A Precise Measurement of the W Boson Mass at CDF

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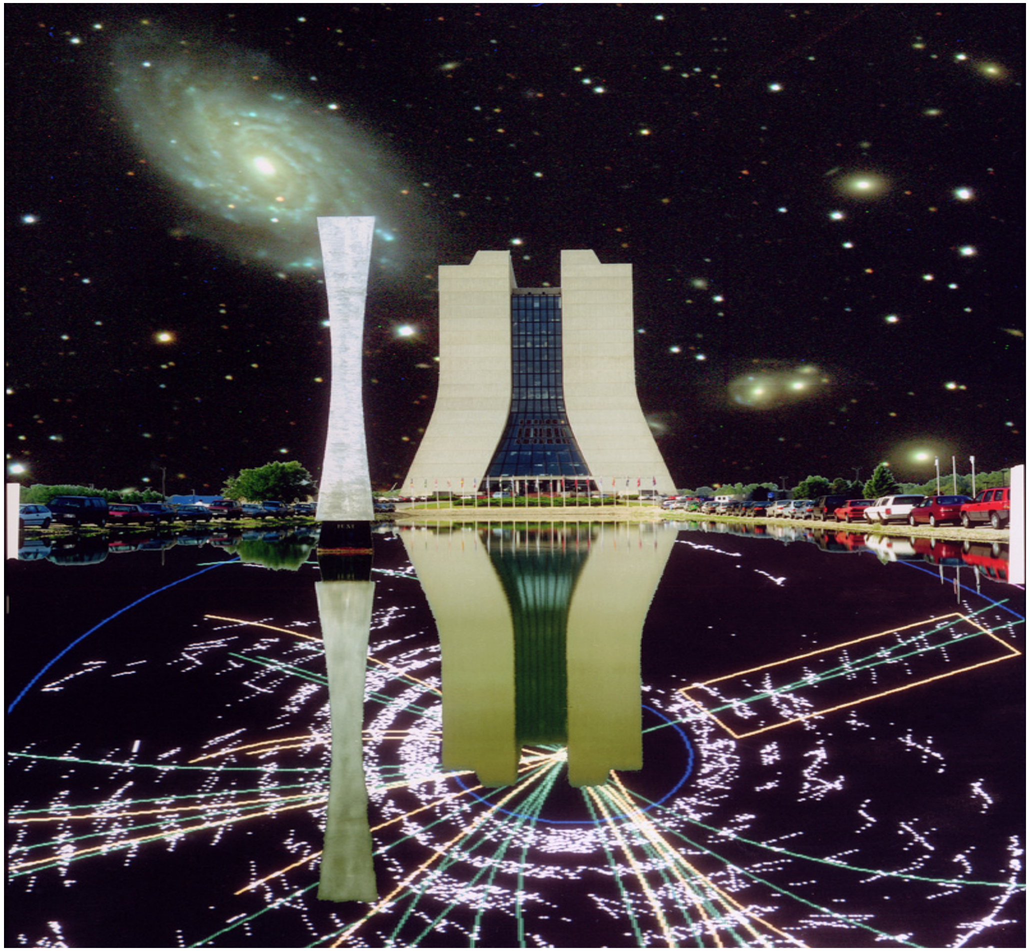


University of Oxford
March 5, 2013

Spontaneous Symmetry Breaking

- 2008 Nobel Prize in Physics

  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"

Yoichiro Nambu

- The mass of the W boson is linked to the mechanism of Electroweak Symmetry Breaking

Spontaneous Symmetry Breaking

- Is the mechanism of Electroweak Symmetry Breaking, the Standard Model Higgs mechanism?

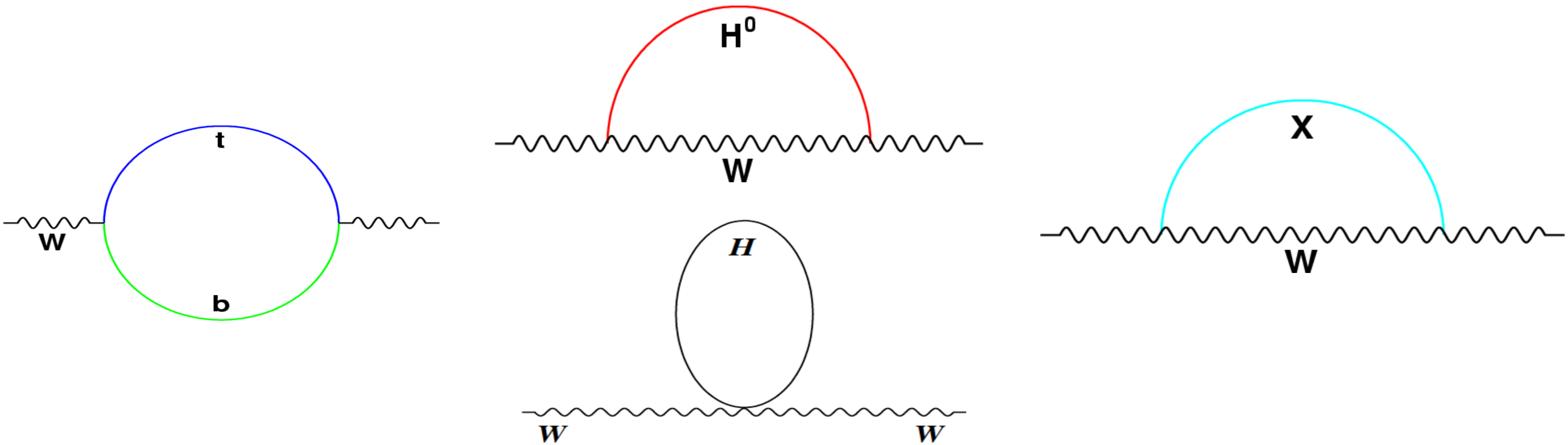
Motivation for Precision Measurements

- 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

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

Motivation for Precision Measurements

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

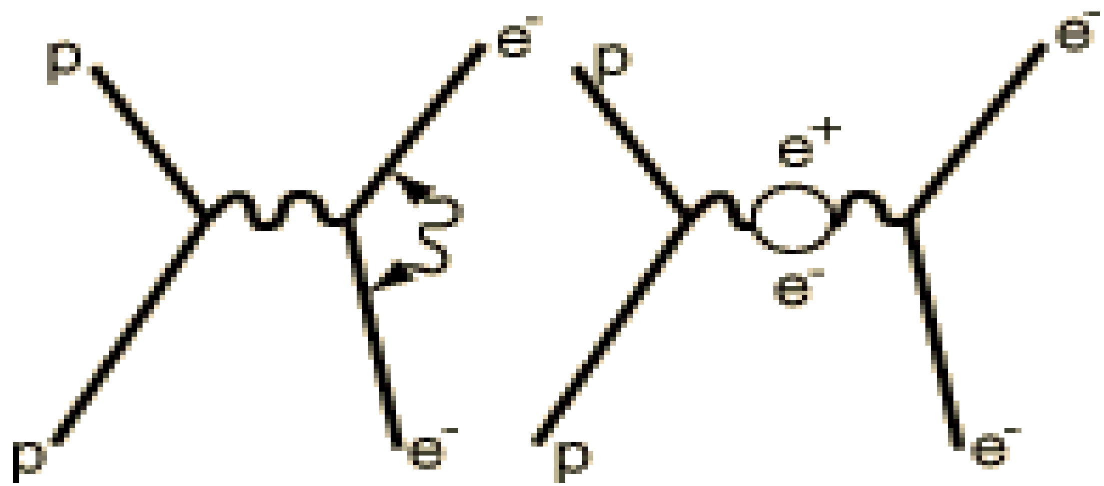


Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\text{tree})]^2$
with the predictions $\Delta\rho = (\rho - 1) \sim M_{top}^2$ and $\Delta\rho \sim \ln M_H$

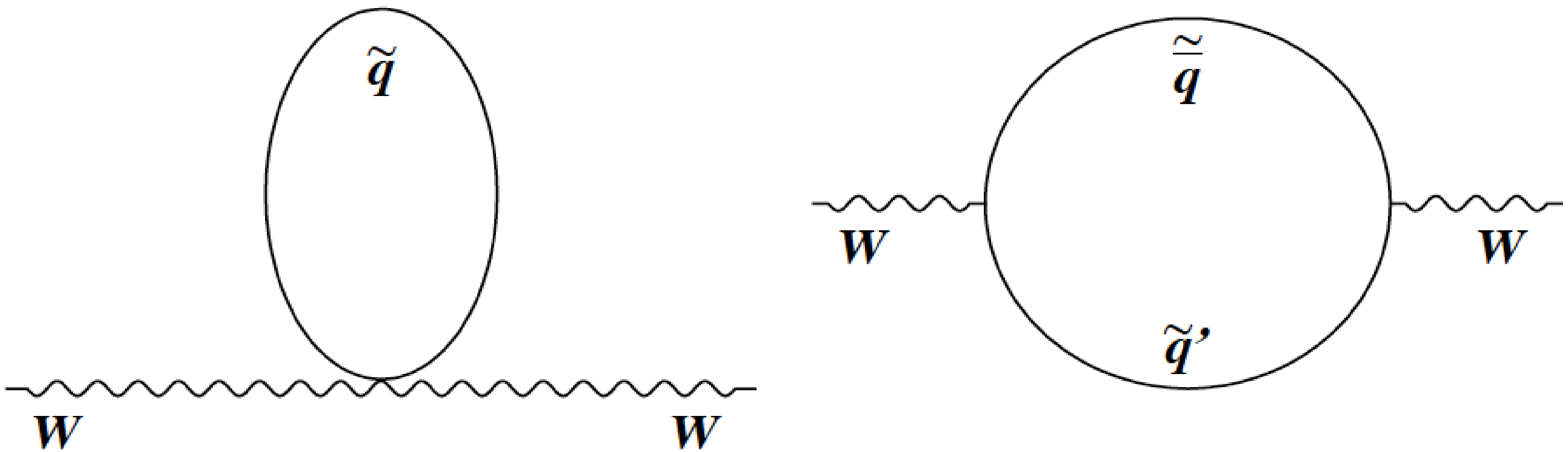
- In conjunction with M_{top}, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

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)

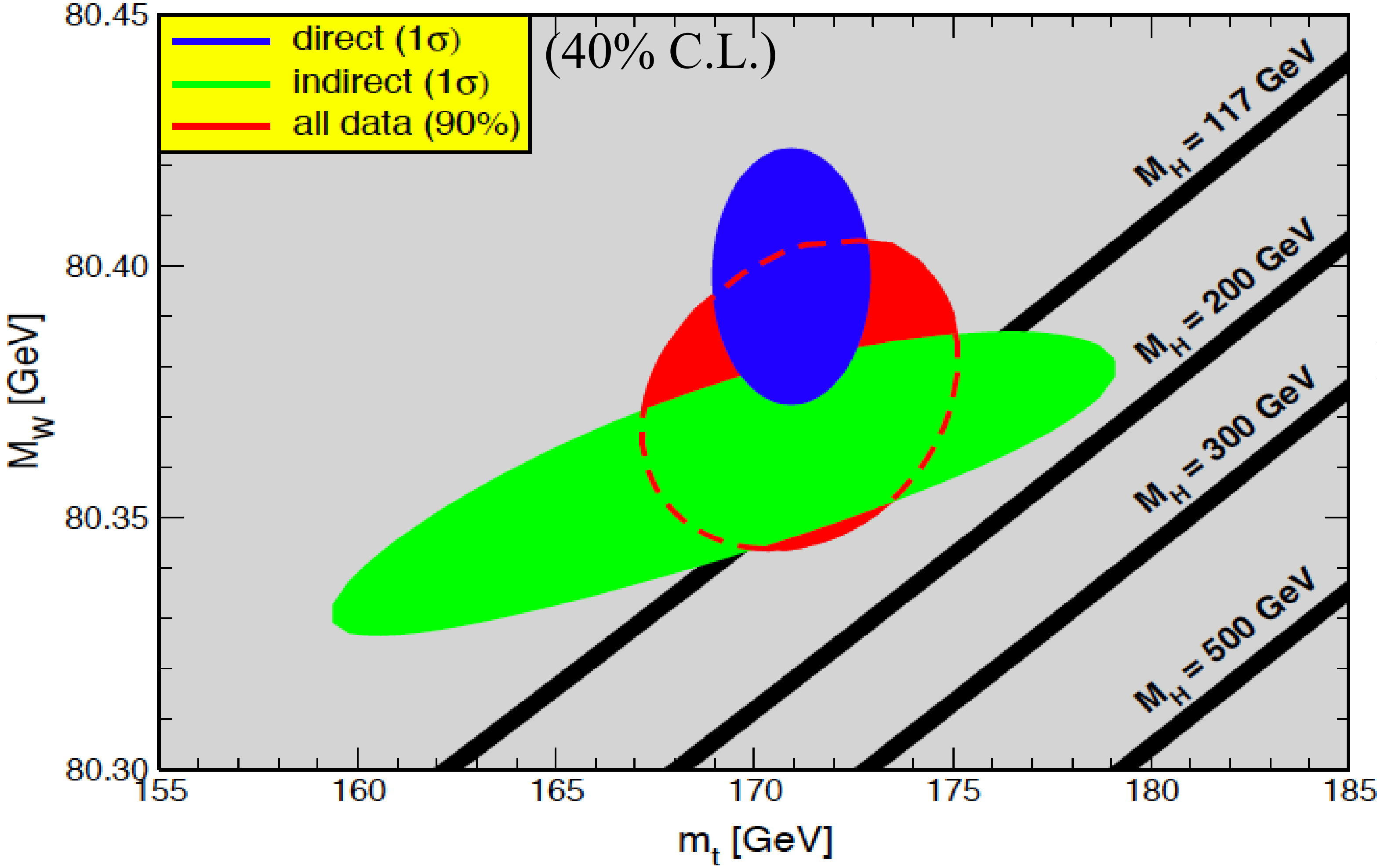


Contributions from Supersymmetric Particles



- Radiative correction depends on chiral structure of SUSY sector and 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

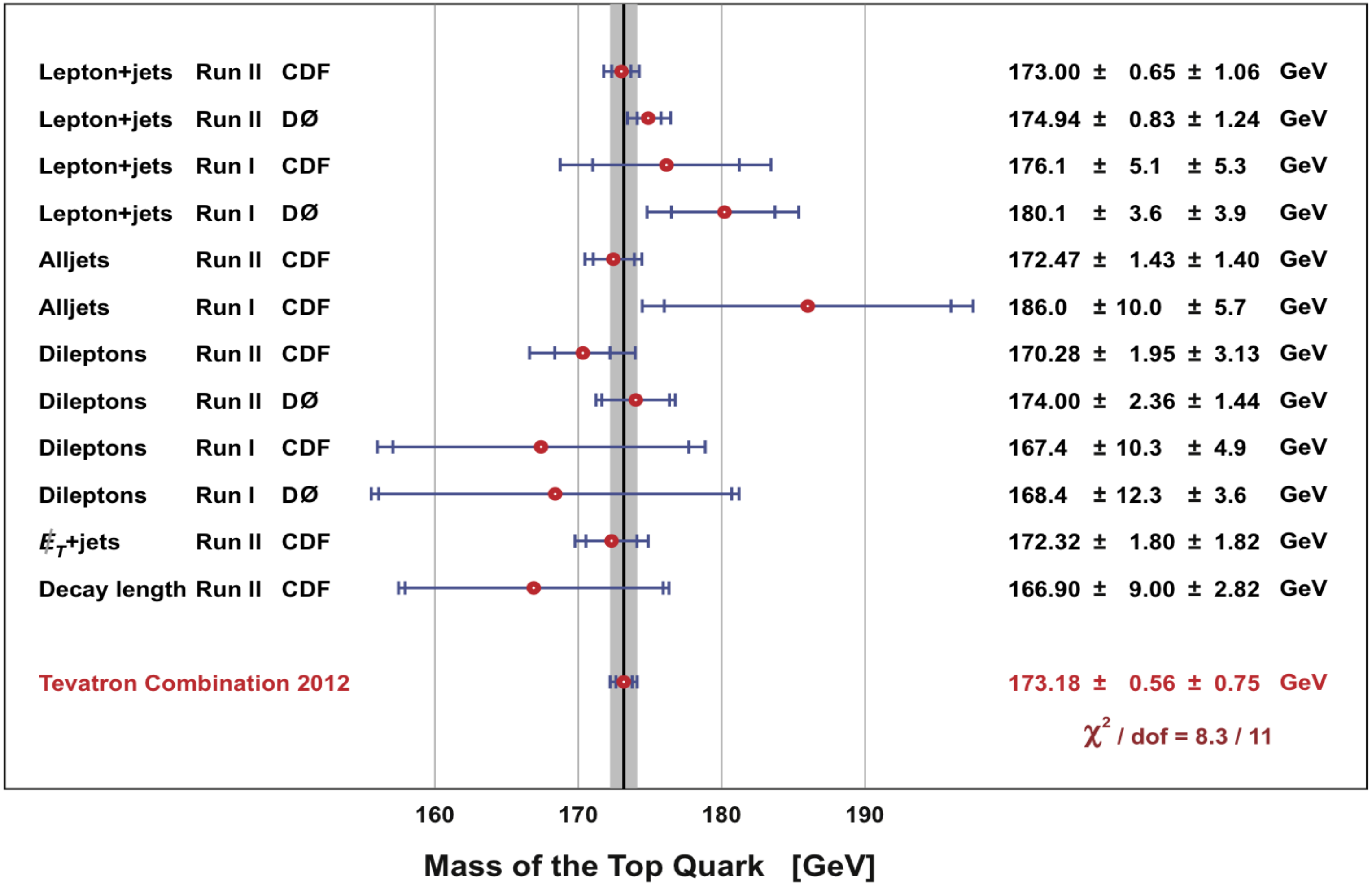
Uncertainty from $\alpha_{EM}(M_Z)$



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

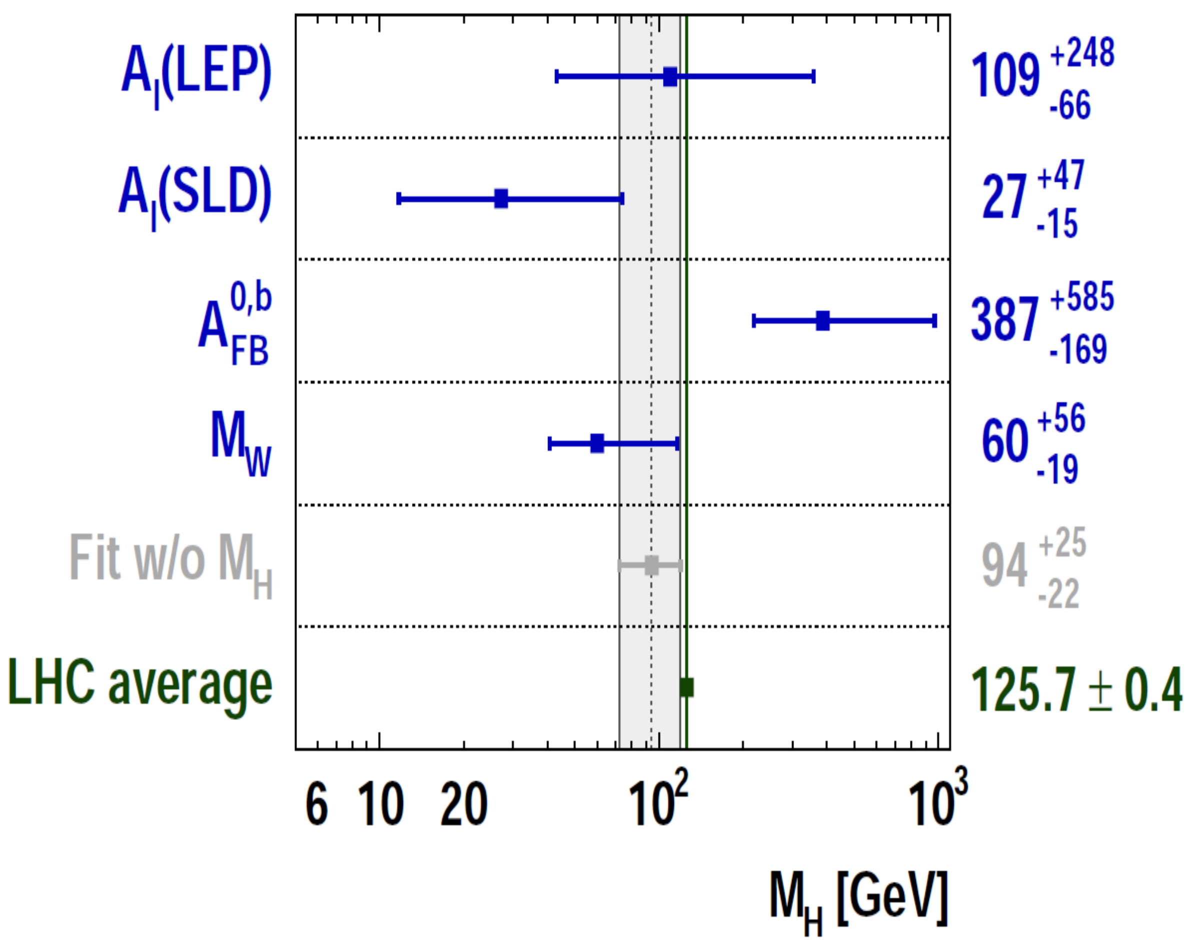


- From the Tevatron, ΔM_{top} = 0.9 GeV => $\Delta M_H / M_H$ = 8%
- equivalent ΔM_W = 6 MeV for the same Higgs mass constraint (and further improvements possible from Tevatron and LHC)
- 2011 world average ΔM_W = 23 MeV
  - progress on ΔM_W has the biggest impact on Higgs constraint

Motivation II

- SM Higgs fit: $M_H = 94^{+29}_{-24}$ GeV (LEPEWWG)
- Direct searches: $M_H \sim 125$ GeV (ATLAS, CMS)

GFitter



In addition to the Higgs, is there another missing piece ?

A_{FB}^{b} *vs* A_{LR}: $\sim 3\sigma$

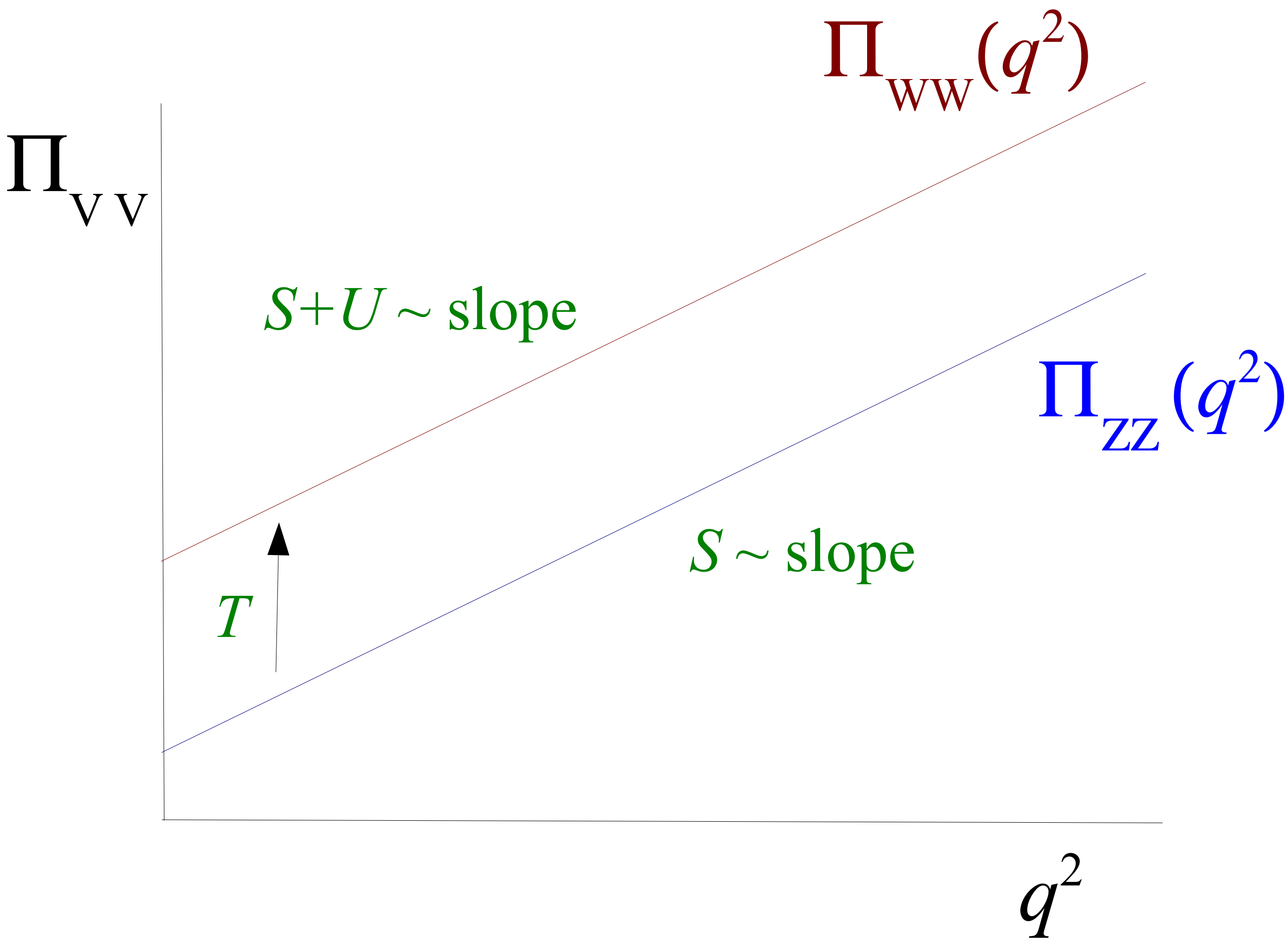
Must continue improving precision of M_W, M_{top} ...

other precision measurements constrain Higgs, equivalent to $\delta M_W \sim 15$ MeV

Motivate direct measurement of M_W at the 15 MeV level and better

Motivation III

- 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 III

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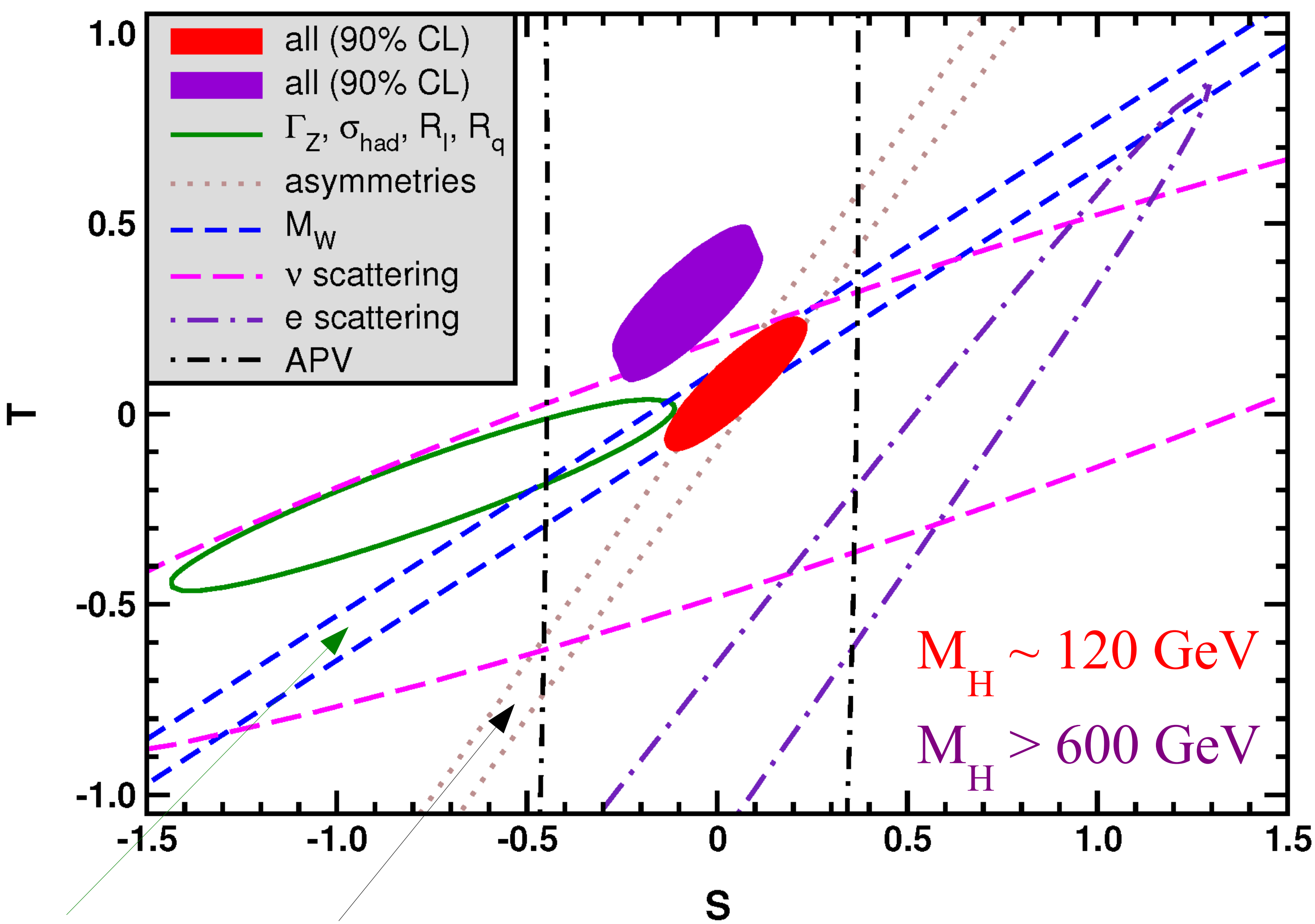


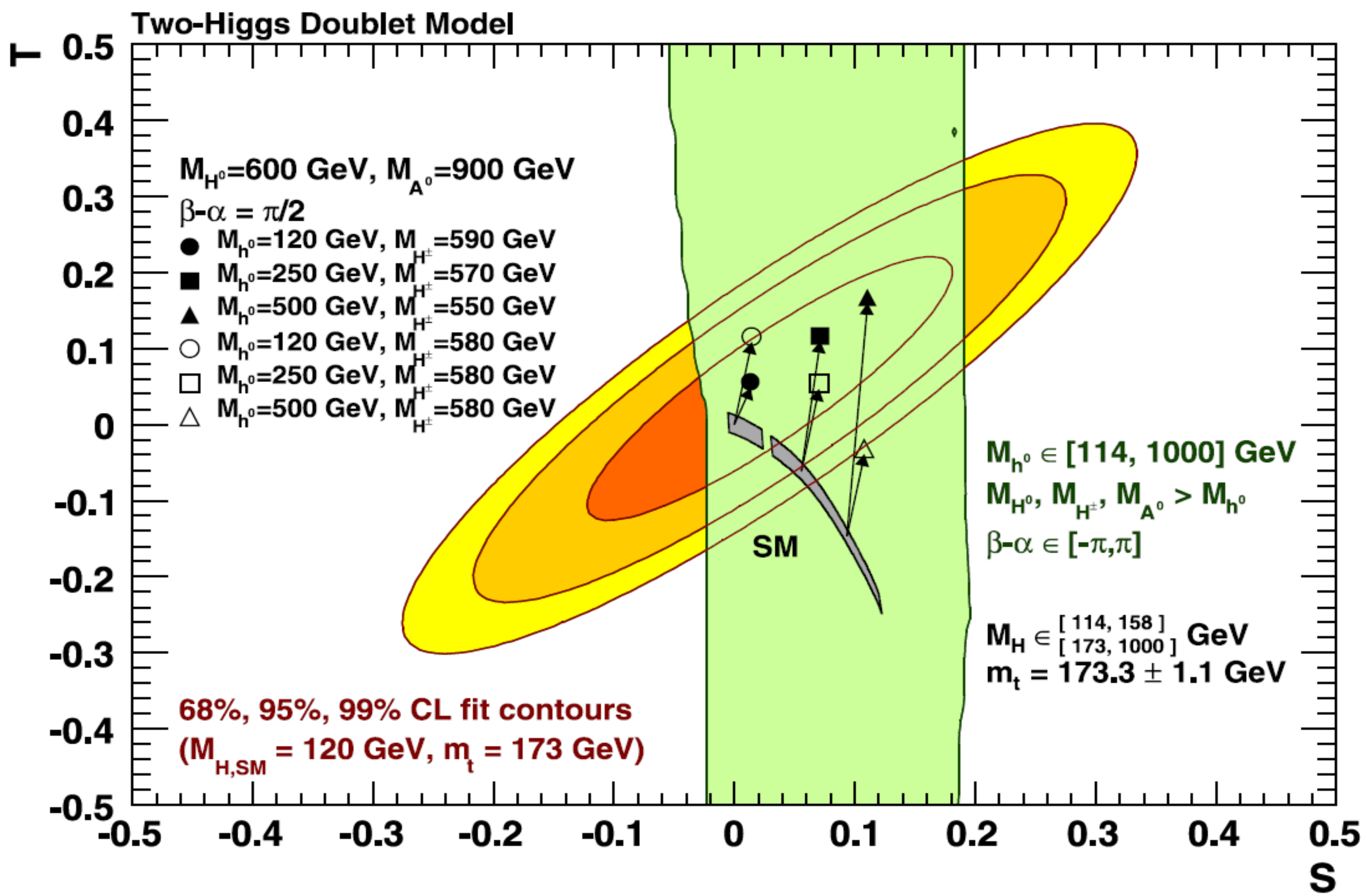
Additionally, M_W is the only measurement which constrains *U*

(from P. Langacker, 2012)

M_W and Asymmetries are the most powerful observables in this parameterization

Motivation III

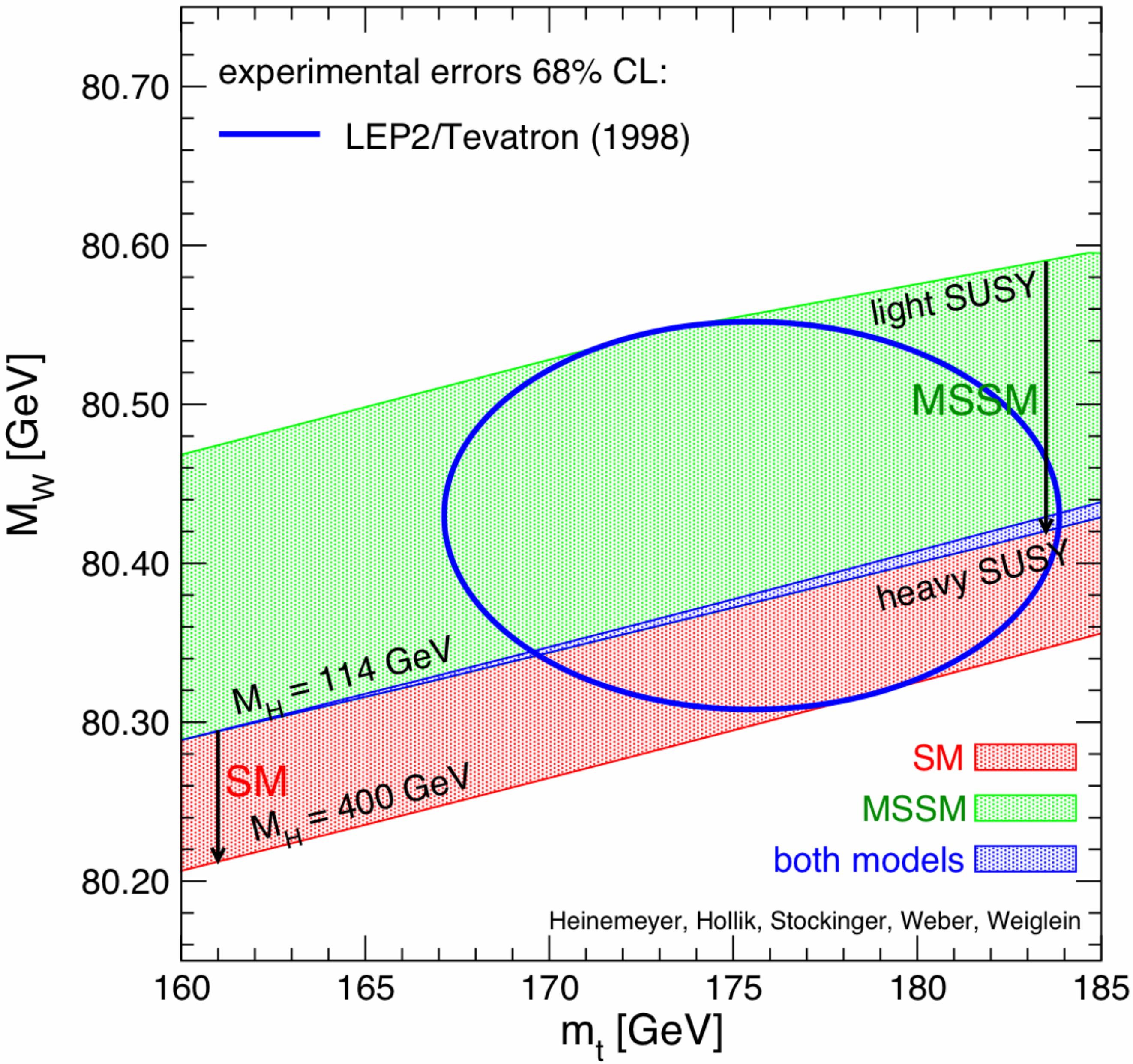
- An example: extending the Higgs sector to two SU(2) doublets (required in SUSY) predicts additional neutral scalar and pseudo-scalar, and charged Higgs bosons



