



Measurement of the W Boson Mass at CDF

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on behalf of the CDF Collaboration

Rencontres de Moriond (Electroweak) 2012
La Thuile, Italy

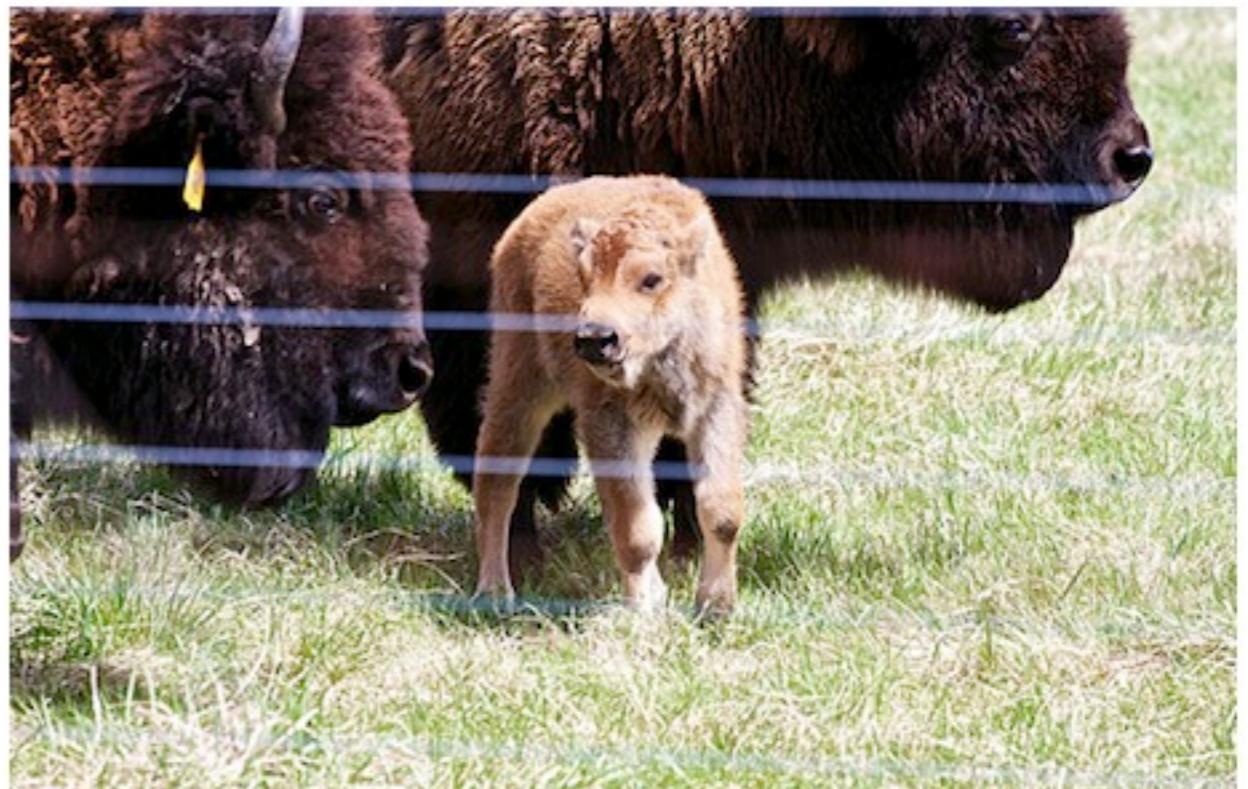
March 4, 2012

Submitted to Phys. Rev. Lett. [arXiv:1203.0275]

Duke
UNIVERSITY

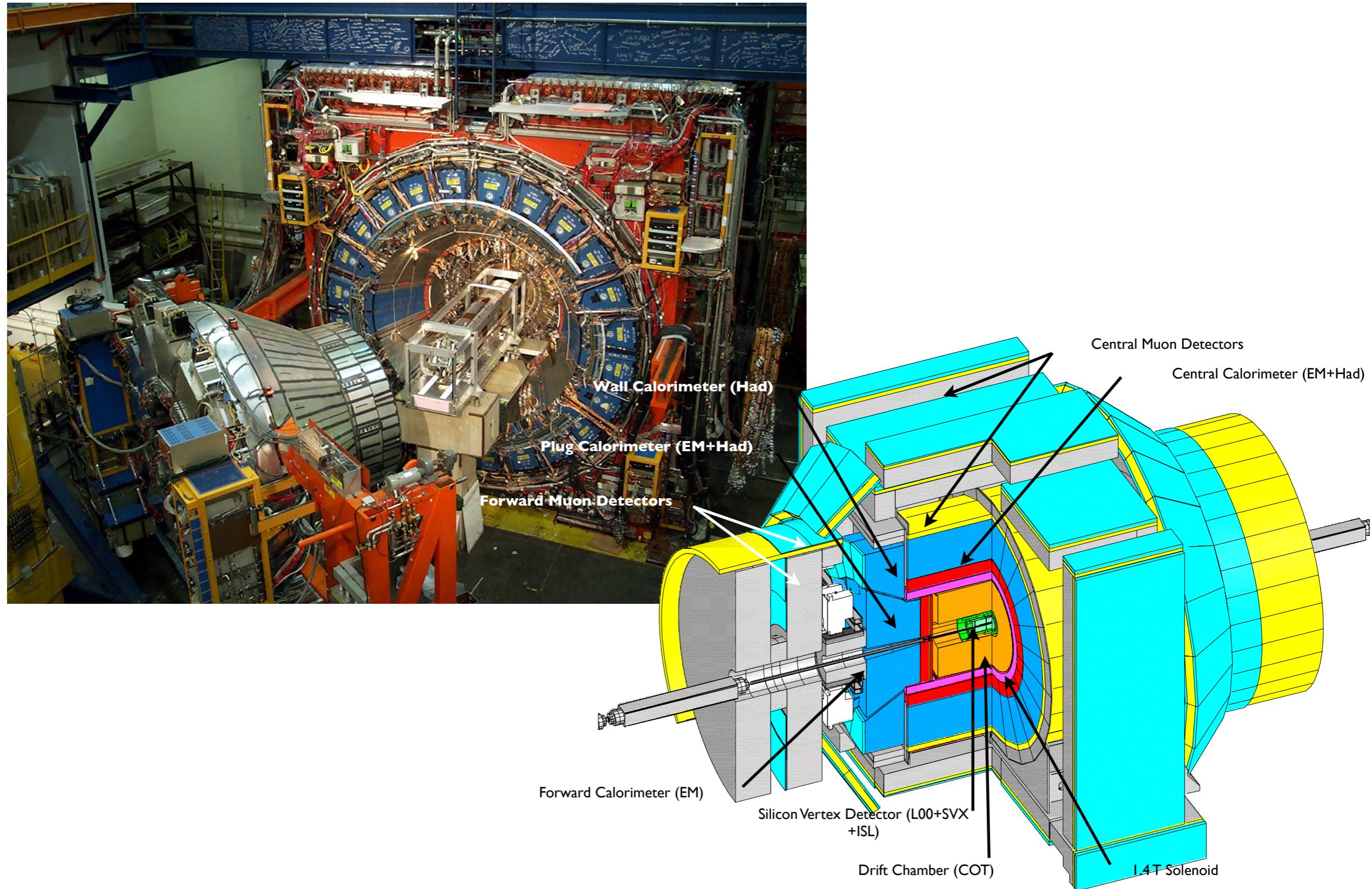
Outline

- CDF detector
- Measurement strategy
- Theoretical model
- Experimental model
 - Momentum scale calibration
 - EM energy scale calibration
 - Hadronic recoil calibration
 - Backgrounds
- Fit results
- SM interpretation and Higgs bounds



“A low mass bison at Fermilab”
-The Guardian (J. Butterworth)
2-Mar-2012

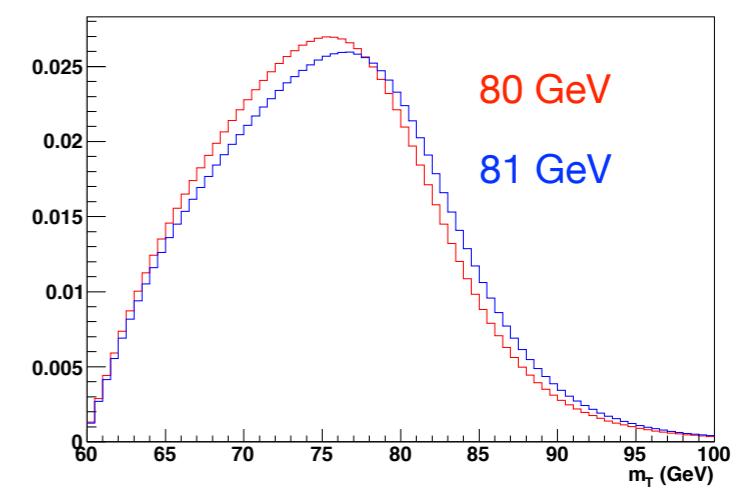
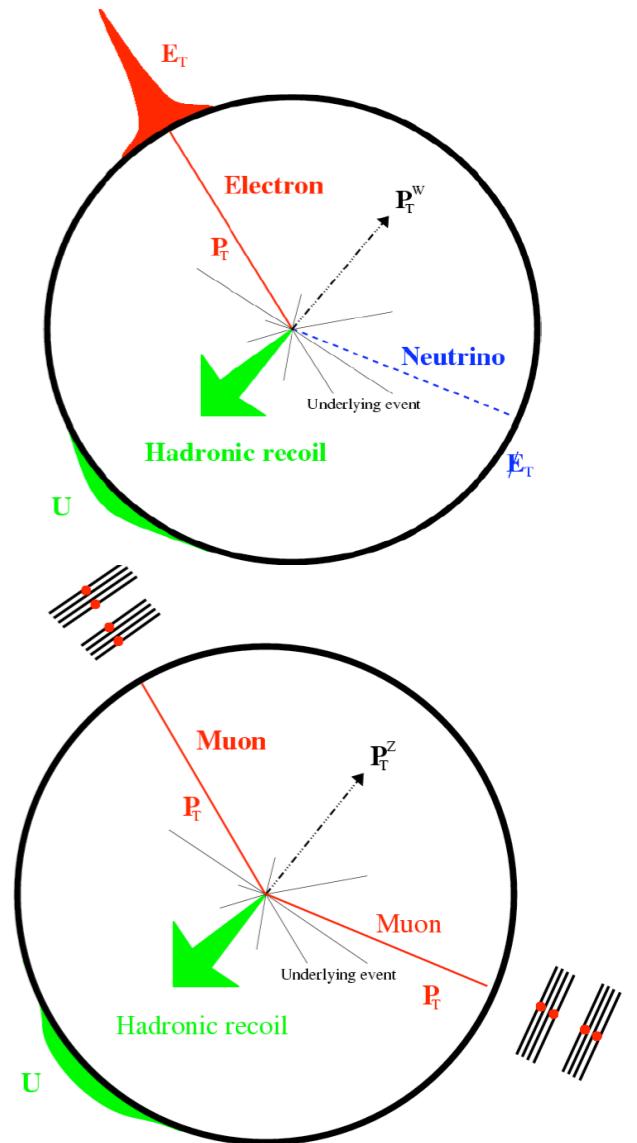
CDF II (2002-2011)



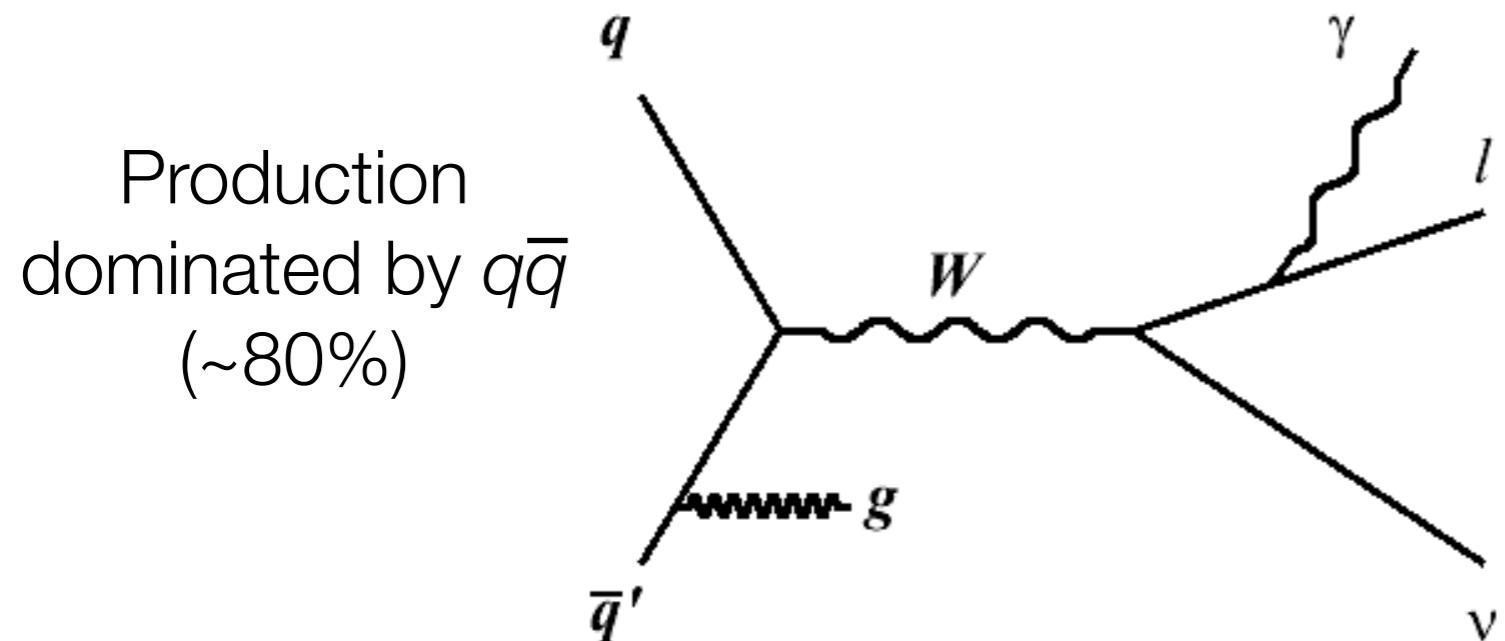
Measurement strategy

- Perform COT alignment with cosmic ray data
 - $\sim 2 \mu\text{m}$ alignment (vs $\sim 50 \mu\text{m}$ 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 $e/\mu p_T$, νp_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



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

$$|\mathbf{u}| < 15 \text{ GeV}$$

$$p_T^\nu > 30 \text{ GeV}$$

$$60 < m_T < 100 \text{ GeV}$$

Z boson candidates:

2 lepton passing cuts

$$66 < m_{ll} < 116 \text{ GeV}$$

Analysis dataset: **2.2 fb⁻¹**

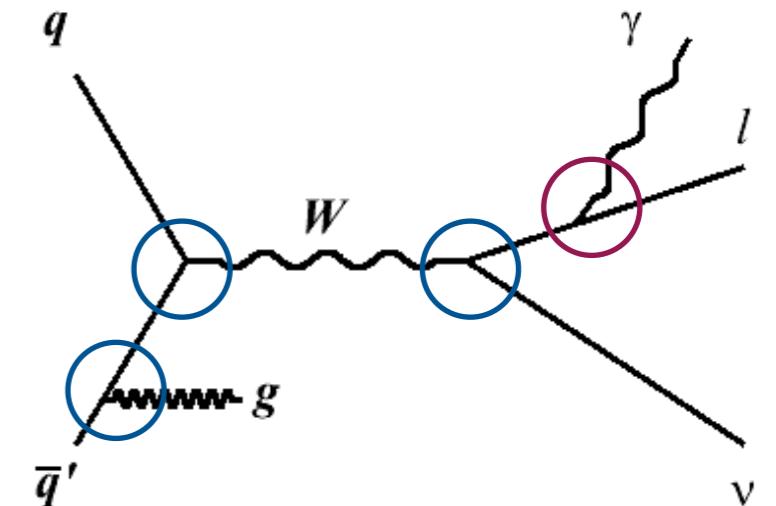
Candidate events:

