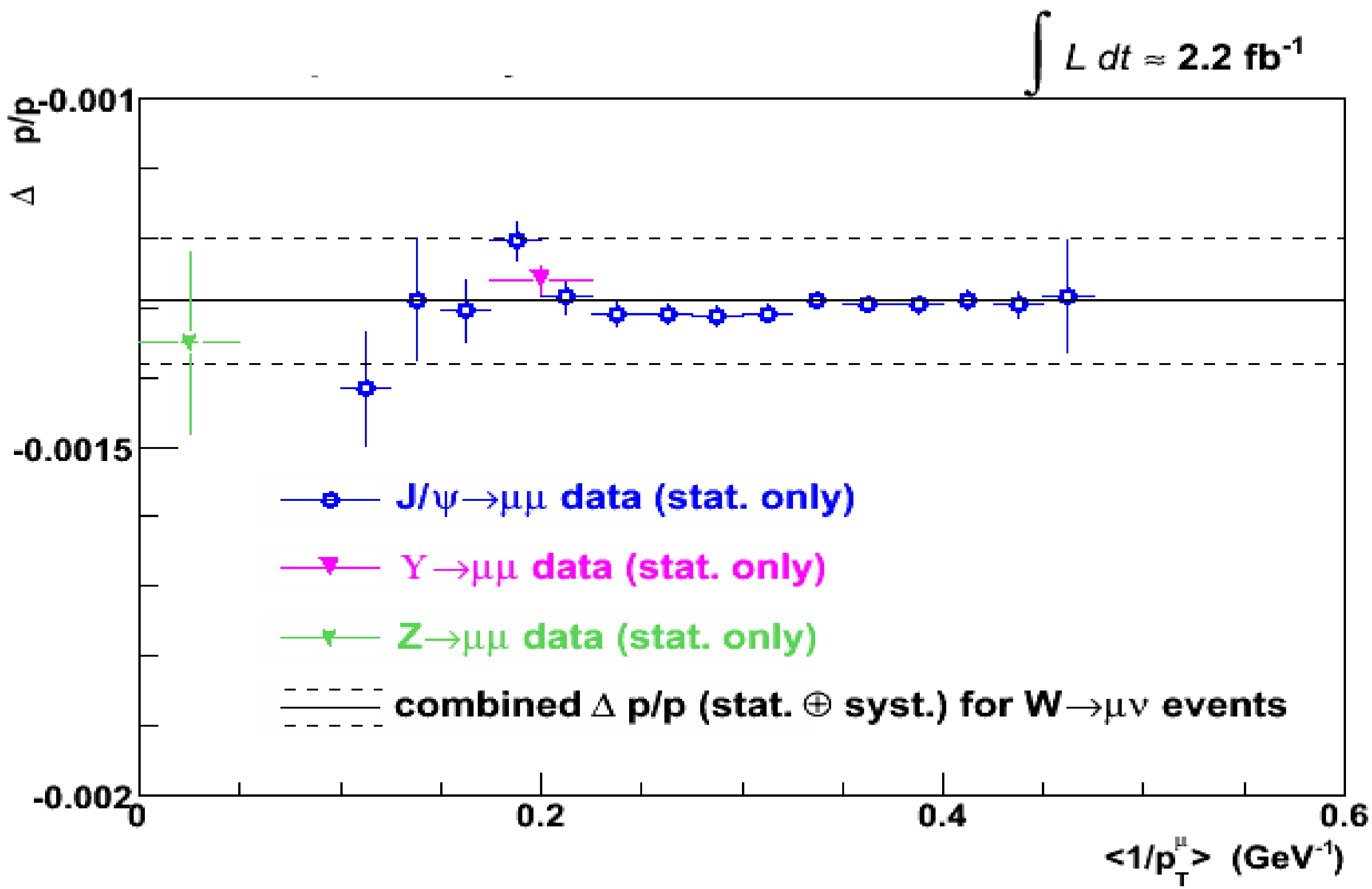


M(μμ) (GeV)

Tracker Linearity Cross-check & Combination

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

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

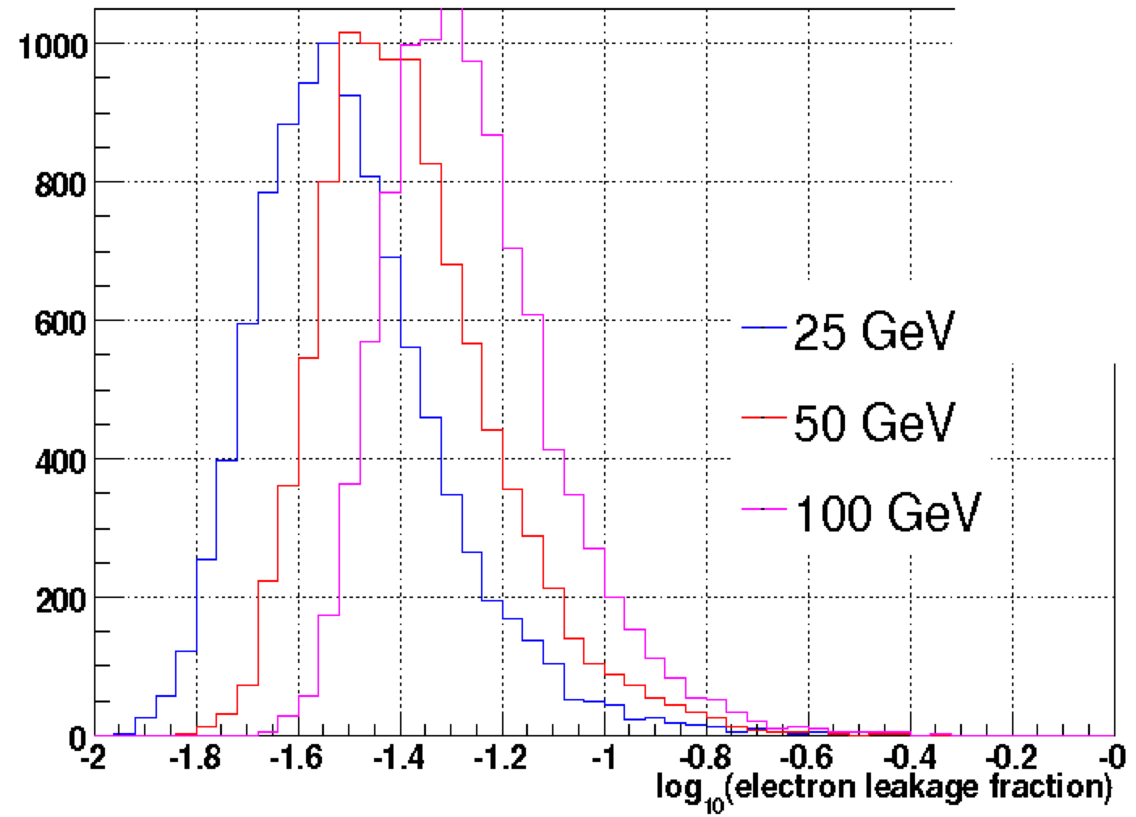


$\Delta M_W = 7$ MeV

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



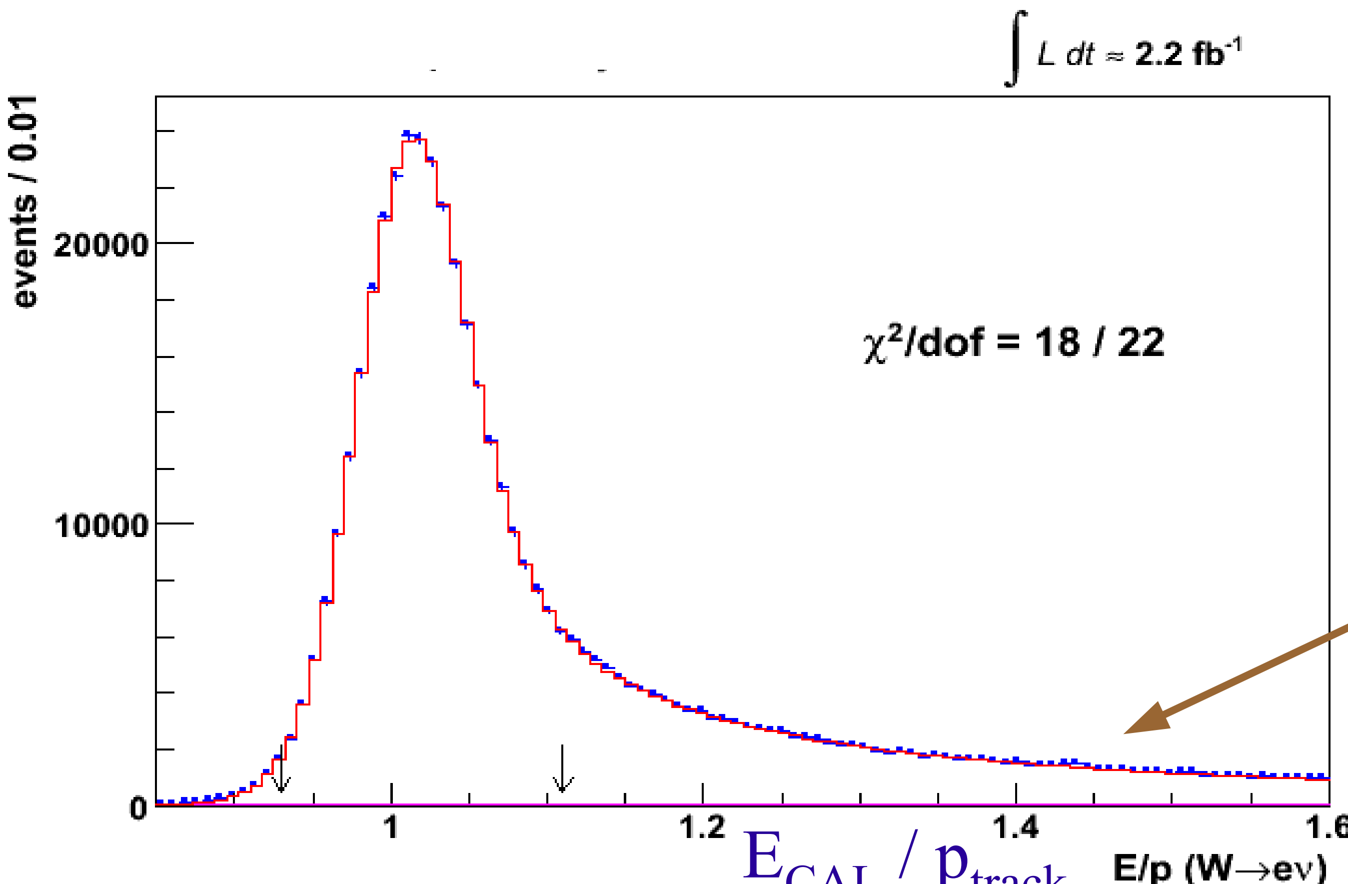
- Energy-dependent gain (non-linearity) parameterized and fit from data
- Energy resolution parameterized as fixed sampling term and tunable constant term
  - Constant terms are fit from the width of E/p peak and $Z \rightarrow ee$ mass peak

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

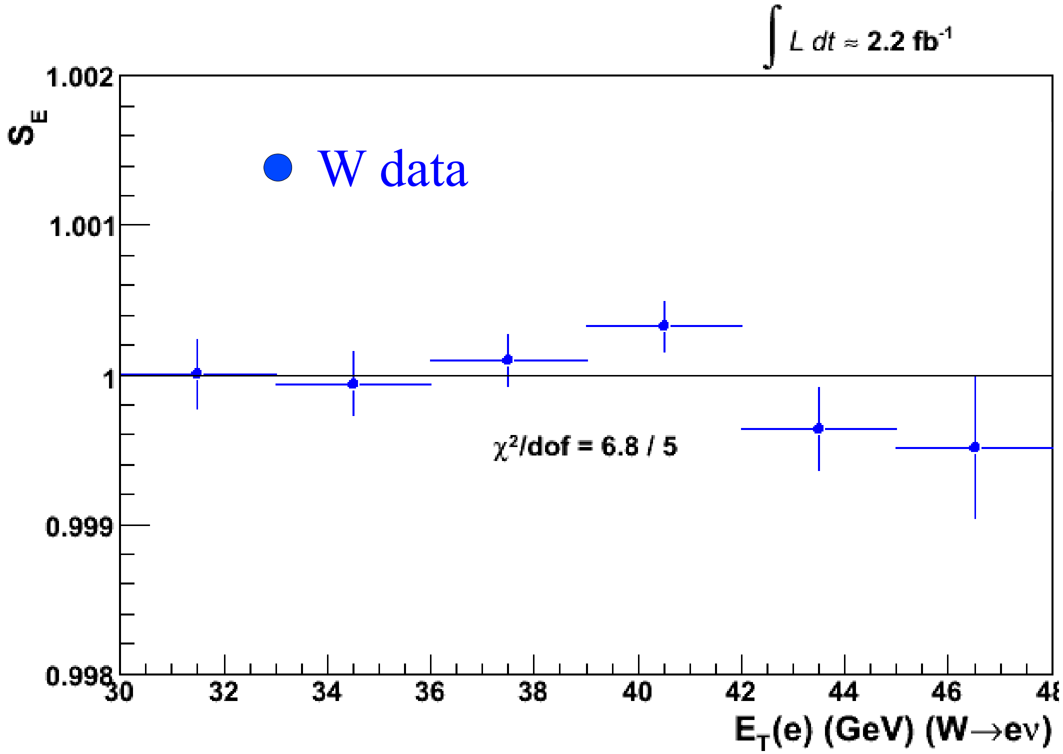
Measurement of EM Calorimeter Non-linearity

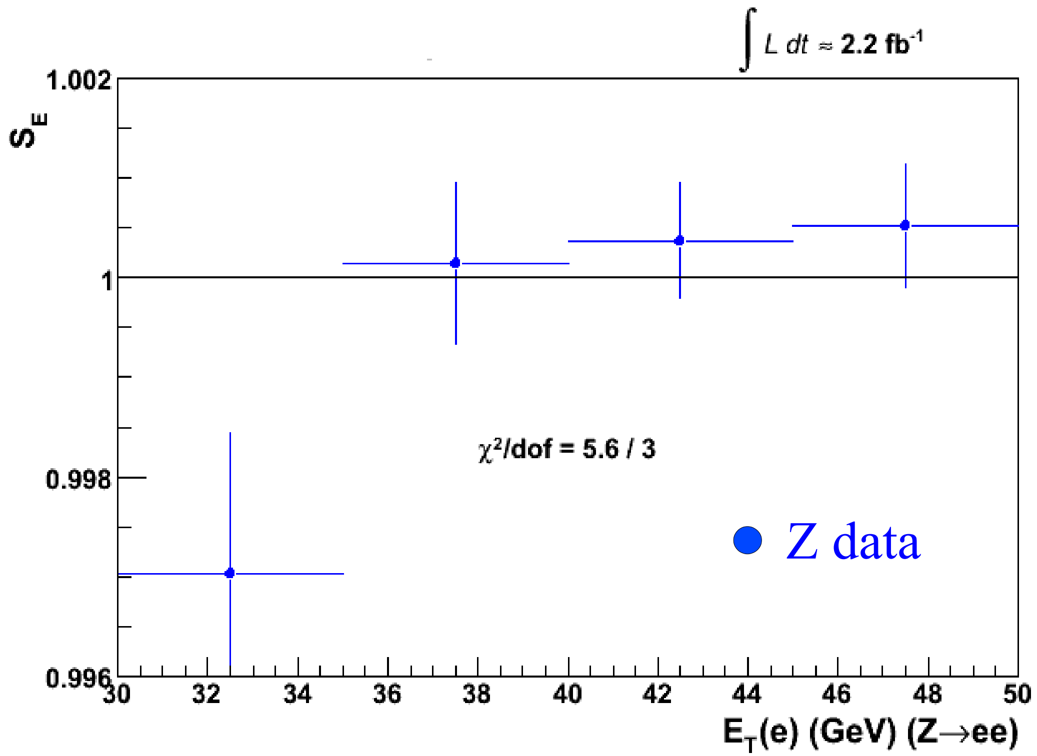
- Perform E/p fit-based calibration in bins of electron E_T
- GEANT-motivated parameterization of non-linear response:

