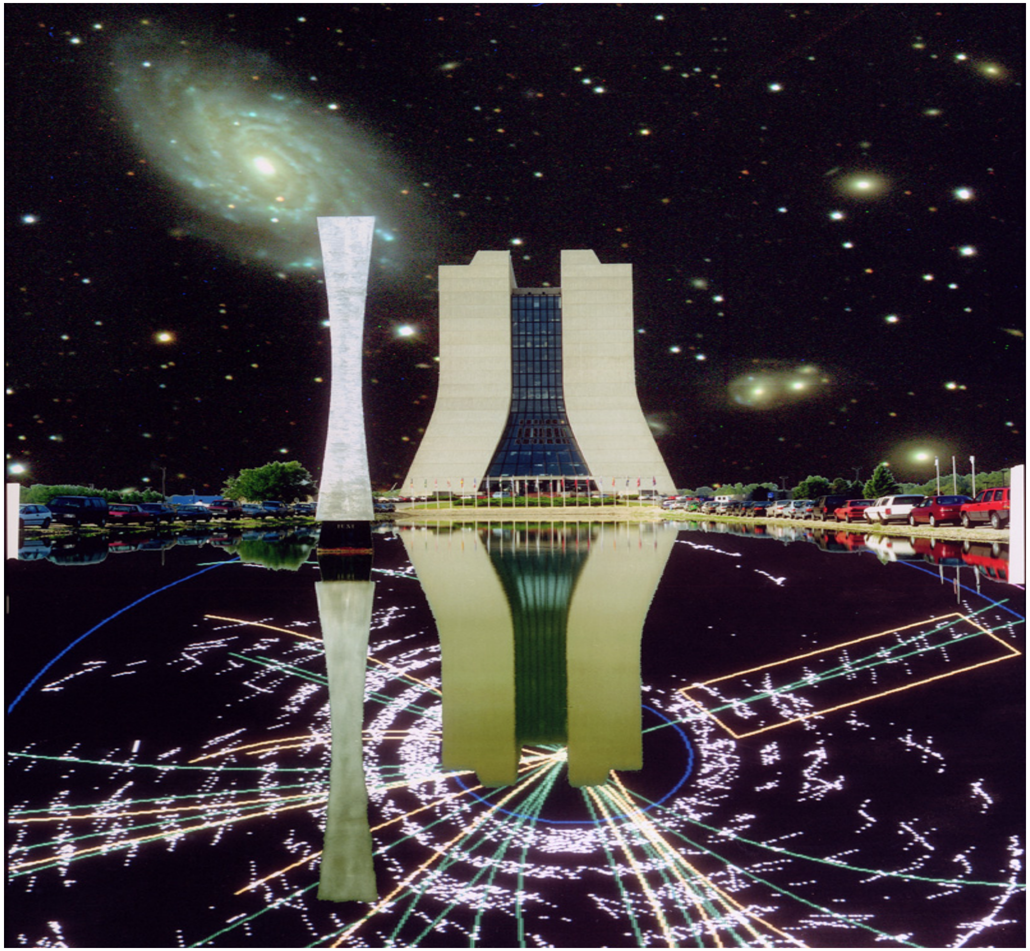
A New Precise Measurement of the W Boson Mass at CDF

Ashutosh Kotwal
Duke University

For the CDF Collaboration



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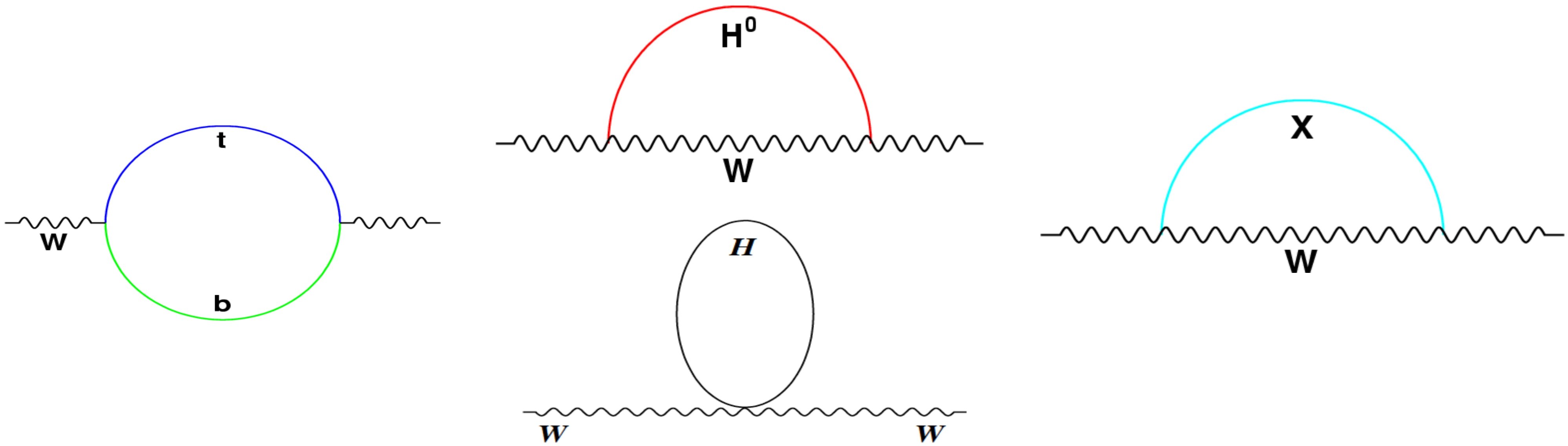
Motivation for Precision Electroweak Measurements

- The electroweak gauge sector of the standard model, defined by *(g, g′, v)*, 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 Electroweak Measurements

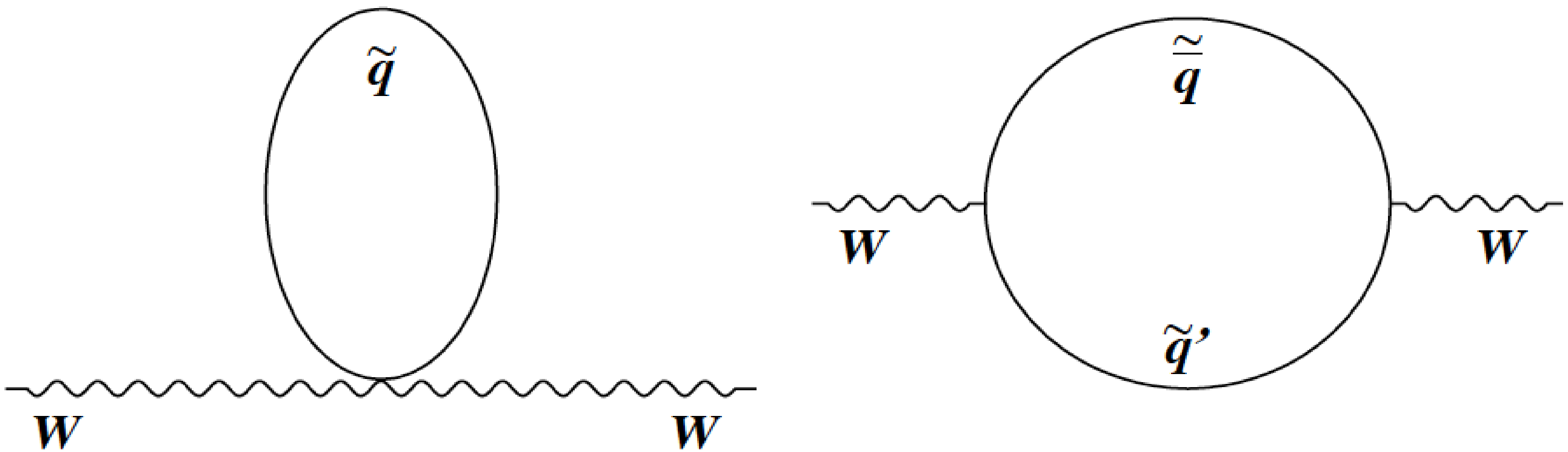
- Radiative corrections due to heavy quark and Higgs loops and exotica



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

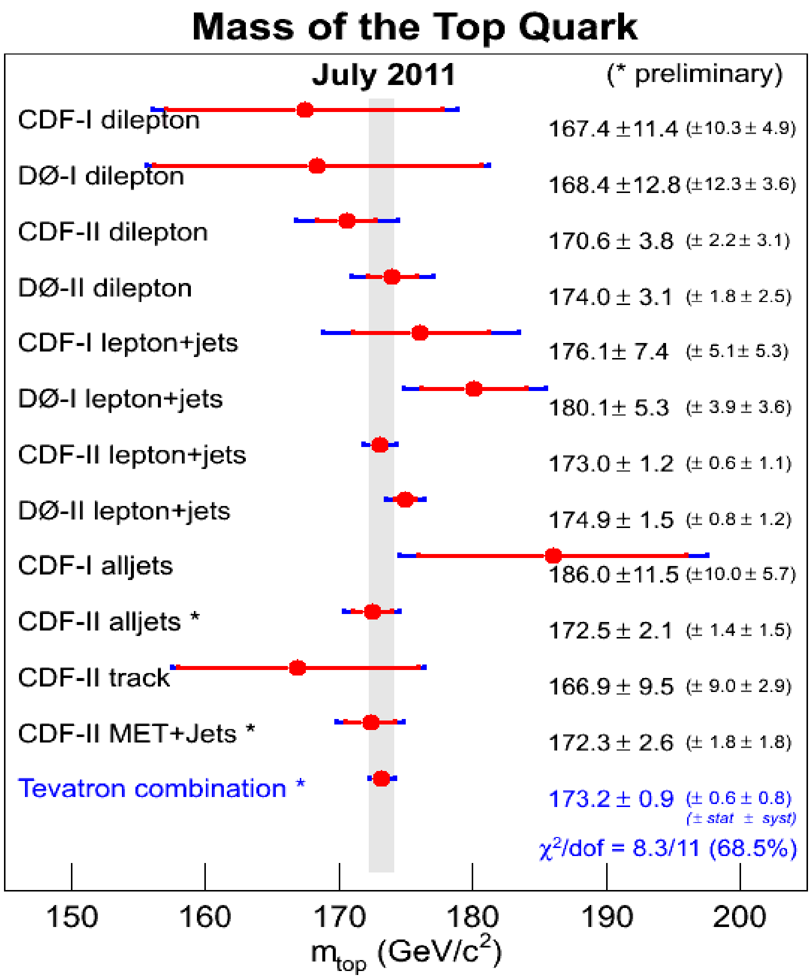
- In conjunction with M_{top}, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

Contributions from Supersymmetric Particles



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

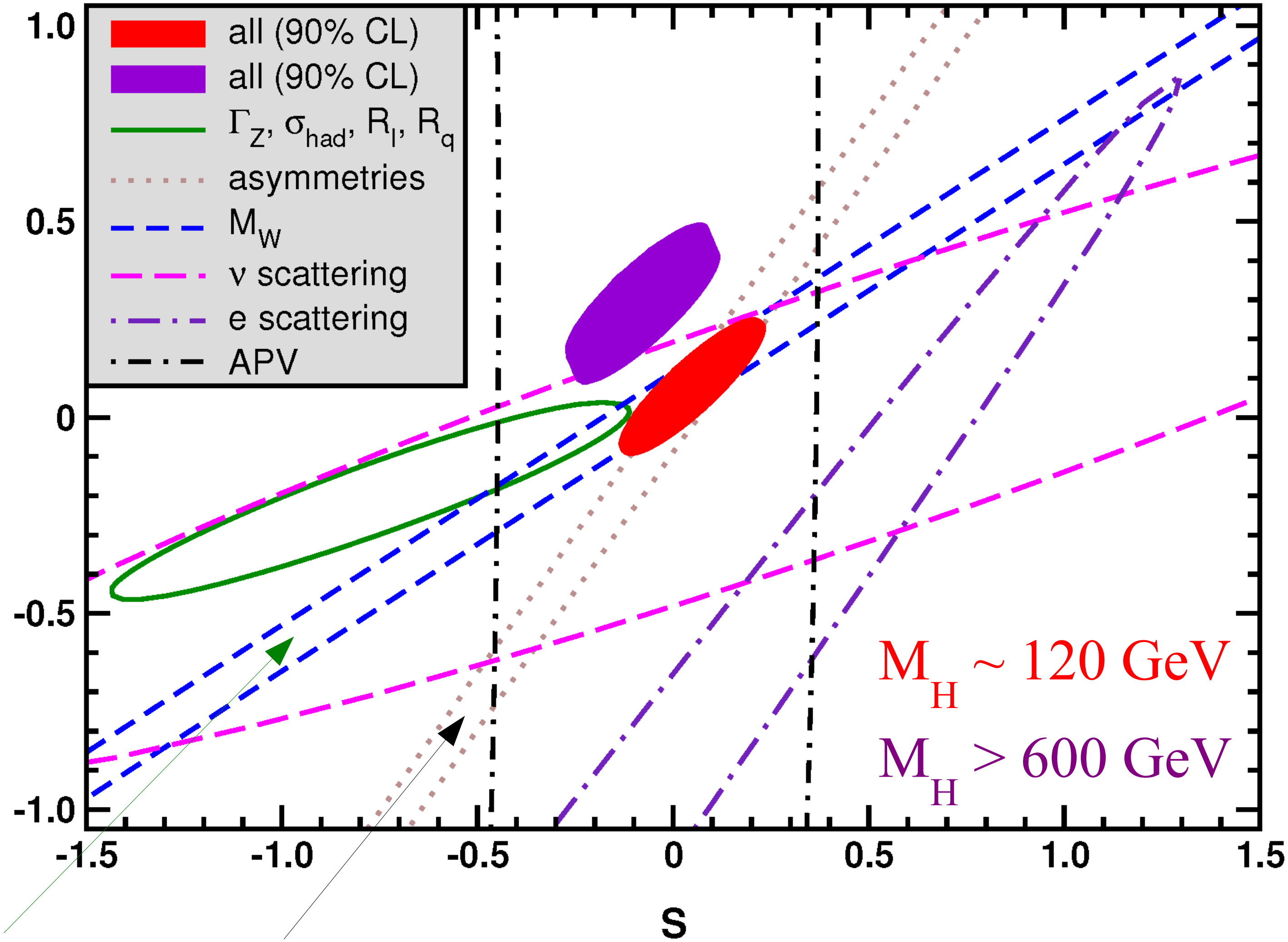
Progress on M_{top} at the Tevatron



- 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 $\Delta M_W = 23$ MeV
  - progress on ΔM_W has the biggest impact on Higgs constraint

Motivation

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

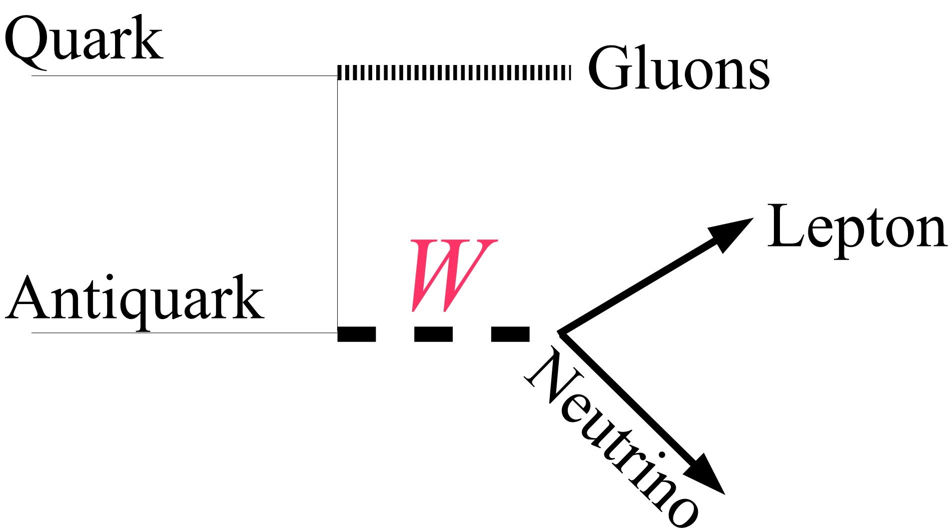


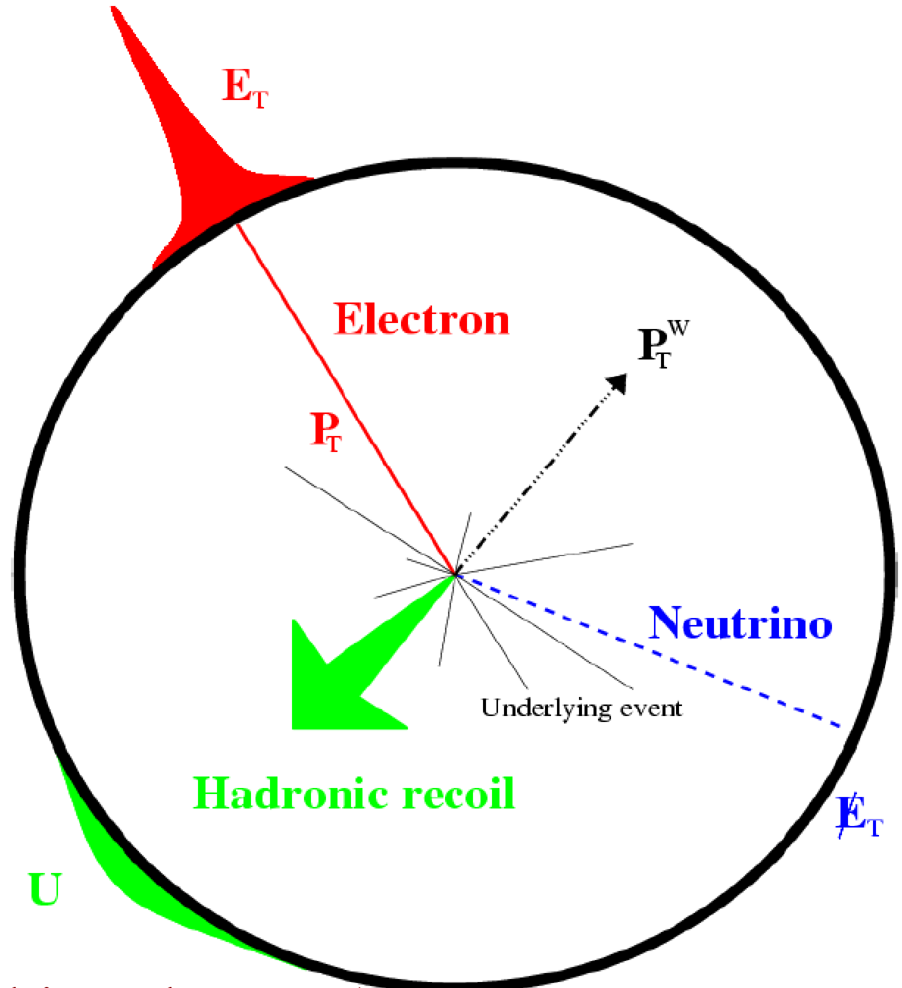
Additionally, M_W is the only measurement which constrains *U*

(from P. Langacker, 2012)

M_W and Asymmetries are the most powerful observables in this parameterization

W Boson Production at the Tevatron





Quark-antiquark annihilation dominates (80%)