$W(e,\mu)$: 470126, 624708

$Z(e,\mu)$: 16134, 59738

Event generation and boson p_T

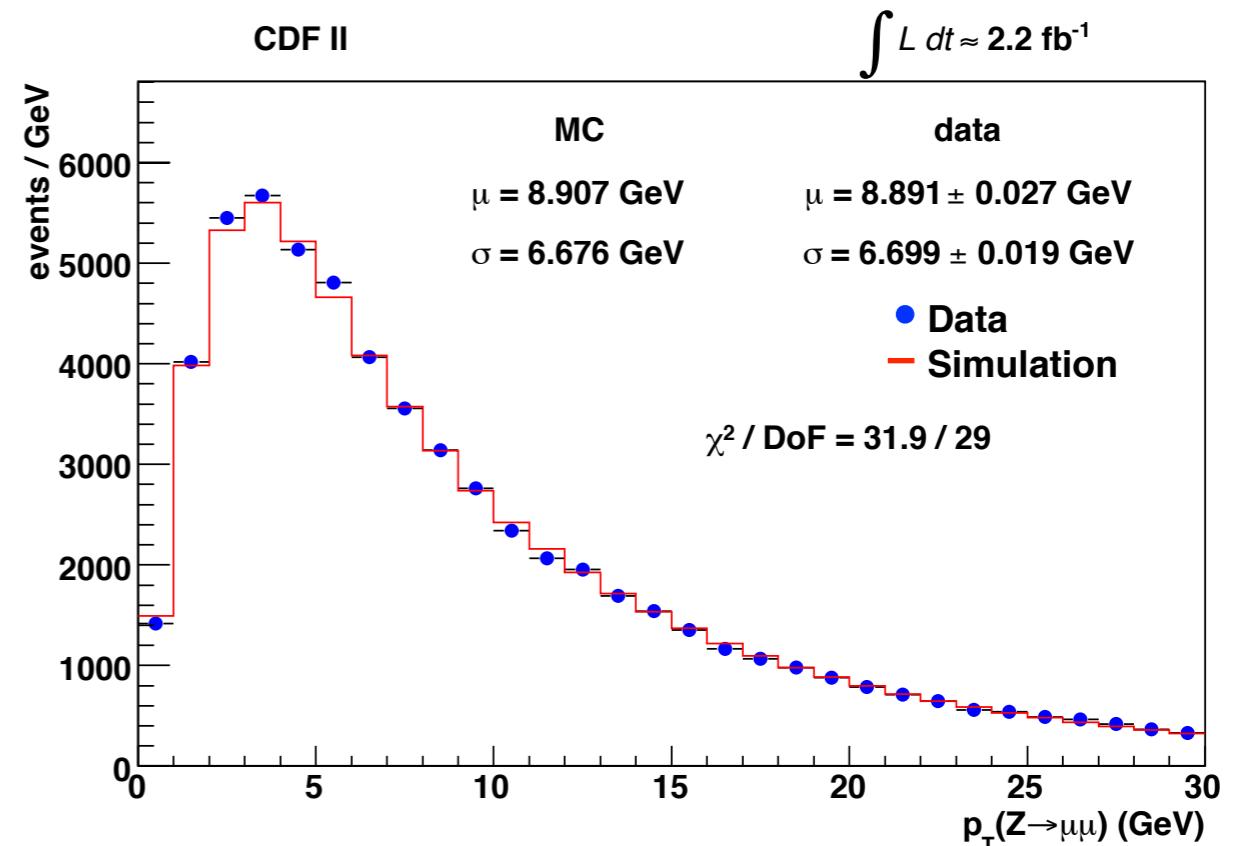
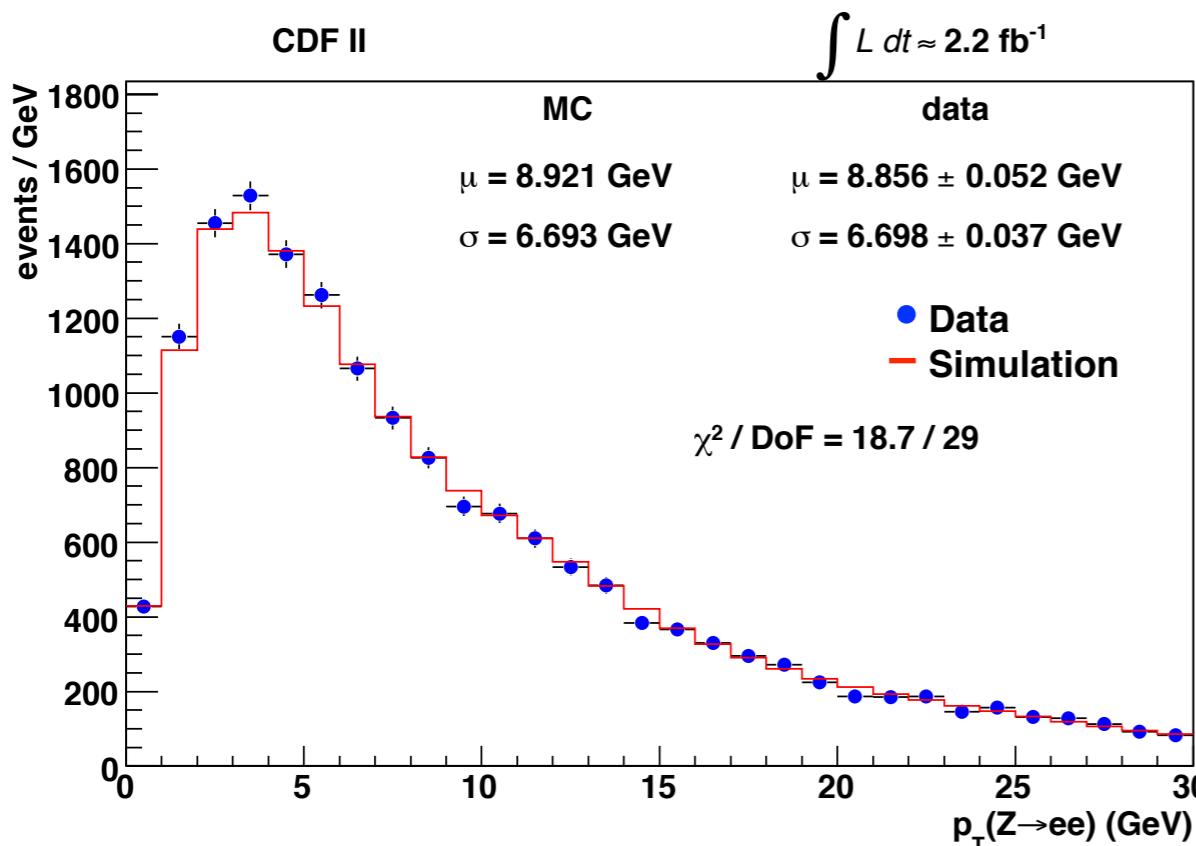
- Generator level simulation from **RESBOS¹**
 - QCD effects, tunable parameters for non-perturbative regime (low- p_T)
- QED radiation simulated by **PHOTOS²**
 - Multiphoton simulation
- Fit parameters in boson p_T shape
 - Low p_T sensitive to g_2
 - Intermediate-high p_T sensitive to α_s



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

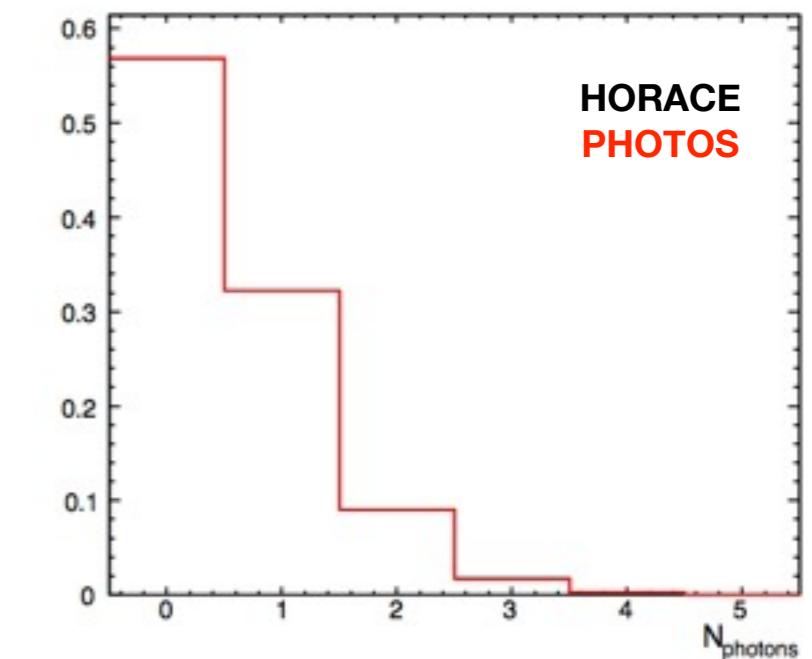
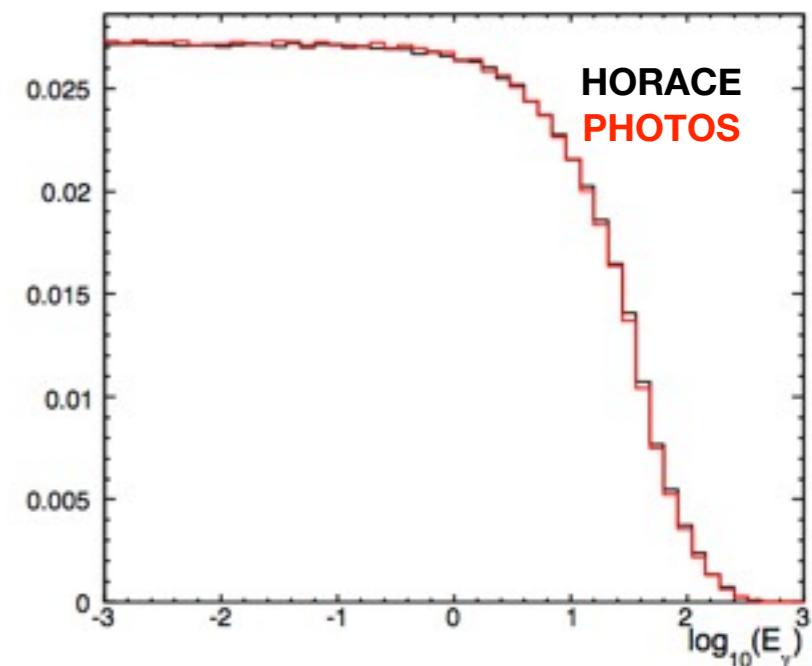
²P. Golonka and Z. Was, Eur. J. Phys. C 45, 97 (2006)

$$\Delta M_W = 5 \text{ MeV}$$



QED Radiation

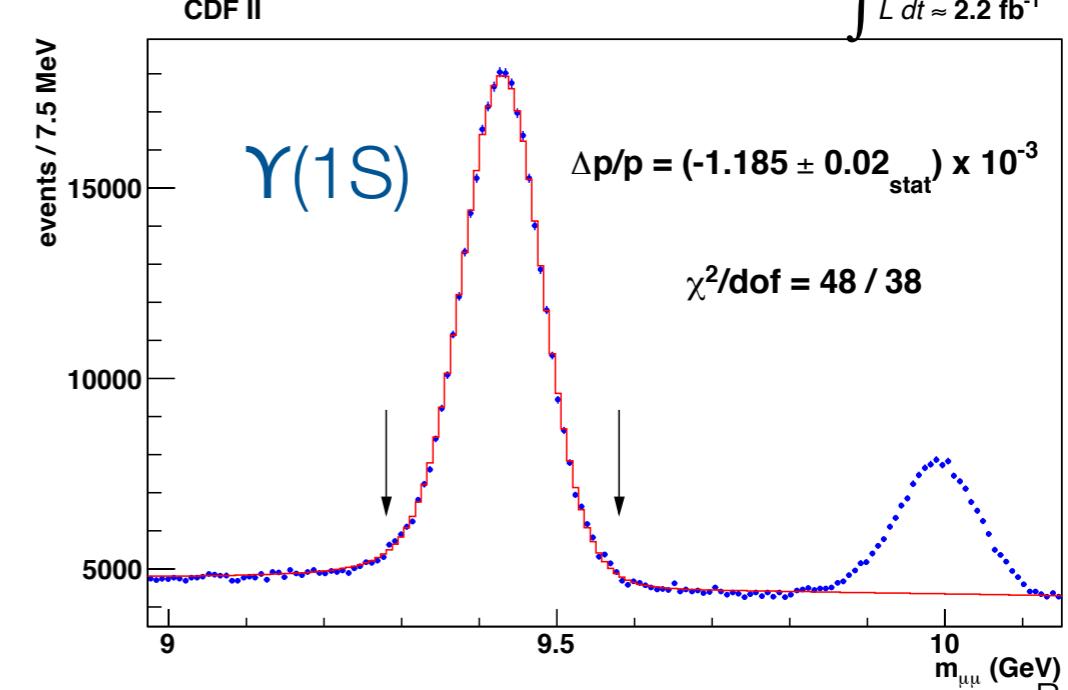
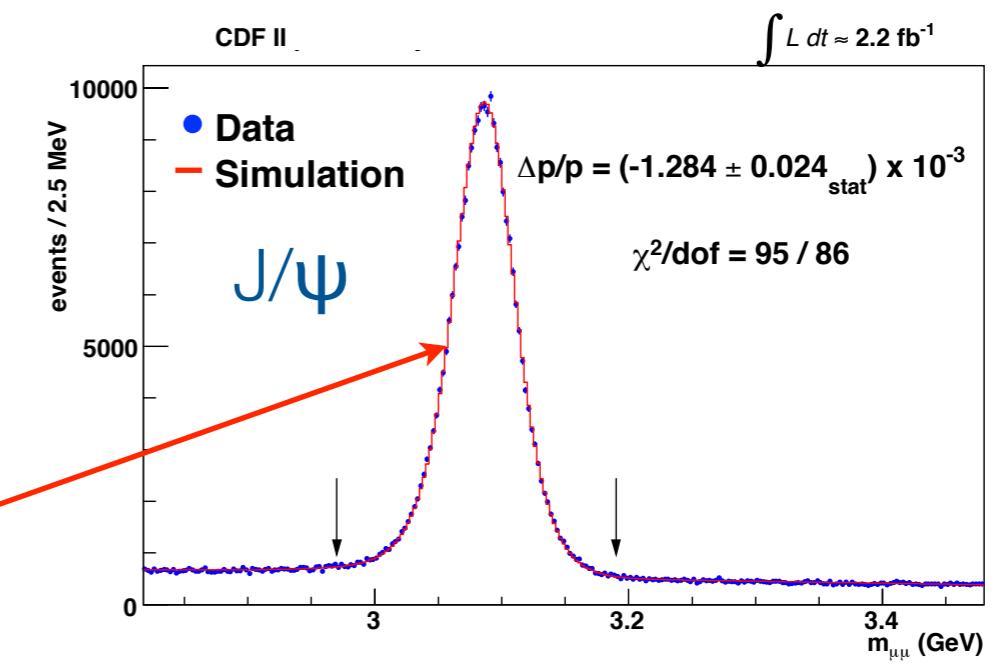
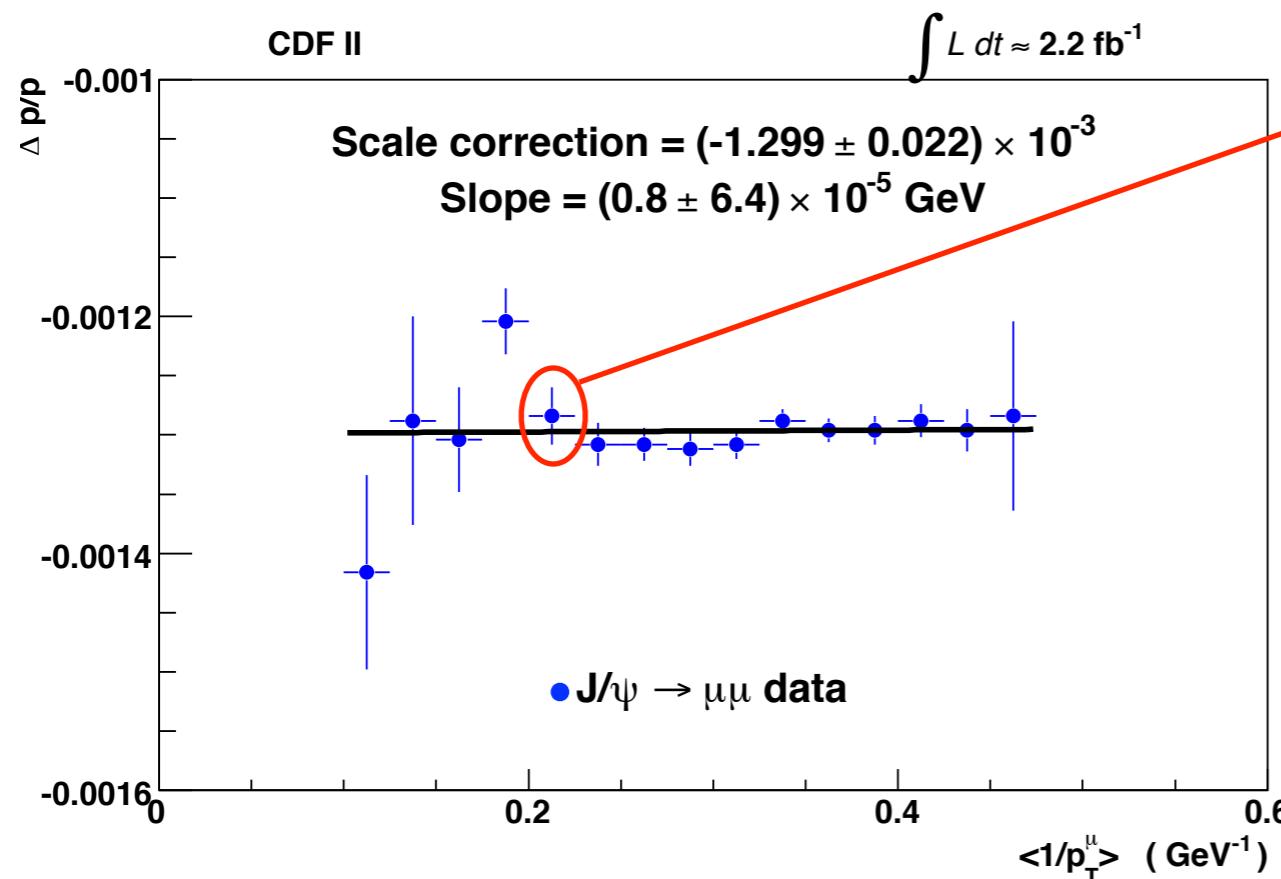
- Extensive studies on QED effects using **HORACE**¹
 - Leading log approximation vs. exact single photon calculation
 - Multi-photon calculations
 - Higher-order soft/virtual corrections
 - e^+e^- pair creation
 - ISR/FSR interference
 - Dependence on electroweak parameters/scheme
- Detailed comparison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