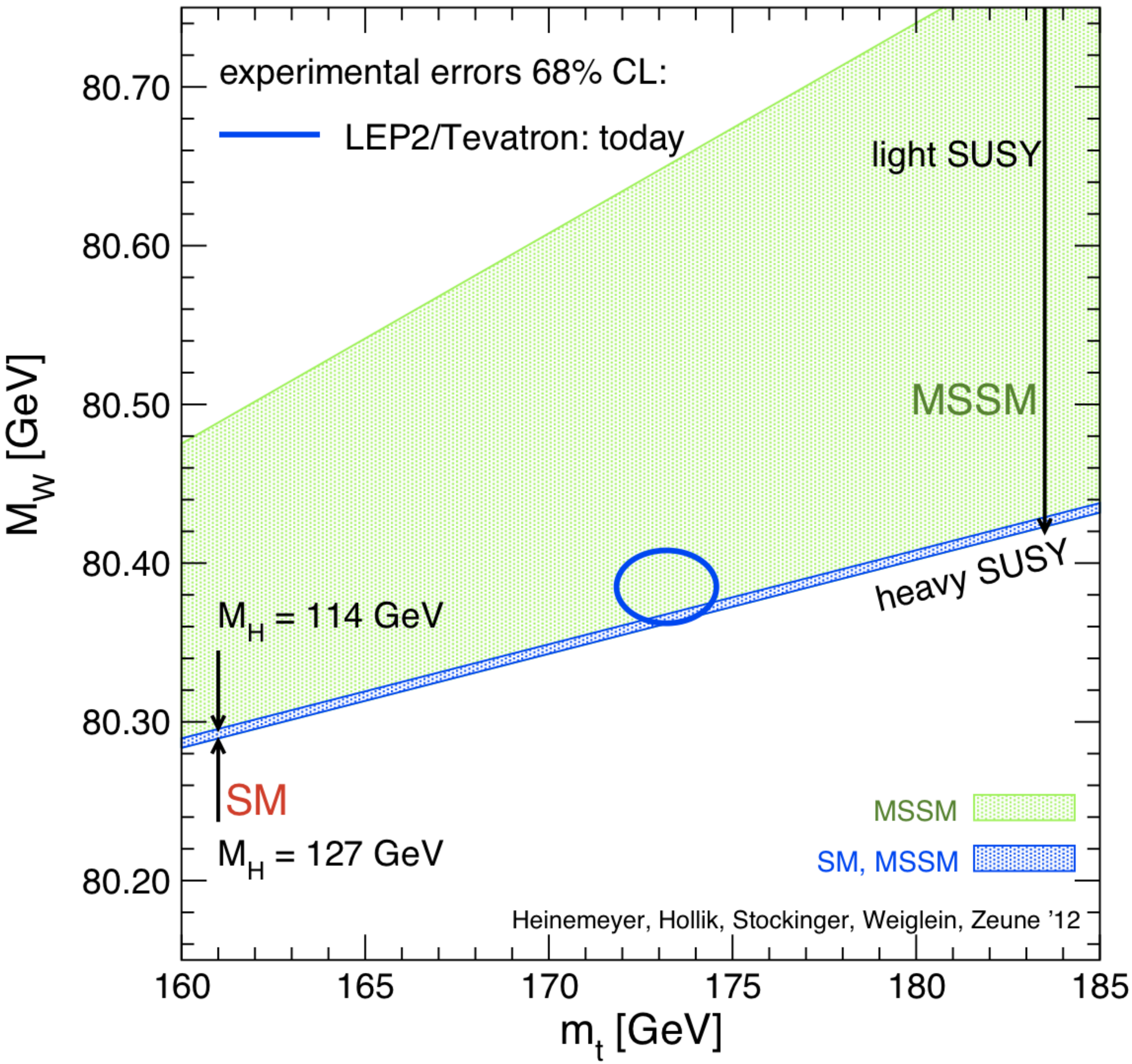
(from M. Baak *et al.* (Gfitter Group) Eur. Phys. J. C (2012) 72:2003)

T parameter responds strongly to 2HDM parameters

1998 Status of M_W *vs* M_{top}



2012 Status of M_W *vs* M_{top}



Previous CDF Result (200 pb^{-1})
Transverse Mass Fit Uncertainties (MeV)

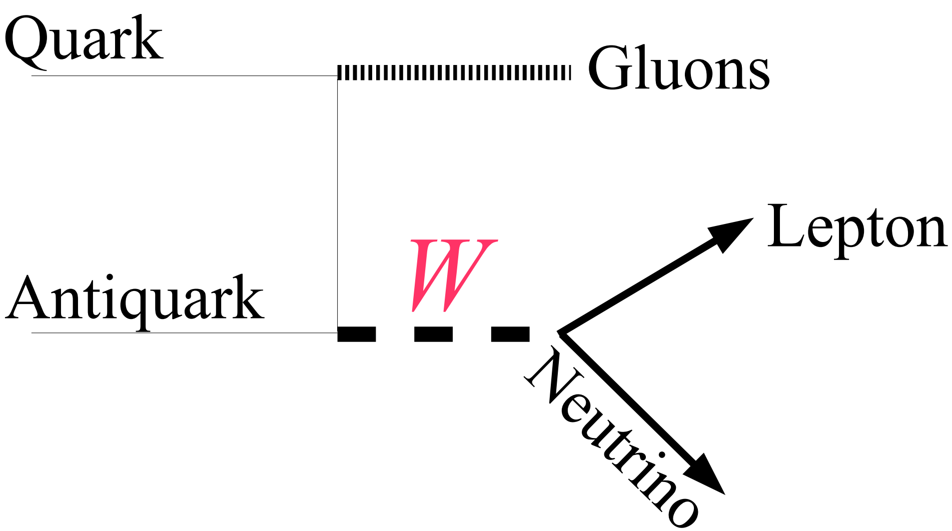
(CDF, PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)

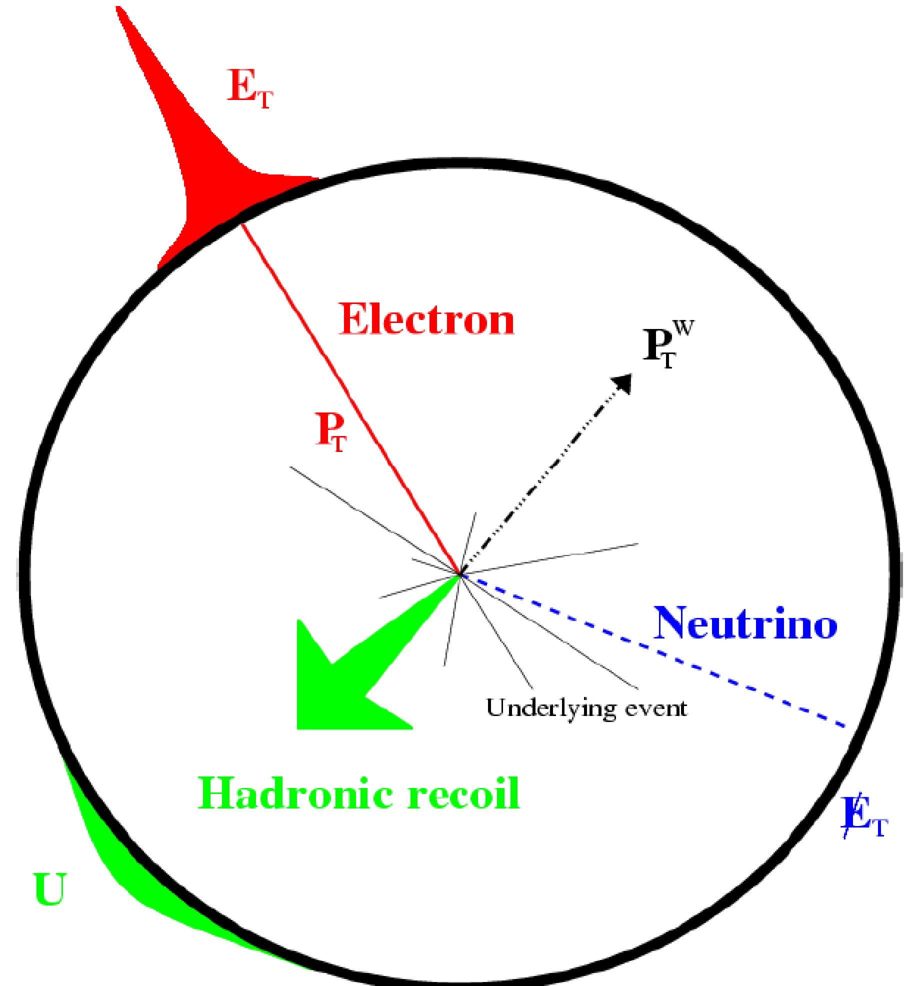
Total uncertainty of 48 MeV on W mass

	electrons	*muons*	*common*
W statistics	48	54	0
Lepton energy scale	30	17	17
Lepton resolution	9	3	-3
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
Selection bias	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
pT(W) model	3	3	3
Parton dist. Functions	11	11	11
QED rad. Corrections	11	12	11
Total systematic	39	27	26
Total	62	60	

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

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

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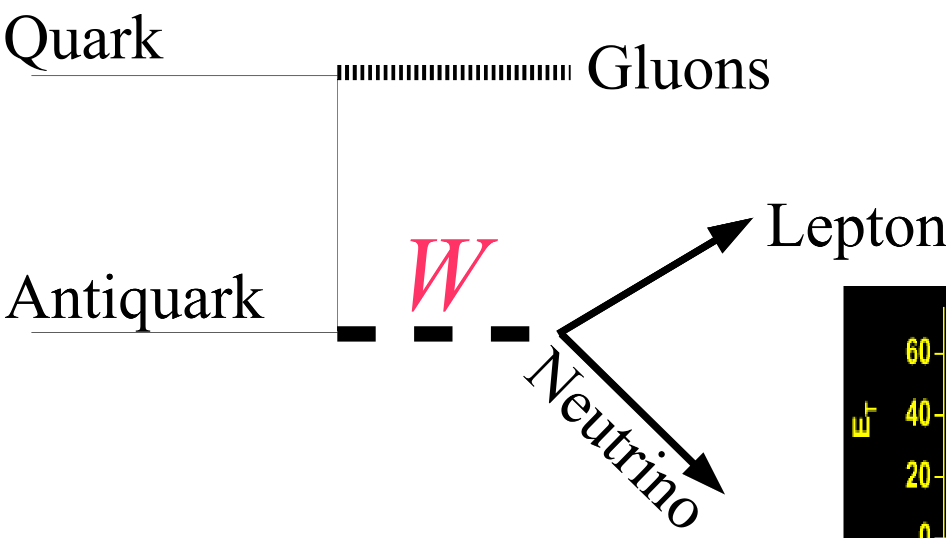

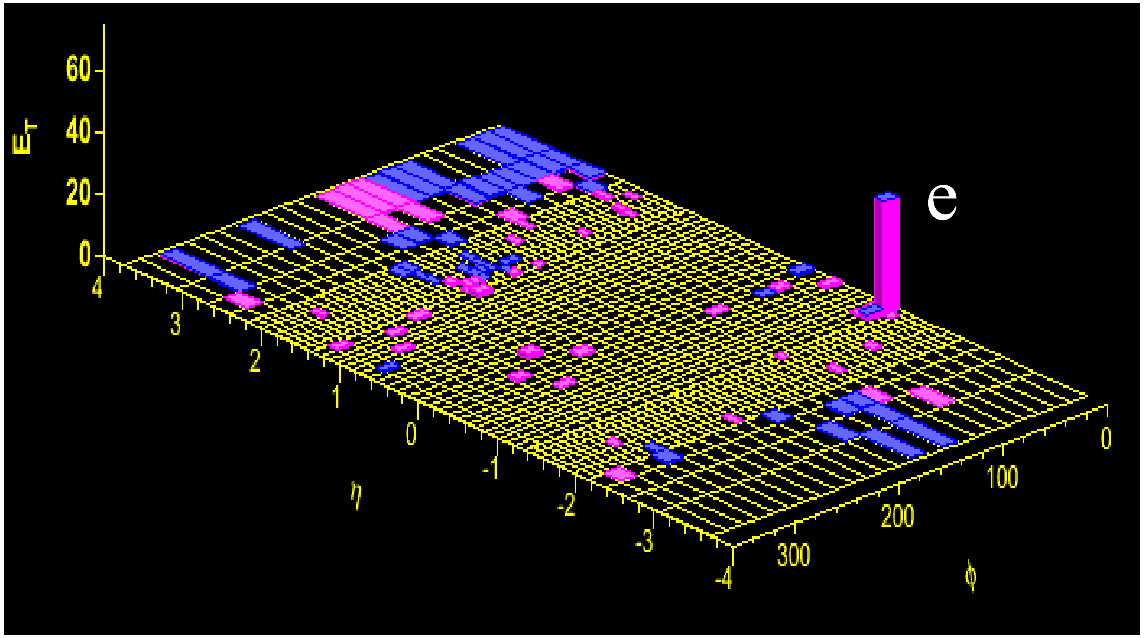

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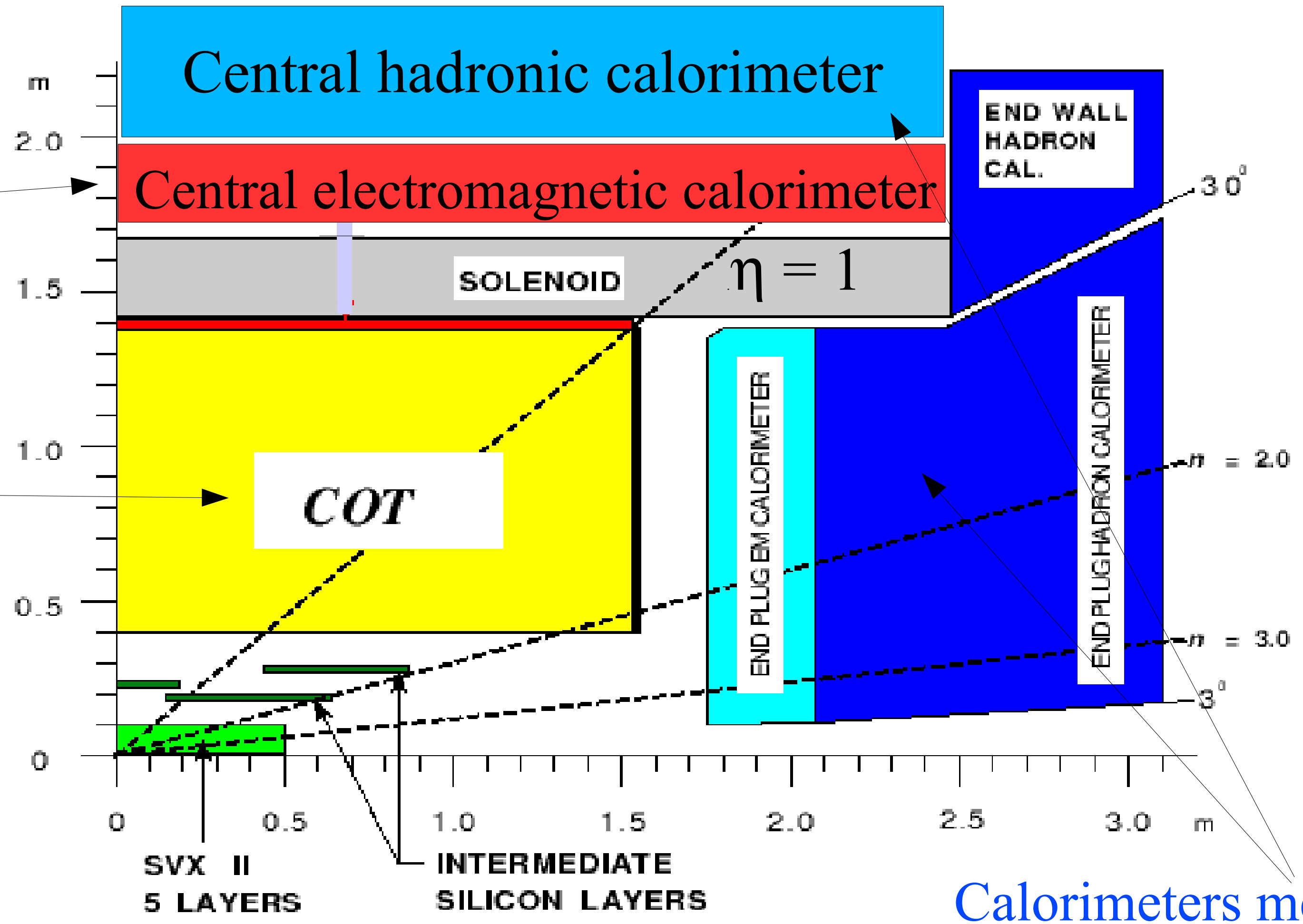
Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

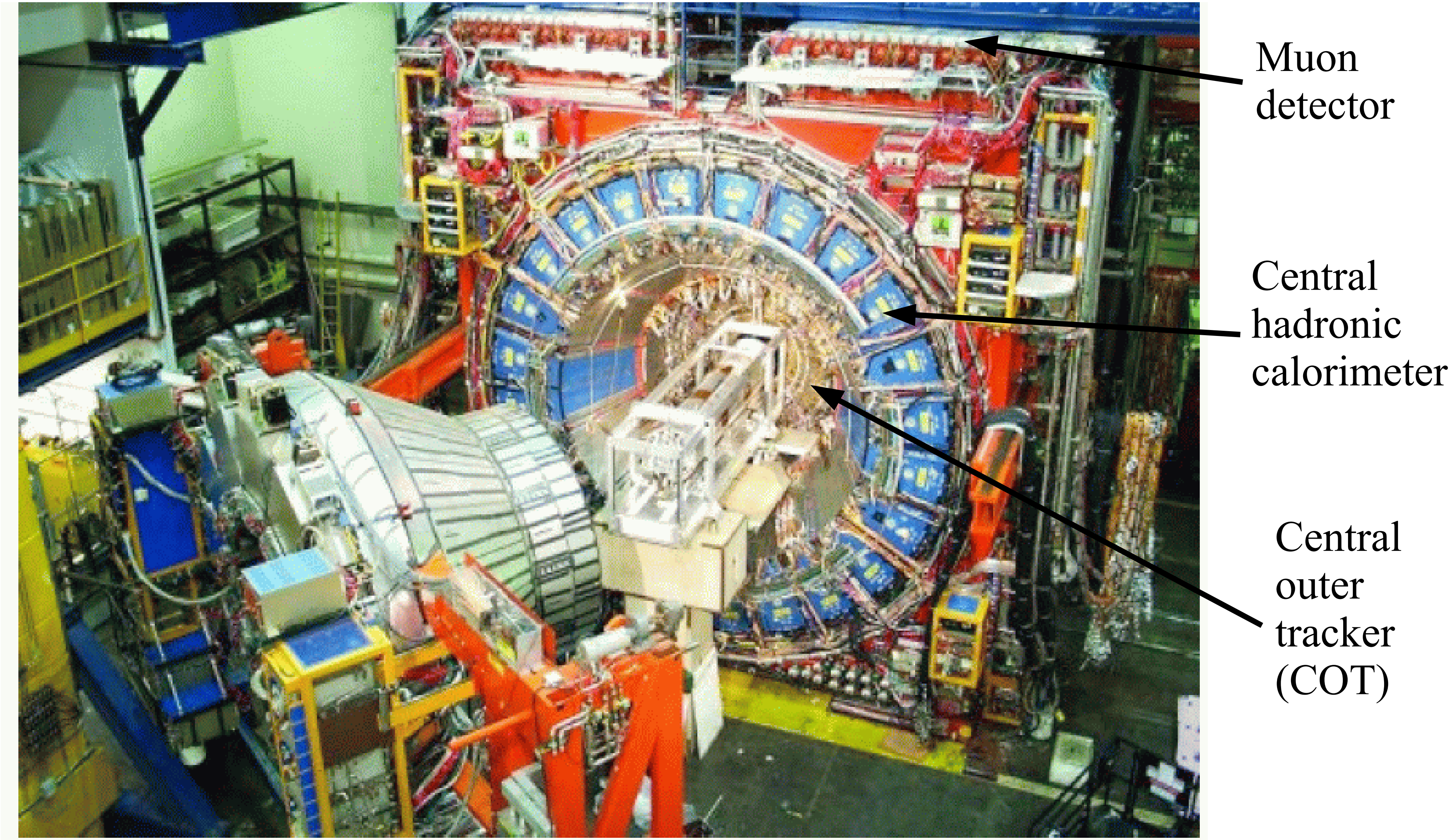
COT provides precise lepton track momentum measurement



Calorimeters measure hadronic recoil particles

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

Collider Detector at Fermilab (CDF)



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

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
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  - COT momentum scale transferred to EM calorimeter using a fit to the peak of the E/p spectrum, around E/p ~ 1
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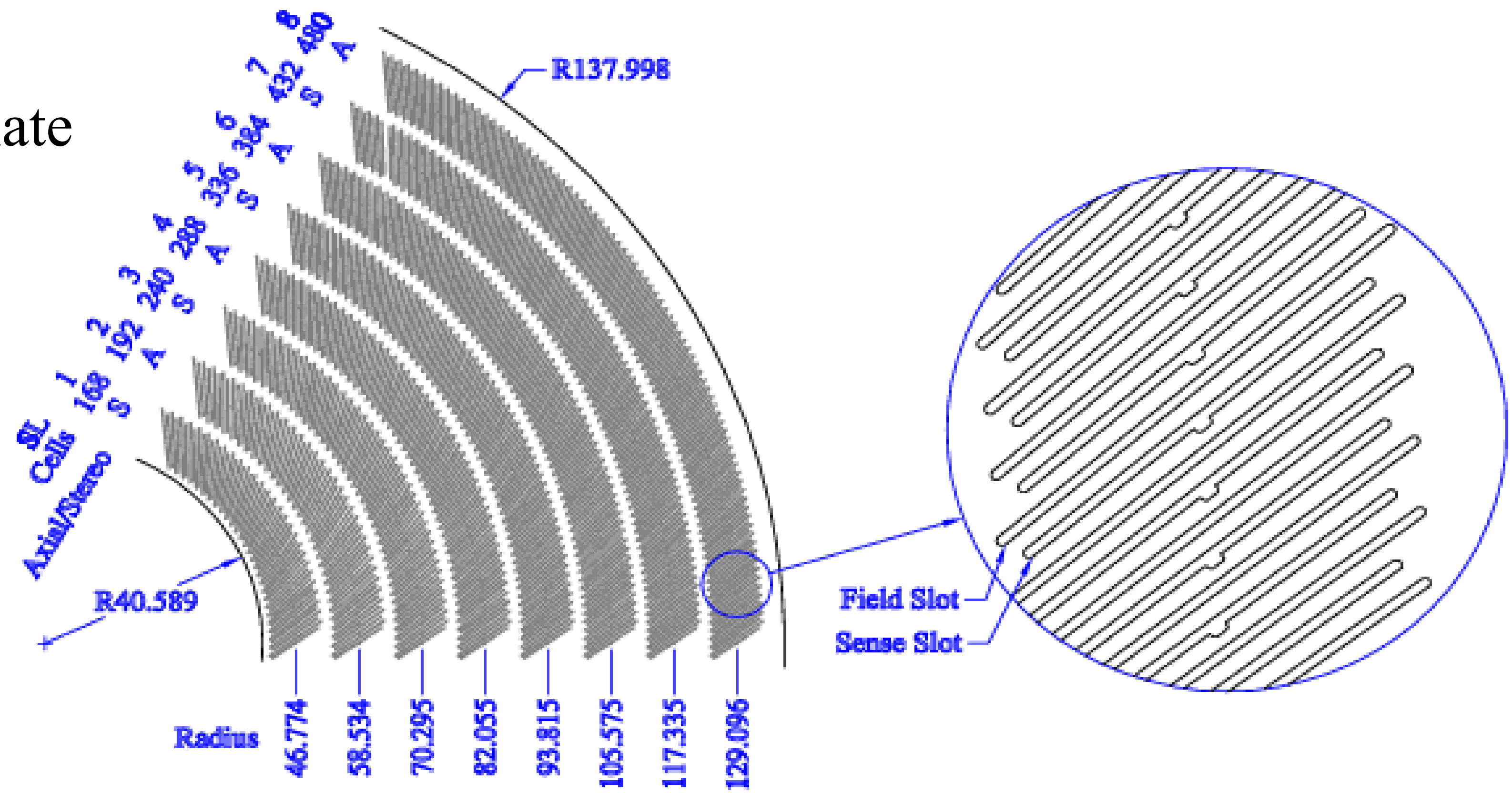
- Tracker and EM Calorimeter resolutions
- Hadronic recoil modelling
  - Characterized using p_T-balance in $Z \rightarrow ll$ events

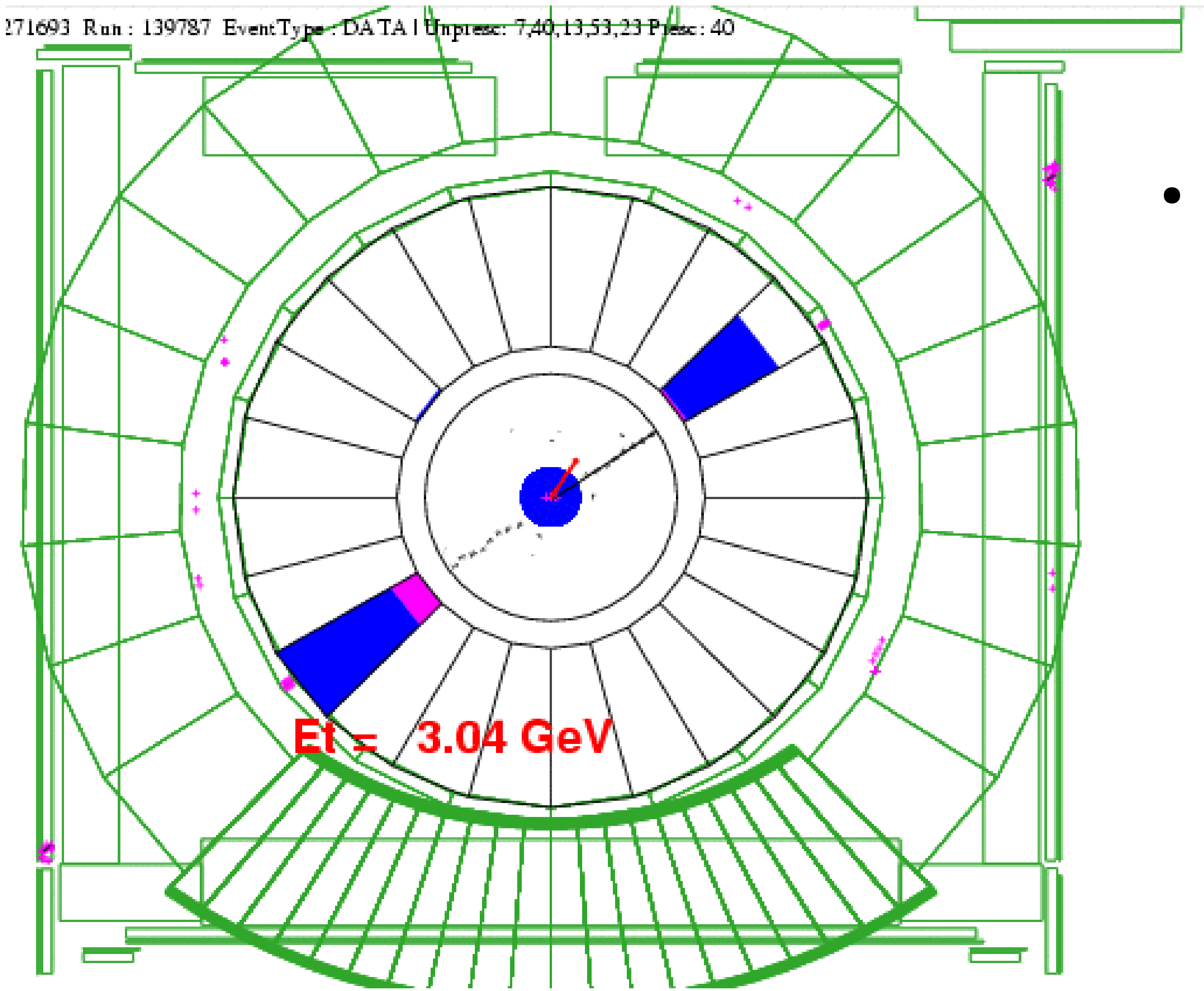
Drift Chamber (COT) Alignment

COT endplate geometry



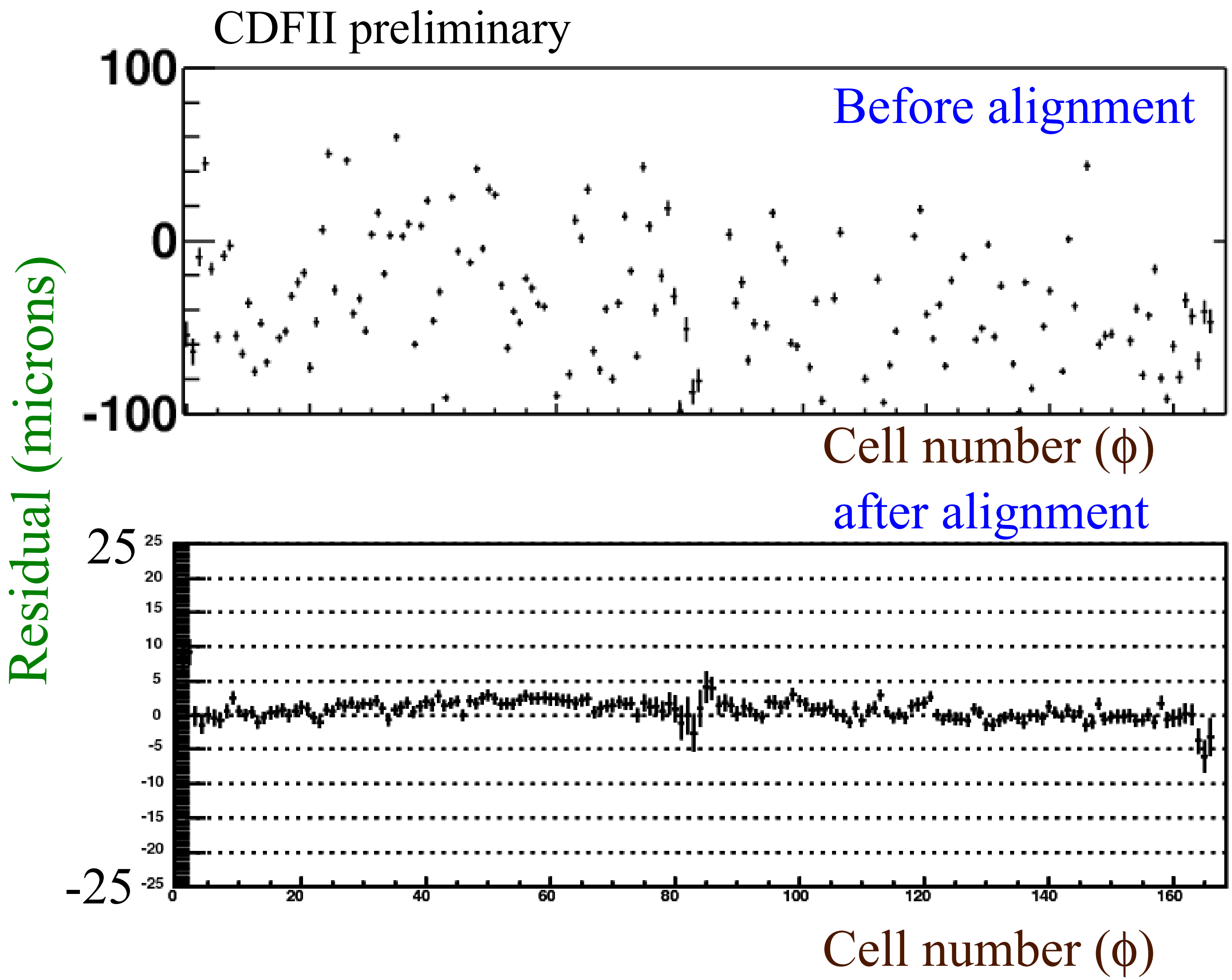
Internal Alignment of COT

- 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, NIM A506, 110 (2003))
  - Time of incidence is a floated parameter in this 'dicosmic fit'

