Precision Measurement of the W Boson Mass at CDF

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Motivation

- Electroweak sector of the standard model (SM) is constrained by

$$G_F = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2}$$
$$\alpha_{EM}(Q^2 = M_Z^2) = 1/127.918(18)$$
$$m_Z = 91.1876(21)\ \mathrm{GeV}/c^2$$

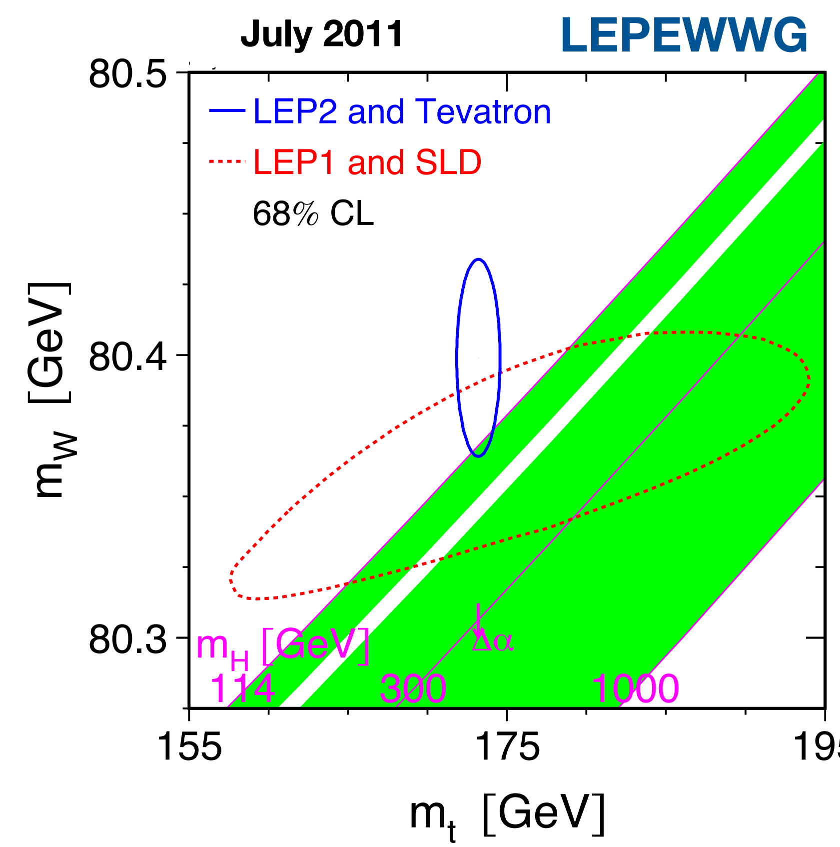
- These constants are all related to m_W by

$$m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_F \sin^2\theta_W (1 - \Delta r)} \qquad \sin\theta_W^2 = 1 - \frac{m_W^2}{m_Z^2}$$

- Radiative corrections Δr dominated by top and Higgs loops

- Precision measurements in m_W and m_{top} constrain SM Higgs mass

Where should the Higgs be?



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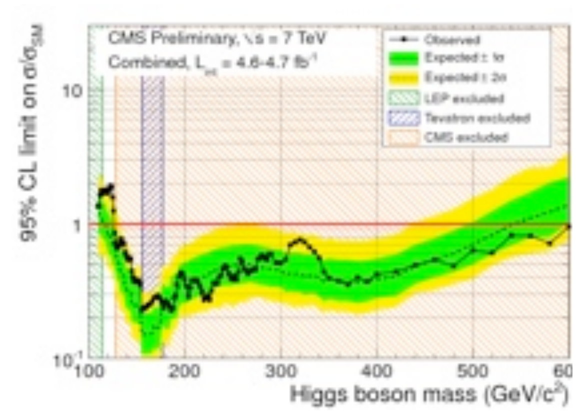
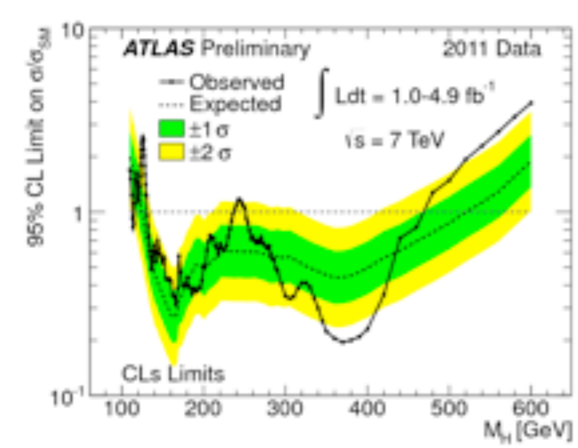




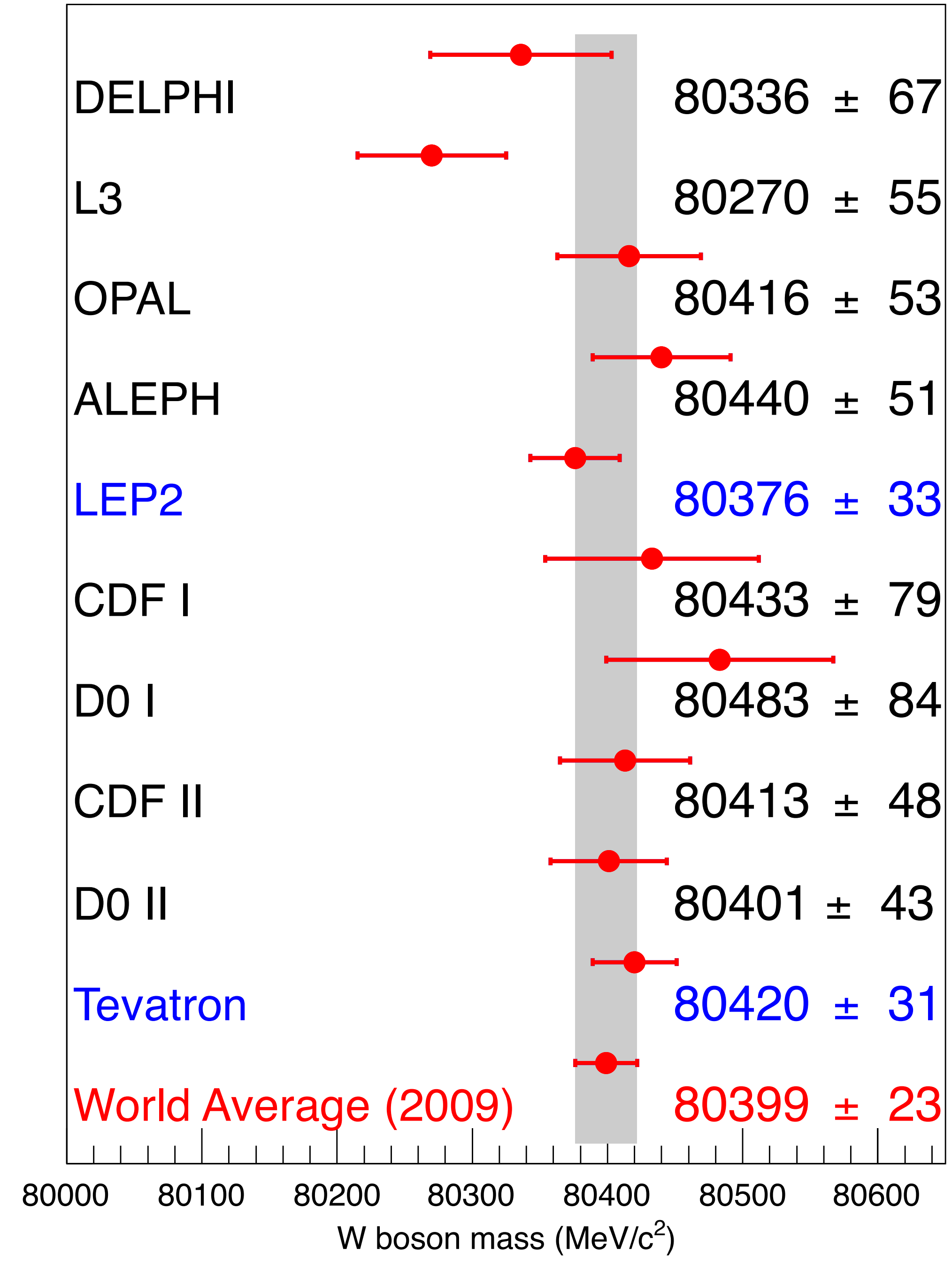
Measurements of M_W

- State-of-the-art
  - DØ M_W=80401±43 MeV [1 fb^{-1}, e]

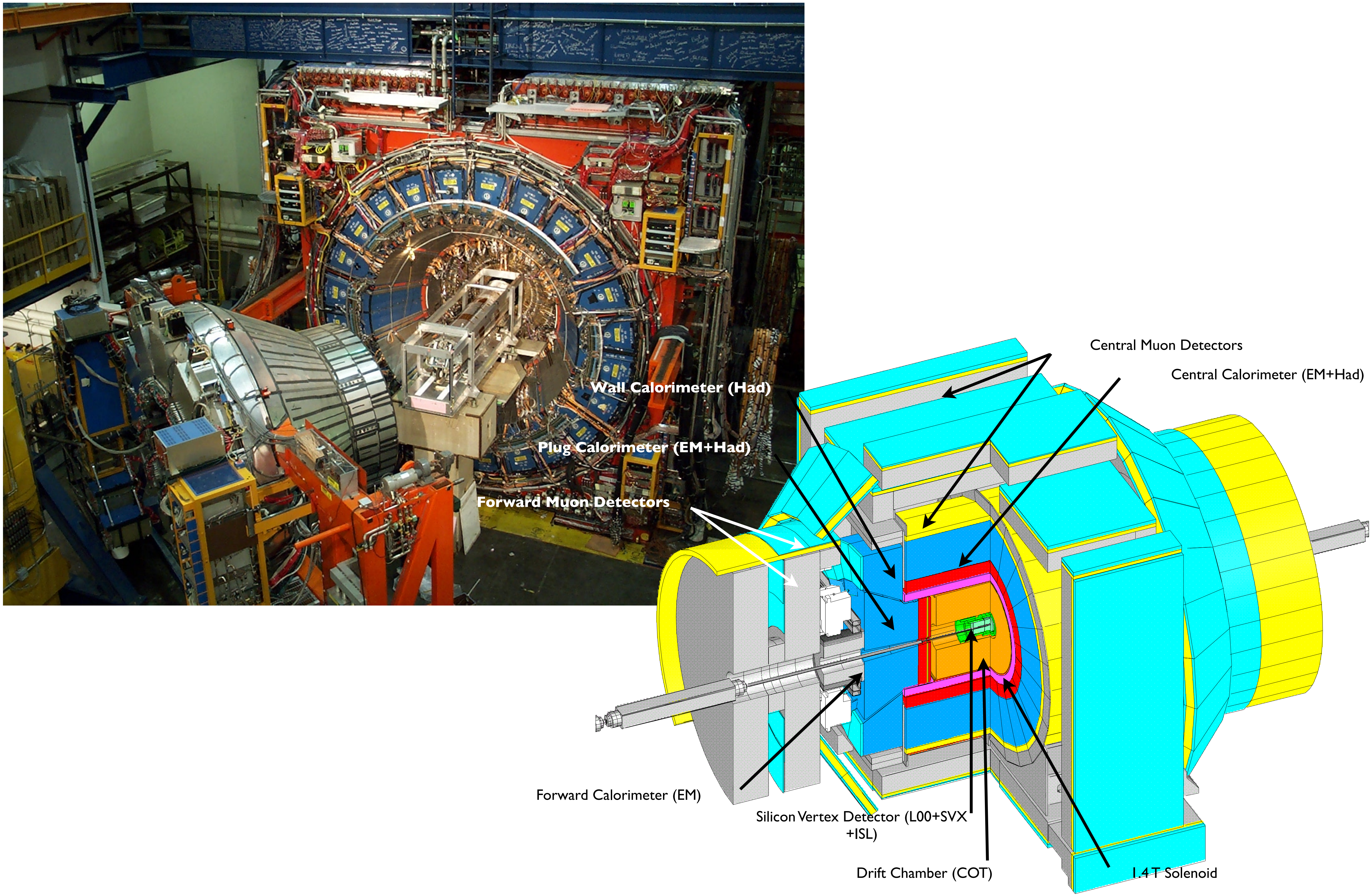
    *PRL **103**:141801 (2009)*
  - CDF M_W=80413±48 MeV [200 pb^{-1}, $e+\mu$]

    *PRL **99:**151801 (2007)*

    *PRD **77:**112001 (2008)*
  - Combining with LEP ΔM_W = 23 MeV
  - SM Fit $M_H = 92^{+34}_{-26}$ GeV
- *Achieved:* exceed precision of e^+e^- machine measurements with hadron collider
- *Goal:* match precision of all previous measurements with single CDF measurement

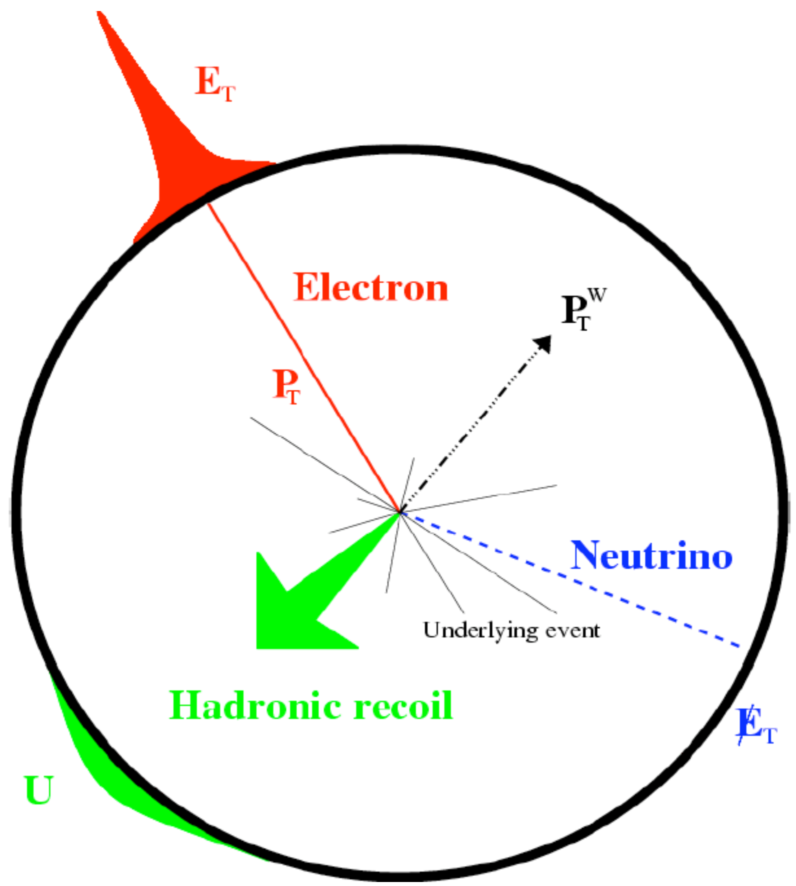


CDF II (2002-2011)



Precision?

- Start with **clean**, **low-background** events
  - *i.e.*, no taus, no hadronic decays
- Lepton p_T carries most information
  - Precision achieved: *0.01%*
- Hadronic recoil affects inference of neutrino energy
  - Calibrate to ~0.5%
  - Can reduce impact by requiring $p_T(W) << M_W$
- Need:
  - Accurate **theoretical model**
    - Including boson p_T model and QED radiation
  - Tunable **fast simulation**
    - Parameterized detector description for study of systematic effects
  - Large data samples of well-measured states
    - Various dimuon resonances
    - *Z* boson



Measurement strategy (broadly speaking)

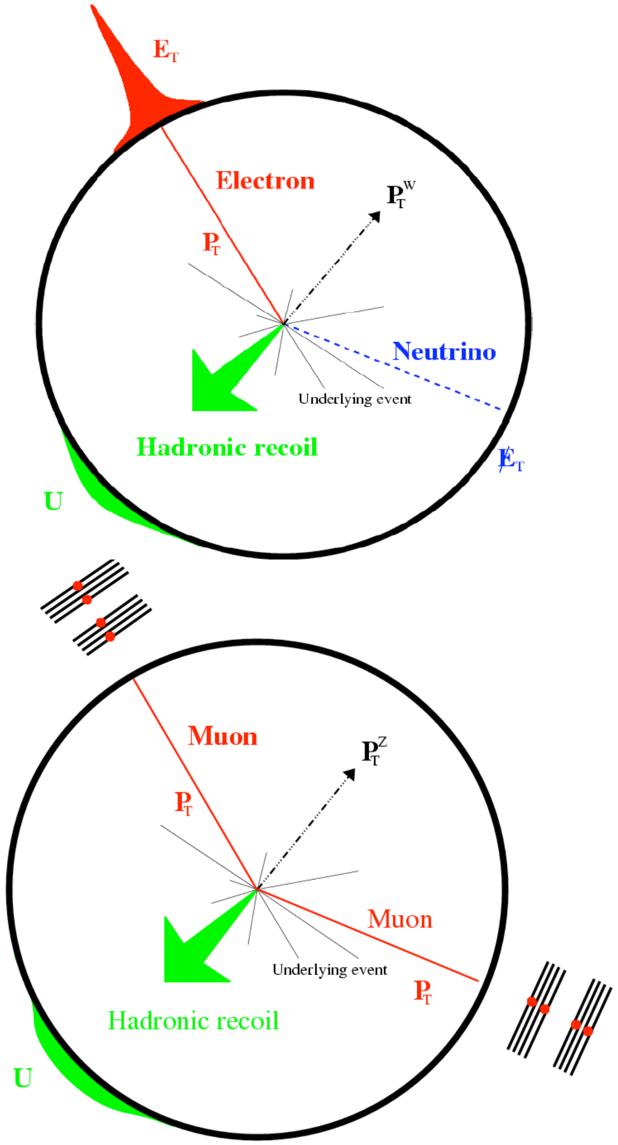
- Maximize internal constraints and cross-checks
- Why?
  1. **Robustness**: Constrain the same parameter multiple ways
  2. **Precision**: After demonstrating 1), combine independent measurements

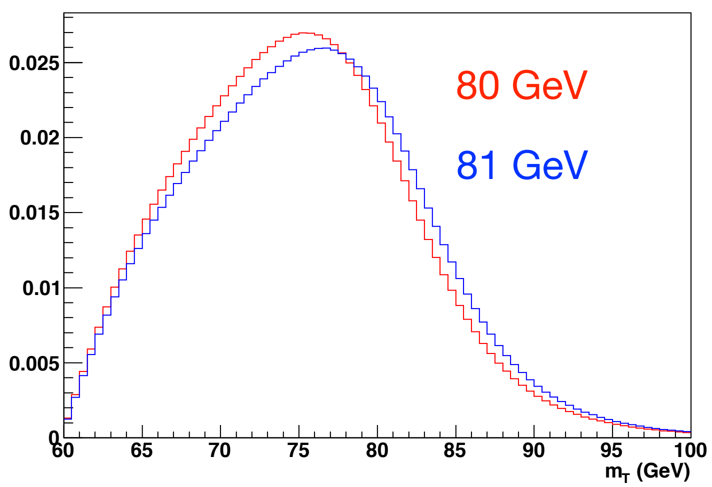
Measurement strategy (more specifically)

- Perform COT alignment with cosmic ray data
  - ~2 μm alignment (vs ~50 μm survey-based)
- Calibrate track momentum scale using dimuon resonances (J/ψ, Υ).
  - **Cross-check** with Z mass measurement and add as further calibration point
- Calibrate calorimeter energy using E/p of W and Z decays
  - **Cross-check** with Z mass measurement
- Calibrate hadronic recoil with Z decays to μ, e
  - **Cross-check** with W recoil distribution
- Perform fits to e/μ p_T, ν p_T, and **transverse mass**

$$m_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos\Delta\theta_{\ell\nu})}$$

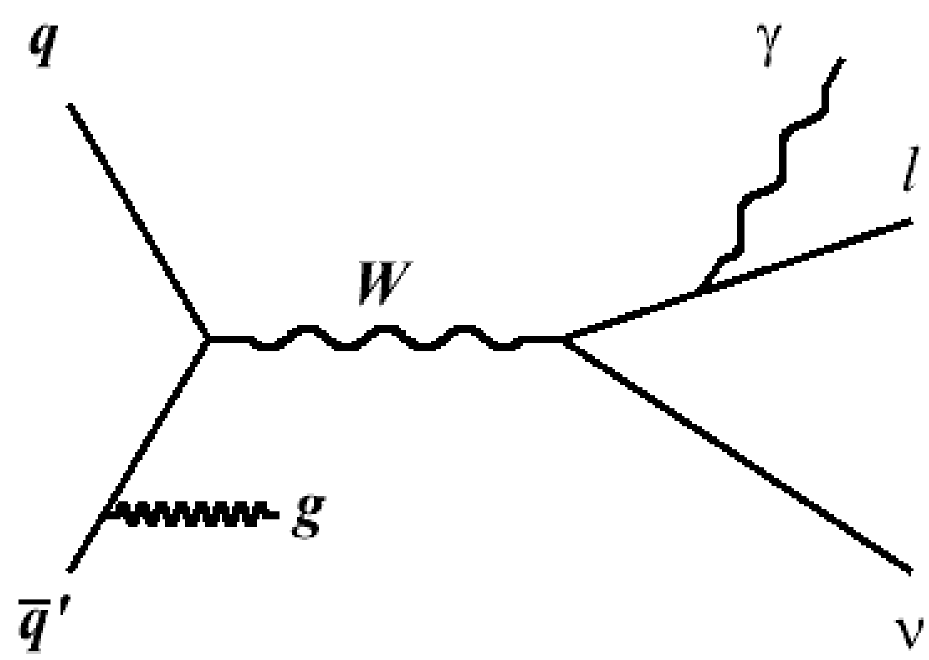
  - Binned maximum likelihood fit to templates from tuned simulation
- Combine all **six** fits to yield final answer





Selecting *W* (and *Z*) bosons at CDF

Production dominated by $q\bar{q}$ (~80%)



Select *e* and *μ* decays with high-p_T lepton trigger

Lepton candidates:
Electron E_T>30 GeV (track p_T>18 GeV) or Muon p_T>30 GeV

W boson candidates:
1 lepton passing cuts
$|\mathbf{u}| < 15$ GeV
$p_T^\nu > 30$ GeV
$60 < m_T < 100$ GeV

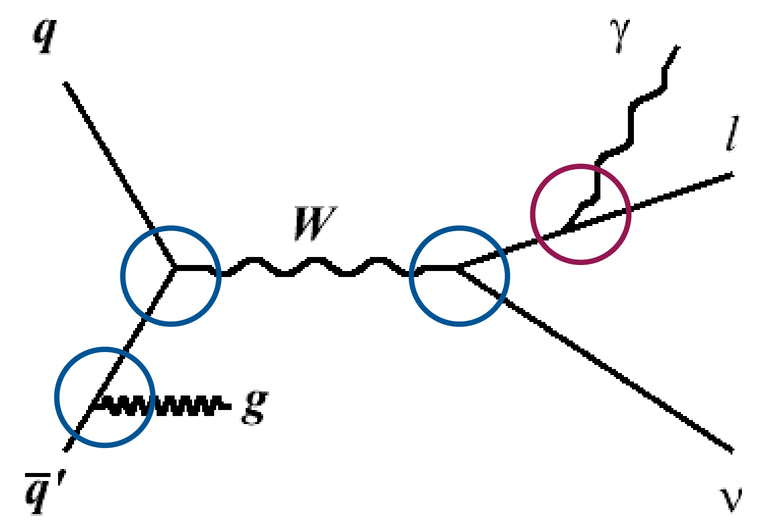
Z boson candidates:
2 lepton passing cuts
$66 < m_{ll} < 116$ GeV