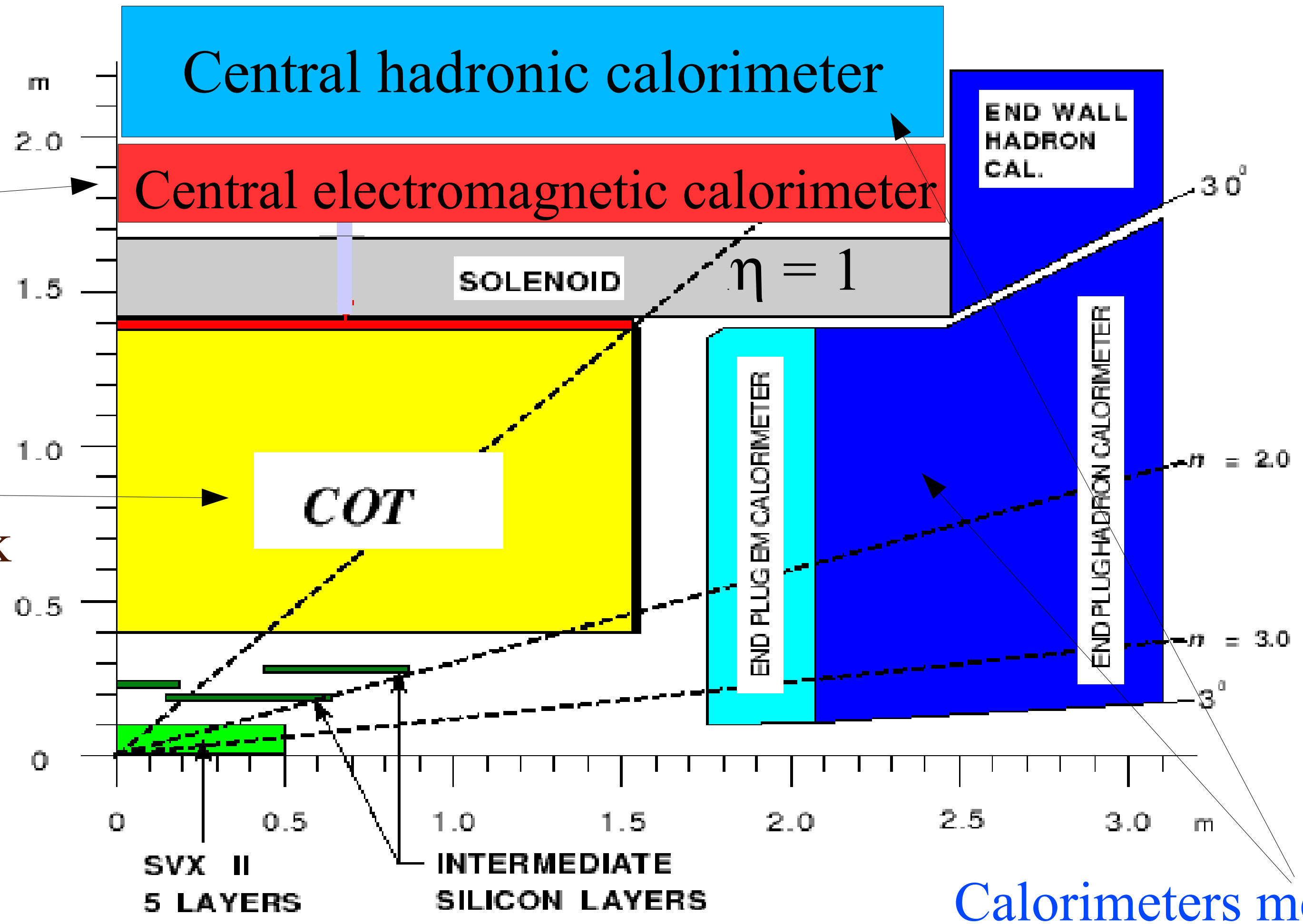
Lepton p_T carries most of *W* mass information, can be measured precisely (achieved 0.01%)

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

Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

Drift chamber provides precise lepton track momentum measurement



Calorimeters measure hadronic recoil particles

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

Analysis Strategy

Maximize the number of internal constraints and cross-checks

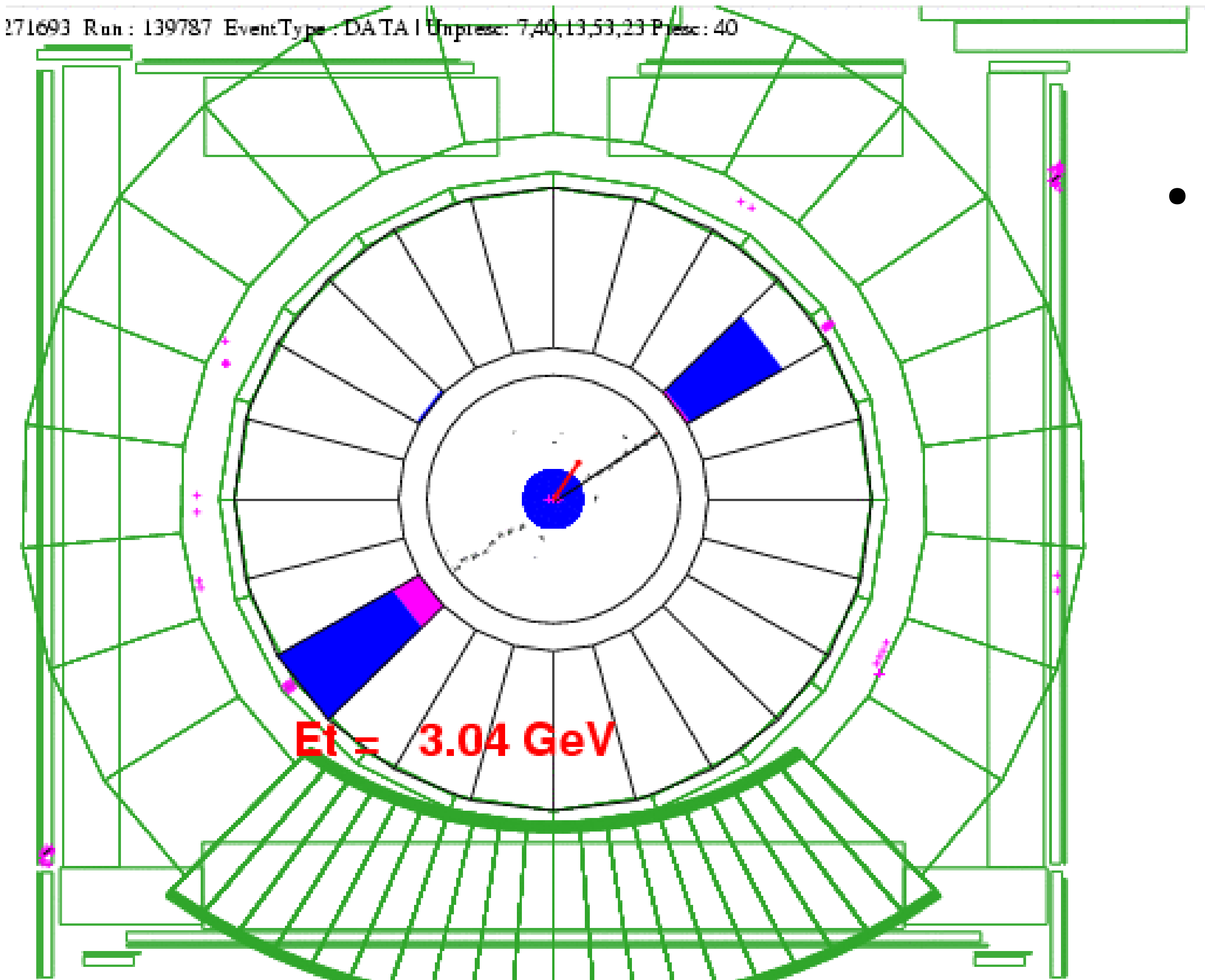
Driven by two goals:

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

2) Precision: combine independent measurements after showing consistency

Internal Alignment of COT

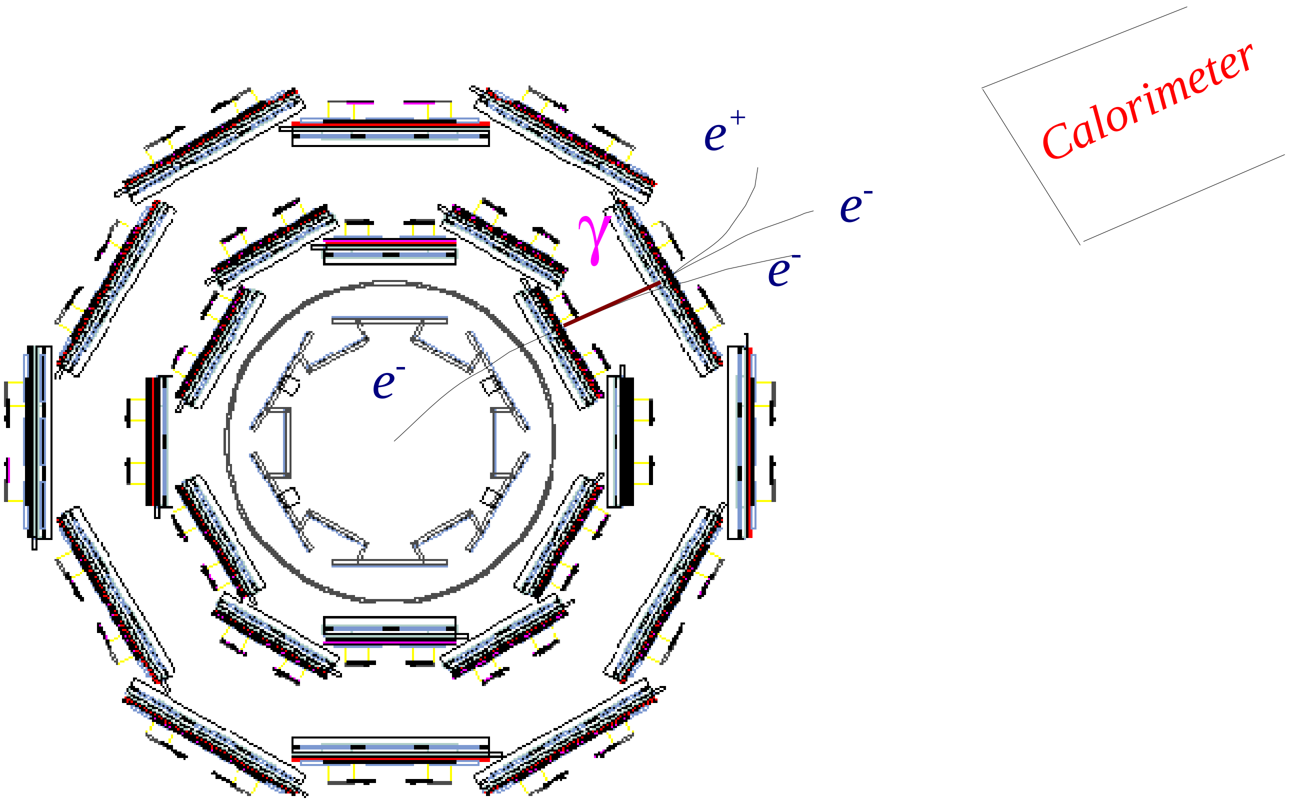
- Use a clean sample of ~400*k* cosmic rays for cell-by-cell internal alignment



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

Custom Monte Carlo Detector Simulation

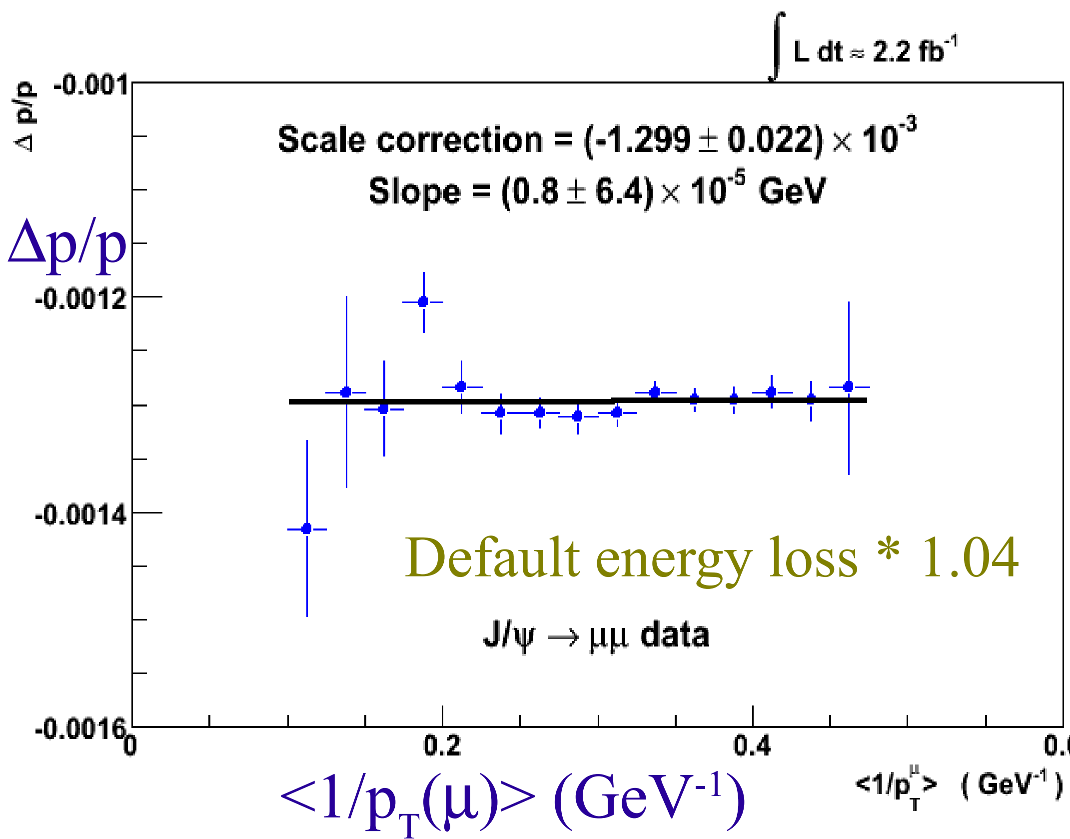
- A complete detector simulation of all quantities measured in the data
- First-principles simulation of tracking
  - Tracks and photons propagated through a high-granularity 3-D lookup table of material properties for silicon detector and COT