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

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

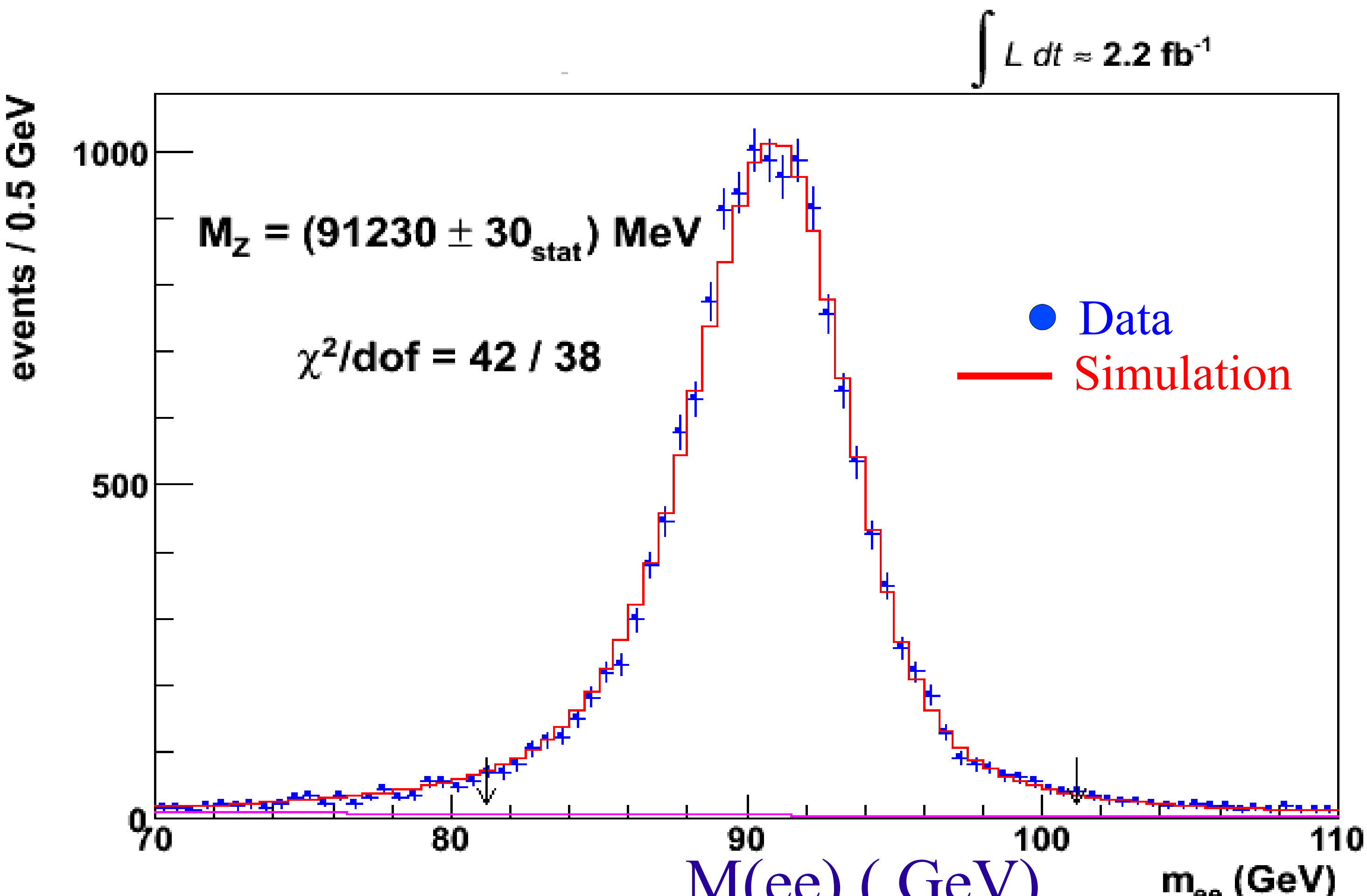
  $\Rightarrow \Delta M_W = 4$ MeV





$Z \rightarrow ee$ 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



M(ee) (GeV)

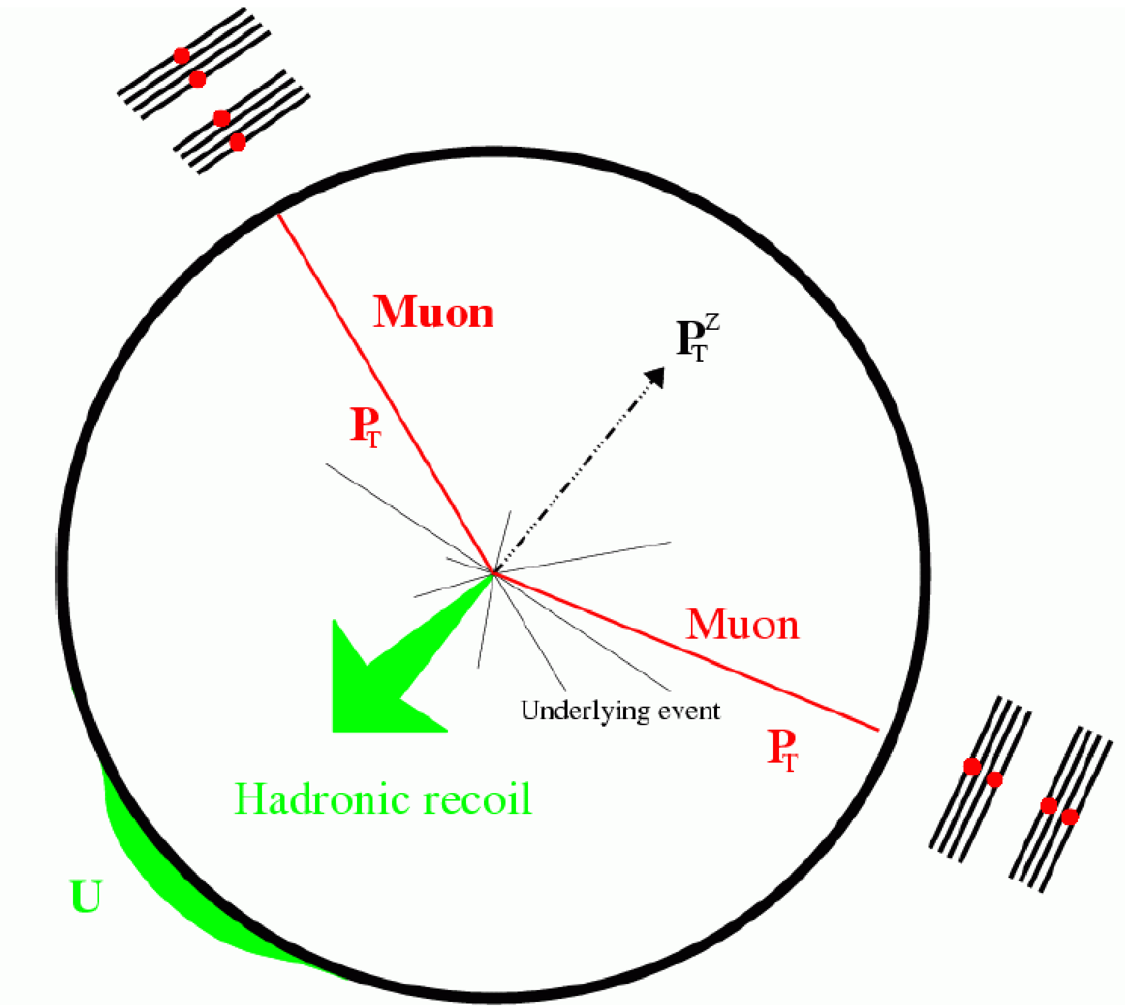
$\Delta M_W = 10$ MeV

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

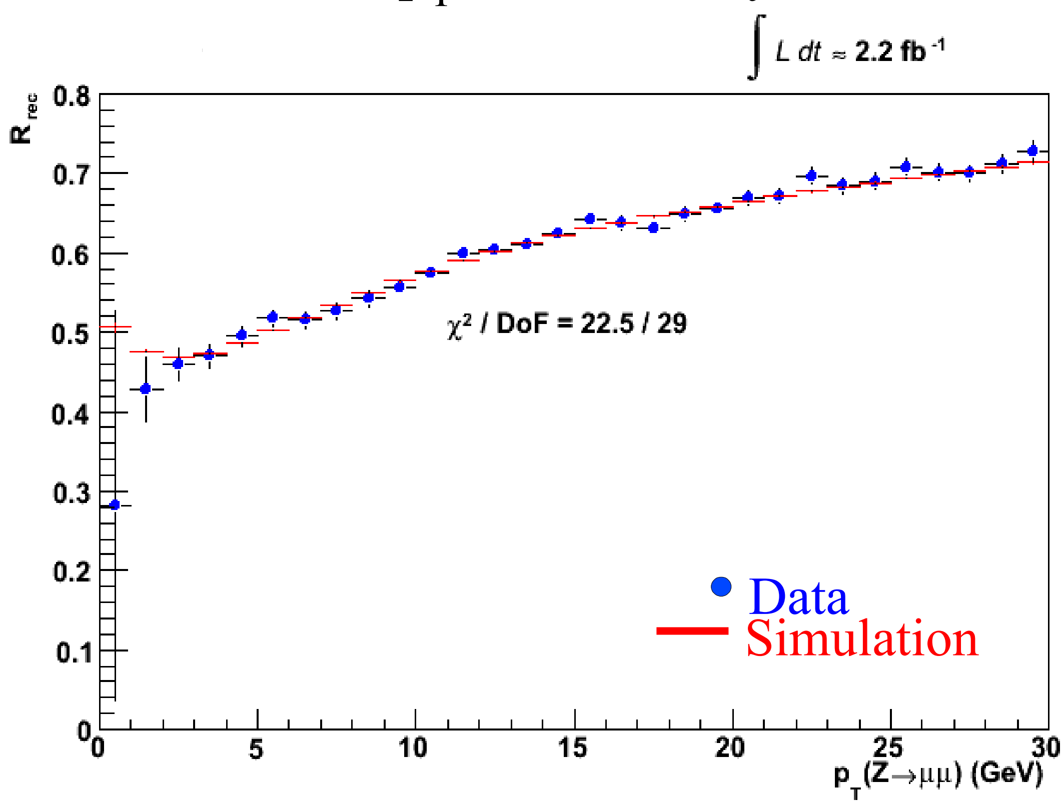


Transverse momentum of Hadronic recoil (***u***) calculated as 2-vector-sum over calorimeter towers

Hadronic Recoil Simulation

Recoil momentum 2-vector $\boldsymbol{u}$ has

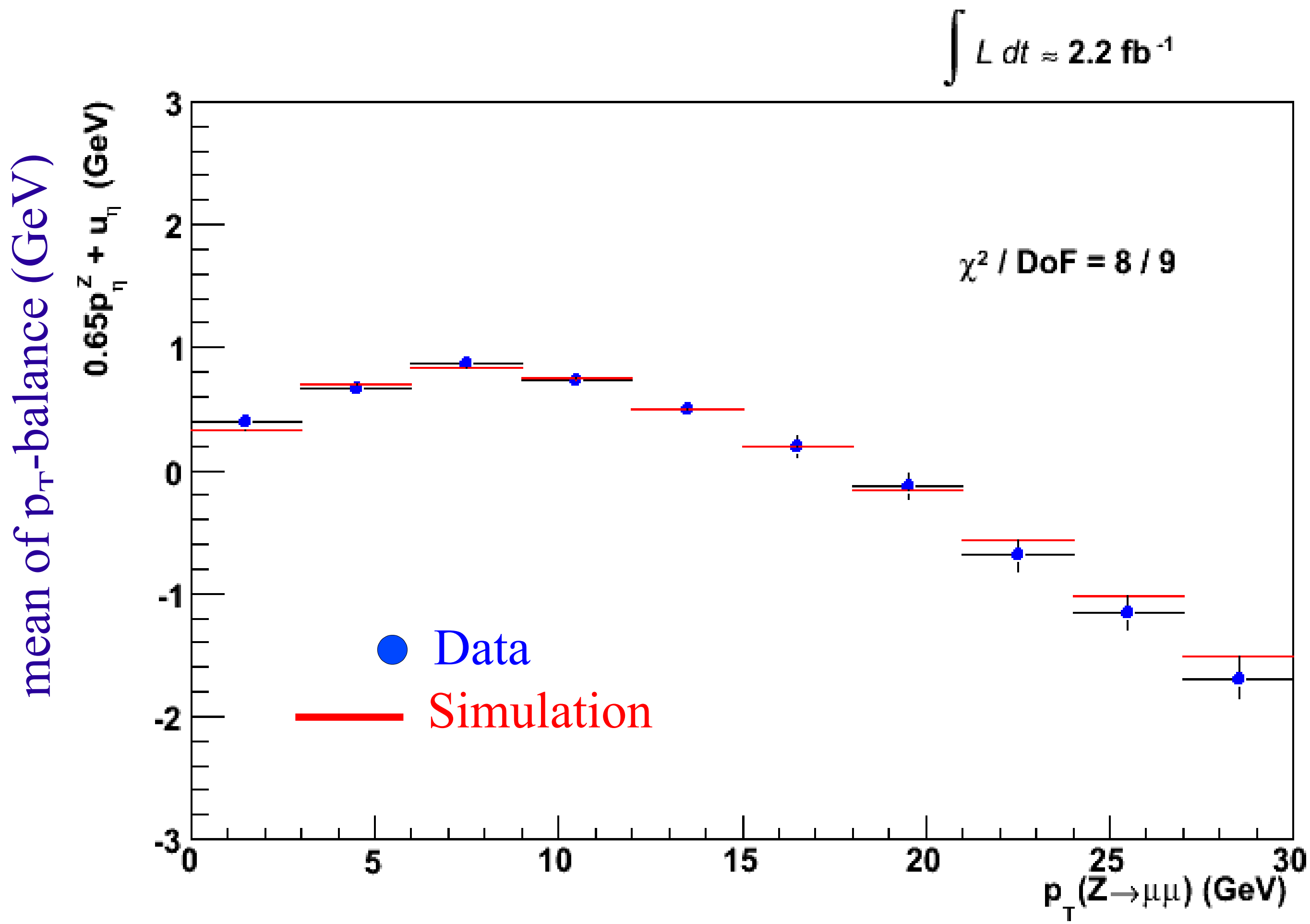
- a soft 'spectator interaction' component, randomly oriented
  - Modelled using minimum-bias data with tunable magnitude
- A hard 'jet' component, directed opposite the boson p_T
  - P_T-dependent response and resolution parameterizations
  - Hadronic response $R = \boldsymbol{u}_{\text{reconstructed}}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