Analysis dataset: **2.2 fb^{-1}**

Candidate events:
W (*e*,*μ*): 470126, 624708
Z (*e*,*μ*): 16134, 59738

Theoretical model

Event generation and boson p_T

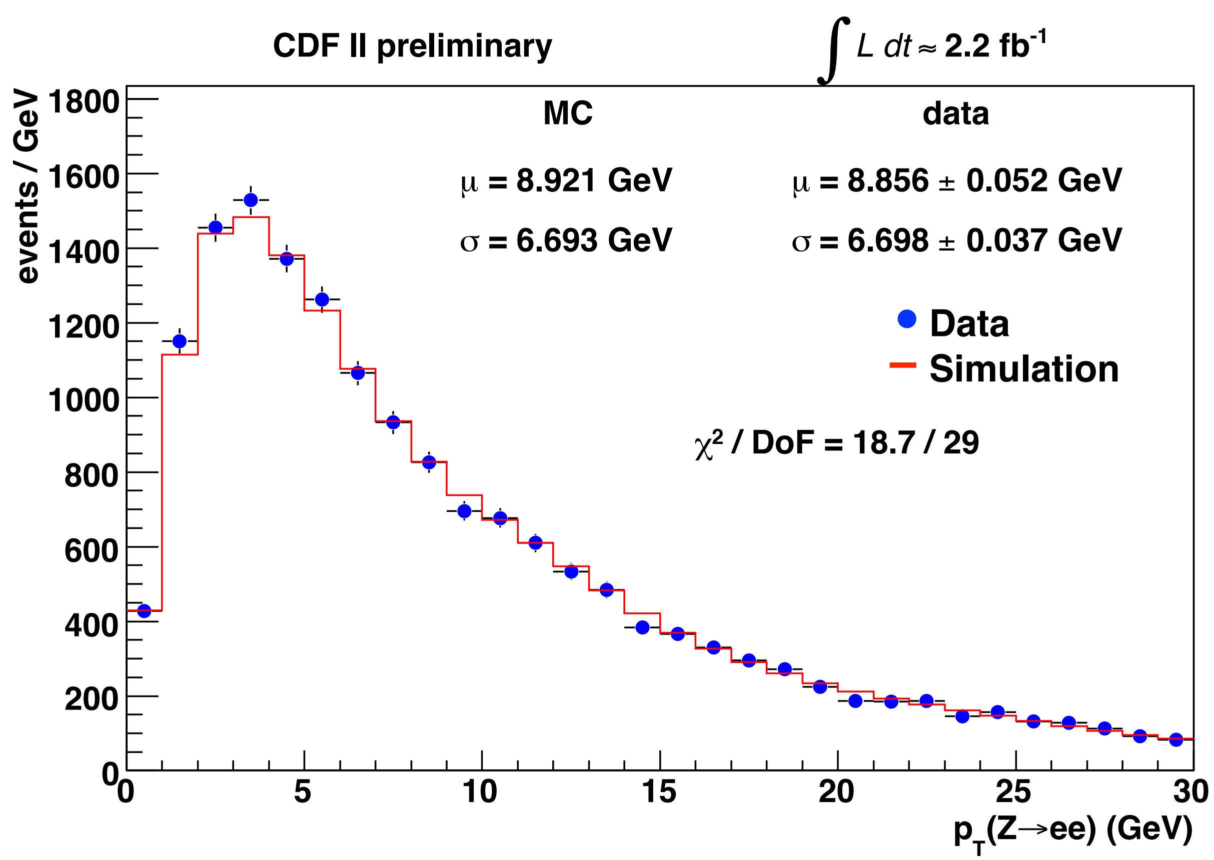


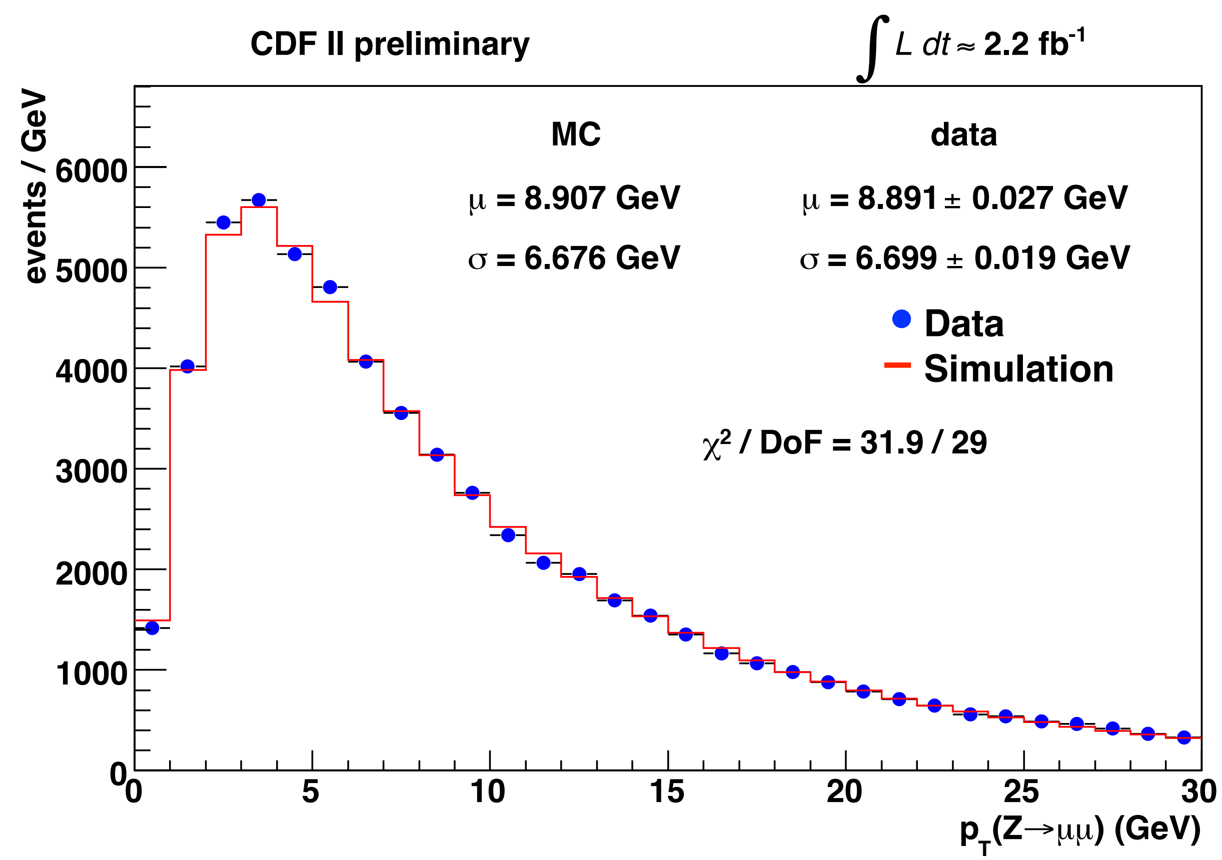
- Generator level simulation from **RESBOS**[1]
  - QCD effects, tunable parameters for non-perturbative regime (low-p_T)
- QED radiation simulated by **PHOTOS**[2]
  - Multiphoton simulation
- Fit parameters in boson p_T shape
  - Low p_T sensitive to g_2
  - Intermediate-high p_T sensitive to α_s

} ΔM_W =5 MeV

[1]*C Balazs and C-P Yuan, PRD* ***55****, 5558 (1997)*

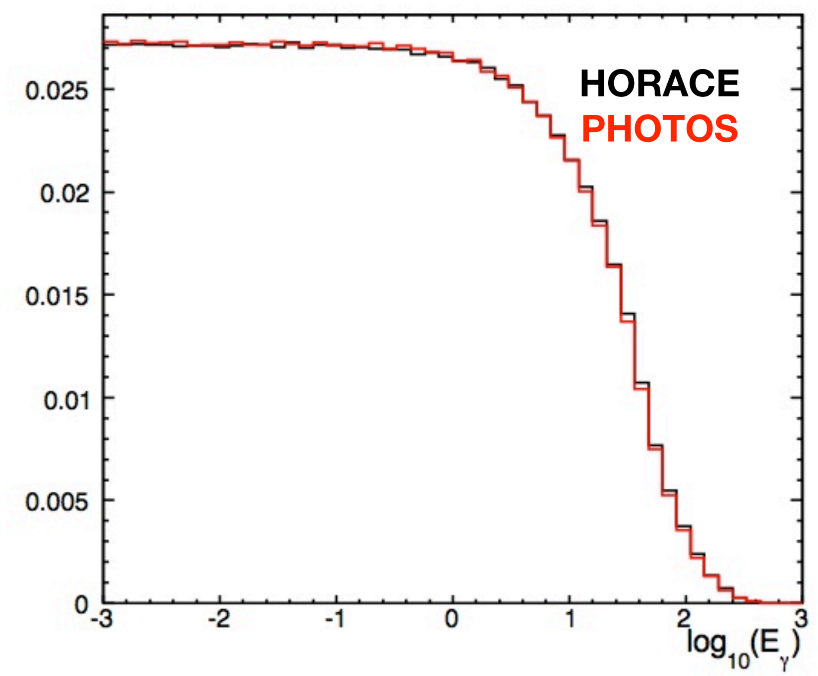
[2]*P. Golonka and Z. Was, Eur. J. Phys. C* ***45****, 97 (2006)*

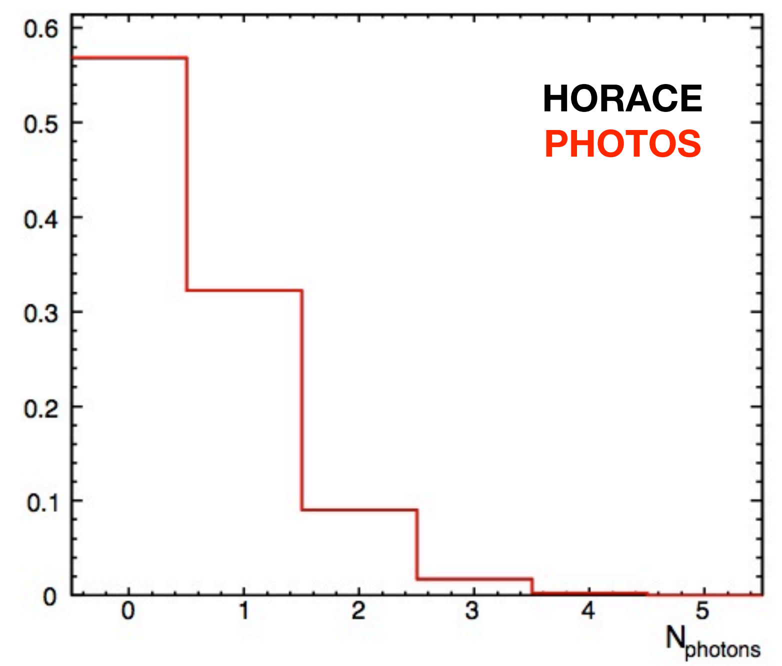




QED Radiation

- Extensive studies on QED effects using **HORACE**[1]
  - Leading log approximation vs. exact single photon calculation
  - Multi-photon calculations
  - Higher-order soft/virtual corrections
  - e^+e^- pair creation
  - ISR/FSR interference
  - Dependence on electroweak parameters/scheme
- Detailed comparison of HORACE and PHOTOS
  - Use PHOTOS in final model
- Total systematic uncertainty due to QED ΔM_W = 4 MeV
  - *c.f.* ΔM_W=11 MeV in 200/pb measurement (uncertainty dominated by subleading photons)



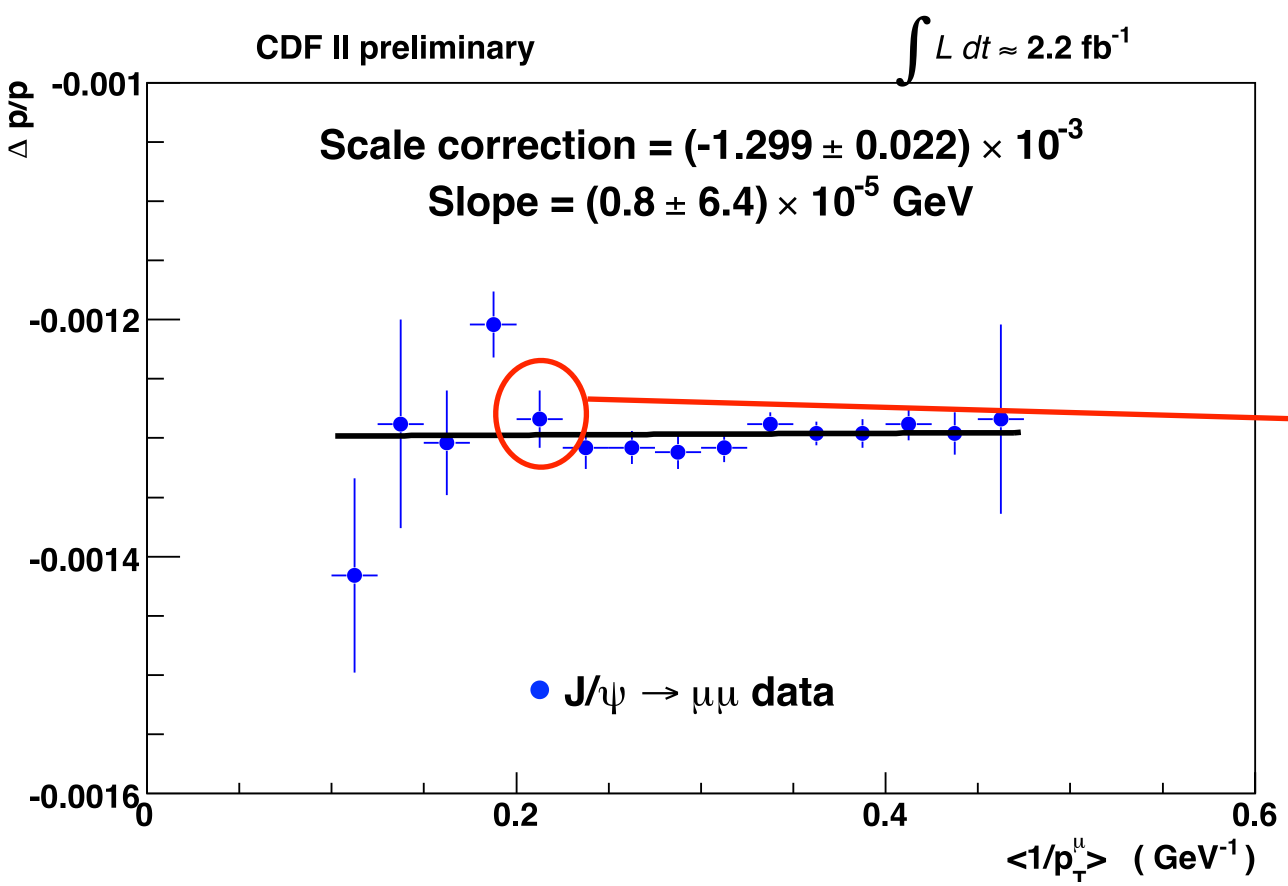


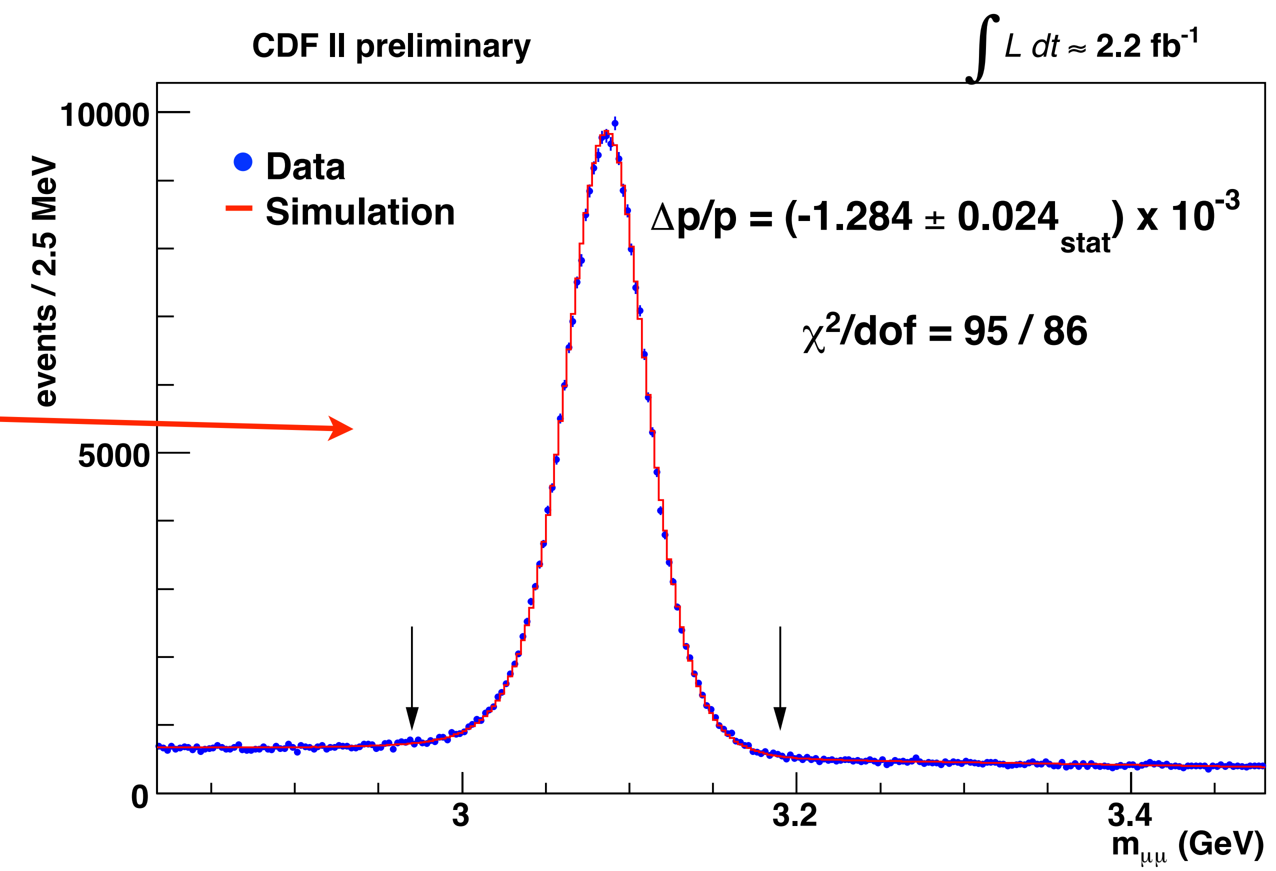
[1]*C.M. Carloni Calame, G. Montagna, O. Nicrosini and A. Vicini, JHEP **0710**:109 (2007)*

Track momentum scale

Track momentum scale: J/ψ

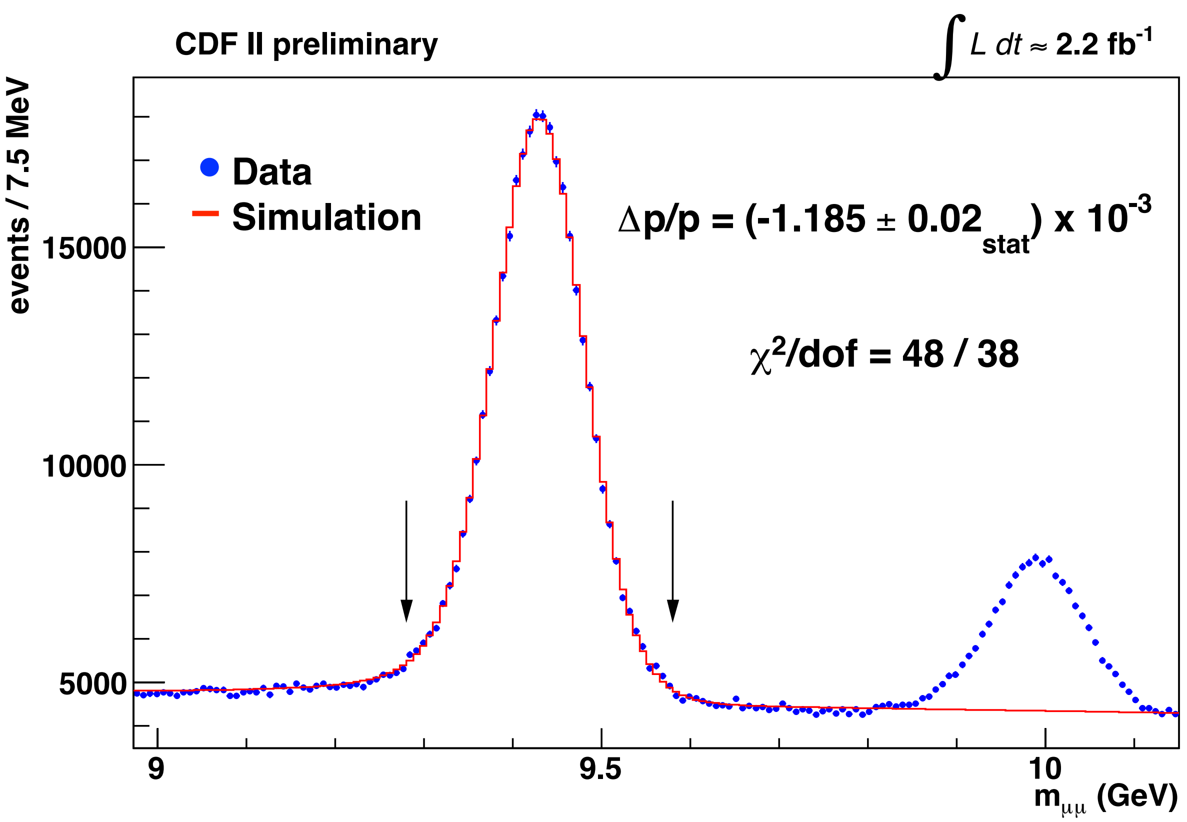
- Utilize large μμ resonances (J/ψ, Υ, Z) to set overall momentum scale
- Size of J/ψ sample allows subsample fits
  - Correct for non-uniformities in B-field
  - Fit J/ψ mass in bins of $<1/p_T(\mu)>$ and apply material scale (4%) to remove depedence
- Apply calibration from J/ψ to Υ



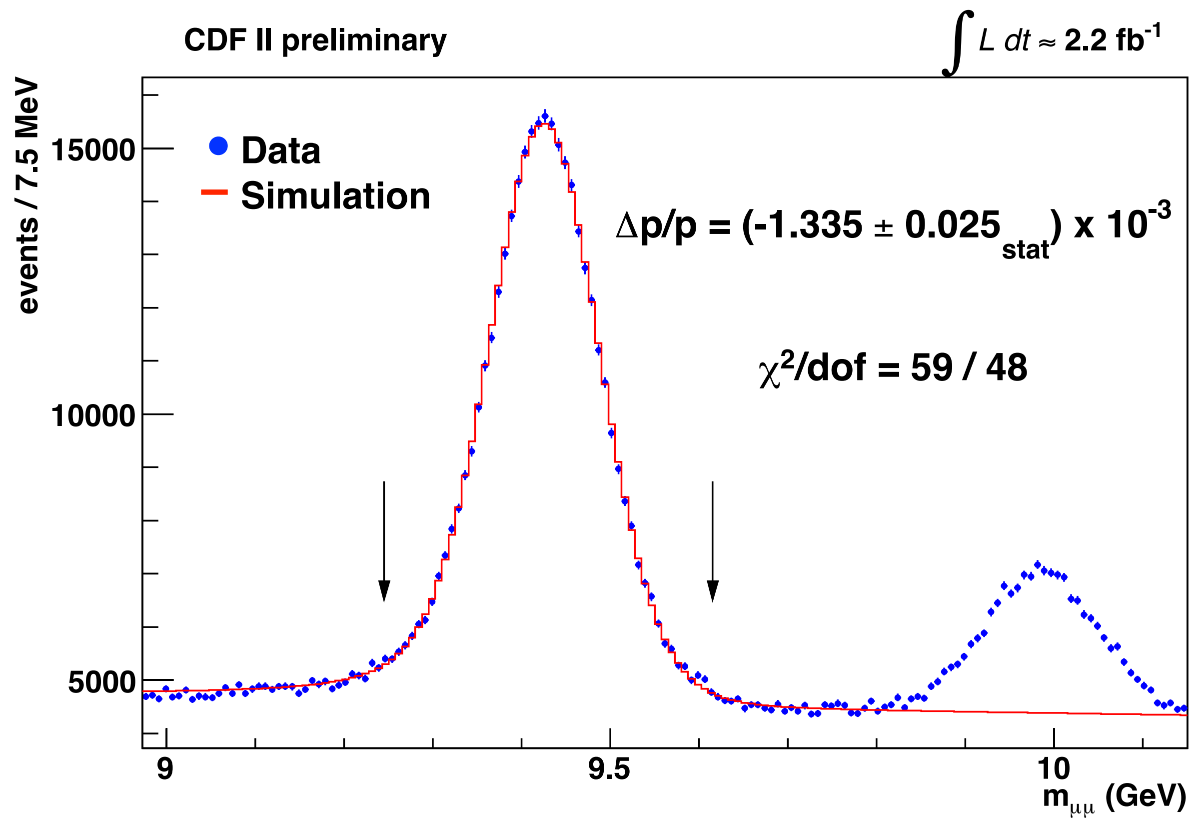


Track momentum scale: Υ

- Υ sample provides higher-p_T sample to tune scale
  - Υs produced promptly: validation of beam-constraining (BC) procedure
  - Perform fit with BC and non-BC tracks
    - Take average of two fits, assign systematic
- Combine J/ψ and Υ scales and apply to Zs