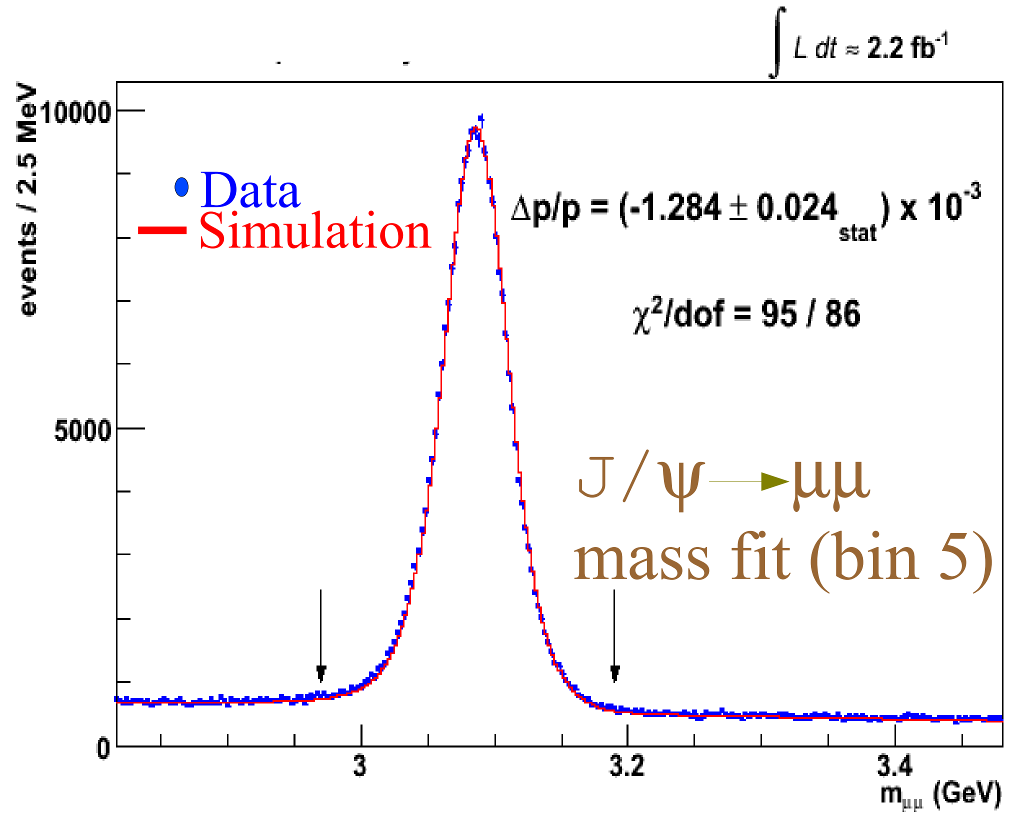


Tracking Momentum Scale

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

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

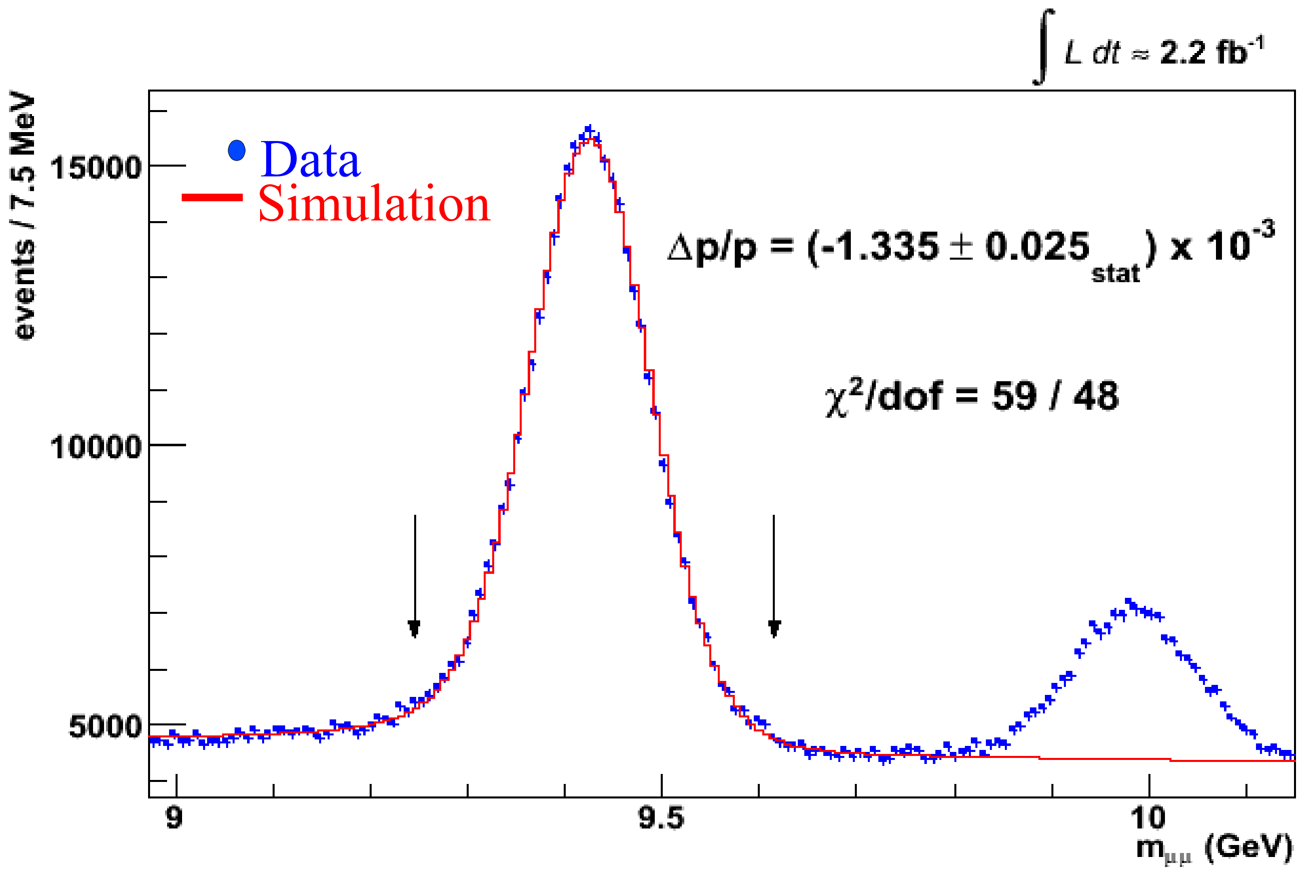




Tracking Momentum Scale

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

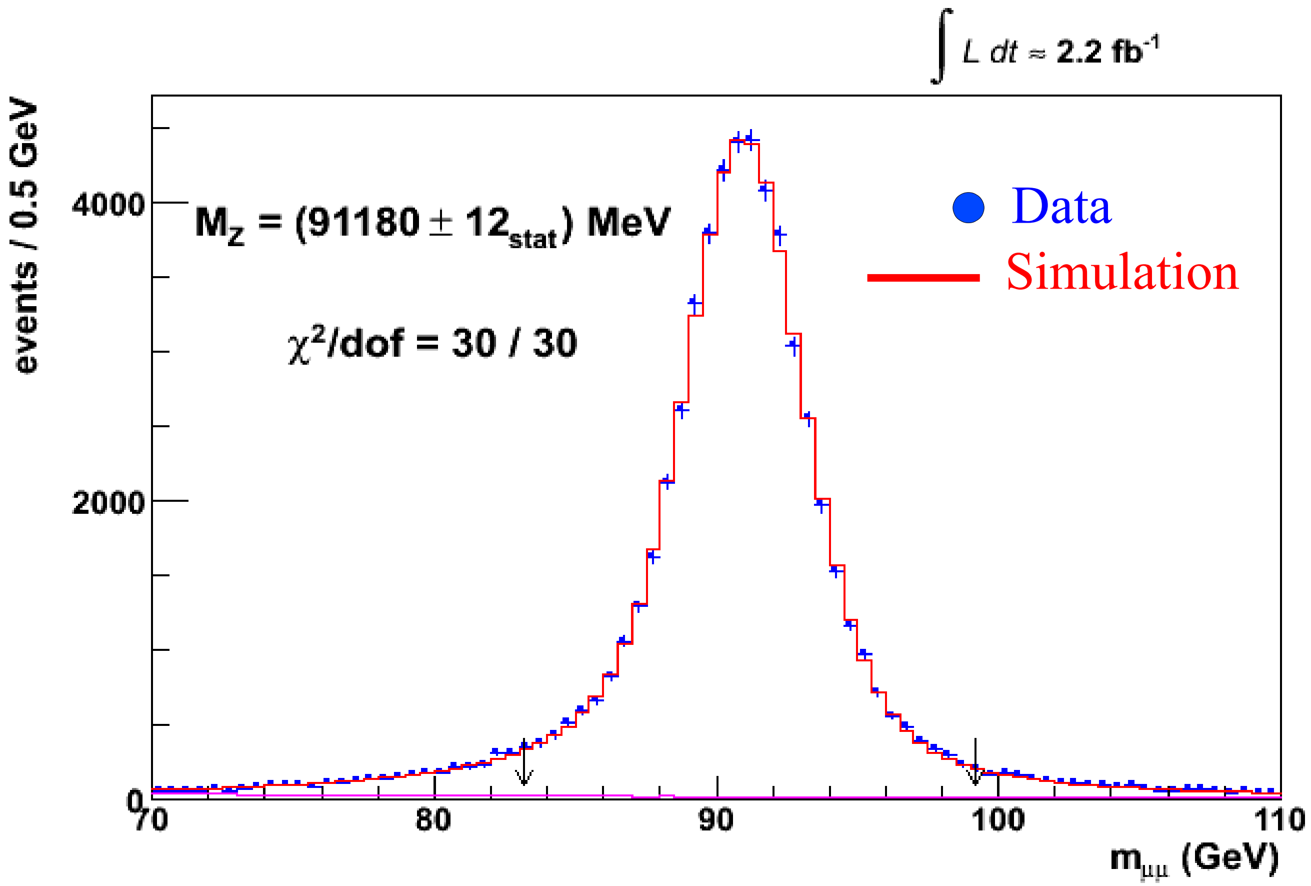
- Momentum scale measurement at higher p_T
- Validation of beam-constaining procedure (upsilons are promptly produced)
- Cross-check of non-beam-constrained (NBC) and beam-constrained (BC) fits



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

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

- 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

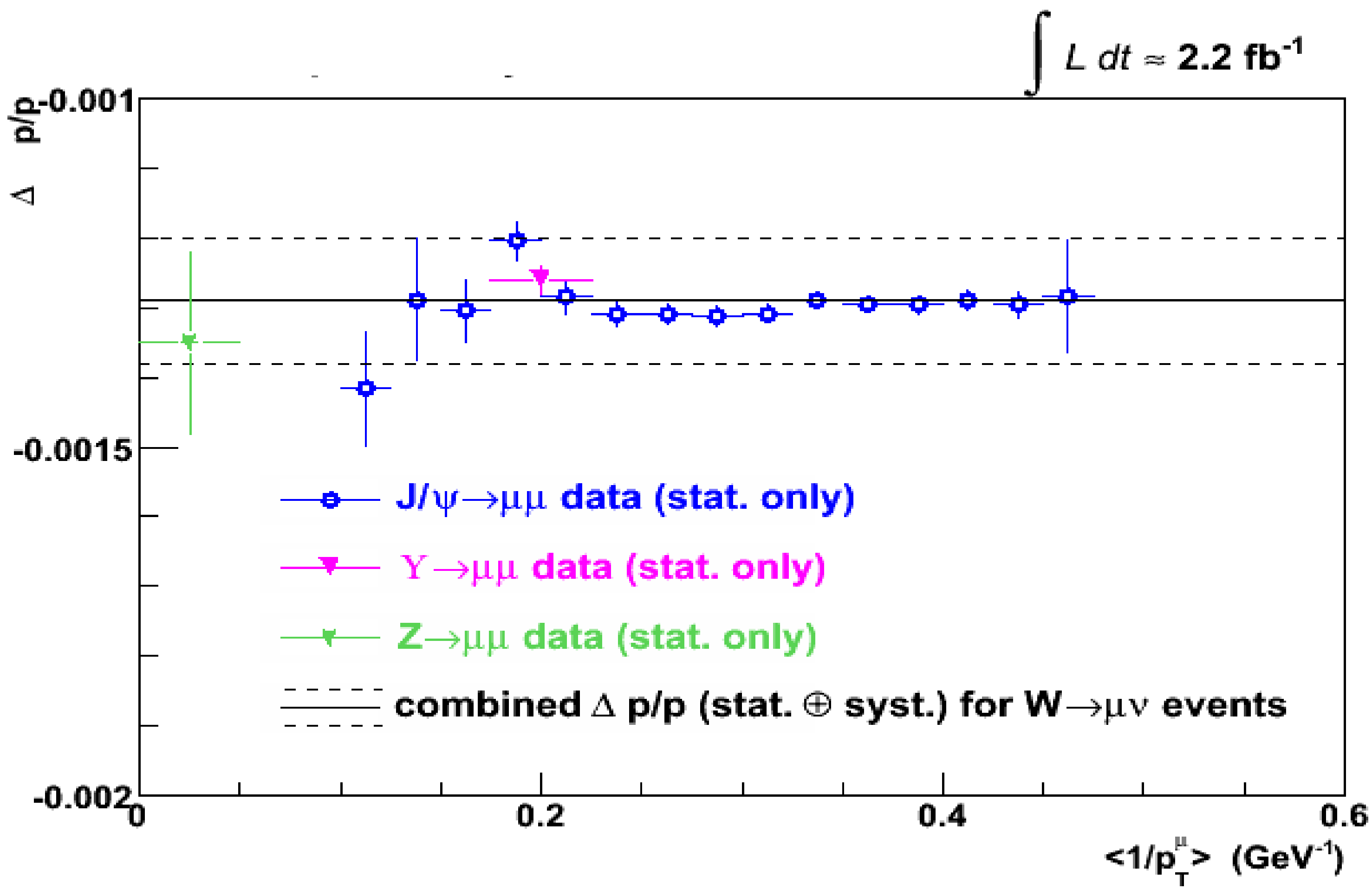


M(μμ) (GeV)

Tracker Linearity Cross-check & Combination

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

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



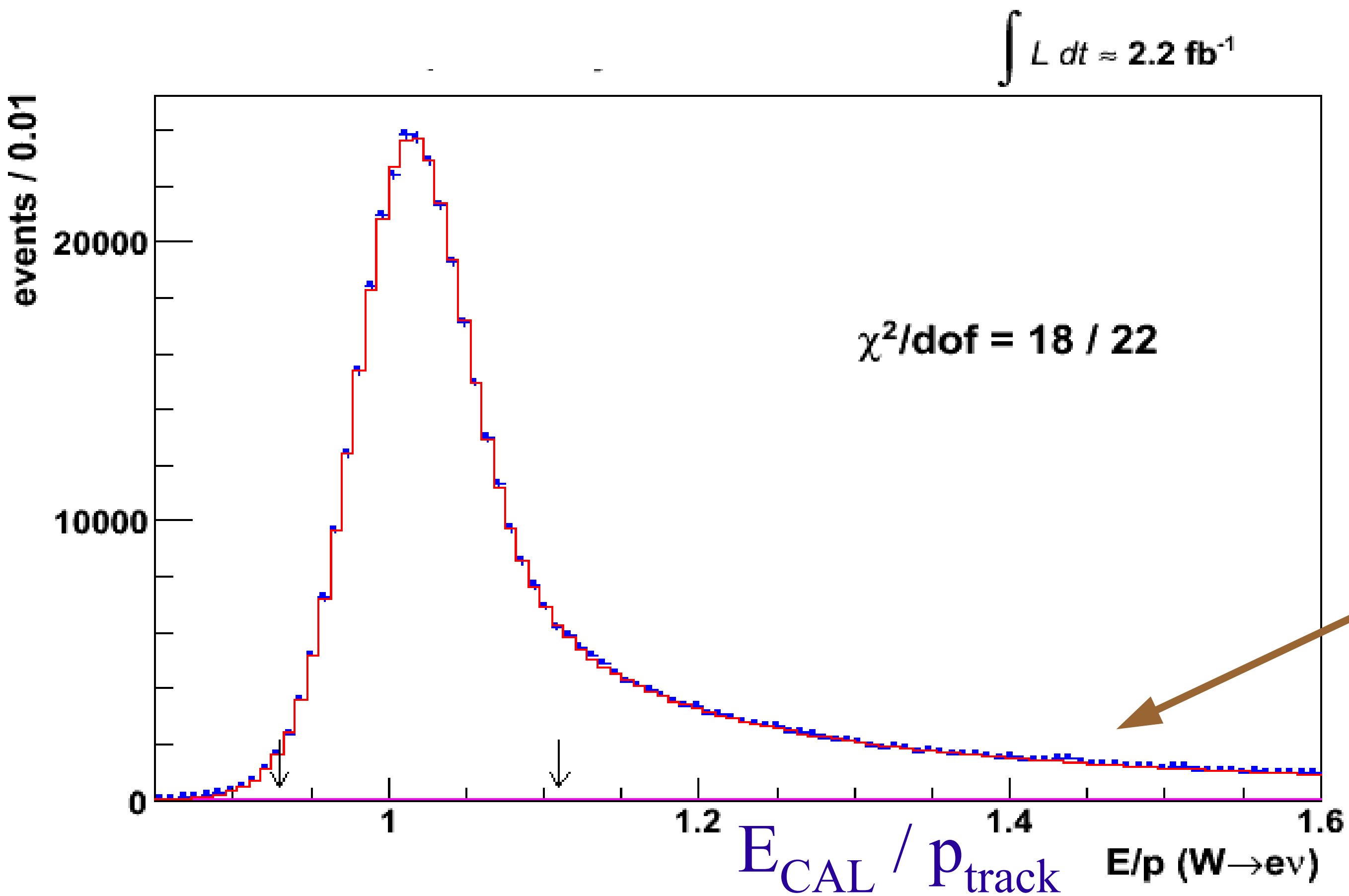
ΔM_W = 7 MeV

EM Calorimeter Scale

- E/p peak from $W \to e\upsilon$ 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 $W \to e\upsilon$ and $Z \to ee$ samples



ΔM_W = 13 MeV

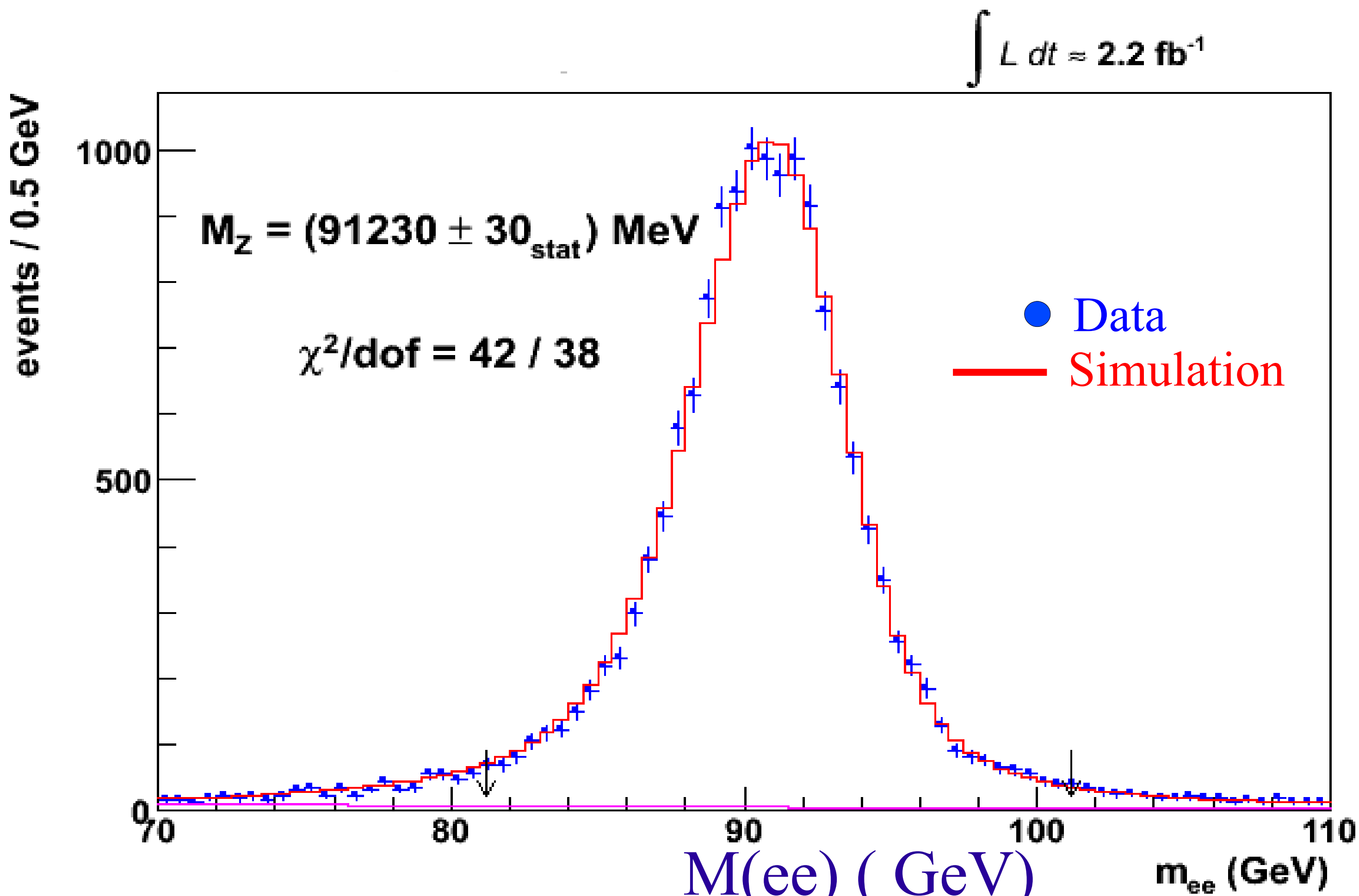
Data

Simulation

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

$Z \longrightarrow ee$ 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 $Z \longrightarrow ee$ mass for maximum precision



$\Delta M_W = 10$ MeV

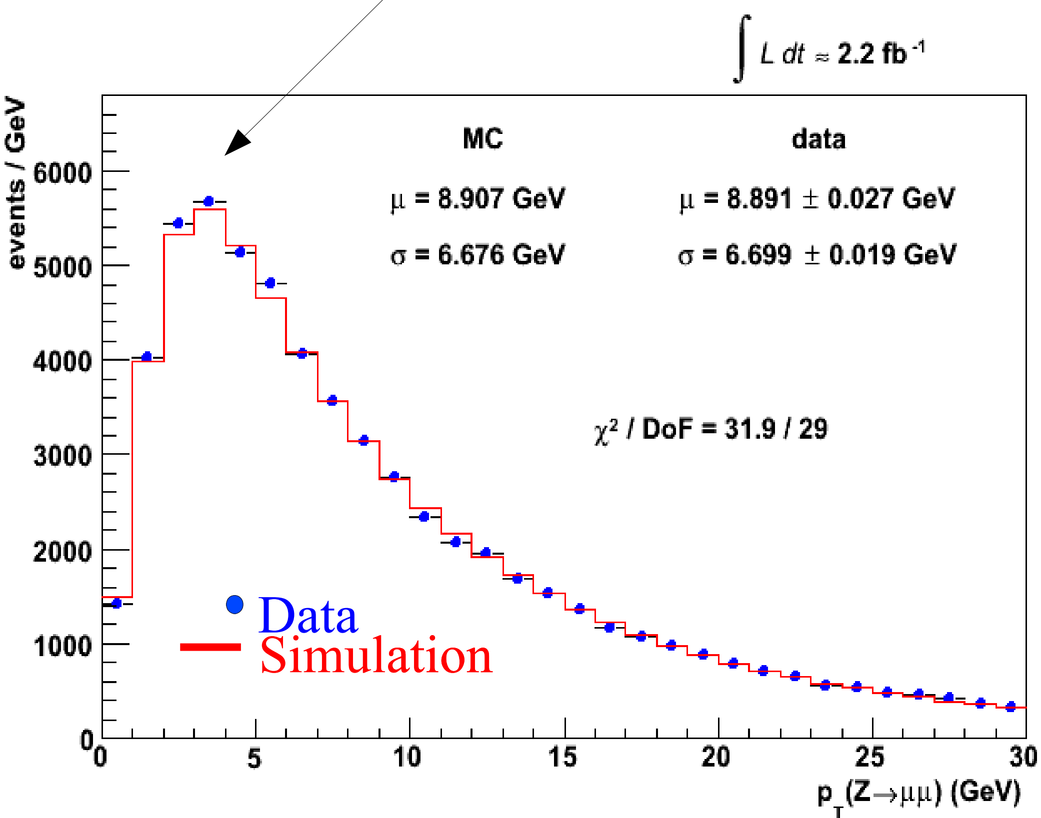
Constraining Boson p_T Spectrum

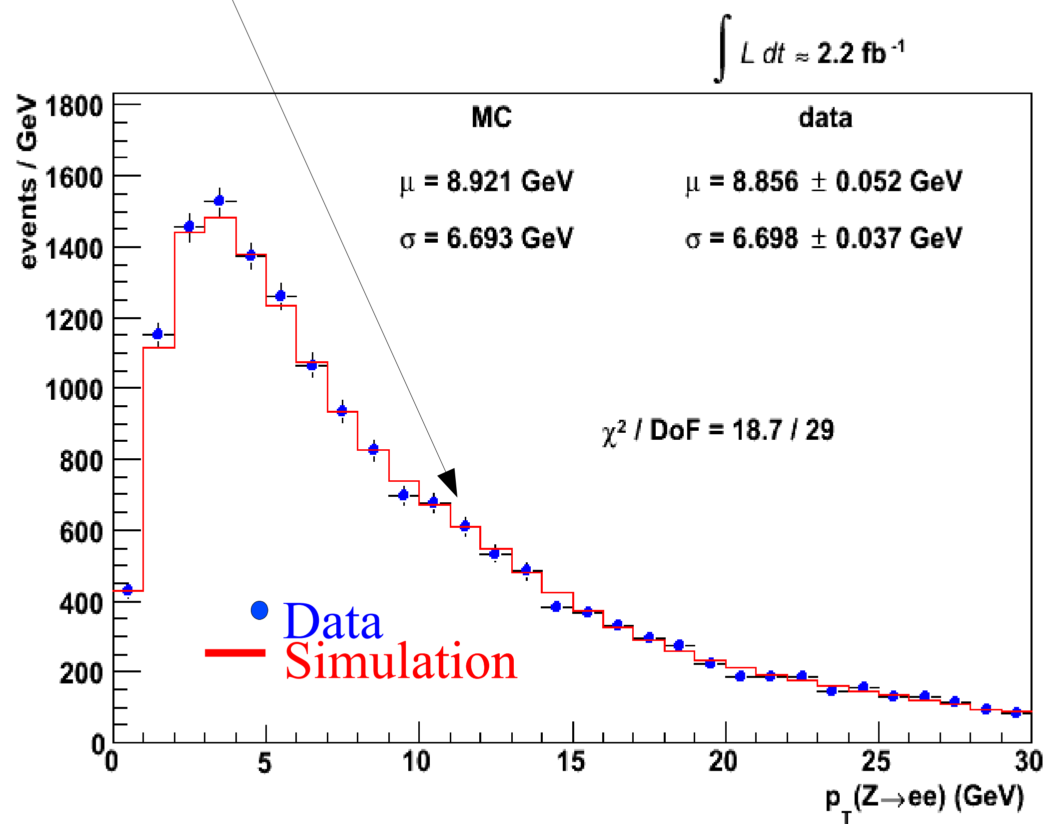
- Fit the non-perturbative parameter g_2 and QCD coupling α_s in RESBOS to $p_T(ll)$ spectra:

$\Delta M_W = 5$ MeV

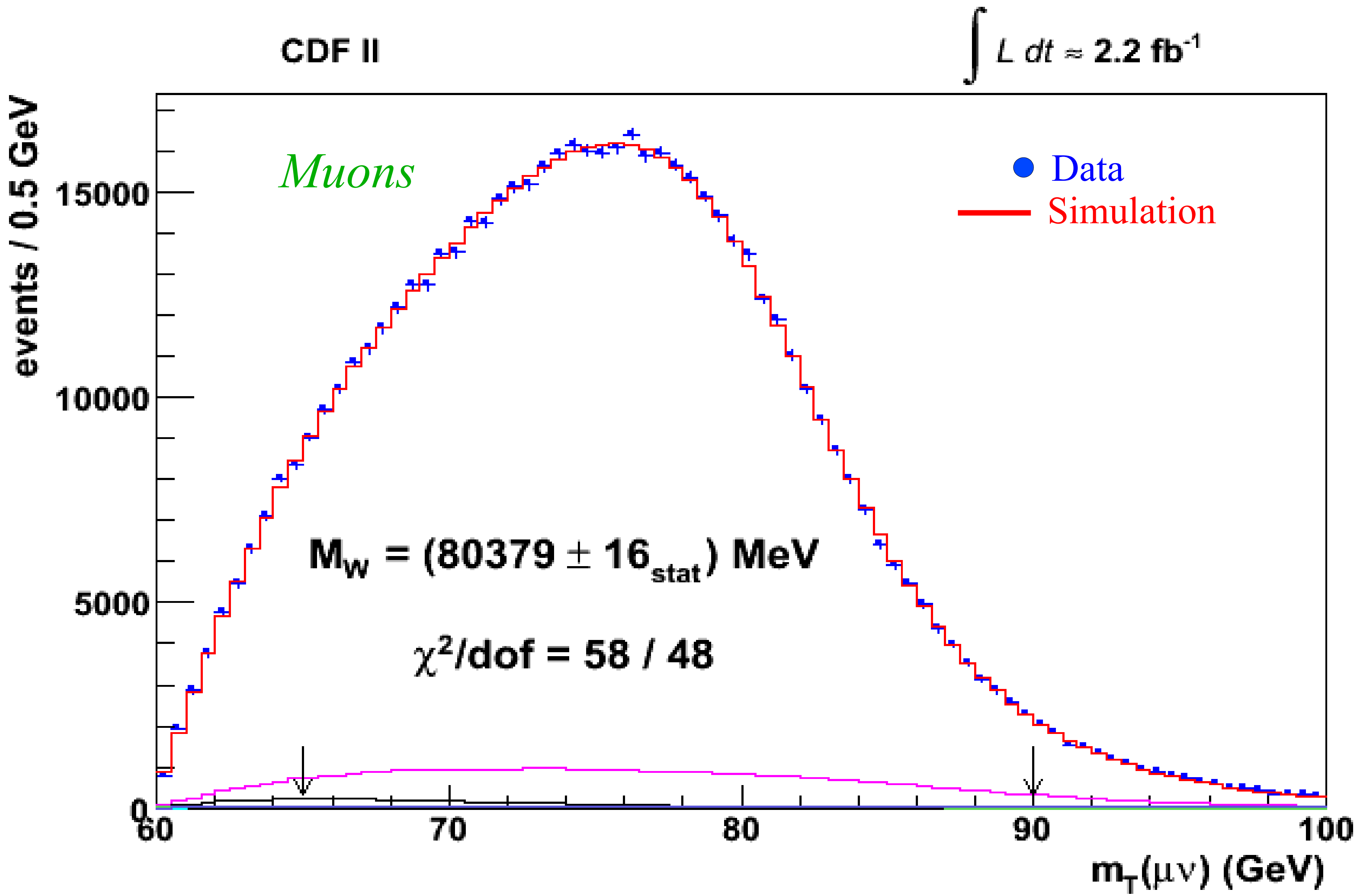
Position of peak in boson p_T spectrum depends on g_2

Tail to peak ratio depends on α_s

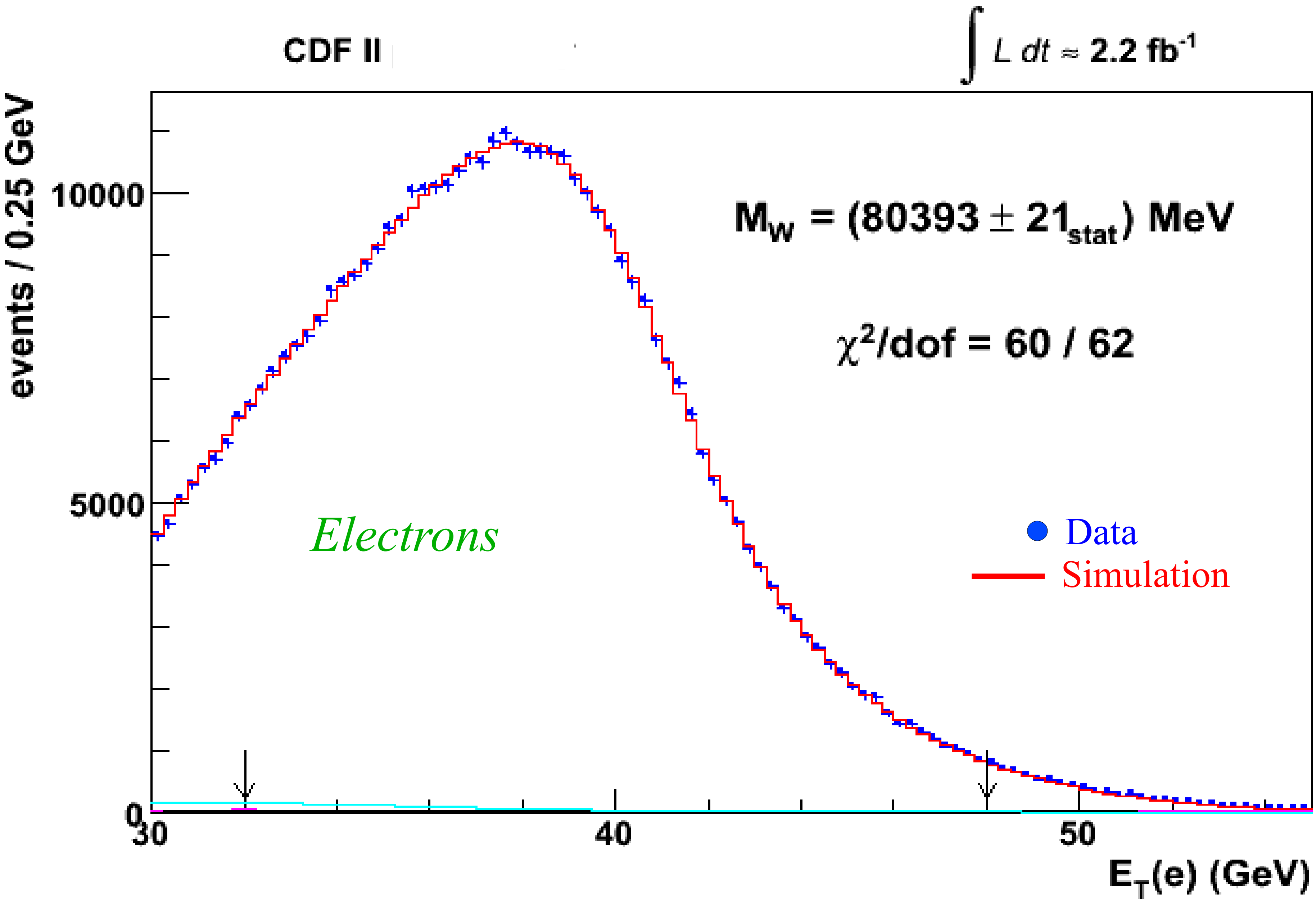




W Transverse Mass Fit

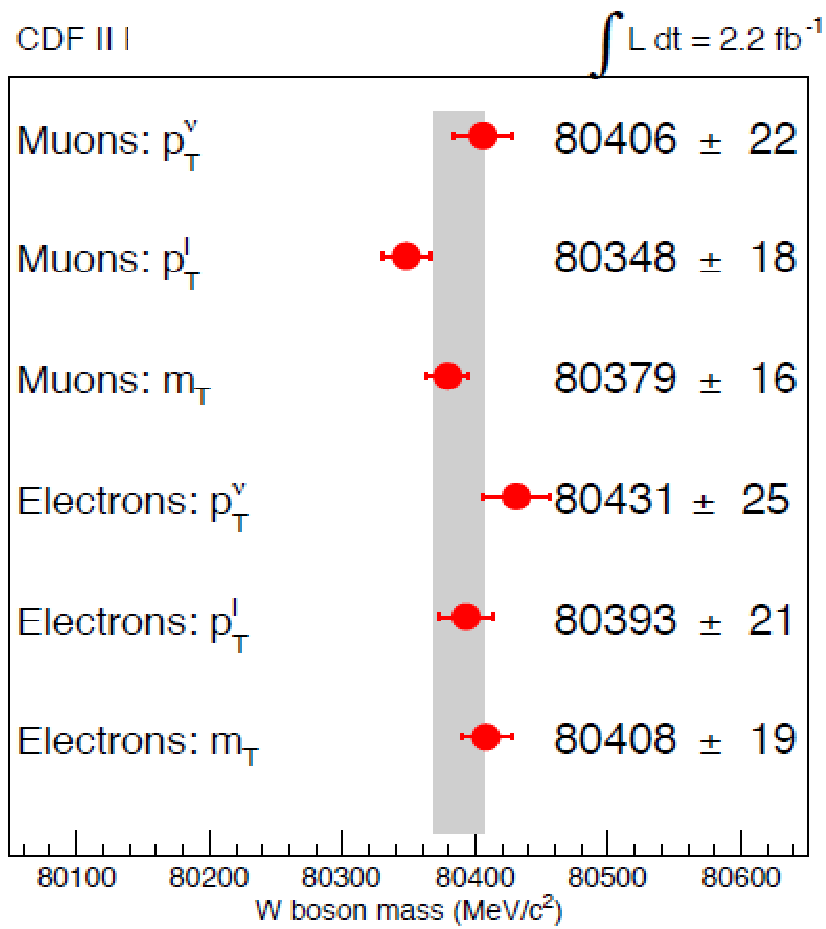


W Mass Fit using Lepton p_T



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



Combined Results

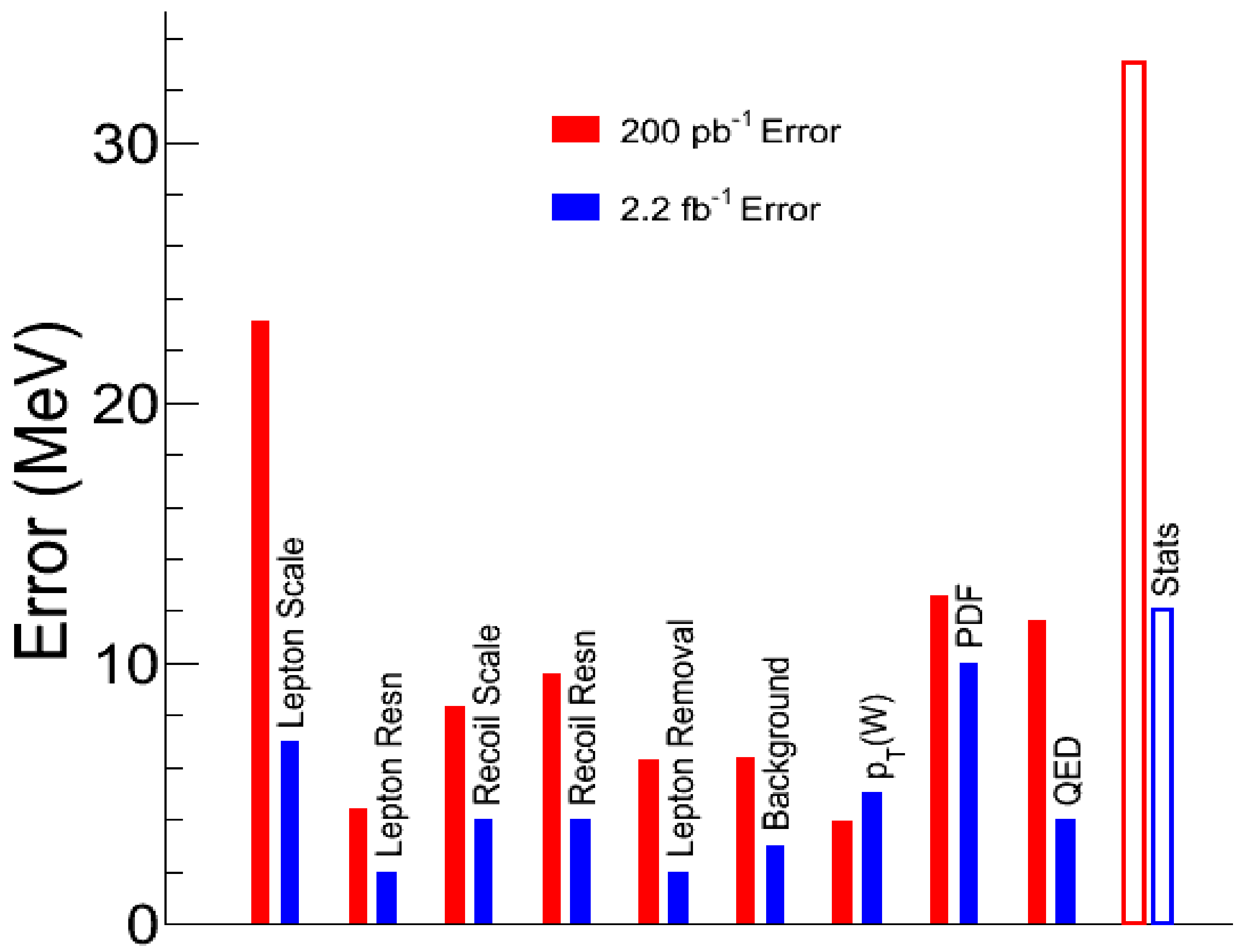
- Combined electrons (3 fits): $M_W = 80406 \pm 25$ MeV, $P(\chi^2) = 49\%$
- Combined muons (3 fits): $M_W = 80374 \pm 22$ MeV, $P(\chi^2) = 12\%$
- All combined (6 fits): $M_W = 80387 \pm 19$ MeV, $P(\chi^2) = 25\%$

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

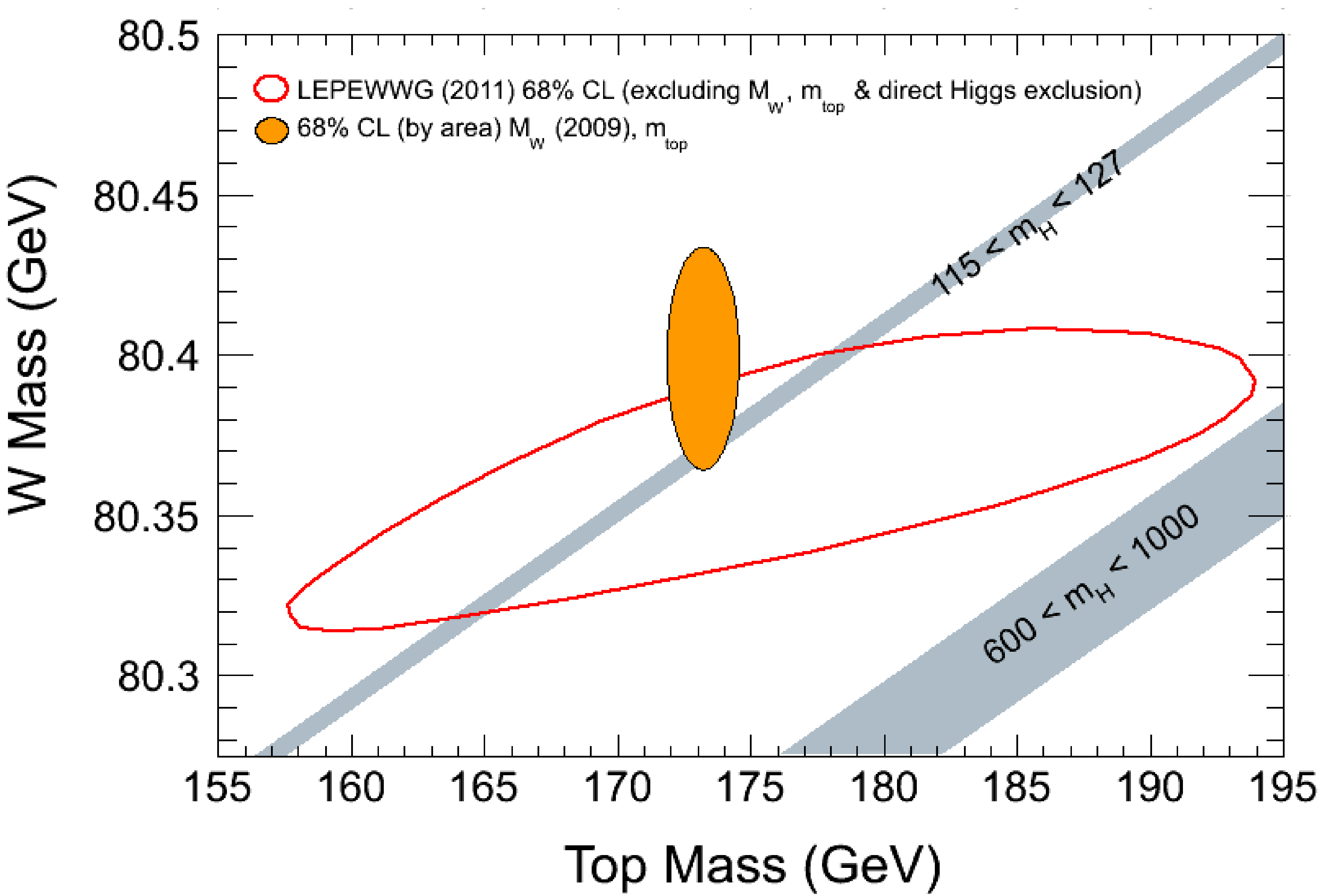
	electrons	*muons*	*common*
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total systematic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