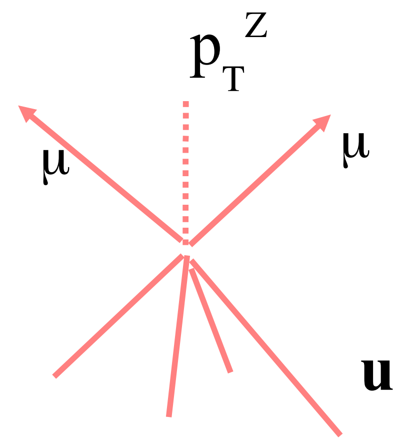


Tuning Recoil Response Model with Z events

Project the vector sum of $p_T(ll)$ and $\boldsymbol{u}$ 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





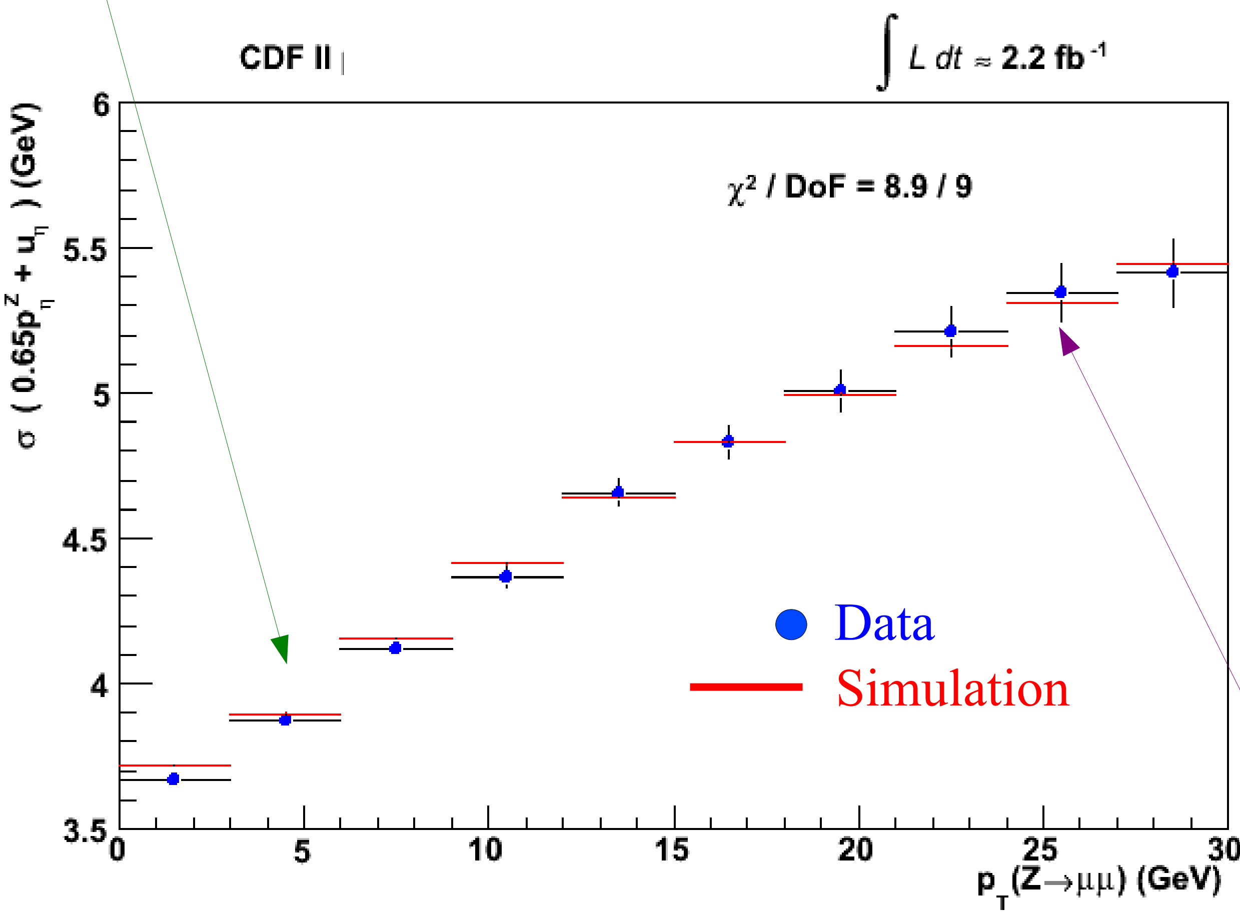
Hadronic model parameters tuned by minimizing χ^2 between data and simulation

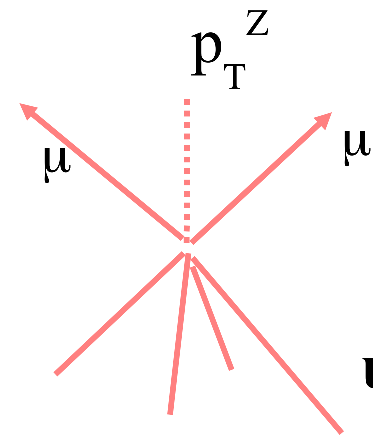
$\Delta M_W = 4$ MeV

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)



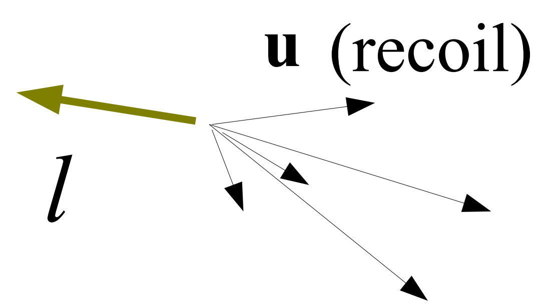


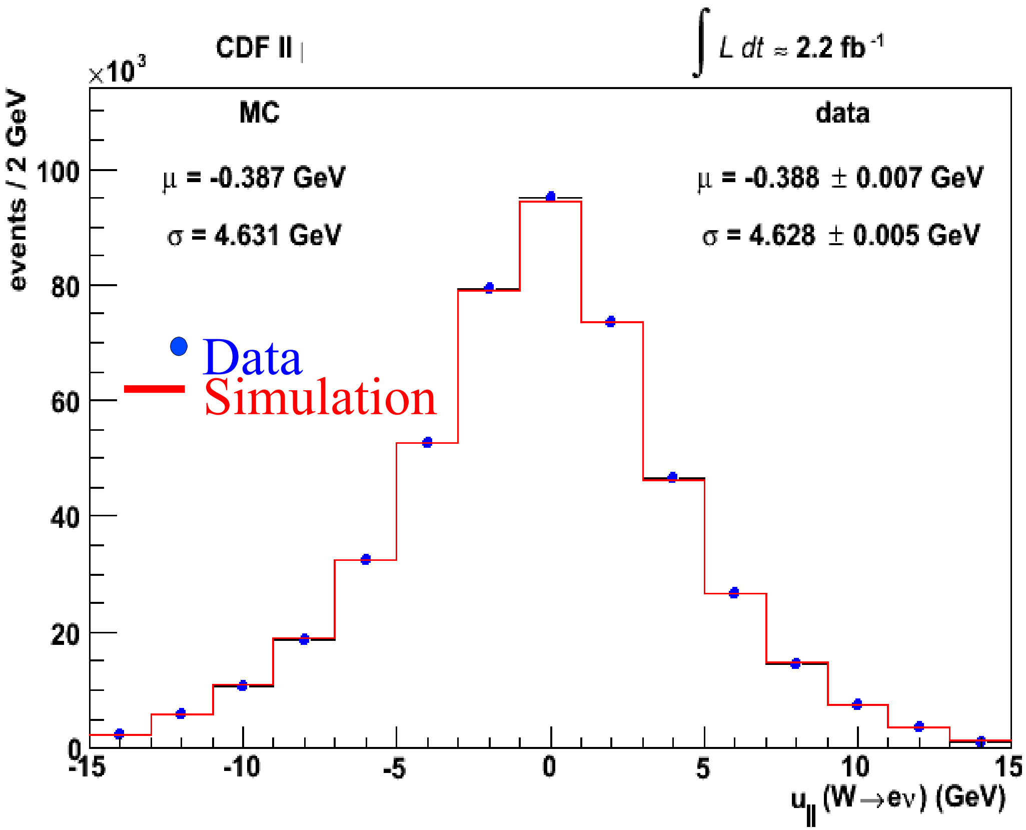
ΔM_W = 4 MeV

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

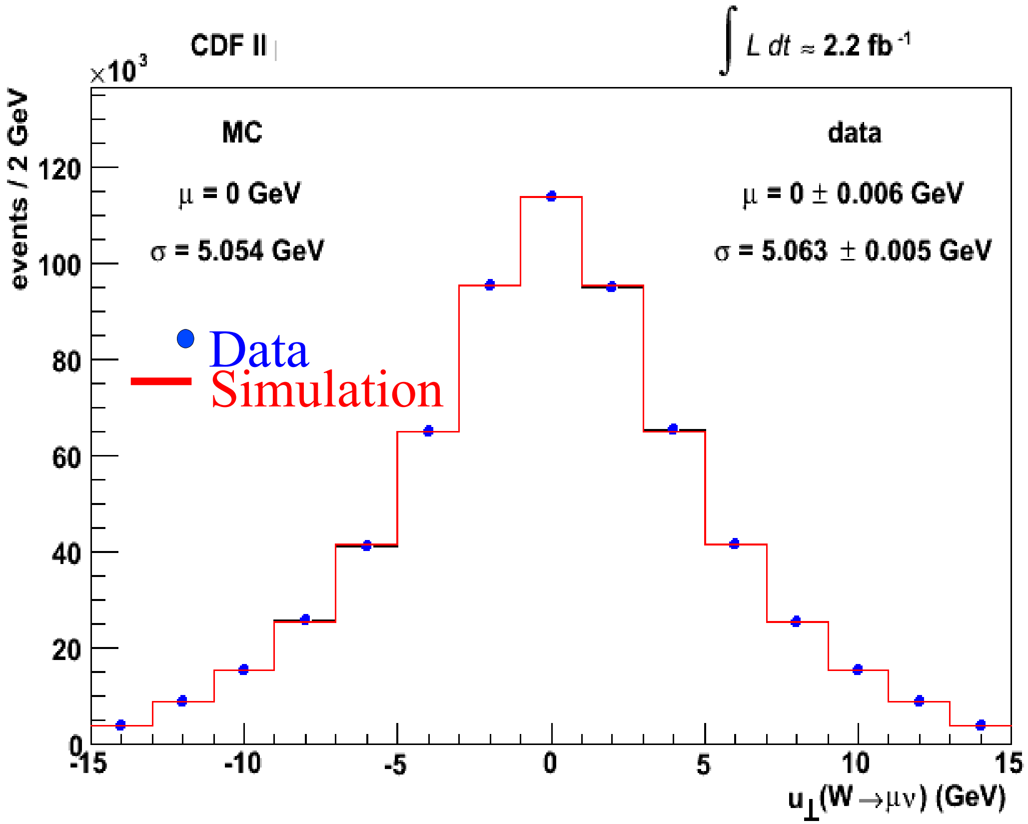
Testing Hadronic Recoil Model with *W* events

Compare recoil distributions between simulation and data





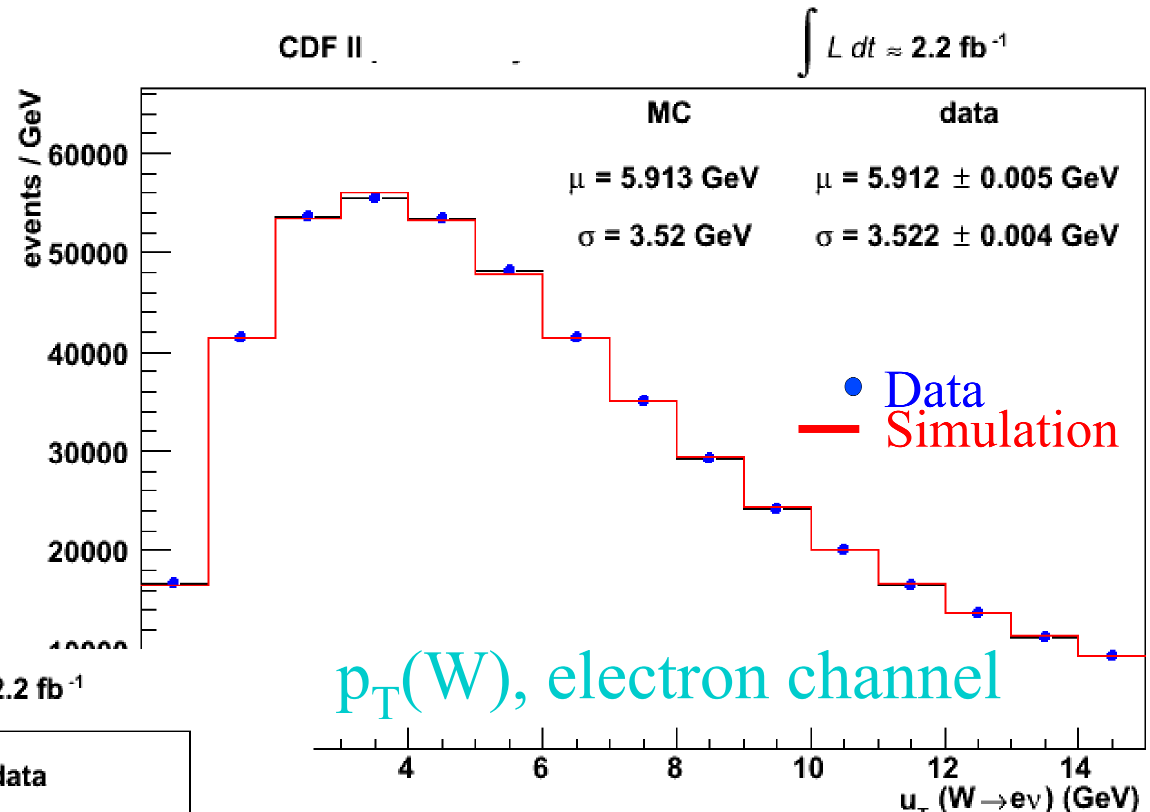
Recoil projection (GeV) on lepton direction