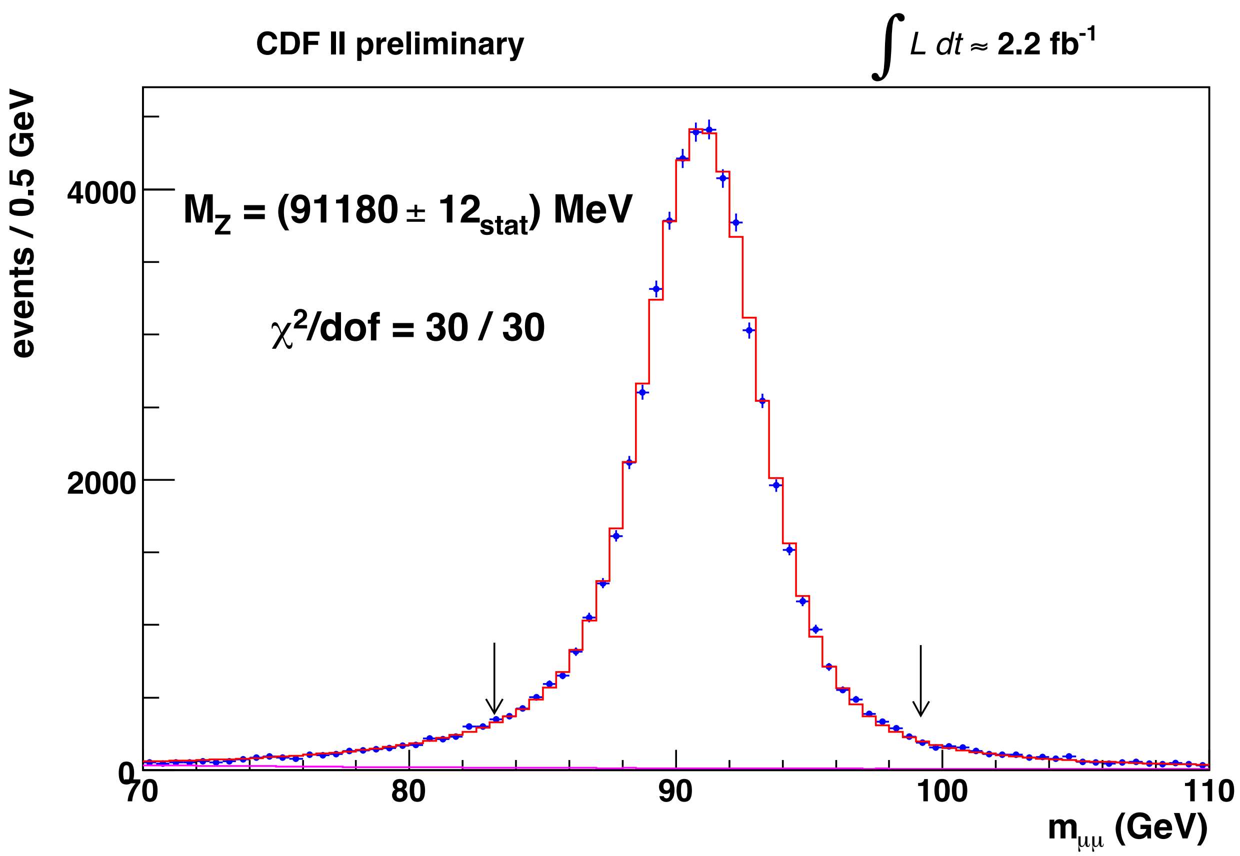
Beam constrained tracks

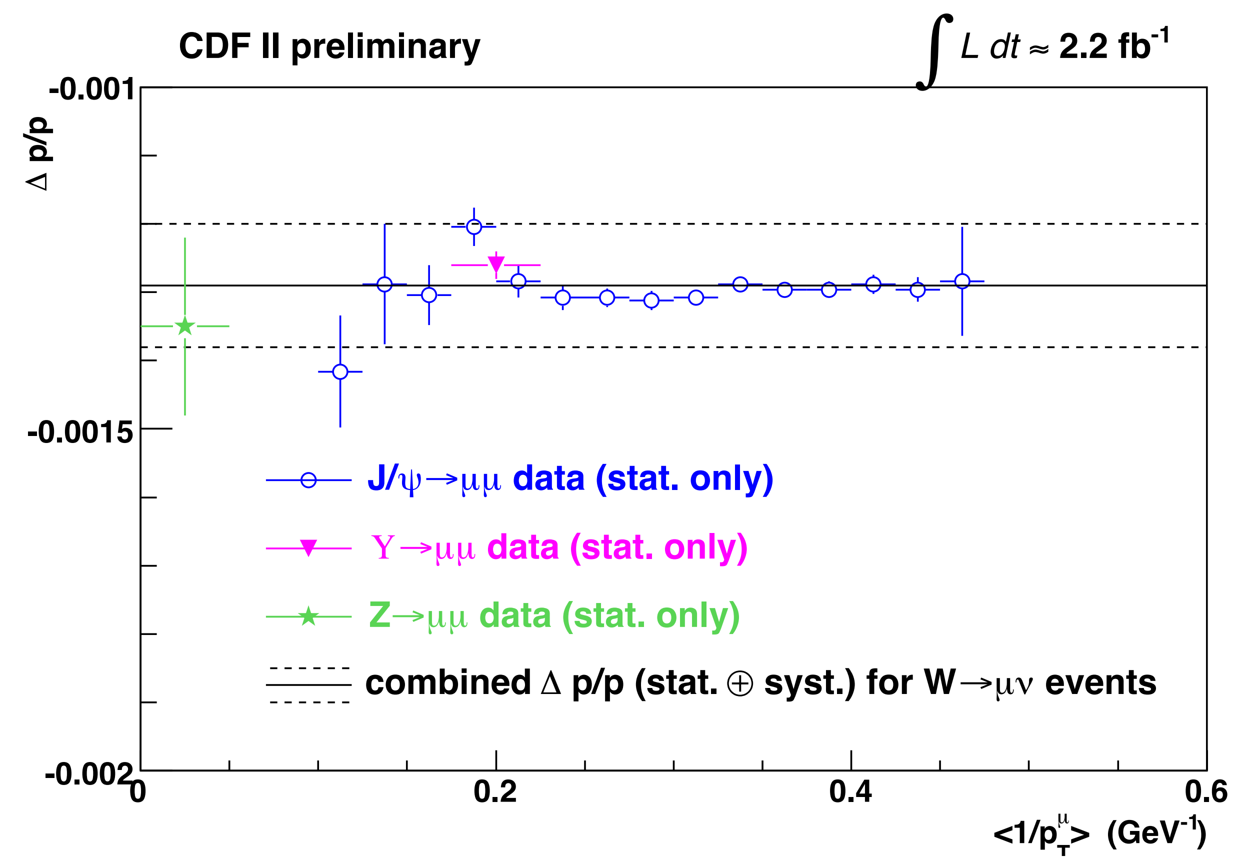


Non-beam constrained tracks

Muon Z mass and final track momentum scale

- Perform **independent** measurement of Z mass using tuned momentum scale
  - $M_Z = 91180 \pm 12_{stat} \pm 9_{p\text{-}scale} \pm 5_{QED} \pm 2_{alignment} = 91180 \pm 16$ MeV
  - Excellent agreement with LEP average (91188±2 MeV)
- Add Z data as final calibration point for momentum scale
  - $\boldsymbol{\Delta p/p_{final} = (-1.29 \pm 0.07_{stat} \pm 0.05_{QED} \pm 0.02_{align}) \times 10^{-3}}$
  - Apply scale to W muons and E/p calibration
  - Systematic uncertainty $\Delta M_W = 7$ MeV

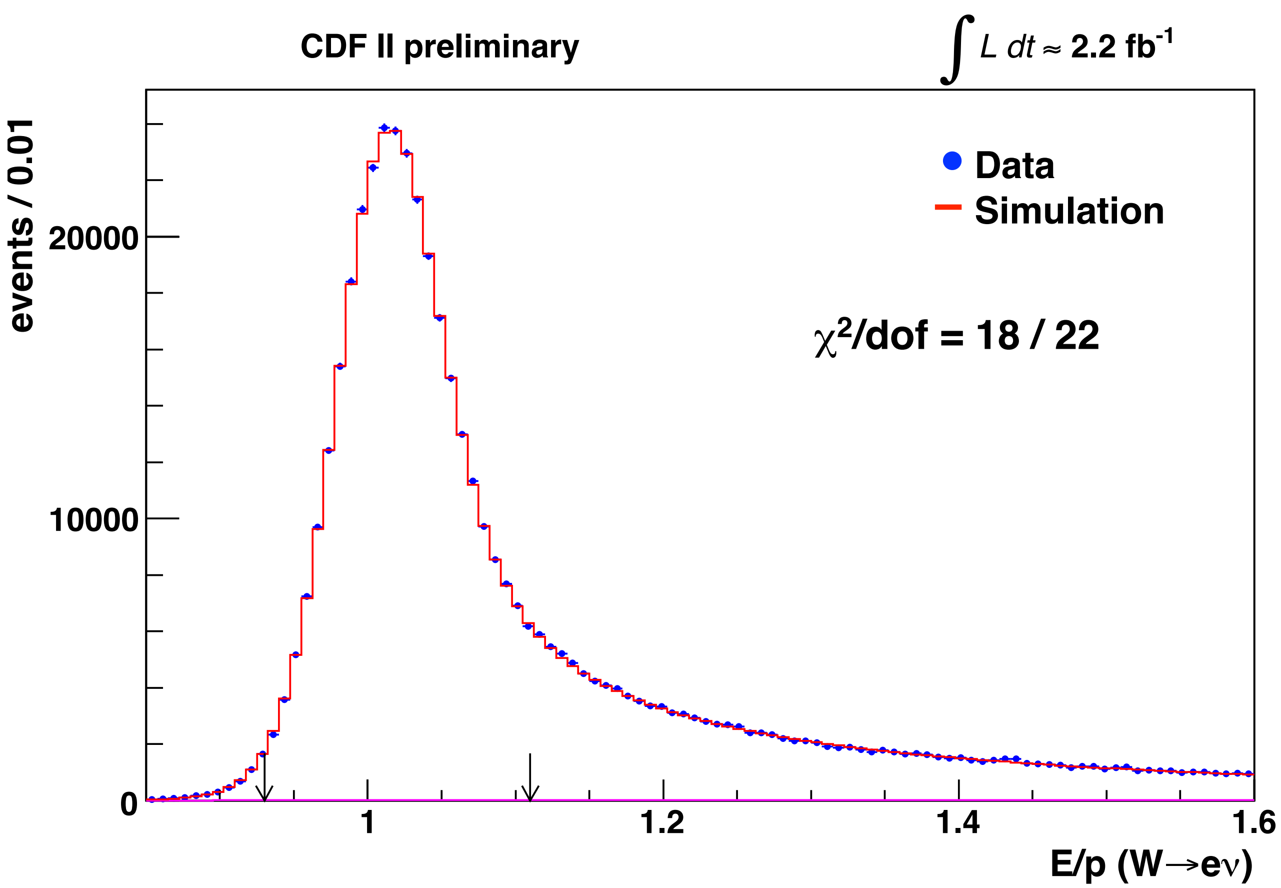


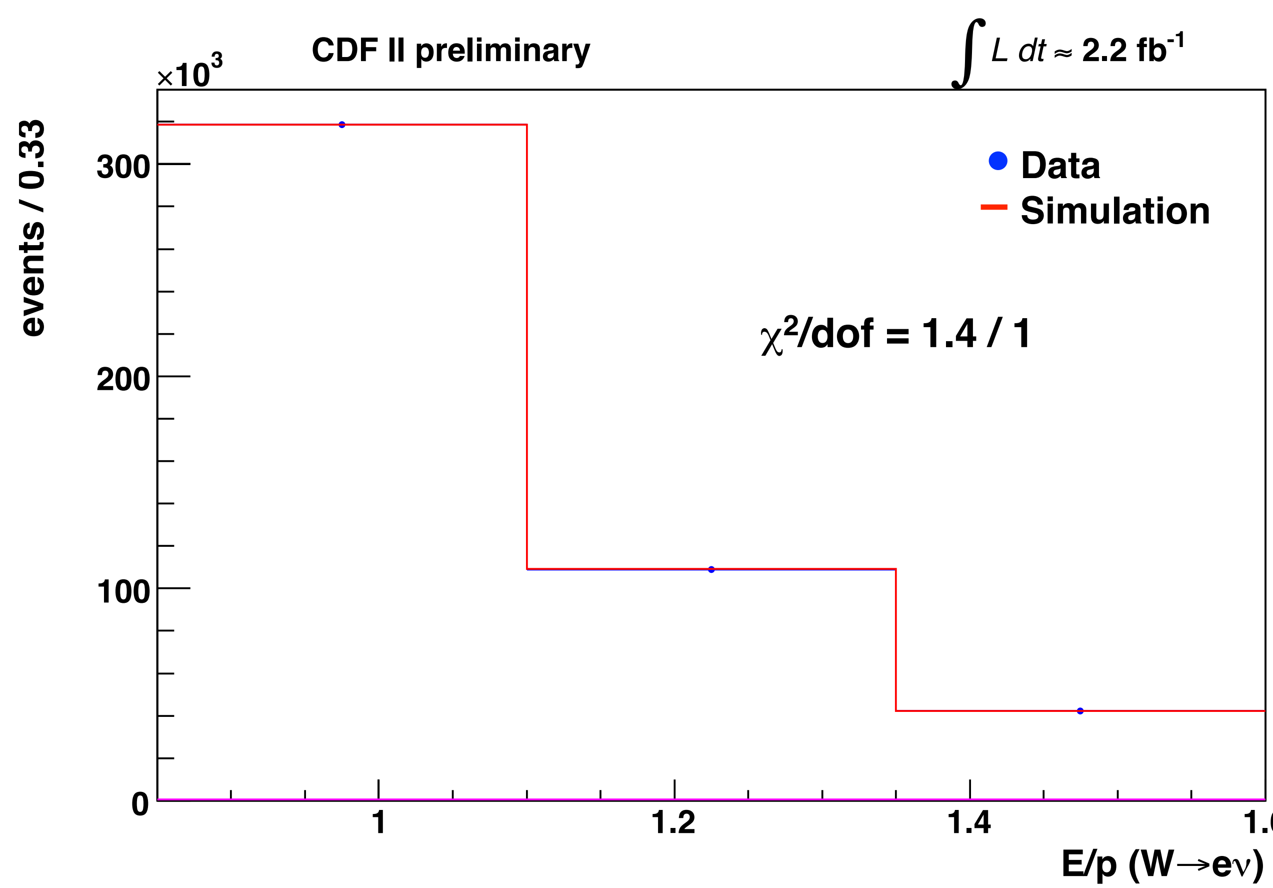


EM calorimeter scale

Energy scale calibration

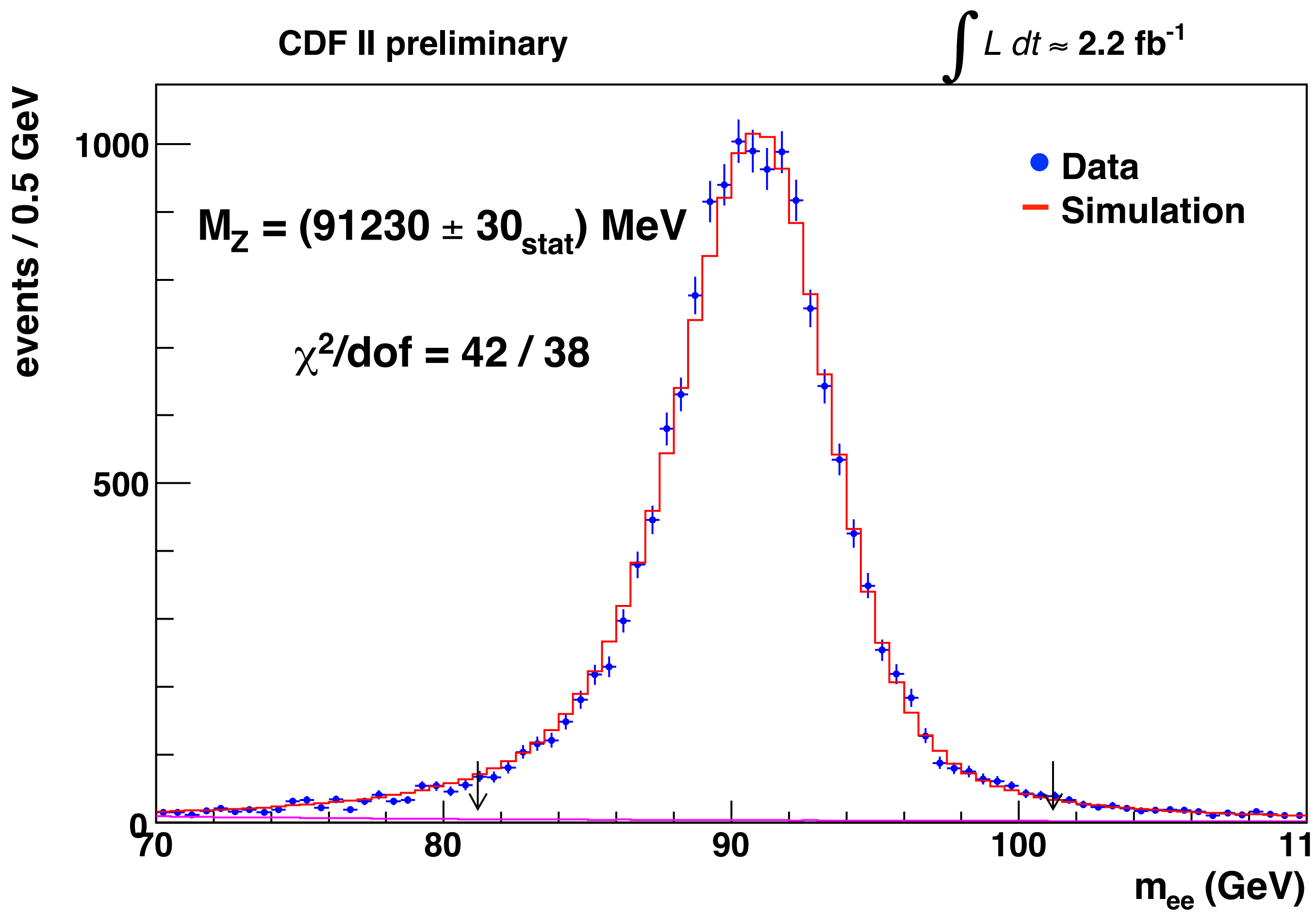
- Simulate energy loss with custom GEANT4-based simulation
  - Simulate coil absorption, leakage into had. calorimeter, E_T dependence
- Calibrate EM calorimeter response using *W* and *Z E/p* distributions
  - Fit to peak to obtain scale and non-linearity (E_T dependent)
    - $\Delta S_E = (9_{stat} \pm 5_{non\text{-}linearity}) \times 10^{-5}$
  - Fit to tail to tune amount of radiative material
    - $S_{X0} = 1.026 \pm 0.003_{stat} \pm 0.002_{bkg}$
- Systematic uncertainty ΔM_W=13 MeV





Electron Z mass and final EM energy scale

- Perform **independent** measurement of Z mass using calibrated EM scale
  - Does not use p-scale that includes Z mass calibration
  - $M_Z = 91230 \pm 30_{stat} \pm 10_{E/p} \pm 8_{p\text{-}scale} \pm 5_{QED} \pm 2_{alignment} = 91230 \pm 33$ MeV
  - Excellent agreement with world average M_Z=91188±2 MeV
- Additional calibration using M_Z combined with calibration
  - Systematic uncertainty ΔM_W =10 MeV



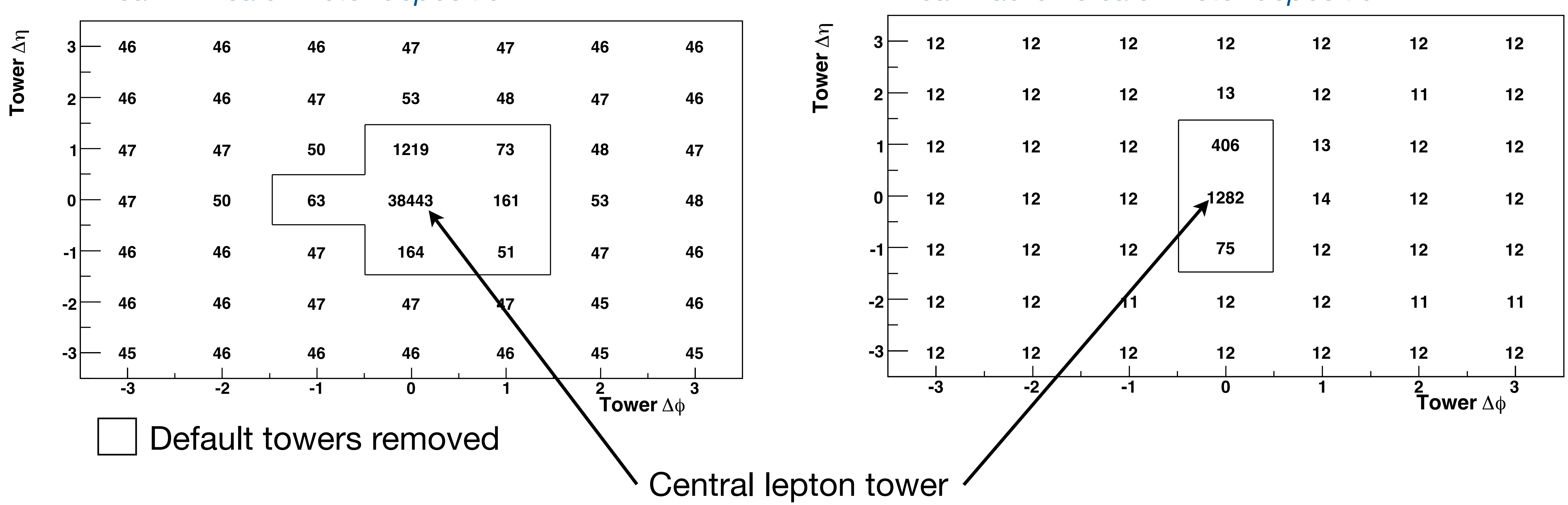
Hadronic recoil

Hadronic recoil: lepton removal

- Hadronic recoil ***u*** is vector sum of all calorimeter towers minus towers containing lepton energy
- Some underlying event energy removed with “lepton towers”
  - Estimate using rotated lepton removal windows
  - Systematic uncertainty $\Delta M_W = 2$ MeV

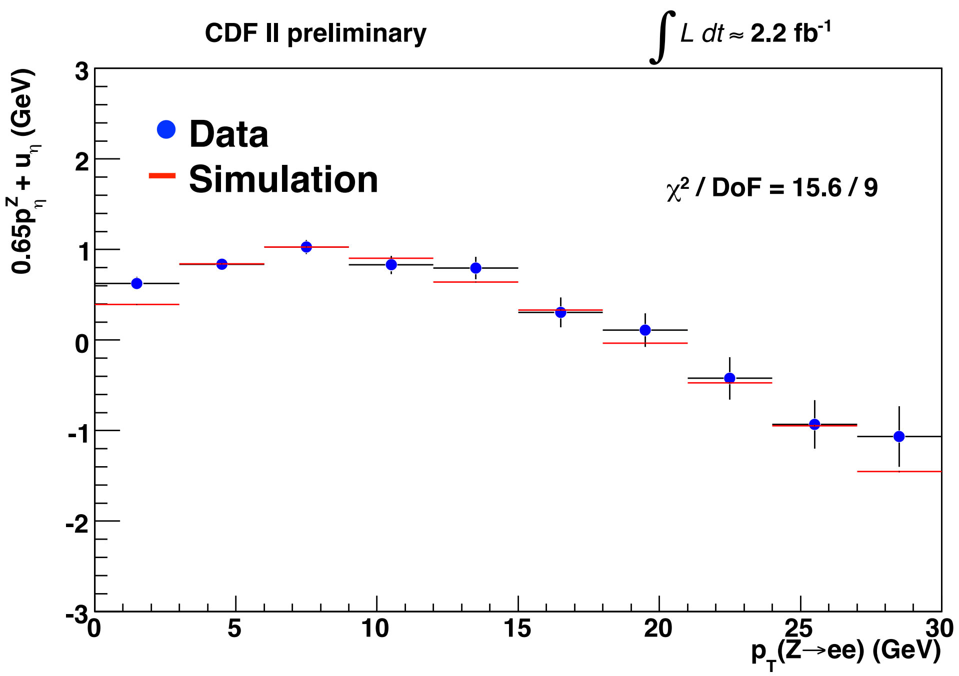
Electron channel W data:
Mean EM calorimeter deposition