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

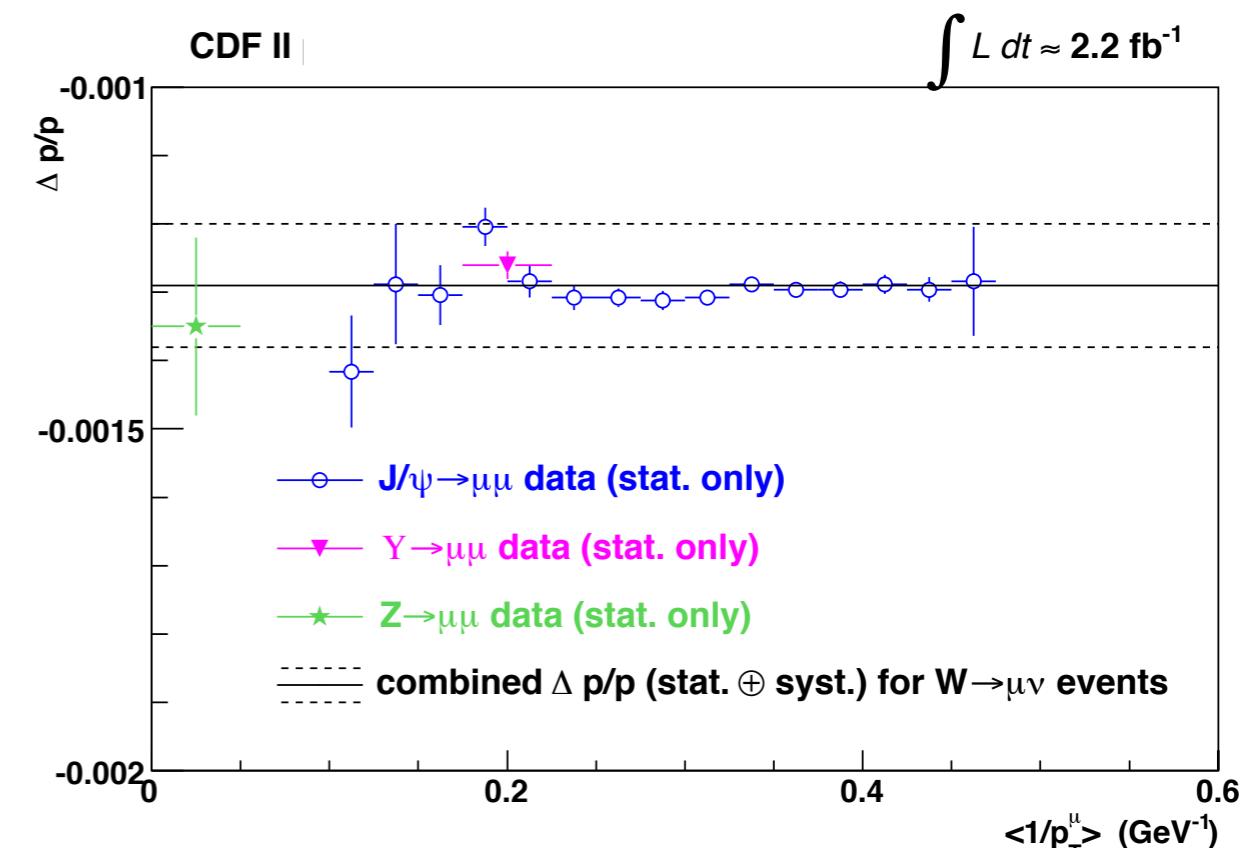
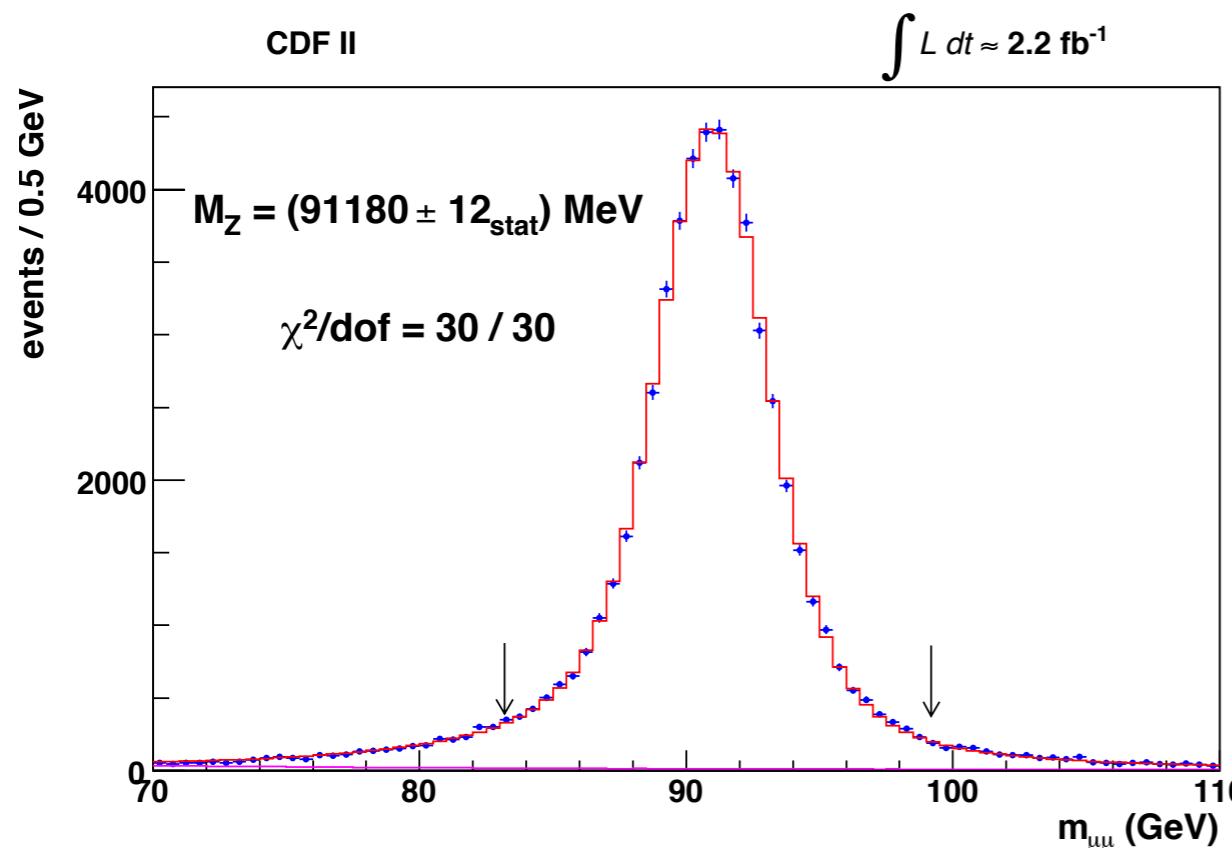
Track momentum scale: J/ψ , Υ

- Utilize large $\mu\mu$ resonances (J/ψ , Υ , Z) to set overall momentum scale
- Size of J/ψ sample allows subsample fits
 - Fit J/ψ mass in bins of $\langle 1/p_T(\mu) \rangle$ and apply material scale (4%) to remove dependence
- Apply calibration from J/ψ to Υ
 - Intermediate p_T
 - Allows check of beam constraint



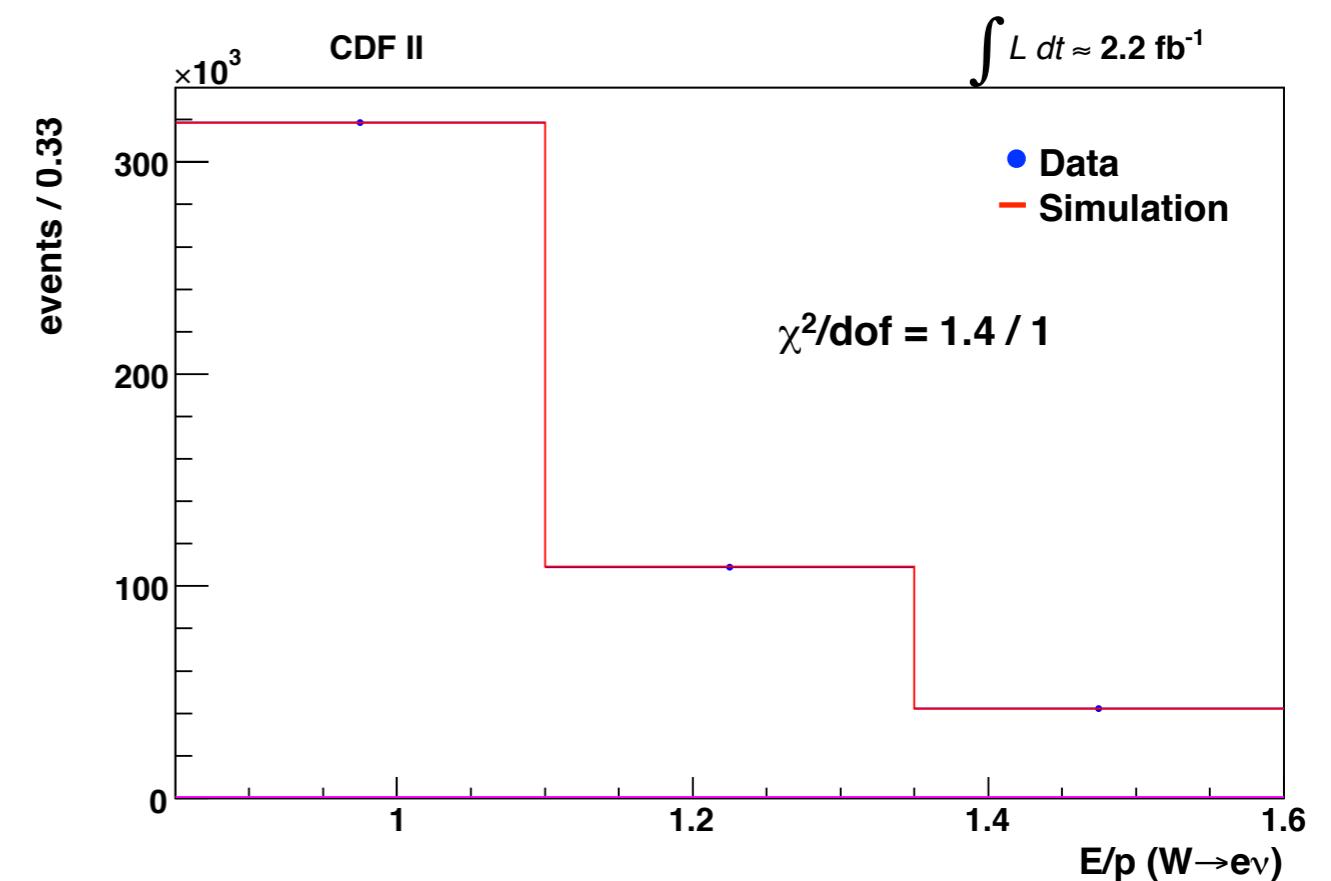
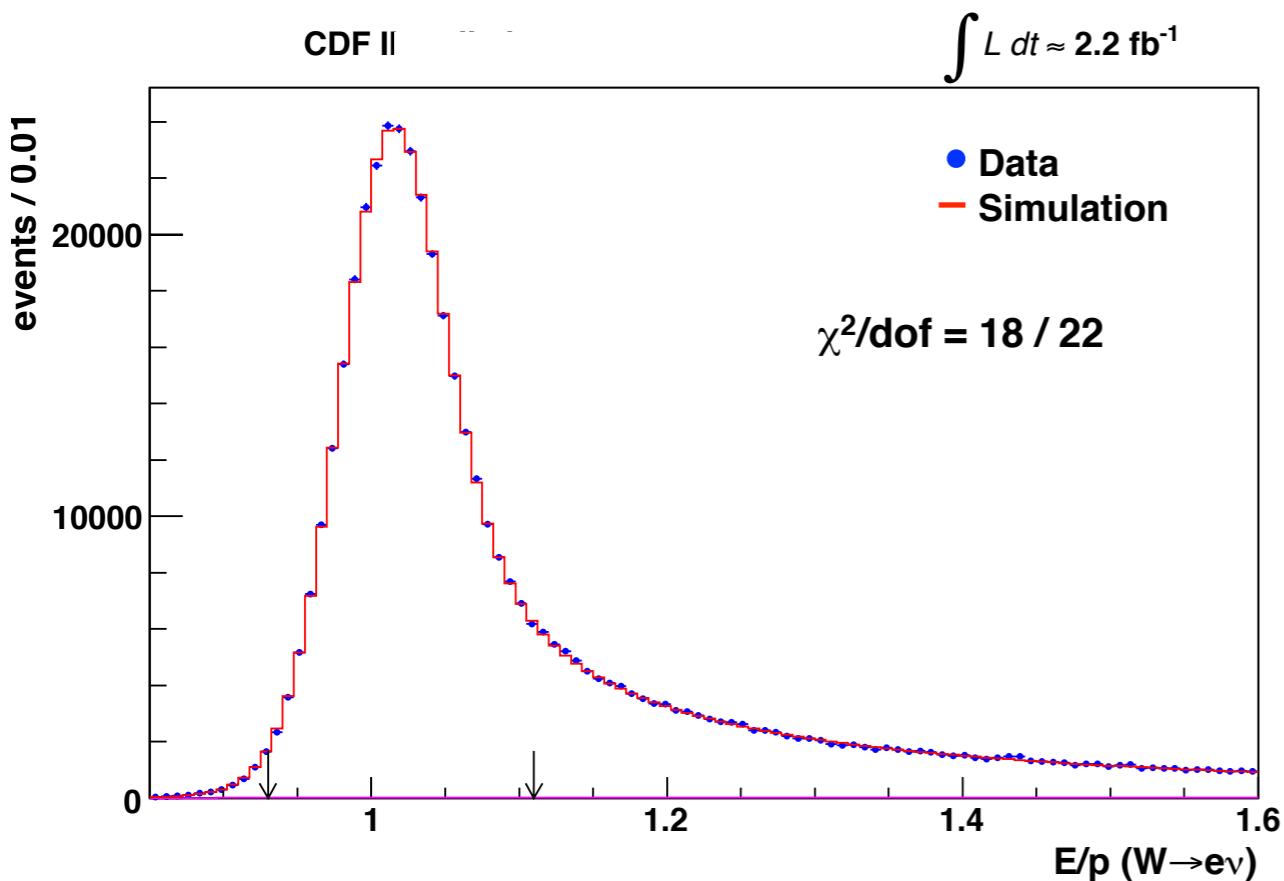
Muon Z mass and final track momentum scale

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



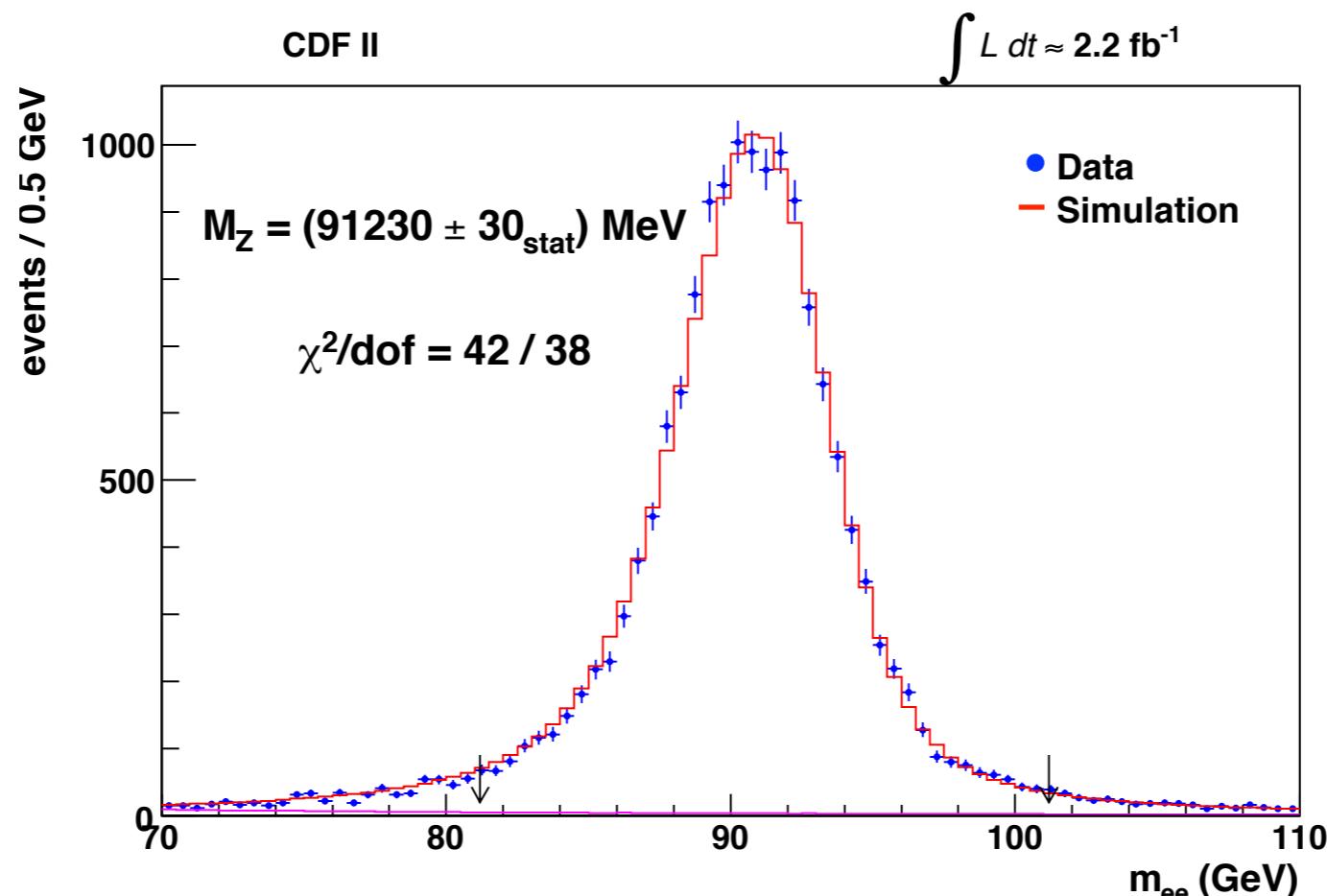
Energy scale calibration

- 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)
 - $\Delta S_E = (9_{\text{stat}} \pm 5_{\text{non-linearity}}) \times 10^{-5}$
 - Fit to tail to tune amount of radiative material
 - $S_{x0} = 1.026 \pm 0.003_{\text{stat}} \pm 0.002_{\text{bkg}}$
 - Systematic uncertainty $\Delta M_W = 13$ MeV