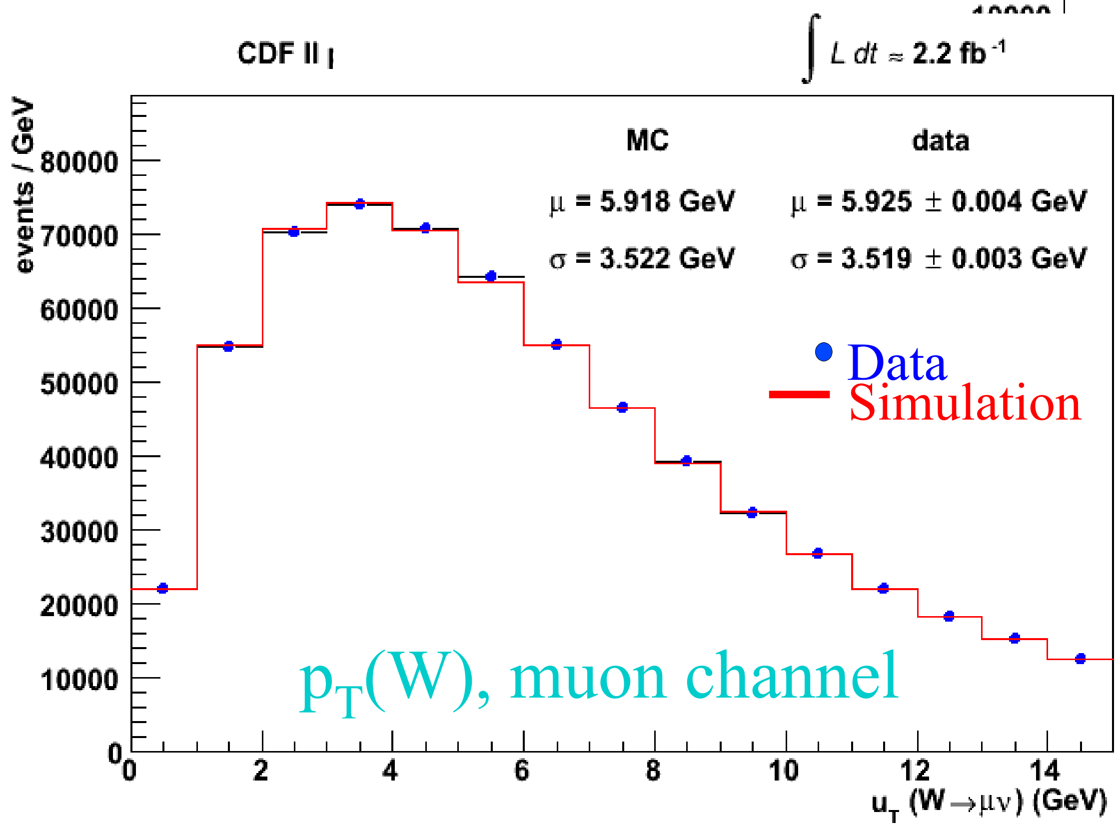


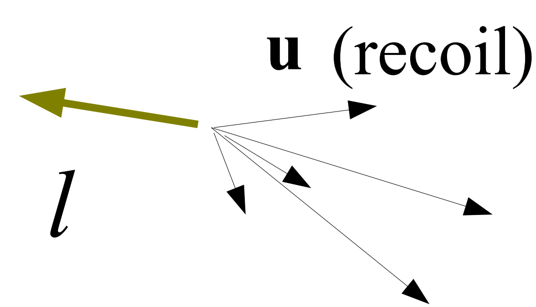
Recoil projection (GeV) perpendicular to lepton

Testing Hadronic Recoil Model with *W* events

Recoil model validation plots confirm the consistency of the model







Parton Distribution Functions

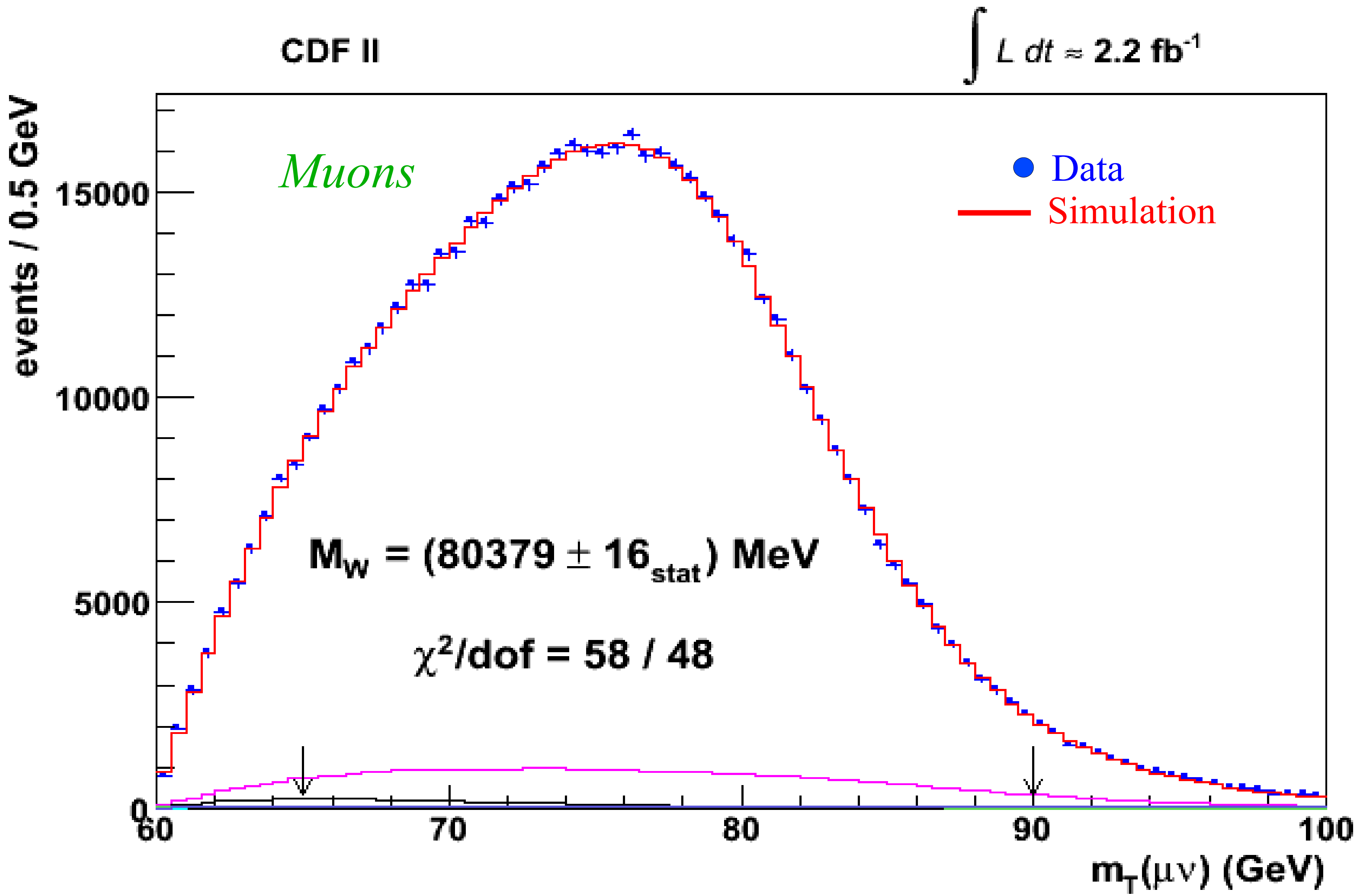
- Affect W kinematic lineshapes through acceptance cuts
- In the rest frame, $p_T = m \sin \theta^* / 2$
- Longitudinal cuts on lepton in the lab frame sculpt the distribution of θ^*, hence biases the distribution of lepton p_T
  - Relationship between lab frame and rest frame depends on the boost of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