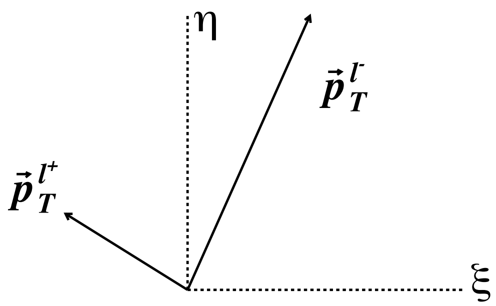
Muon channel W data:
Mean hadronic calorimeter deposition

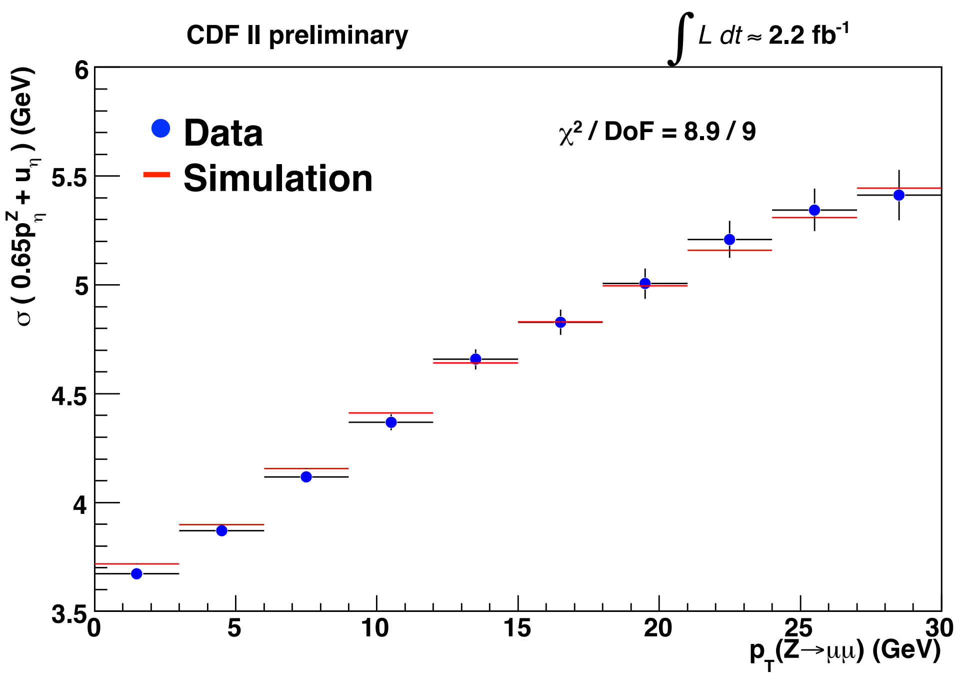


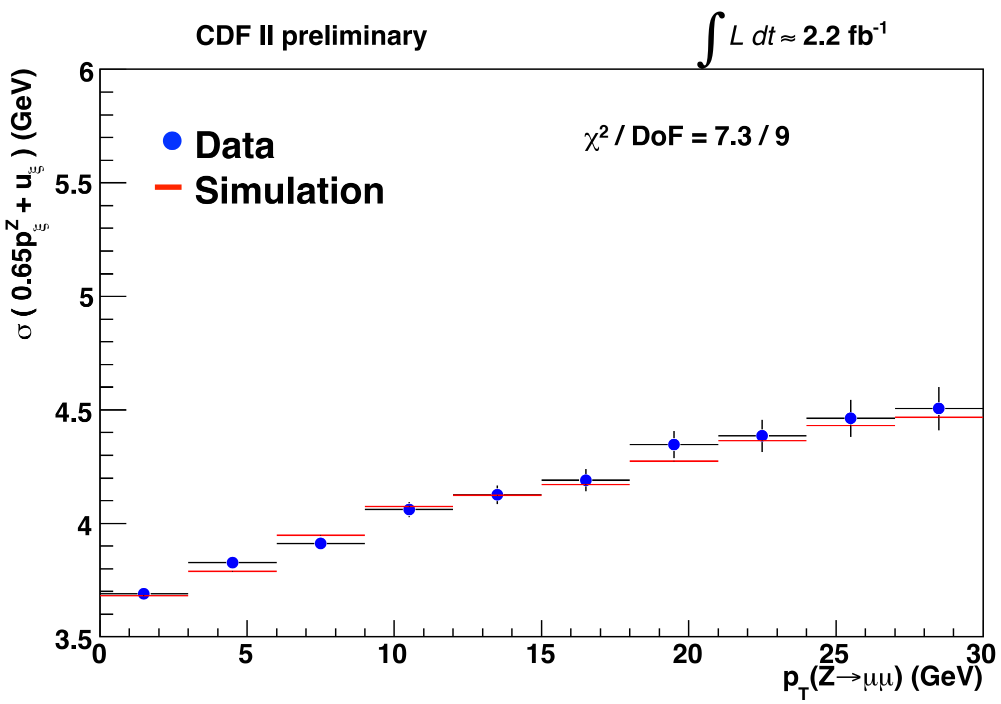
Recoil calibration

- Recoil scale $R = u_{meas}/u_{true}$
  - Calibrate by balancing Z p_T against p_T+u along eta axis ΔM_W = 4 MeV
- Recoil resolution
  - Calibrate balancing Z p_T against rms(p_T+u) along both axes ΔM_W = 4 MeV



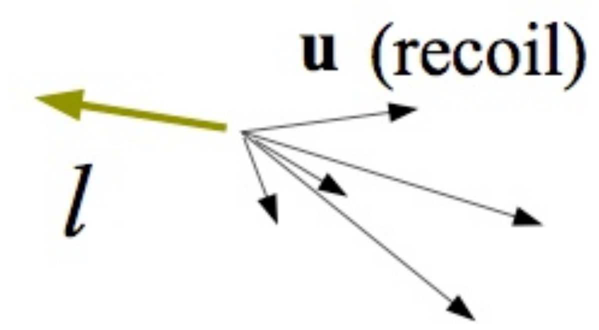


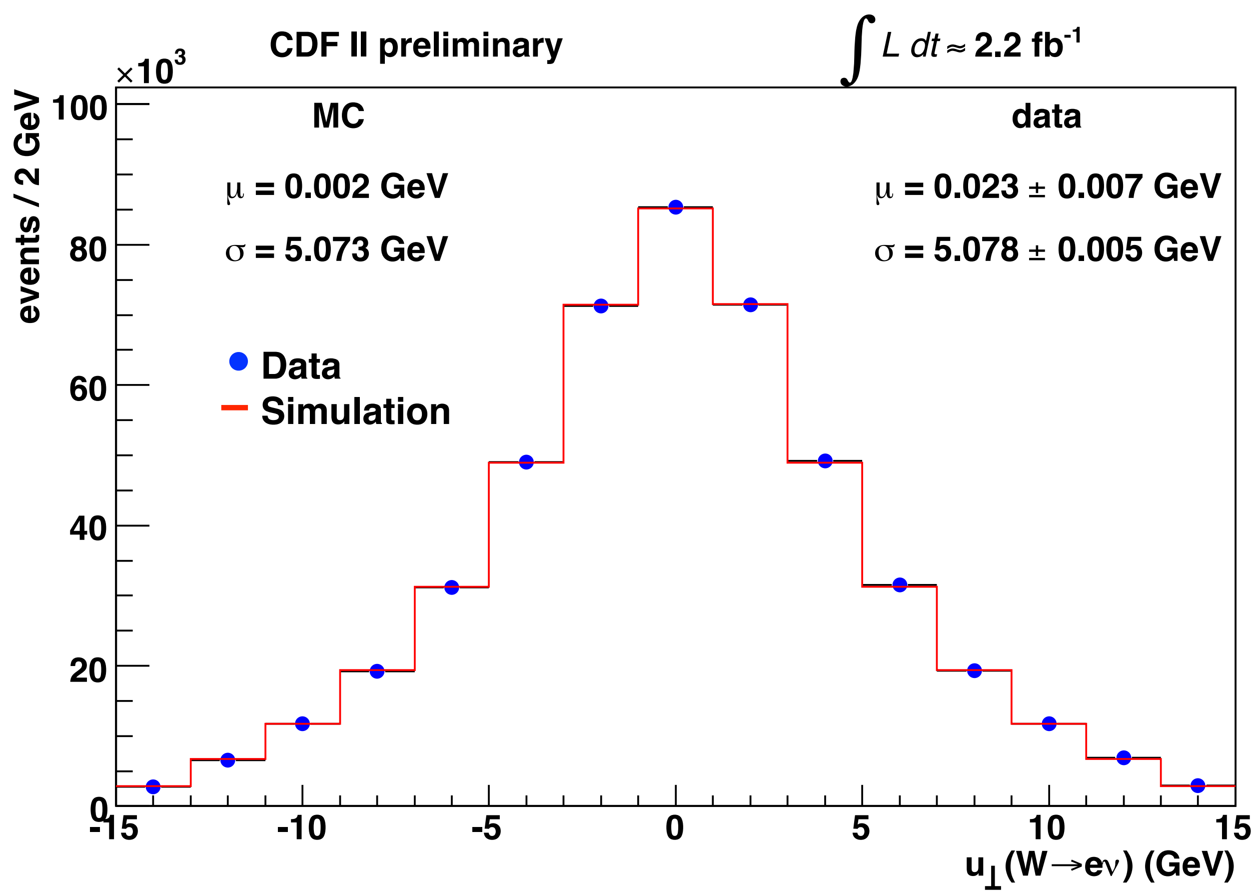




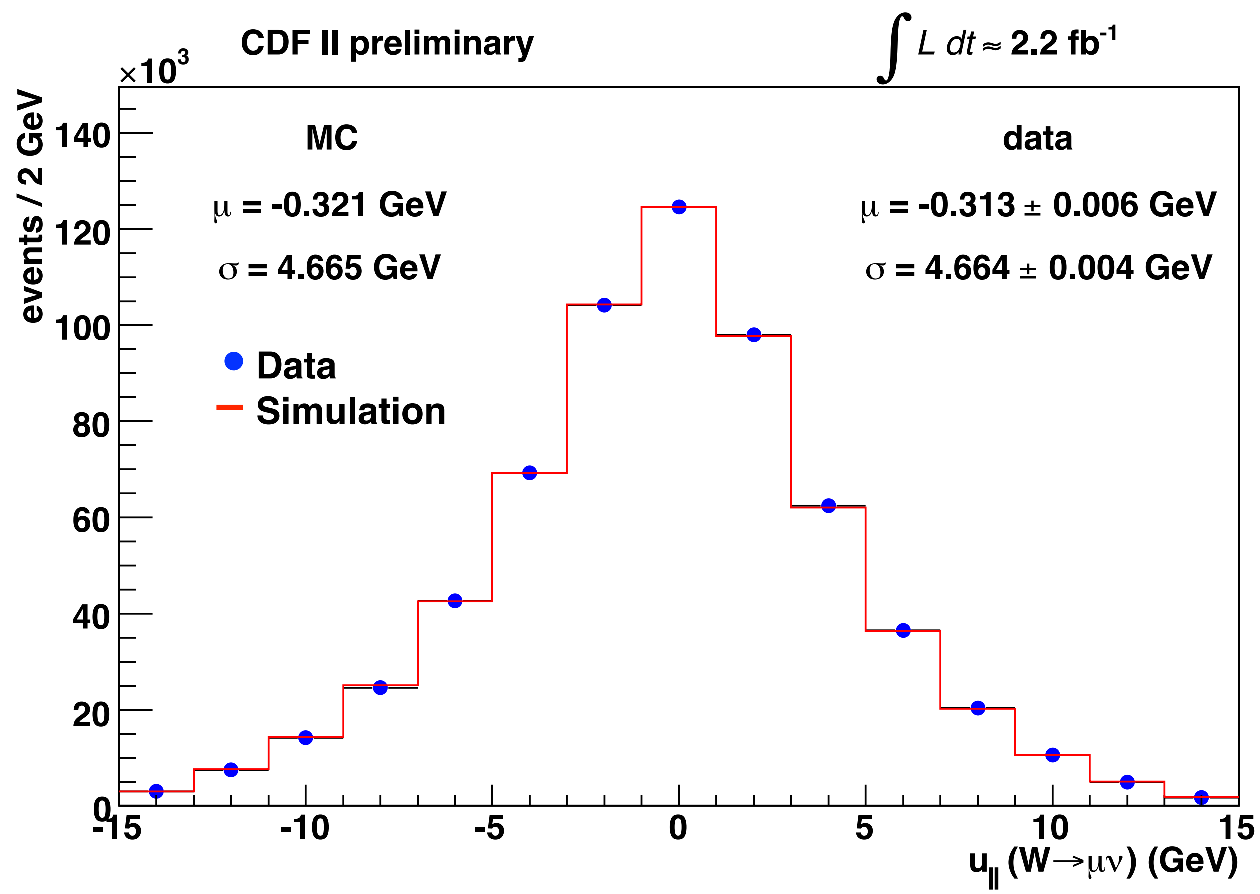
Recoil validation

- Test recoil model with W events
  - Compare measured recoil in data to model tuned with Z





Recoil projection perpendicular to lepton



Recoil projection in direction of lepton

Parton distribution functions and backgrounds

PDFs

- Utilize CTEQ6.6 PDF as default
- Evaluate 90% CL uncertainty eigenvectors for MSTW2008 and CTEQ6.6 (consistent)
- Use 68% CL MSTW2008 to determine systematic ΔM_W=10 MeV

Backgrounds

- Estimated using a combination of data and MC-driven methods
- Except $Z \to \mu\mu$ (lost forward muon), backgrounds are small
- Include all estimated background shapes in final templates

			Δm_W (MeV)					
Background	**Fraction of W data (%)**		m_T		p_T^l		p_T^ν	
	muons	electrons	muons	electrons	muons	electrons	muons	electrons
$Z \to ll$	7.35±0.09	0.139±0.014	2	1	4	2	5	1
$W \to \tau\nu$	0.880±0.004	0.93±0.01	0	1	0	1	0	1
QCD	0.035±0.025	0.39±0.14	1	4	1	2	1	4
Decay-in-flight	0.24±0.02		1		3		1	
Cosmic Rays	0.02±0.02		1		1		1	
Total			*3*	*4*	*5*	*3*	*6*	*4*

muons

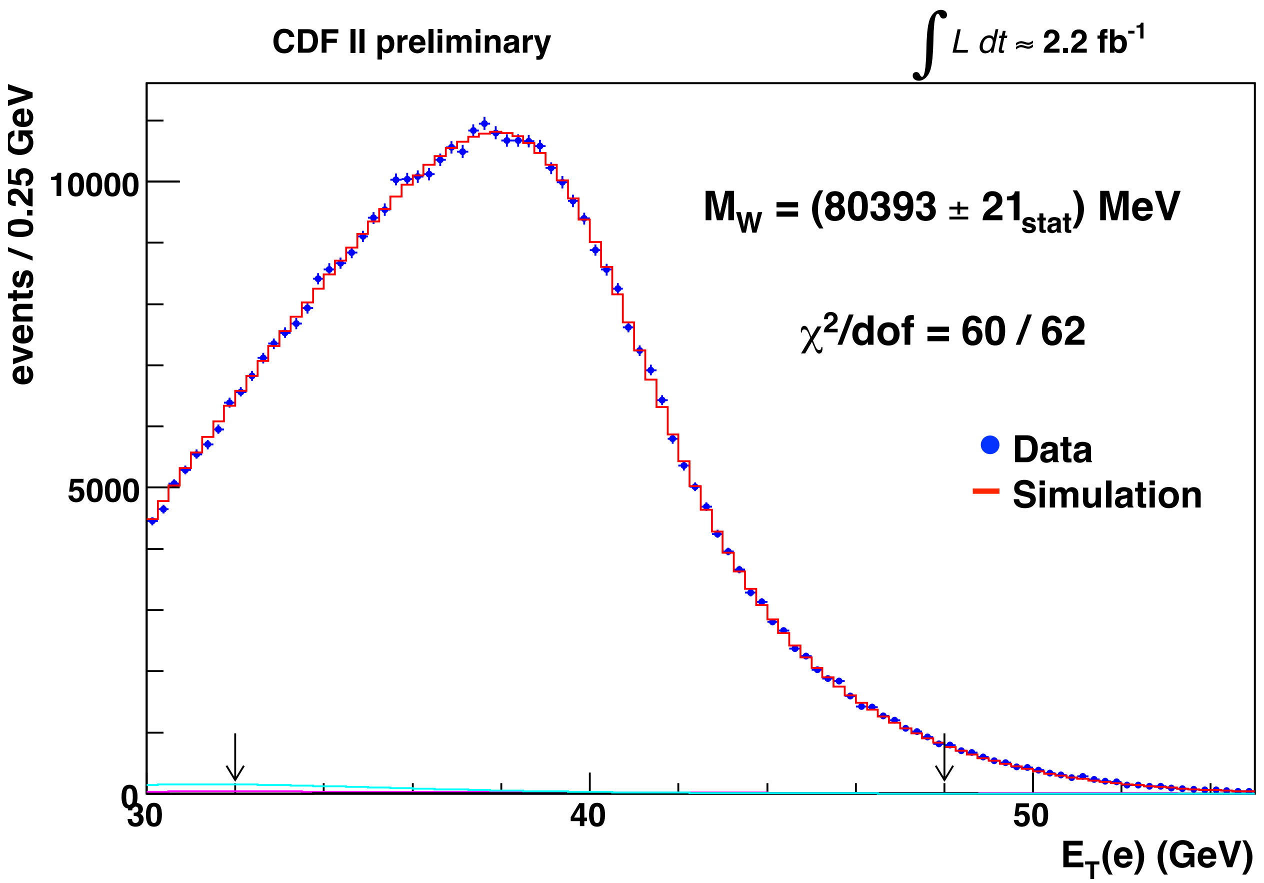
electrons

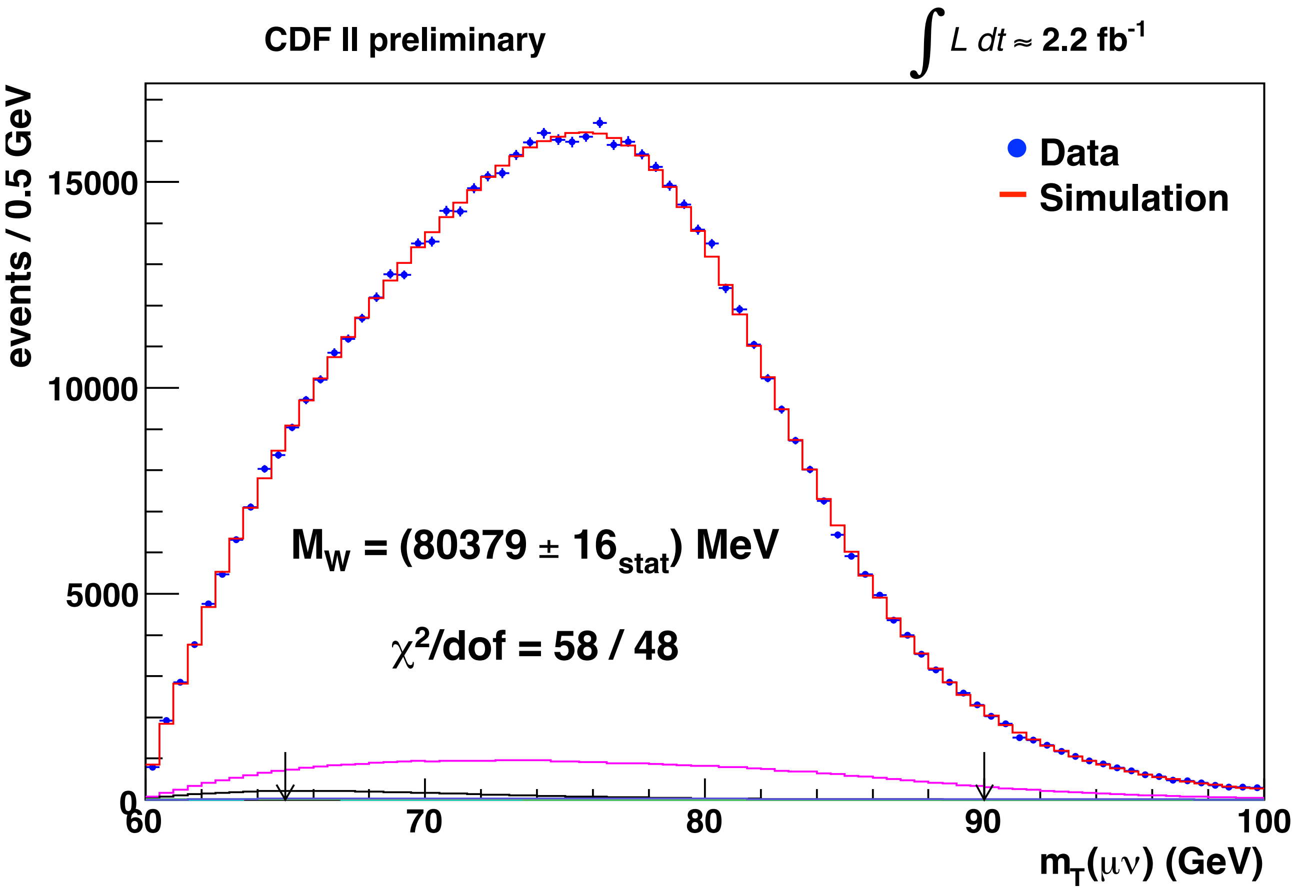
Results

A word on blinding

- During development of analysis, all fits **blinded** with random offset from [-75,75] MeV
  - Common offset applied to all six mass fits
    - Allows for comparison and cross-check
  - During calibration of energy scales, separate offset applied to Z mass fits
- Blinding offset removed only after analysis frozen
  - No changes made since removal

Example mass fits



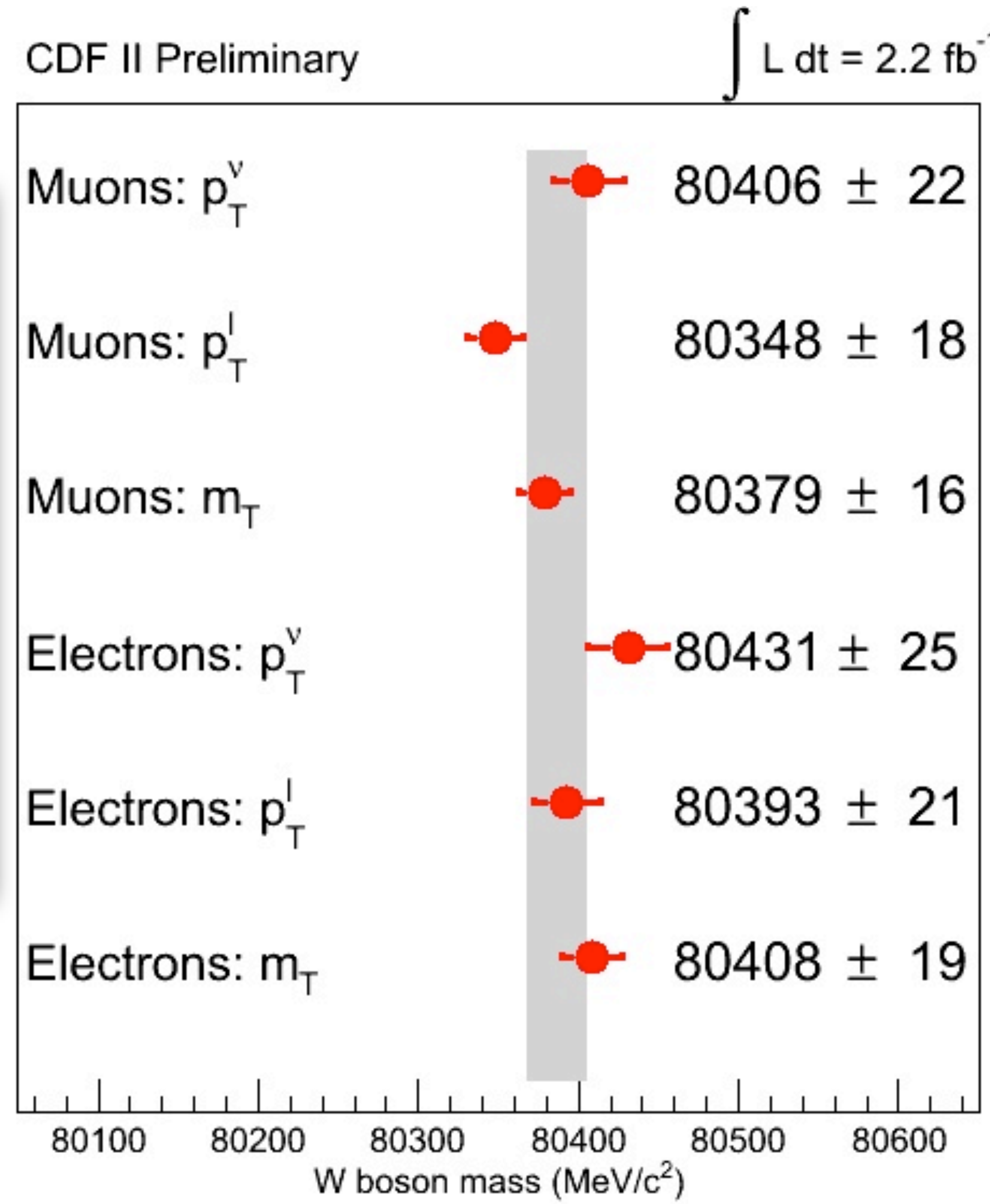


p_T^l: electrons

m_T: muons

All fits

Fit	Fit result (MeV)	χ^2/dof
$W \to e\nu$ (m_T)	80408±19	52/48
$W \to e\nu$ (p_T^l)	80393±21	60/62
$W \to e\nu$ (p_T^ν)	80431±25	71/62
$W \to \mu\nu$ (m_T)	80379±16	57/48
$W \to \mu\nu$ (p_T^l)	80348±18	58/62
$W \to \mu\nu$ (p_T^ν)	80406±22	82/62



Combined results

- 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%)

Combine using *BLUE*
L. Lyons, D. Gibaut, and P. Clifford,
NIM A **270**, 110 (1988).