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

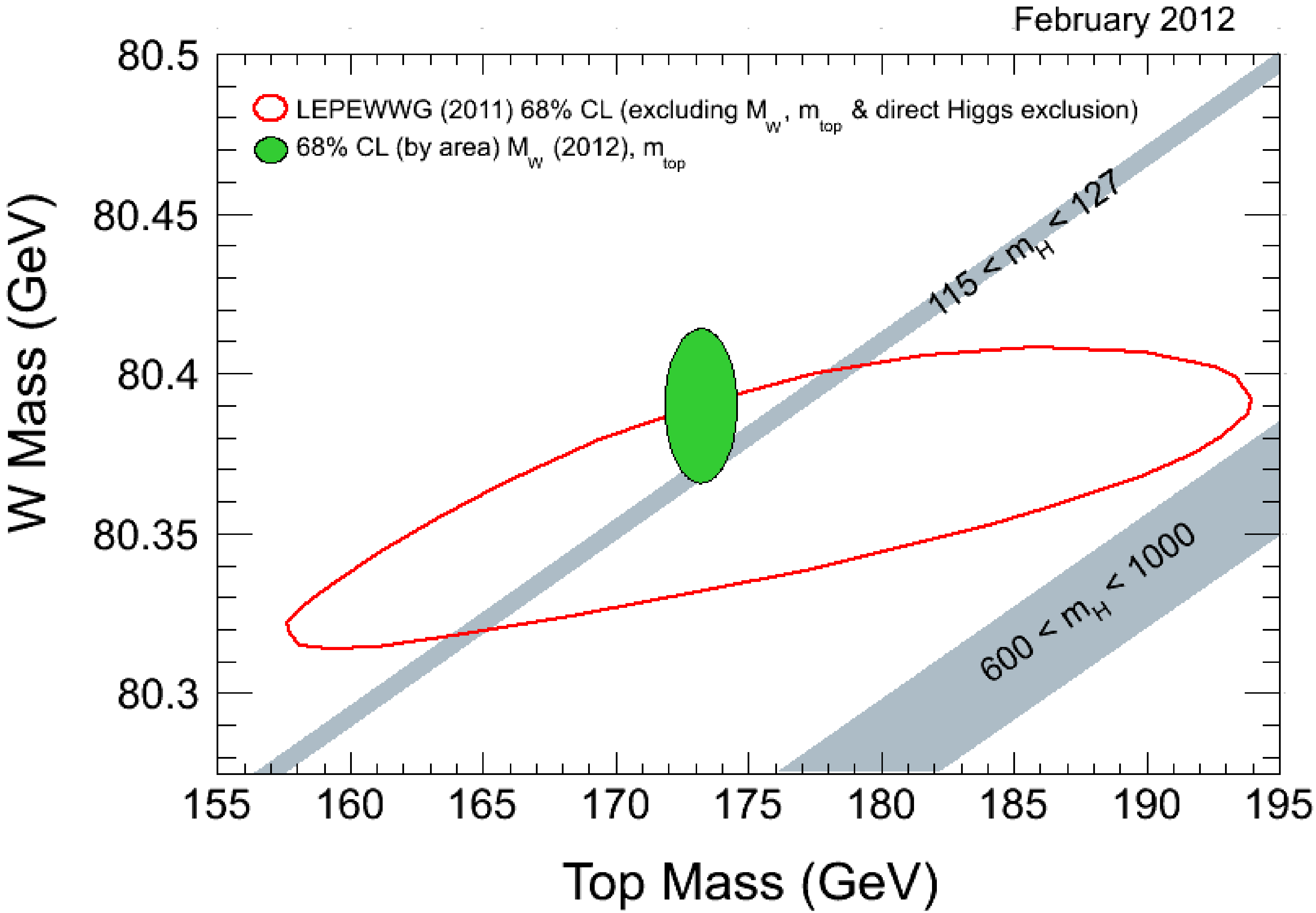
Combined W Mass Result, Error Scaling



Previous M_W *vs* M_{top}



Updated M_W *vs* M_{top}

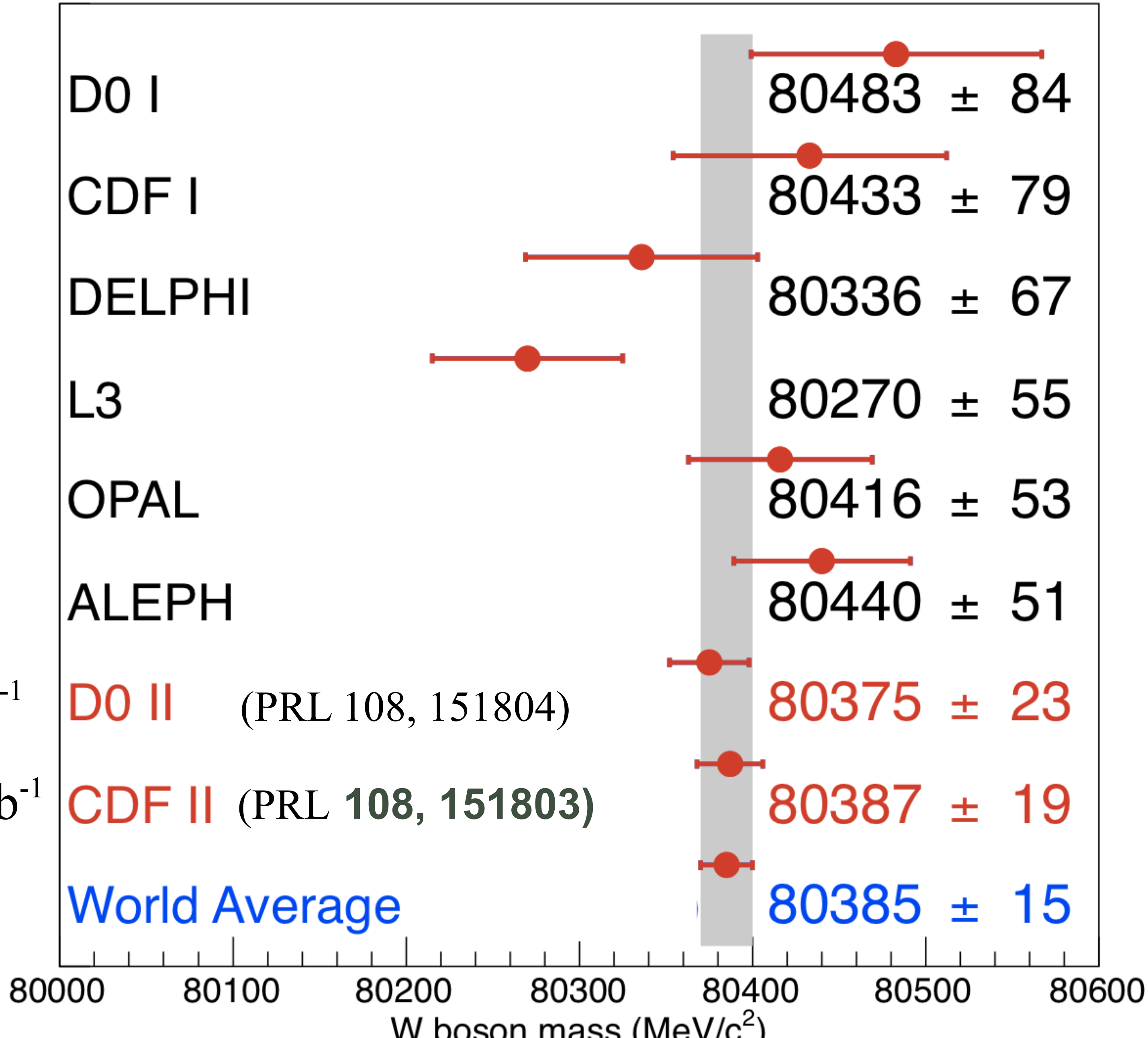


W Boson Mass Measurements from Different Experiments

World average
computed by TeVEWWG
ArXiv: 1204.0042

5 fb^{-1}

2.2 fb^{-1}



Previous world
average
= 80399 ± 23 MeV

new CDF result is significantly more precise than other measurements

PDF Uncertainties – scope for improvement

- Factor of 5 bigger samples of W and Z bosons available

- 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

Summary

- The W boson mass is a very interesting parameter to measure with increasing precision
- New CDF W mass result from 2.2 fb^{-1} is the most precise in the world
  - $M_W = 80387 \pm 12_{stat} \pm 15_{syst}$ MeV
    $= 80387 \pm 19$ MeV
- New indirect limit $M_H < 152$ GeV @ 95% CL
  - SM Higgs prediction is pinned in the low-mass range => confront mass from direct search results
- Looking forward to $\Delta M_W < 10$ MeV from 10 fb^{-1} of CDF data

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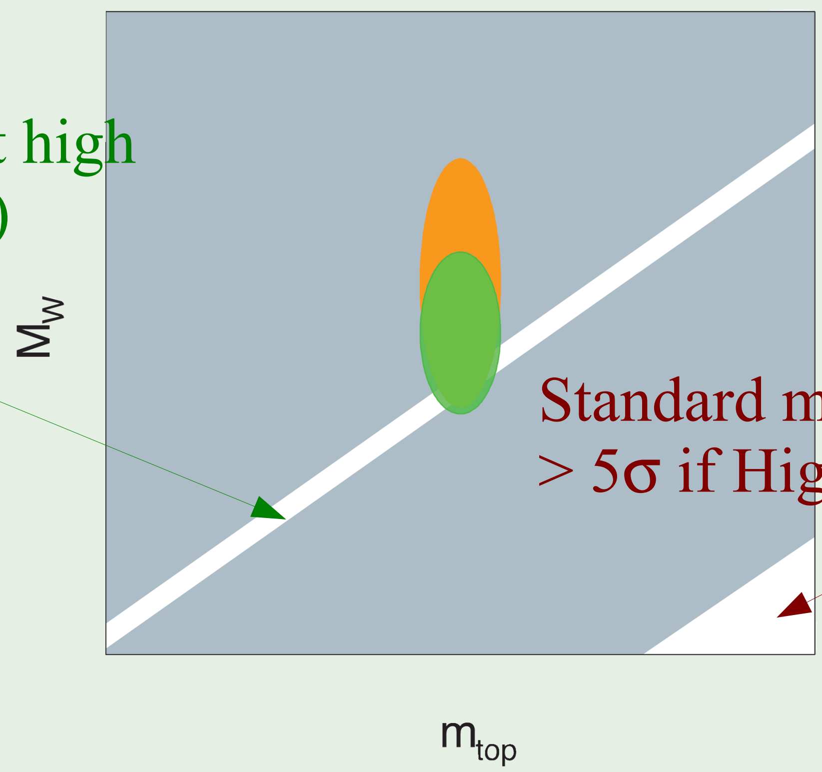
Standard model confirmed at high precision if light (~125 GeV) Higgs boson



Standard model inconsistent at > 5σ if Higgs mass > 600 GeV

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Backup

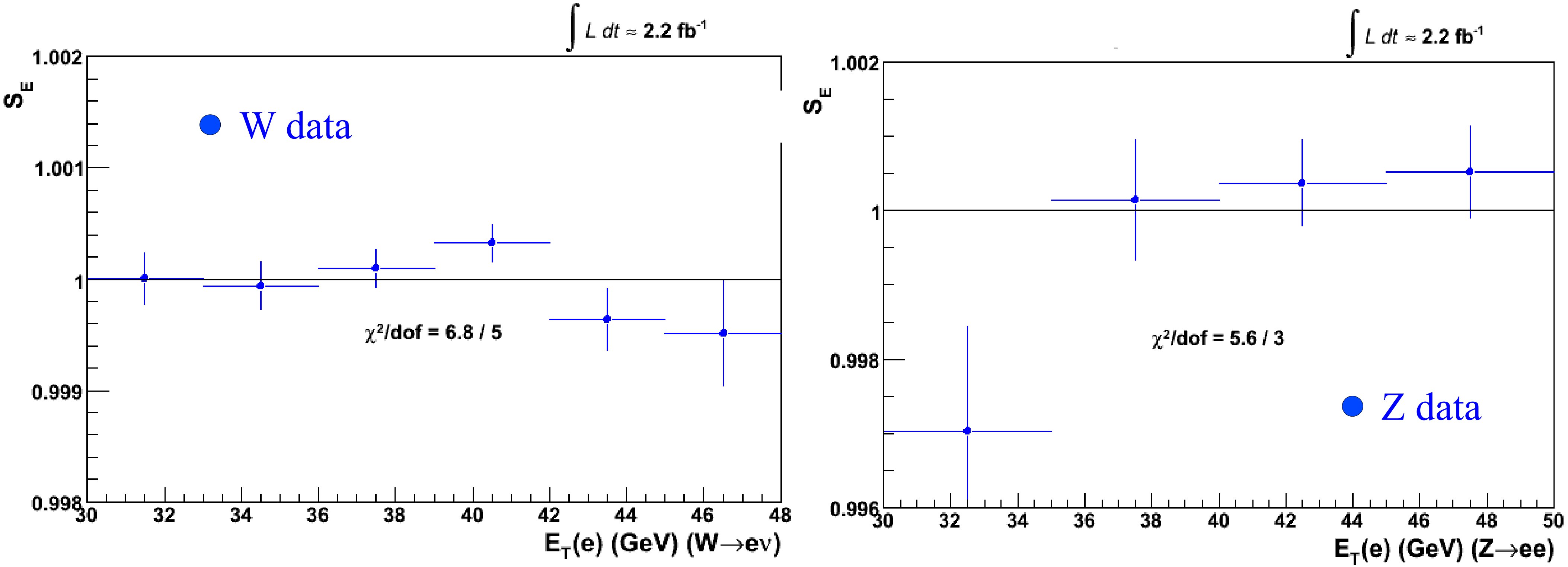
Measurement of EM Calorimeter Non-linearity

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

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

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

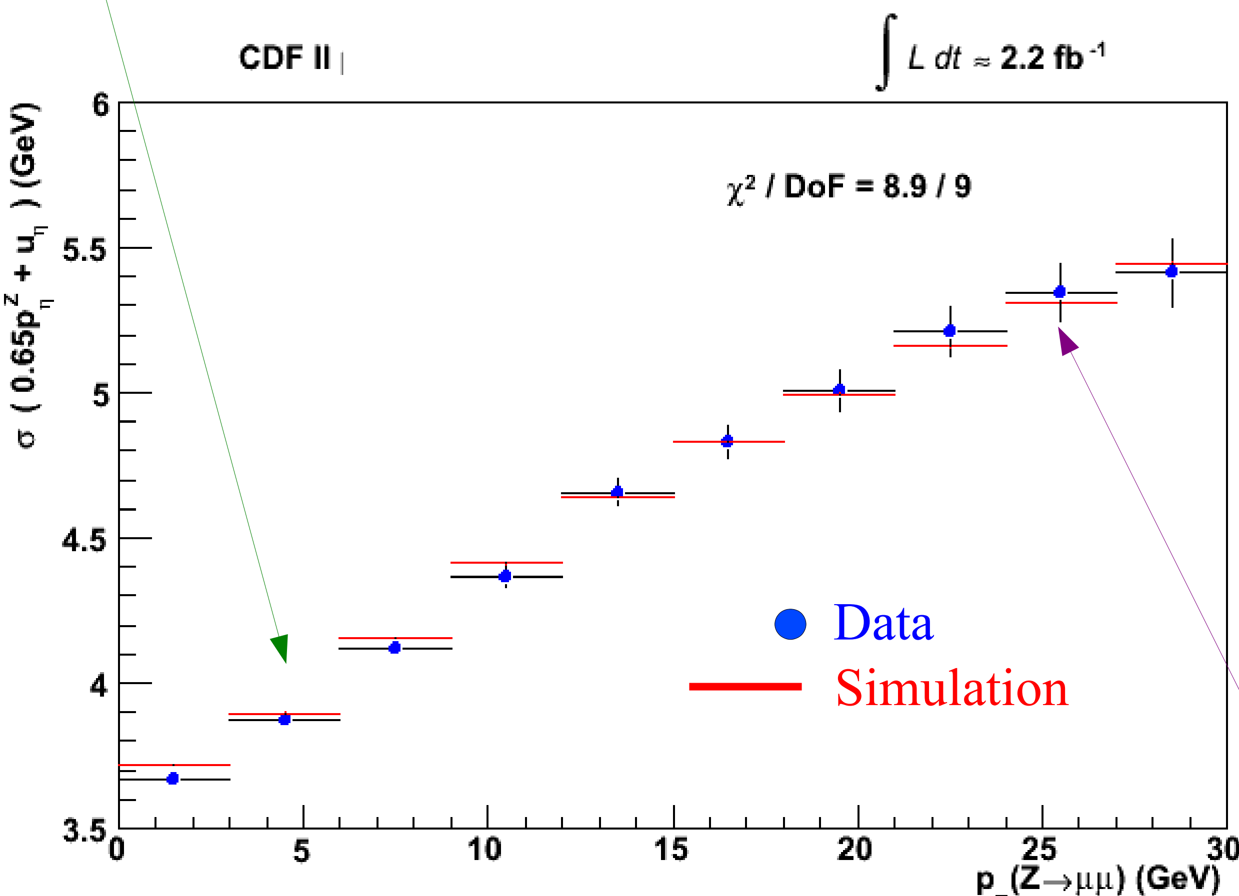
  $\Rightarrow \Delta M_W = 4$ MeV

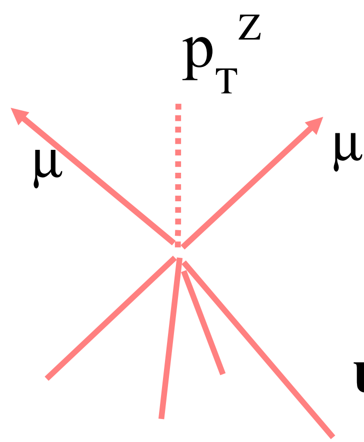


Tuning Recoil Resolution Model with Z events

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

Resolution of p_T-balance (GeV)



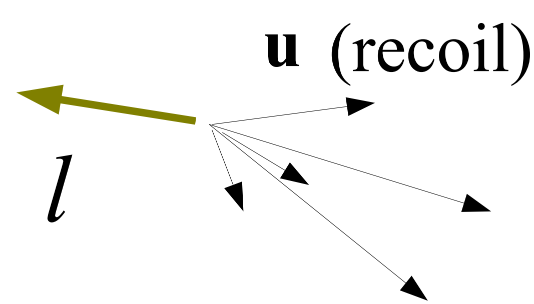


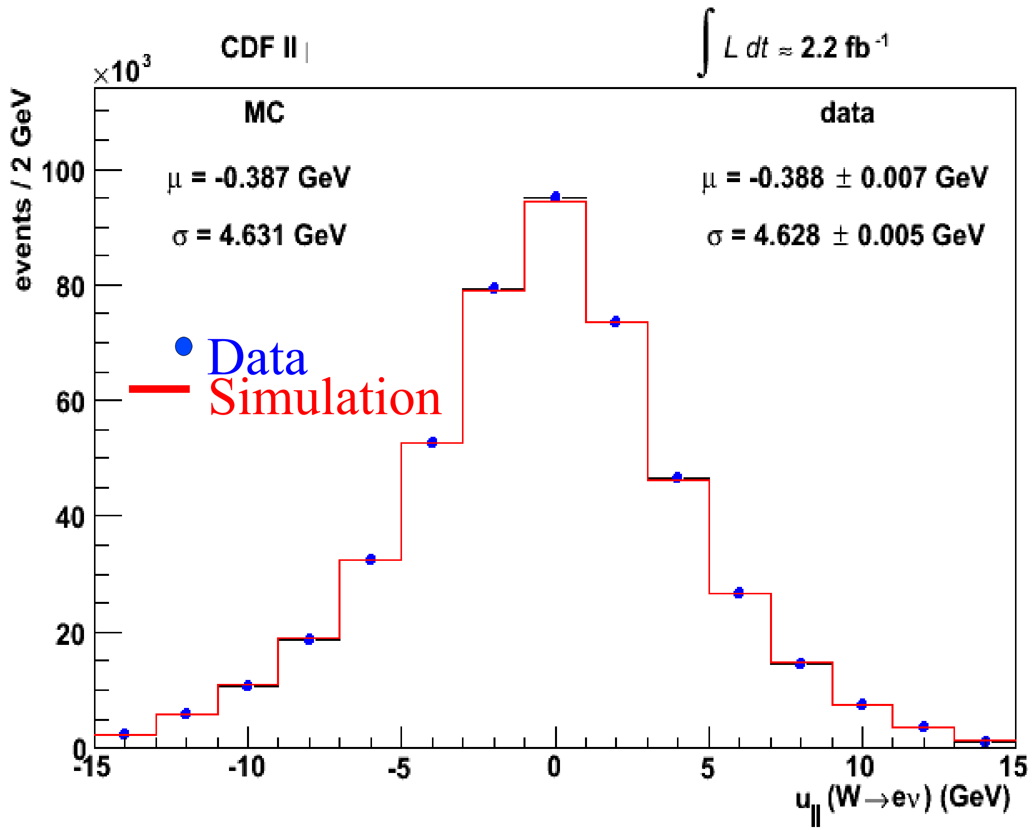
ΔM_W = 4 MeV

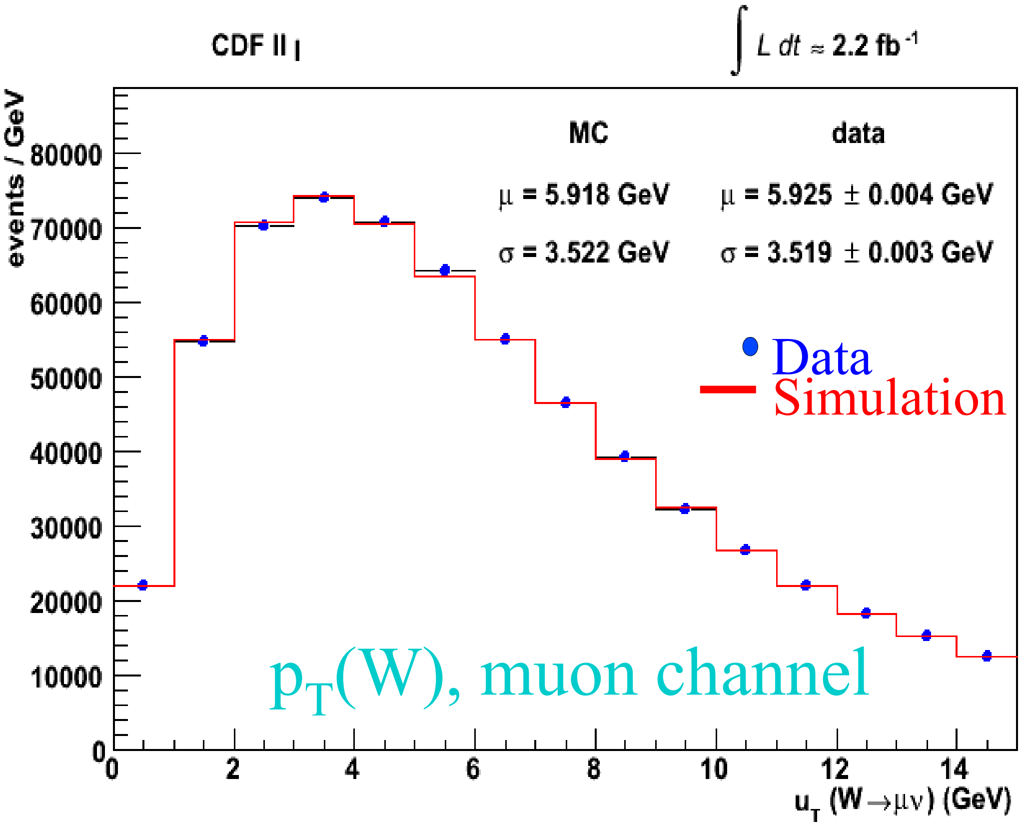
At high $p_T(Z)$, p_T-balance constrains jet resolution