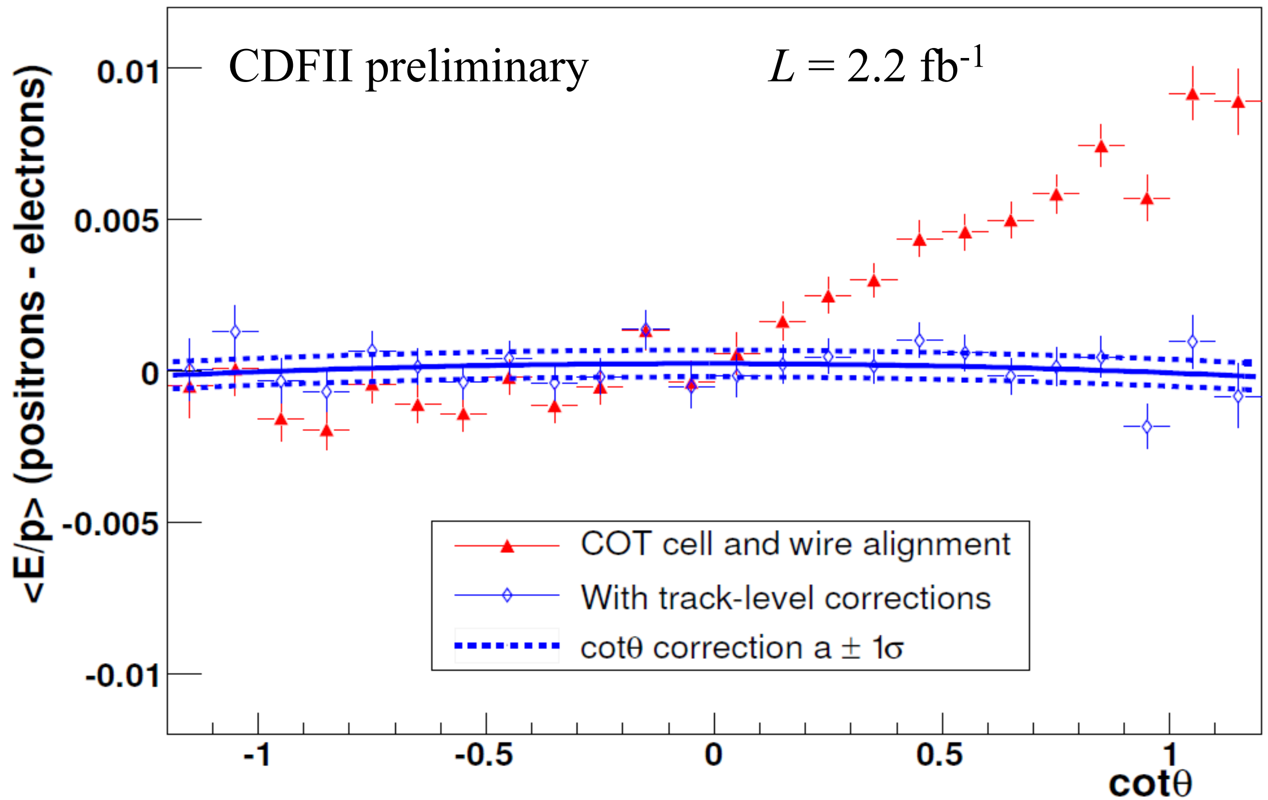
Residuals of COT cells after alignment



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

Cross-check of COT alignment

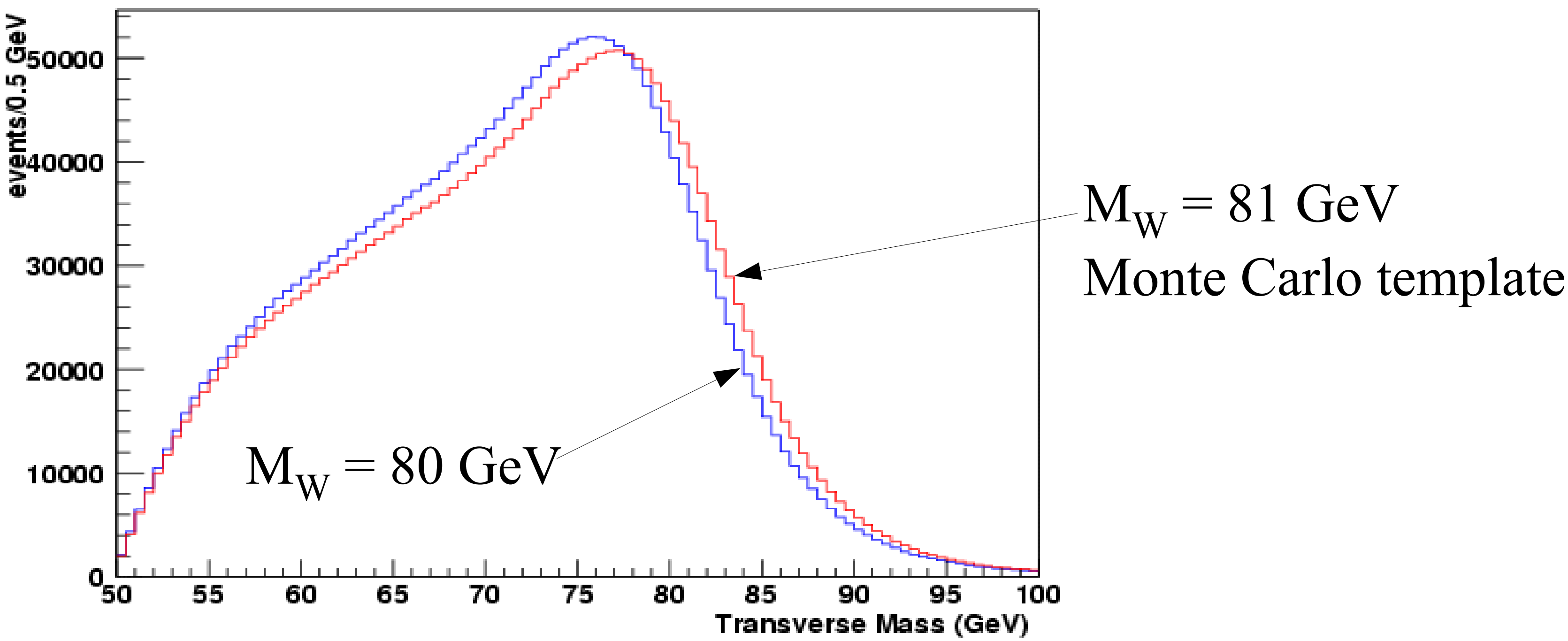
- Cosmic ray alignment removes most deformation degrees of freedom, but "weakly constrained modes" remain
- Final cross-check and correction to beam-constrained track curvature based on difference of <E/p> for positrons *vs* electrons
- Smooth ad-hoc curvature corrections as a function of polar and azimuthal angle: statistical errors => $\Delta M_W = 2$ MeV



Signal Simulation and Fitting

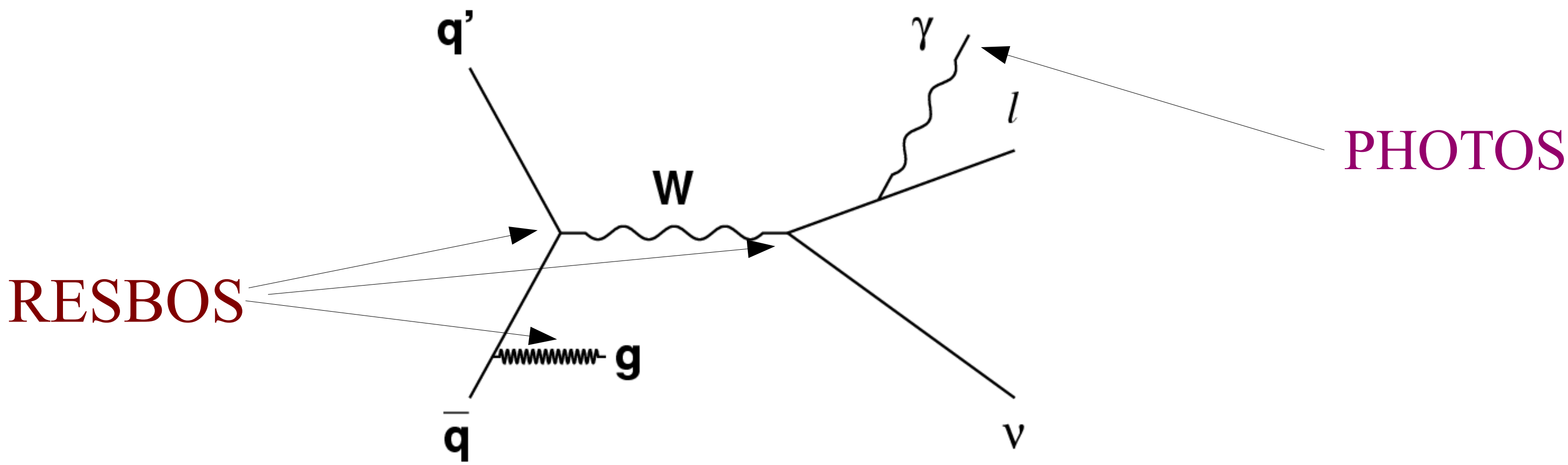
Signal Simulation and Template Fitting

- 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



- 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

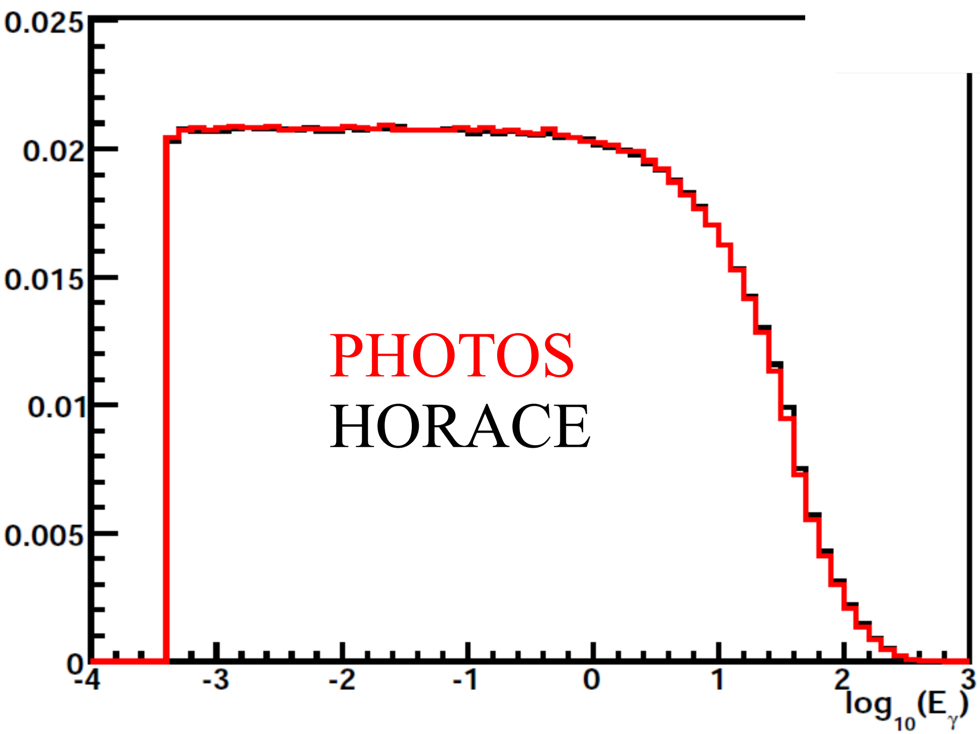
Generator-level Signal Simulation

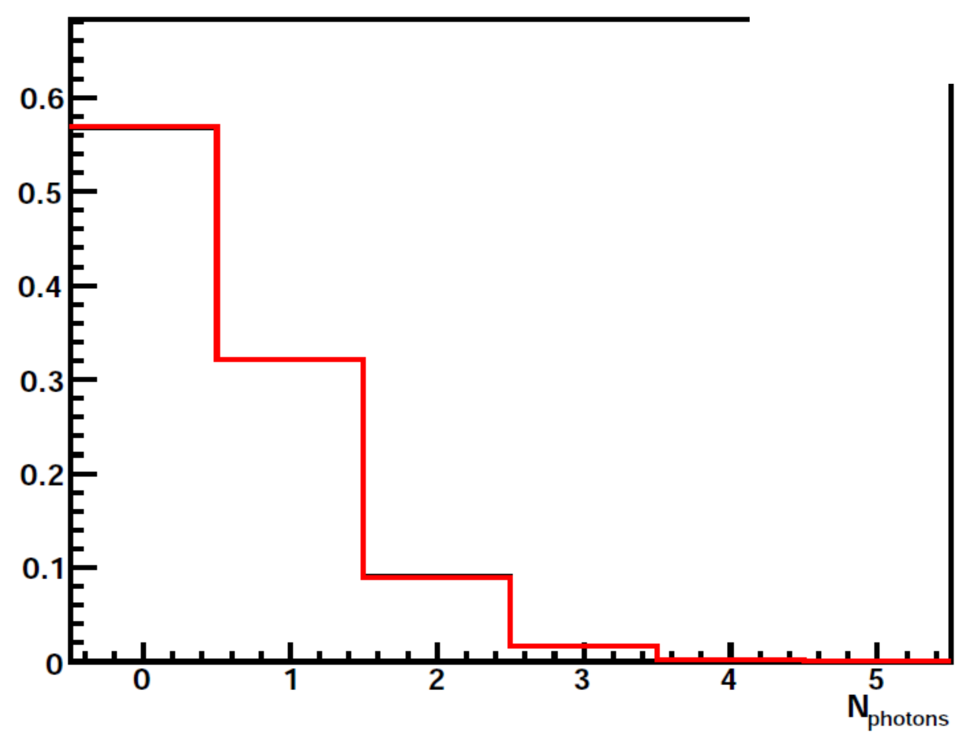


- Generator-level input for W & Z simulation provided by RESBOS (C. Balazs & C.-P. Yuan, PRD56, 5558 (1997) and references therein), which
  - Calculates triple-differential production cross section, and p_T-dependent double-differential decay angular distribution
  - calculates boson p_T spectrum reliably 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)

Validation of QED Calculations

- Extensive comparisons between PHOTOS and HORACE (C.M. Carloni Calame, G. Montagna, O. Nicrosini and A. Vicini, JHEP 0710:109,2007) programs
    - Comparing multi-photon final state radiation algorithms
    - Including multi-photon radiation from all charged lines (HORACE), and consistency with exact one-photon calculation





Validations confirm systematic uncertainty due to QED radiation of 4 MeV

Uncertainties in QED Calculations

- Extensive studies performed on uncertainties arising from
  - leading logarithm approximation
  - Multi-photon calculation
  - higher order soft and virtual corrections
  - Electron-positron pair creation (included at LO)
  - QED/QCD interference
  - dependence on electroweak parameters/scheme

- Total systematic uncertainty due to QED radiation of 4 MeV on W mass

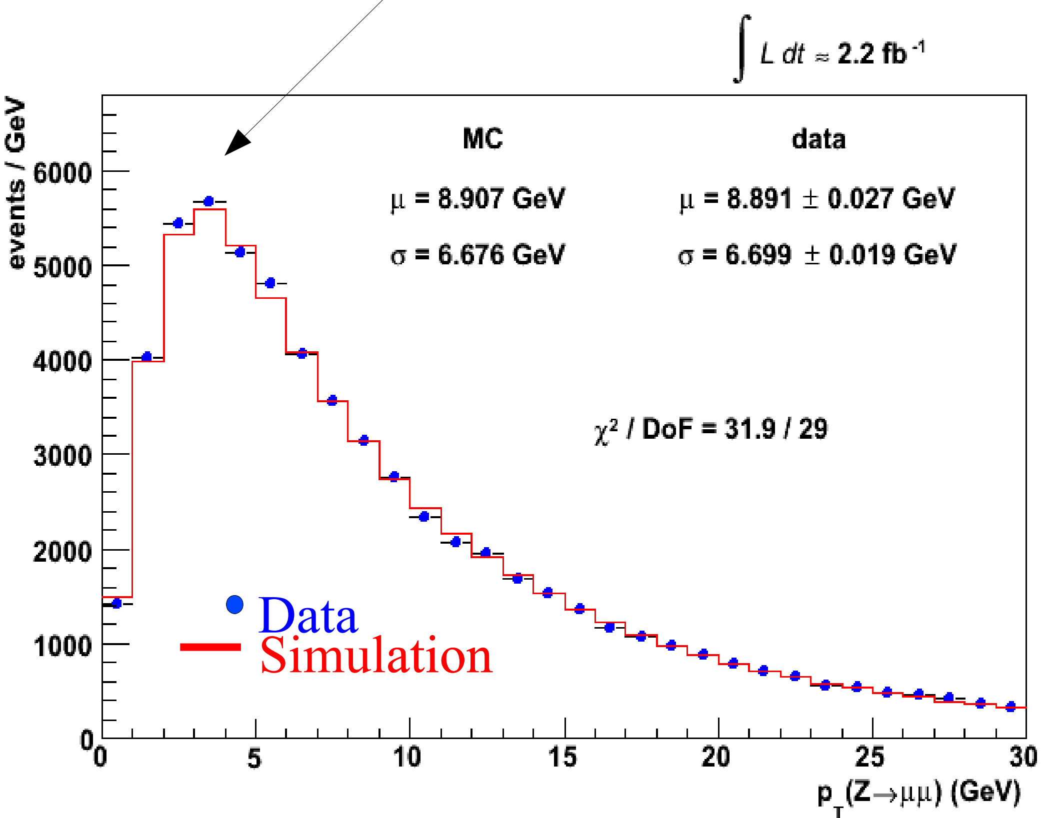
Constraining Boson p_T Spectrum

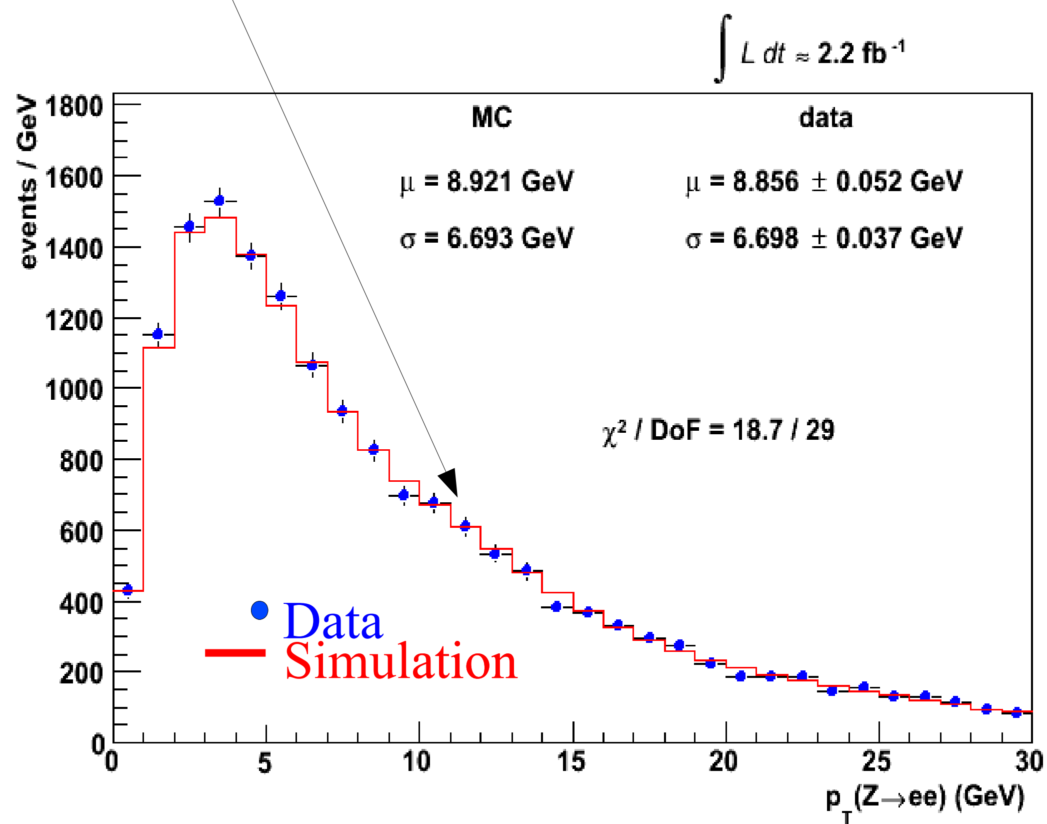
- Fit the non-perturbative parameter g_2 and QCD coupling α_s in RESBOS to $p_T(ll)$ spectra:

ΔM_W = 5 MeV

Position of peak in boson p_T spectrum depends on g_2

Tail to peak ratio depends on α_s





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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

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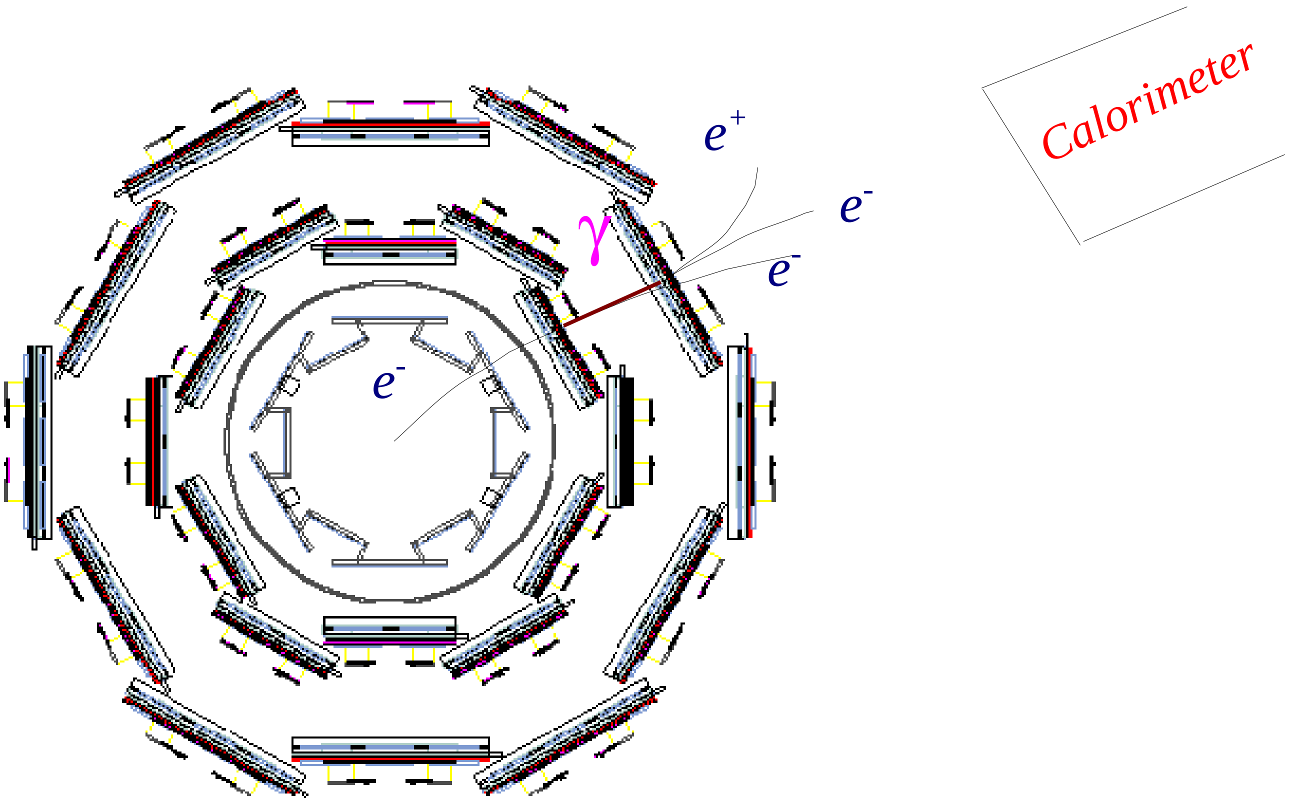
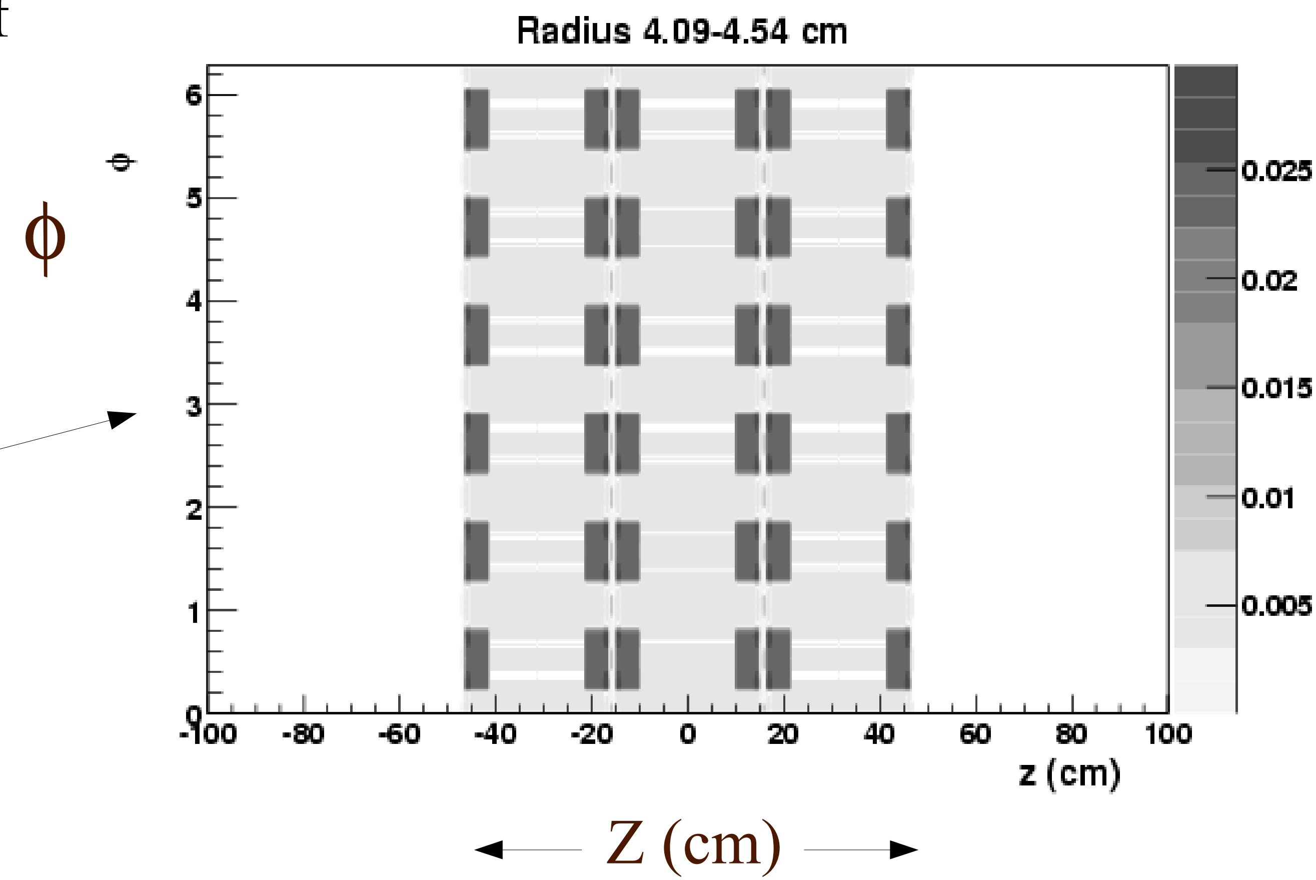


3-D Material Map in Simulation

- 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



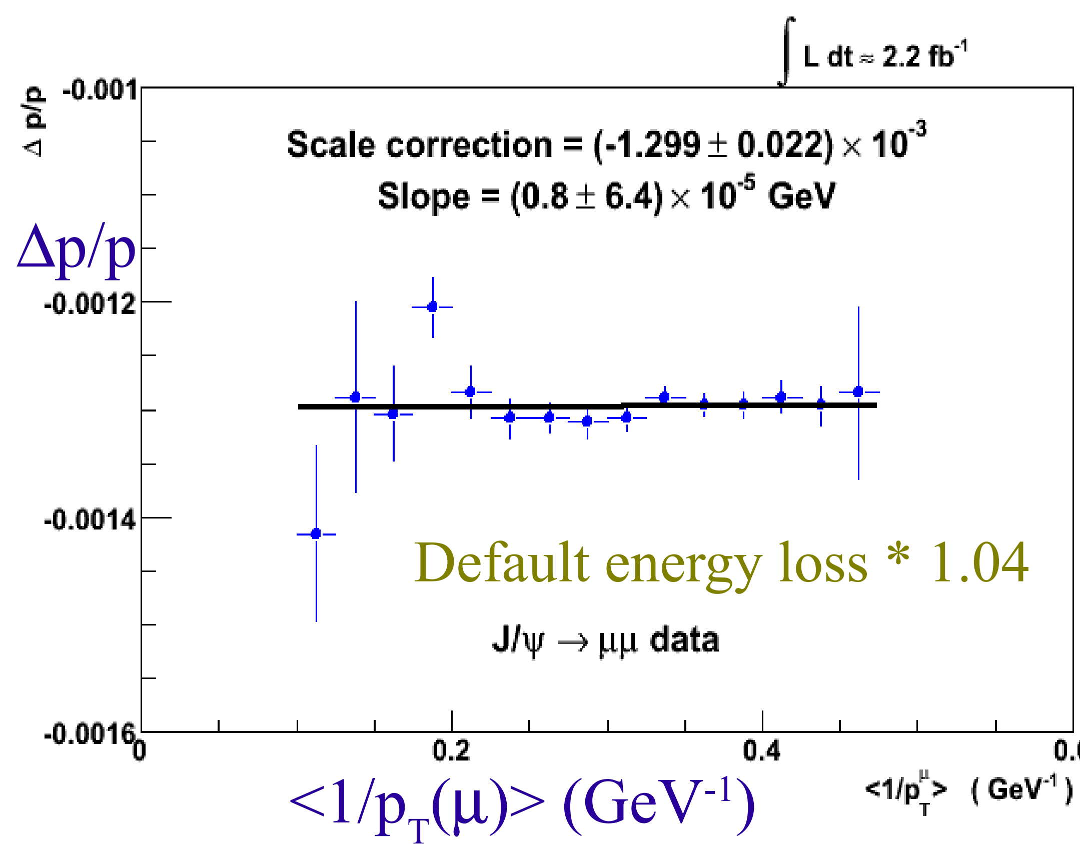
- Include dependence on type of material via Landau-Pomeranchuk-Migdal suppression of soft bremsstrahlung

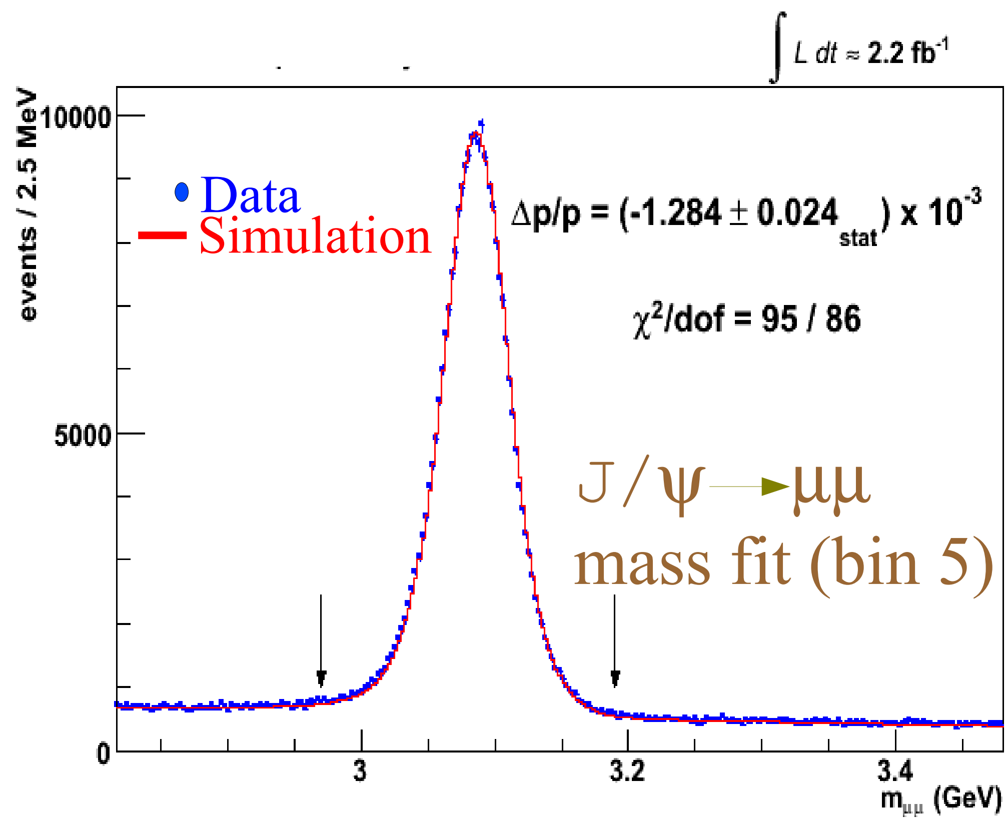
Tracking Momentum Scale

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

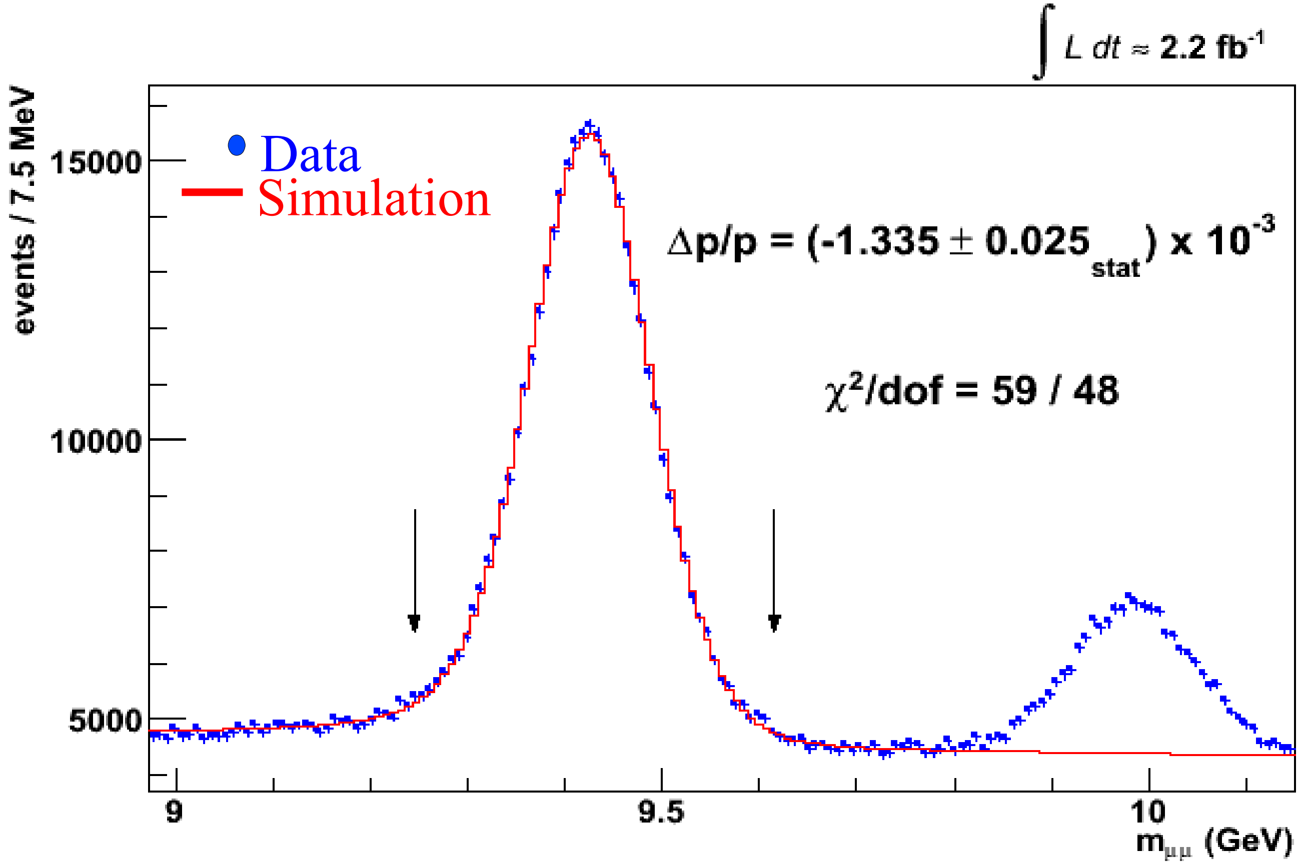




Tracking Momentum Scale

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

- Momentum scale measurement at higher p_T
- 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