Combined uncertainties

Source	Uncertainty 2.2 fb^{-1} (MeV)
Lepton energy scale	7
Lepton energy resolution	2
Recoil energy scale	4
Recoil energy resolution	4
Lepton removal	2
Backgrounds	3
p_T (W) model	5
PDFs	10
QED radiation	4
Total systematics	*15*
W statistics	12
Total	***19***

$$M_W = 80387 \pm 12_{stat} \pm 15_{syst}\ \mathrm{MeV}/c^2$$

Combined uncertainties

Statistics limited by control data

Theory based (external inputs)

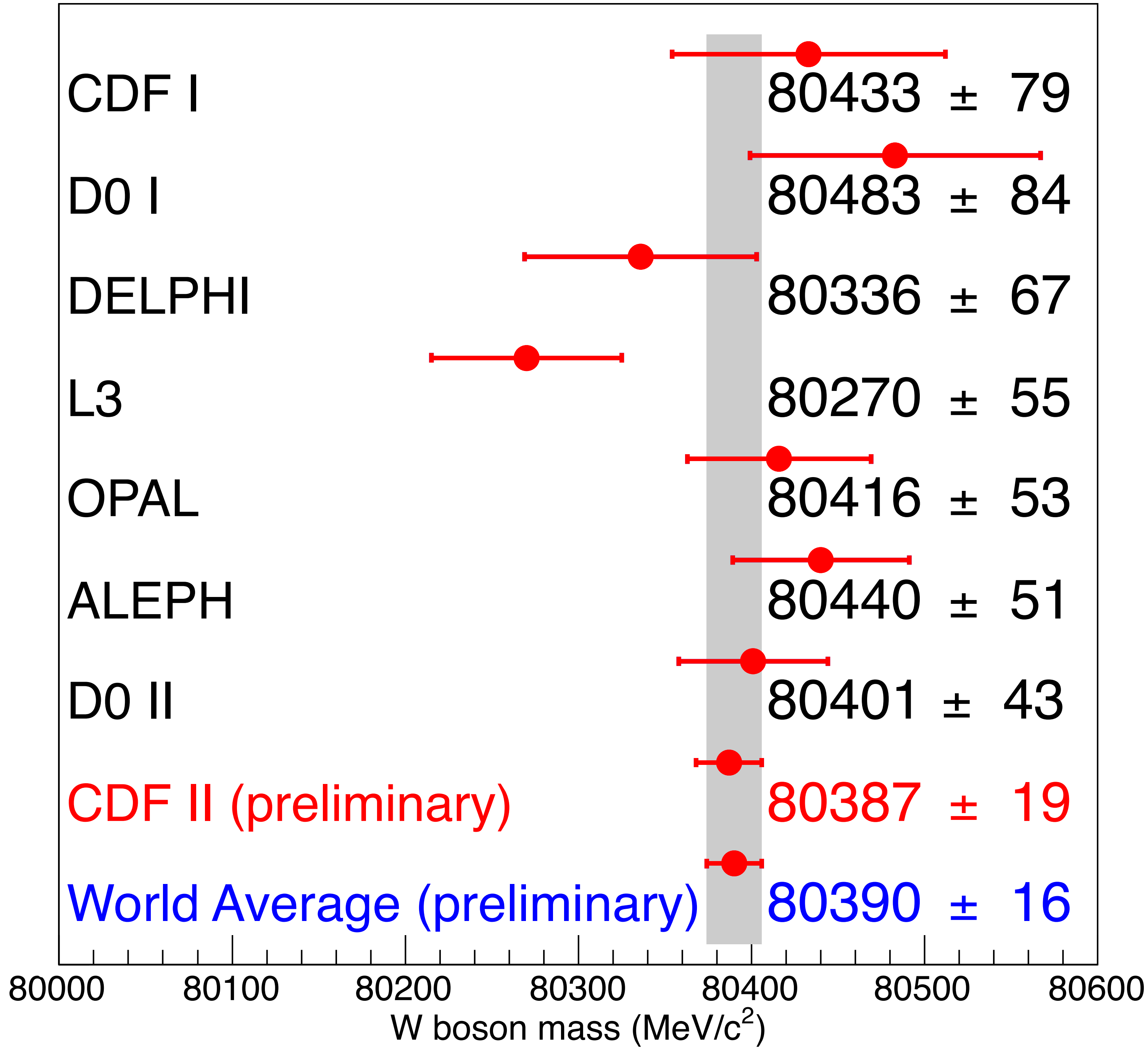
Source	Uncertainty 2.2 fb^{-1} (MeV)	Uncertainty 0.2 fb^{-1} (MeV)
Lepton energy scale	7	23
Lepton energy resolution	2	4
Recoil energy scale	4	8
Recoil energy resolution	4	10
Lepton removal	2	6
Backgrounds	3	6
p_T (W) model	5	4
PDFs	10	11
QED radiation	4	10
Total systematics	*15*	*34*
W statistics	12	34
Total	***19***	***48***

$$M_W = 80387 \pm 12_{stat} \pm 15_{syst} \text{ MeV}/c^2$$

W mass measurements and world average

Previous world average
M_W = 80399 ± 23 MeV

New CDF measurement significantly exceeds precision of all previous measurements of M_W combined!



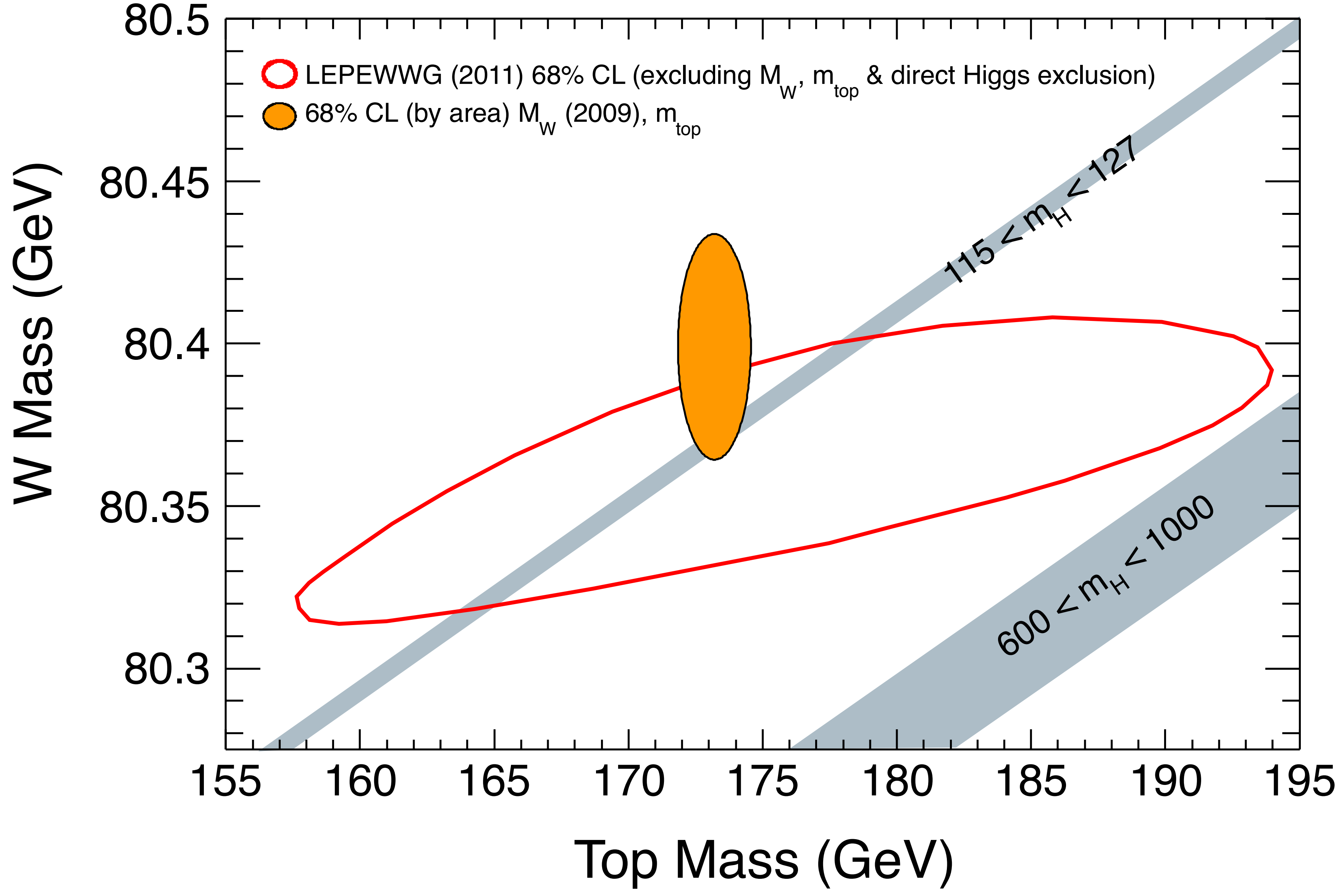
Averaging procedure from TeVEWWG (arXiv:0908.1374)

M_W vs. m_{top}

With M_W = 80399±23 MeV

$M_H = 92^{+34}_{-26}$ GeV
M_H < 161 GeV @95% CL

LEPEWWG/ZFitter



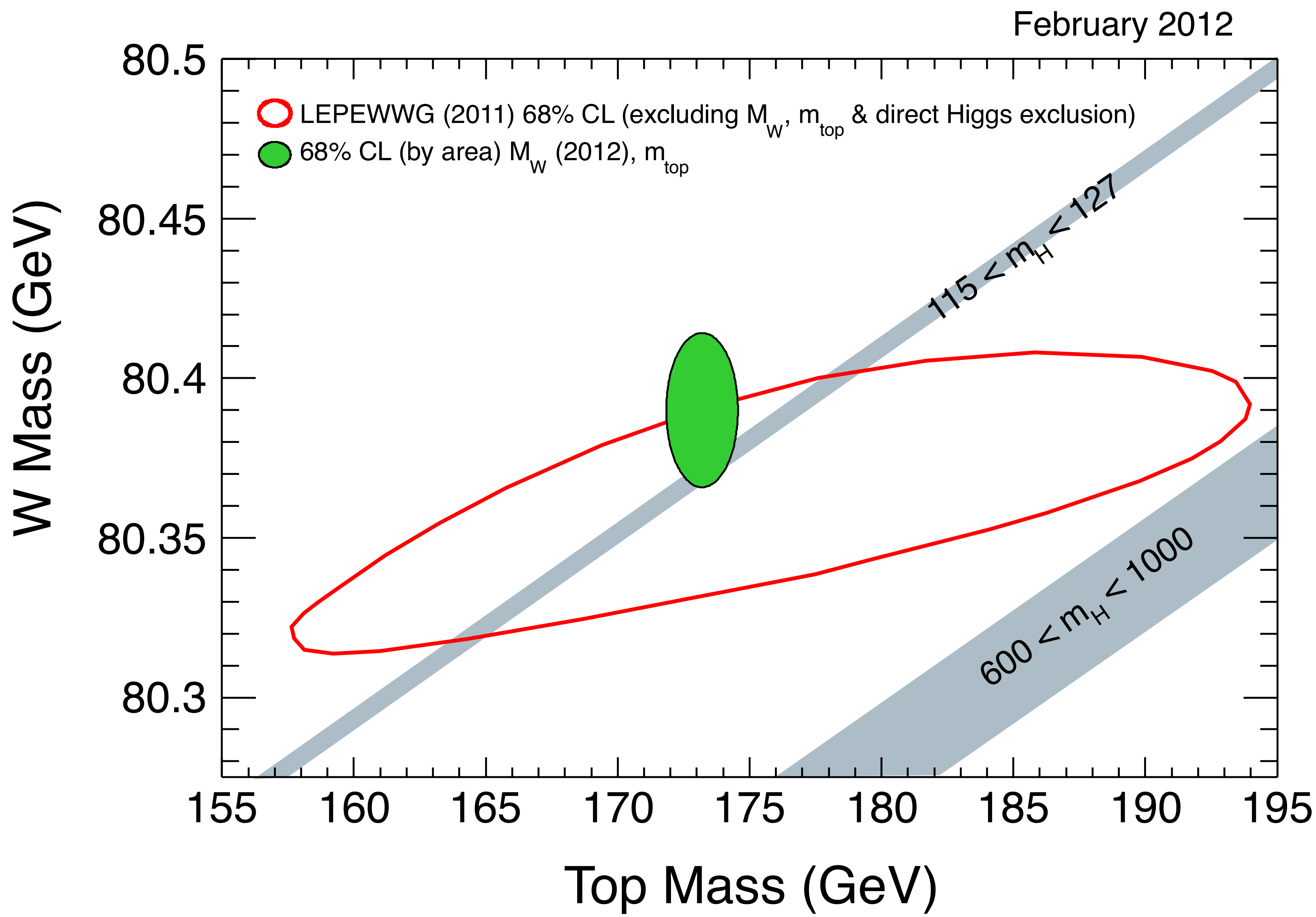
M_W vs. m_{top}

With M_W = 80390±16 MeV

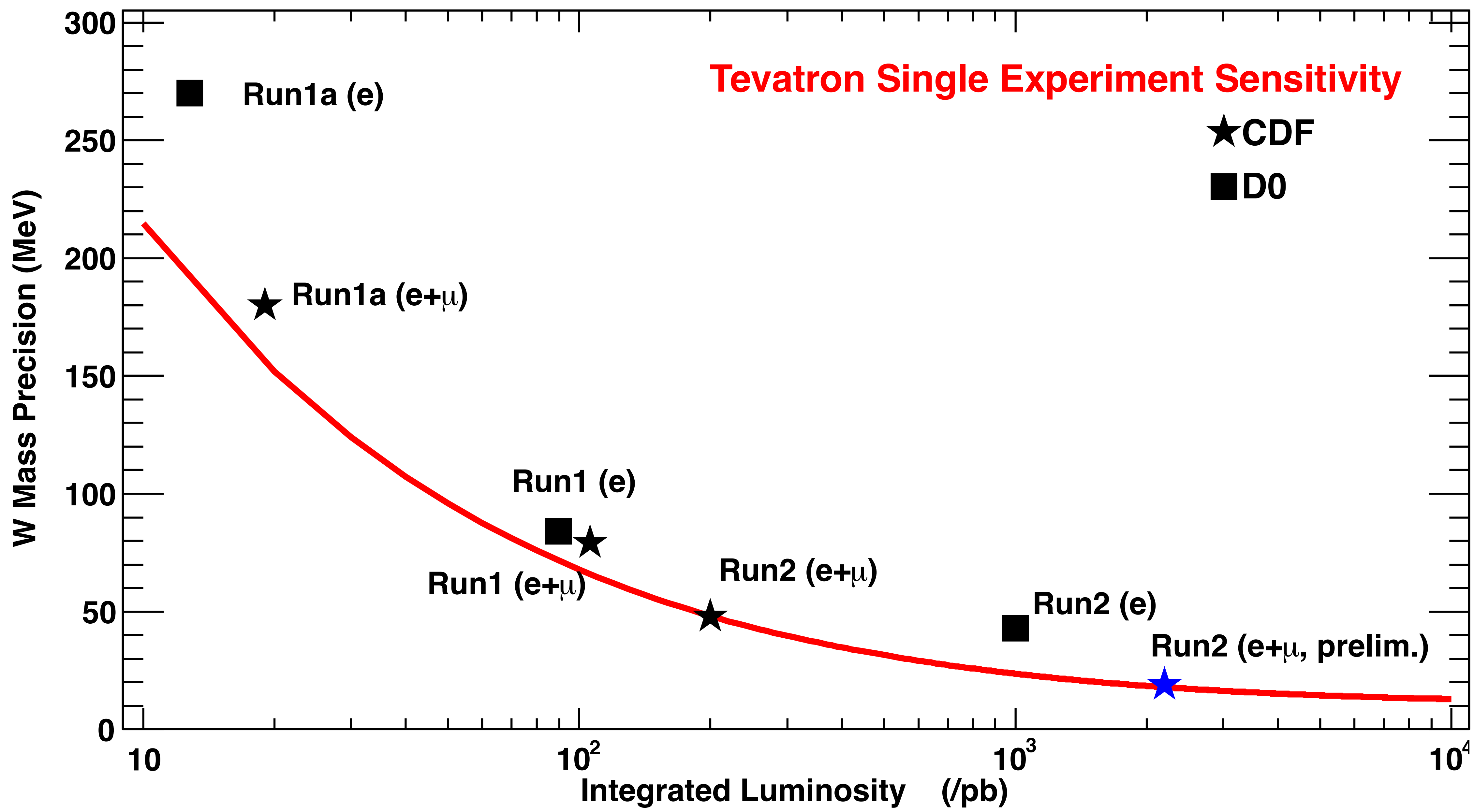
$M_H = 90^{+29}_{-23}$ GeV

M_H < 145 GeV @95% CL

LEPEWWG/ZFitter



Uncertainty projections



- Projection assumes PDF+QED errors (11 MeV) fixed
  - Become limiting uncertainty for measurements with full Tevatron dataset

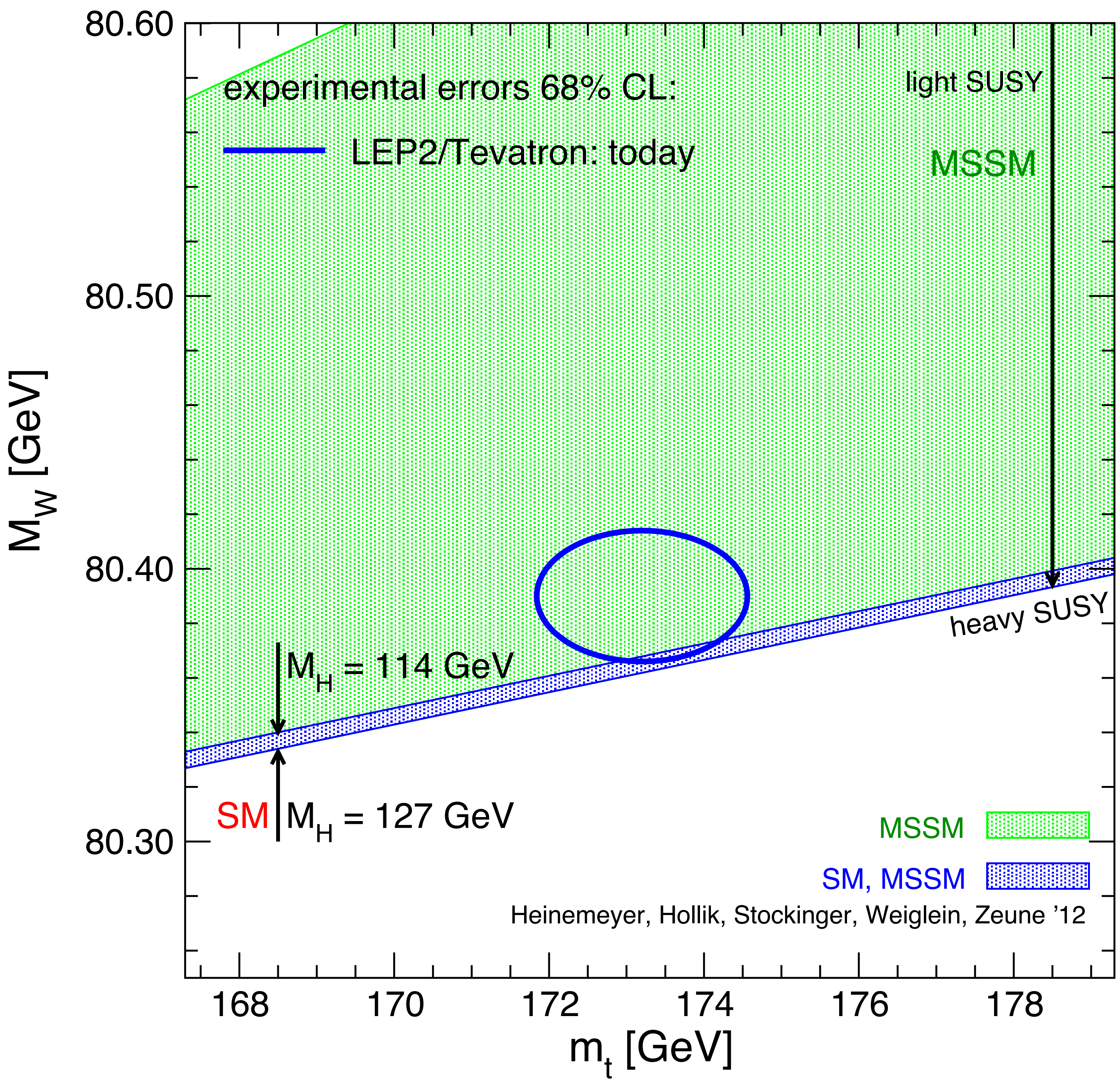
Conclusion

- CDF has performed the most precise measurement of the W boson mass
  - M_W = 80387±19 MeV (CDF, preliminary)
  - More precise than all previous measurements combined
- New world average M_W = 80390±16 MeV (TeVEWWG, preliminary)
  - Uncertainty will be further reduced by imminent DØ result
- Results in SM fits of $M_H < 145$ GeV @ 95% CL
  - Previously $M_H < 161$ GeV @ 95% CL
  - M_W still is the limiting factor in M_H prediction
- Full Tevatron dataset (~10 fb^{-1}) on hand
  - $\Delta M_W \sim 15$ MeV achievable