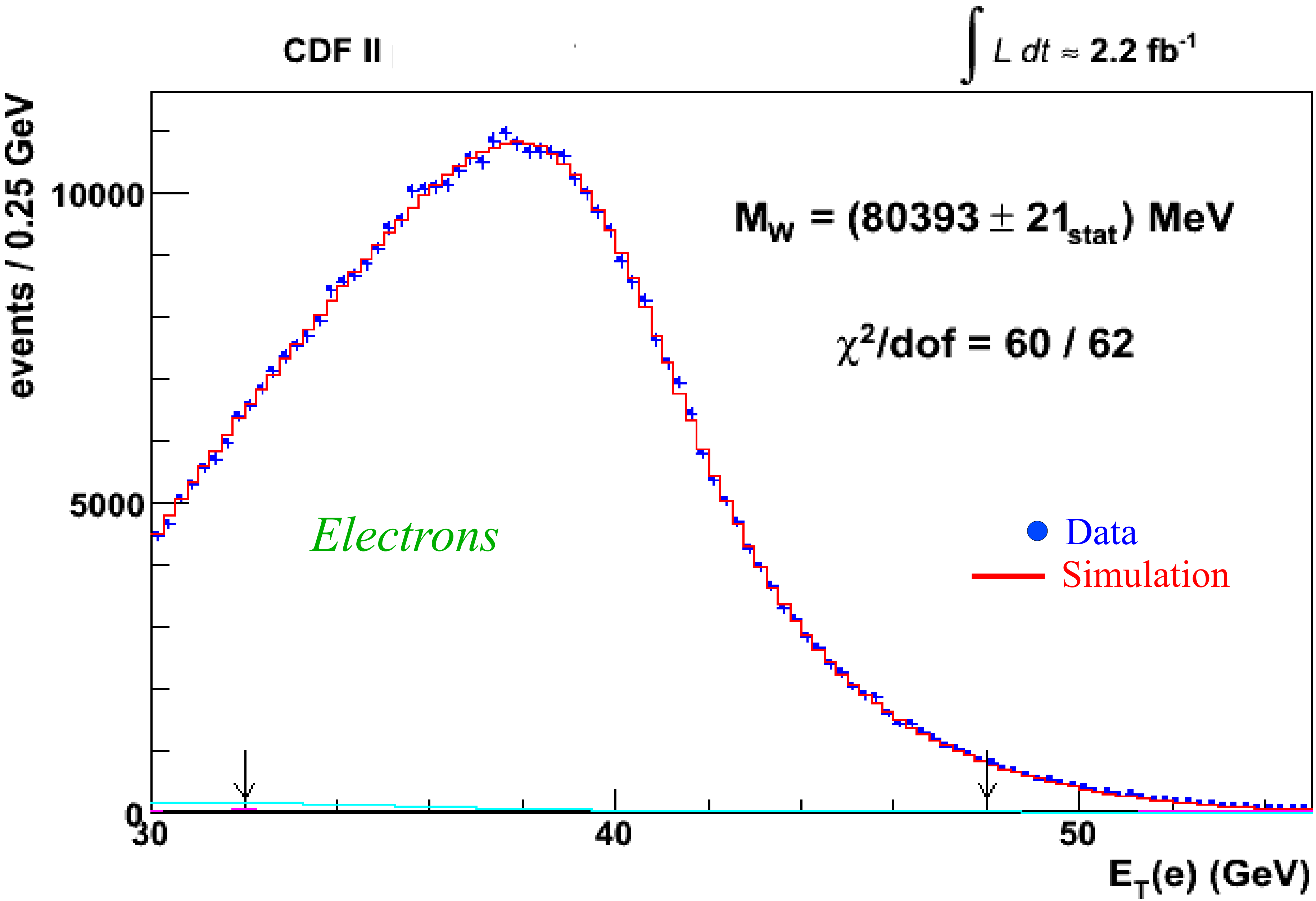
Blind Analysis Technique

- 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

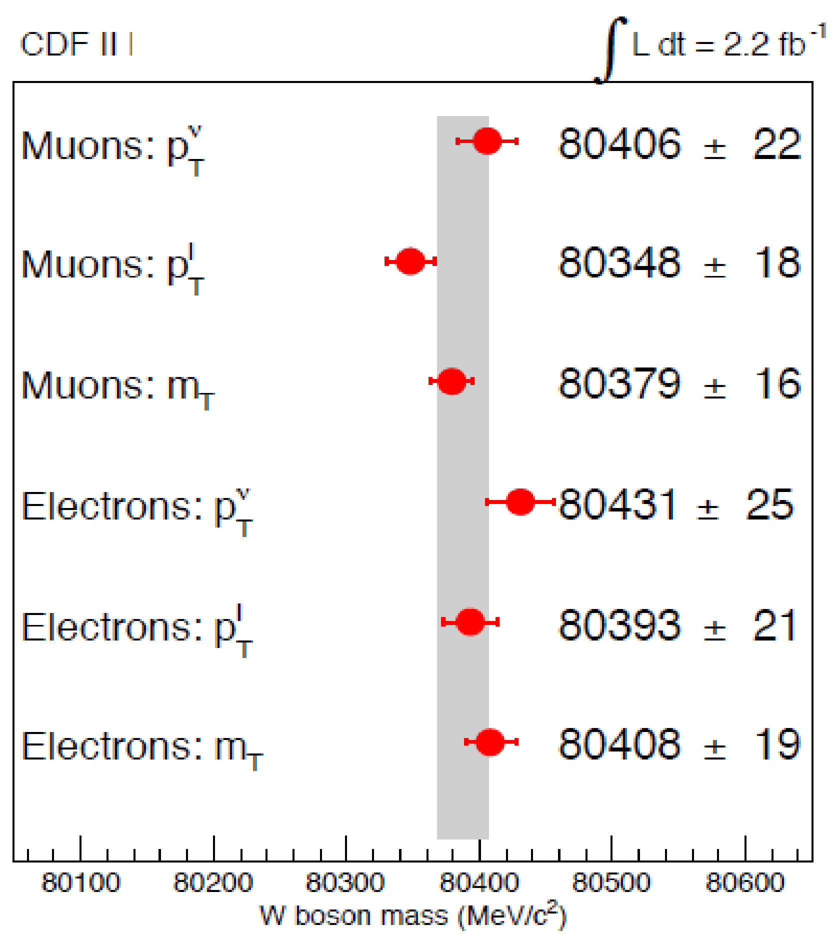


W Mass Fit using Lepton p_T



Summary of *W* Mass Fits

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

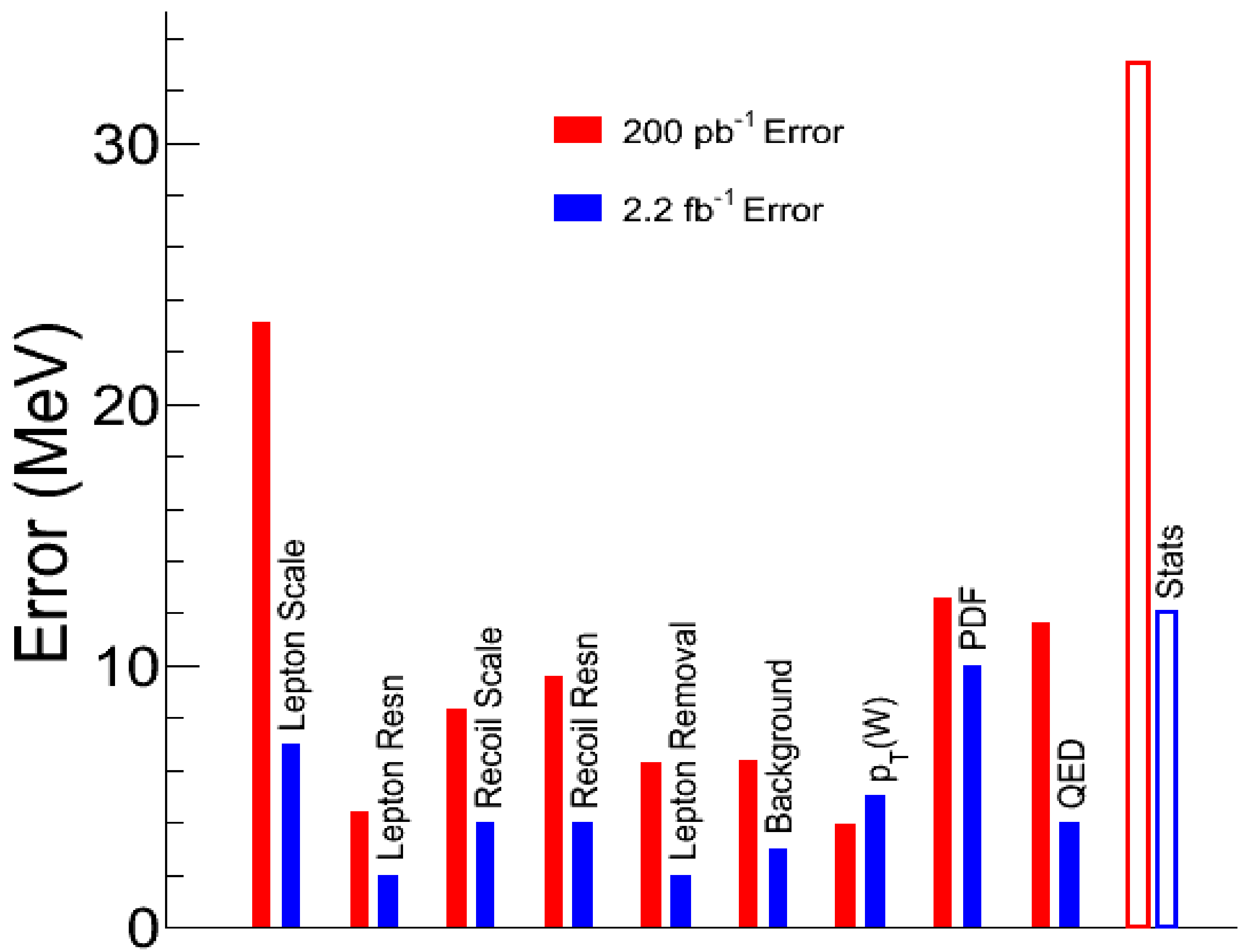


CDF Result (2.2 fb^{-1})
Transverse Mass Fit Uncertainties (MeV)

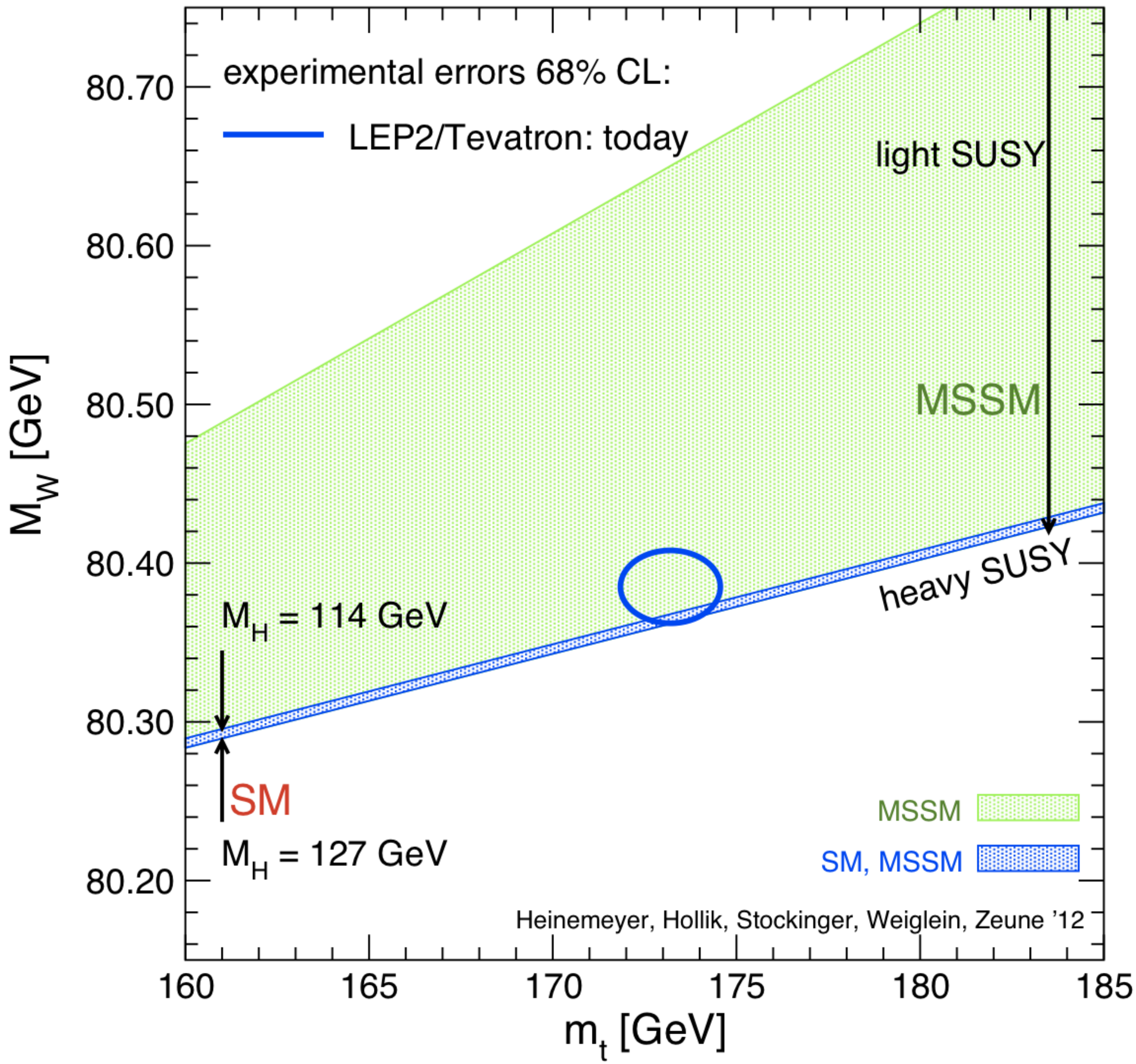
	electrons	*muons*	*common*
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total systematic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

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

Combined W Mass Result, Error Scaling

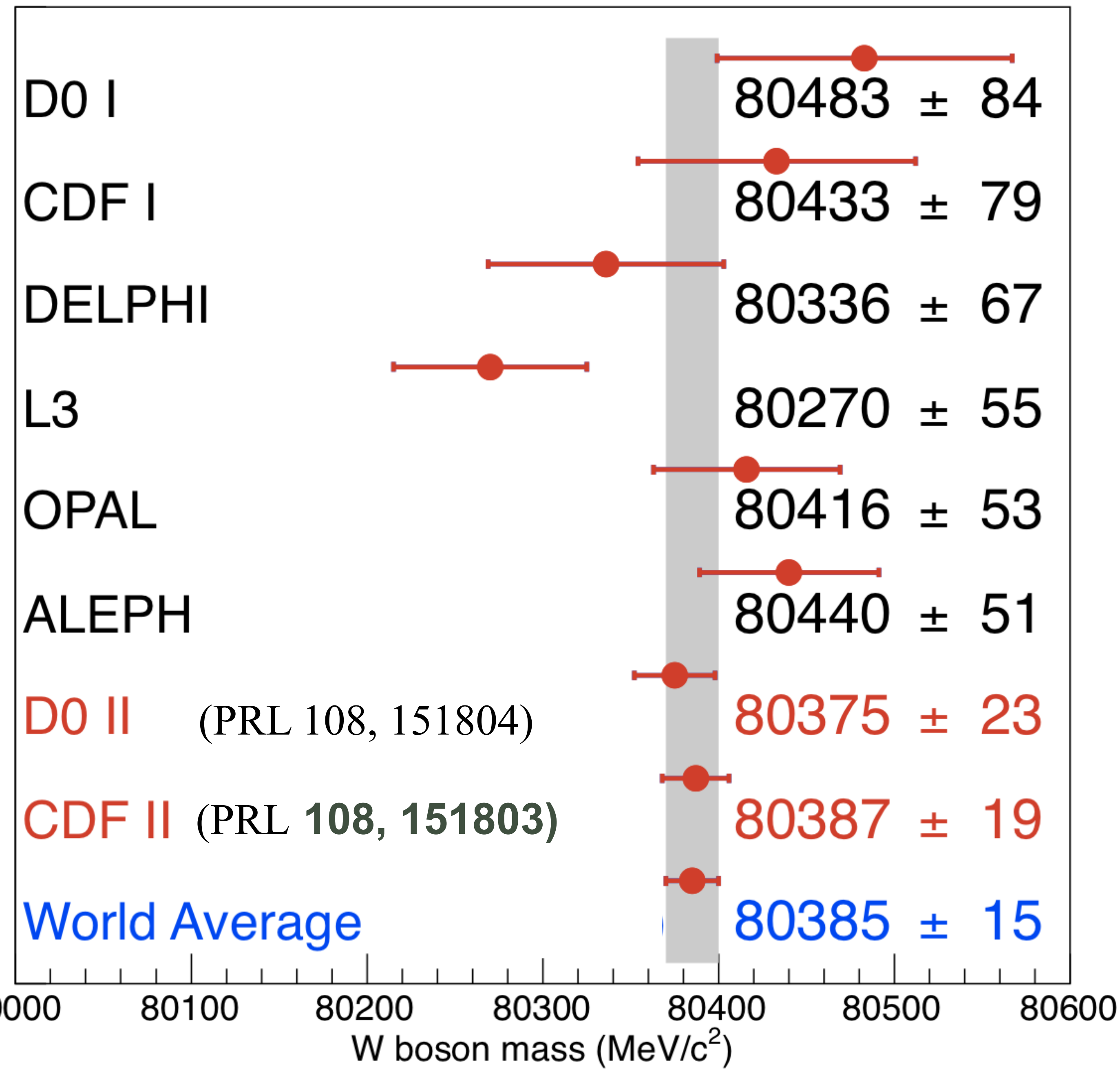


2012 Status of M_W *vs* M_{top}



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_{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

PDF Constraint – *W* Charge Asymmetry

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

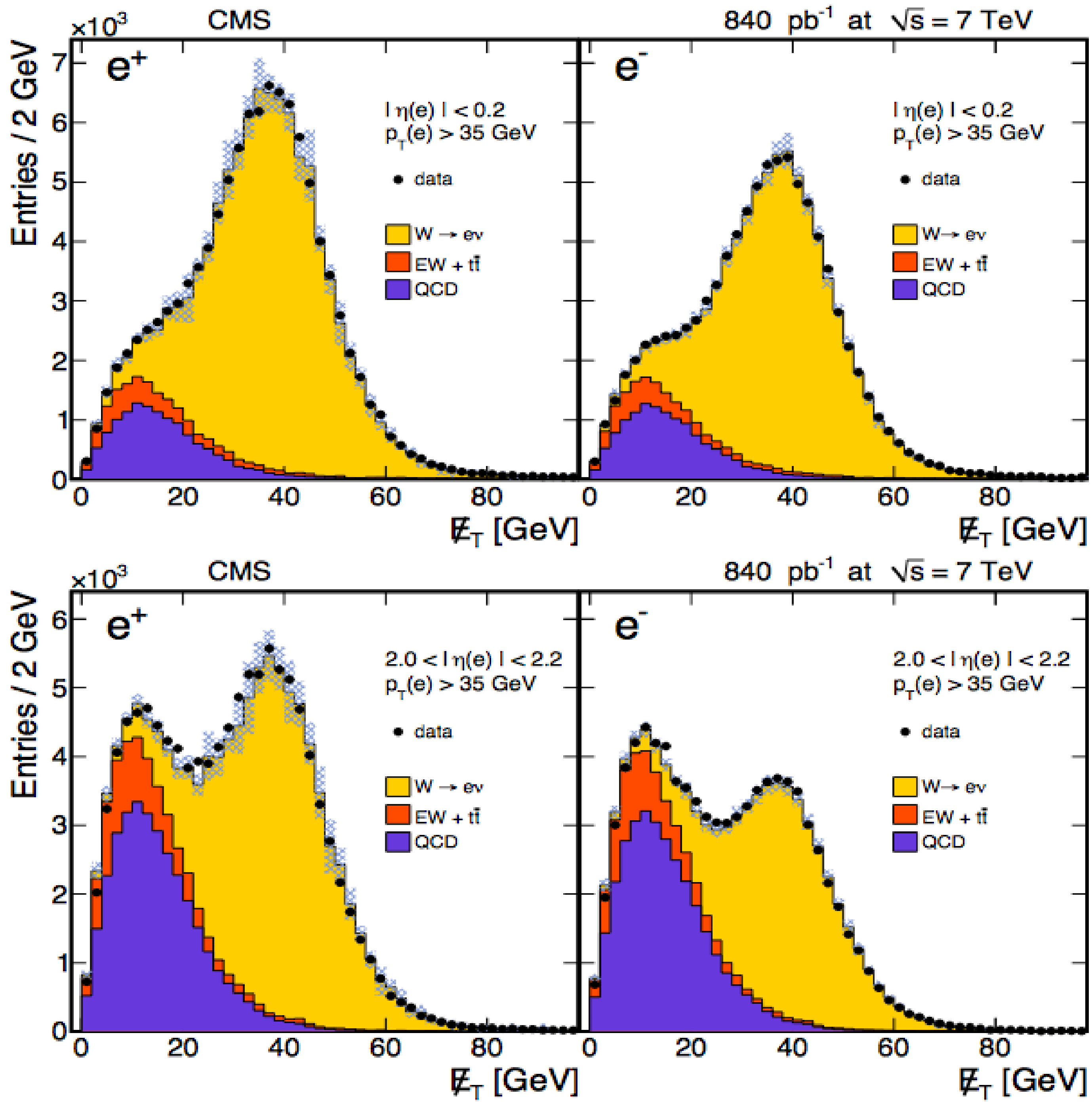
$$\mathcal{A}(\eta) = \frac{\mathrm{d}\sigma/\mathrm{d}\eta(\mathrm{W}^+ \to \mathrm{e}^+\nu) - \mathrm{d}\sigma/\mathrm{d}\eta(\mathrm{W}^- \to \mathrm{e}^-\bar{\nu})}{\mathrm{d}\sigma/\mathrm{d}\eta(\mathrm{W}^+ \to \mathrm{e}^+\nu) + \mathrm{d}\sigma/\mathrm{d}\eta(\mathrm{W}^- \to \mathrm{e}^-\bar{\nu})}$$