Testing Hadronic Recoil Model with *W* events

Compare recoil distributions between simulation and data







Recoil projection (GeV) on lepton direction

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

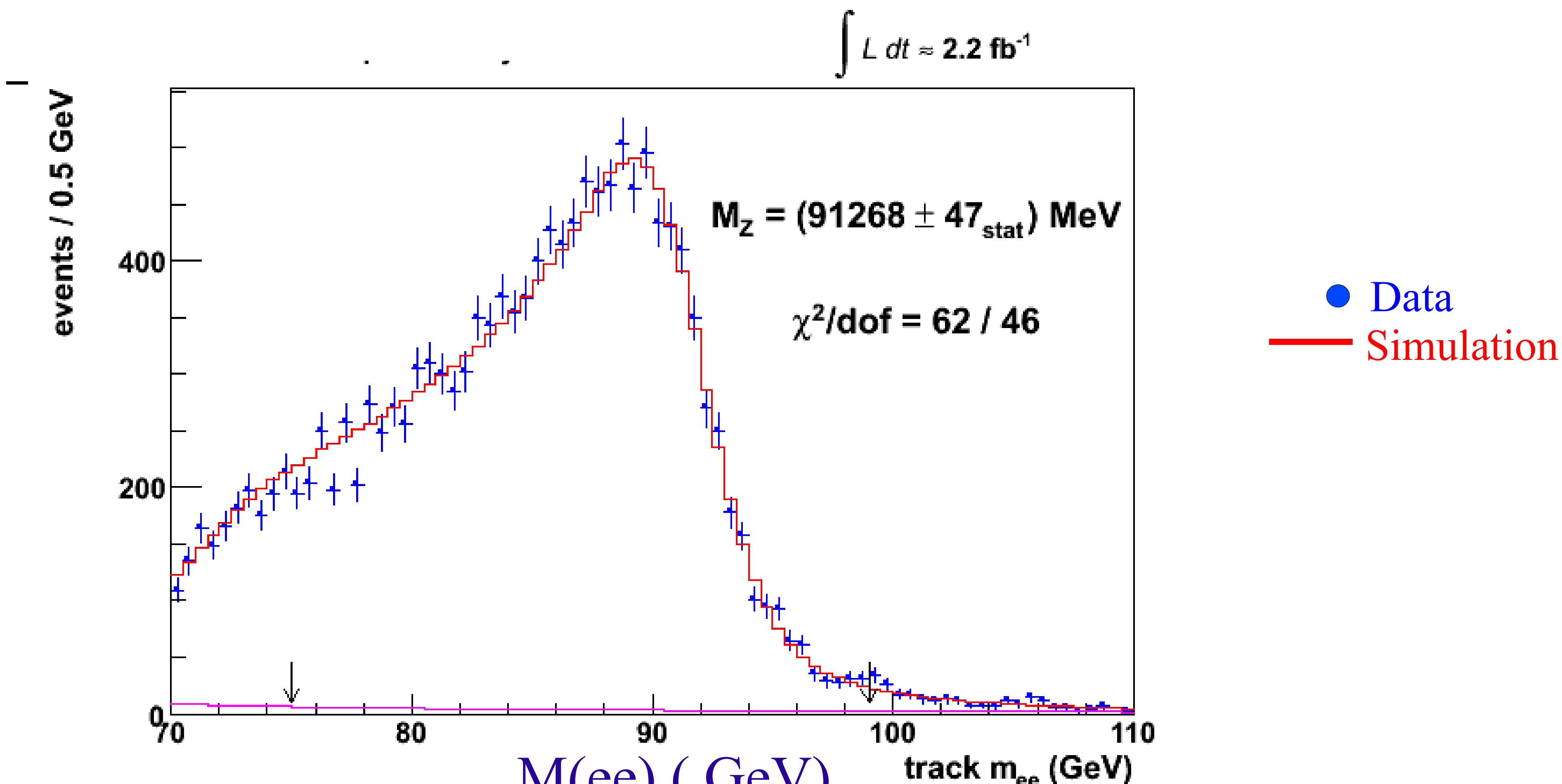
Electrons

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)

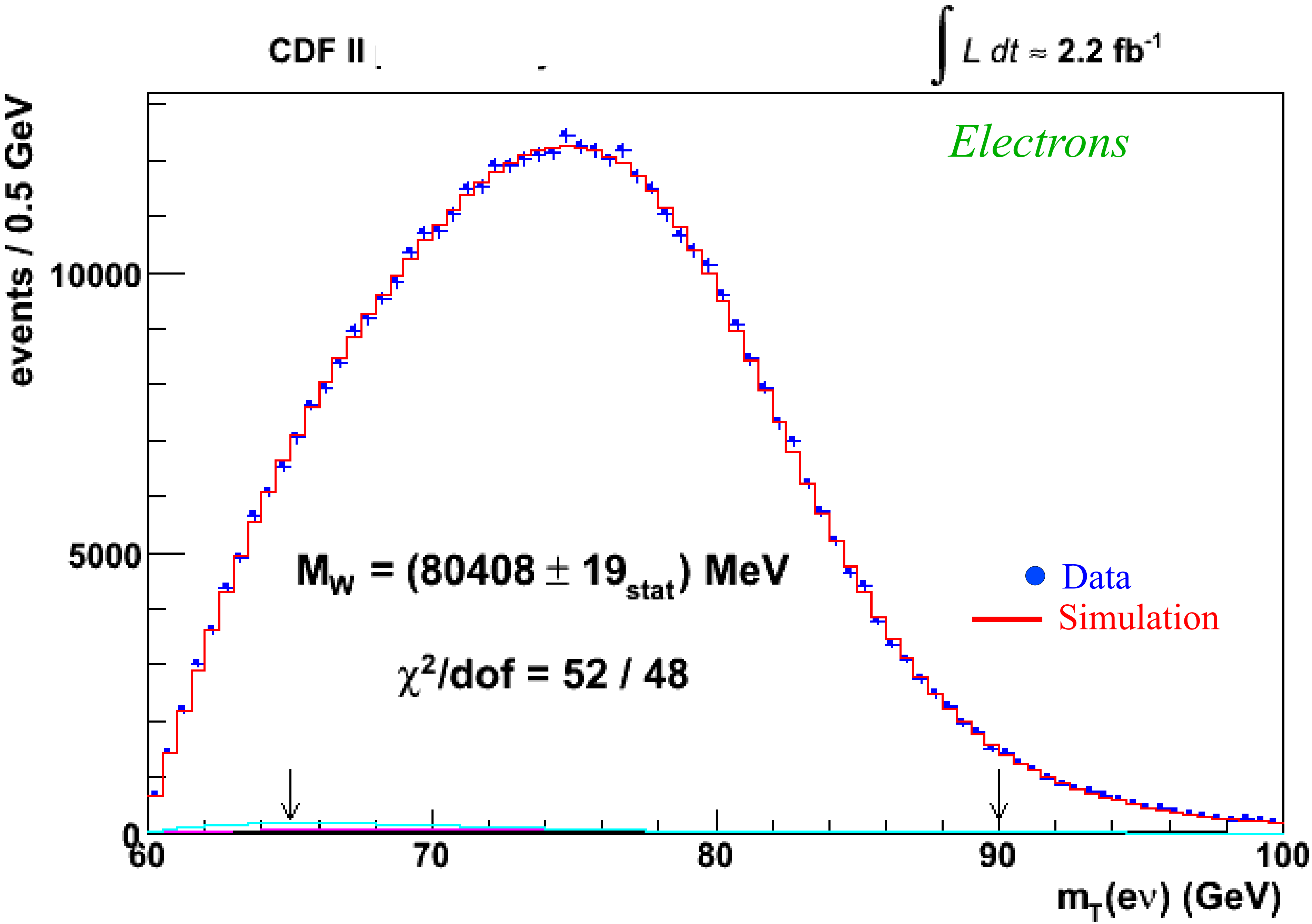
Z → ee Mass Cross-check using Electron Tracks

- Performed "blind" measurement of Z mass using electron tracks
  - Consistent with PDG value within 1.8σ (statistical)
- Checks tracking for electrons vs muons, and model of radiative energy loss

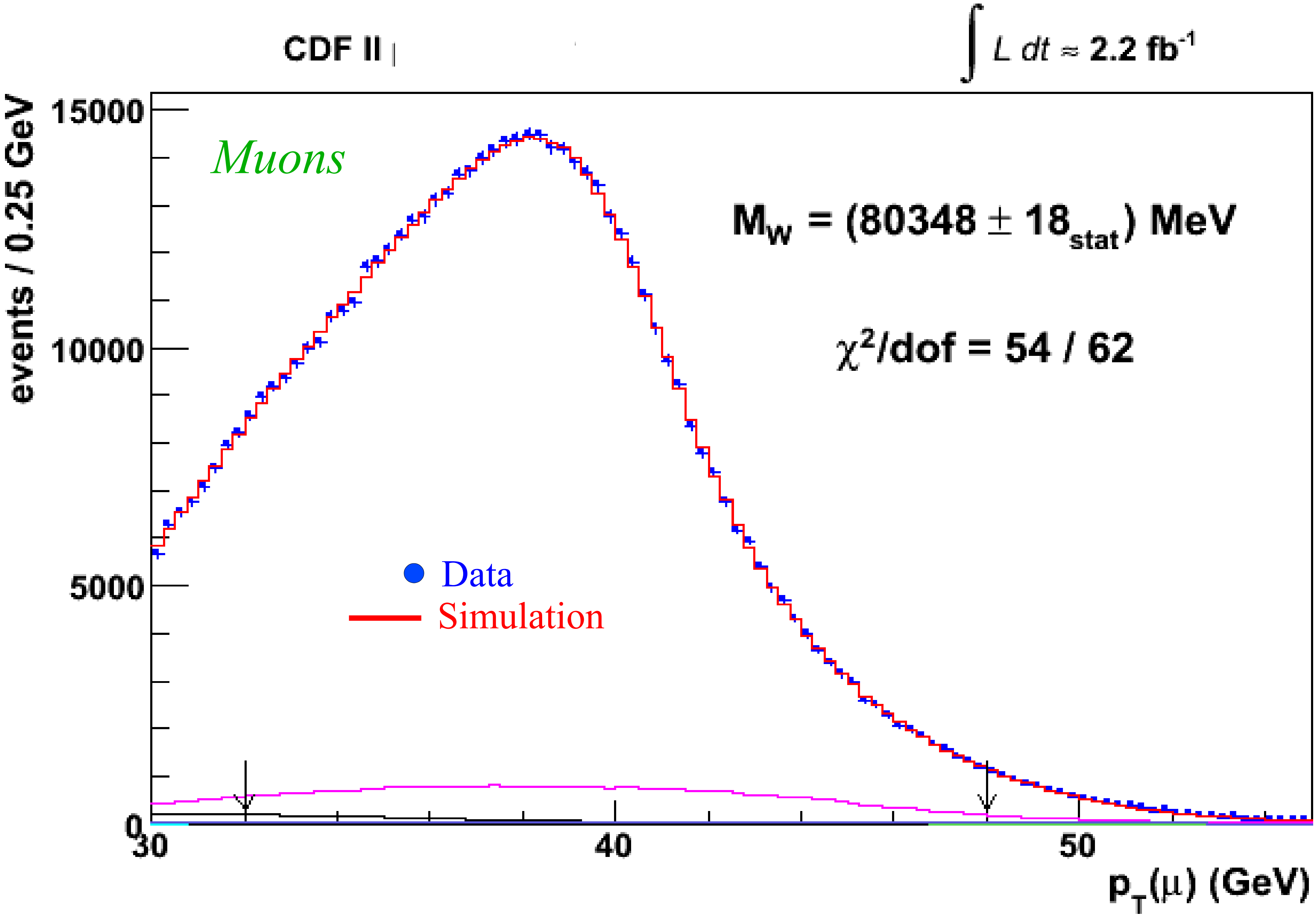


M(ee) (GeV)