Backup

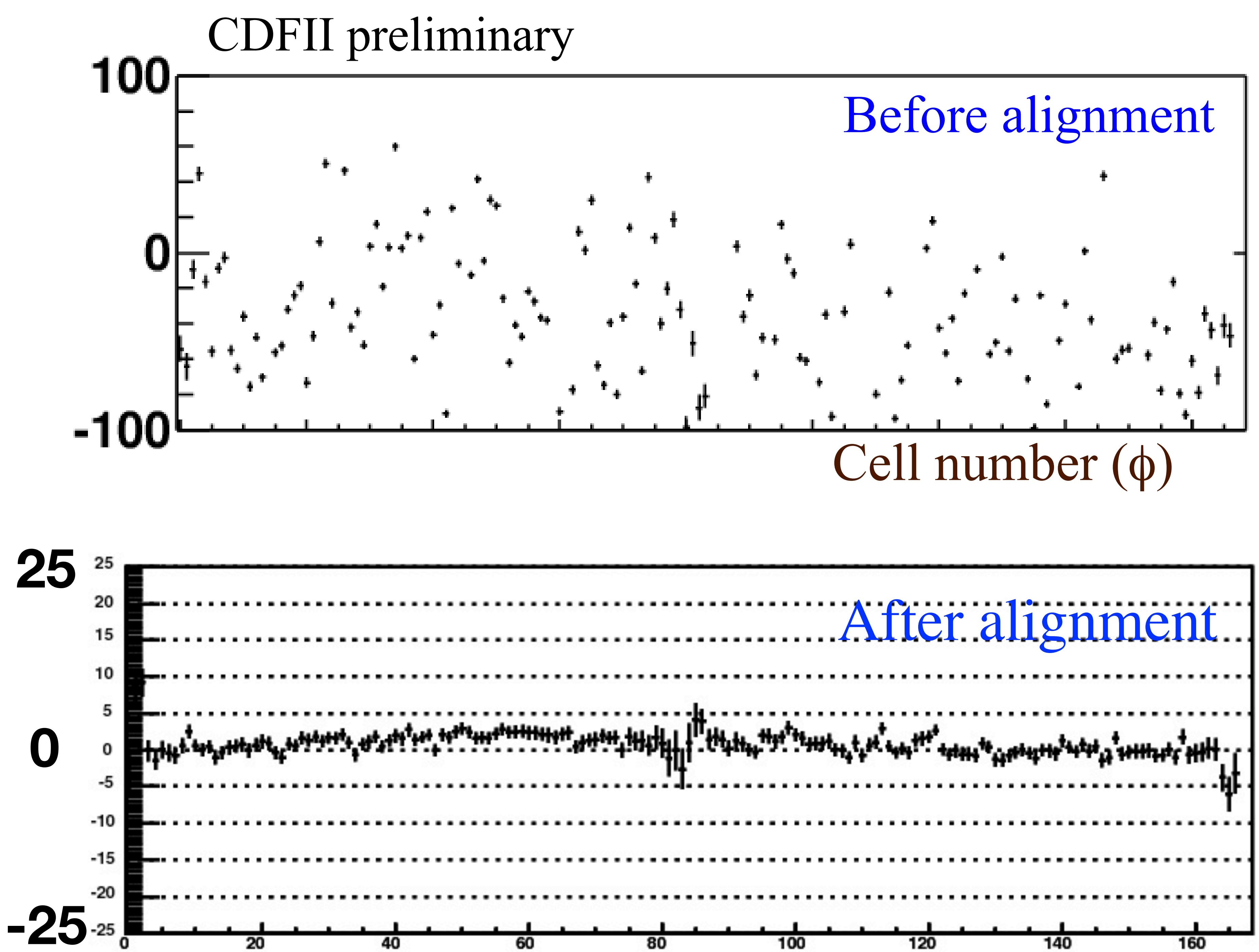
MSSM allowed region

Heinemeyer, Hollik, Stockinger, Weiglein, Zeune



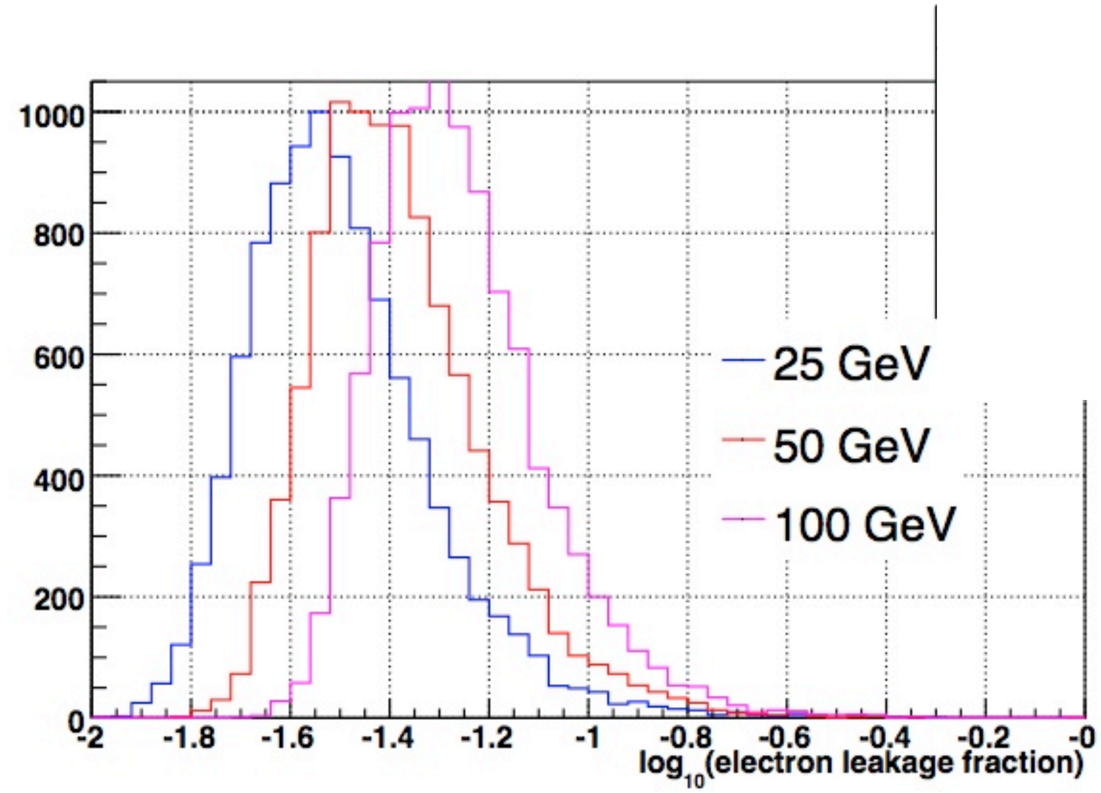
Tracker alignment

- Align COT using cosmic rays triggered *in-situ* with collider data
- Improve alignment from ~50μm to ~2μm



Simulation for electrons and photons

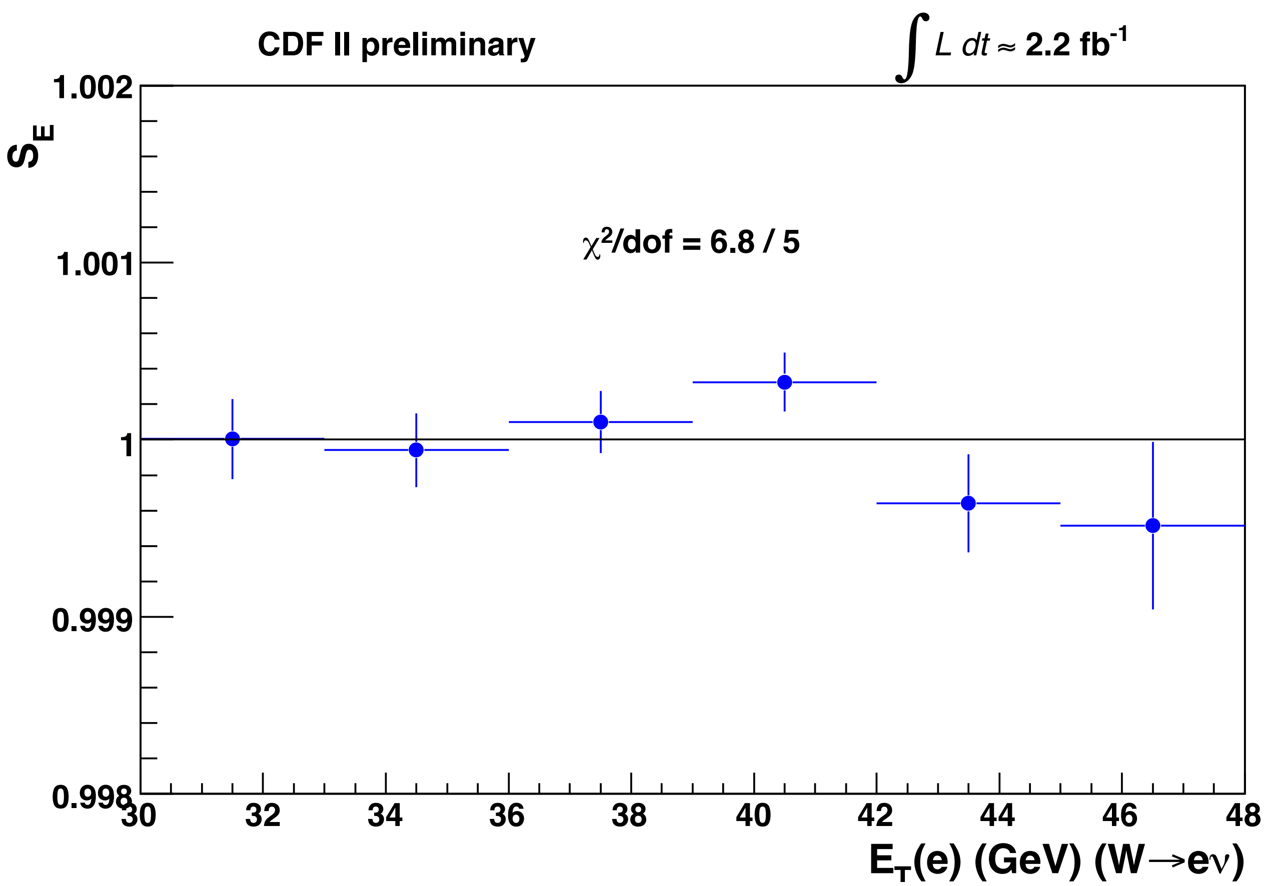
- EM energy loss simulated using detailed GEANT4-based simulation
  - Leakage into hadronic calorimeter
  - Absorption into coil
  - Dependence on incident angle and E_T

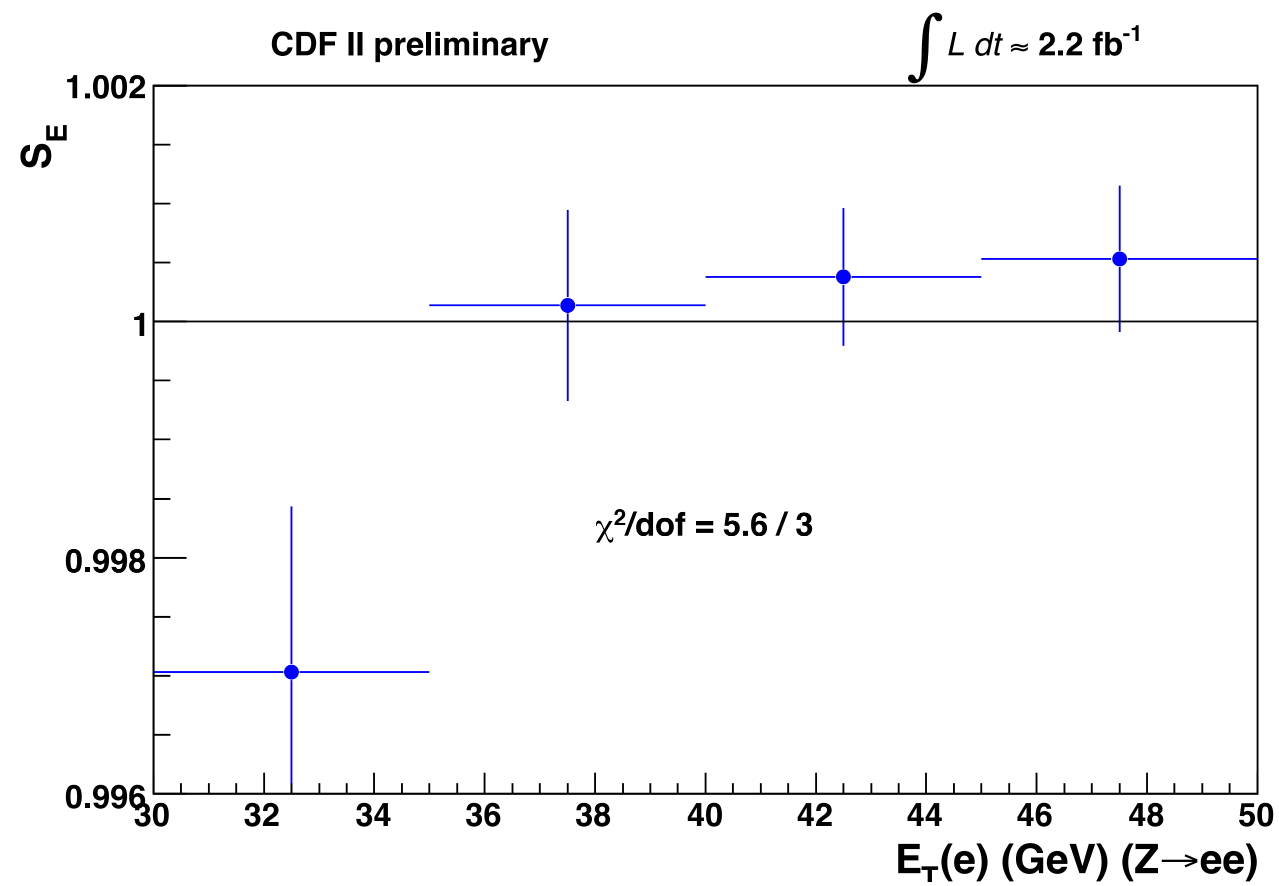


- Improved model of Landau-Pomeranchuk-Migdal (LPM) suppression of bremsstrahlung
  - Sophisticated material map for tracker region of detector

EM scale non-linearity

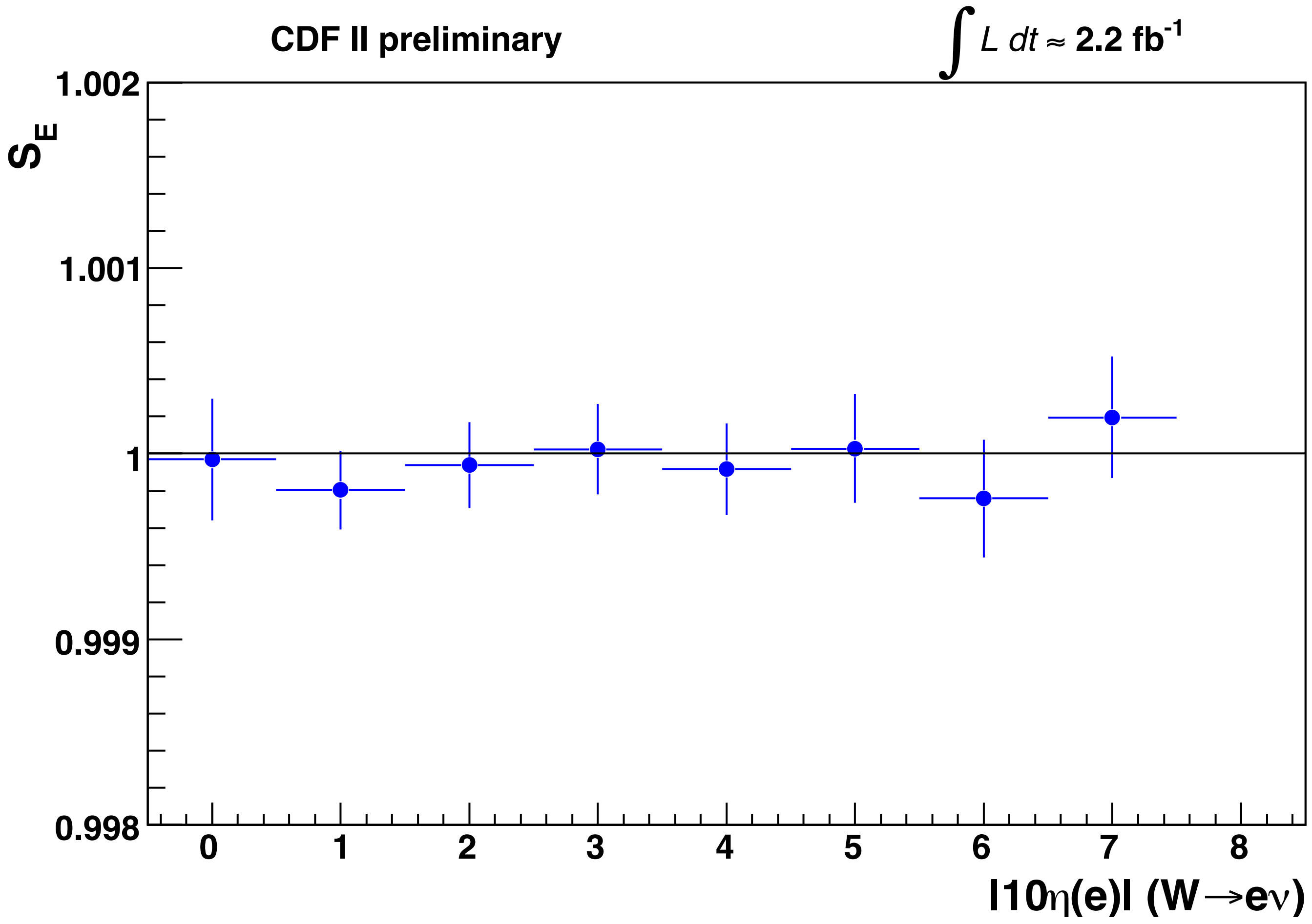
- Fit E/p in bins of electron E_T
- Parameterize non-linearity as $S_E = 1 + \beta \log(E_T/39 \text{ GeV})$
- Tune using W and Z data and obtain $\beta = (5.2 \pm 0.7_{stat}) \times 10^{-3}$
  - ΔM_W = 4 MeV
- Obtain flat response in E_T after tuning

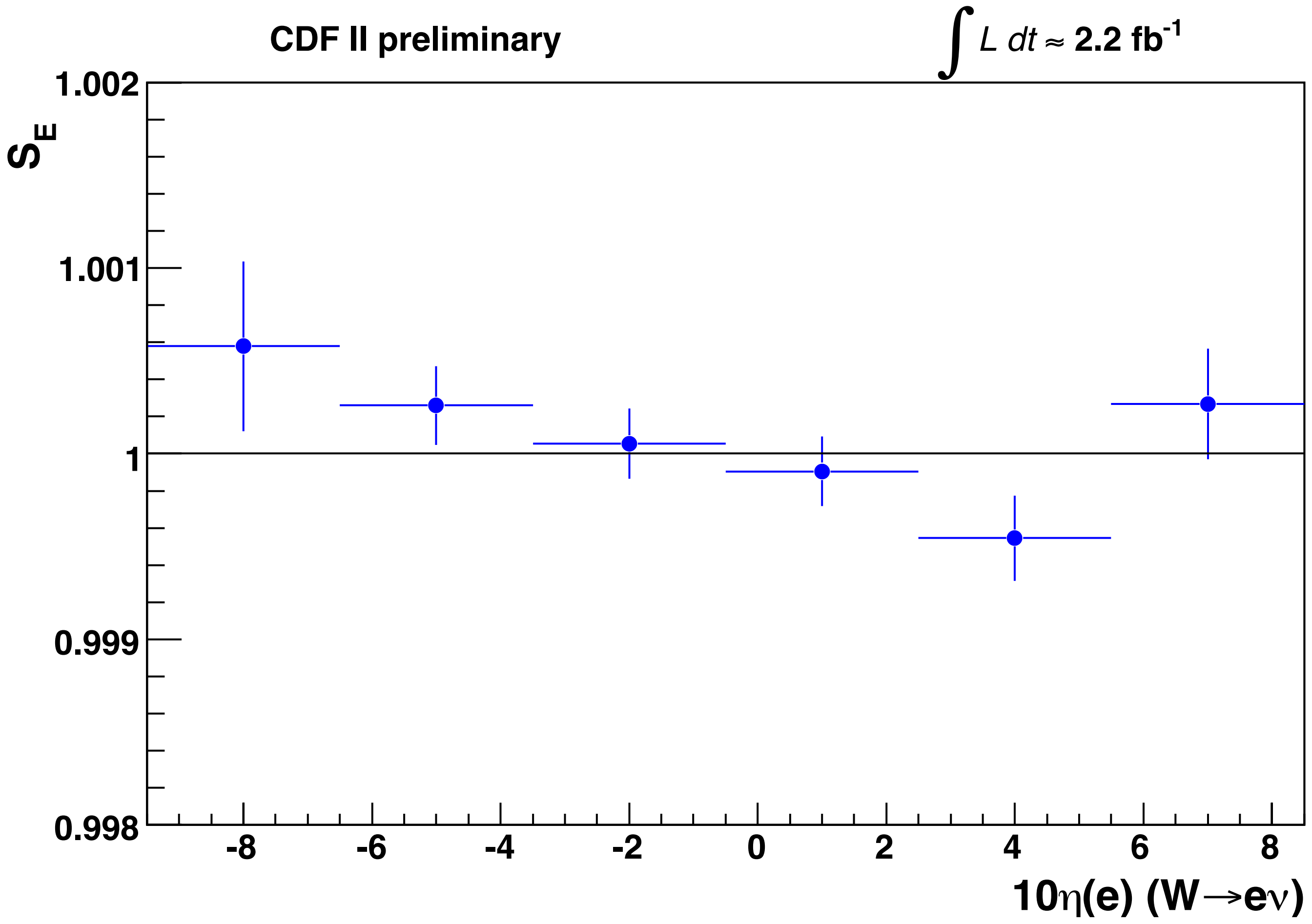




EM calorimeter spatial uniformity

- Apply tower-by-tower correction to flatten response in eta
  - Response after tuning flat





Lepton resolution

- Muons
  - Track resolution determined by uncertainty on beamspot size (35±1 μm) and track hit resolution (150±1 μm)
  - Tuned using widths of Z and ϒ peaks

- Electrons
  - EM calorimeter resolution defined by sampling term and constant term

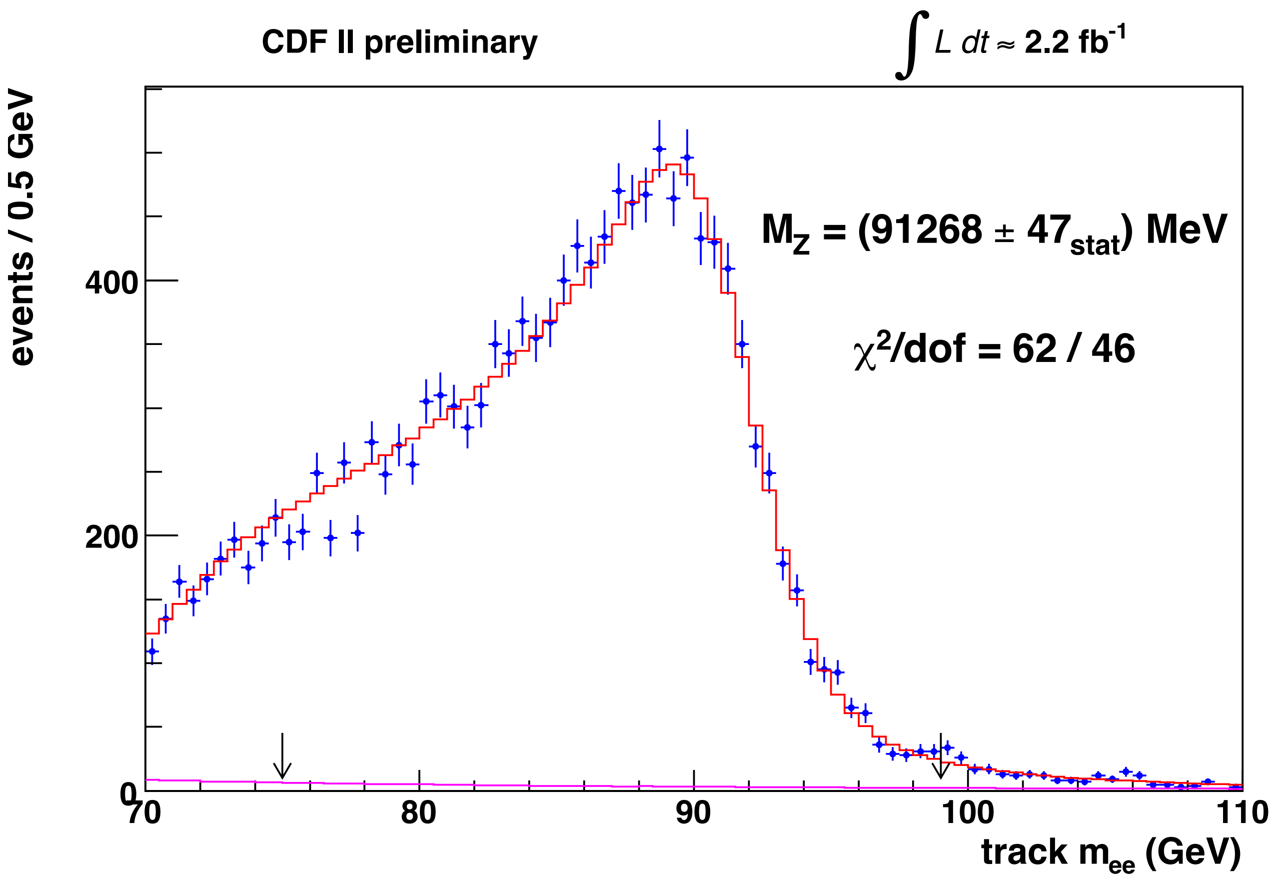
$$\sigma = 12.6\% \sqrt{E_T/\mathrm{GeV}} \oplus \kappa$$