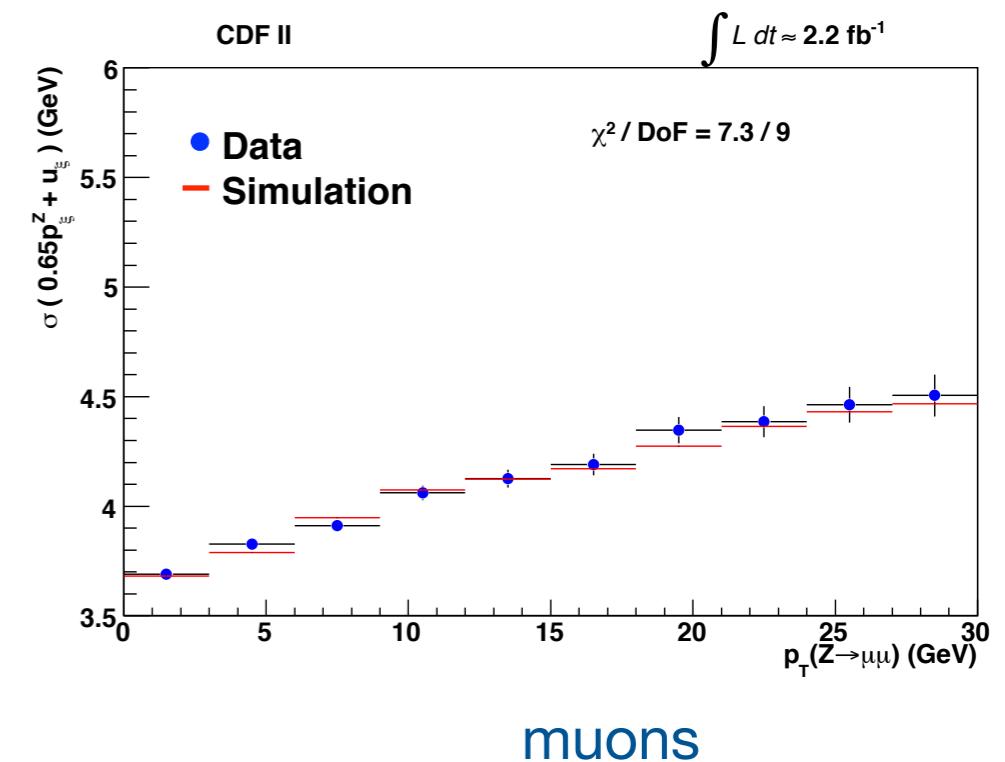
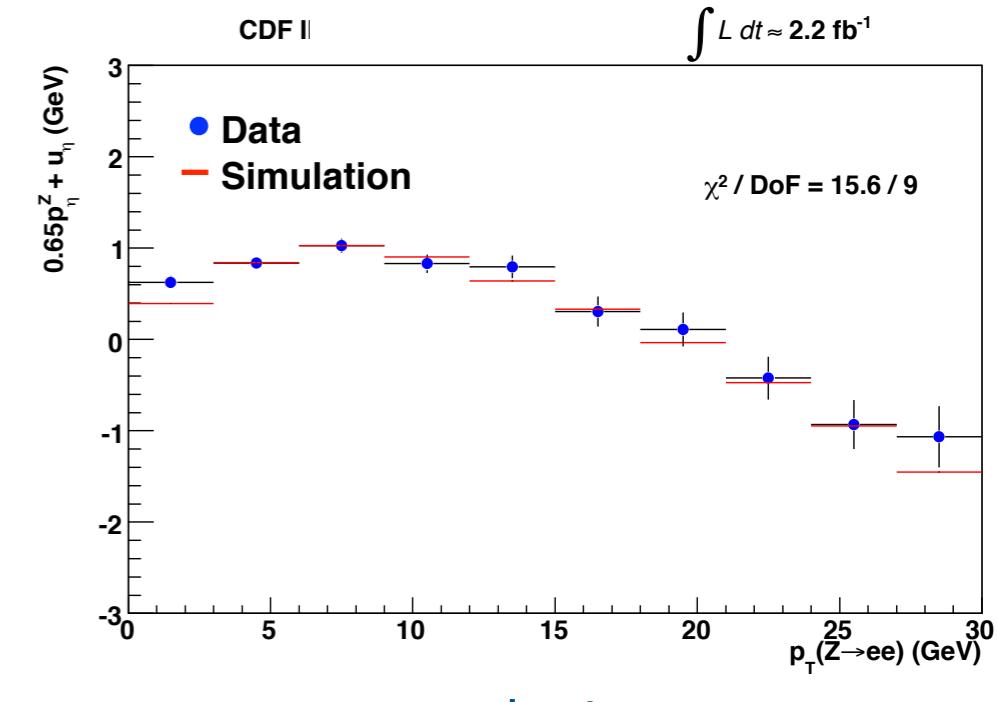
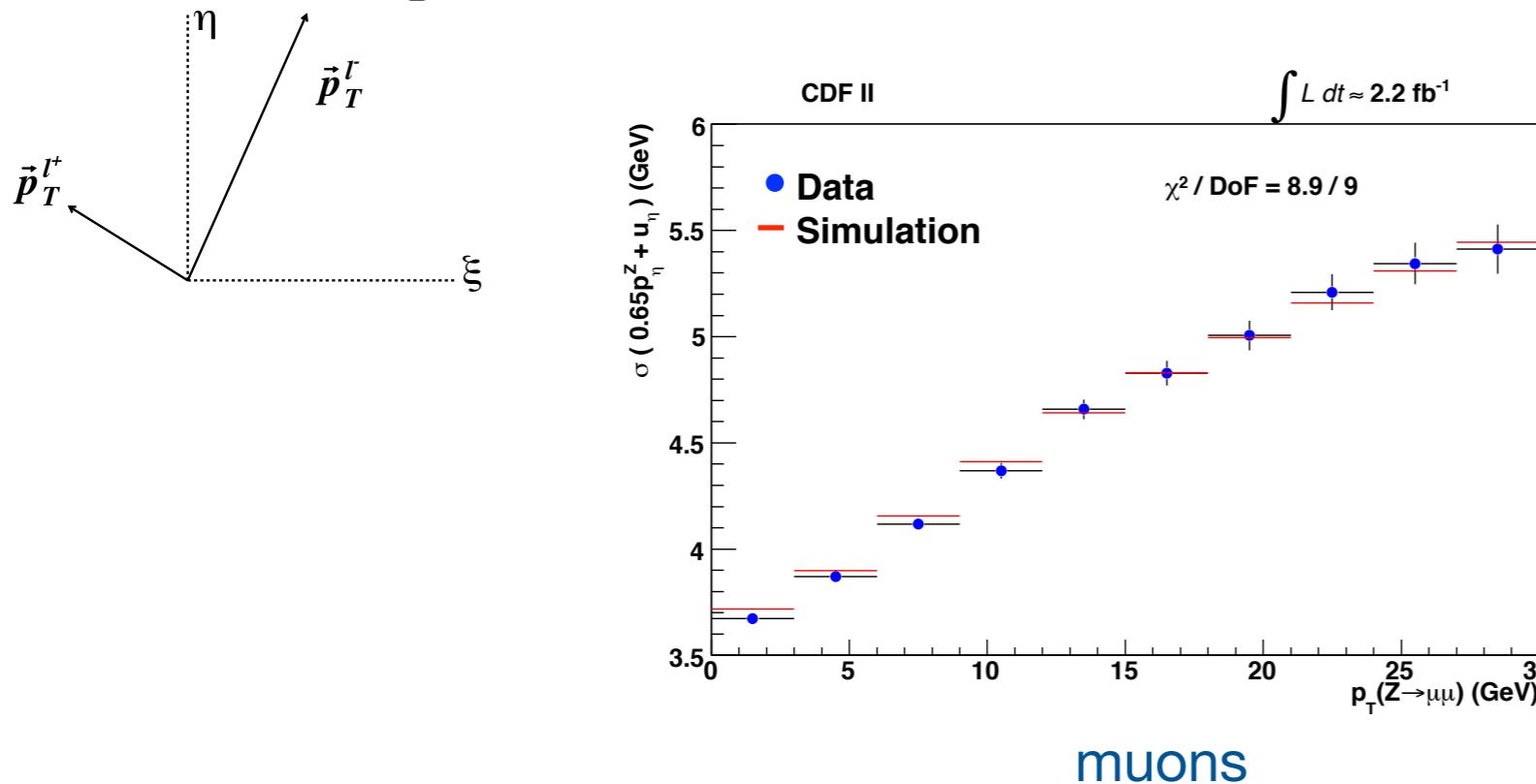
Electron Z mass and final EM energy scale

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



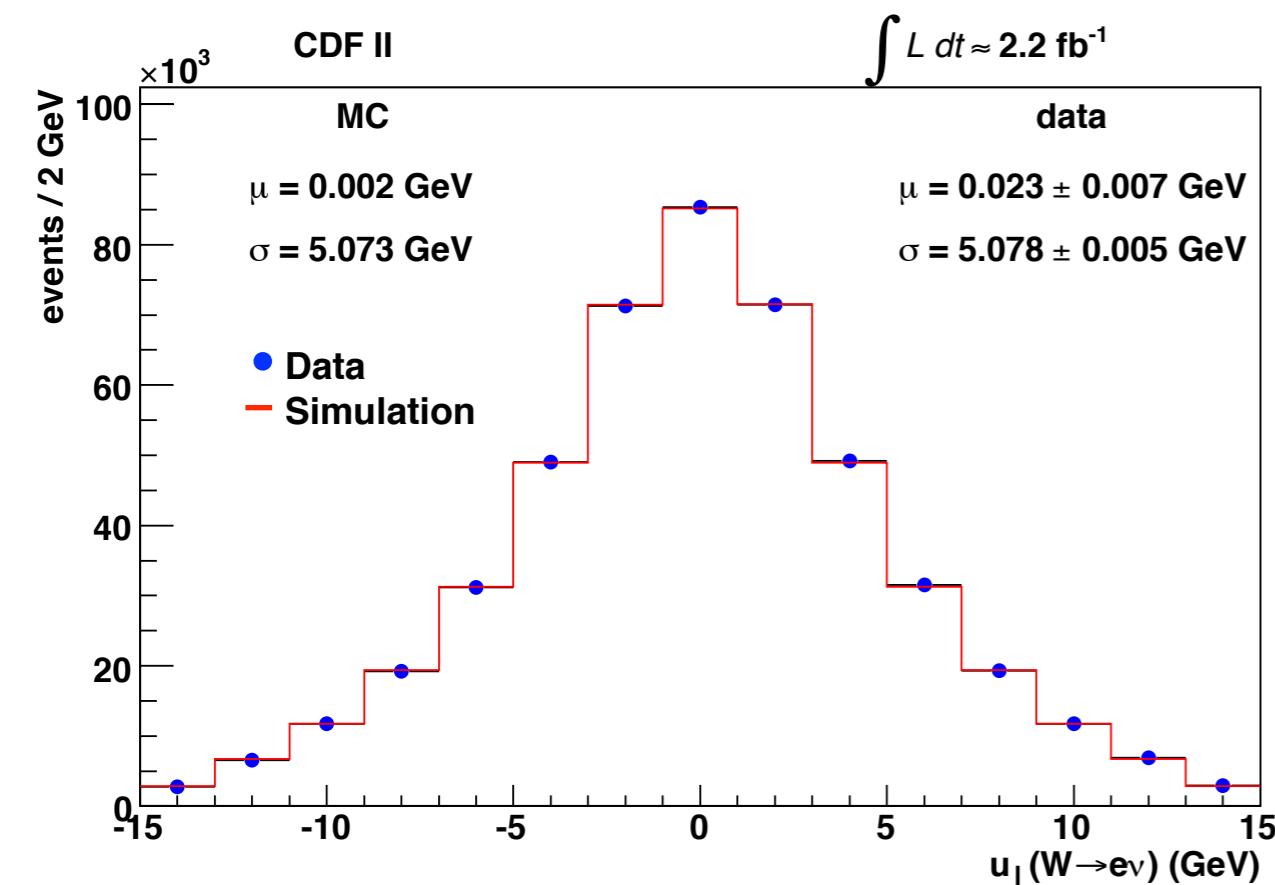
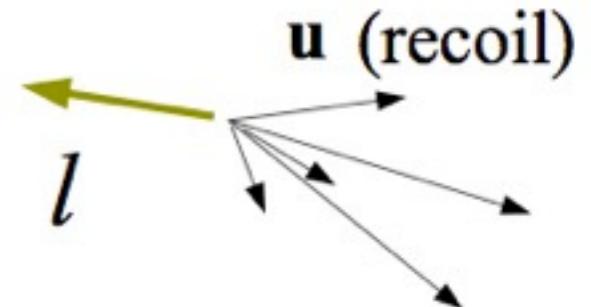
Recoil calibration

- Recoil: $\mathbf{u} = (\sum_{\text{towers}} E_i) - E_{\text{lepton}}$
 - Estimate impact of UE energy in subtracted lepton towers $\Delta M_W = 2 \text{ MeV}$
- Recoil scale $R = u_{\text{meas}} / u_{\text{true}}$
 - Calibrate by balancing $Z p_T$ against $p_T + u$ along eta axis $\Delta M_W = 4 \text{ MeV}$
- Recoil resolution
 - Calibrate balancing $Z p_T$ against $\text{rms}(p_T + u)$ along both axes $\Delta M_W = 4 \text{ MeV}$

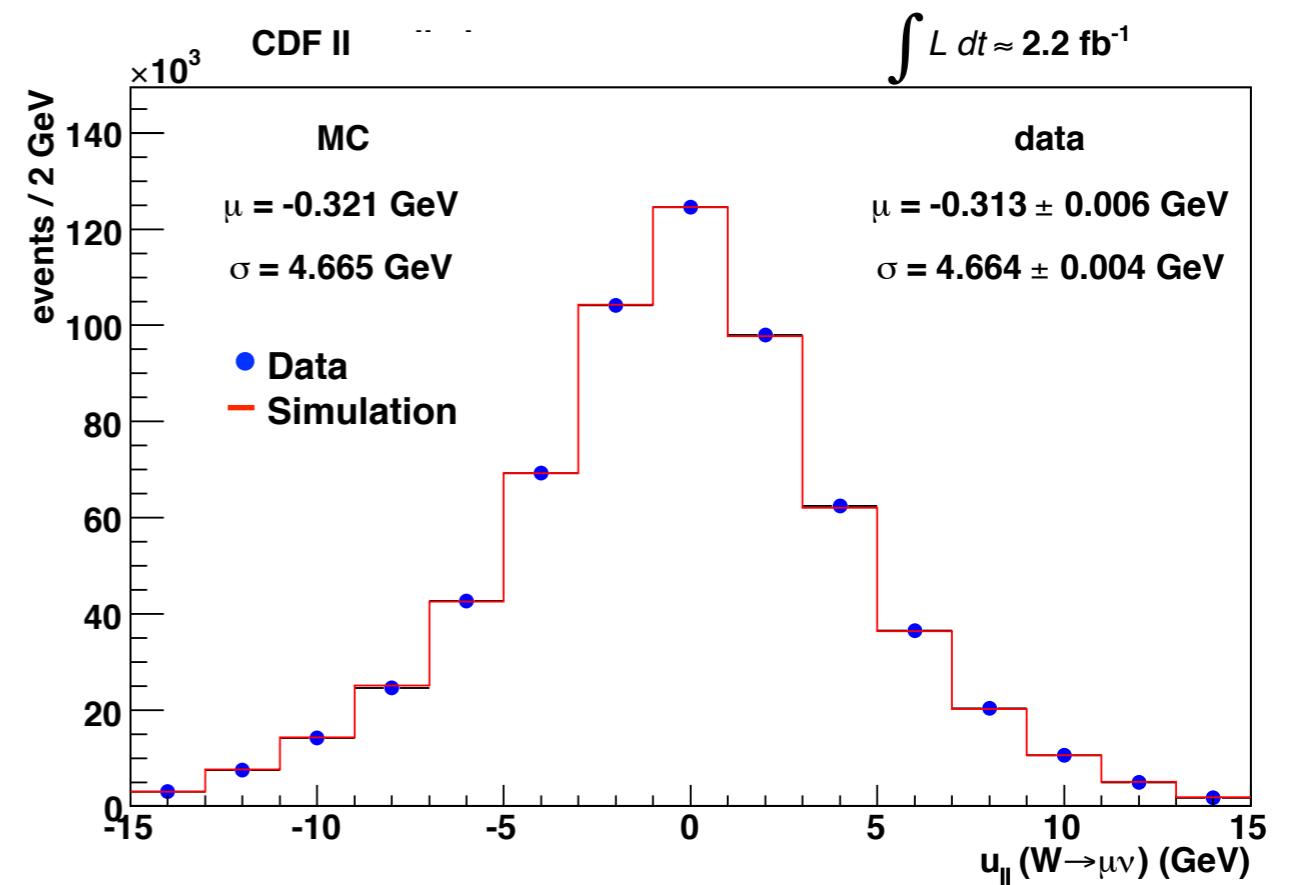


Recoil validation

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



Recoil projection perpendicular to lepton
(electrons)

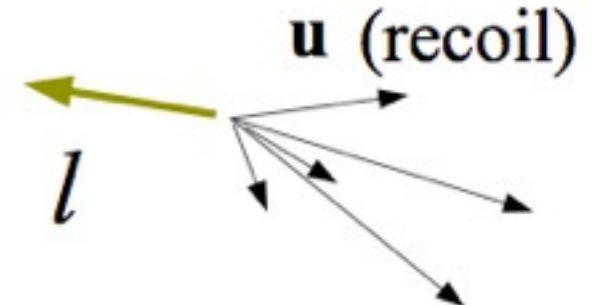


Recoil projection in direction of lepton
(muons)

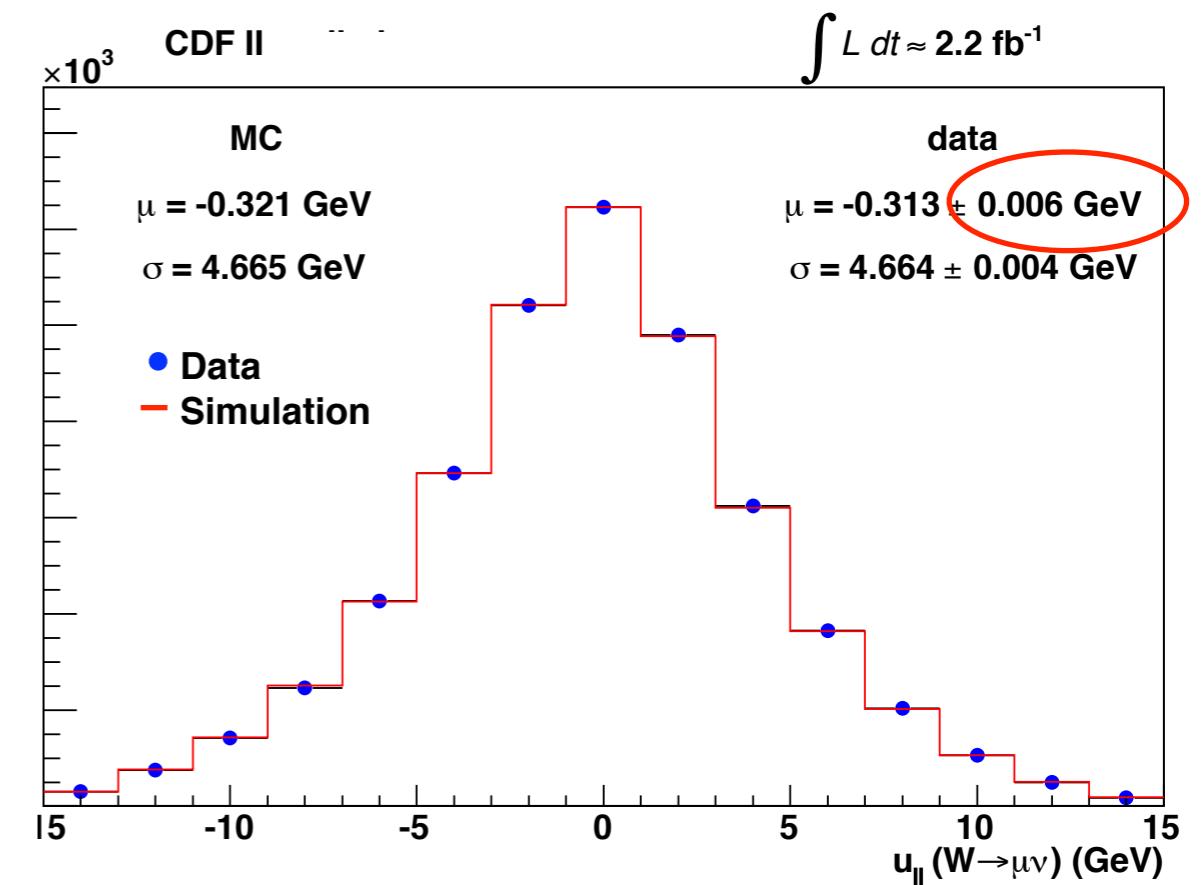
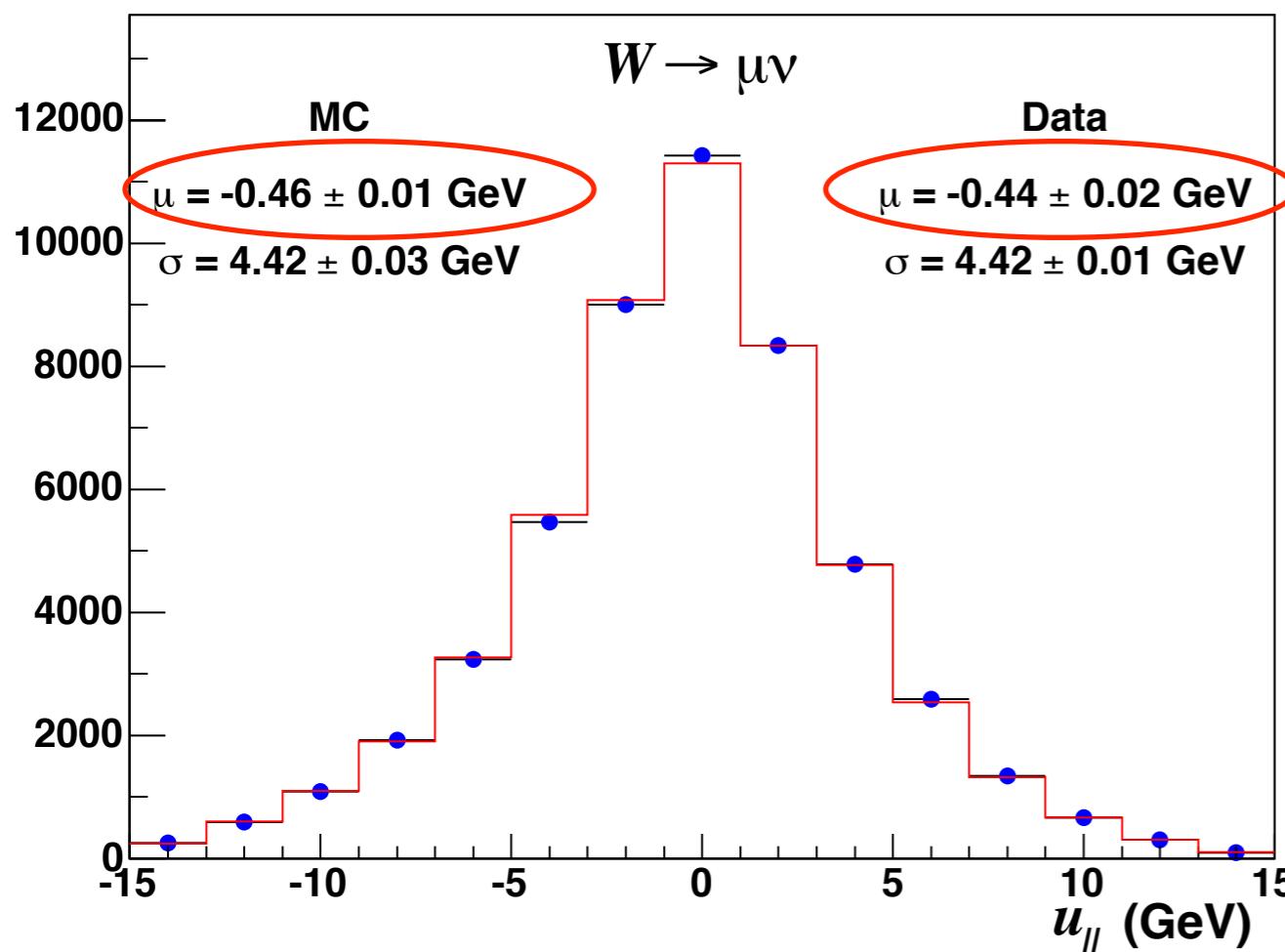
$$m_T \approx 2p_T^I + u_{||}, p_T^V \approx 2p_T^I + 2u_{||}$$