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

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

$$x_1 x_2 \propto \mathrm{M}_\mathrm{W}^2/s \quad \& \quad ln(x_1/x_2) \propto \eta$$

Missing E_T in Inclusive W Boson Events (CMS)



Systematic Uncertainties in Electron Asymmetry (CMS)

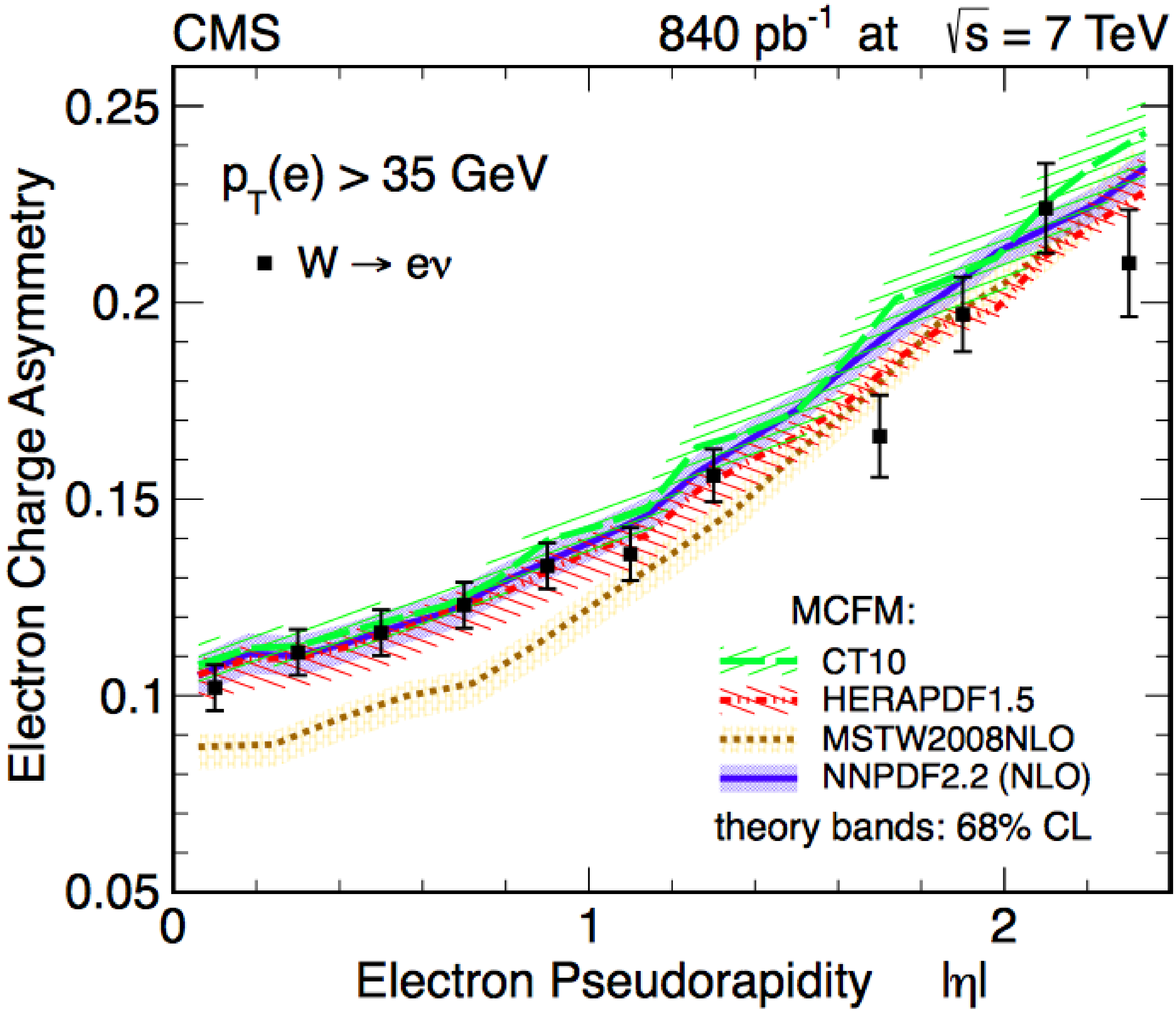
Table 1: Summary of the systematic uncertainties on the asymmetry. All values are given in units of 10^{-3}.

$\lvert\eta\rvert$ 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
  - $\Psi \to e^{i\,g\,\xi(x)}\,\Psi$ (gauge transformation of fermion field)
- Introduction of a vector potential A_μ (a.k.a. gauge field),
  - $\partial_\mu \Psi \to D_\mu \Psi = (\partial_\mu - i\,g\,A_\mu)\,\Psi$
  - $A_\mu \to A_\mu + \partial_\mu \xi$
- 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"
  - $F_{\mu\nu} F^{\mu\nu}$

Trilinear and Quartic Gauge Couplings

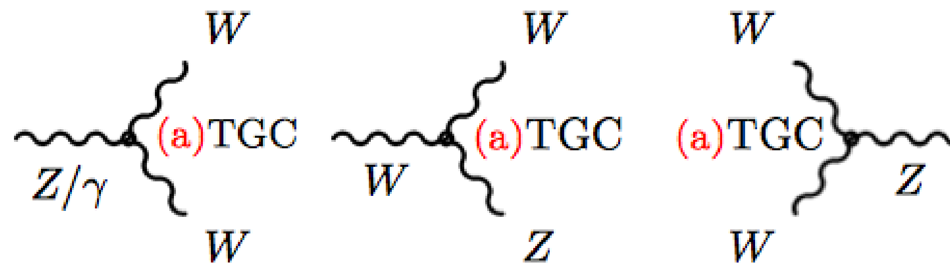
- For non-Abelian Gauge group, Gauge-invariant Field Strength tensor $F_{\mu\nu}$
  - $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g[A_\mu, A_\nu]$
- (gauge and Lorentz-invariant) kinetic energy term $F_{\mu\nu} F^{\mu\nu}$ yields
  - terms which are quadratic in gauge field (these yield the gauge boson propagator)
  - Cubic terms
  - Quartic terms
- Latter two types of terms yield trilinear and quartic gauge couplings

Anomalous Trilinear Gauge Coupling

$V = Z, \gamma$

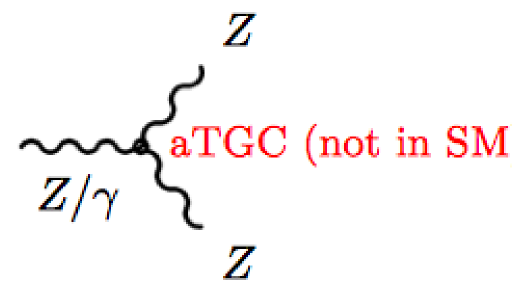
- effective parametrizations for anomalous couplings:
  - WWV vertex: $\Delta g_1^Z, \Delta\kappa_Z, \Delta\kappa_\gamma, \lambda_Z, \lambda_\gamma$

    → 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

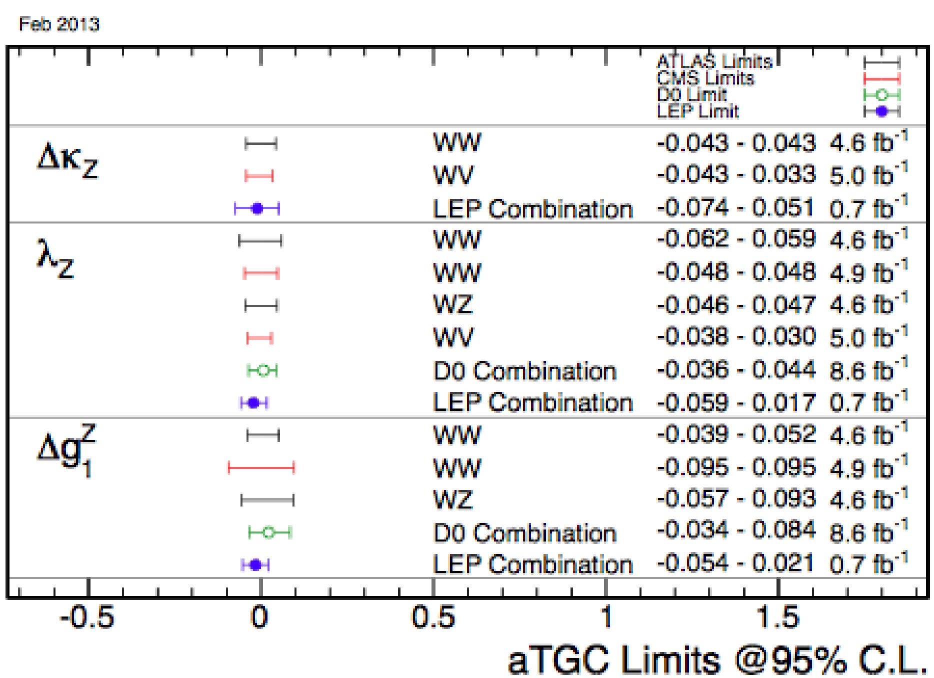


- 1- and 2-dimensional 95% confidence intervals for aTGC from 7 TeV data, e.g.

  → without and with form factors to avoid unitarity violation

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

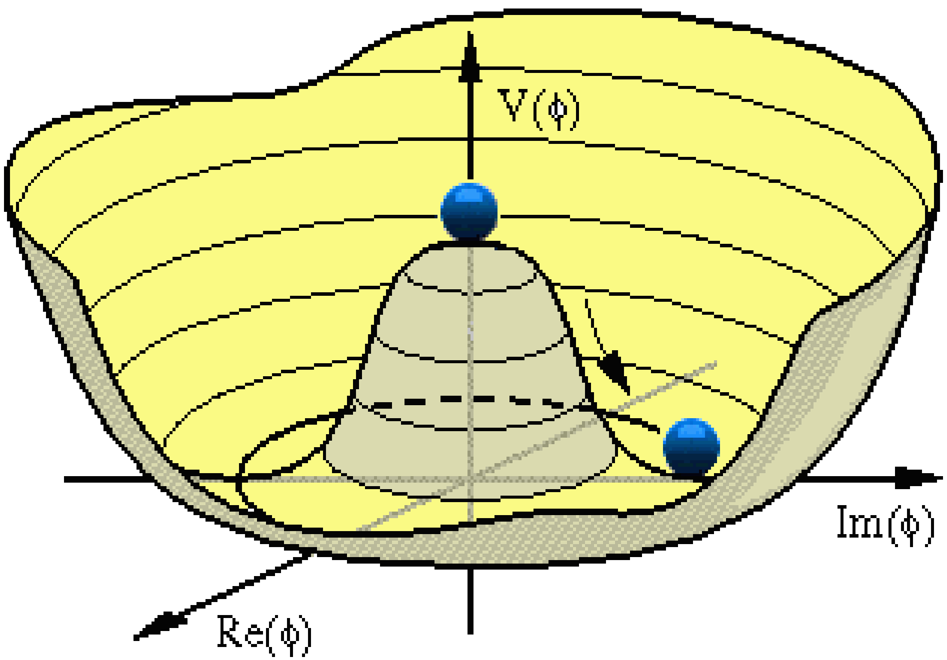
(Λ_{FF}: form factor scale)



(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 !!

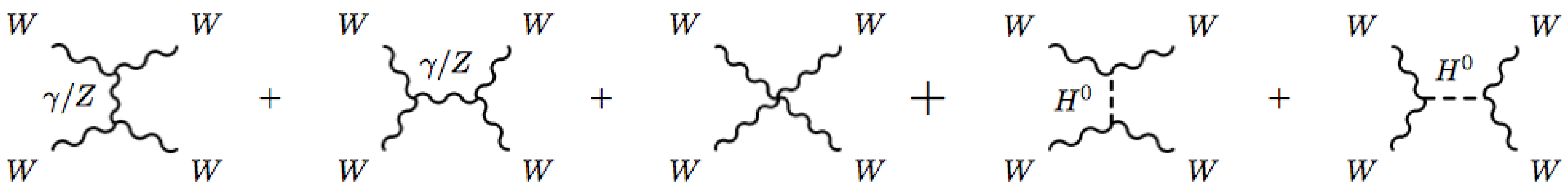
Quartic Gauge Couplings

$V = W, Z$

- 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!

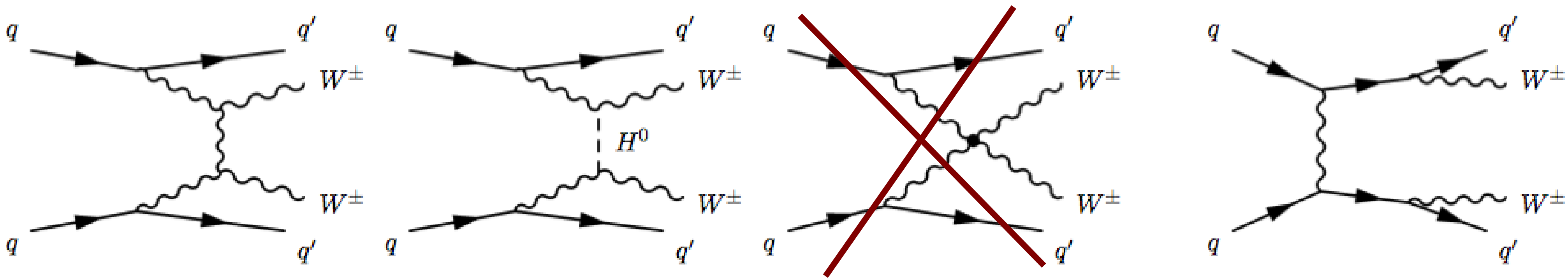
- at the LHC: measure $VVjj$ final states $\rightarrow$ same-sign $W^{\pm}W^{\pm}jj$ most promising

(from A. Vest, TU-Dresden)

Same-Sign Boson-boson Scattering

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

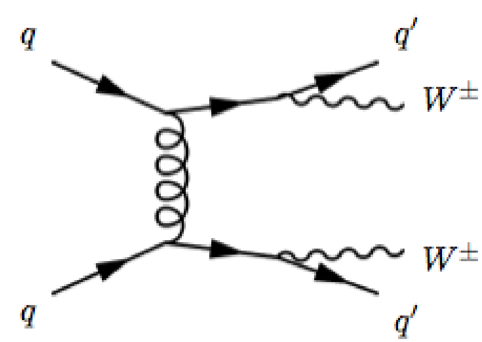
$W^\pm W^\pm jj$-EW VBS: no s-channel diagrams   non-VBS diagrams, e.g.