  - Constant term tuned using E/p distribution $\kappa = (0.58\pm0.05)\%$
  - Apply secondary constant term for radiative electrons (E/p > 1.1)
    - $\kappa_\gamma = (7.4\pm1.8)\%$

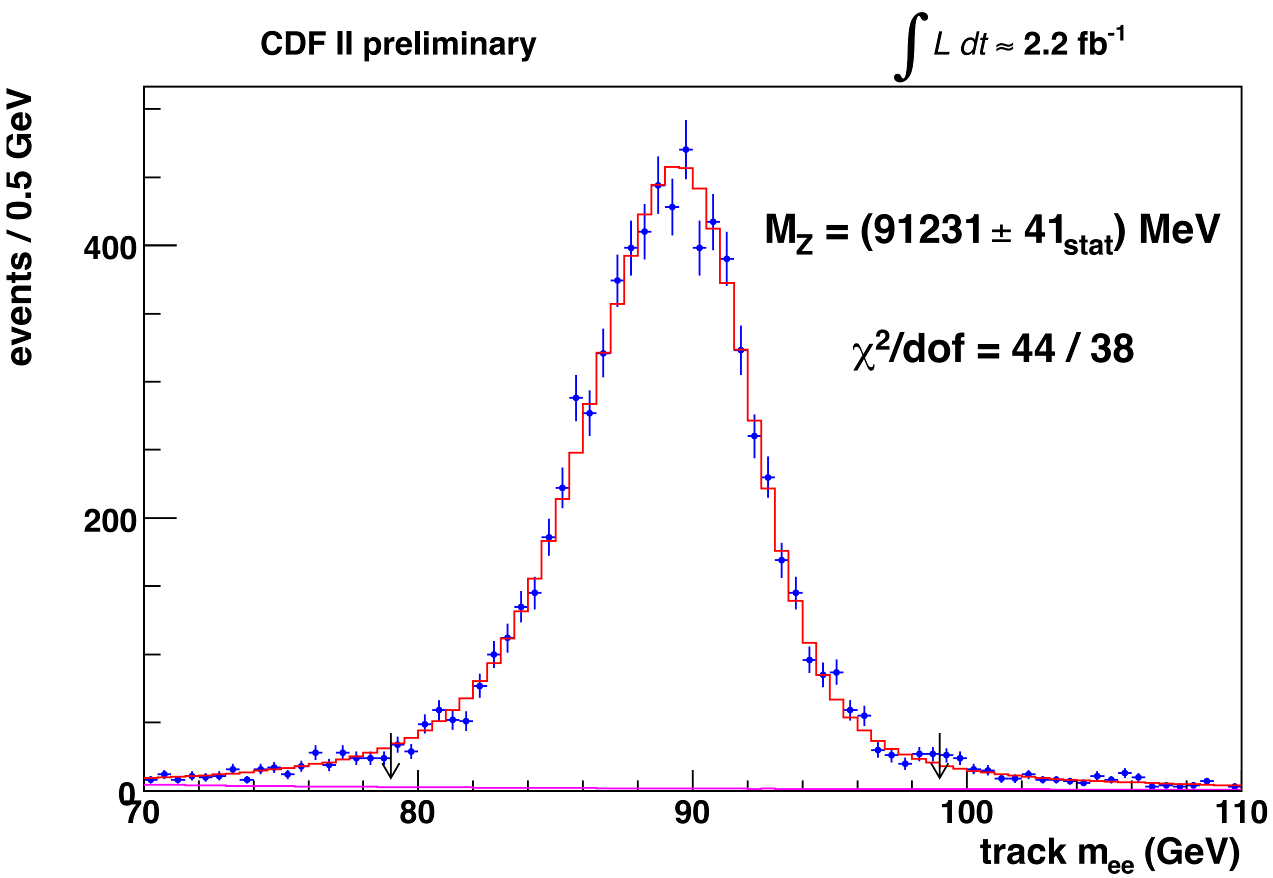
- Resolution terms total $\Delta M_W = 4$ MeV

Z mass with electron tracks

- Measurement made with only track momenta of Z electrons
- Validates application of momentum scale to high-p_T electron tracks