Recoil validation

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



200 pb^{-1} [PRD77:112001, 2008]



Recoil projection in direction of lepton
(muons)

$$m_T \approx 2p_T^I + u_{||}, \quad p_T^V \approx 2p_T^I + 2u_{||}$$

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 $\Delta M_W = 10 \text{ MeV}$

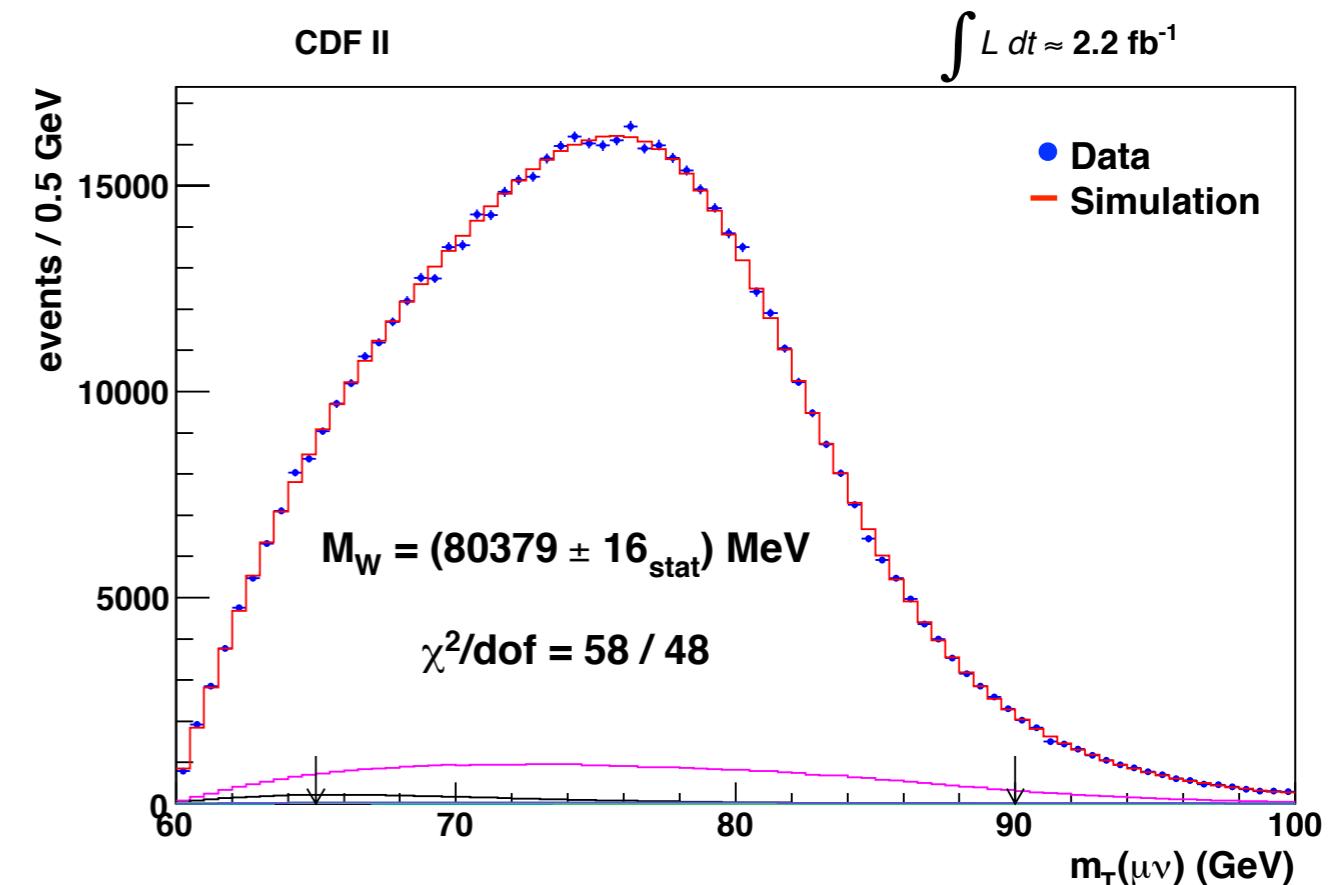
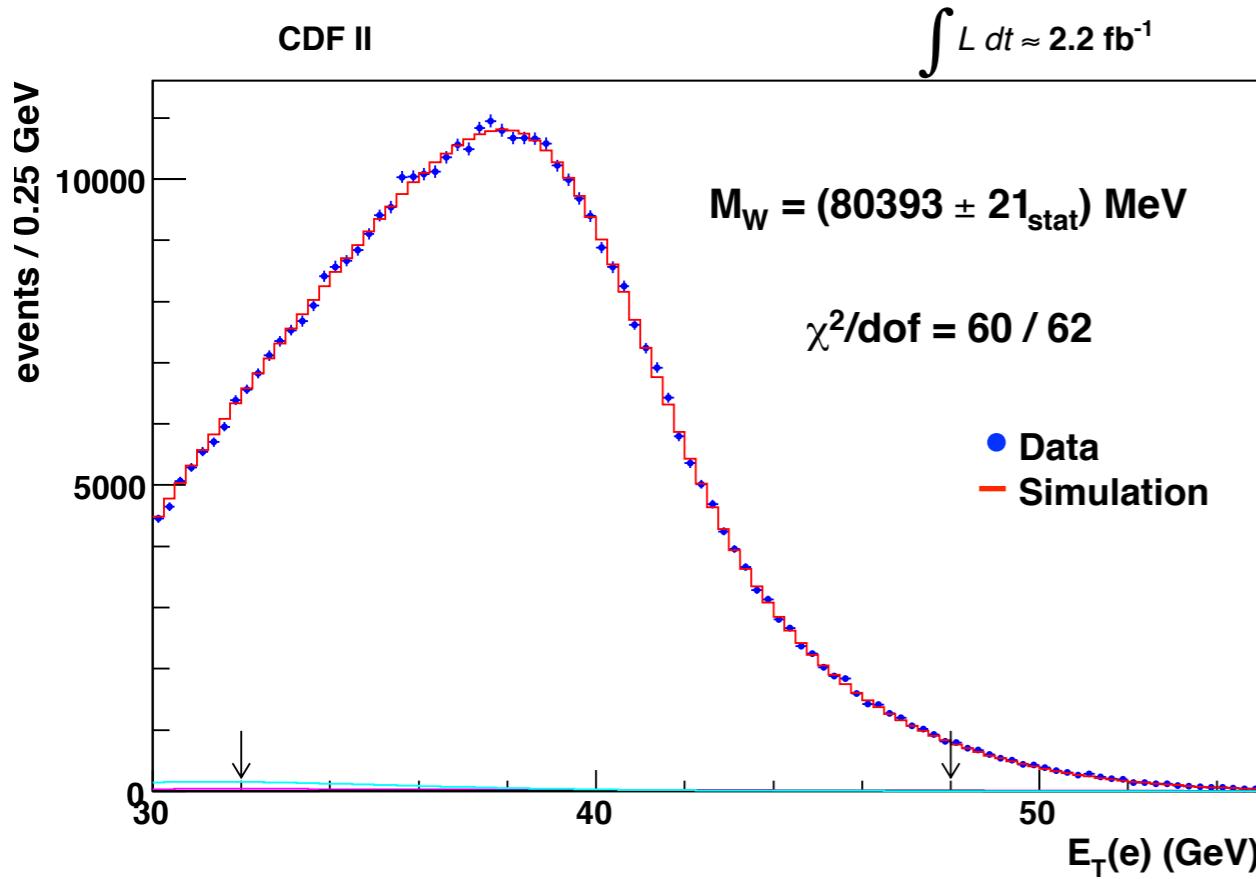
Backgrounds

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

Background	$\Delta m_W (\text{MeV})$								
	Fraction of W data (%)		m_T			p_T^l		p_T^v	
$Z \rightarrow ll$	7.35 ± 0.09	0.139 ± 0.014	2	1	4	2	5	1	
$W \rightarrow \tau\nu$	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		
<i>Total</i>			3	4	5	3	6	4	

muons
electrons

Example mass fits

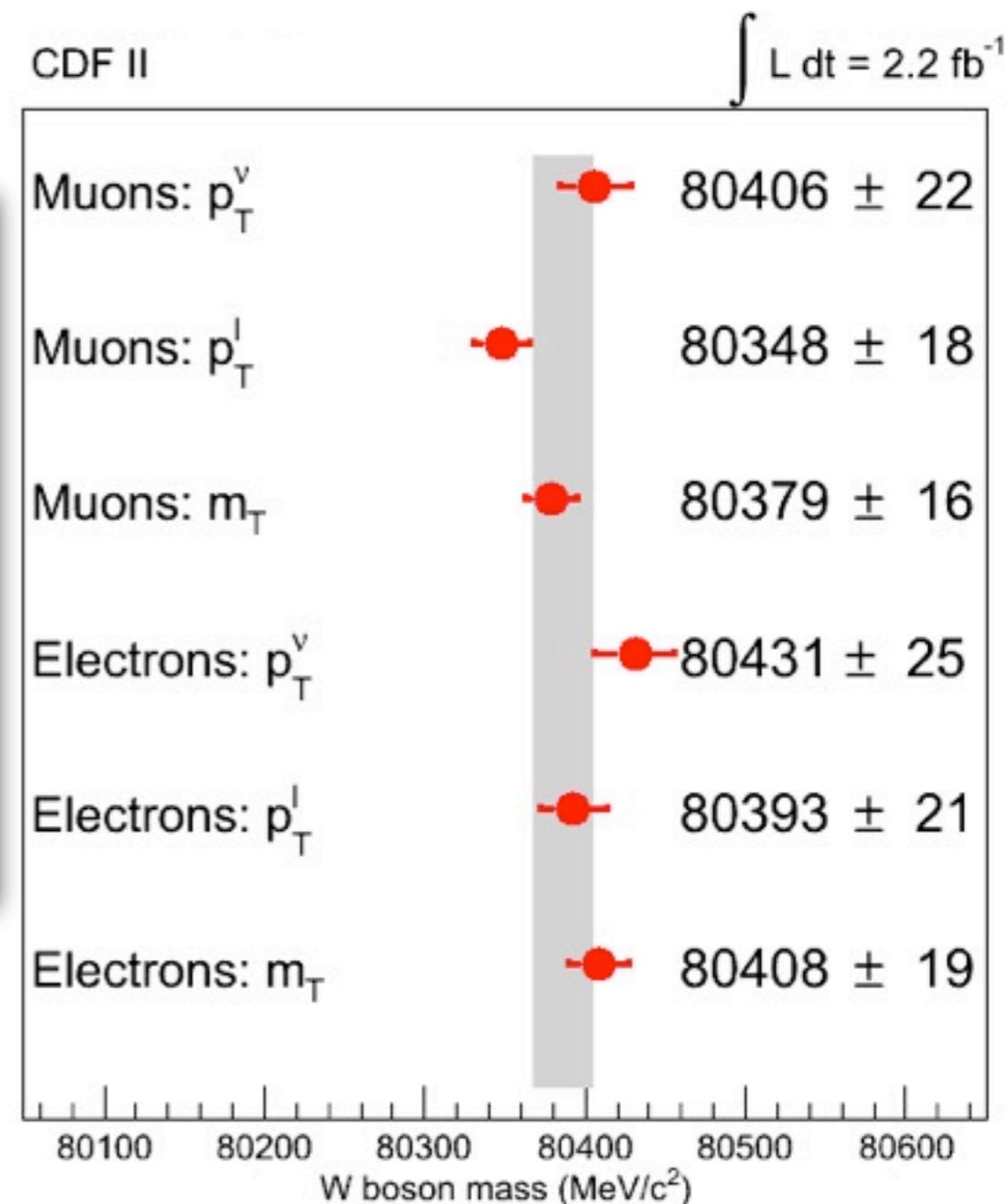


p_T^l : electrons

m_T : muons

All fits

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



Combined results

- All electron fits combined

$M_W = 80406 \pm 25 \text{ MeV}$, $\chi^2/\text{dof} = 1.4/2$ (49%)

- All muon fits combined

$M_W = 80374 \pm 22 \text{ MeV}$, $\chi^2/\text{dof} = 4/2$ (12%)

- All fits combined

$M_W = 80387 \pm 19 \text{ MeV}$, $\chi^2/\text{dof} = 6.6/5$ (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
<i>Total systematics</i>	15
W statistics	12
<i>Total</i>	19

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

Combined uncertainties

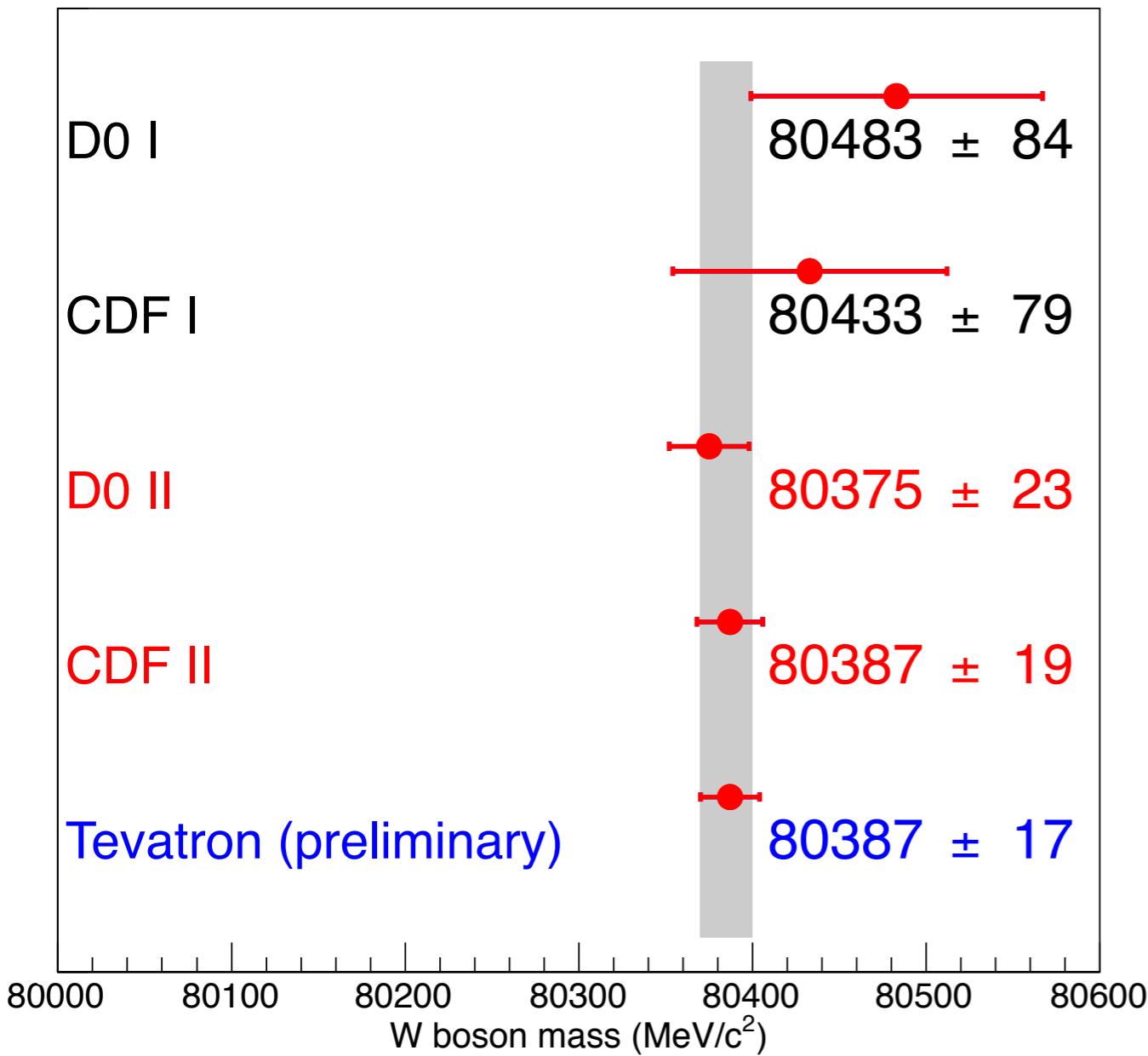
Statistics limited by control data

Theory based (external inputs)