→ 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)

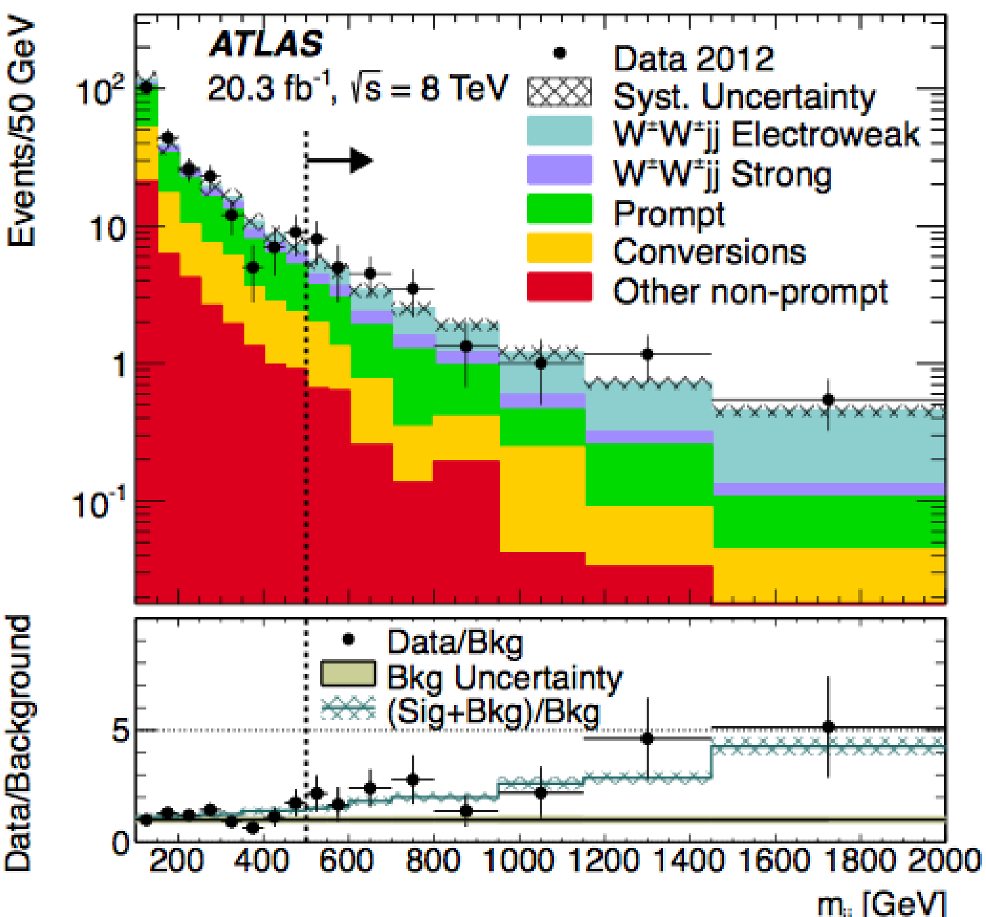
$W^{\pm}W^{\pm}$ Scattering

for EW+strong measurement

("inclusive signal region")

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

invariant mass of the 2 tagging jets

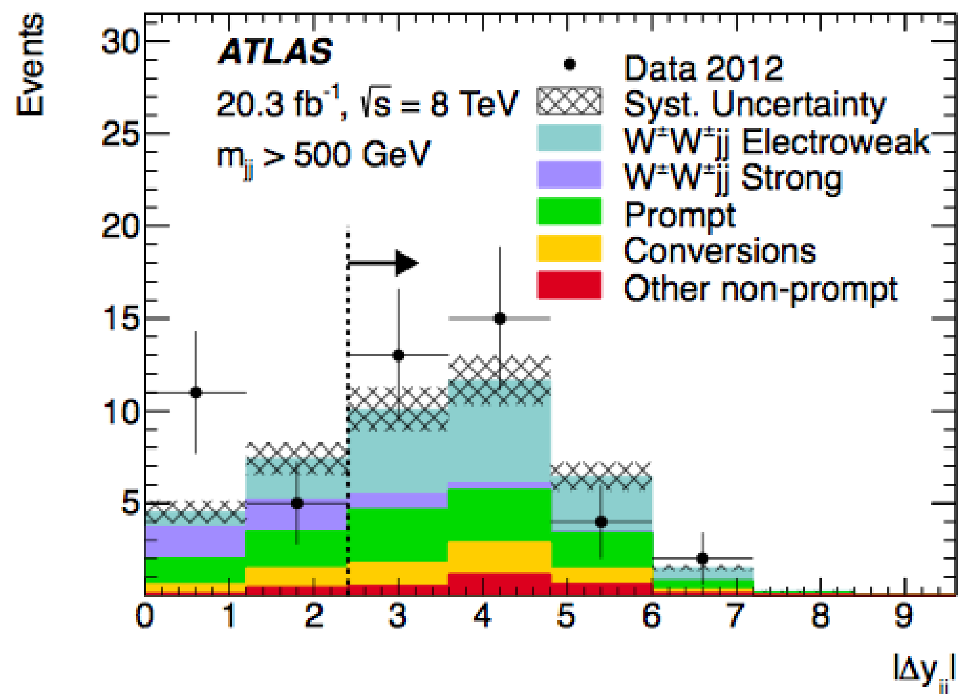


for EW measurement

("VBS signal region")

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

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

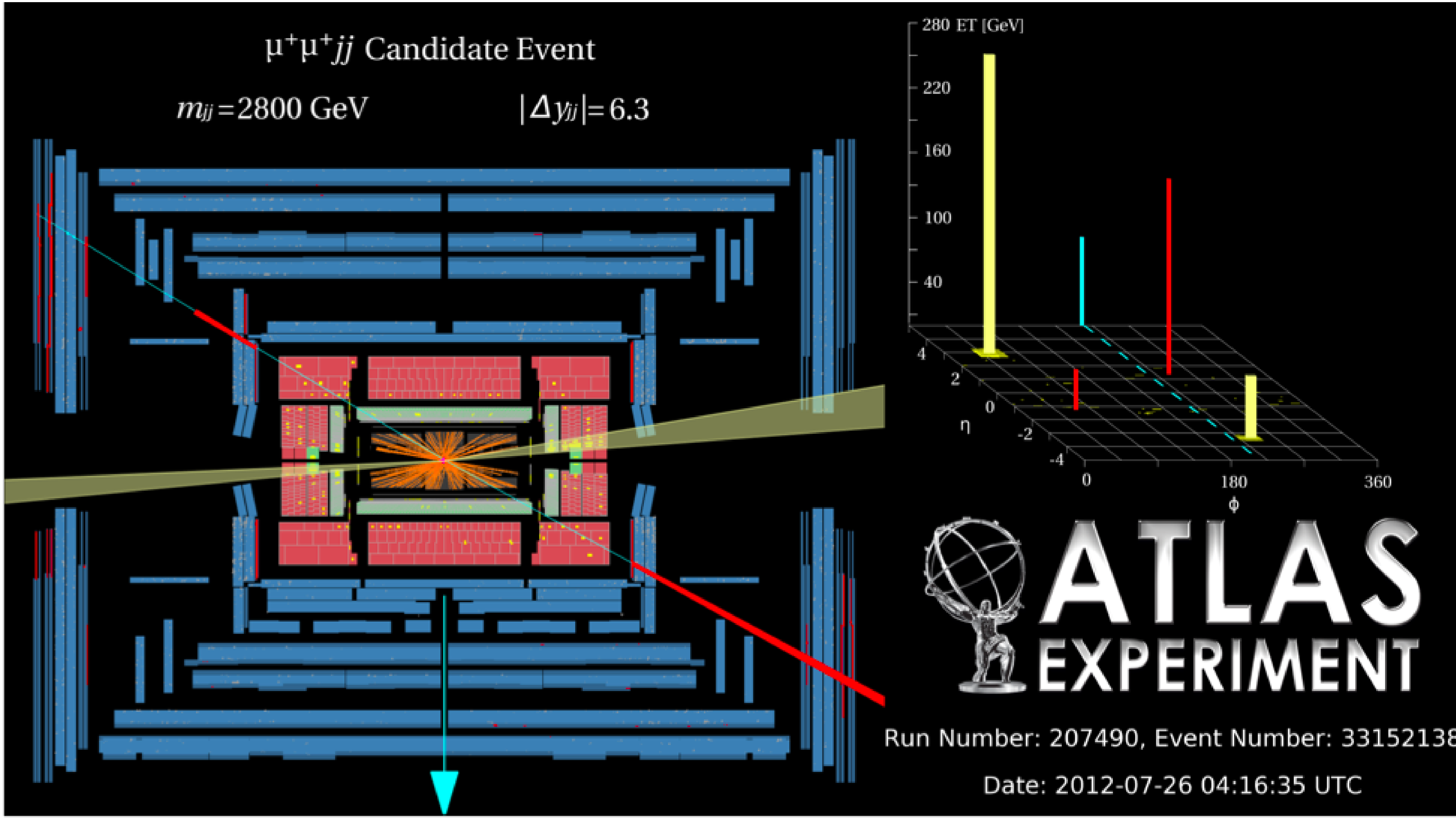


EW and strong $W^{\pm}W^{\pm}jj$ from SHERPA, normalized with POWHEG

(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, $\eta^{j1} = 2.9$, $\eta^{j2} = -3.4$ $E_T^{\rm miss} = 75$ 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 in vector boson scattering mode

  - 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

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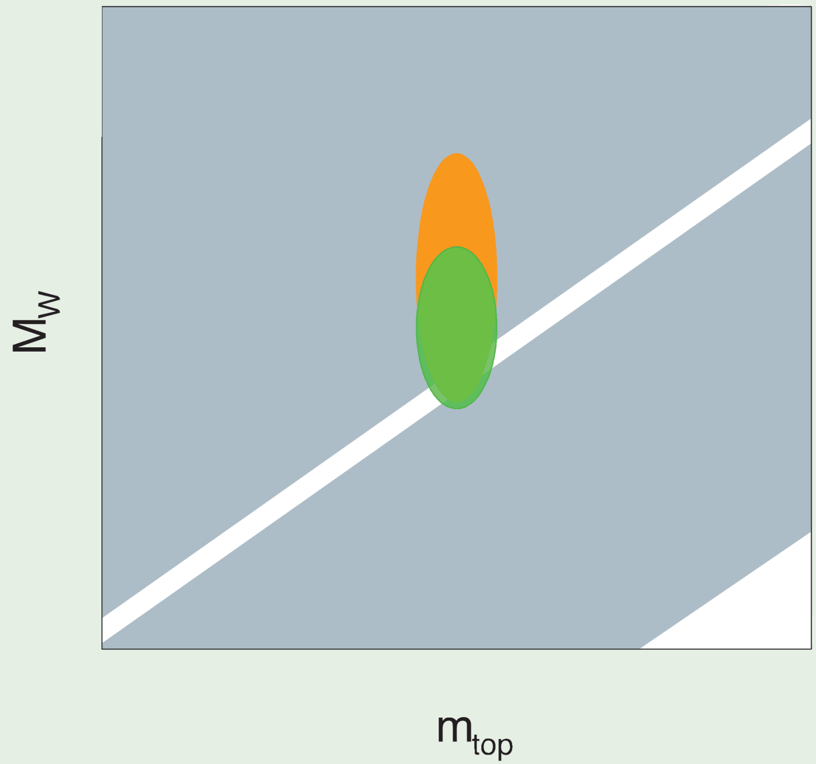