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

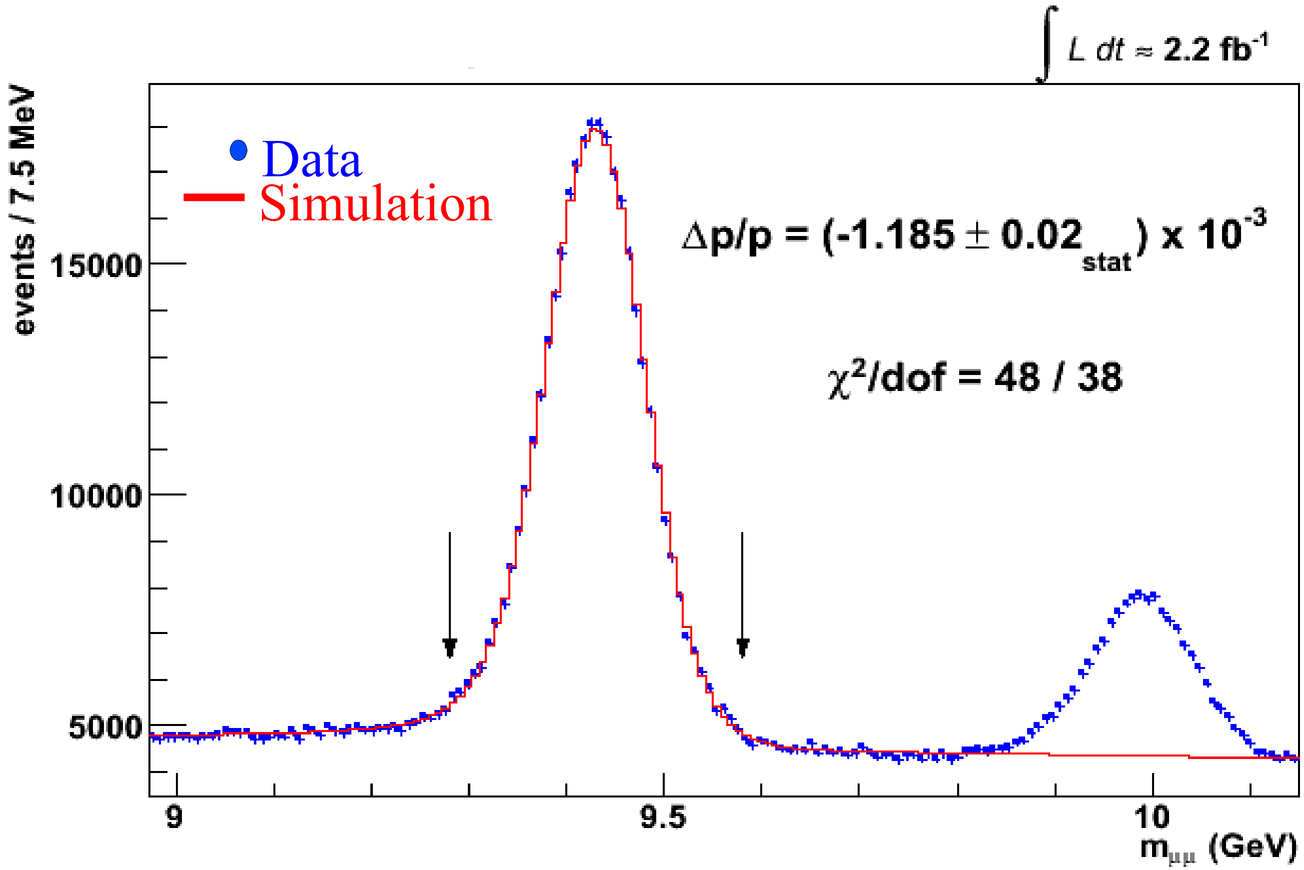
$\Delta M_{W,Z}$ = 6 MeV

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

Tracking Momentum Scale

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

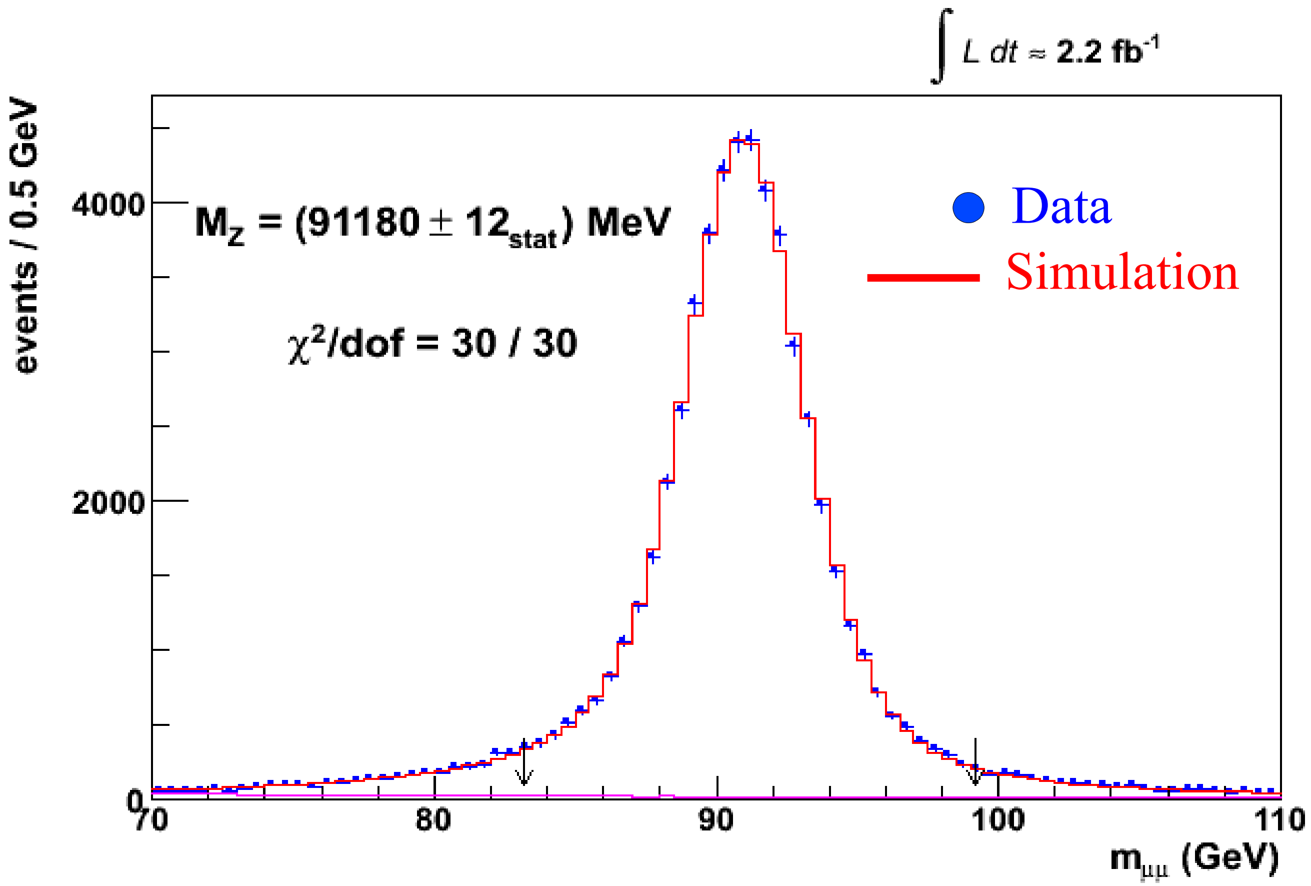
- Cross-check of non-beam-constrained (NBC) and beam-constrained (BC) fits
- Difference used to set additional systematic uncertainty



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

$Z \rightarrow \mu\mu$ 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

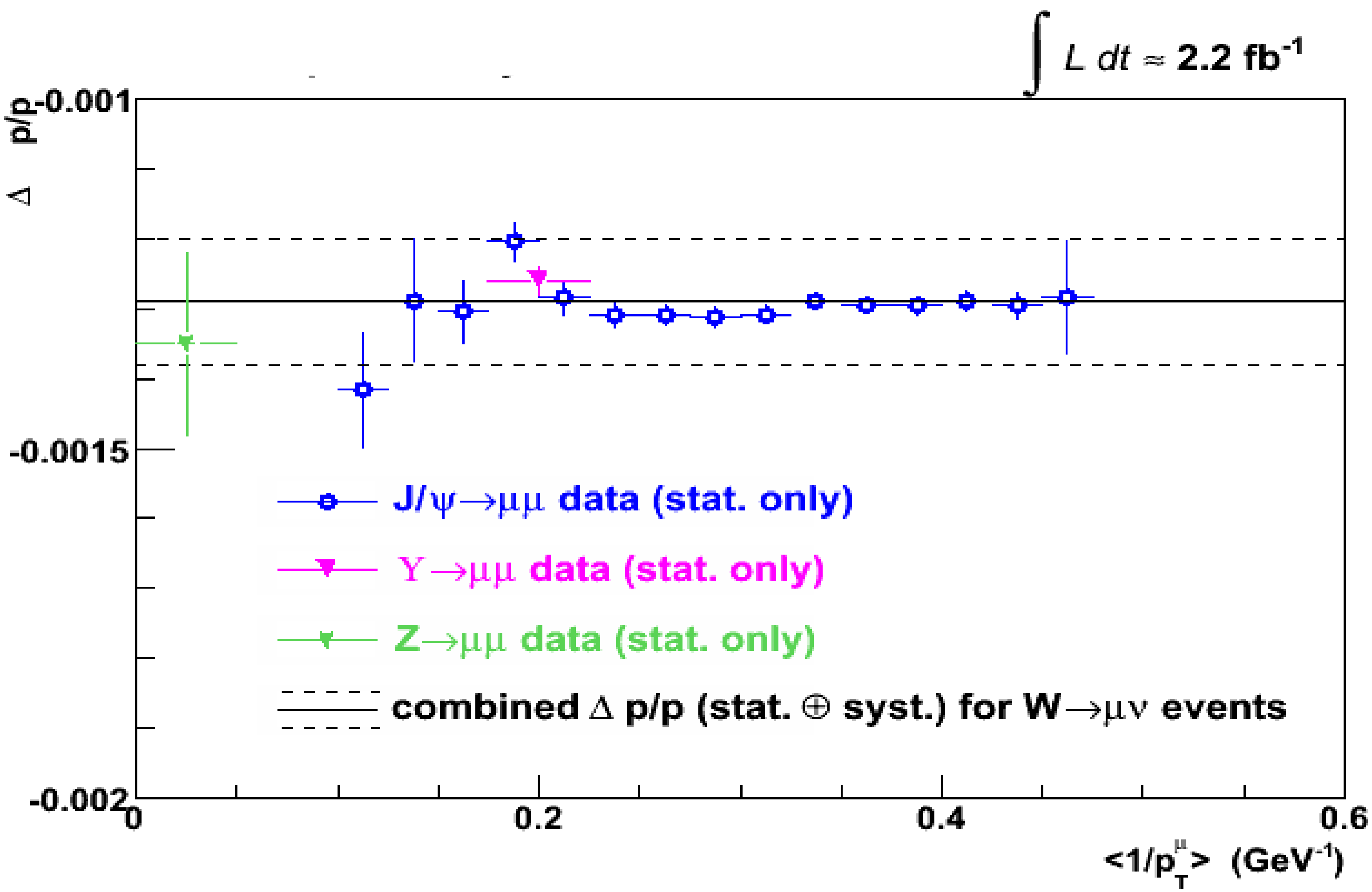


M(μμ) (GeV)

Tracker Linearity Cross-check & Combination

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

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

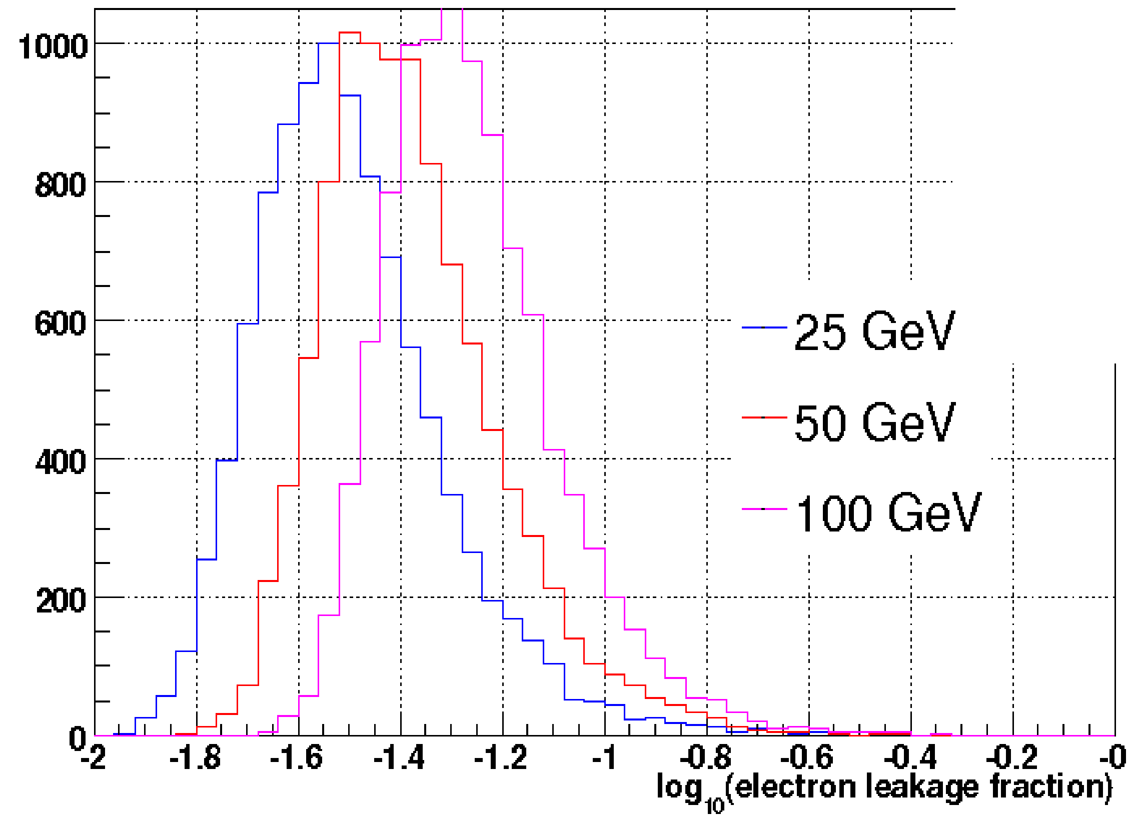


ΔM_W = 7 MeV

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



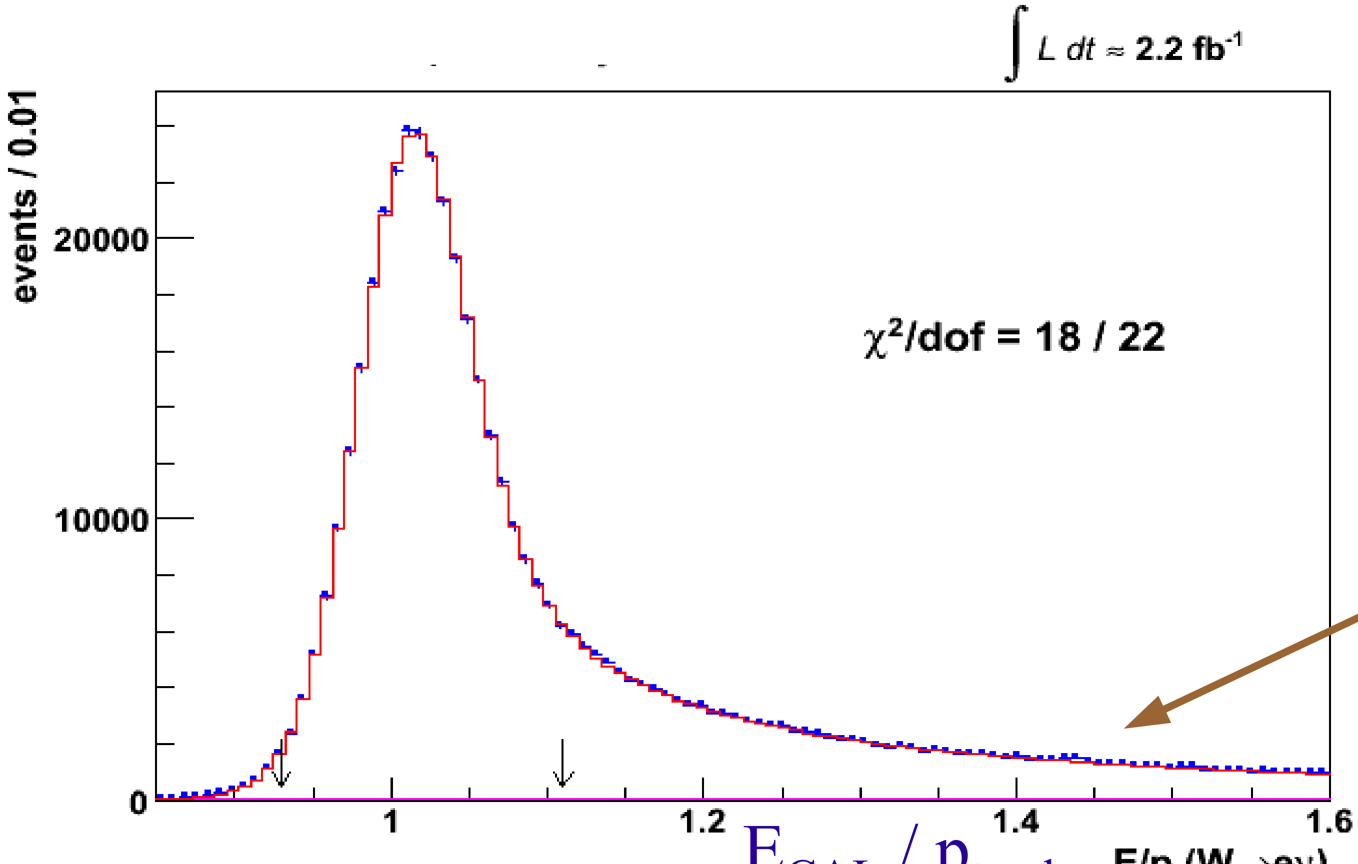
- Energy-dependent gain (non-linearity) parameterized and fit from data
- Energy resolution parameterized as fixed sampling term and tunable constant term
  - Constant terms are fit from the width of E/p peak and $Z \rightarrow ee$ mass peak

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}

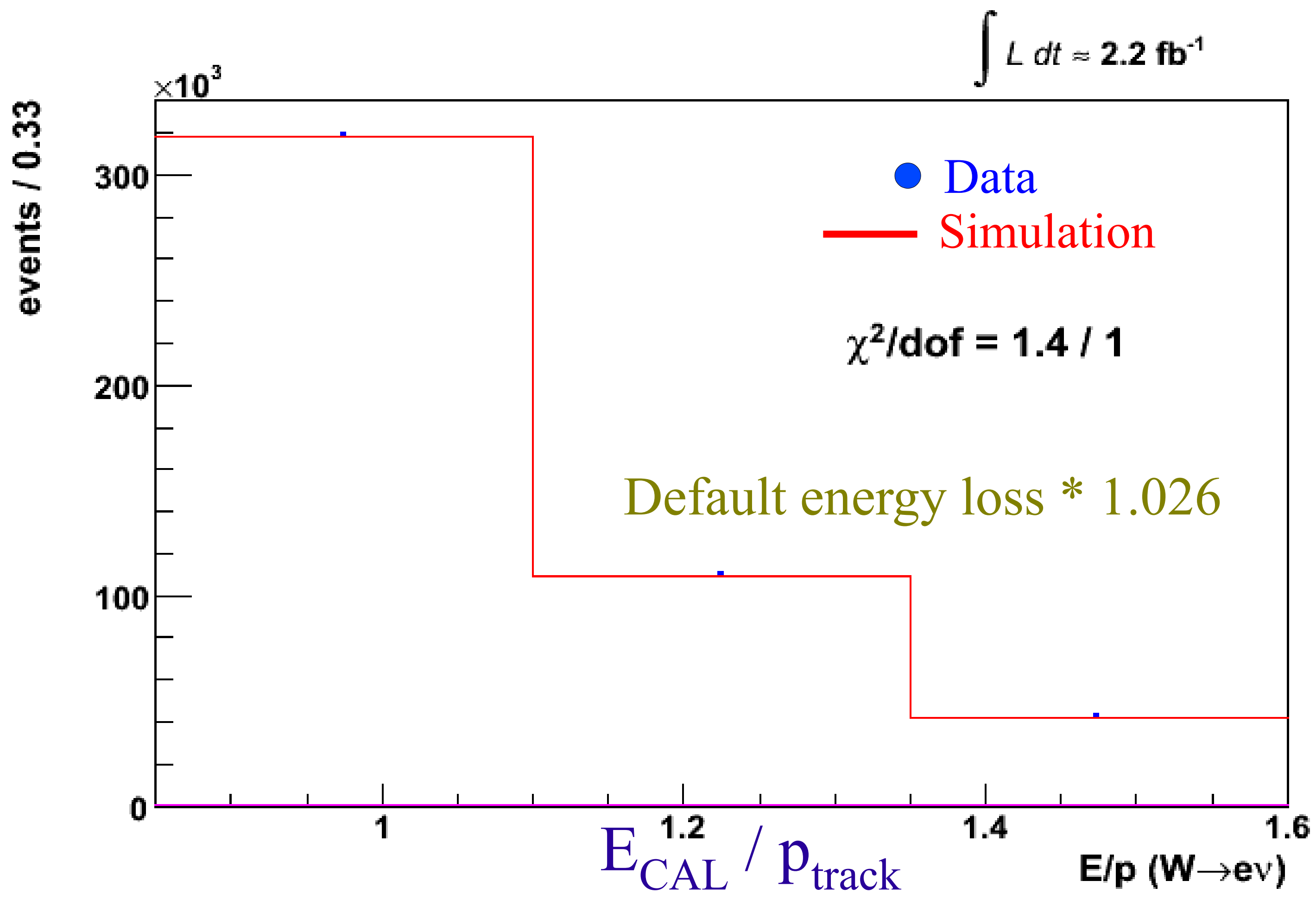
$\Delta M_W = 13$ MeV

- Data
- Simulation

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

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



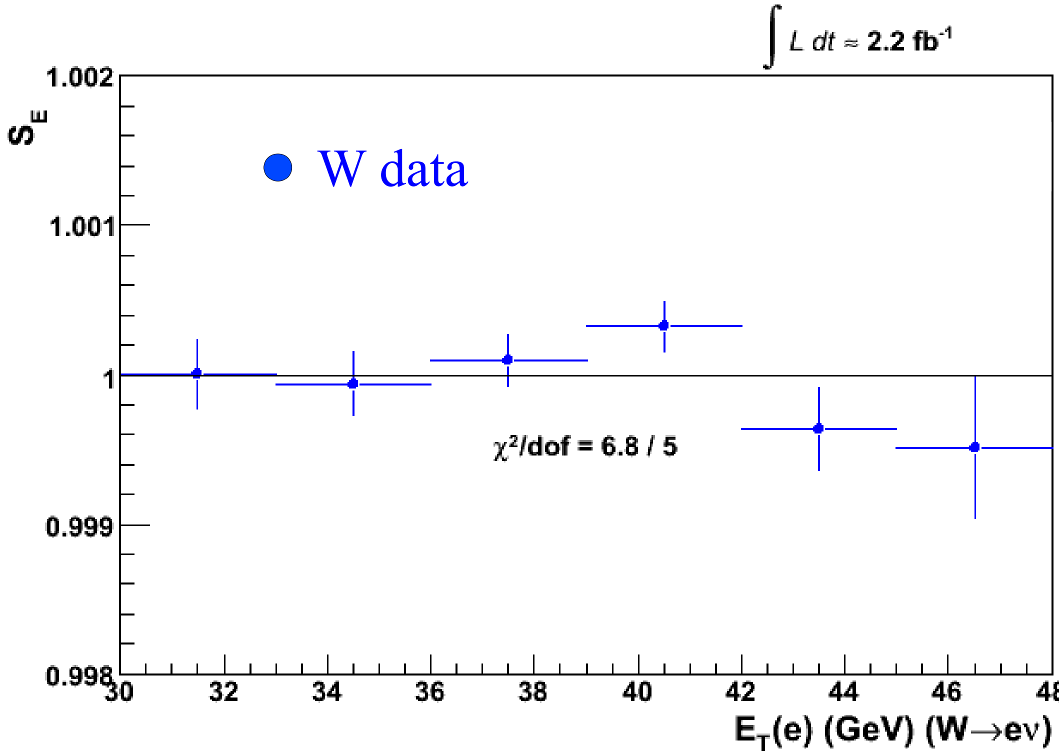
Measurement of EM Calorimeter Non-linearity

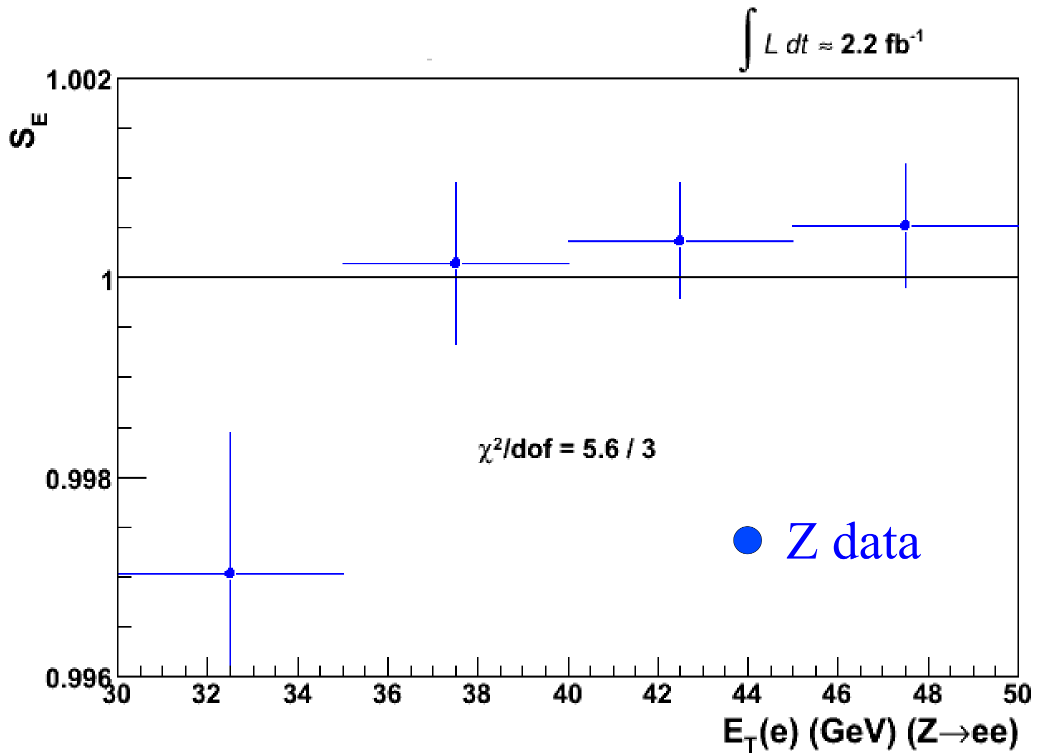
- Perform E/p fit-based calibration in bins of electron E_T
- GEANT-motivated parameterization of non-linear response:

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

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

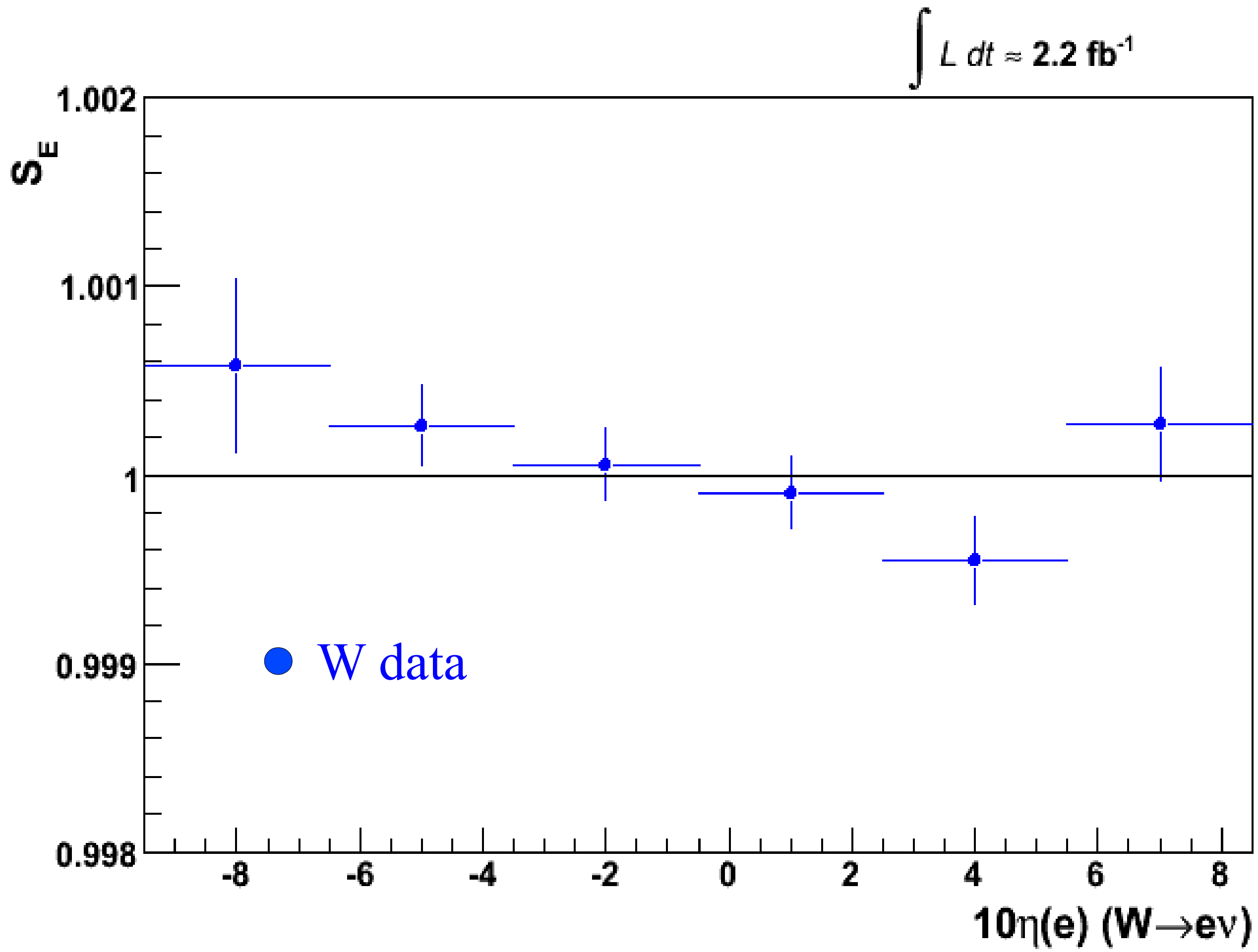
$\Rightarrow \Delta M_W = 4$ MeV





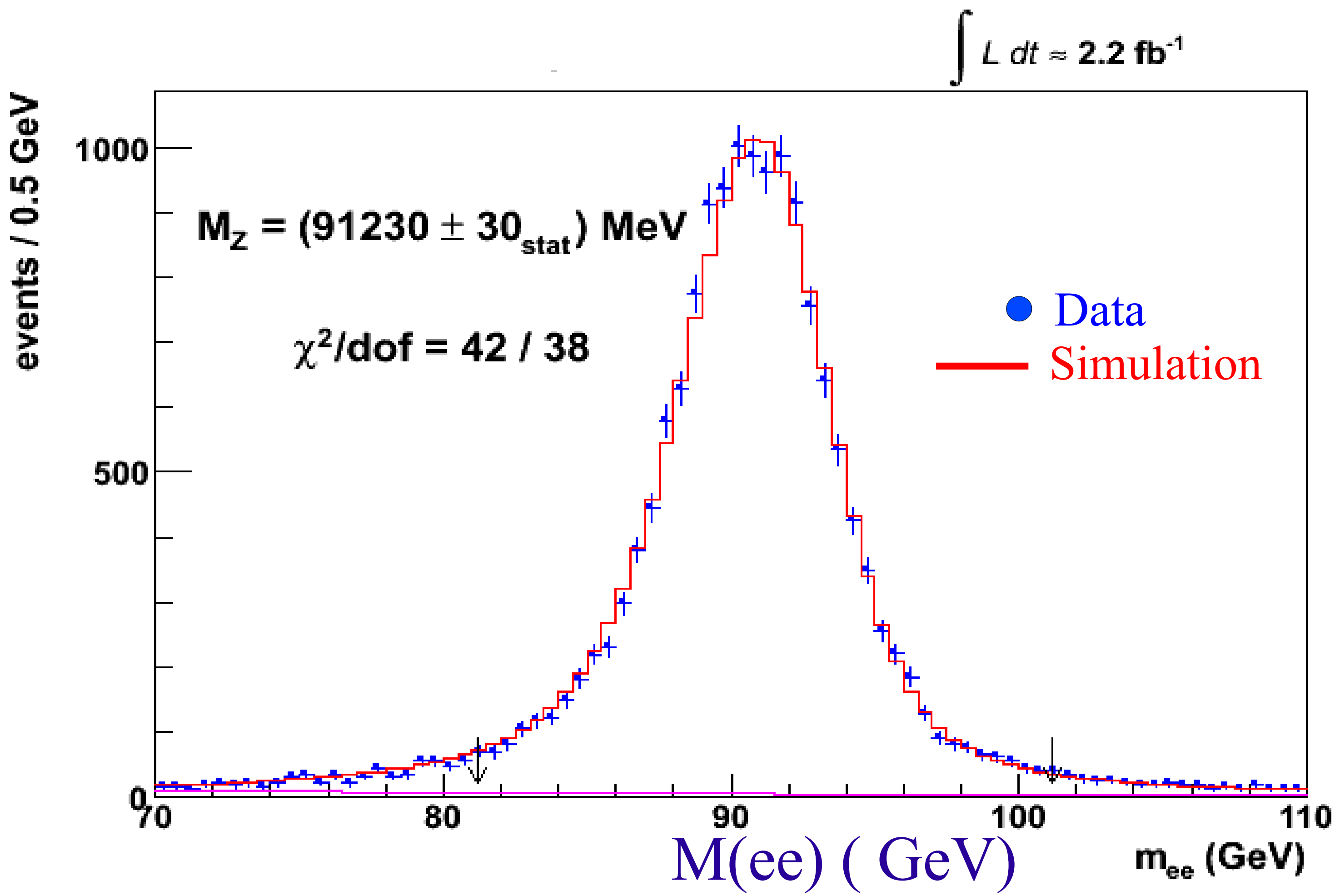
EM Calorimeter Uniformity

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



$Z \rightarrow ee$ 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

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 $Z \rightarrow \mu\mu$ (beam-constrained) and $\Upsilon \rightarrow \mu\mu$ (both beam constrained and non-beam constrained) mass peaks

=> ΔM_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)

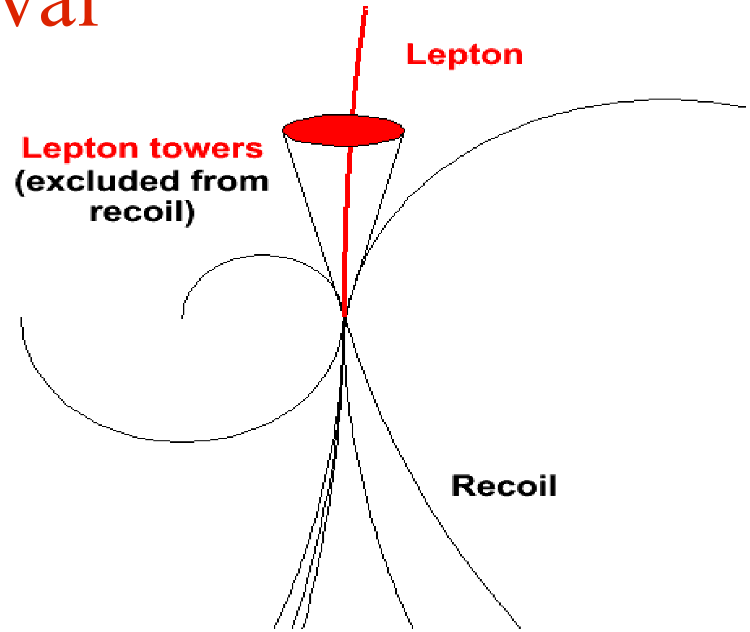
=> ΔM_W = 4 MeV (electrons)

Hadronic Recoil Model

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 Δη \ Tower Δφ	-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

η ϕ

Muon channel W data

Muon Hadronic E_T (MeV)