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

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

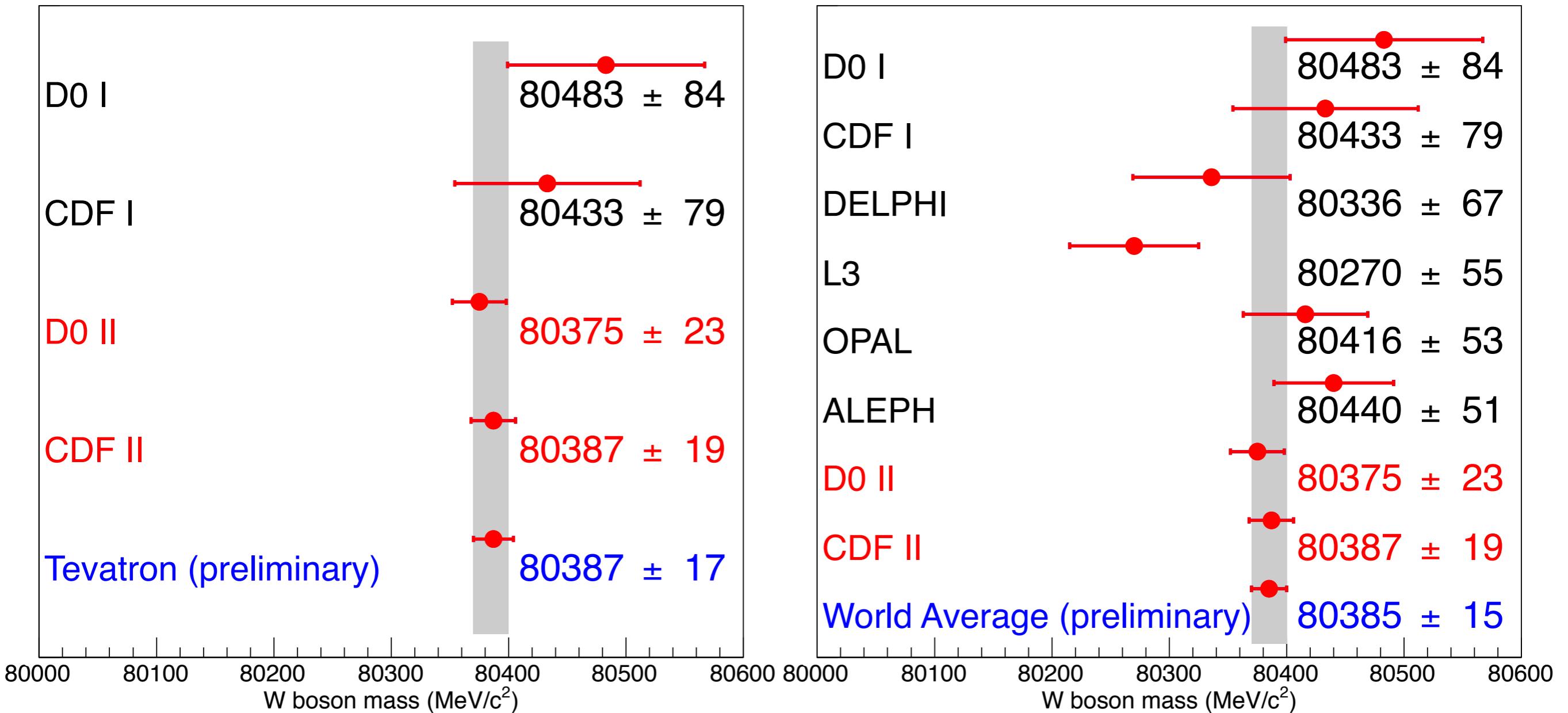
Tevatron and world combinations



nb: 2009 world average

$$M_W = 80399 \pm 23 \text{ MeV}$$

Tevatron and world combinations



nb: 2009 world average

$$M_W = 80399 \pm 23 \text{ MeV}$$

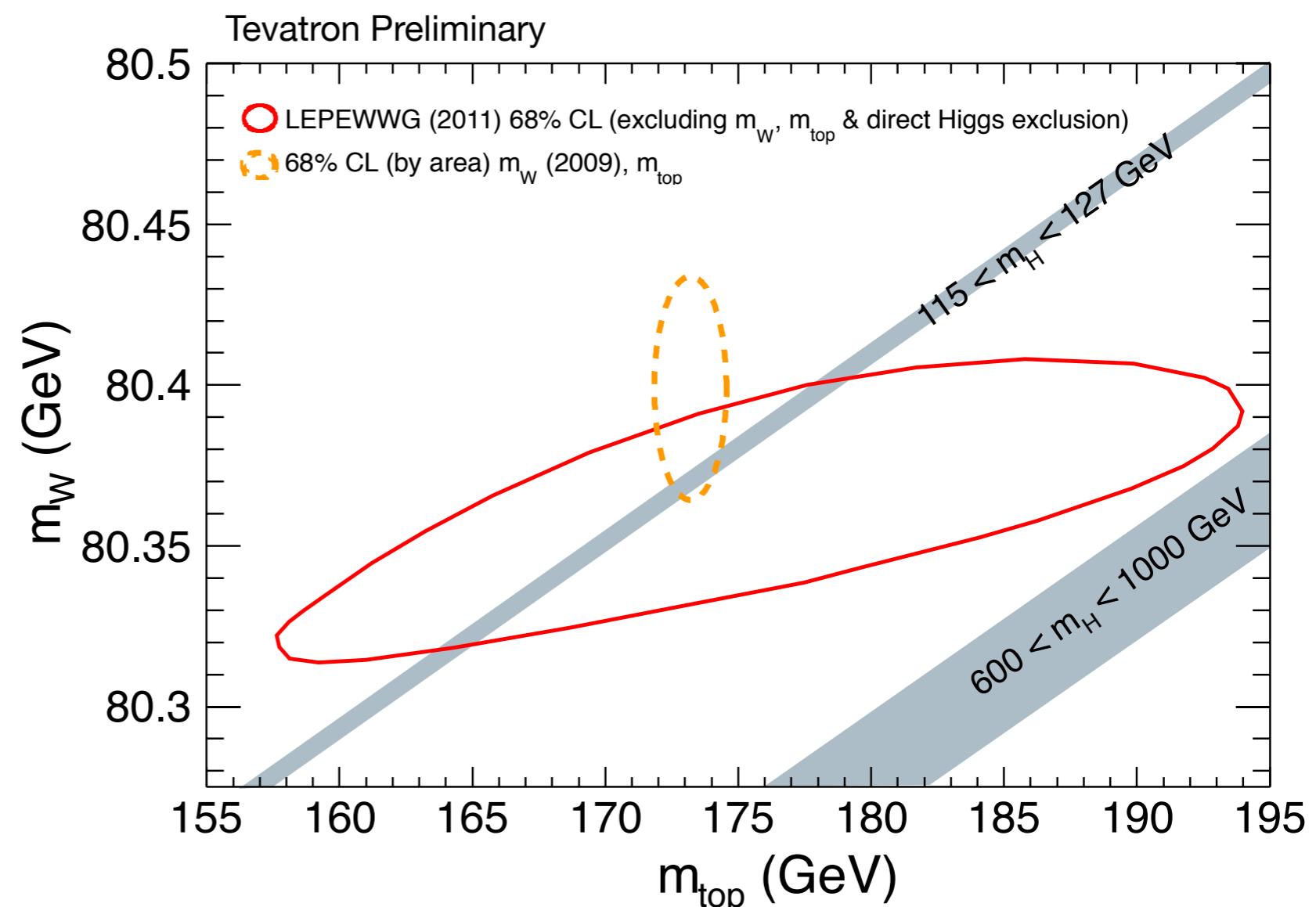
W mass vs. top mass

With $M_W = 80399 \pm 23$ MeV

$M_H = 92^{+34}_{-26}$ GeV

$M_H < 161$ GeV @95% CL

LEPEWWG/ZFitter



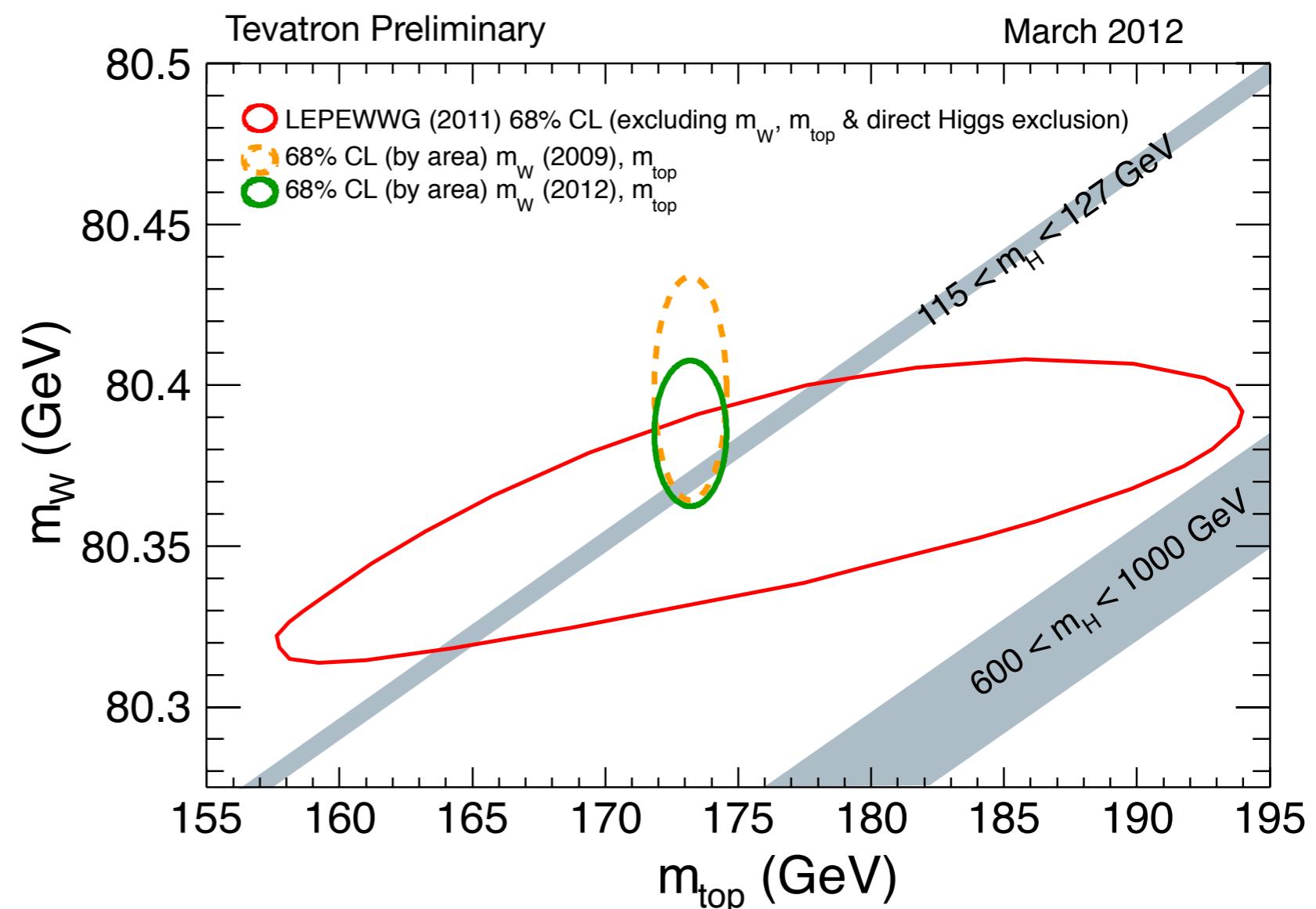
W mass vs. top mass

With $M_W = 80385 \pm 15$ MeV

$M_H = 94^{+29}_{-24}$ GeV

$M_H < 152$ GeV @95% CL

LEPEWWG/ZFitter



Conclusion

- CDF has performed the most precise measurement of the W boson mass
 - $M_W = 80387 \pm 19$ MeV [[arXiv:1203.0275](#)]
 - More precise than all previous measurements combined
- Combine with DØ result [[arXiv:1203.0293](#)]
 - **Tevatron:** $M_W = 80387 \pm 17$ MeV (TeVWWG, preliminary)
 - **World:** $M_W = 80385 \pm 15$ MeV (TeVWWG, preliminary)
- Results in SM fits of $M_H < 152$ 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
 - $\Delta M_W < 15$ MeV per experiment achievable
- Thank you for your patience

Backup

Motivation

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

$$G_F = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2}$$

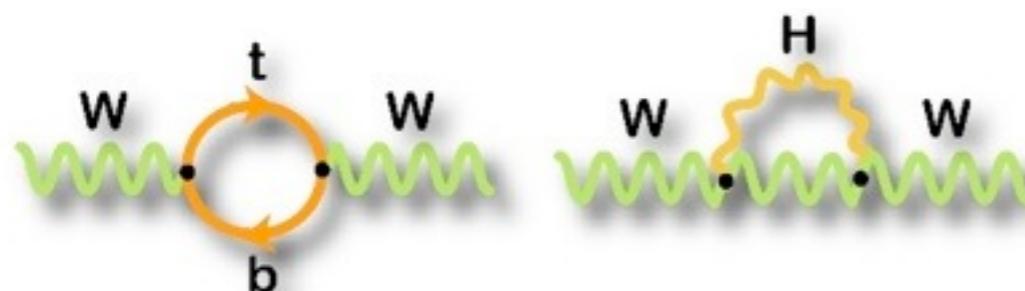
$$\alpha_{EM}(Q^2 = M_Z^2) = 1/127.918(18)$$

$$m_Z = 91.1876(21) \text{ GeV}/c^2$$

- These constants are all related to m_W by

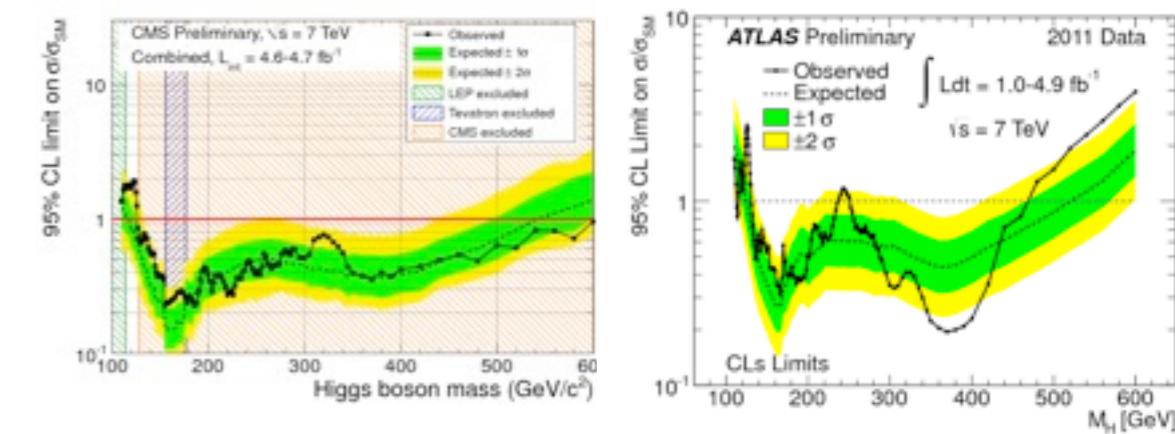
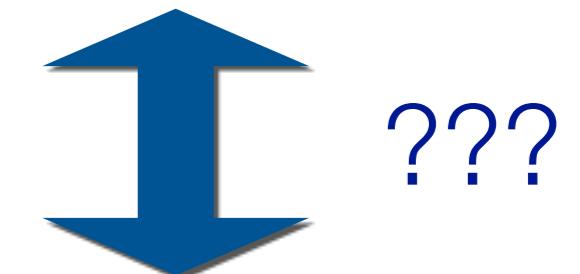
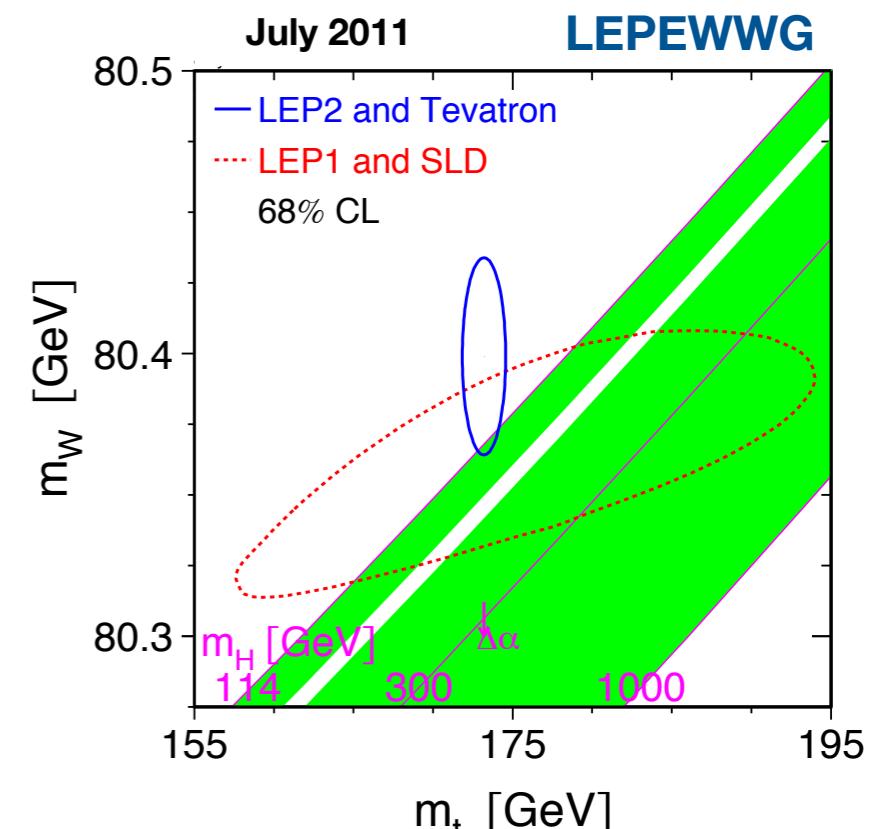
$$m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_F \sin^2 \theta_W (1 - \Delta r)} \quad \sin \theta_W^2 = 1 - \frac{m_W^2}{m_Z^2}$$