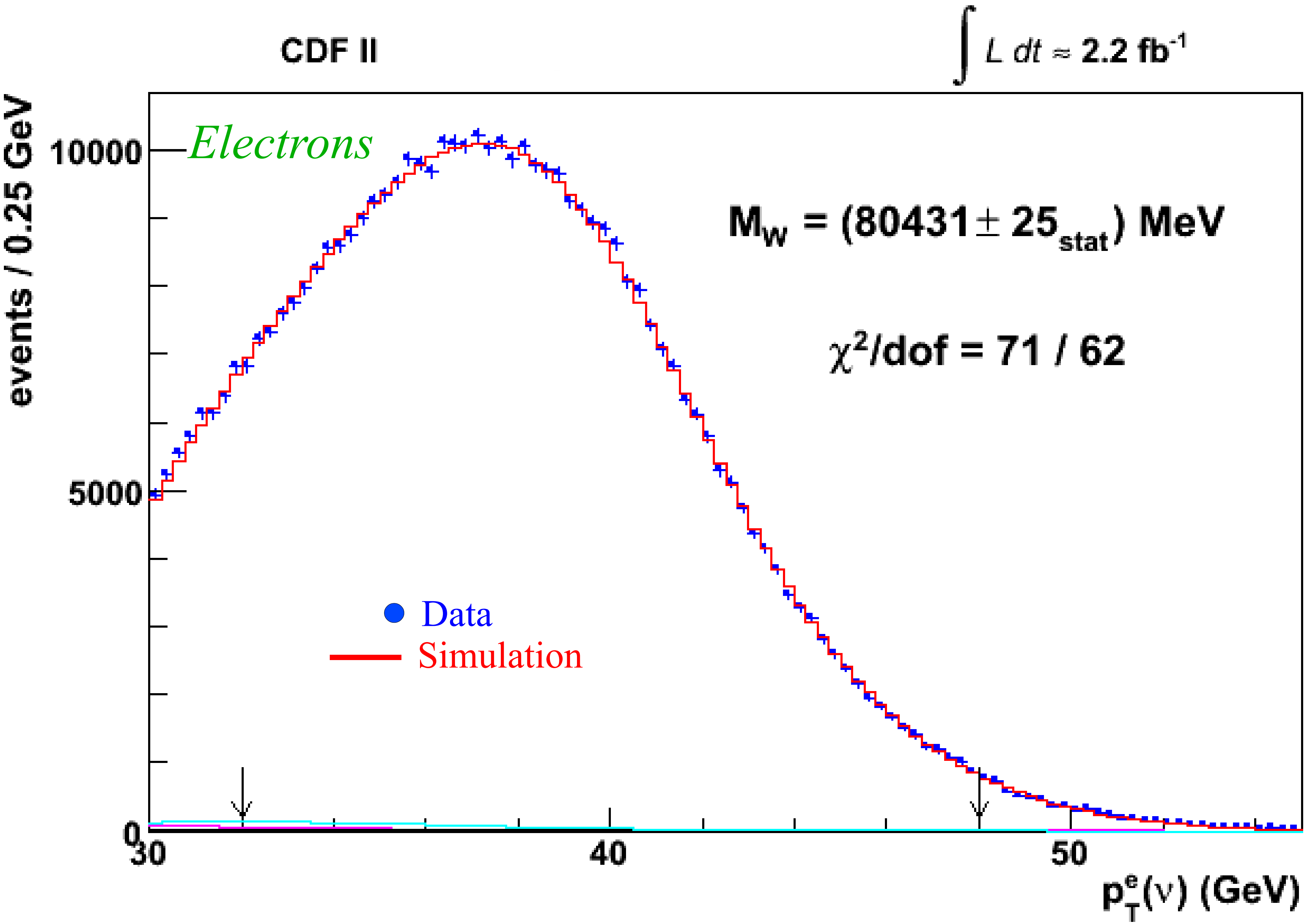
W Transverse Mass Fit



W Lepton p_T Fit



W Missing E_T Fit



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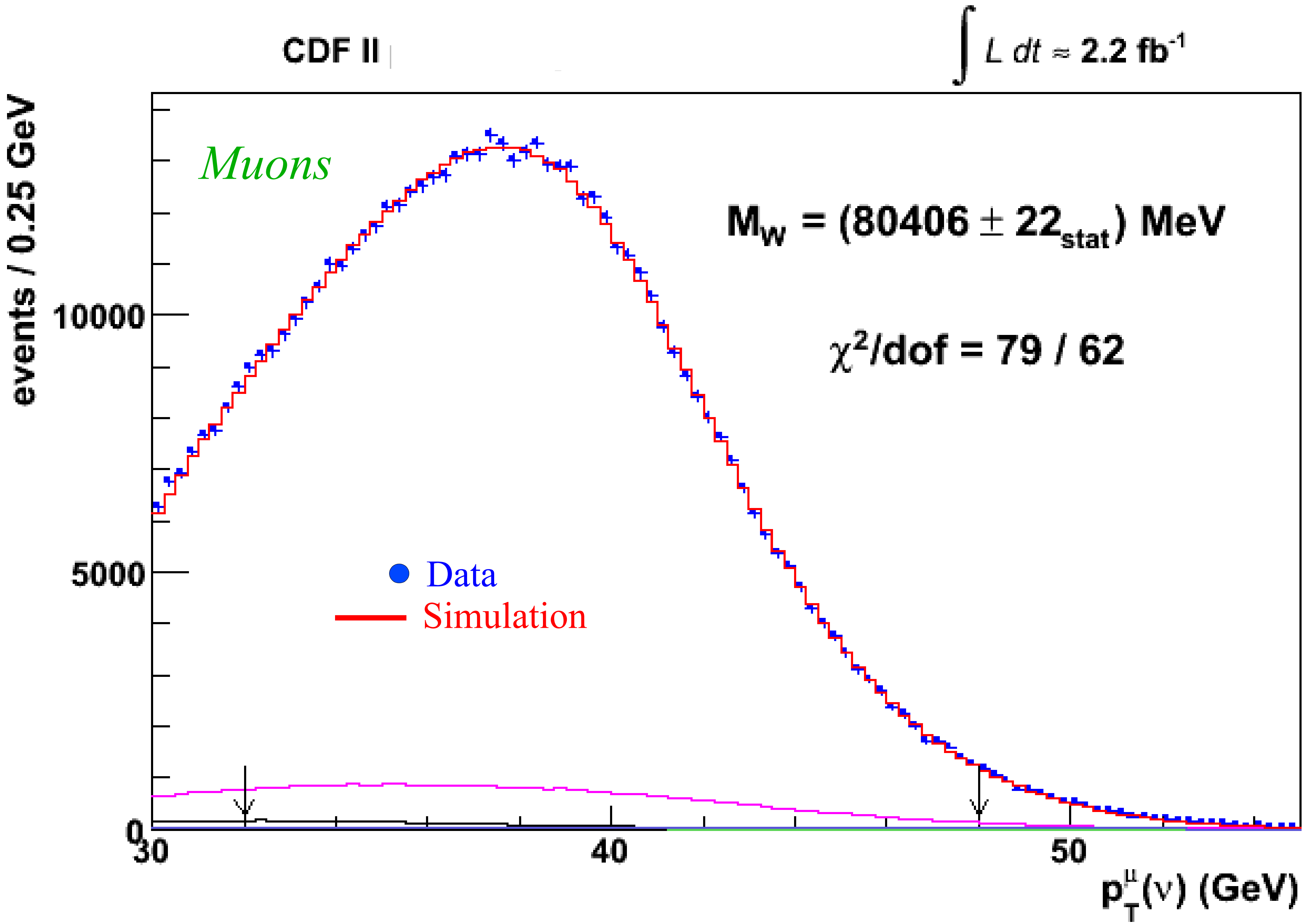
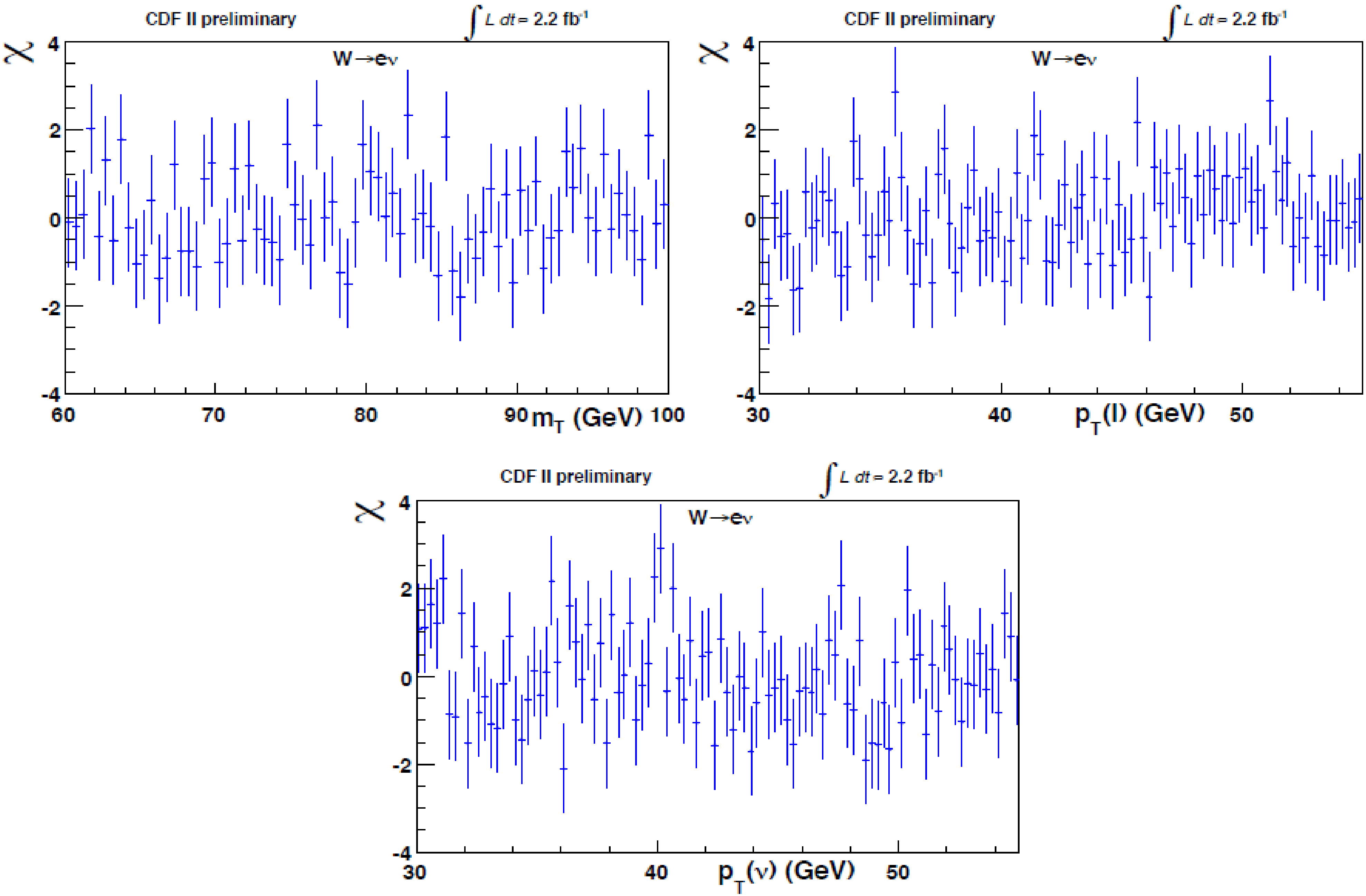
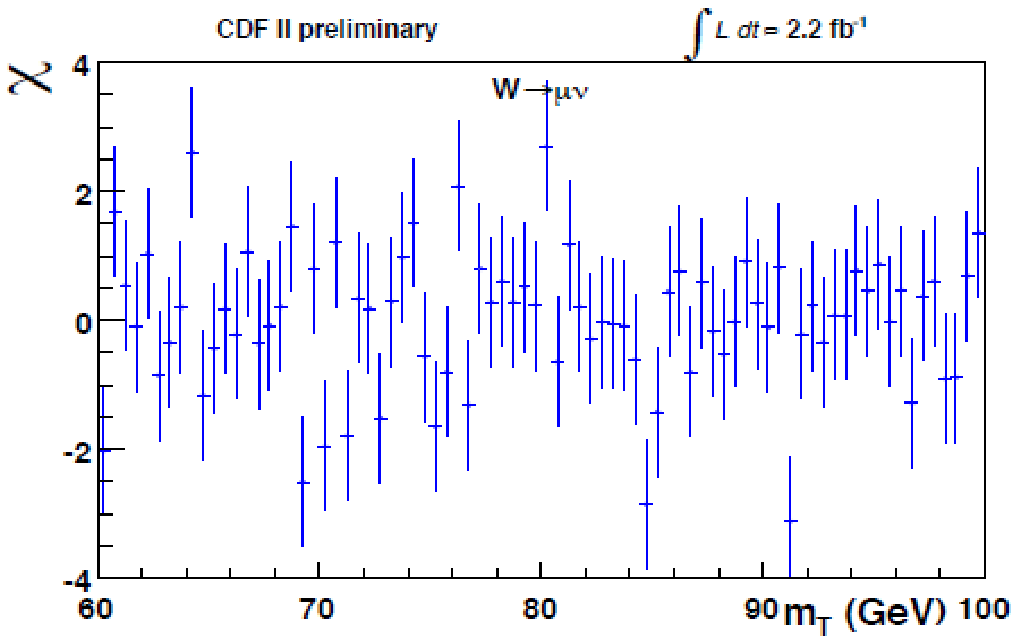
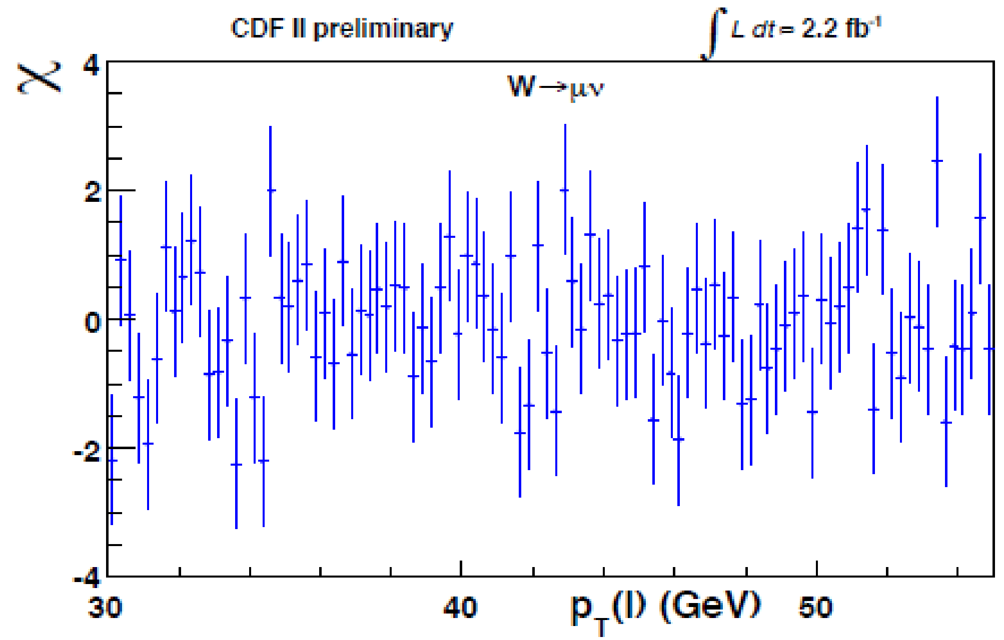