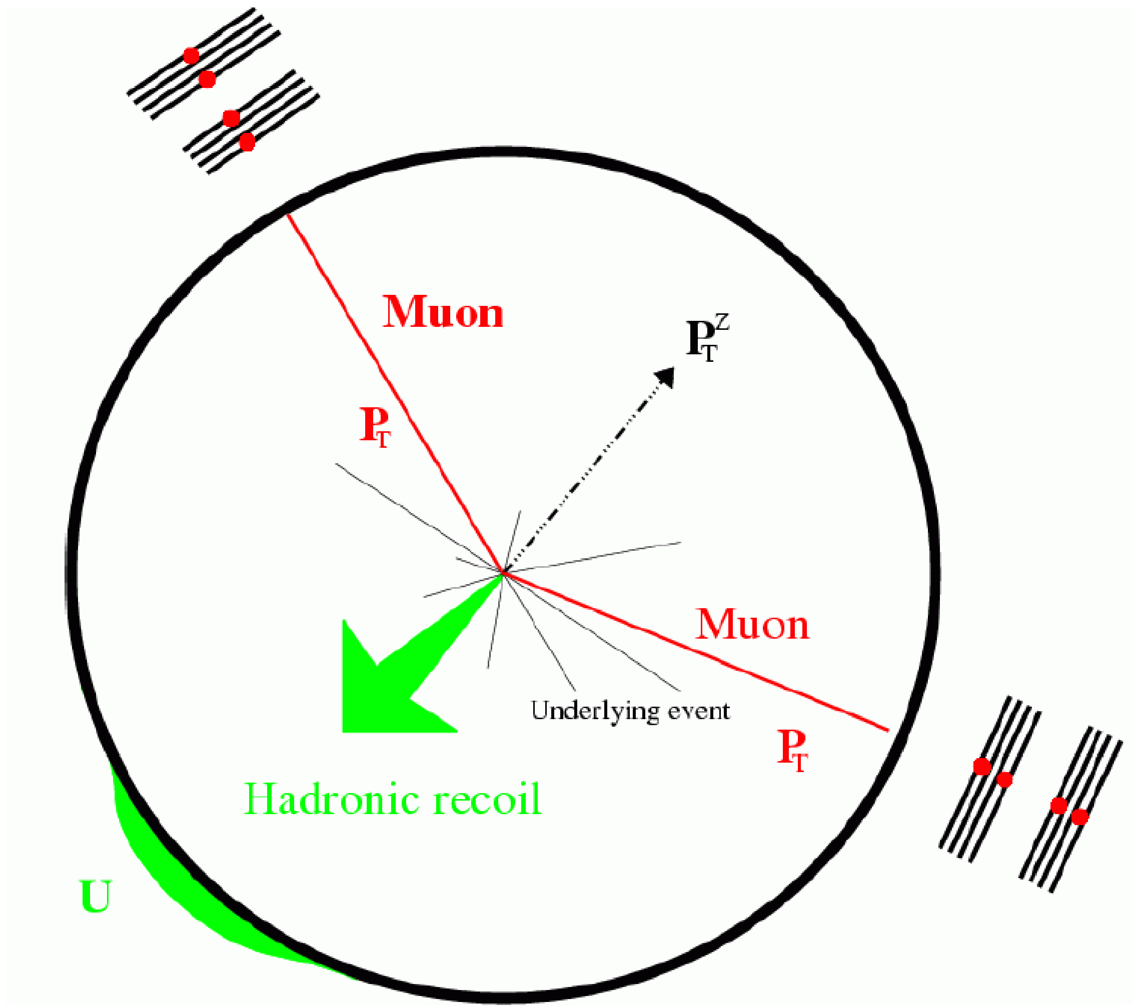
Tower Δη \ Tower Δφ	-3	-2	-1	0	1	2	3
3	12	12	12	12	12	12	12
2	12	12	12	13	12	11	12
1	12	12	12	406	13	12	12
0	12	12	12	1282	14	12	12
-1	12	12	12	75	12	12	12
-2	12	12	11	12	12	11	11
-3	12	12	12	12	12	12	12

η ϕ

Constraining the Hadronic Recoil Model

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

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

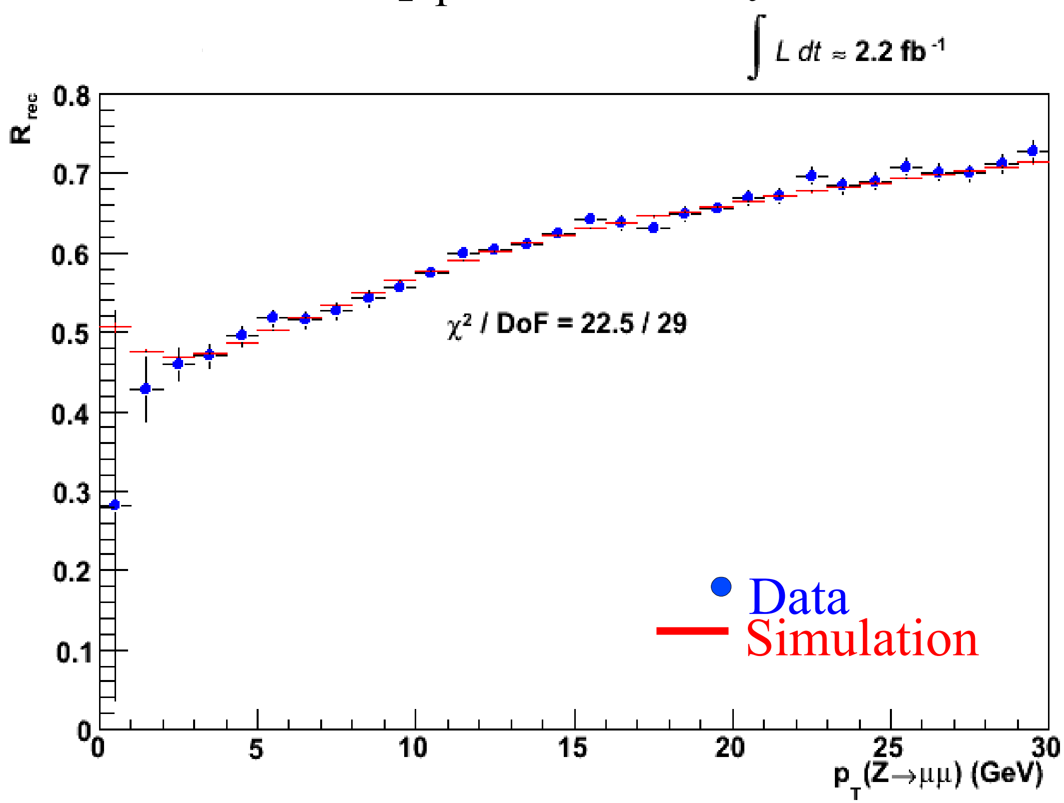


Transverse momentum of Hadronic recoil (***u***) calculated as 2-vector-sum over calorimeter towers

Hadronic Recoil Simulation

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

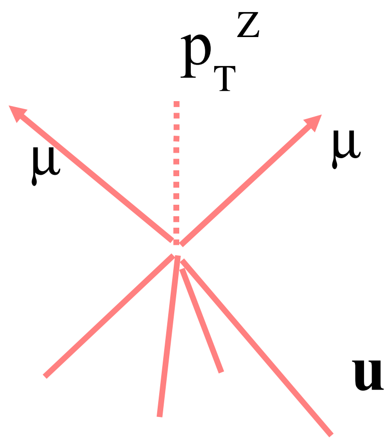
- a soft 'spectator interaction' component, randomly oriented
  - Modelled using minimum-bias data with tunable magnitude
- A hard 'jet' component, directed opposite the boson p_T
  - P_T-dependent response and resolution parameterizations
  - Hadronic response $R = \boldsymbol{u}_{\text{reconstructed}}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

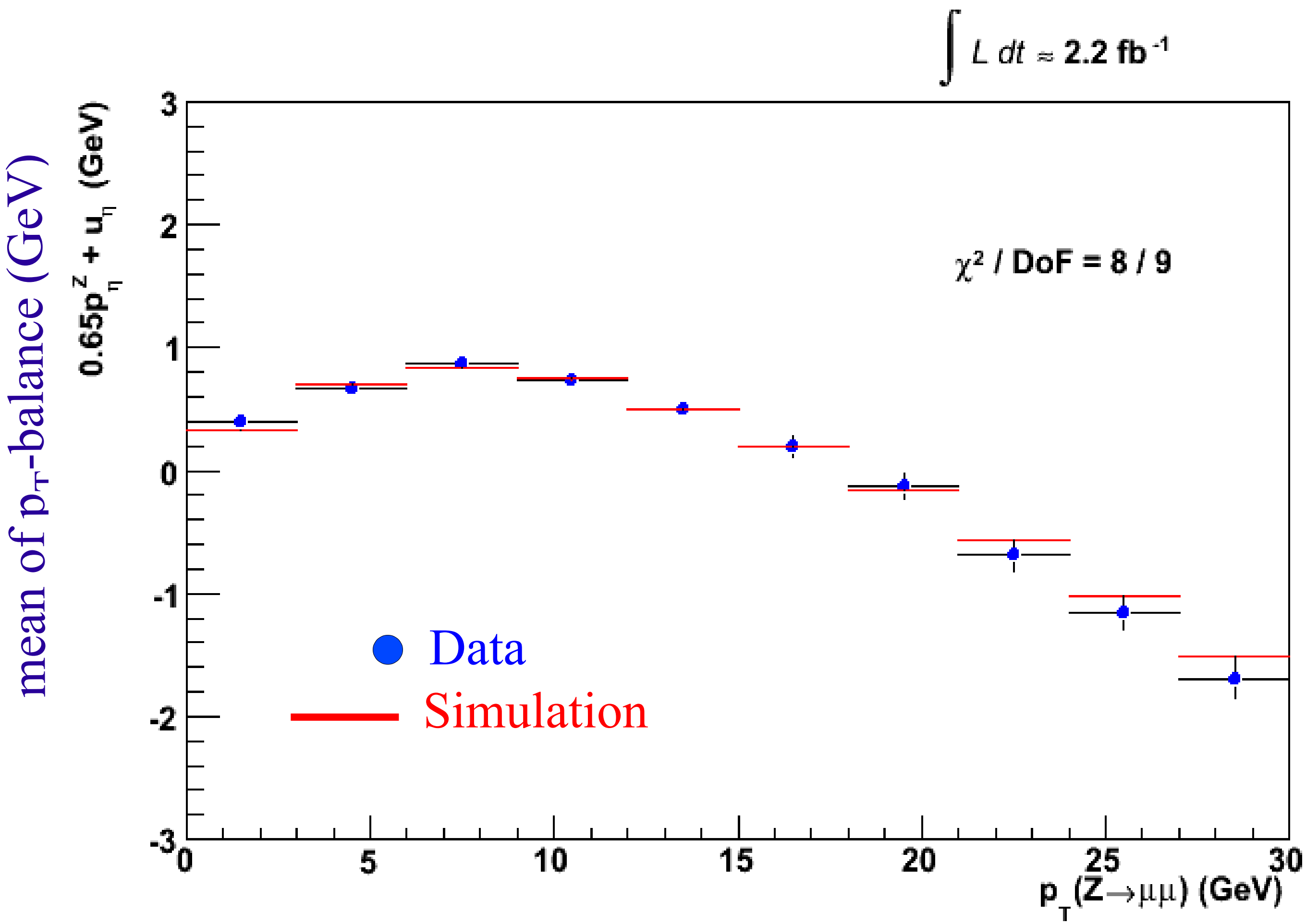


Tuning Recoil Response Model with *Z* events

Project the vector sum of $p_T(ll)$ and ***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





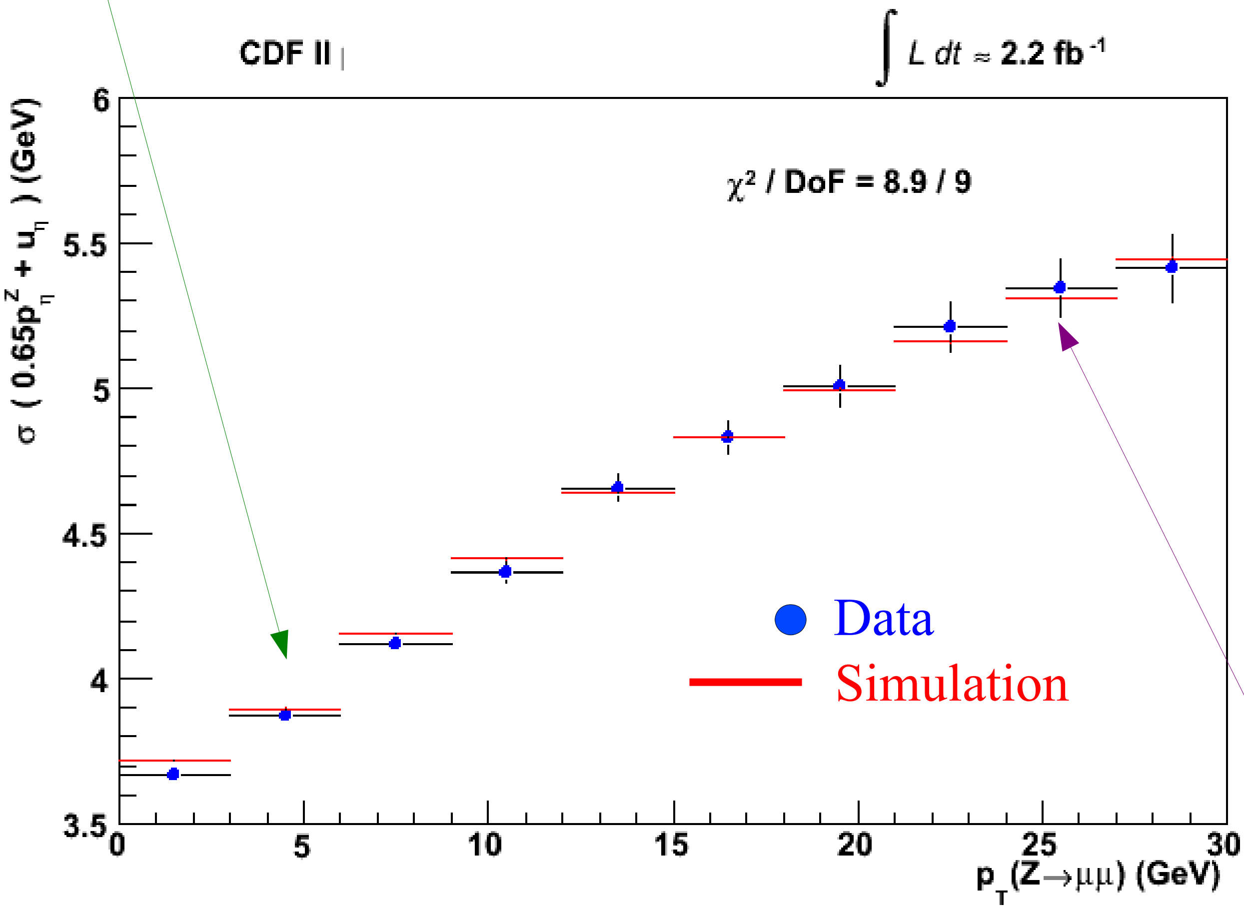
Hadronic model parameters tuned by minimizing χ^2 between data and simulation

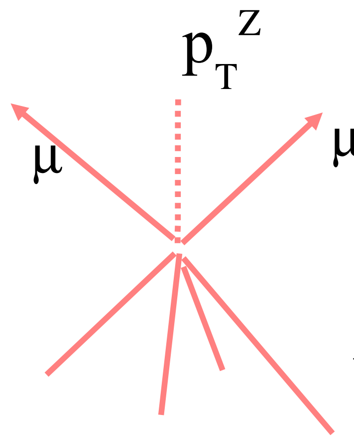
$\Delta M_W = 4$ MeV

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)



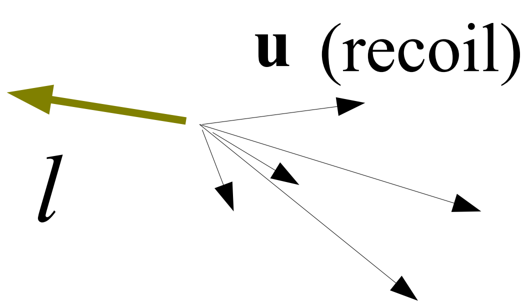


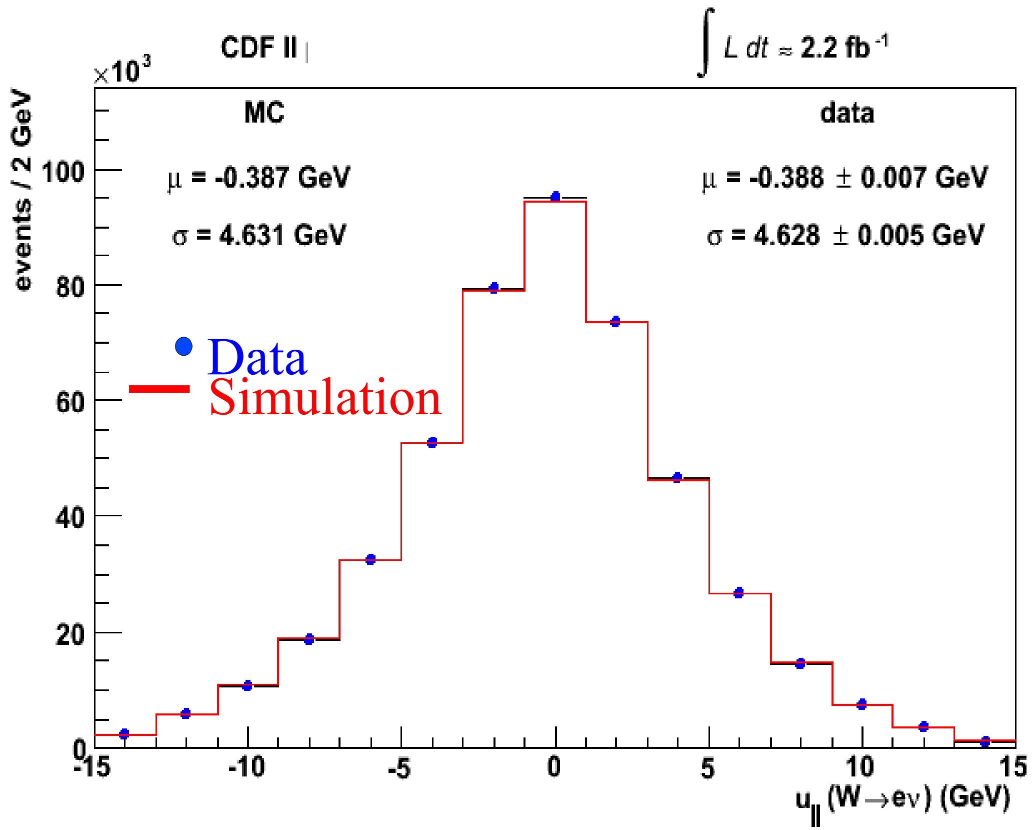
ΔM_W = 4 MeV

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

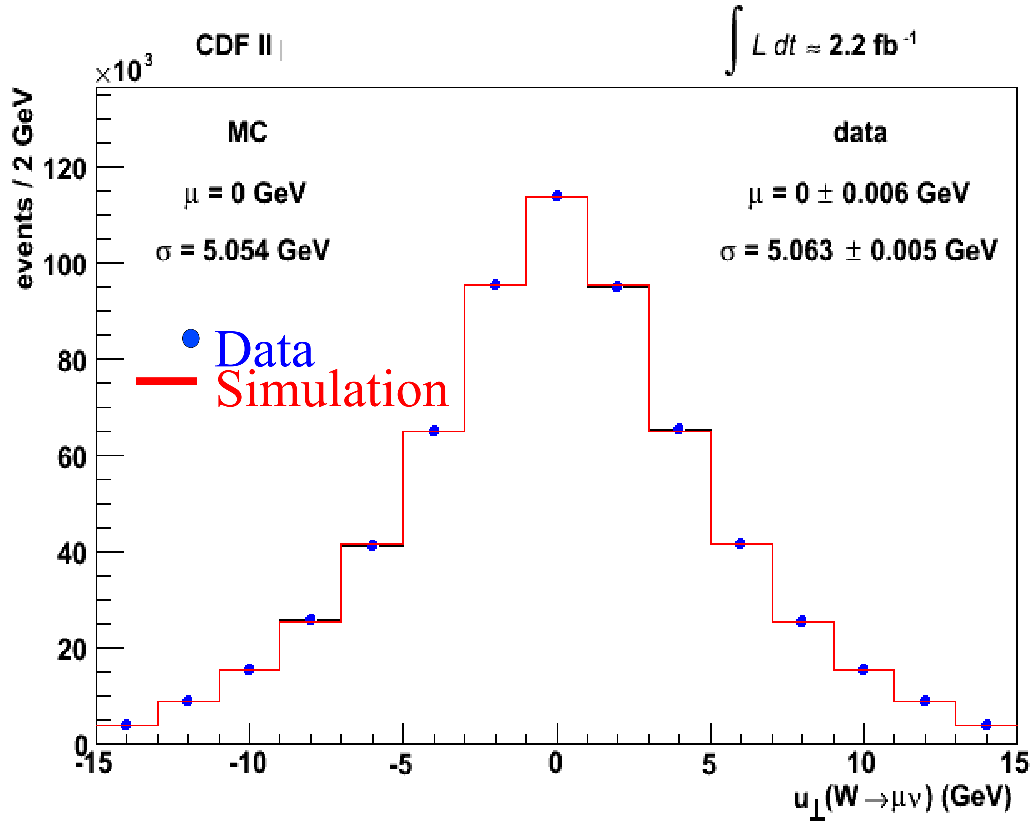
Testing Hadronic Recoil Model with *W* events

Compare recoil distributions between simulation and data





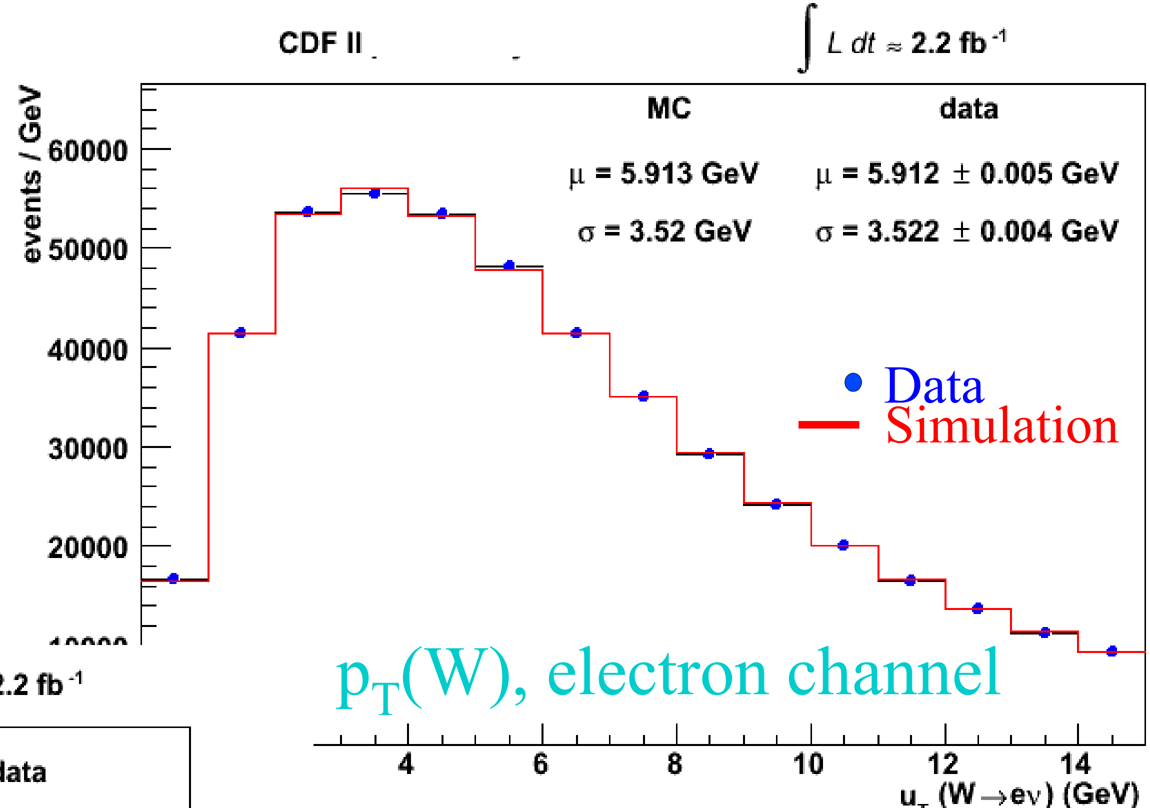
Recoil projection (GeV) on lepton direction

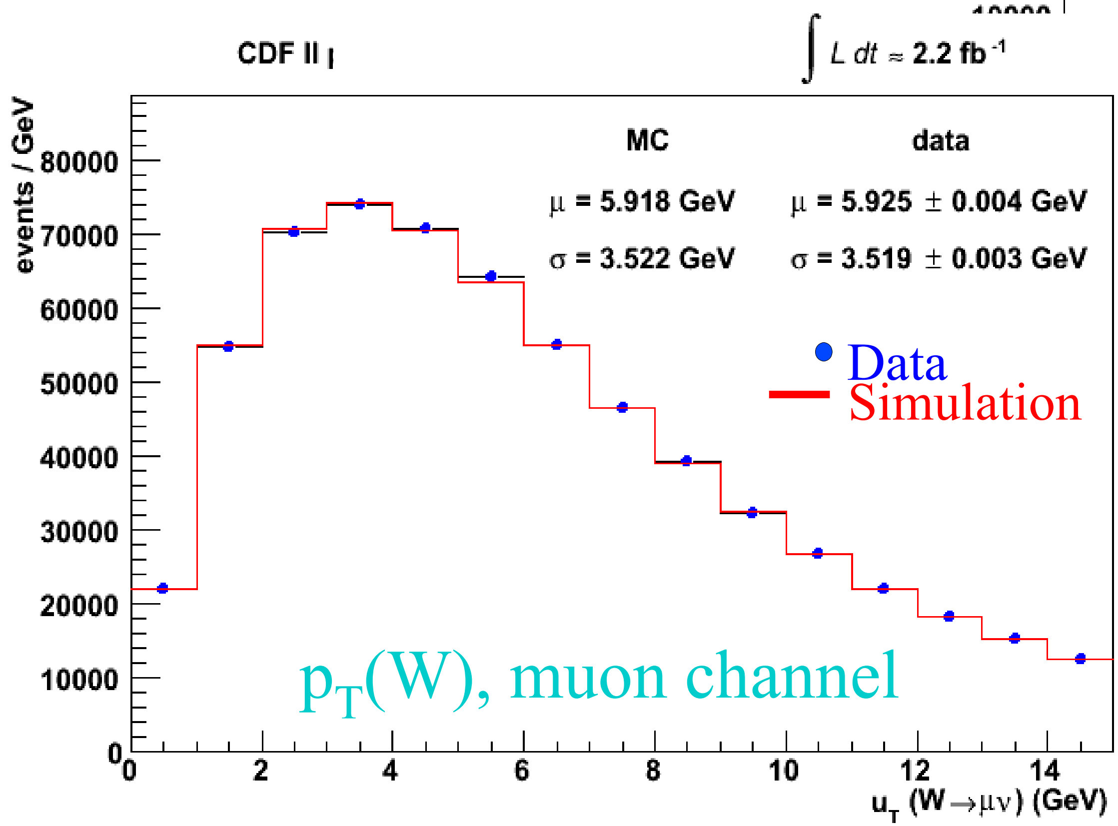


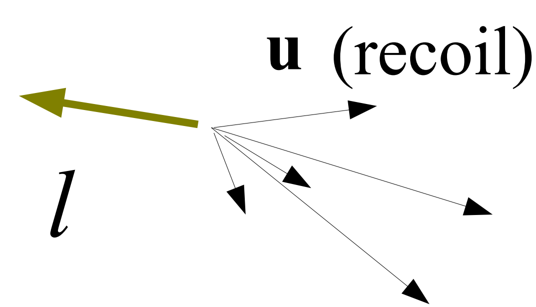
Recoil projection (GeV) perpendicular to lepton

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
- 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

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

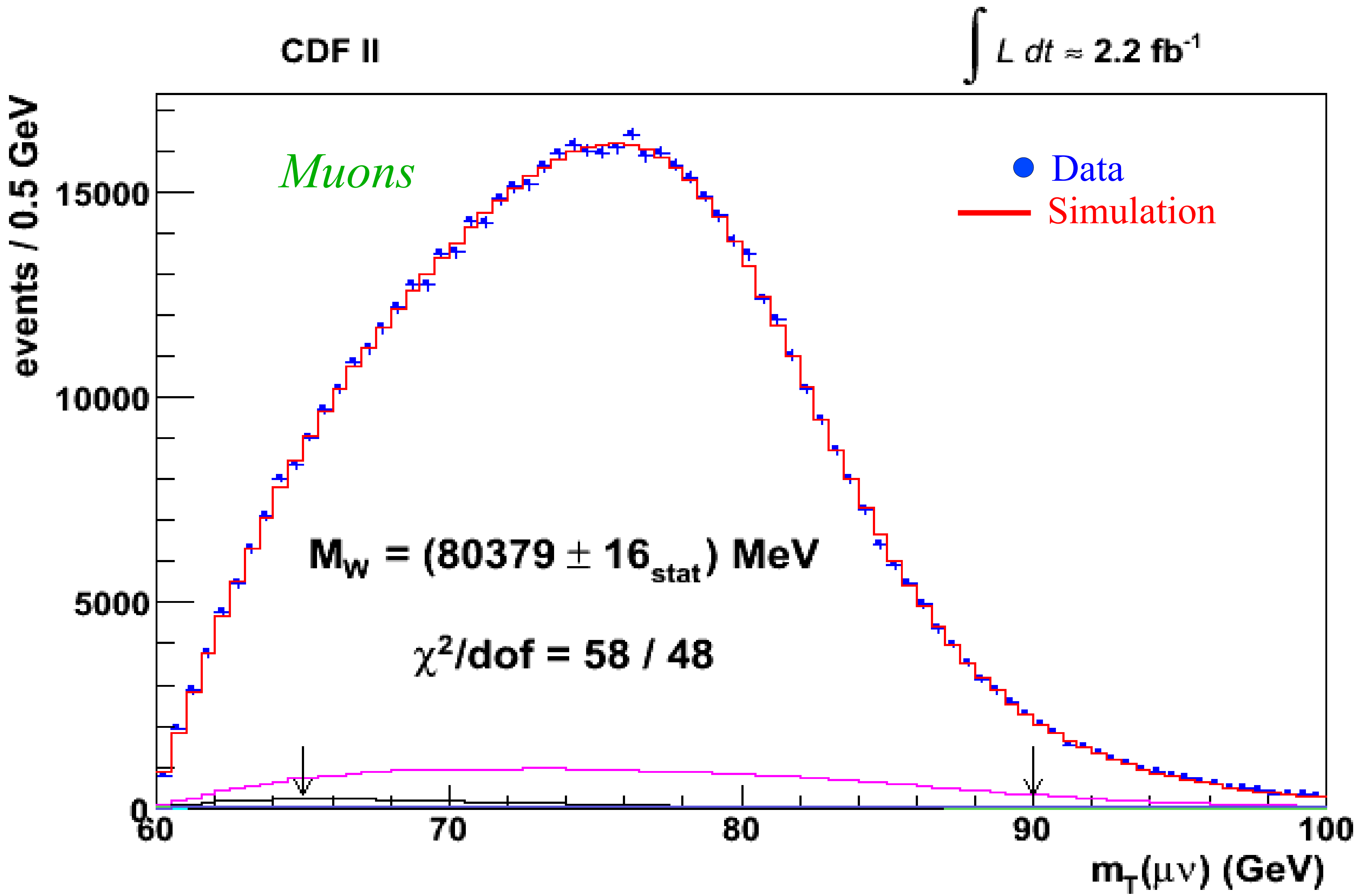
Backgrounds are small (except $Z \to \mu\mu$ with a forward muon)

W Mass Fits

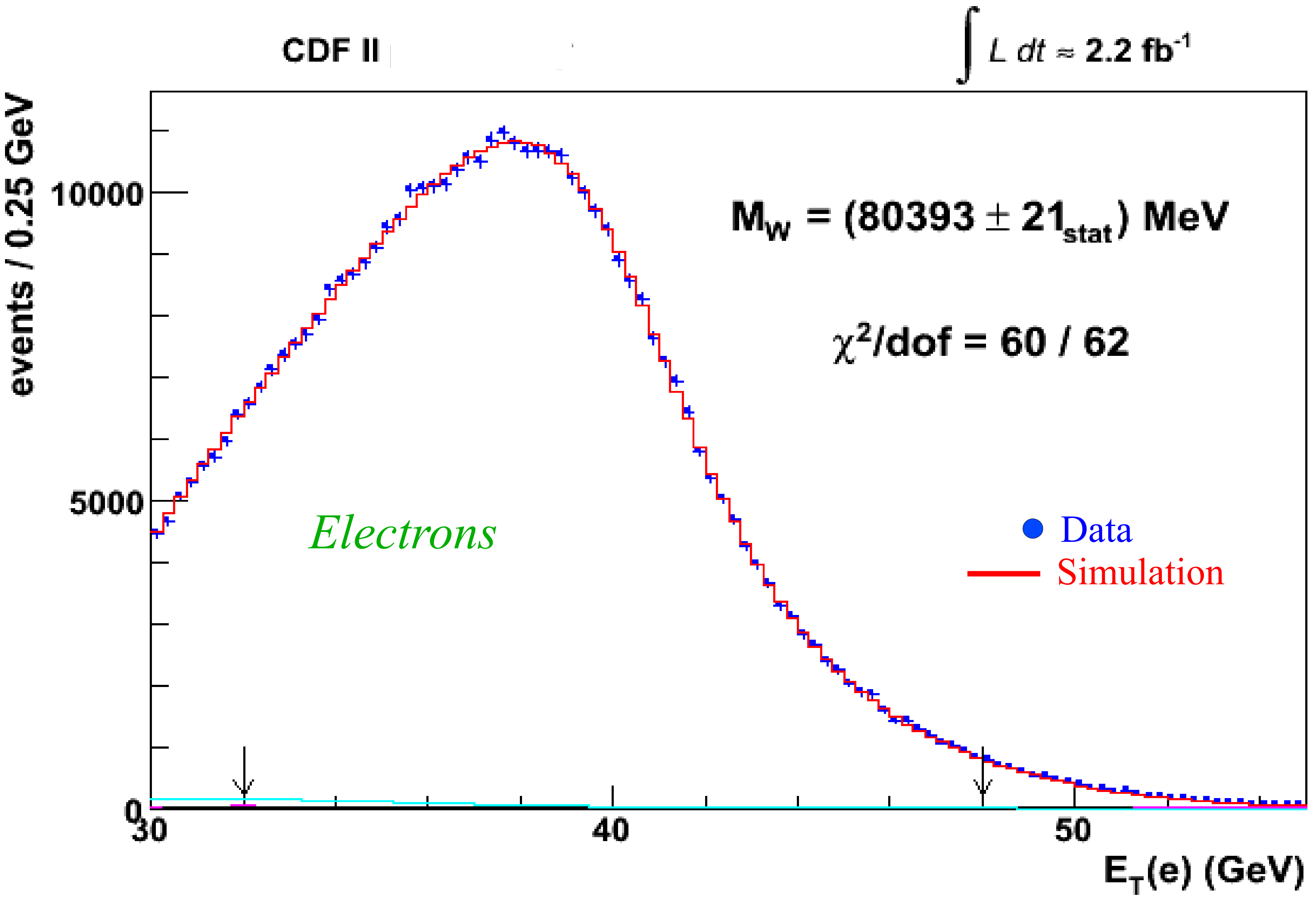
Blind Analysis Technique

- 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

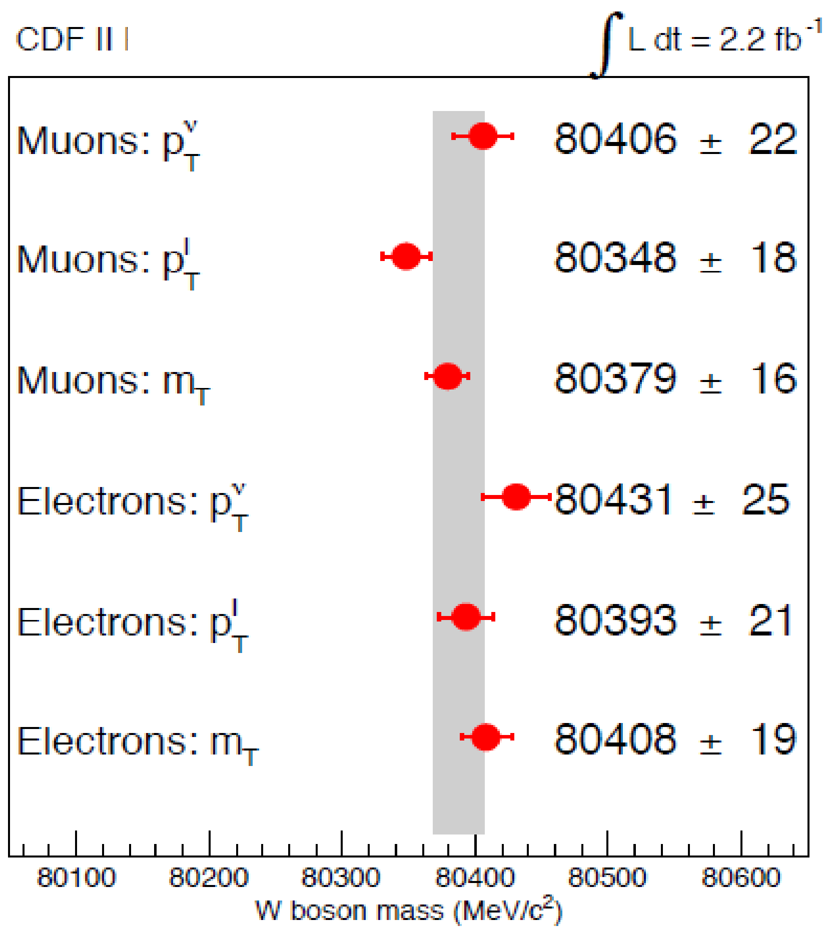


W Mass Fit using Lepton p_T



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	$82/62$



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, $P(\chi^2) = 25\%$

Previous CDF Result (200 pb^{-1})
Transverse Mass Fit Uncertainties (MeV)

	electrons	*muons*	*common*
W statistics	48	54	0
Lepton energy scale	30	17	17
Lepton resolution	9	3	-3
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
Selection bias	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
pT(W) model	3	3	3
Parton dist. Functions	11	11	11
QED rad. Corrections	11	12	11
Total systematic	39	27	26
Total	62	60	