- Radiative corrections Δr dominated by top and Higgs loops



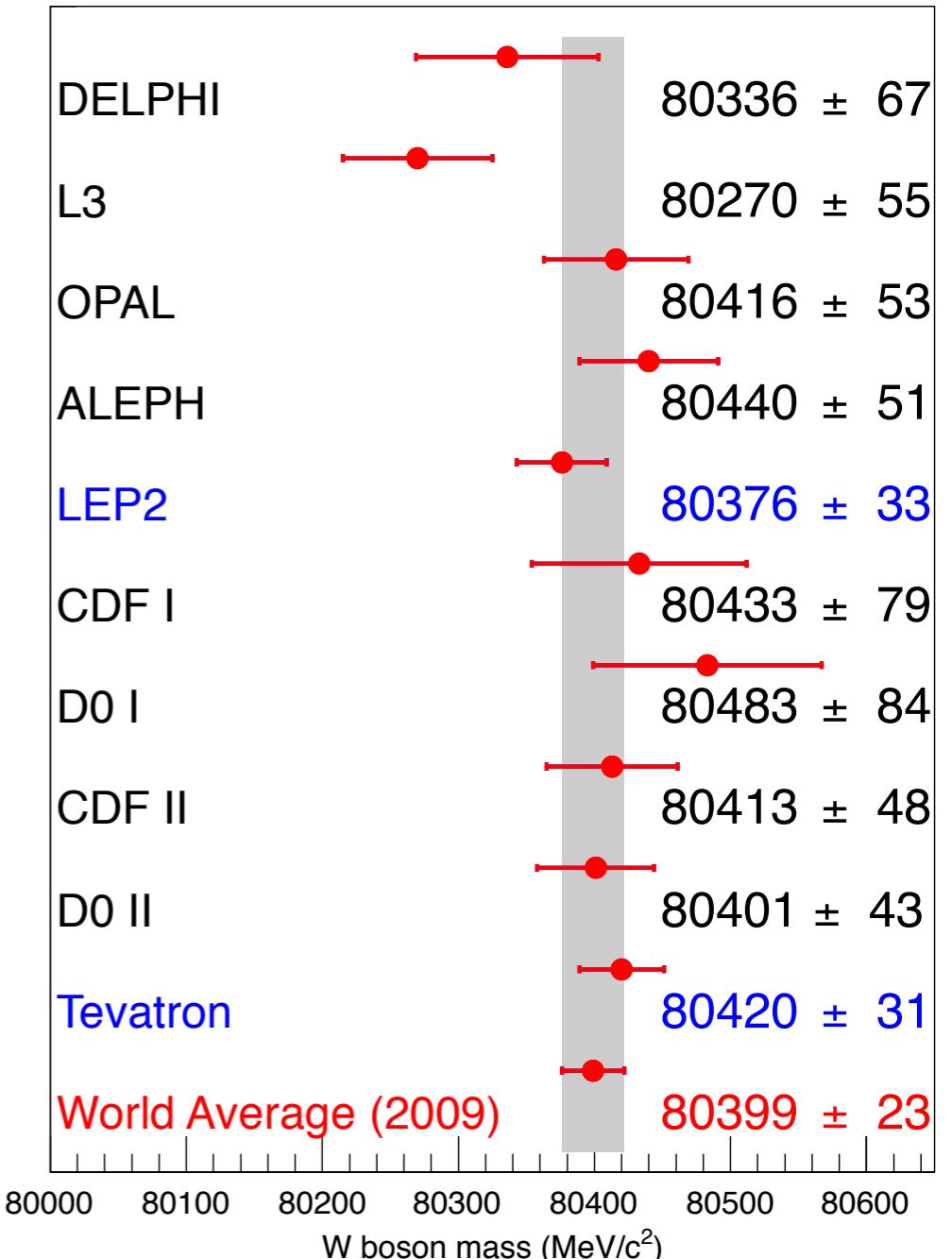
- Precision measurements in m_W and m_{top} constrain SM Higgs mass

Where should the Higgs be?



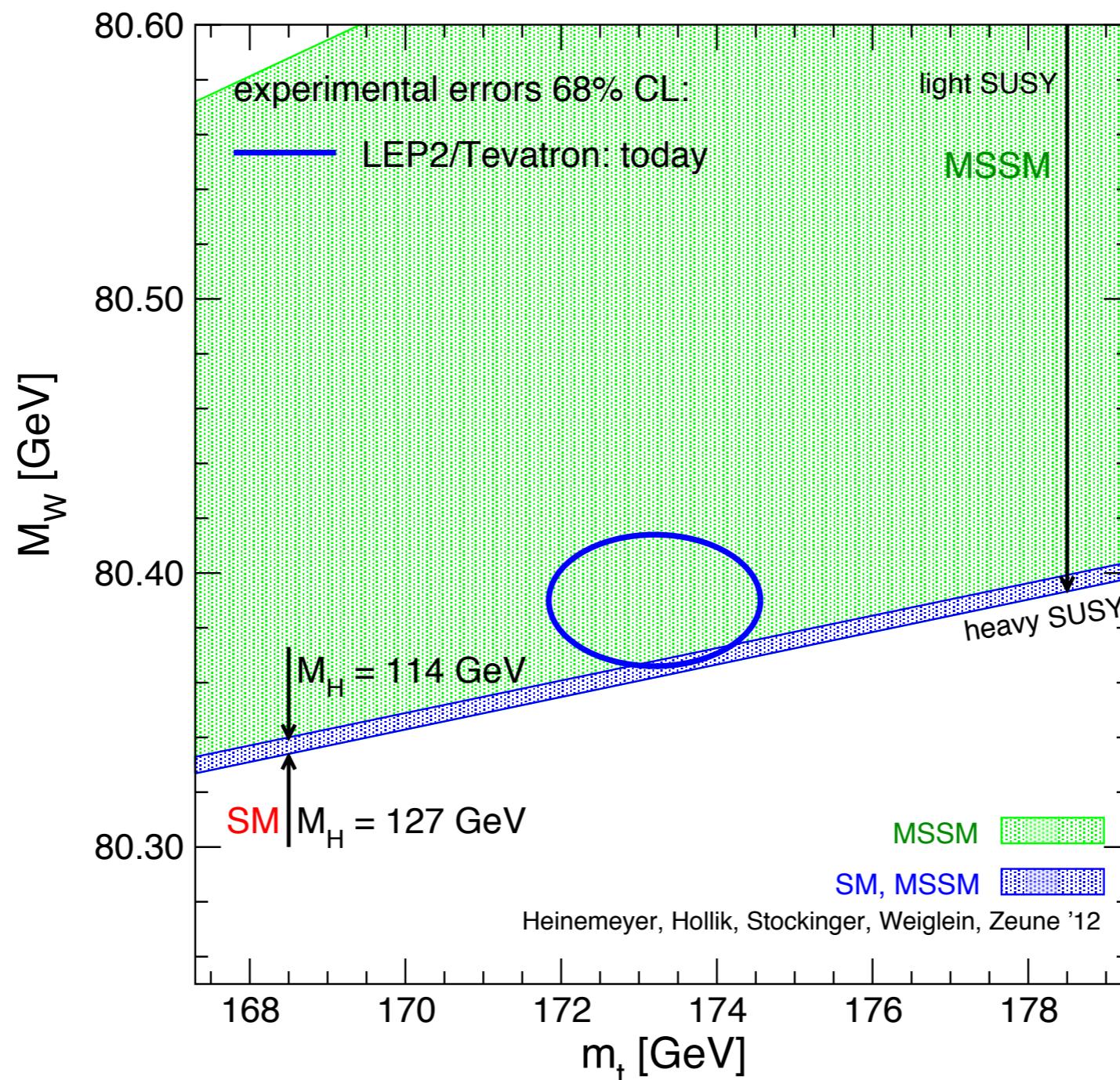
Measurements of M_W

- State-of-the-art
 - DØ $M_W = 80401 \pm 43$ MeV [1 fb^{-1} , e]
PRL 103:141801 (2009)
 - CDF $M_W = 80413 \pm 48$ MeV [200 pb^{-1} , e+ μ]
PRL 99:151801 (2007)
PRD 77:112001 (2008)
 - Combining with LEP $\Delta M_W = 23$ 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



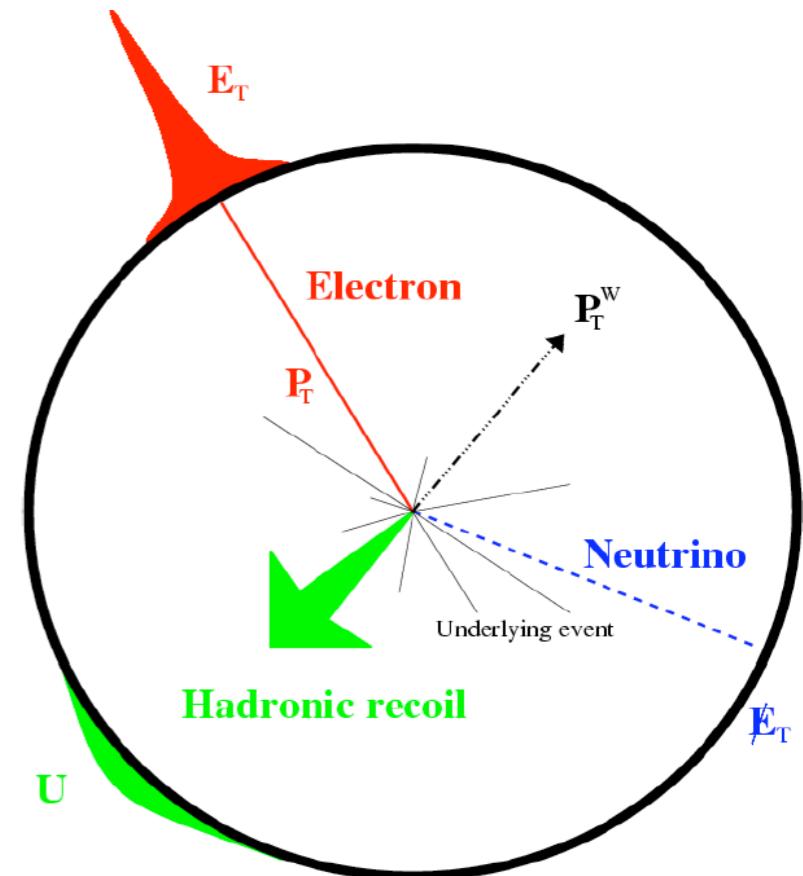
MSSM allowed region

Heinemeyer, Hollik, Stockinger, Weiglein, Zeune



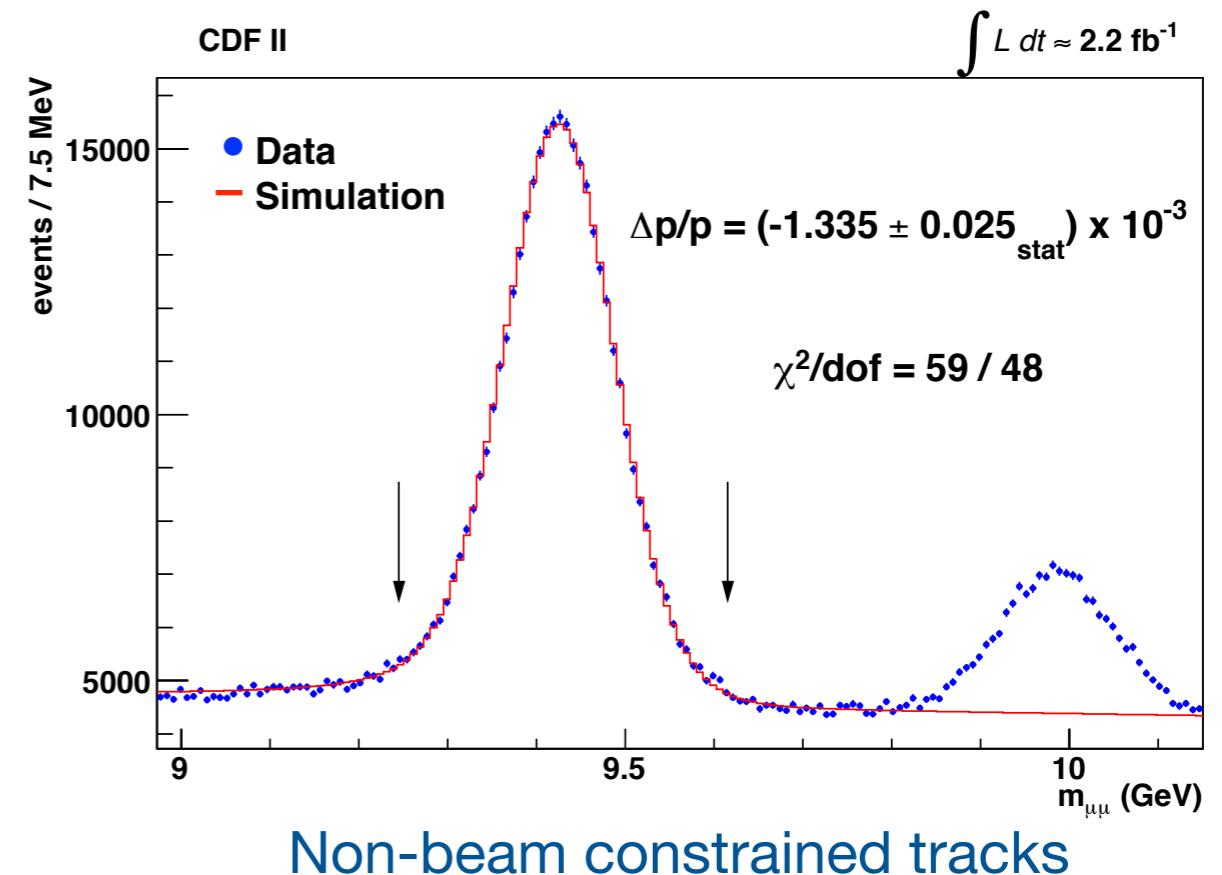
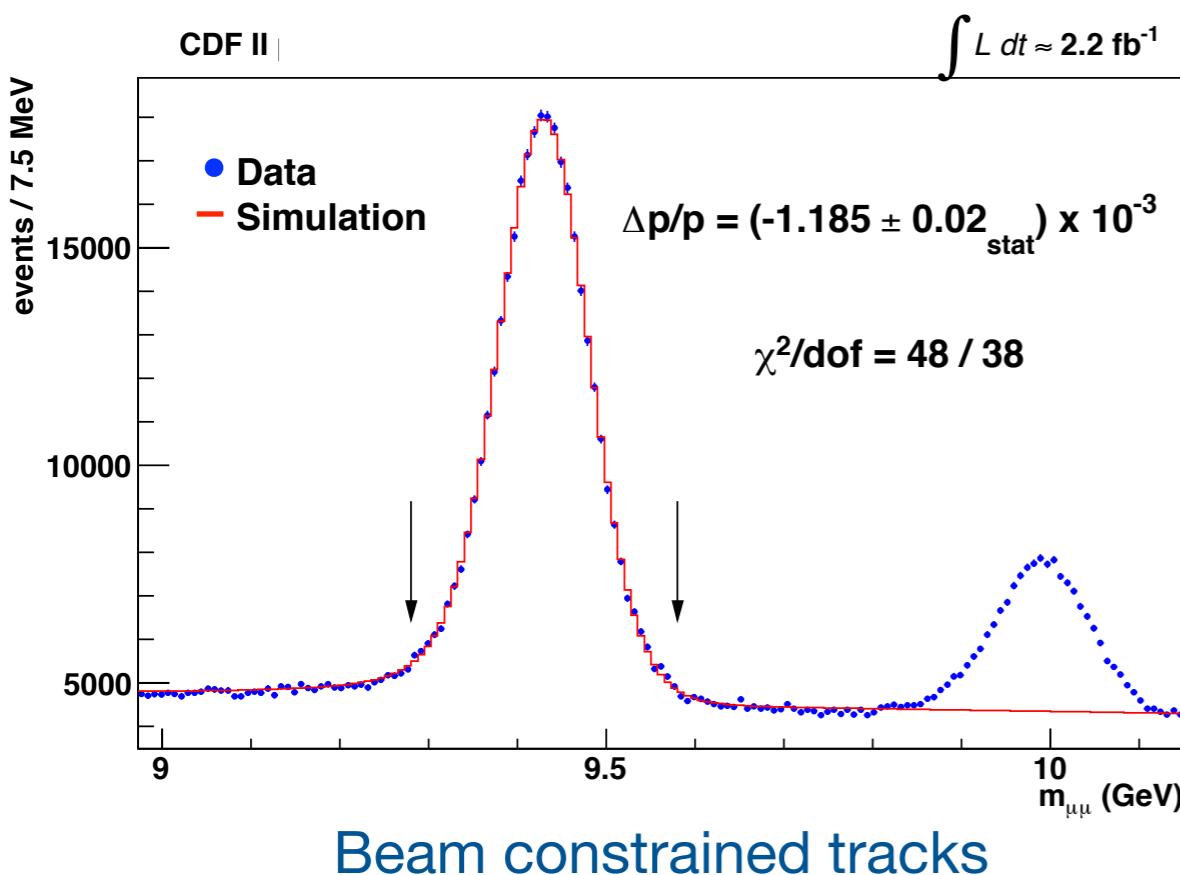
Precision?