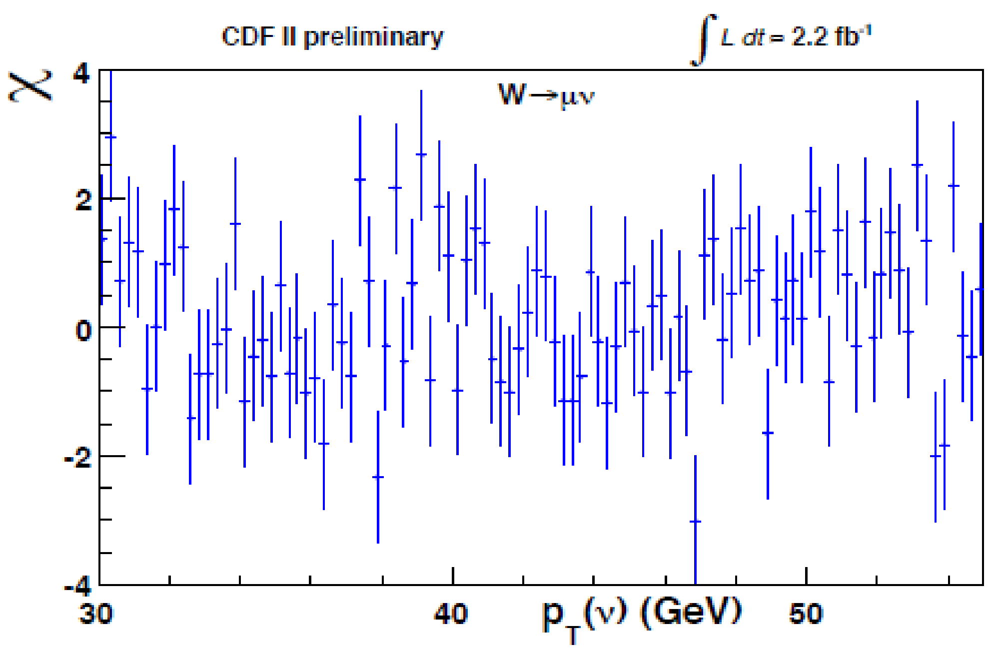
W Mass Fit Residuals, Electron Channel



W Mass Fit Residuals, Muon Channel



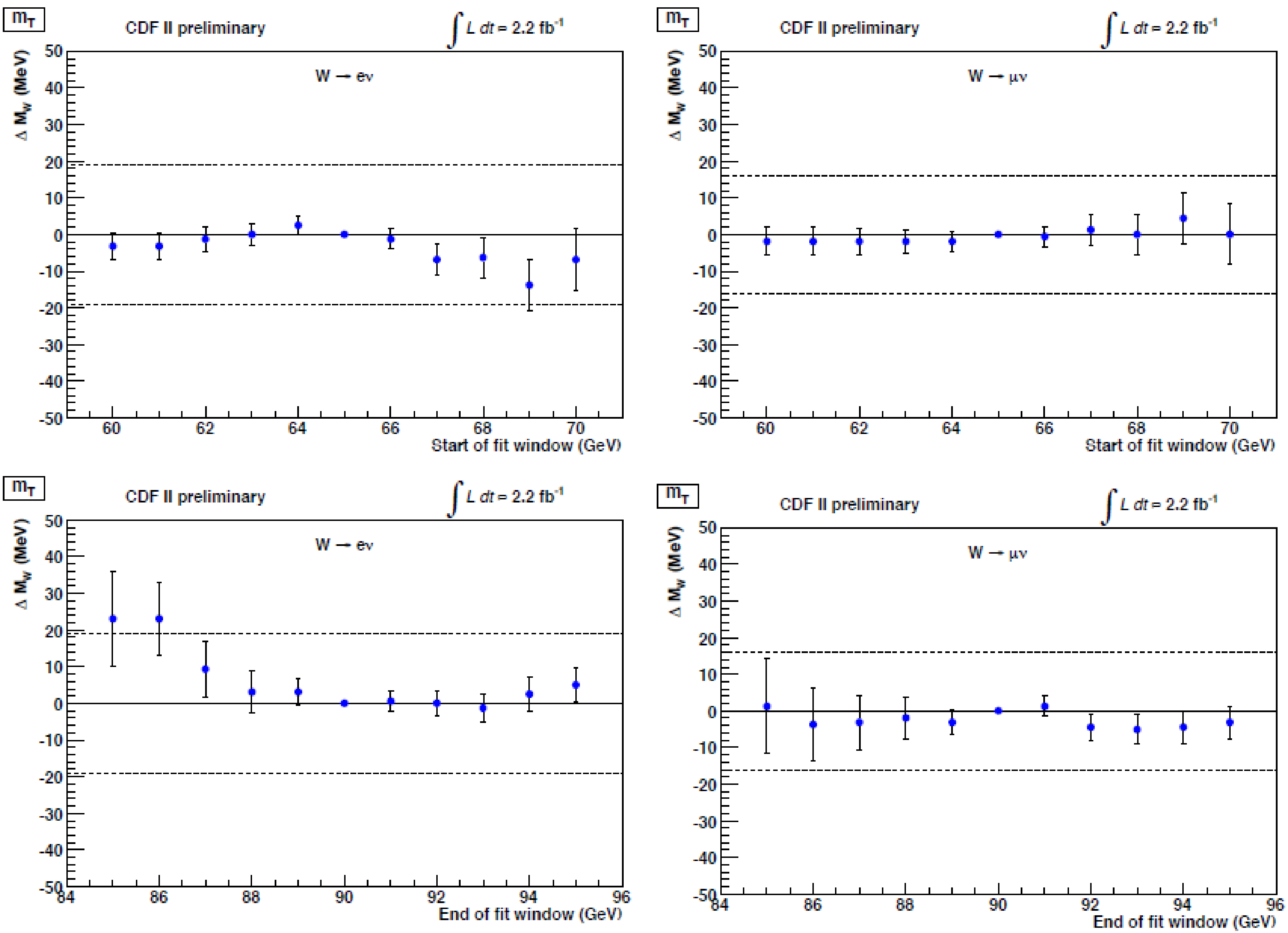




W Mass Fit Window Variation, m_T Fit

lower

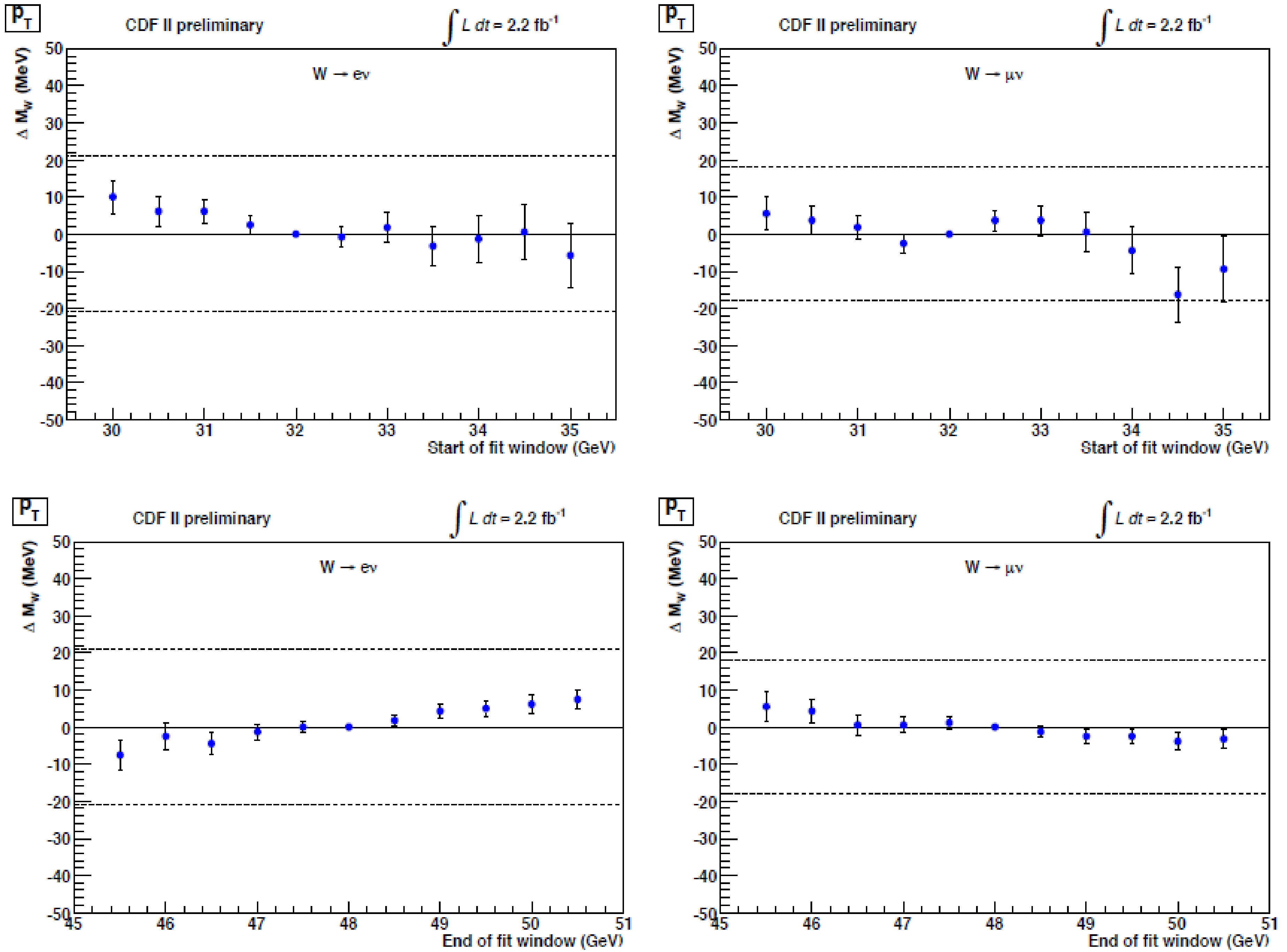
upper



W Mass Fit Window Variation, $p_T(l)$ Fit

lower

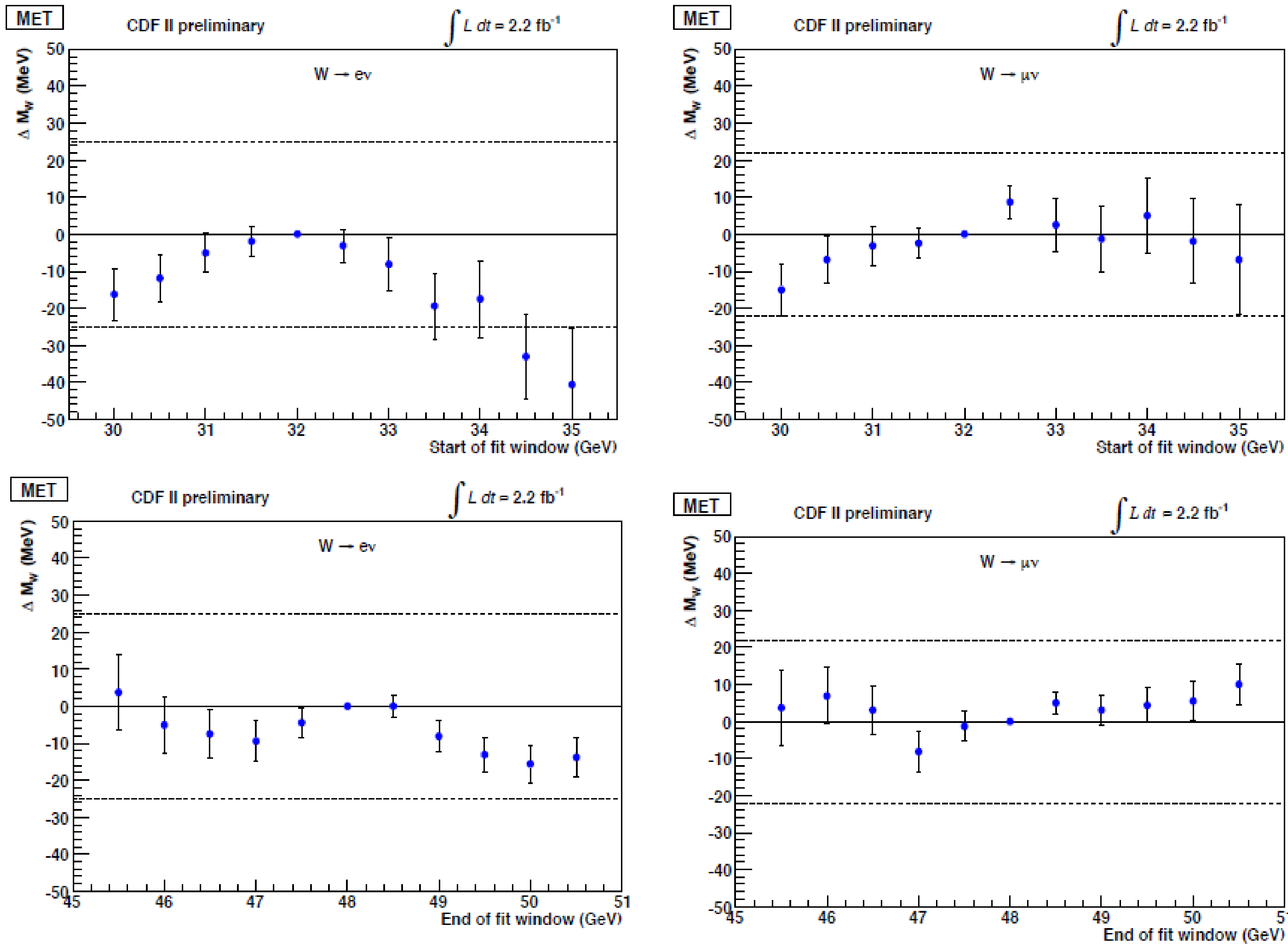
upper



W Mass Fit Window Variation, $p_T(\upsilon)$ Fit

lower

upper



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

$p_T(\nu)$ Fit Systematic Uncertainties

Systematic (MeV/c^2)	Electrons	Muons	Common
Lepton Energy Scale	10	7	5
Lepton Energy Resolution	7	1	0
Recoil Energy Scale	2	2	2
Recoil Energy Resolution	11	11	11
$u_{\vert\vert}$ efficiency	$\vert$ -3 $\vert$	$\vert$ -2 $\vert$	0
Lepton Removal	6	4	4
Backgrounds	4	6	0
$p_T(W)$ model	4	4	4
Parton Distributions	11	11	11
QED radiation	4	4	4
Total	22	20	18

Combined Fit Systematic Uncertainties

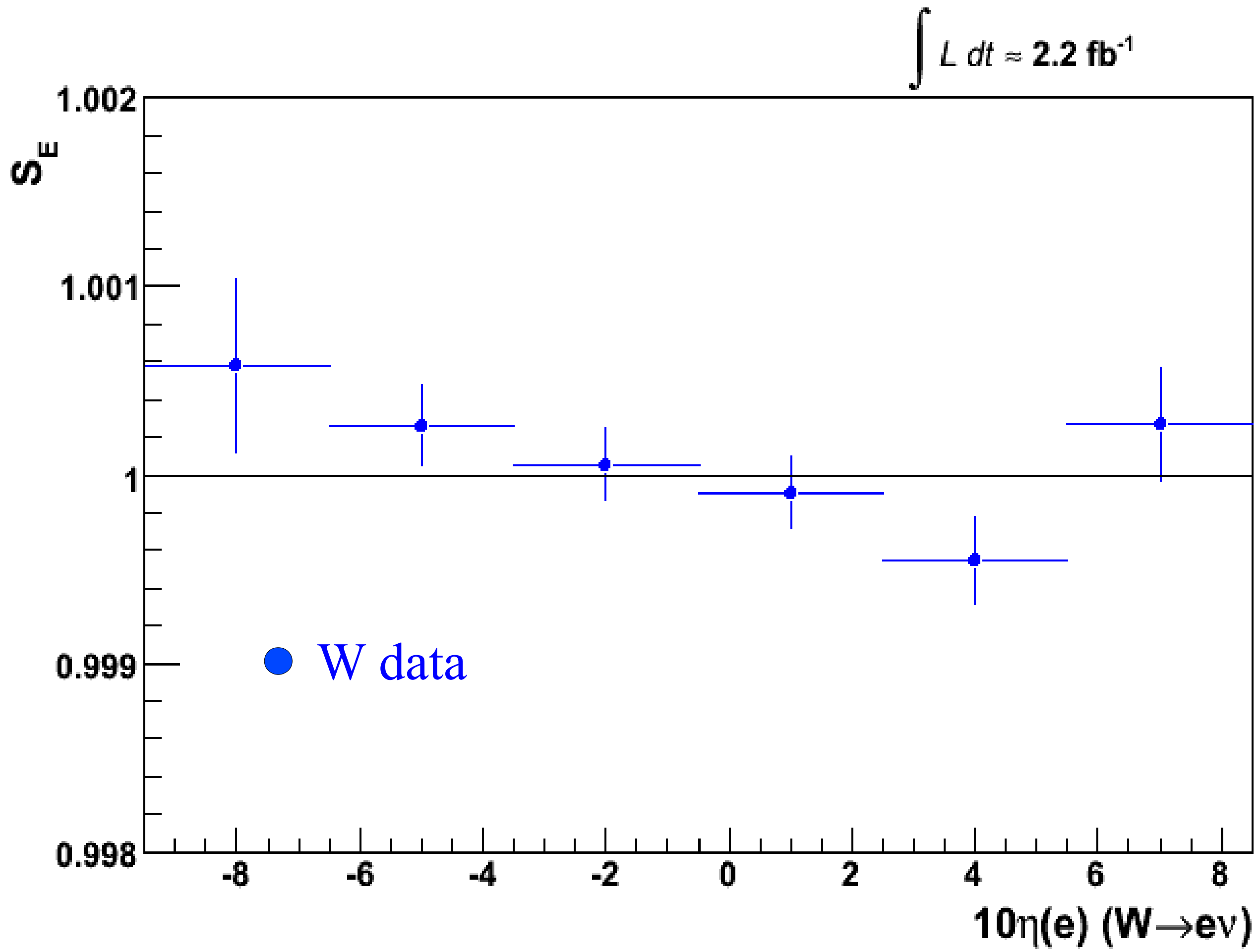
Source	Uncertainty (MeV)
Lepton Energy Scale	7
Lepton Energy Resolution	2
Recoil Energy Scale	4
Recoil Energy Resolution	4
$u_{\|\|}$ efficiency	0
Lepton Removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton Distributions	10
QED radiation	4
W boson statistics	12
Total	19

Systematic Uncertainties in QED Radiative Corrections

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

EM Calorimeter Uniformity

- Checking uniformity of energy scale in bins of electron pseudo-rapidity



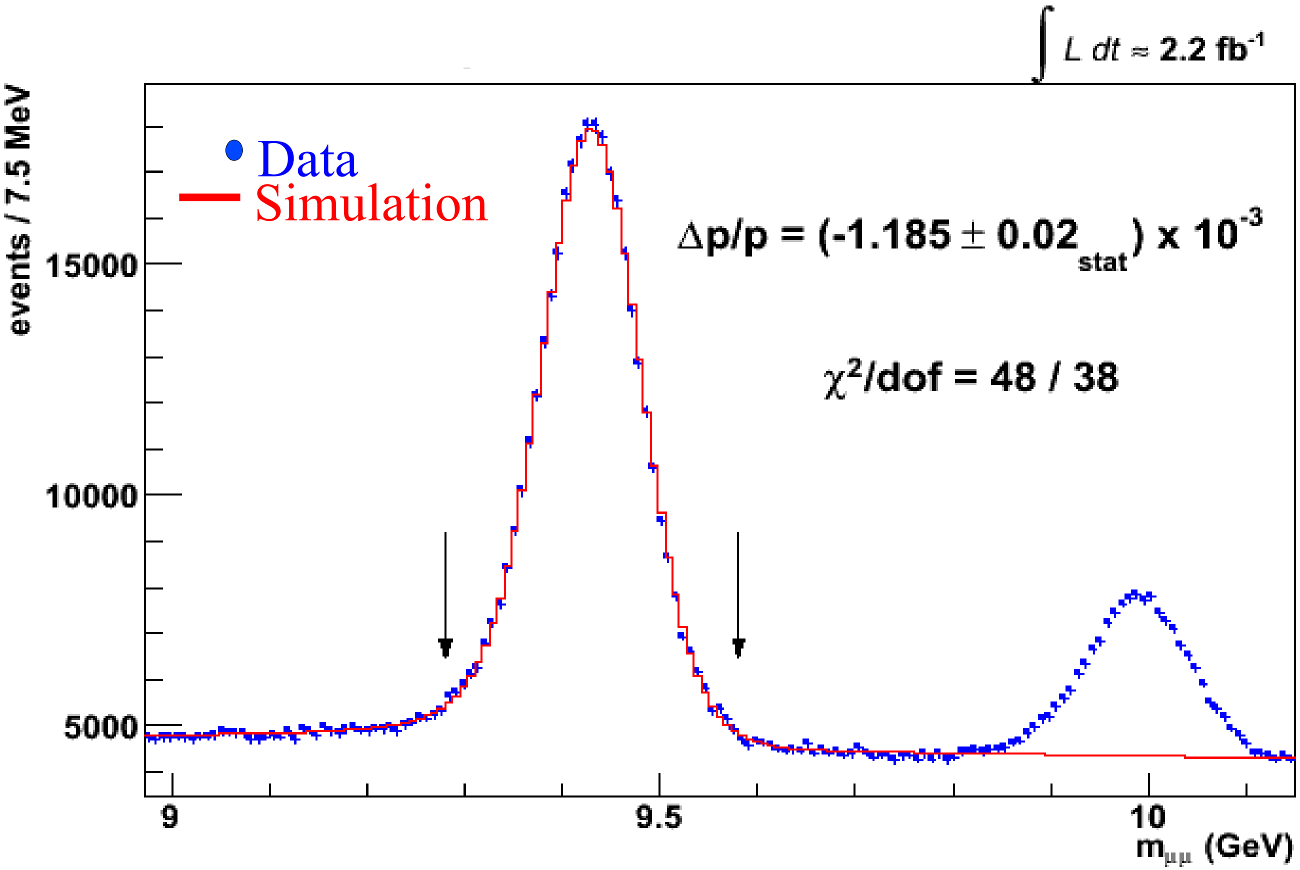
Parton Distribution Functions

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

Tracking Momentum Scale

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

- Cross-check of non-beam-constrained (NBC) and beam-constrained (BC) fits
- Difference used to set additional systematic uncertainty



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

Lepton Resolutions

- Tracking resolution parameterized in the custom simulation by
  - Radius-dependent drift chamber hit resolution $\sigma_h \sim (150 \pm 1_{stat})\ \mu m$
  - Beamspot size $\sigma_b = (35 \pm 1_{stat})\ \mu m$
  - Tuned on the widths of the $Z \rightarrow \mu\mu$ (beam-constrained) and $\Upsilon \rightarrow \mu\mu$ (both beam constrained and non-beam constrained) mass peaks

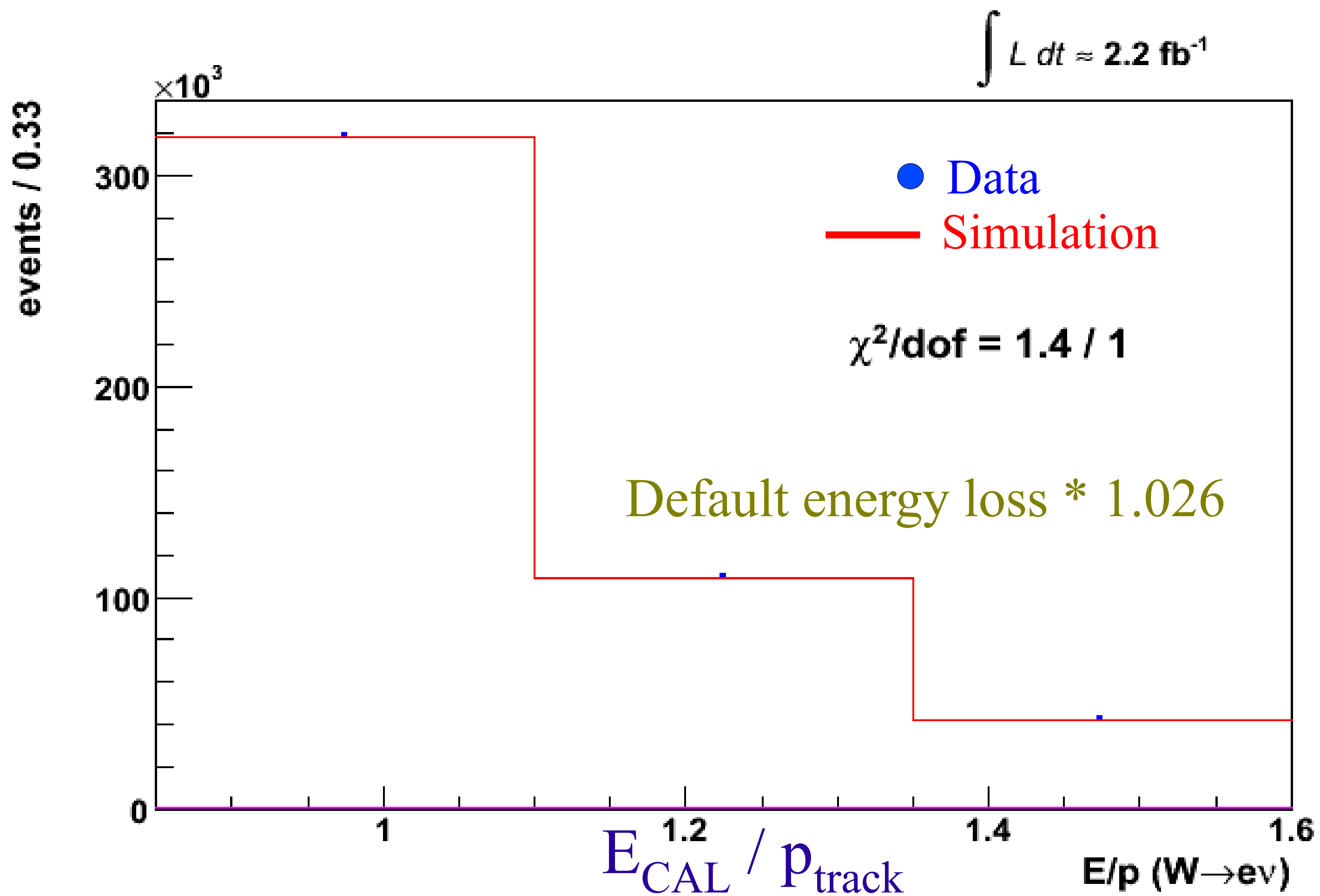
=> $\Delta M_W = 1$ MeV (muons)

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

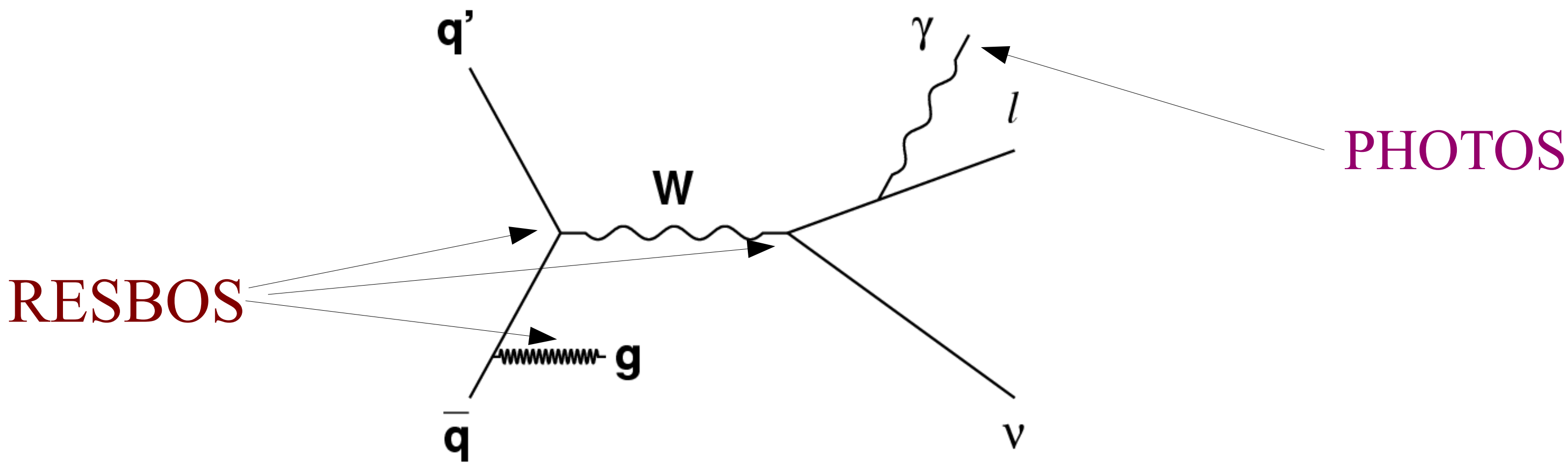
=> $\Delta M_W = 4$ MeV (electrons)

Consistency of Radiative Material Model

- Excellent description of E/p spectrum tail
- radiative material tune factor: $S_{X0} = 1.026 \pm 0.003_{stat} \pm 0.002_{background}$ achieves consistency with E/p spectrum tail



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)

Tracking Momentum Scale Systematics

Systematic uncertainties on momentum scale

Source	J/ψ $(\cdot 10^{-3})$	NBC-Υ $(\cdot 10^{-3})$	common $(\cdot 10^{-3})$
QED	0.080	0.045	0.045
B field non-uniformity	0.032	0.034	0.032
Ionizing material	0.022	0.014	0.014
Resolution	0.010	0.005	0.005
Backgrounds	0.011	0.005	0.005
Misalignment	0.009	0.018	0.009
Trigger efficiency	0.004	0.005	0.004
Fitting window	0.004	0.005	0.004
$\Delta p/p$ step size	0.002	0.003	0
World-average	0.004	0.027	0
Total systematic	0.092	0.068	0.058
Statistical	0.004	0.025	0
Total	0.092	0.072	0.058

$\Delta M_{W,Z} = 6$ MeV

Uncertainty dominated by QED radiative corrections and magnetic field non-uniformity

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 => ΔM_W = 2 MeV