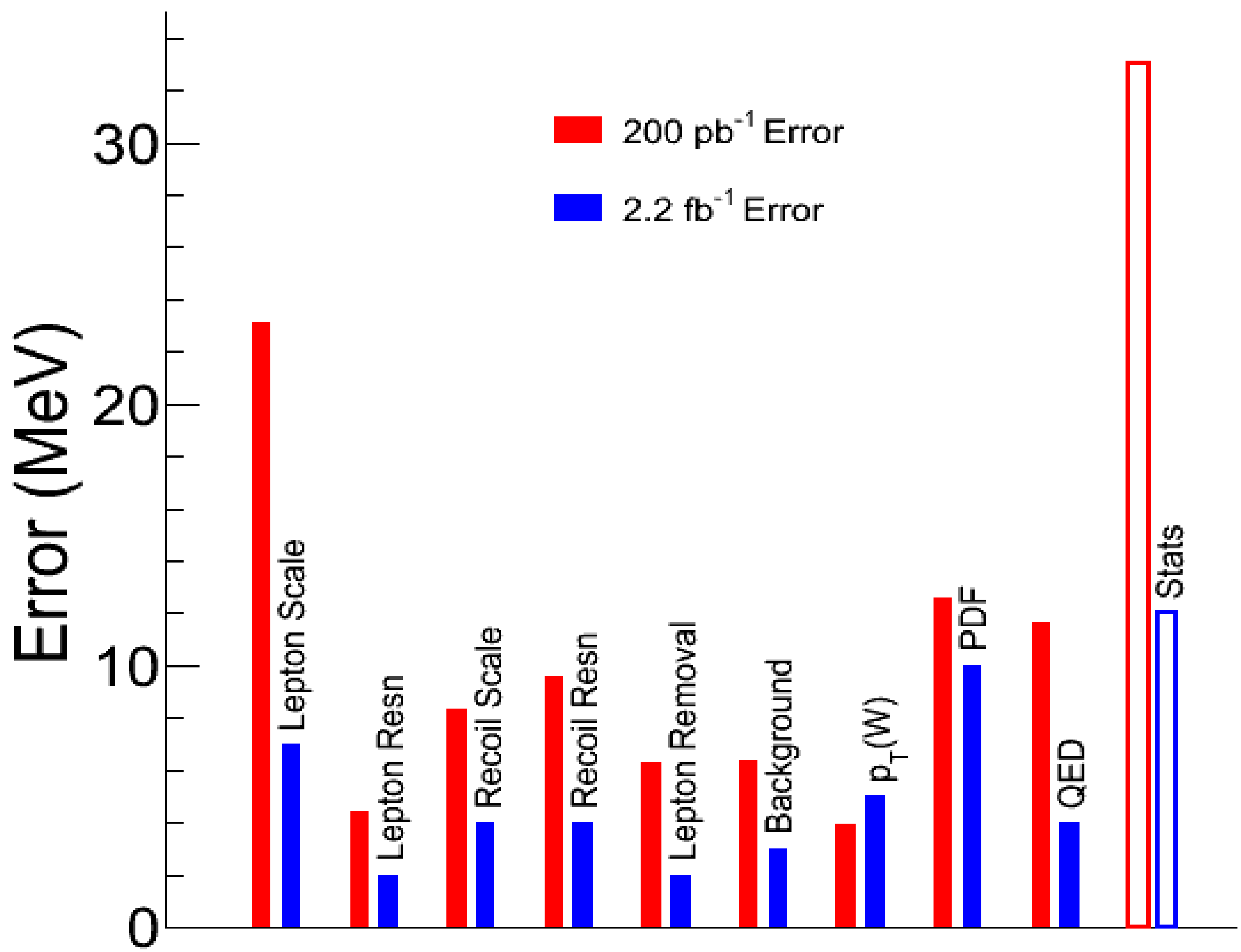
Systematic uncertainties shown in green: statistics-limited by control data samples

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

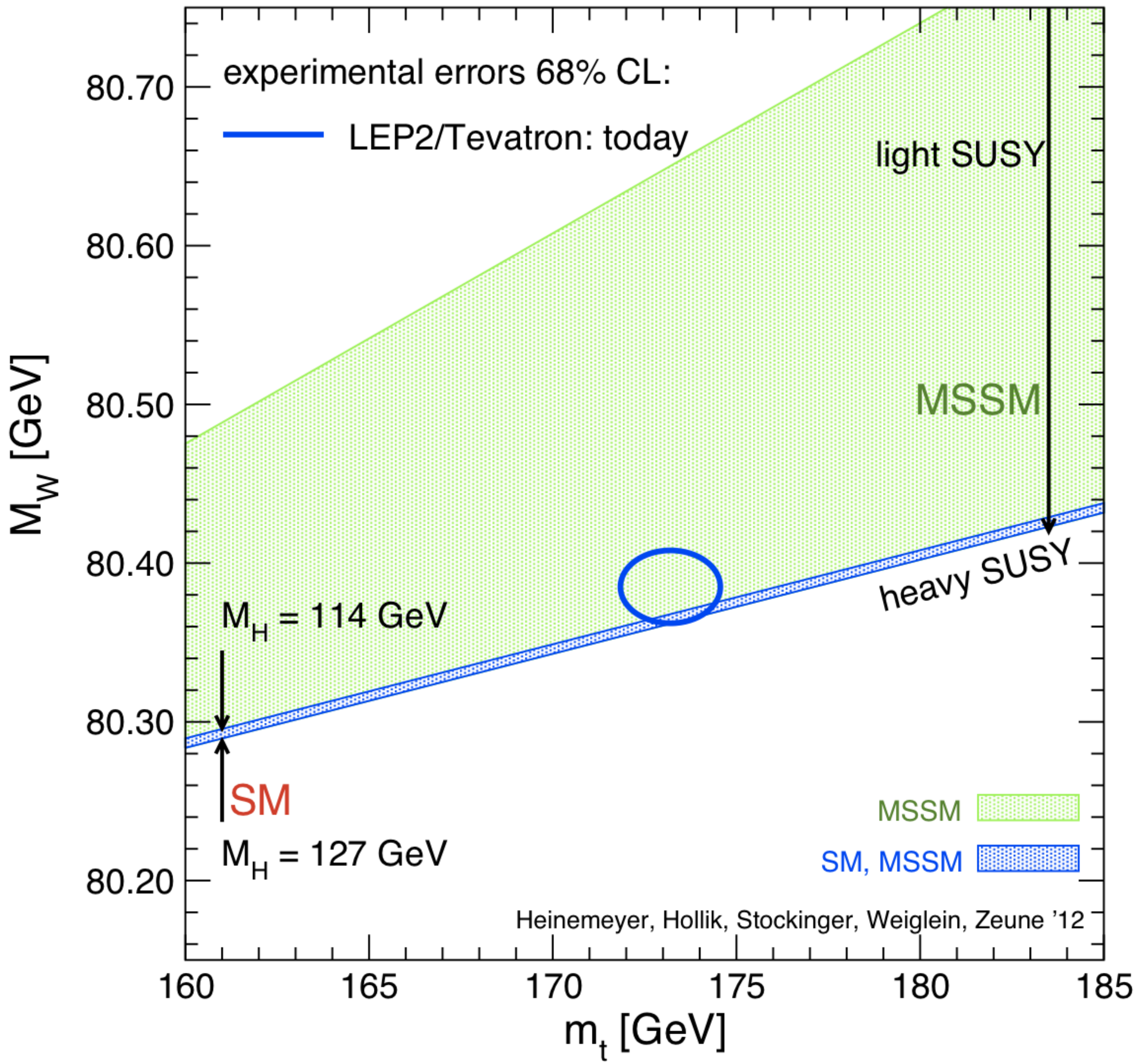
	electrons	*muons*	*common*
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total systematic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

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

Combined W Mass Result, Error Scaling



2012 Status of M_W *vs* M_{top}



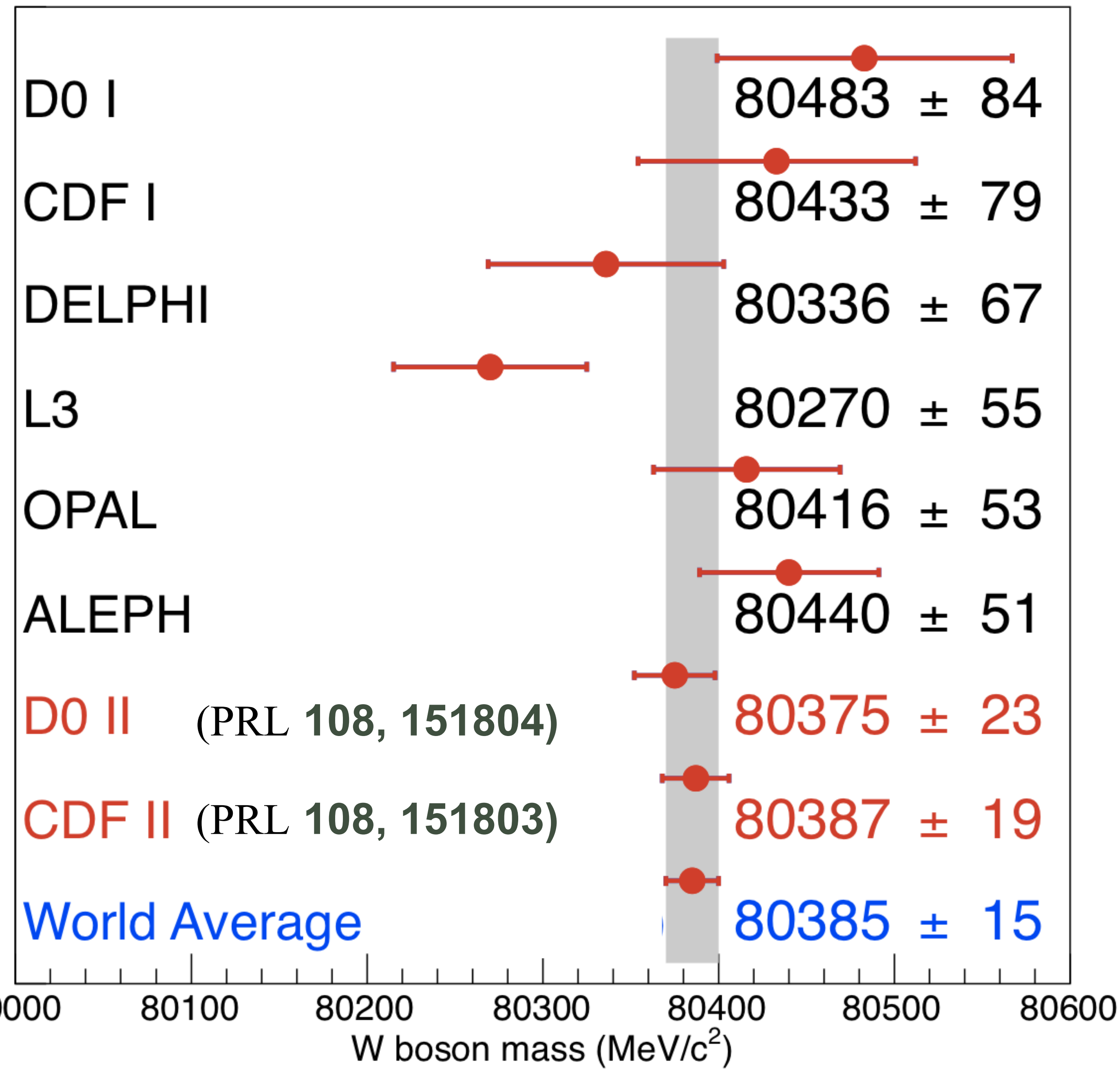
W Boson Mass Measurements from Different Experiments

World average computed by TeVEWWG ArXiv: 1204.0042

5 fb^{-1}

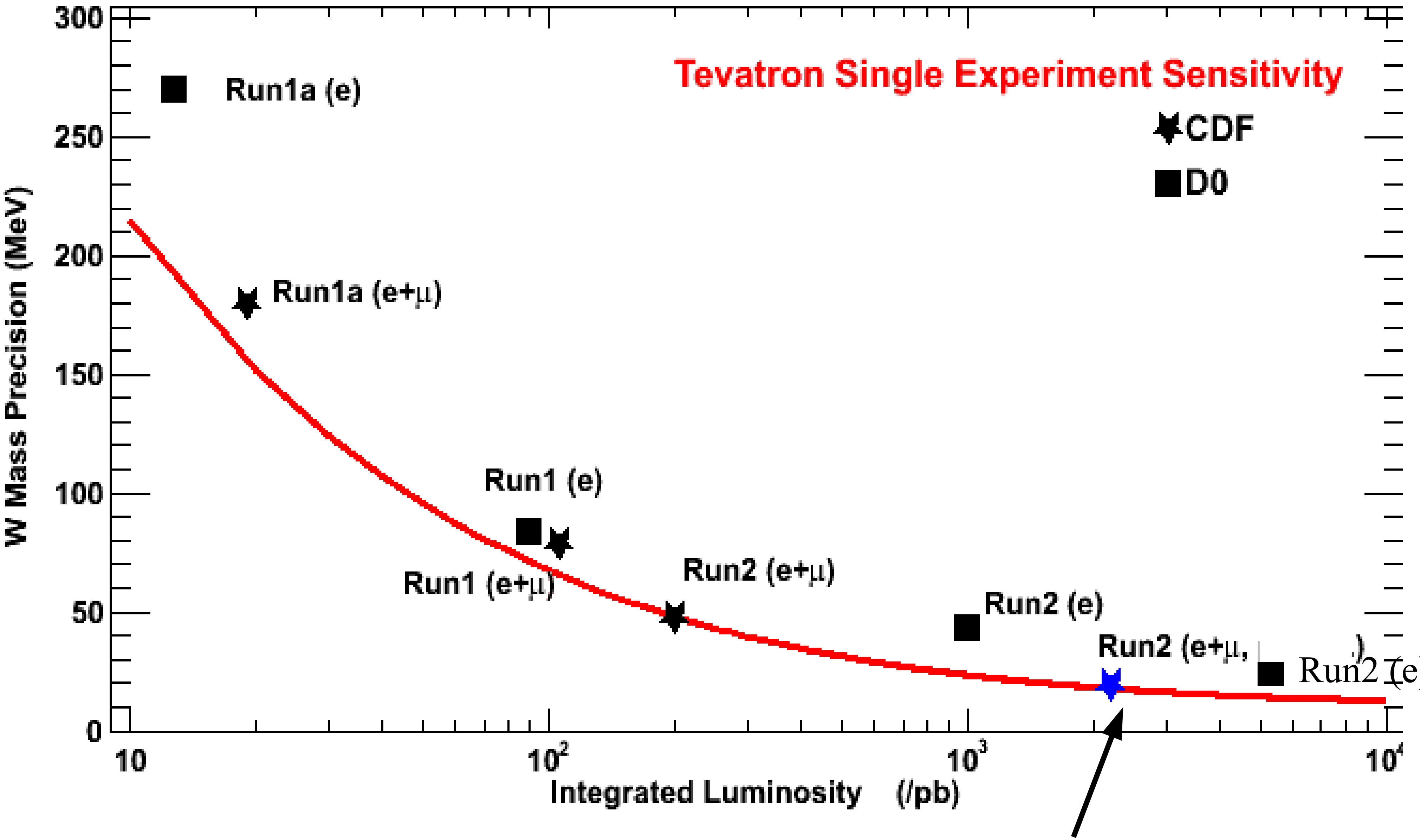
2.2 fb^{-1}

Previous world average = 80399 ± 23 MeV



new CDF result more precise than other measurements

Improvement of M_W Uncertainty with Sample Statistics



Non-scaling floor (11 MeV) dominated by PDF uncertainty (10 MeV)

Future M_W Measurements at Tevatron and LHC

- Factor of 2-5 bigger samples of W and Z bosons available
- 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? 5 MeV at the LHC?
- (A.V. Kotwal and J. Stark, Ann. Rev. Nucl. Part. Sci., vol. 58, Nov 2008)

PDF Uncertainties – scope for improvement

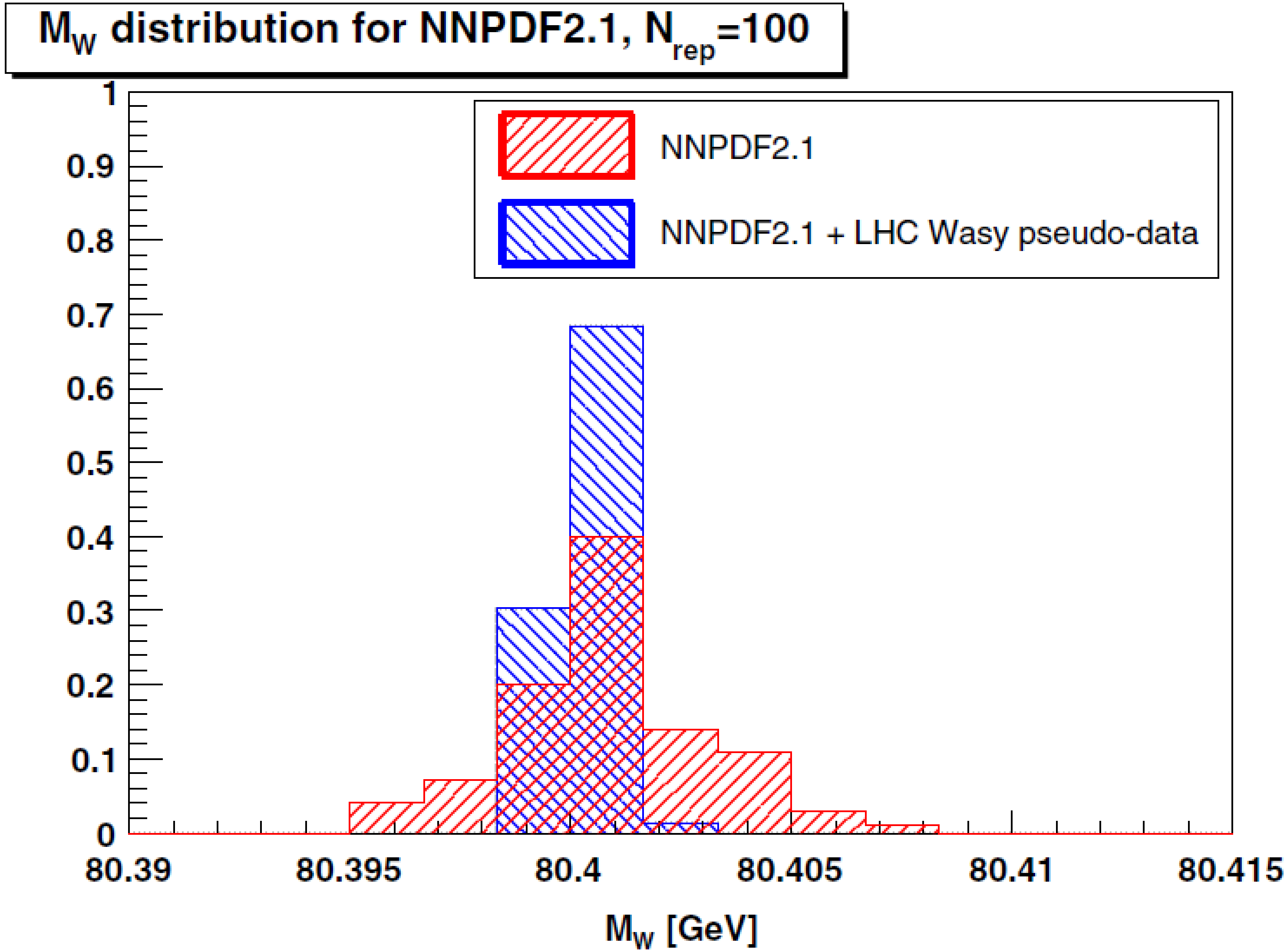
- Newer PDF sets, *e.g.* CT10W include more recent data, such as Tevatron W charge asymmetry data

- 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

- Fermilab/Seaquest, Tevatron and LHC measurements that can further constrain PDFs:
  - Drell-Yan, Z boson rapidity distribution
  - W $\rightarrow l\nu$ lepton rapidity distribution
  - W boson charge asymmetry

Improvement of M_W Uncertainty with *W* Asymmetry data

G. Bozzi *et al*, PHYSICAL REVIEW D **83,** 113008 (2011)



ATLAS and CMS measurements of W charge asymmetry (~35 pb^{-1}) with 7% uncertainty => pseudo-data with 1% uncertainty

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
  - Consistent with mass of Higgs-like boson ~ 125 GeV

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

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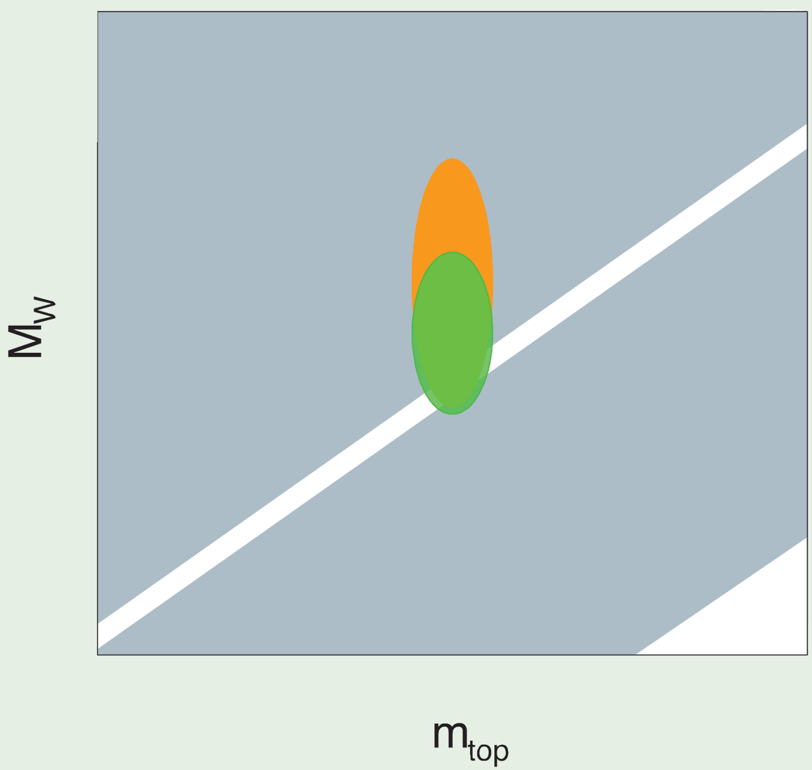

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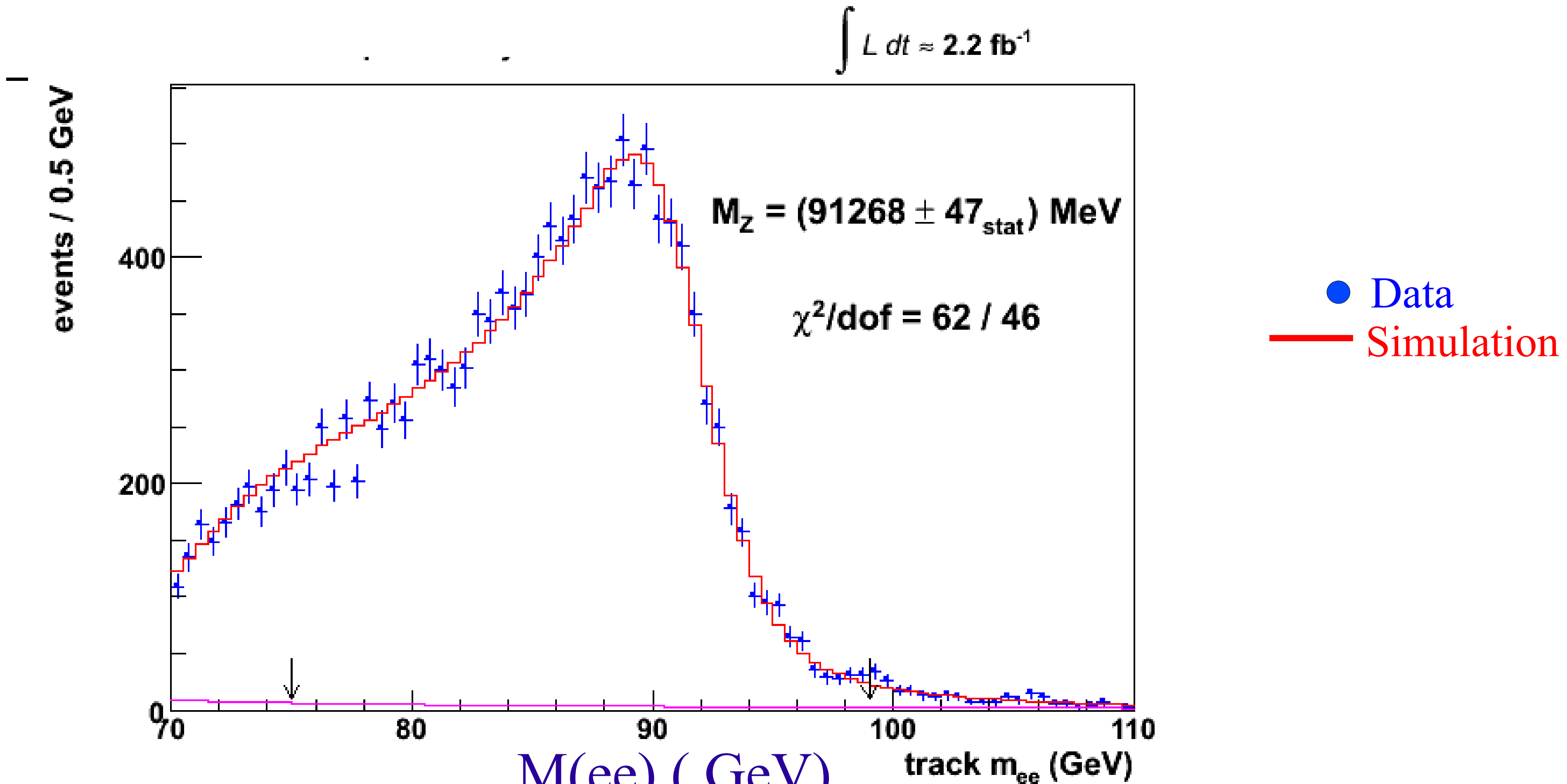
APS physics

Volume 108, Number 15

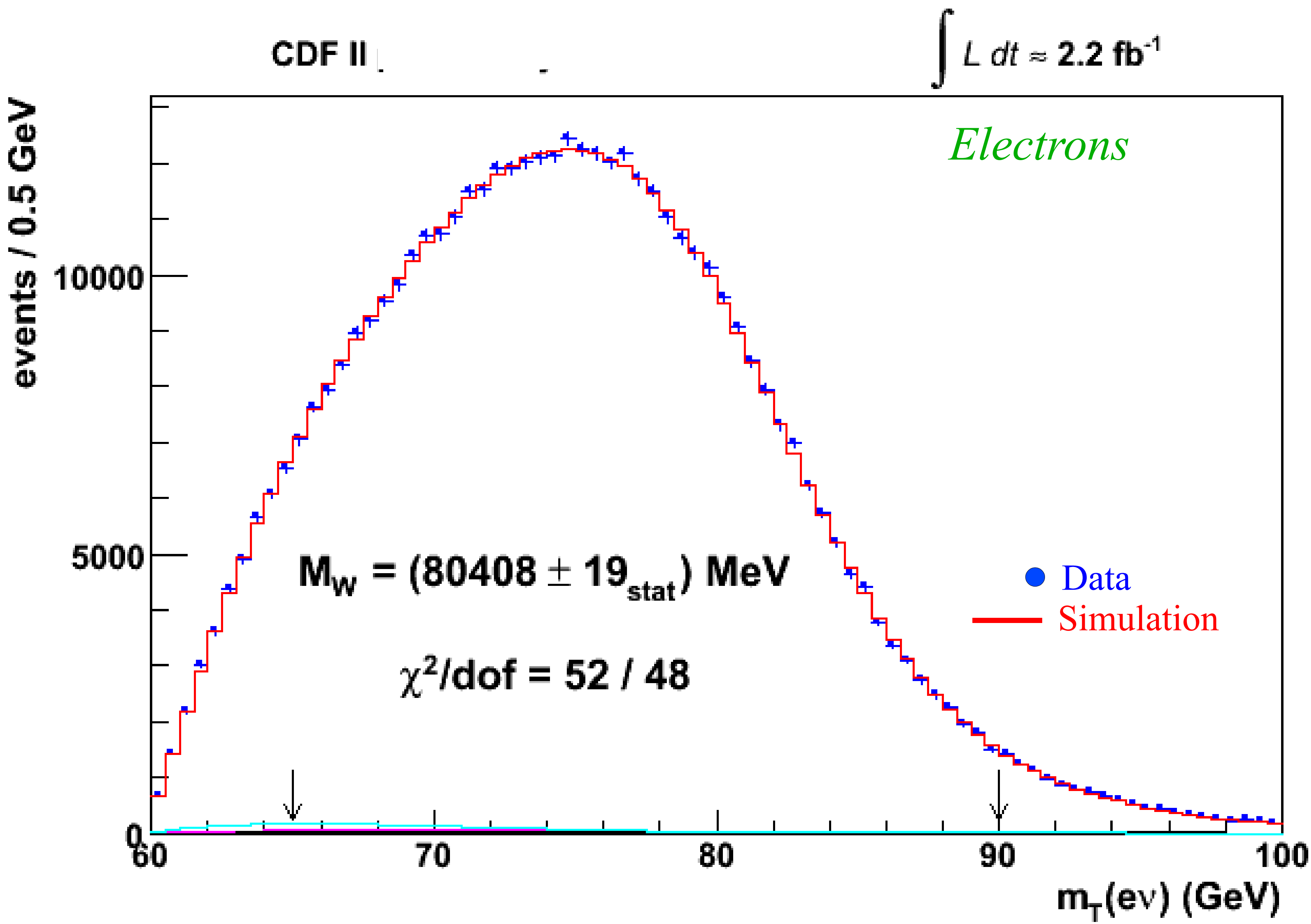
$Z \rightarrow ee$ Mass Cross-check using Electron Tracks

- 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

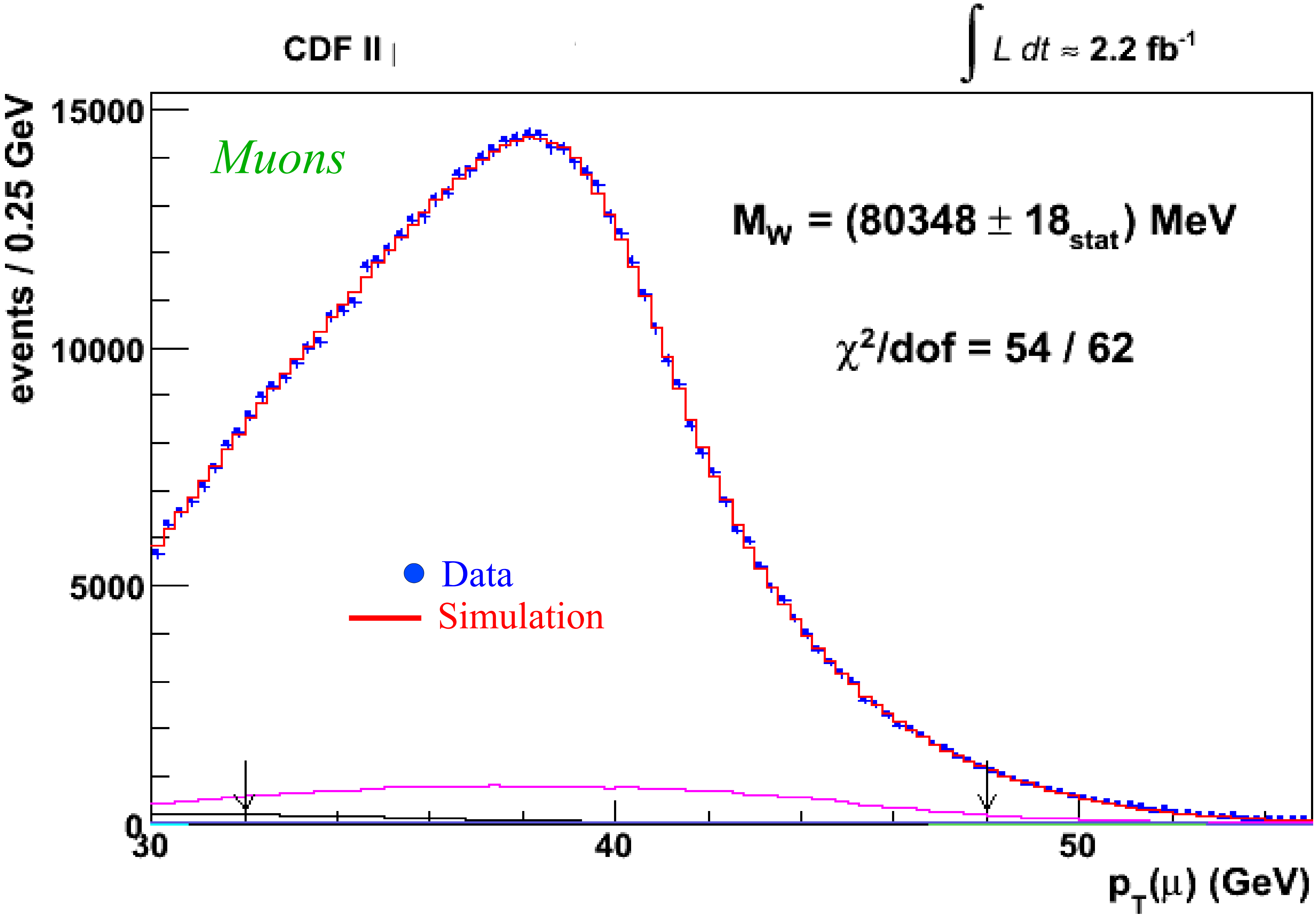


M(ee) (GeV)