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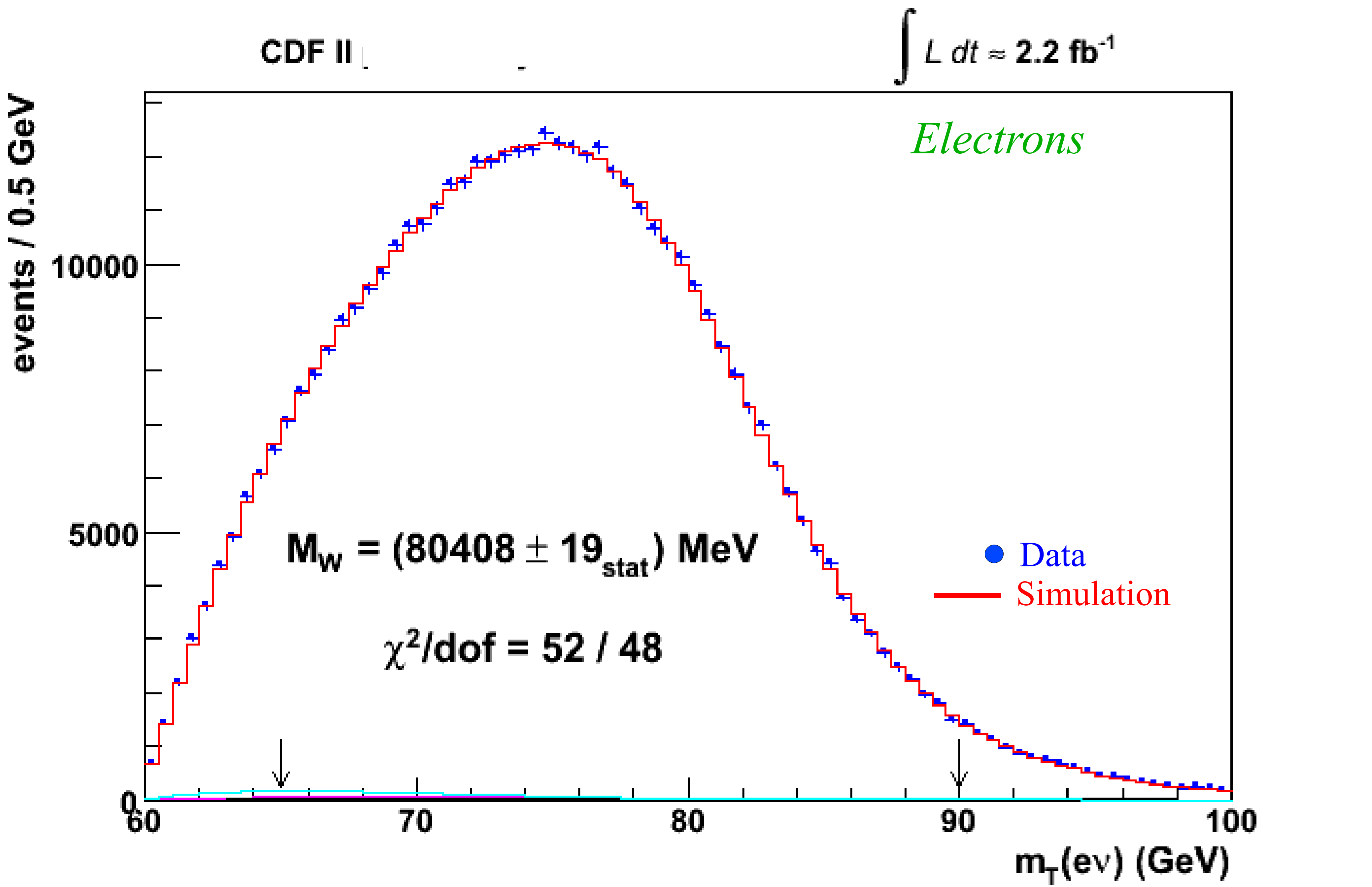
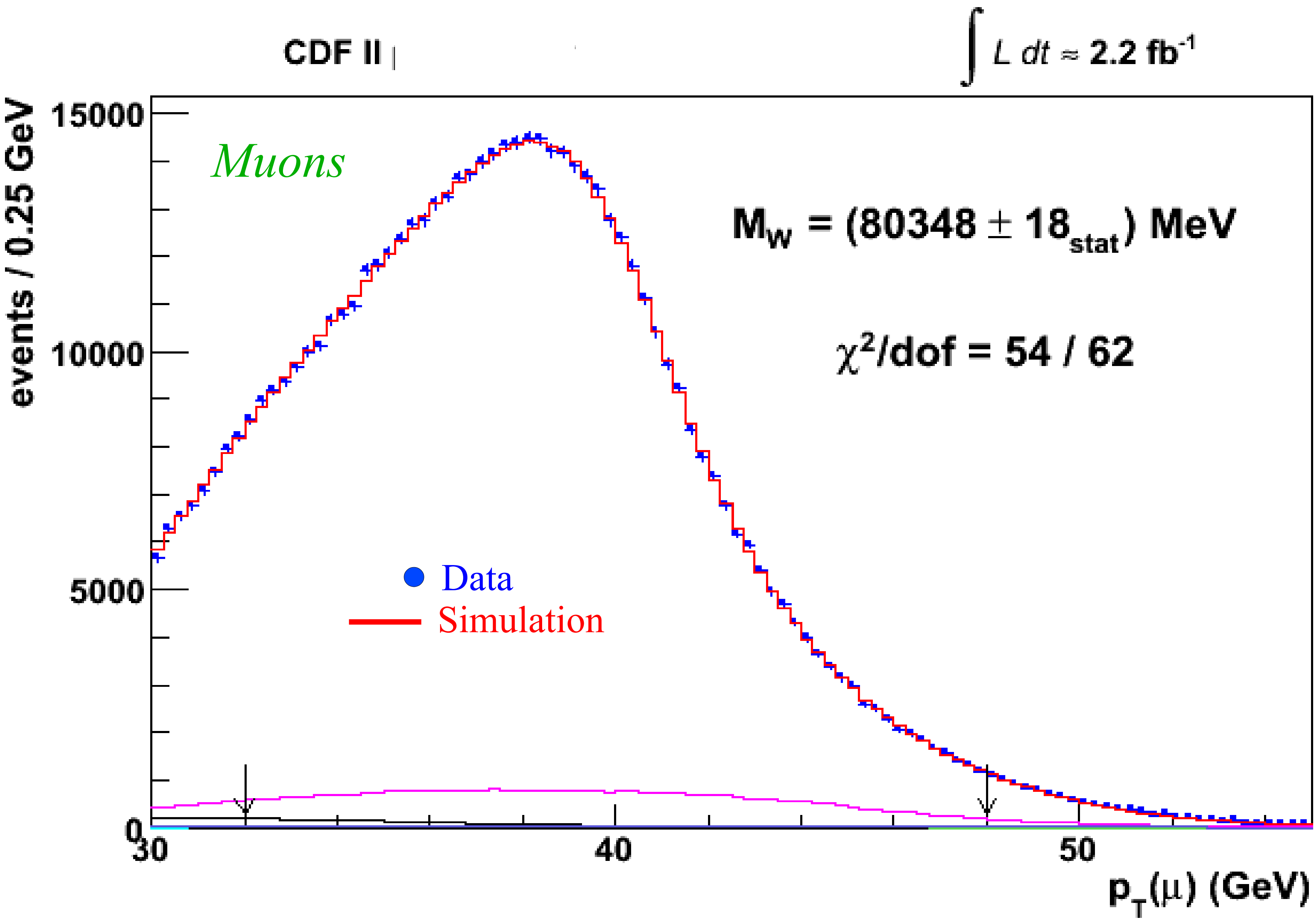
Volume 108, Number 15

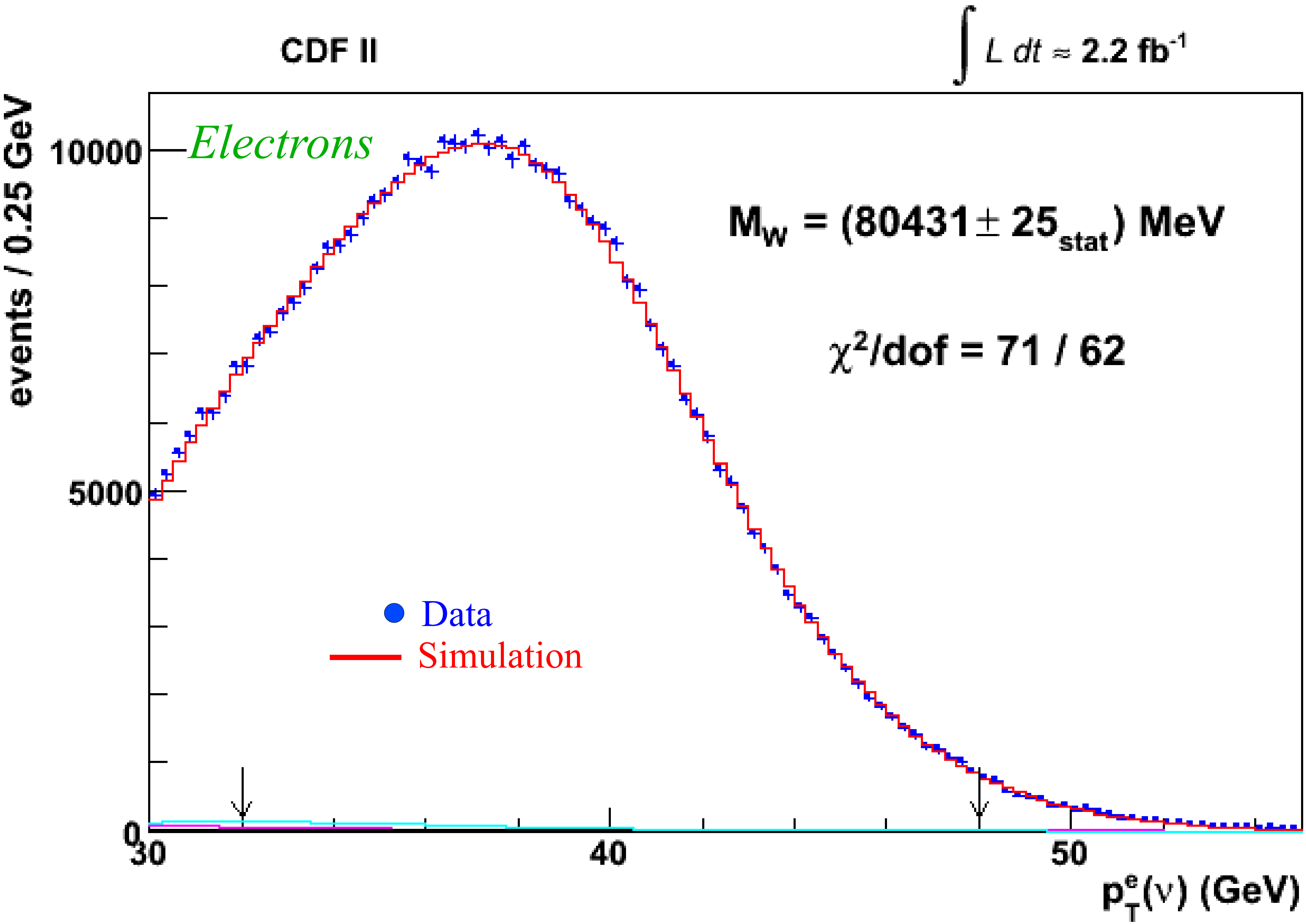
W Transverse Mass Fit



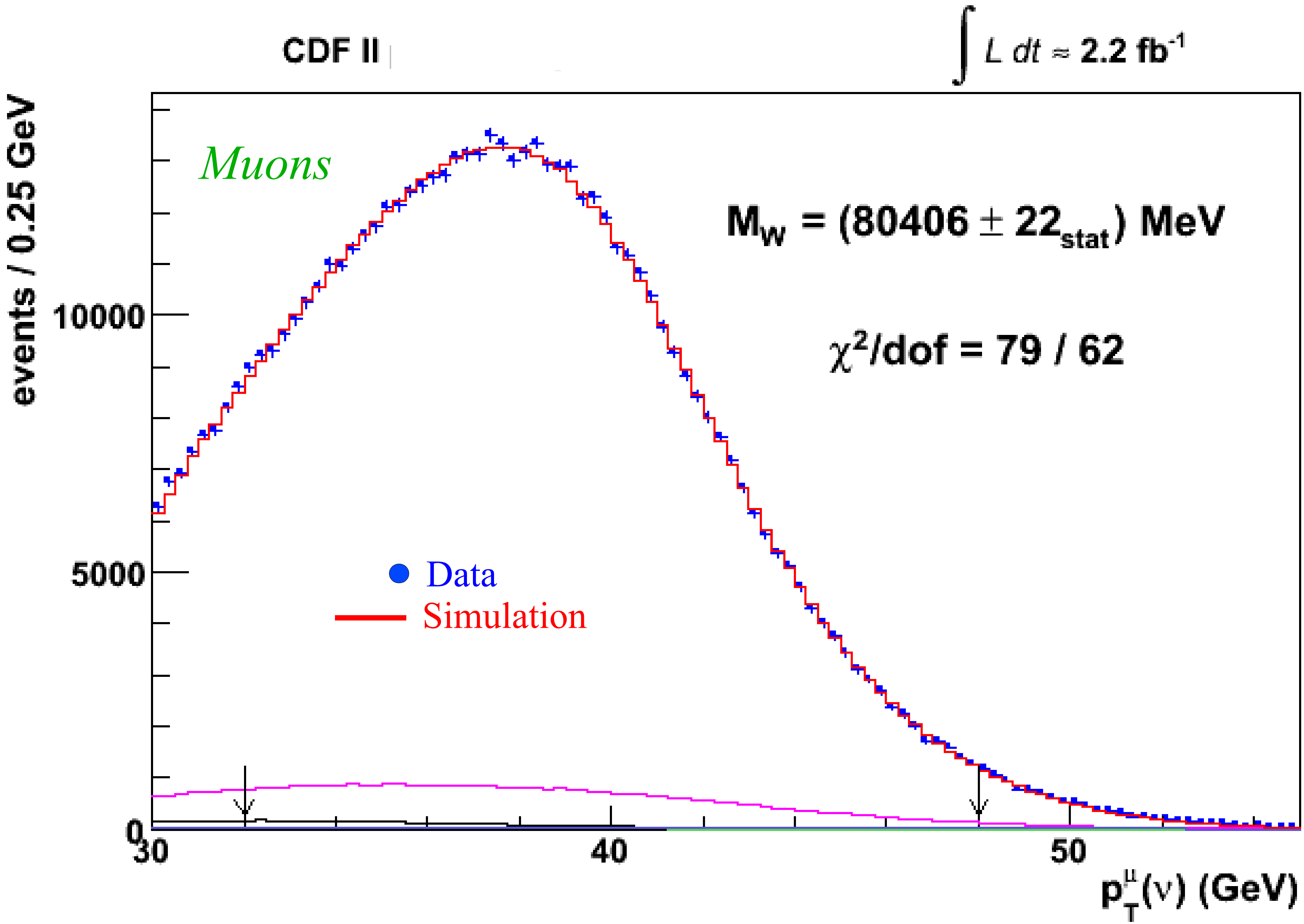
W Lepton p_T Fit



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

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

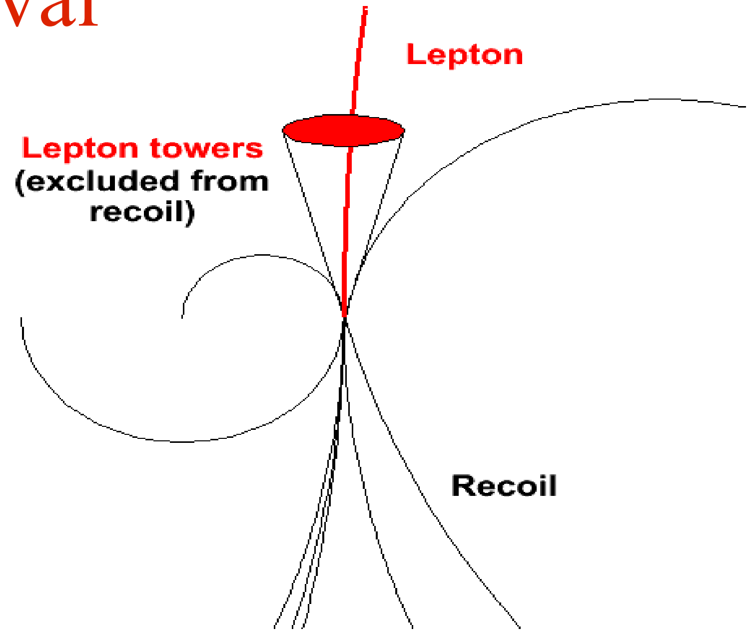
- Electron cluster resolution parameterized in the custom simulation by
  - 12.6% / $\sqrt{E_T}$ (sampling term)
  - Primary constant term $\kappa = (0.68 \pm 0.05_{stat})$ %
  - Secondary photon resolution $\kappa_\gamma = (7.4 \pm 1.8_{stat})$ %
  - Tuned on the widths of the E/p peak and the $Z \to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

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



Electron channel W data

Electron Electromagnetic E_T(MeV)

Tower $\Delta\eta$ (η) \ Tower $\Delta\phi$ (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 $\Delta\eta$ (η) \ Tower $\Delta\phi$ (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	δm_W (MeV) m_T fit	p_T^μ fit	p_T^ν fit
$Z \to \mu\mu$	7.35 ± 0.09	2	4	5
$W \to \tau\nu$	0.880 ± 0.004	0	0	0
QCD	0.035 ± 0.025	1	1	1
DIF	0.24 ± 0.08	1	3	1
Cosmic rays	0.02 ± 0.02	1	1	1
Total		3	5	6

Electrons

Background	% of $W \to e\nu$ data	δm_W (MeV) m_T fit	p_T^e fit	p_T^ν fit
$Z \to ee$	0.139 ± 0.014	1	2	1
$W \to \tau\nu$	0.93 ± 0.01	1	1	1
QCD	0.39 ± 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, χ^2/dof = 1.2/1 (28%)
- Electron and muon p_T fits combined

  m_W = 80366 ± 22 MeV, χ^2/dof = 2.3/1 (13%)
- Electron and muon MET fits combined

  m_W = 80416 ± 25 MeV, χ^2/dof = 0.5/1 (49%)
- All electron fits combined

  m_W = 80406 ± 25 MeV, χ^2/dof = 1.4/2 (49%)
- All muon fits combined

  m_W = 80374 ± 22 MeV, χ^2/dof = 4/2 (12%)
- All fits combined

  m_W = 80387 ± 19 MeV, χ^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