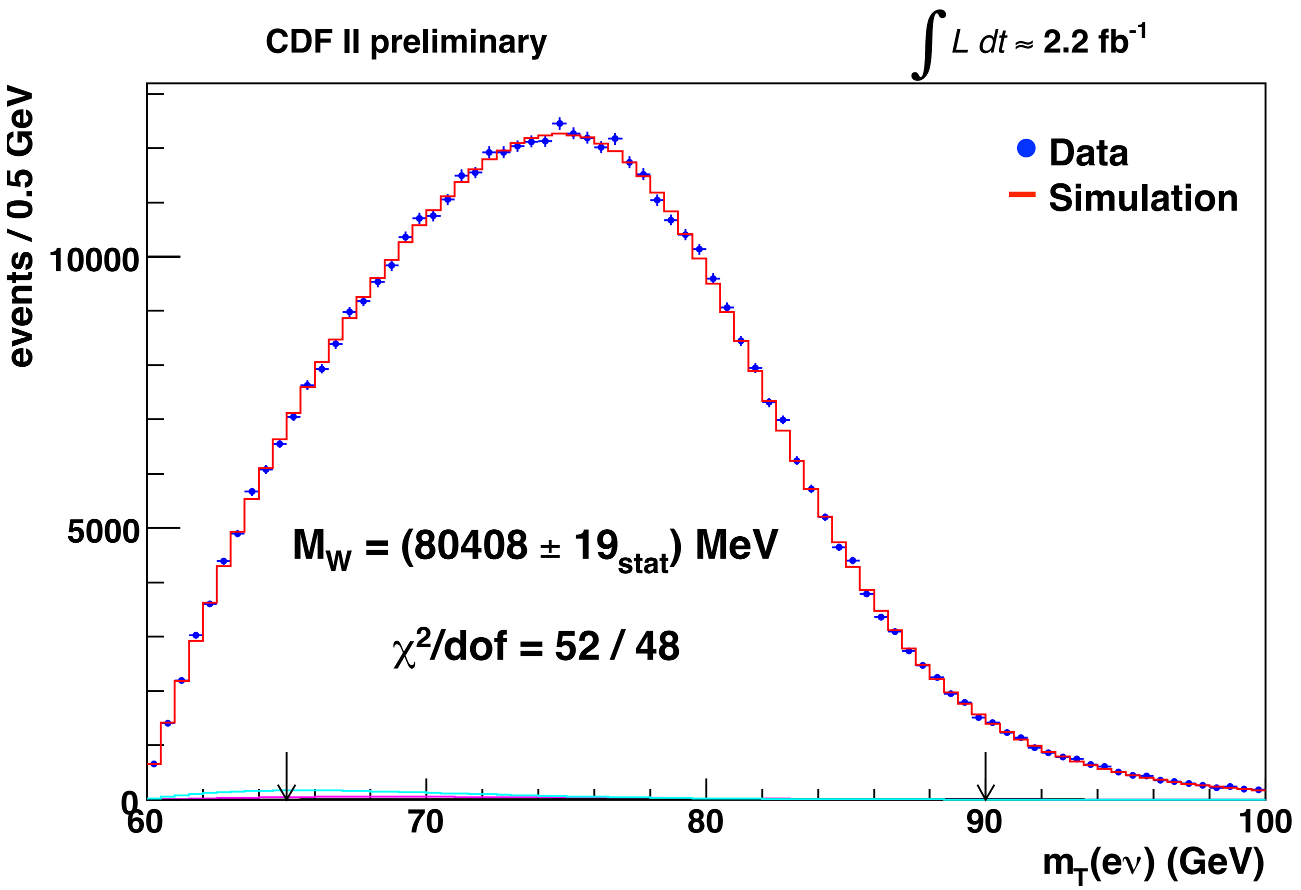


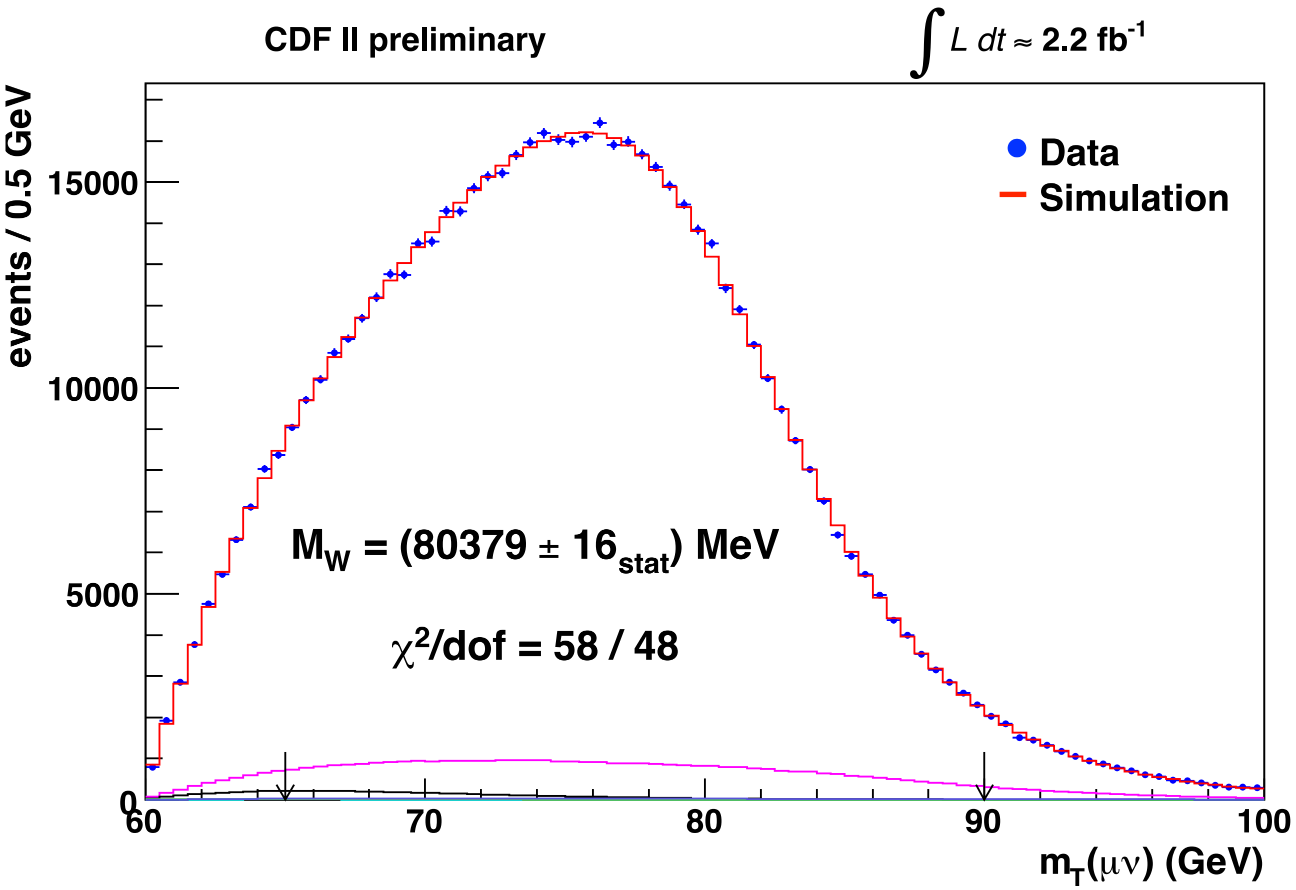
All electrons



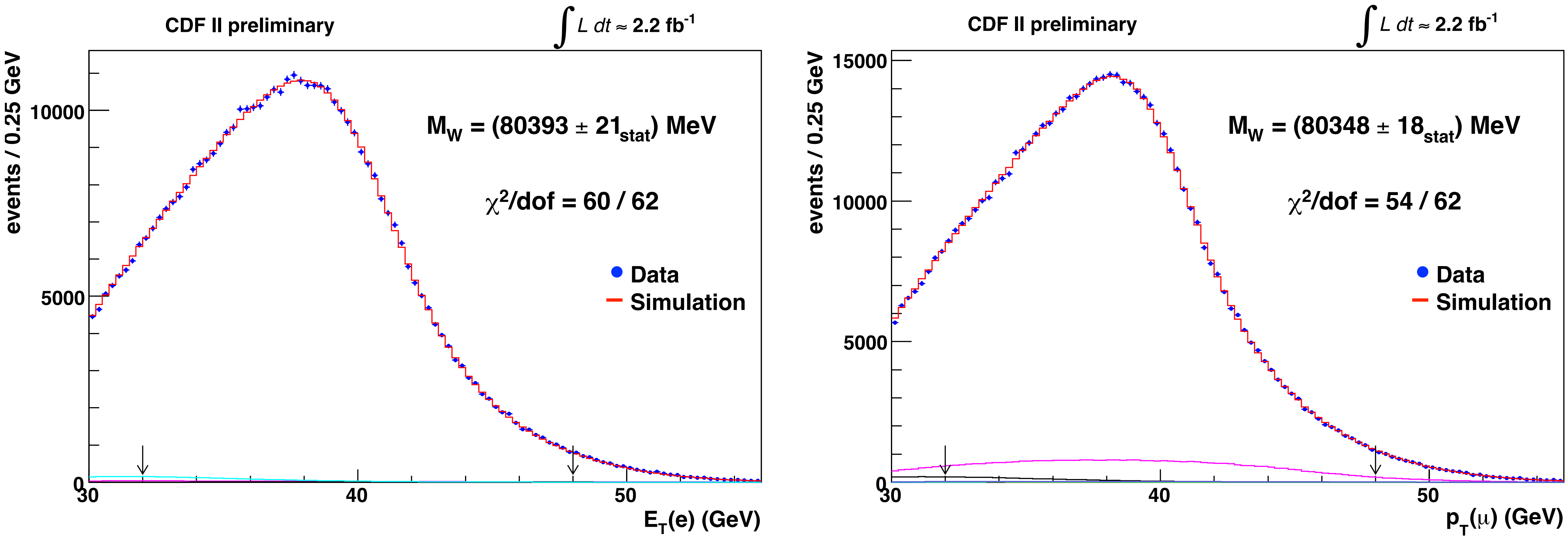
Non-radiative electrons only

W mass fits: m_T

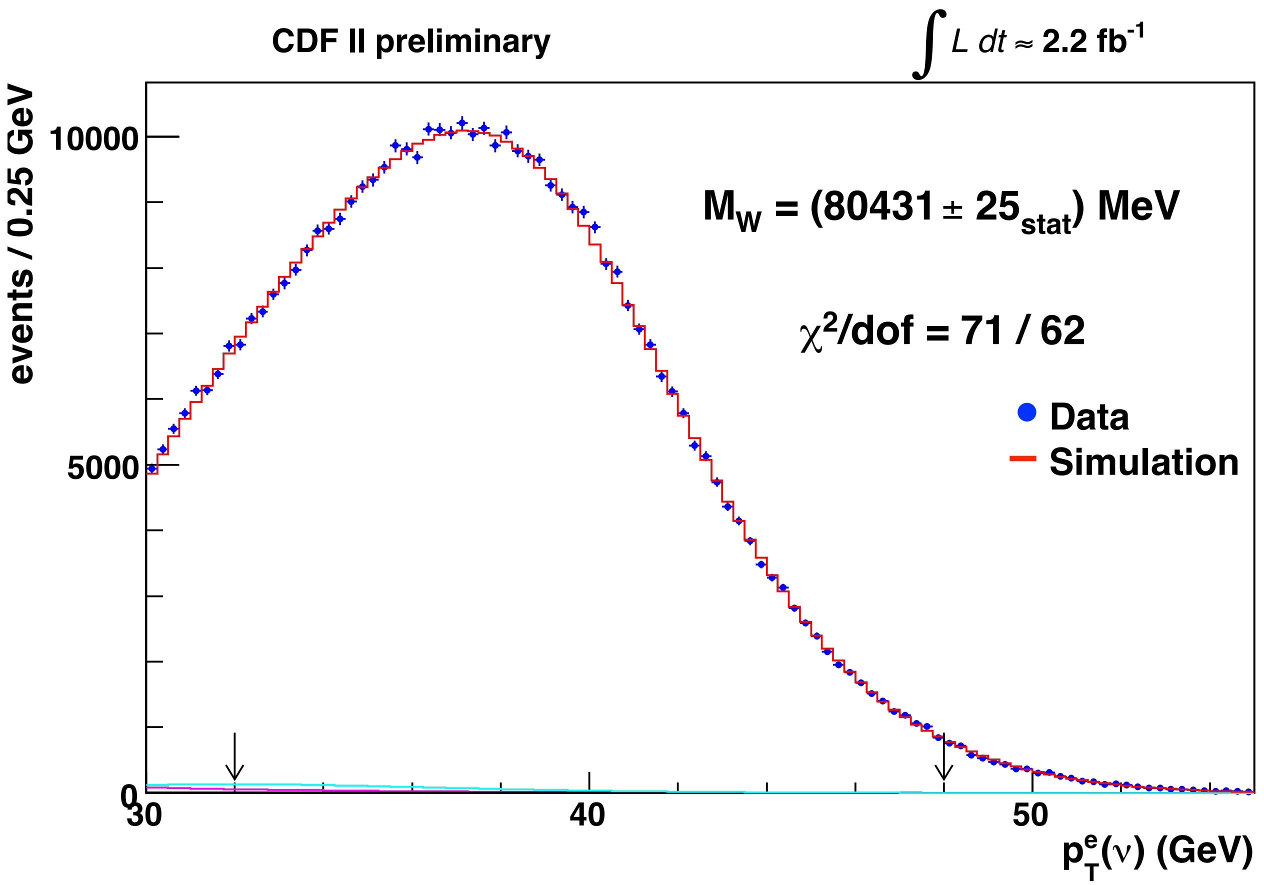


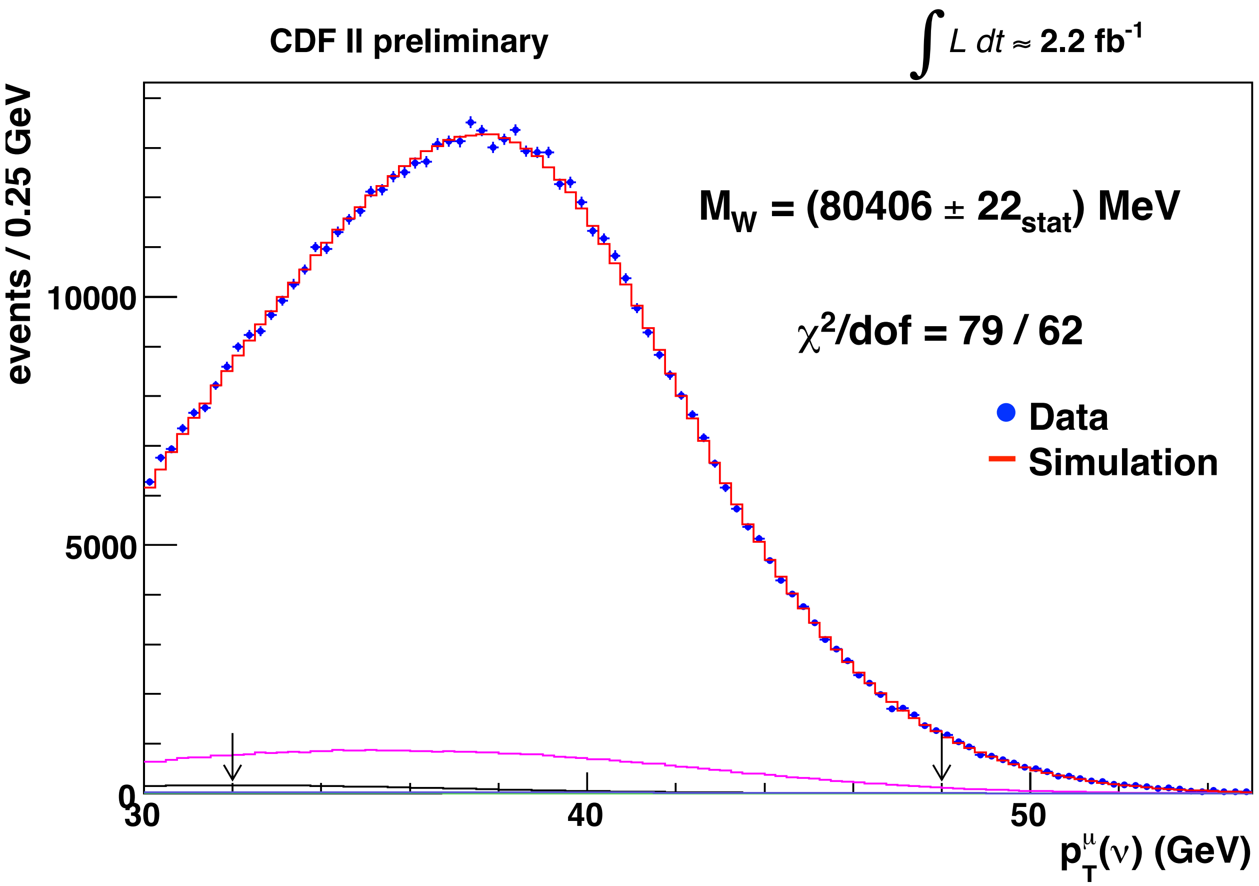


W mass fits: lepton p_T

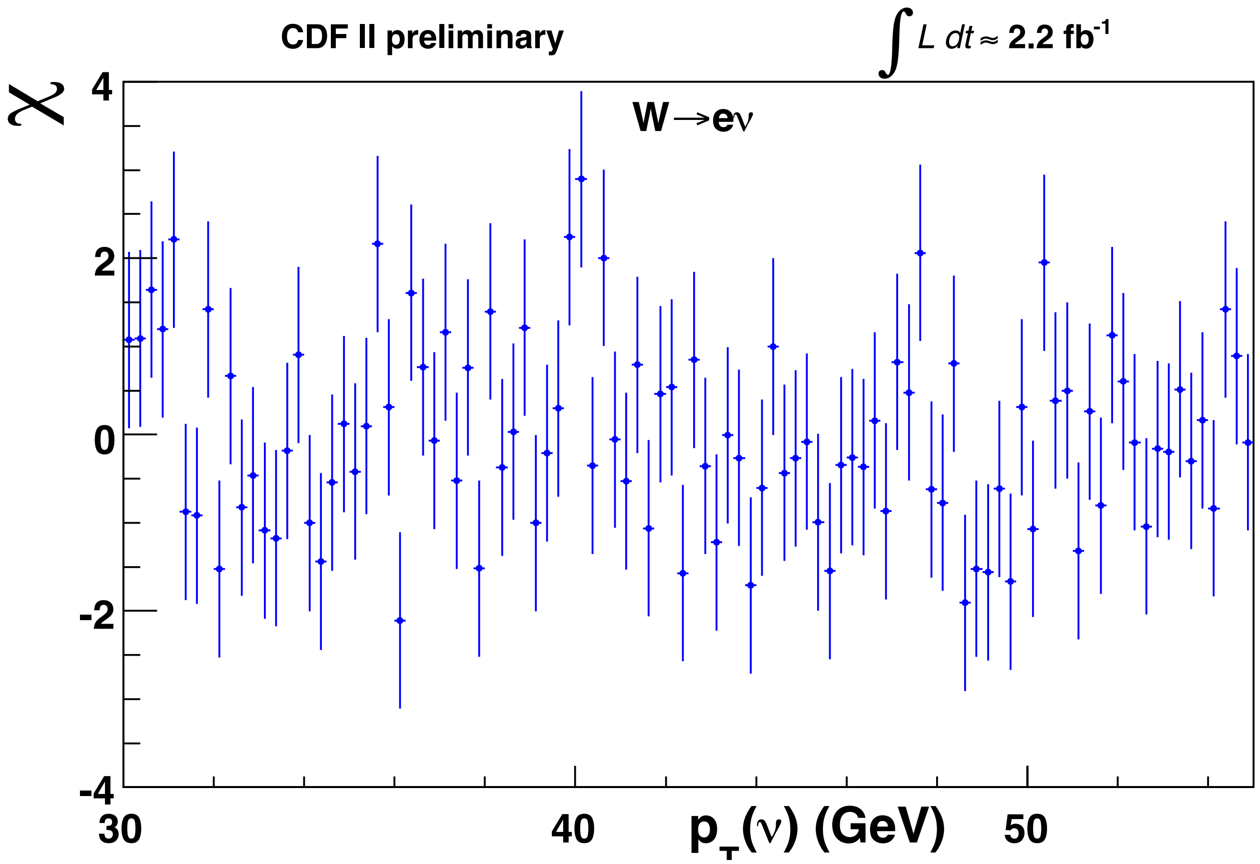


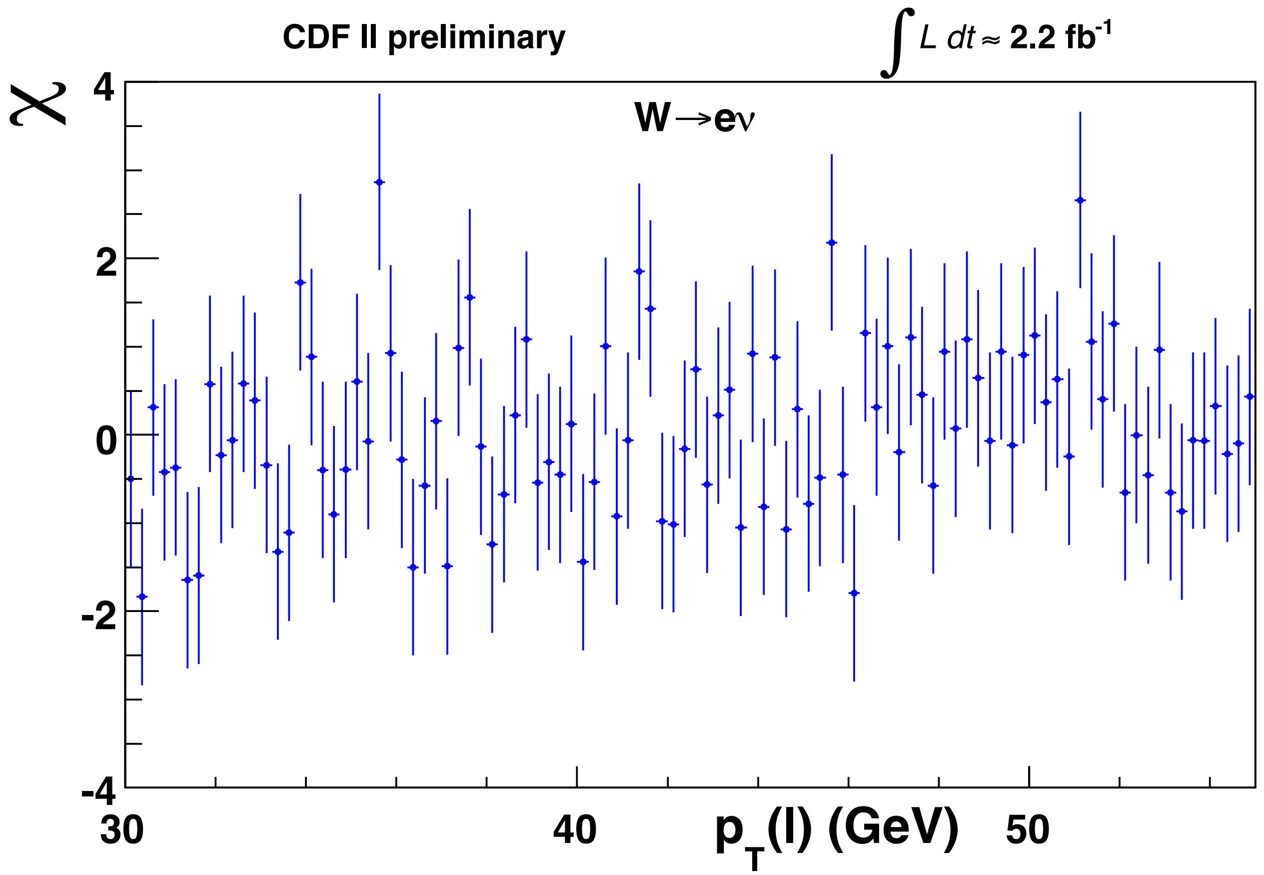
W mass fits: neutrino p_T

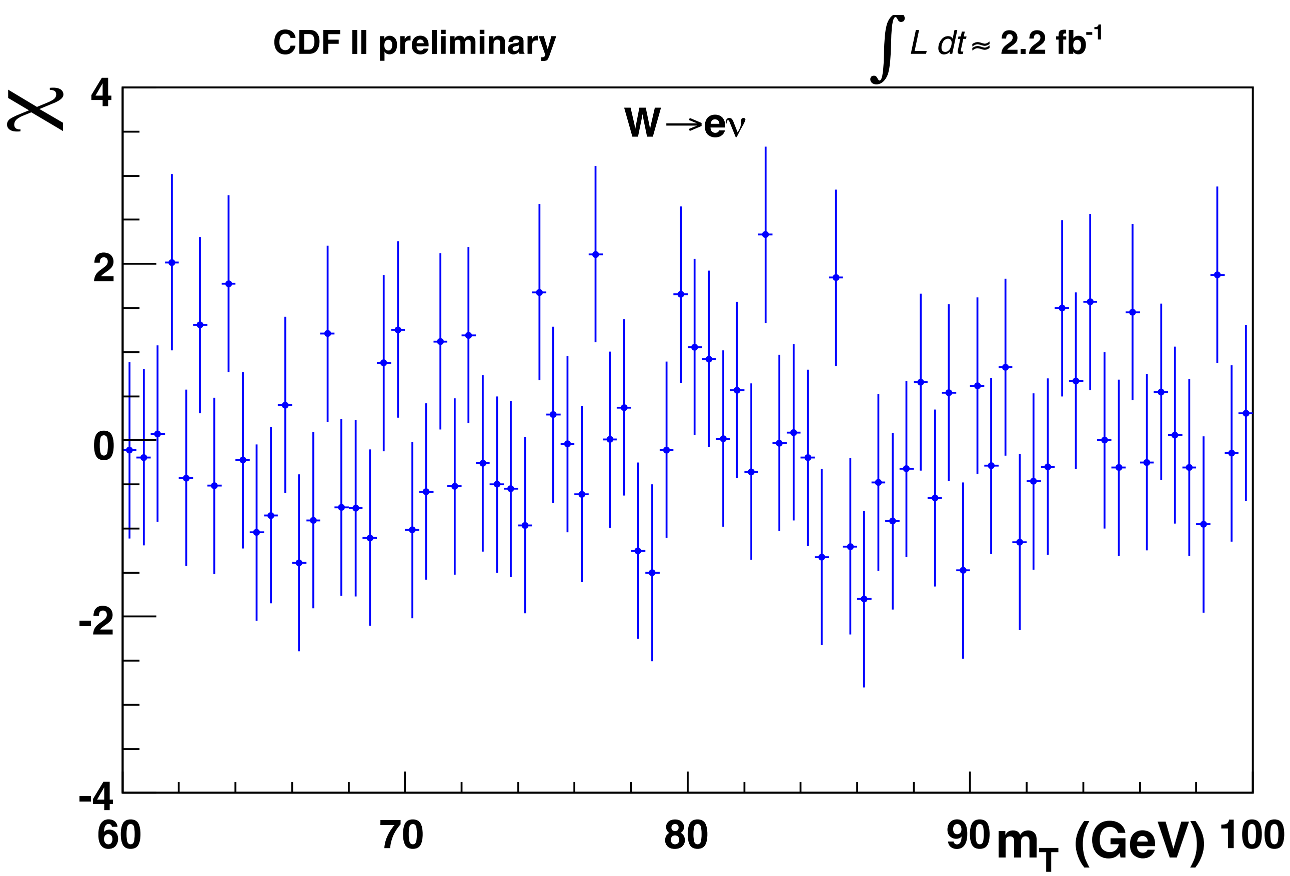




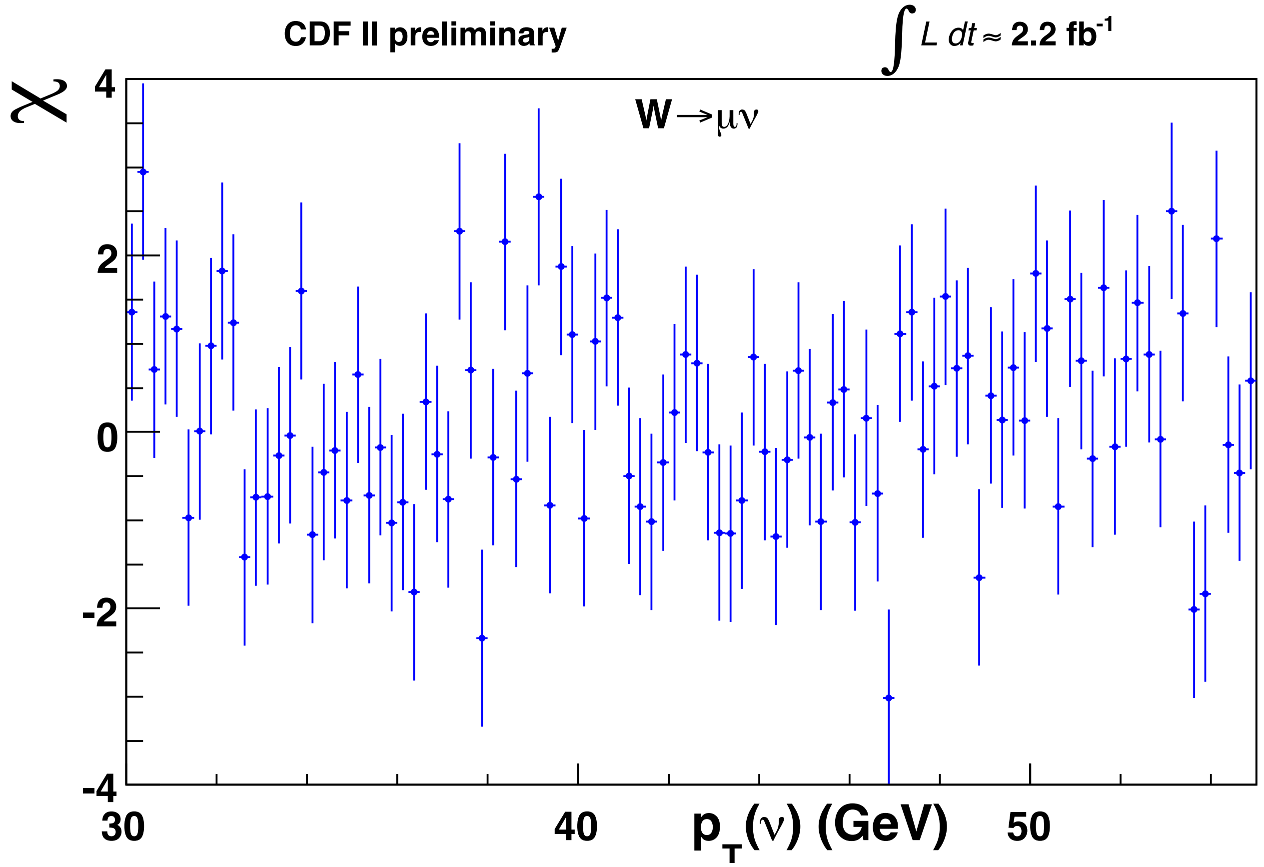
Electron fit residuals

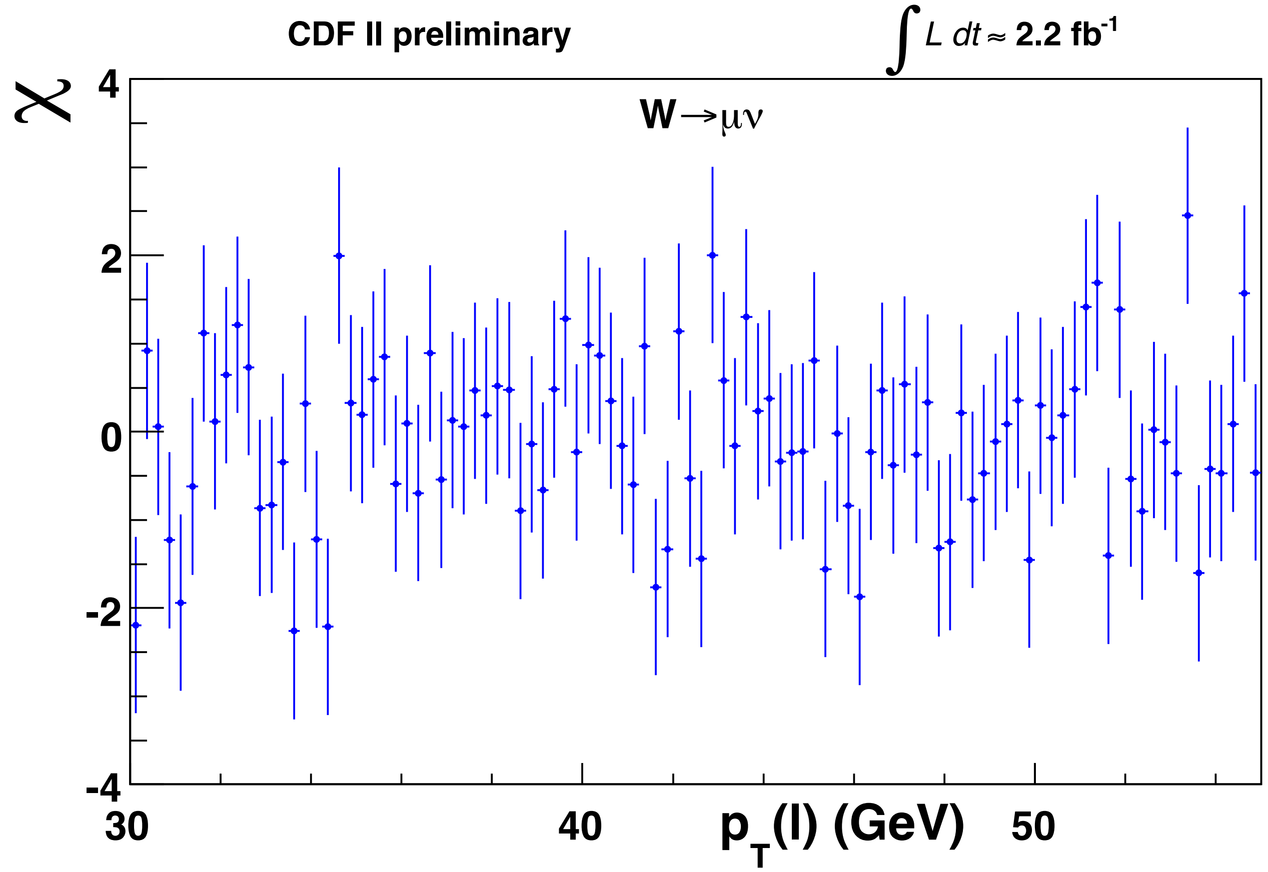


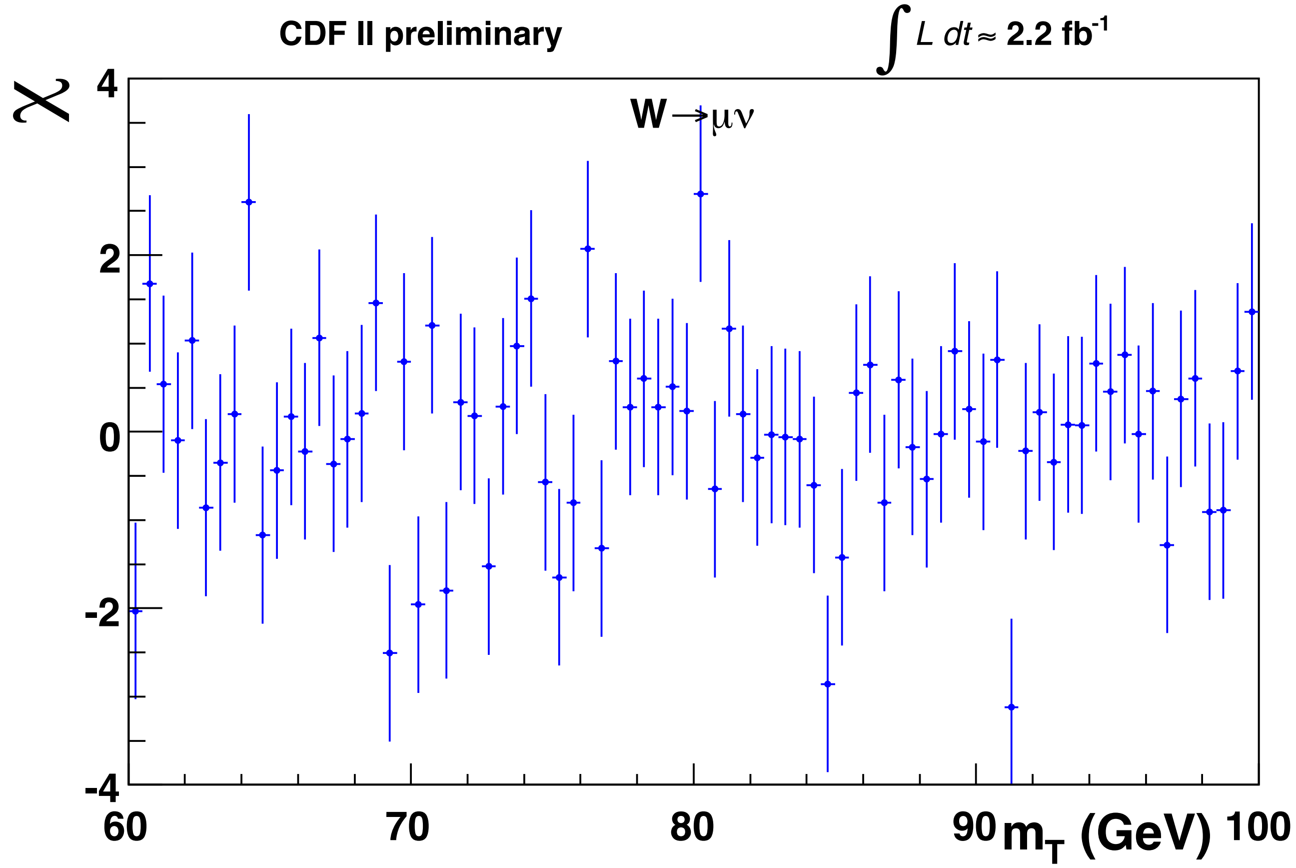




Muon fit residuals



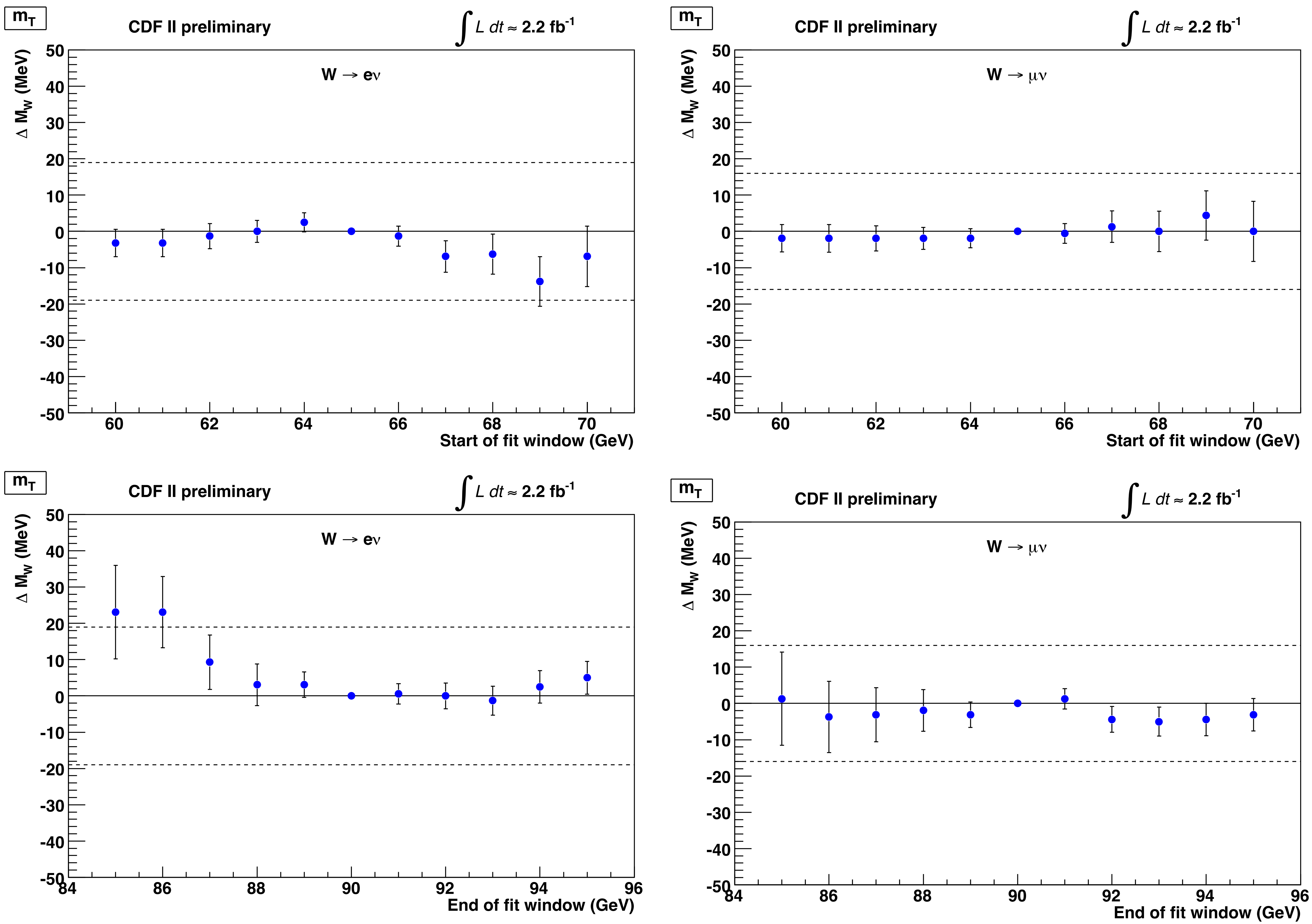




Fit window variation: m_T

lower

upper



Systematics: m_T

Systematic (MeV)	Electrons	Muons	Common
Lepton Energy Scale	10	7	5
Lepton Energy Resolution	4	1	0
Recoil Energy Scale	5	5	5
Recoil Energy Resolution	7	7	7
$u_{\|\|}$ Efficiency	0	0	0
Lepton Removal	3	2	2
Backgrounds	4	3	0
$p_T(W)$ Model (g_2, g_3, α_s)	3	3	3
Parton Distributions	10	10	10
QED Radiation	4	4	4
Total	18	16	15

Systematics: p_T^l

Systematic (MeV)	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 (g_2, g_3, α_s)	9	9	9
Parton Distributions	9	9	9
QED radiation	4	4	4
Total	19	18	16

Systematics: p_T^ν

Systematic (MeV)	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
$u_{\|\|}$ efficiency	3	2	0
Lepton Removal	6	4	4
Backgrounds	4	6	0
$p_T(W)$ model (g_2, g_3, α_s)	4	4	4
Parton Distributions	11	11	11
QED radiation	4	4	4
Total	22	20	18

Mass fit combinations

- 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%)

Uncertainty progress