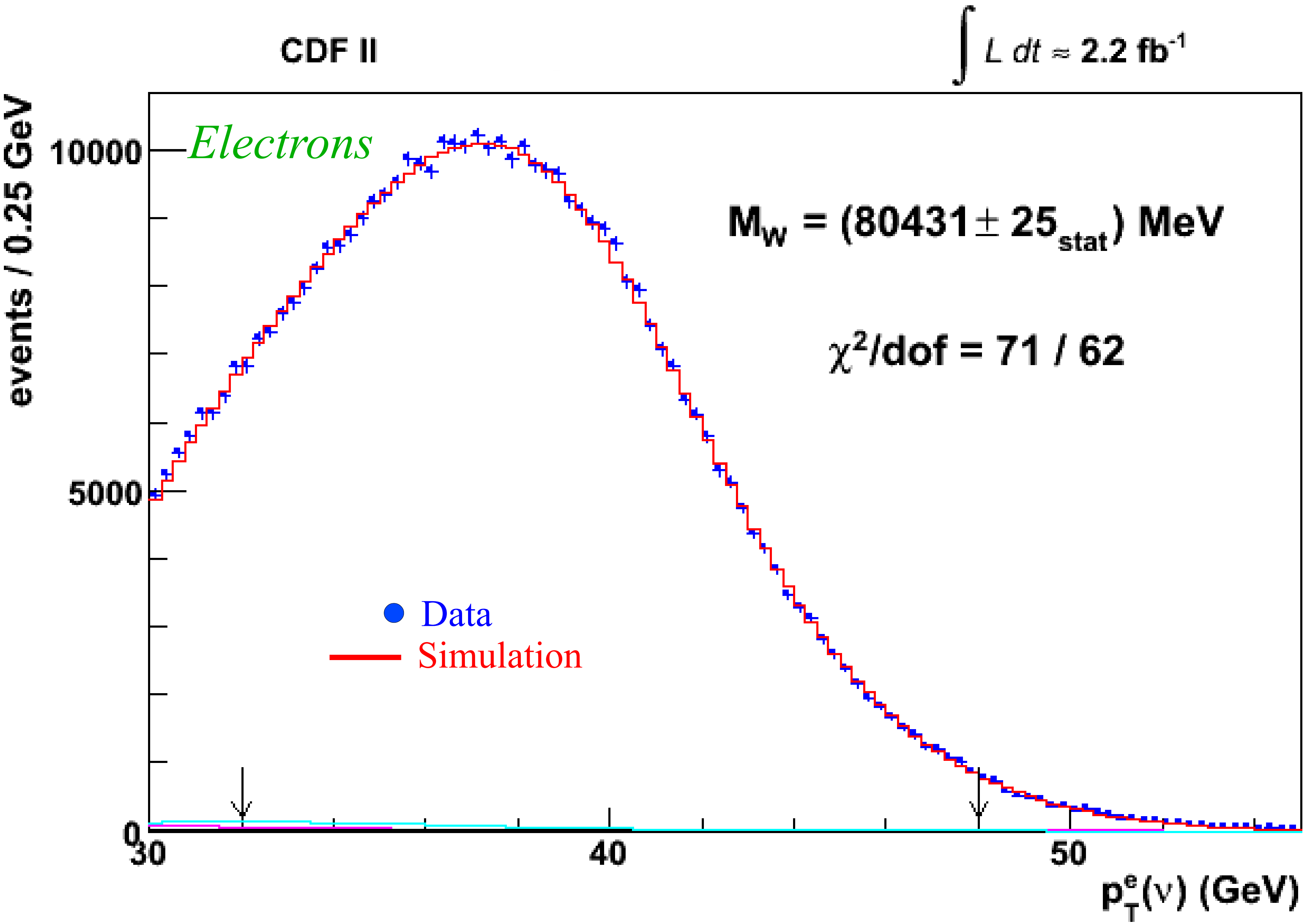
W Transverse Mass Fit



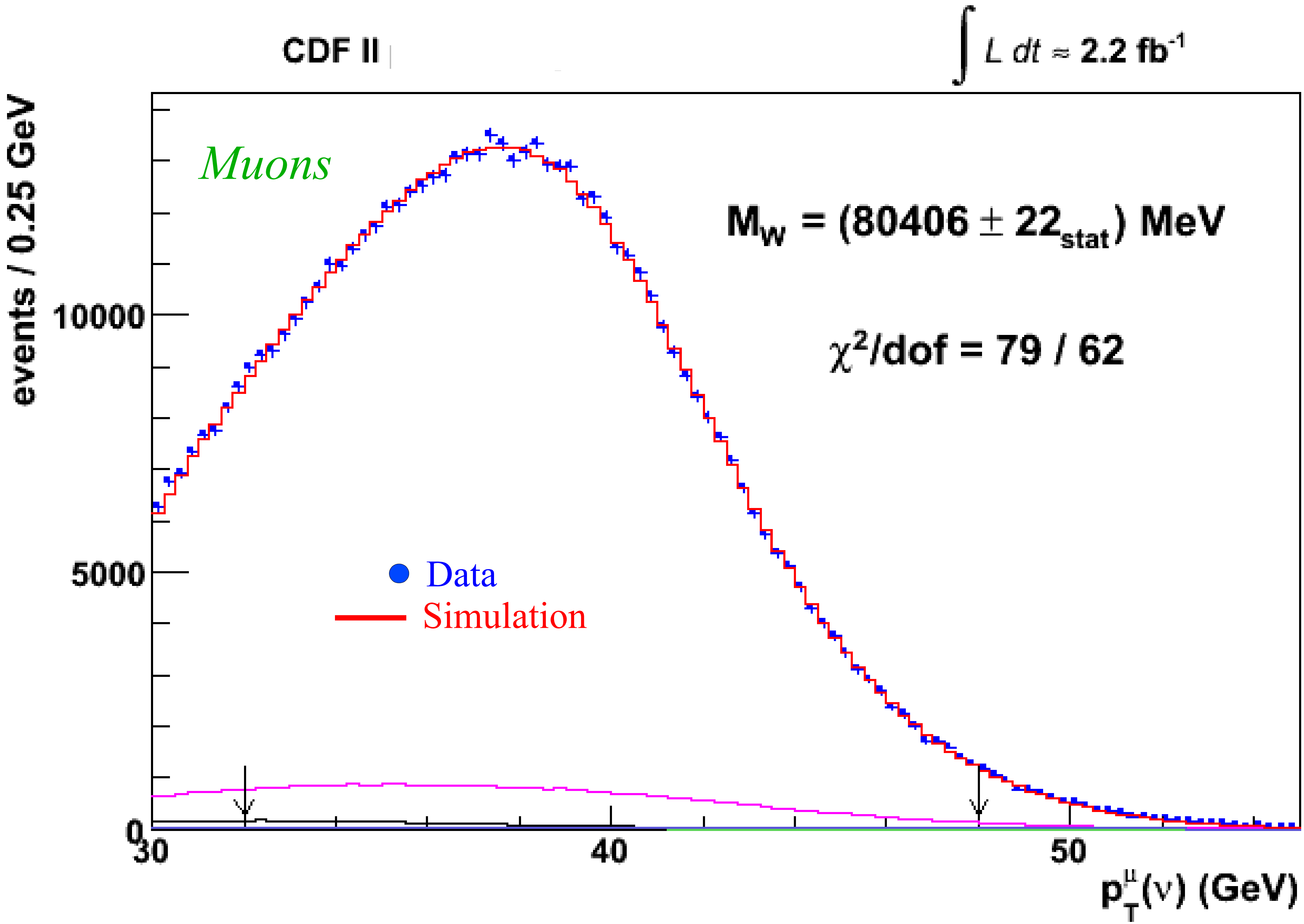
W Lepton p_T Fit



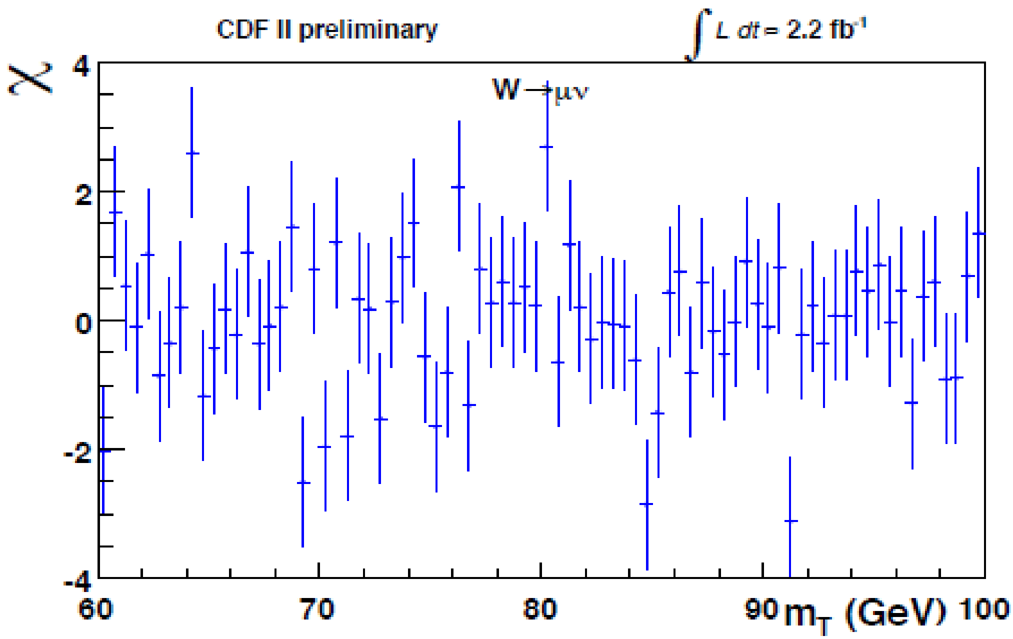
W Missing E_T Fit

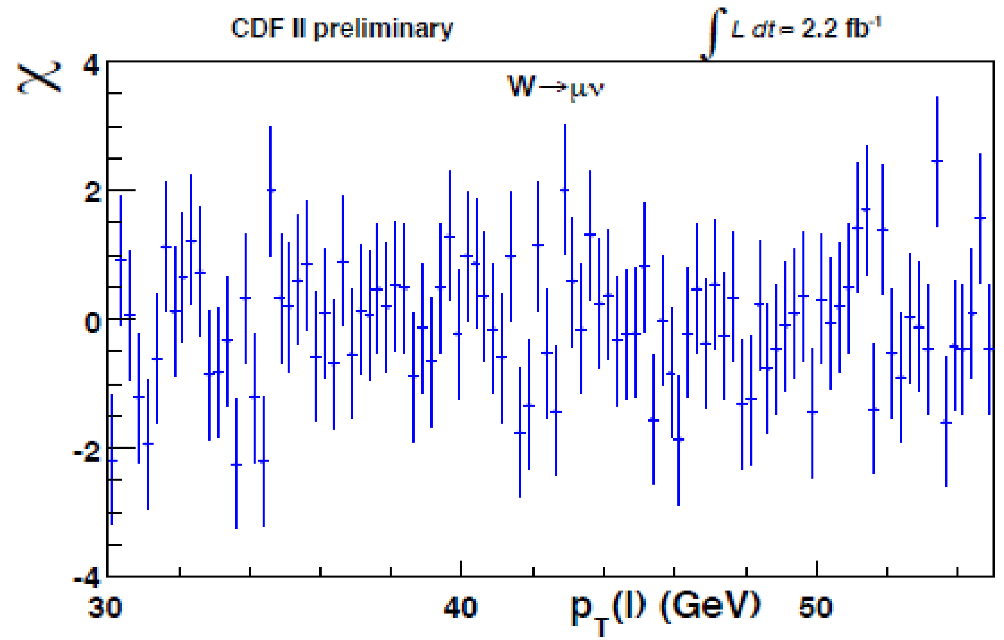


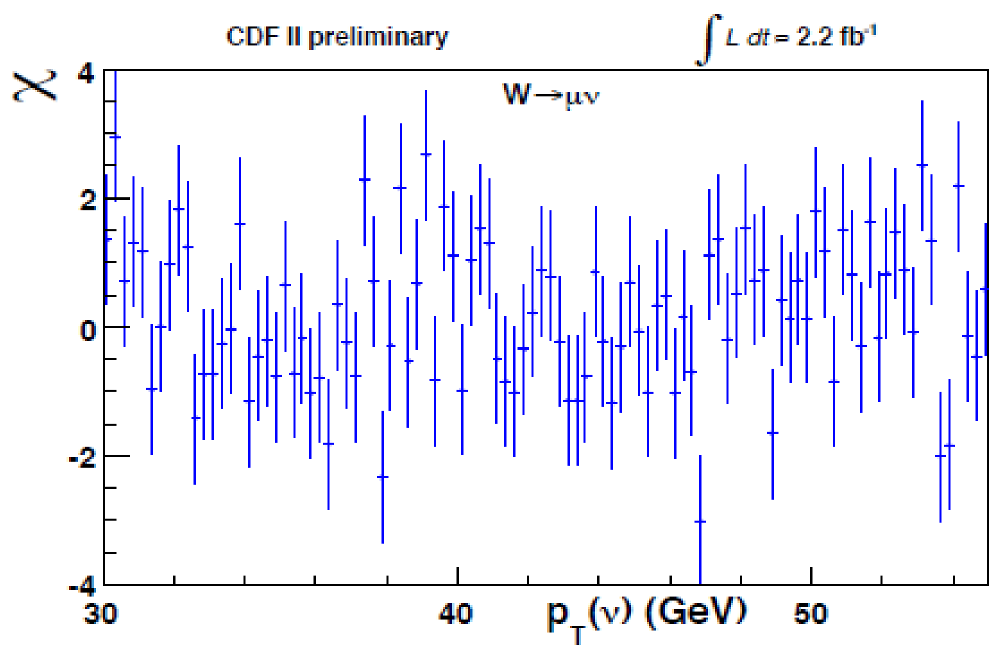
W Missing E_T Fit



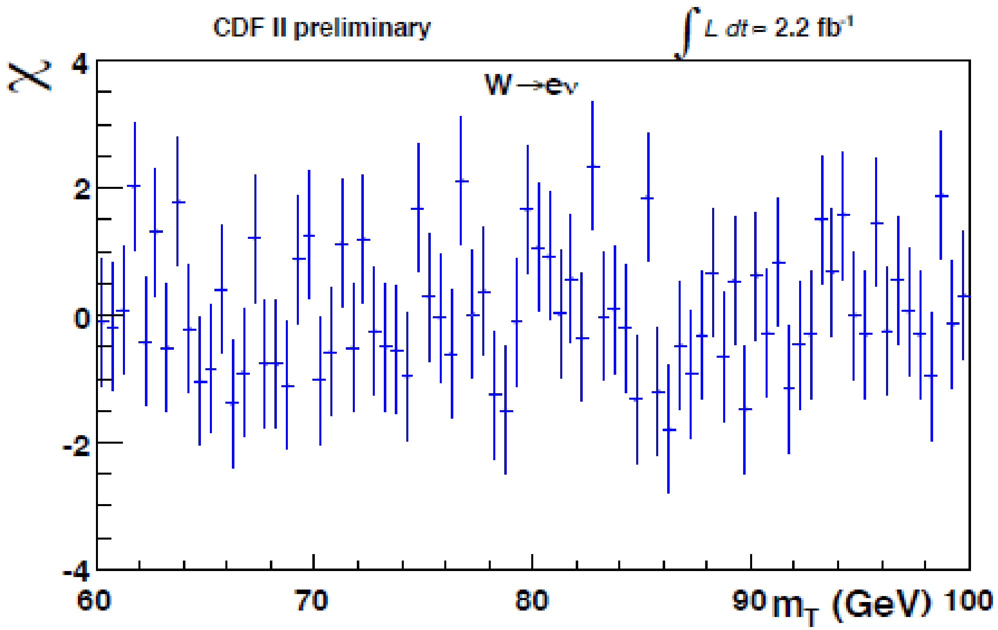
W Mass Fit Residuals, Muon Channel

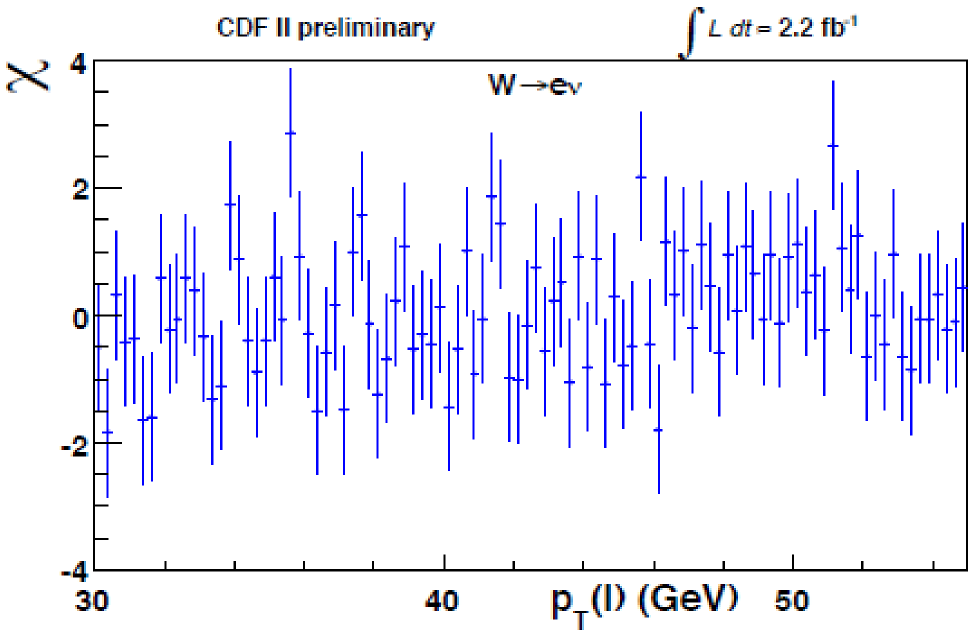


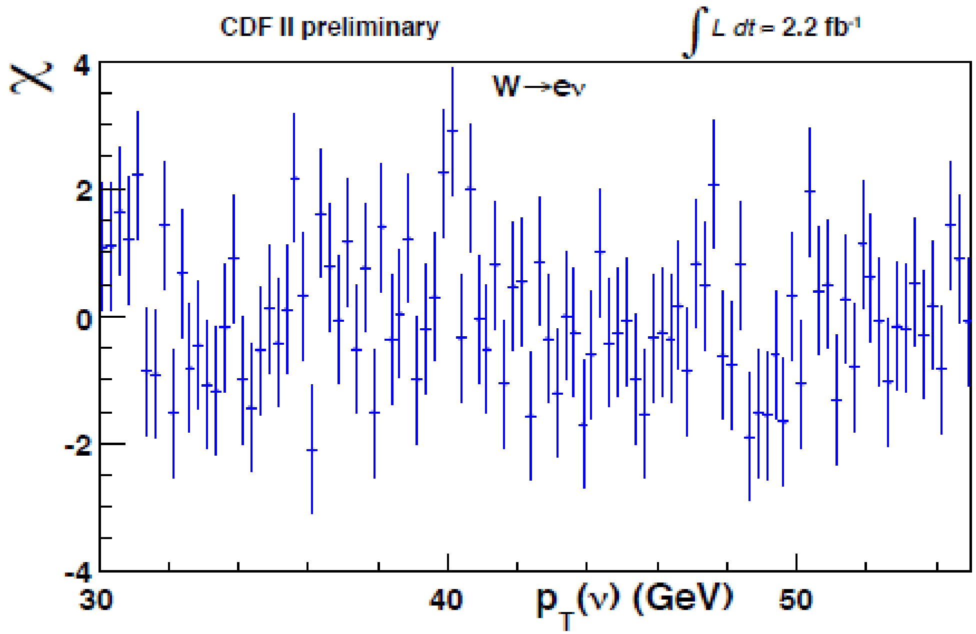




W Mass Fit Residuals, Electron Channel



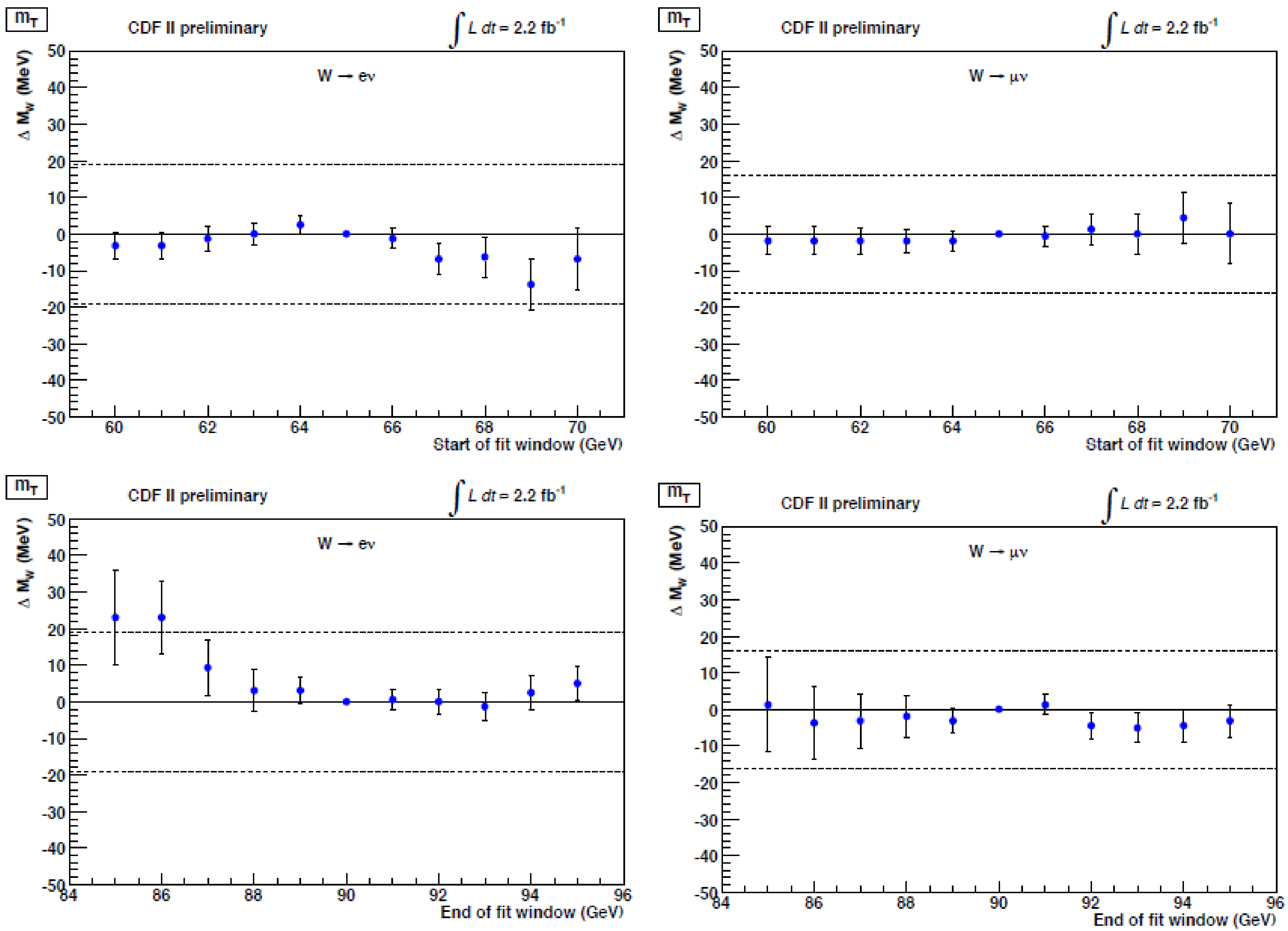




W Mass Fit Window Variation, m_T Fit

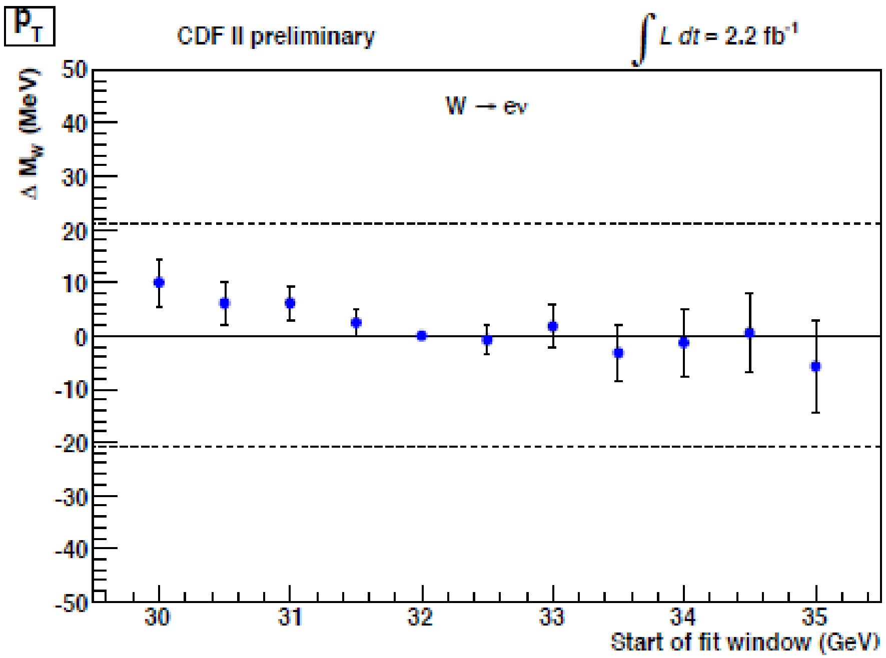
lower

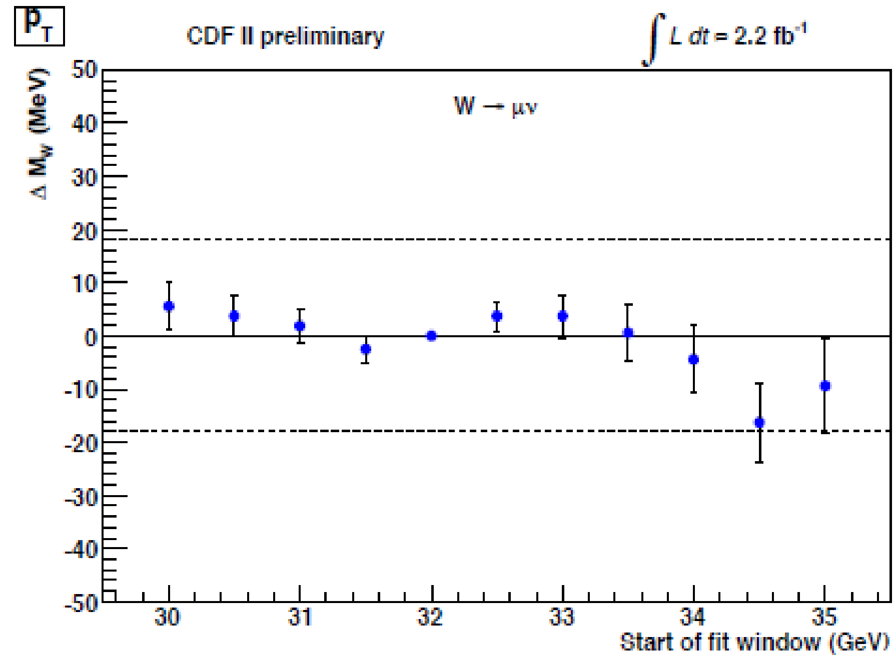
upper



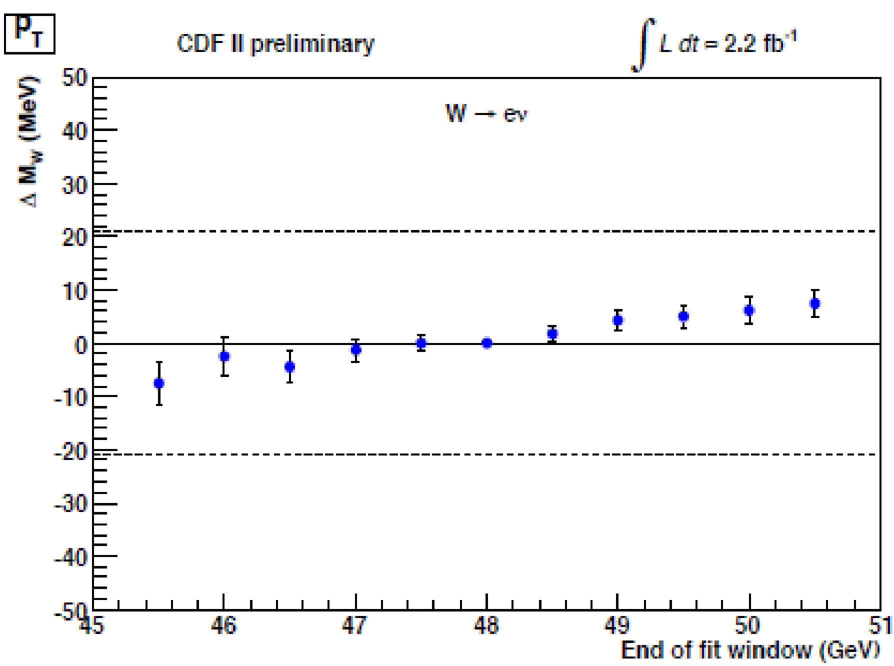
W Mass Fit Window Variation, $p_T(l)$ Fit

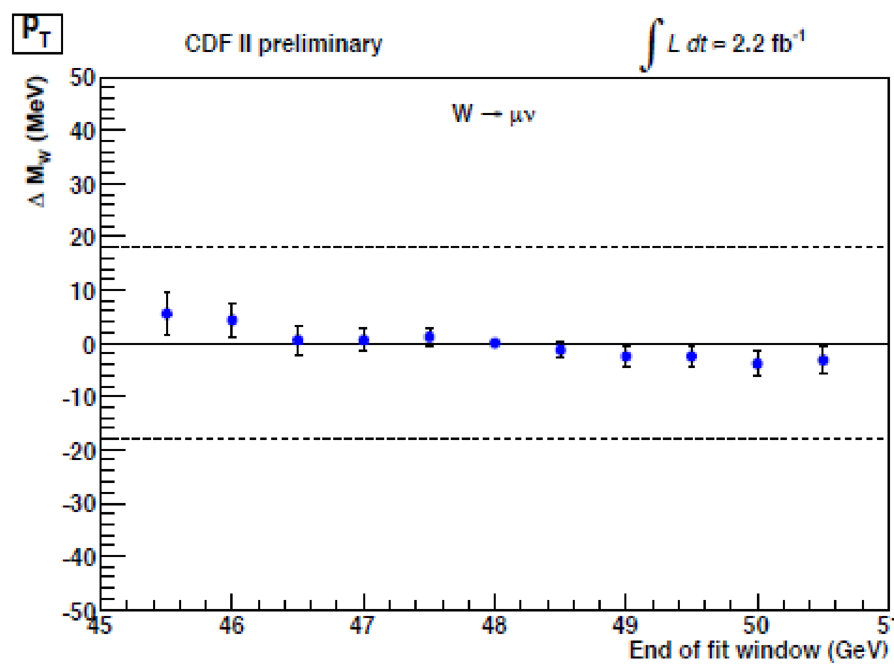
lower





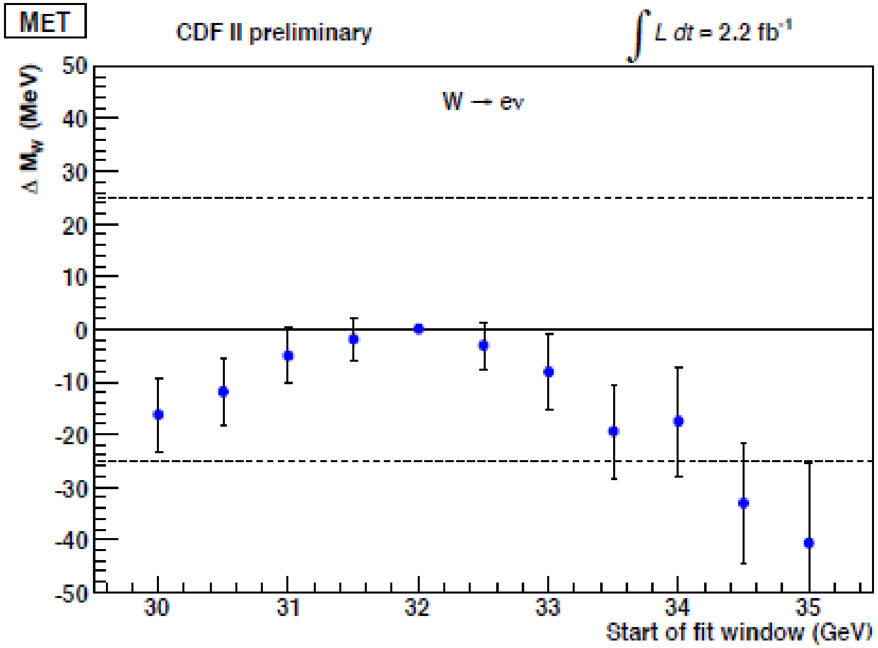
upper

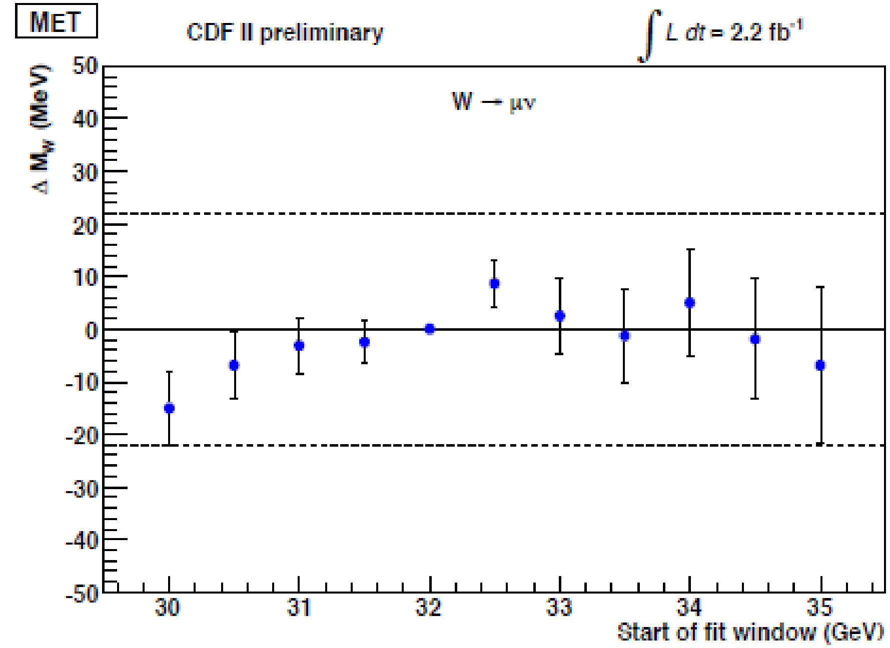




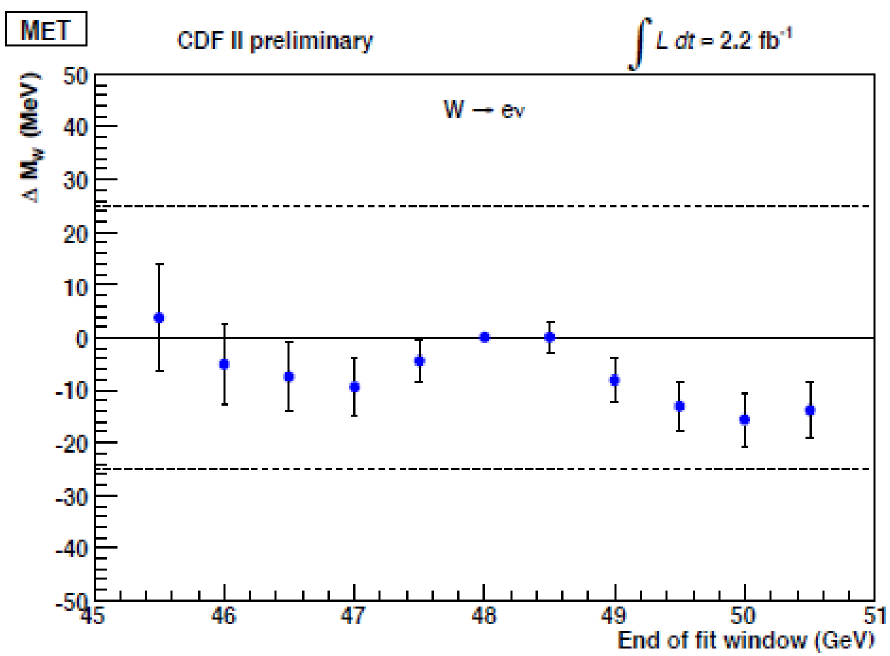
W Mass Fit Window Variation, $p_T(\nu)$ Fit

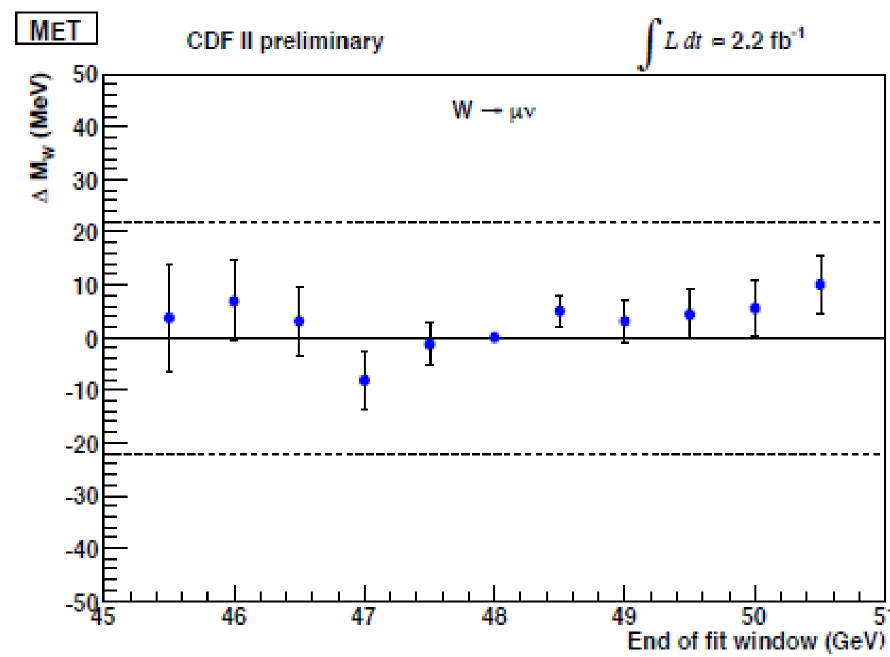
lower





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%)

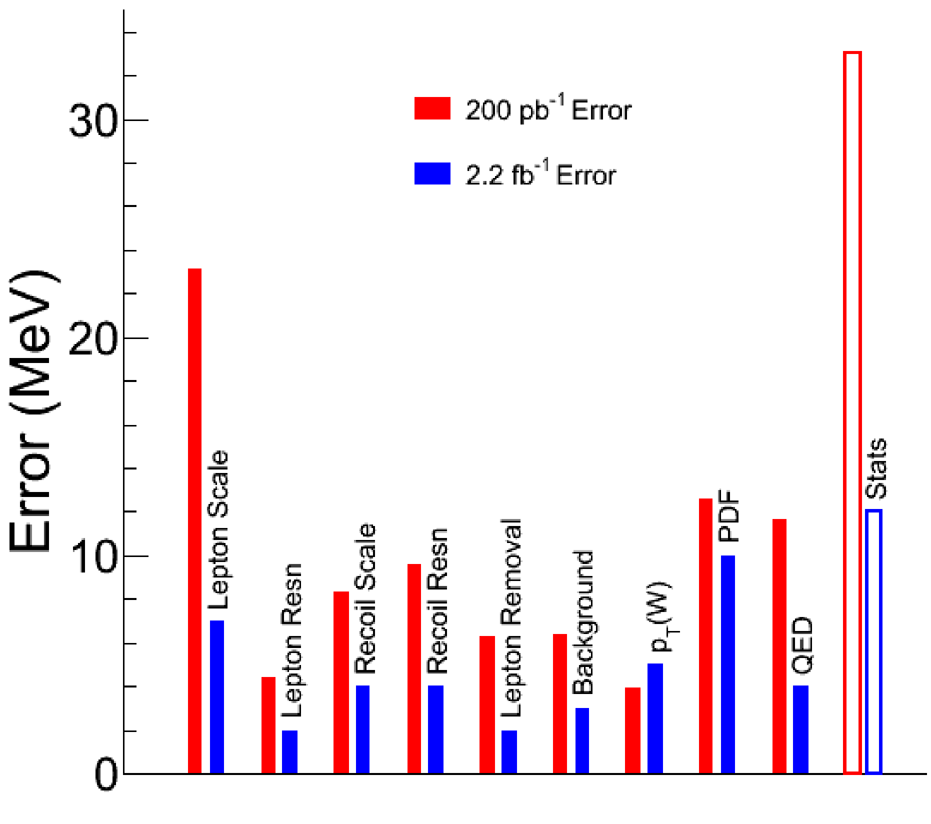
- All muon fits combined

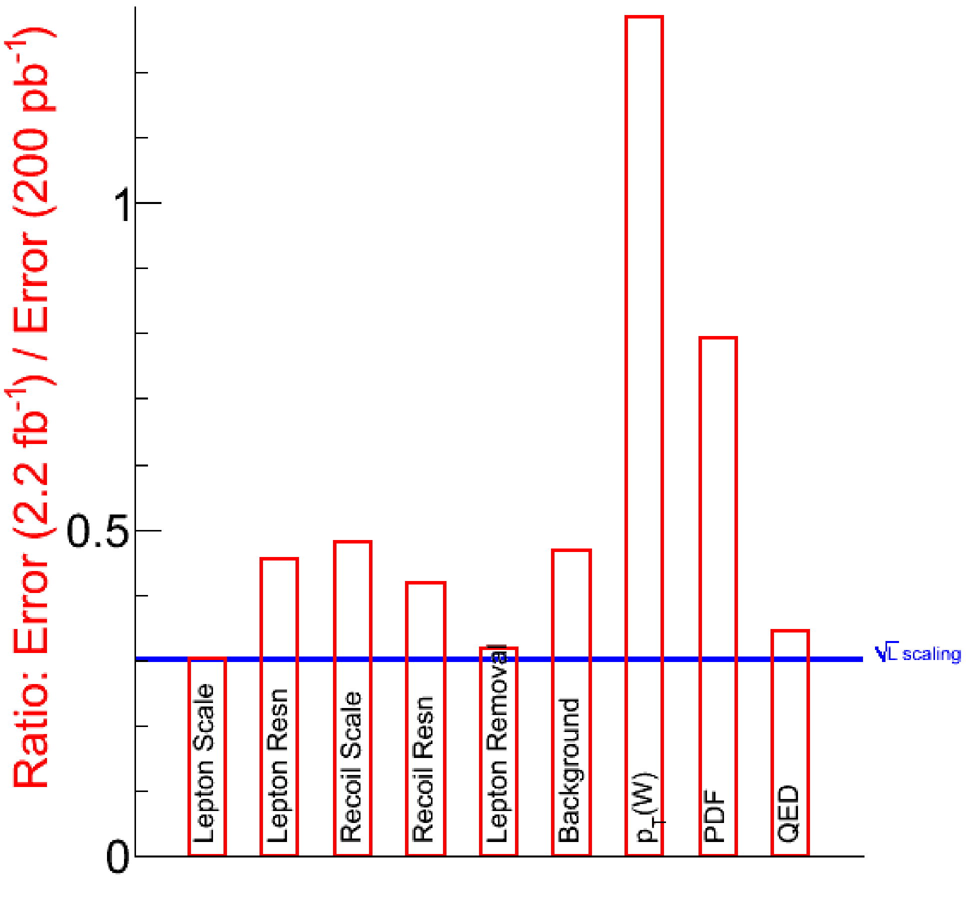
  m_W = 80374 ± 22 MeV, χ^2/dof = 4/2 (12%)

- All fits combined

  m_W = 80387 ± 19 MeV, χ^2/dof = 6.6/5 (25%)

Combined W Mass Result, Error Scaling





$p_T(\nu)$ 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

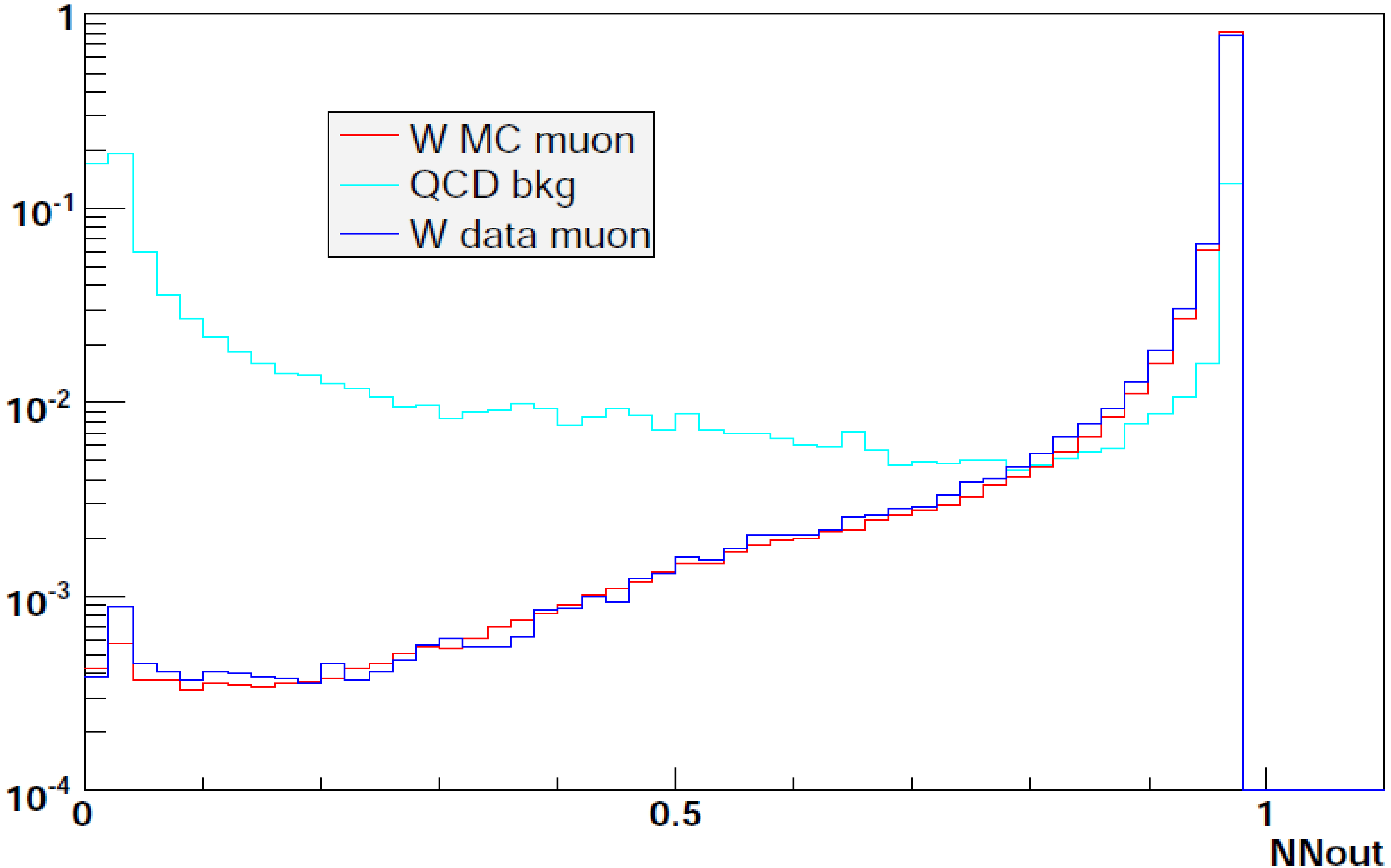
Combined Fit Systematic Uncertainties

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

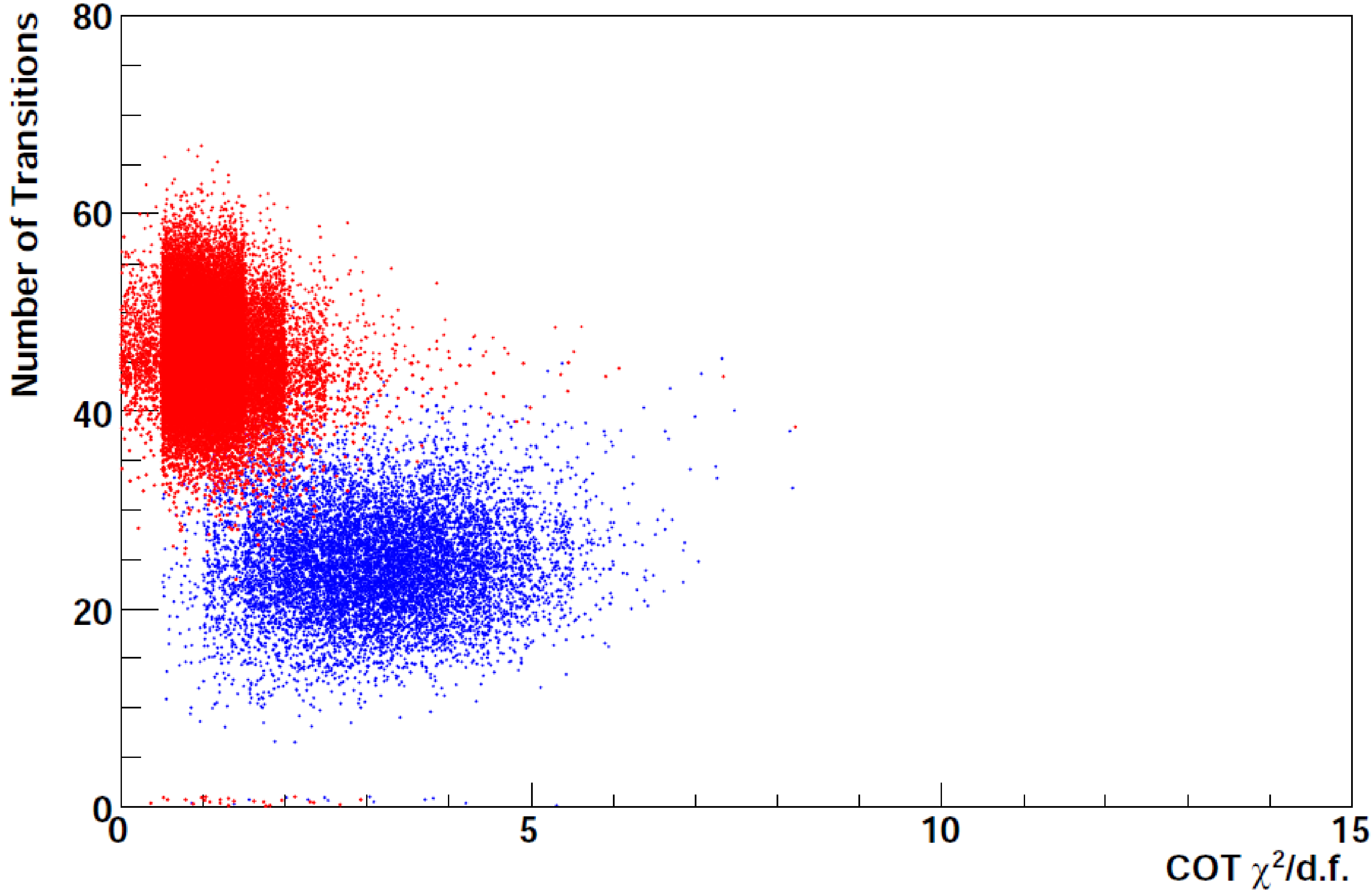
$p_T(l)$ Fit Systematic Uncertainties

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

QCD Background Estimation in Muon Channel



Decay-in-Flight Background Estimation in Muon Channel



Motivation II

- Separate fits for M_H using only leptonic and only hadronic measurements of asymmetries: marginal difference in preferred Higgs mass (from M. Chanowitz, February 2007 Seminar, Fermilab)

Possible explanations:

Statistical fluctuation

Systematic experimental bias

New physics contributions:

To raise M_H prediction of leptonic asymmetries:

Minimal SuperSymmetric Standard Model	Altarelli *et. al.*
4^{th} family of fermions	Okun *et. al.*
Opaque branes	Carena *et. al.*

New physics in b-quark asymmetry requires large modification to Zbb vertex

Parameters of Electro-Weak Interactions

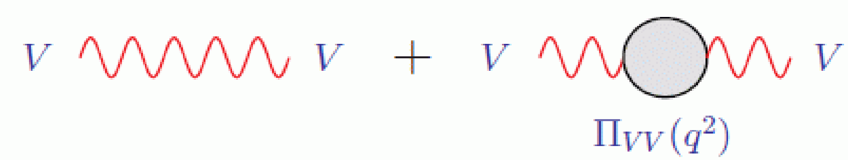
At tree level, all of the observables can be expressed in terms of *three* parameters of the SM Lagrangian: $v,\ g,\ g'$ or, equivalently, $v,\ e,\ s \equiv \sin\theta_W$ (also $c \equiv \cos\theta_W$)

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

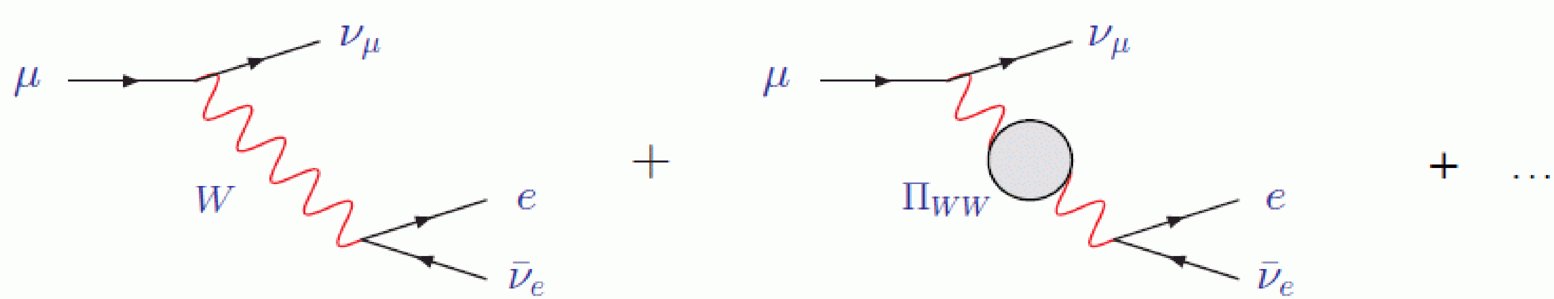
Radiative corrections to the relations between physical observables and Lagrangian params:

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

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



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



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:

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

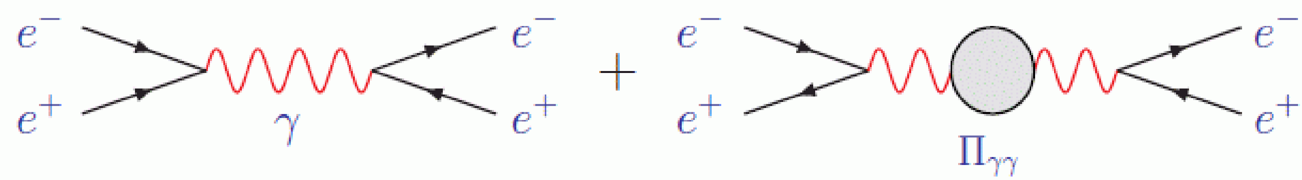
The leading corrections depend quadratically on m_t but only logarithmically on m_H :

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

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

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

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

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

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

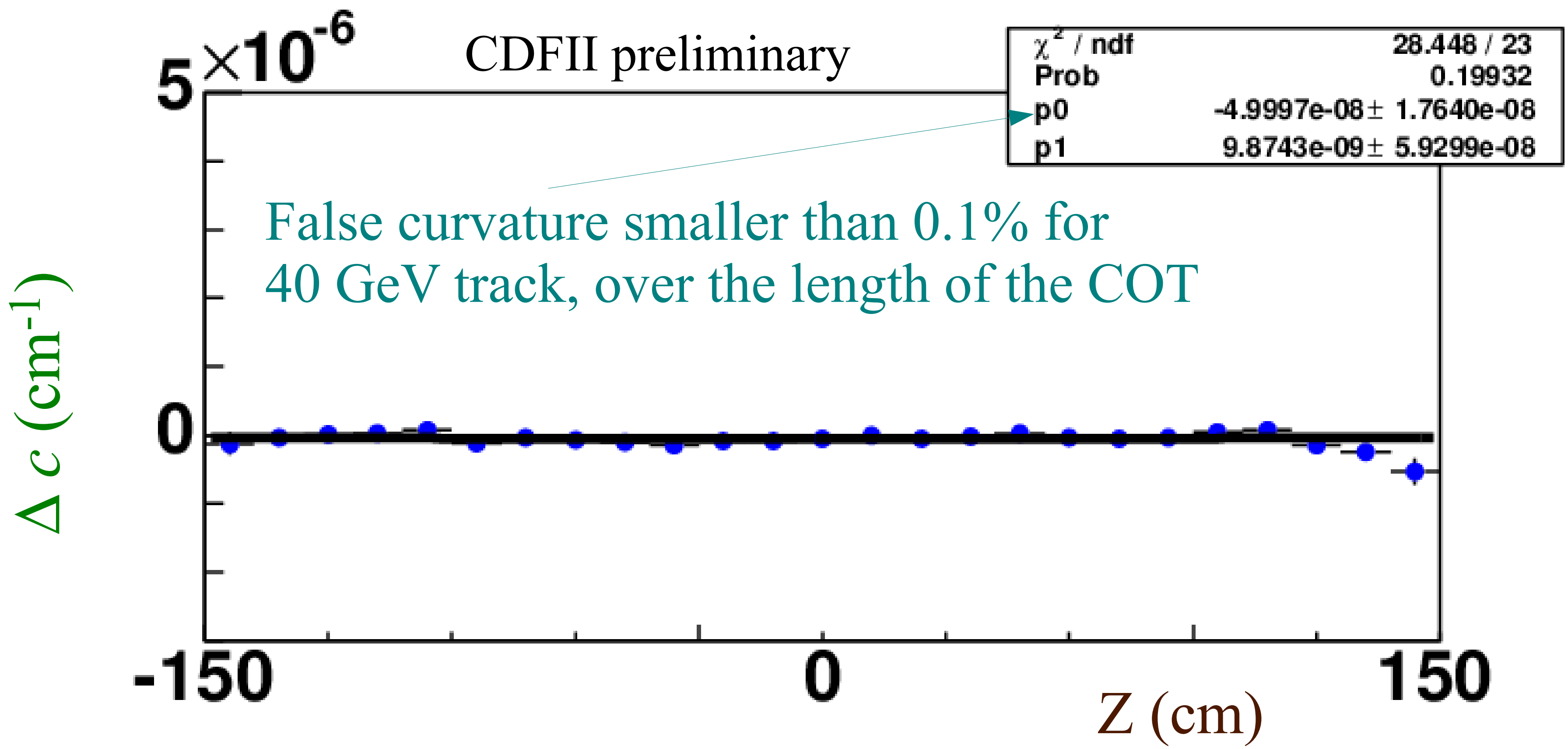
(This hadronic contribution is one of the biggest sources of uncertainty in EW studies)

Systematic Uncertainties in QED Radiative Corrections

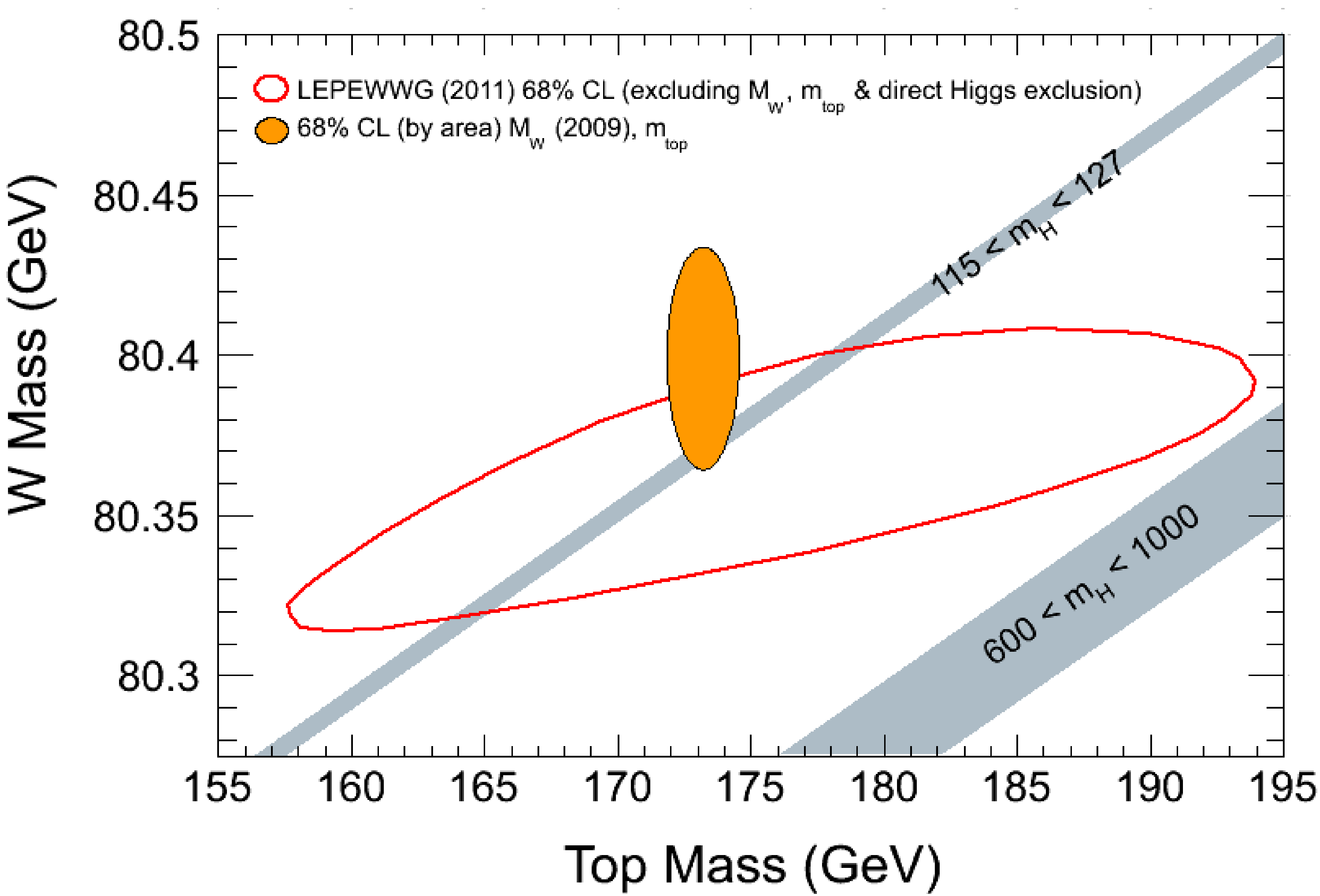
	CDF0	CDFIa	CDFIb	CDFII 200pb^{-1}	CDFII 2.3fb^{-1}	DØ 1fb^{-1}
effects:						
single photon	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
exact $\mathcal{O}(\alpha)$	–	–	–	$\surd$	$\surd$	–
multi-photon	–	–	–	–	$\surd$	$\surd$
ISR	–	–	–	–	$\surd$	–
uncertainties:						
2γ emission	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
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	–	–	–	–	$\surd$	–

Consistency check of COT alignment procedure

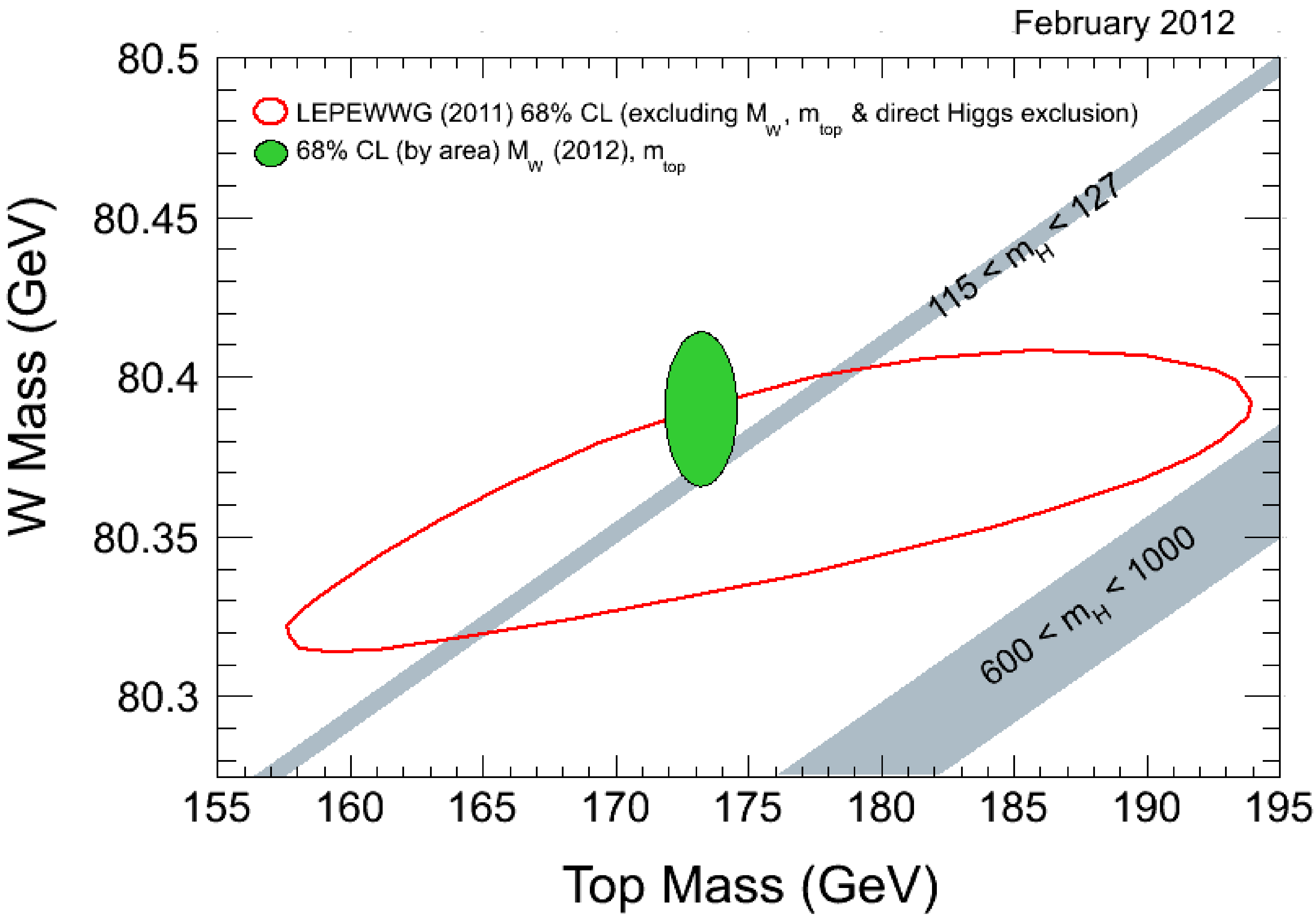
- Fit separate helices to cosmic ray tracks on each side
- Compare track parameters (eg. Curvature, shown below) of the two tracks: a measure of track parameter bias



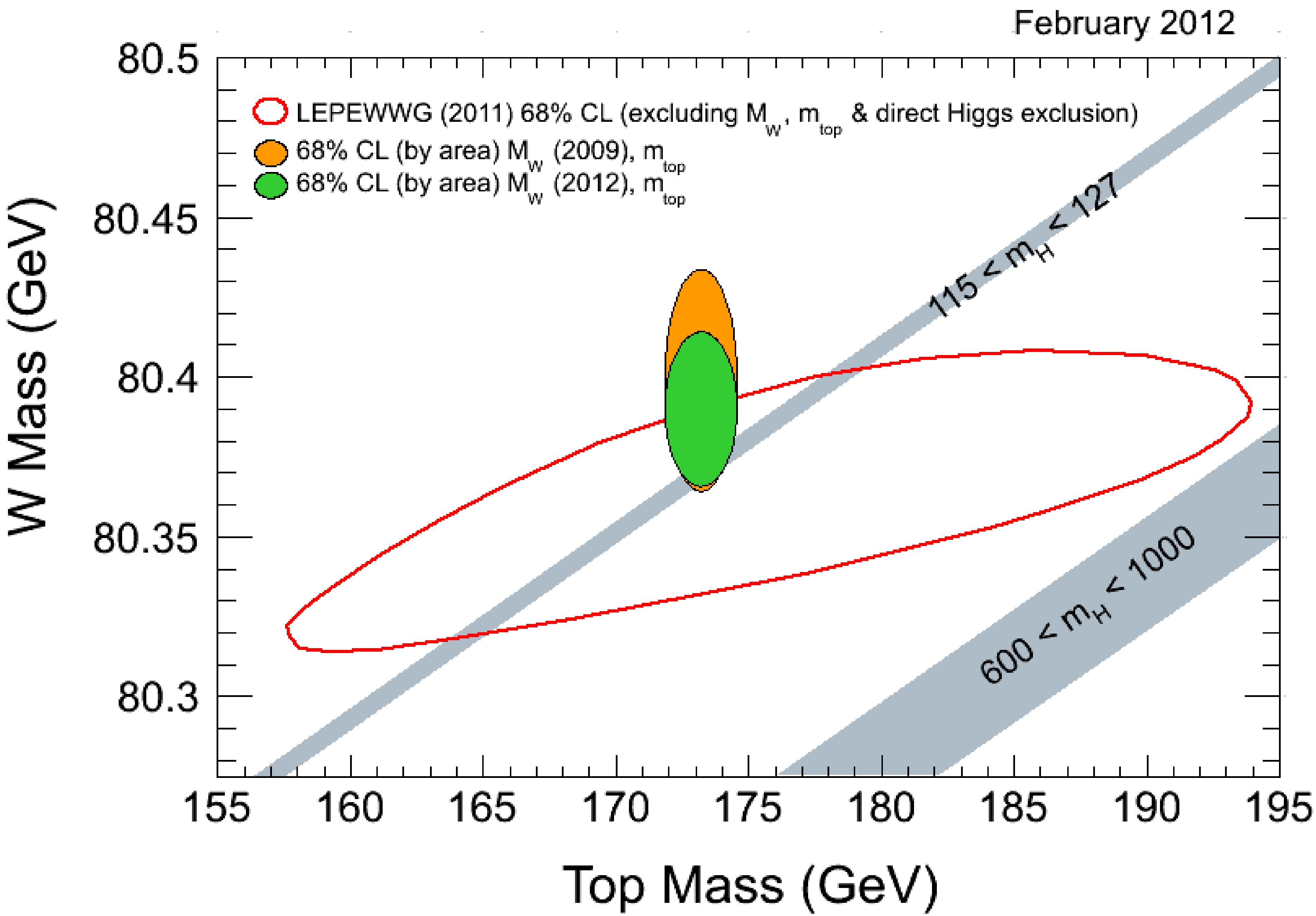
Previous M_W *vs* M_{top}



Updated M_W *vs* M_{top}



M_W *vs* M_{top}


February 2012
LEPEWWG (2011) 68% CL (excluding M_W, m_{top} & direct Higgs exclusion)
68% CL (by area) M_W (2009), m_{top}
68% CL (by area) M_W (2012), m_{top}
$115 < m_H < 127$
$600 < m_H < 1000$
W Mass (GeV)
Top Mass (GeV)
80.5
80.45
80.4
80.35
80.3
155
160
165
170
175
180
185
190
195