- 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 $p_T(W) \ll M_W$
- 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



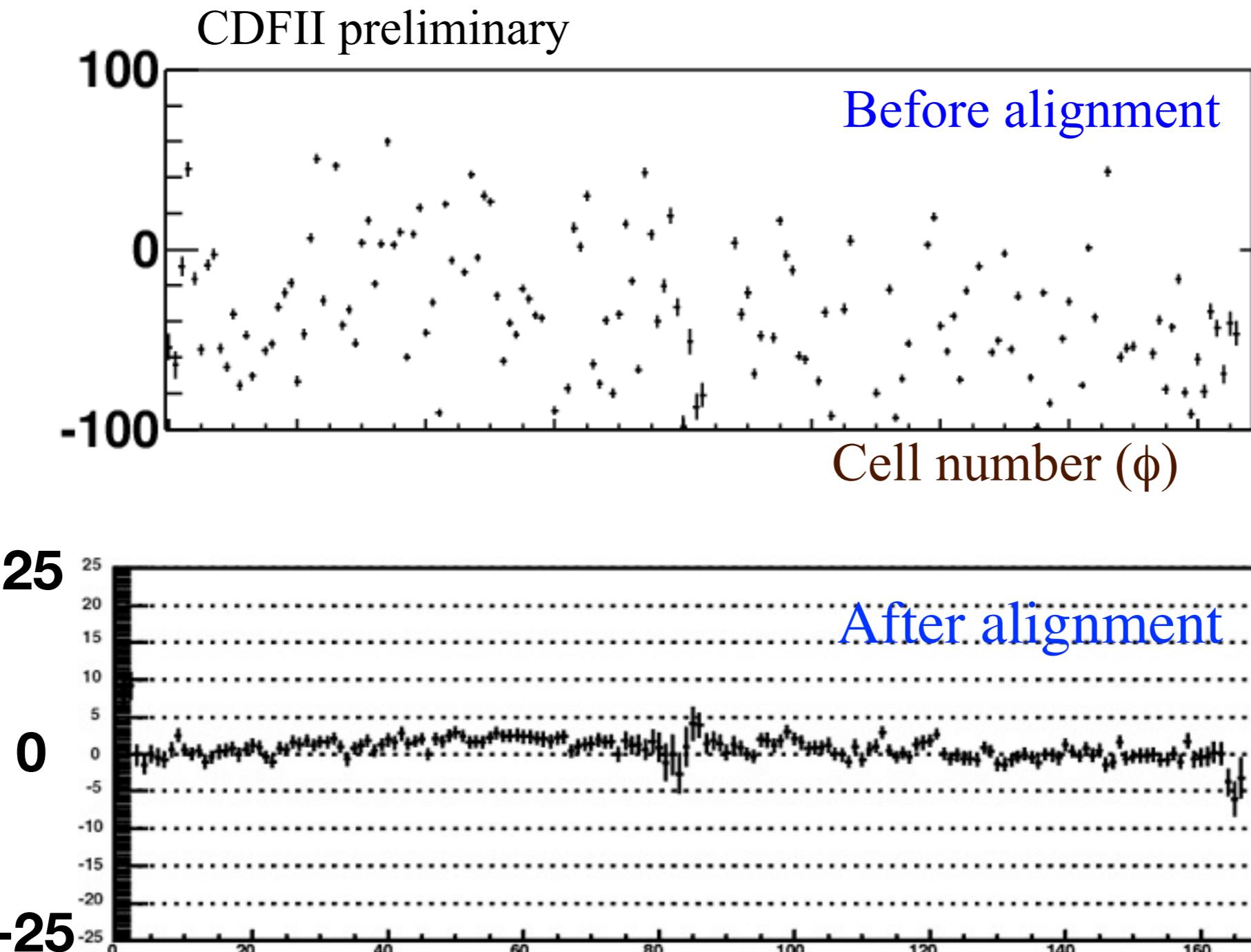
Track momentum scale: Υ

- Υ sample provides higher- p_T sample to tune scale
 - Υ s 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 Z s



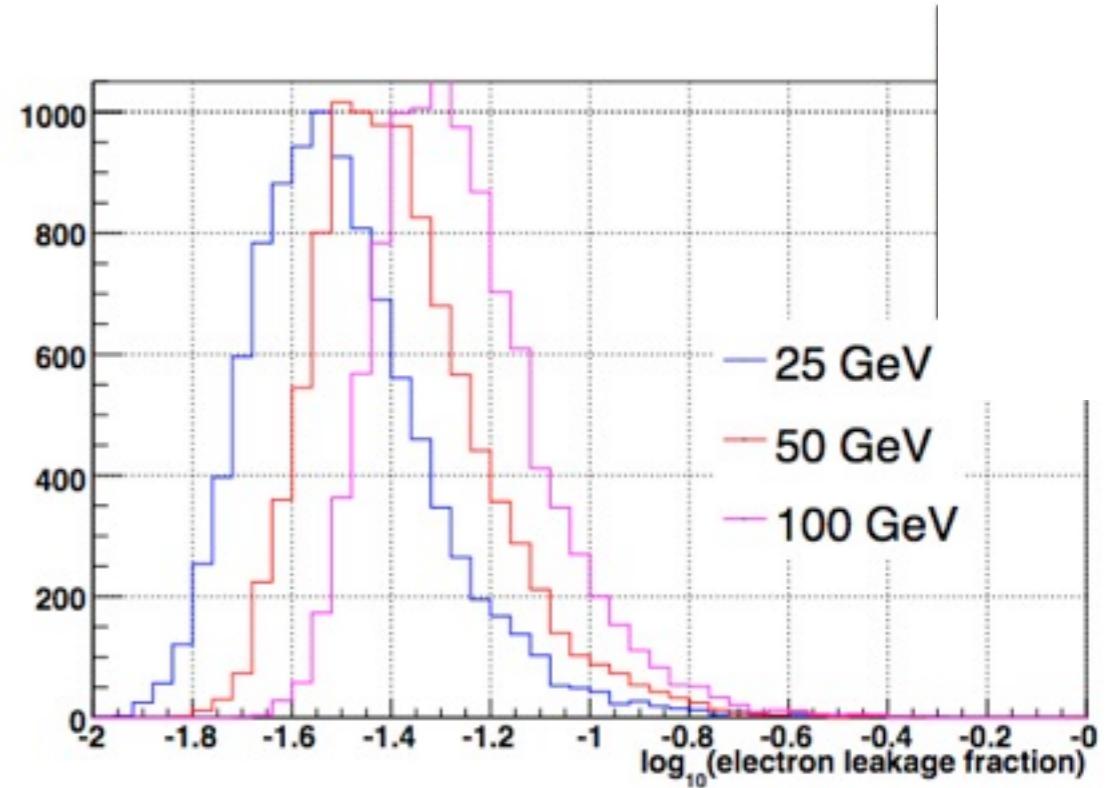
Tracker alignment

- Align COT using cosmic rays triggered *in-situ* with collider data
- Improve alignment from $\sim 50\mu\text{m}$ to $\sim 2\mu\text{m}$



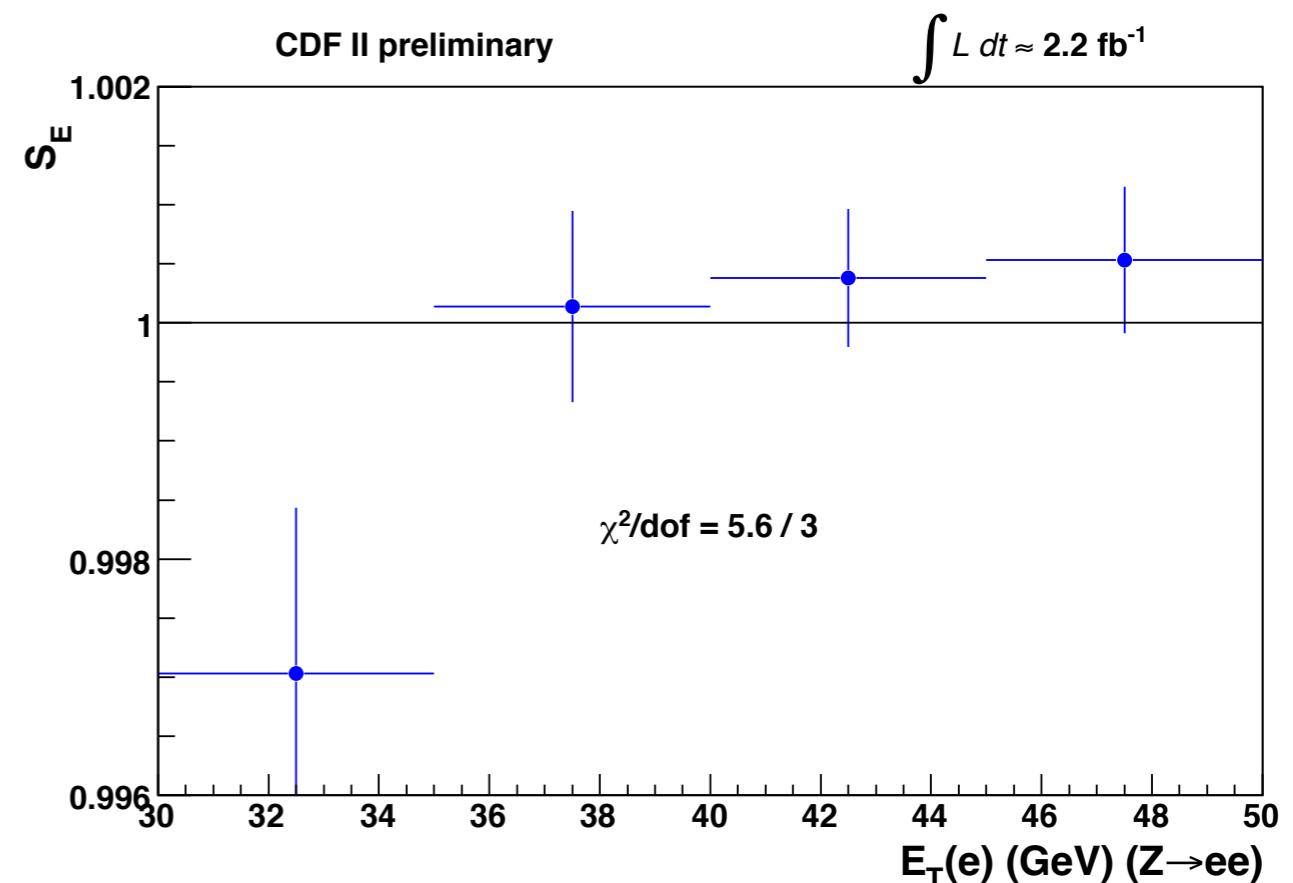
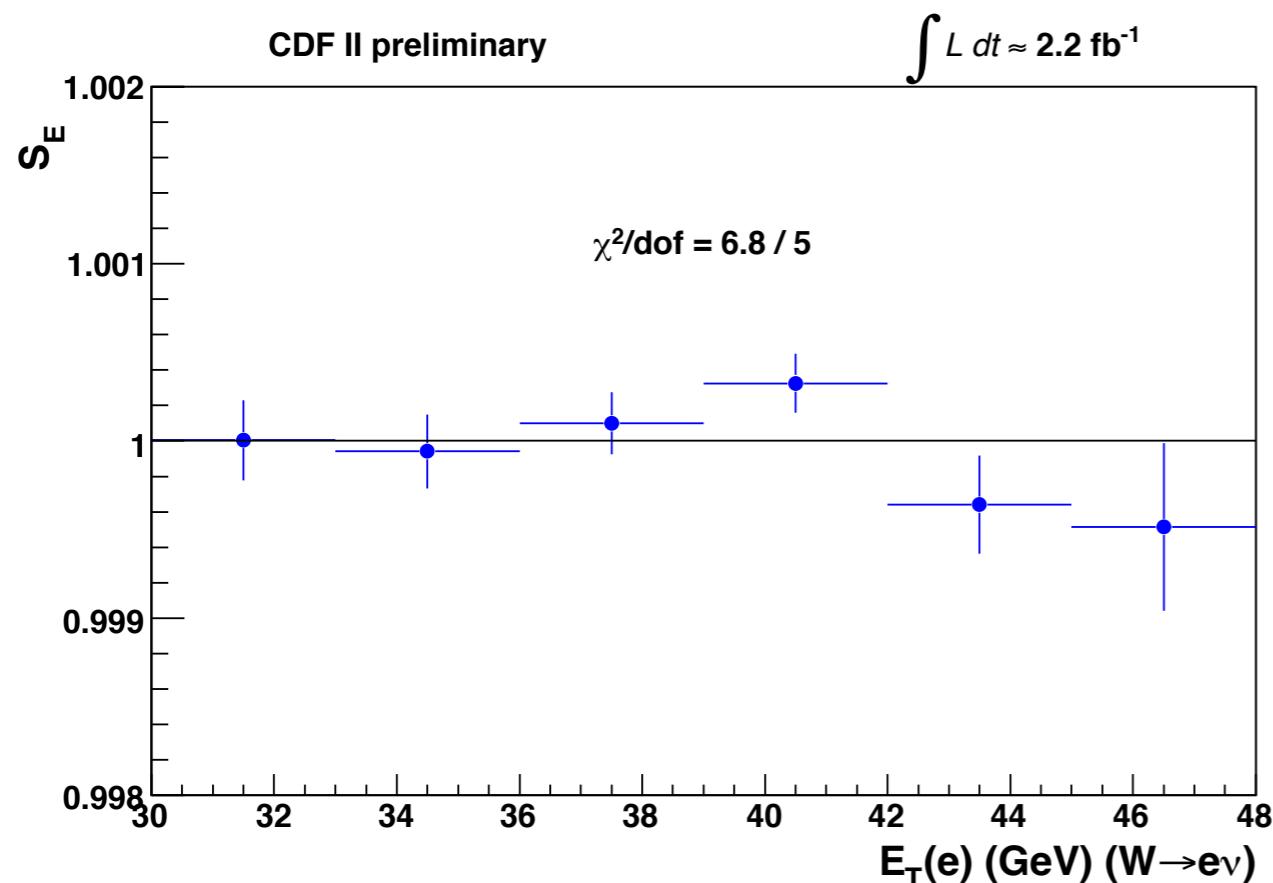
Simulation for electrons and photons

- 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



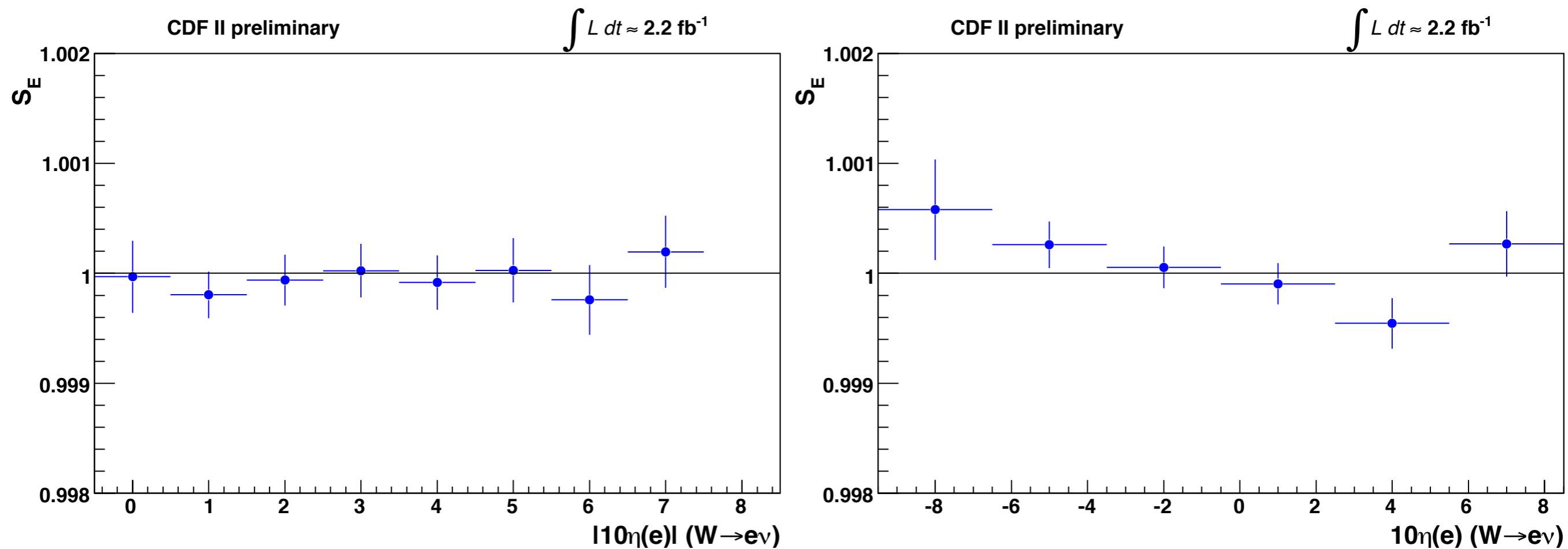
EM scale non-linearity

- 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 $\beta = (5.2 \pm 0.7_{\text{stat}}) \times 10^{-3}$
 - $\Delta M_W = 4 \text{ MeV}$
- 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



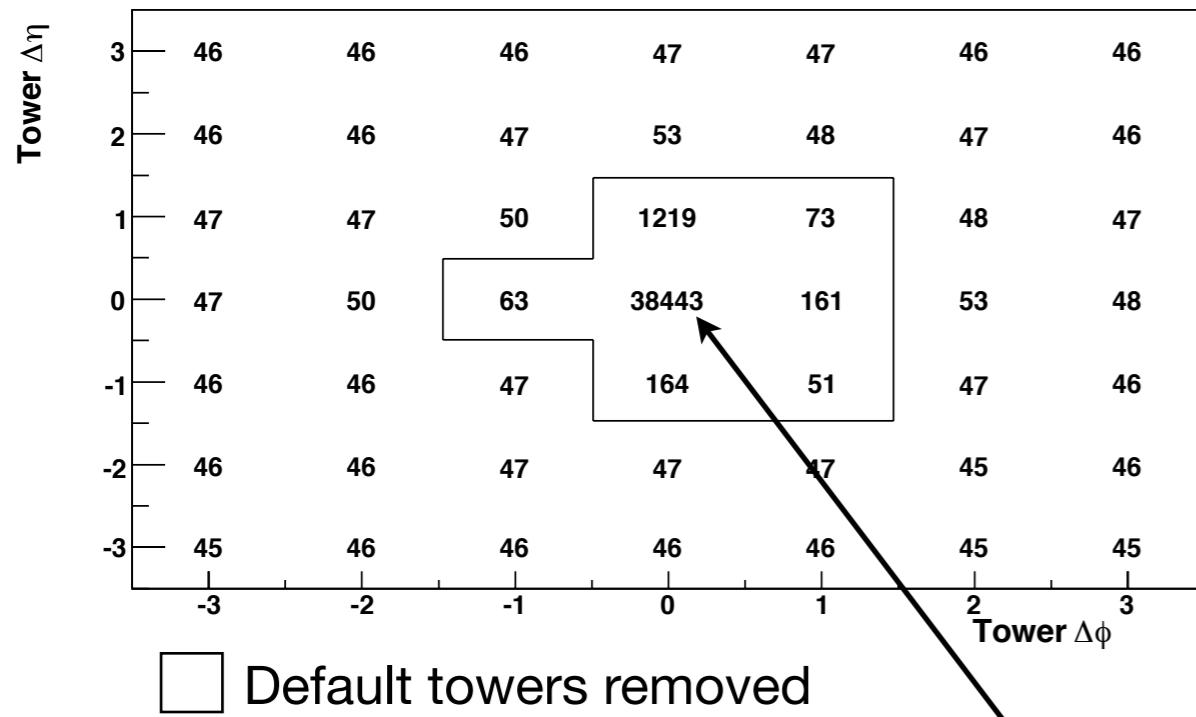
Lepton resolution

- Muons
 - Track resolution determined by uncertainty on beamspot size ($35\pm1 \mu\text{m}$) and track hit resolution ($150\pm1 \mu\text{m}$)
 - Tuned using widths of Z and γ peaks
- Electrons
 - EM calorimeter resolution defined by sampling term and constant term
$$\sigma = 12.6\% \sqrt{E_T/\text{GeV}} \oplus \kappa$$
 - 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 $\Delta M_W = 4 \text{ MeV}$

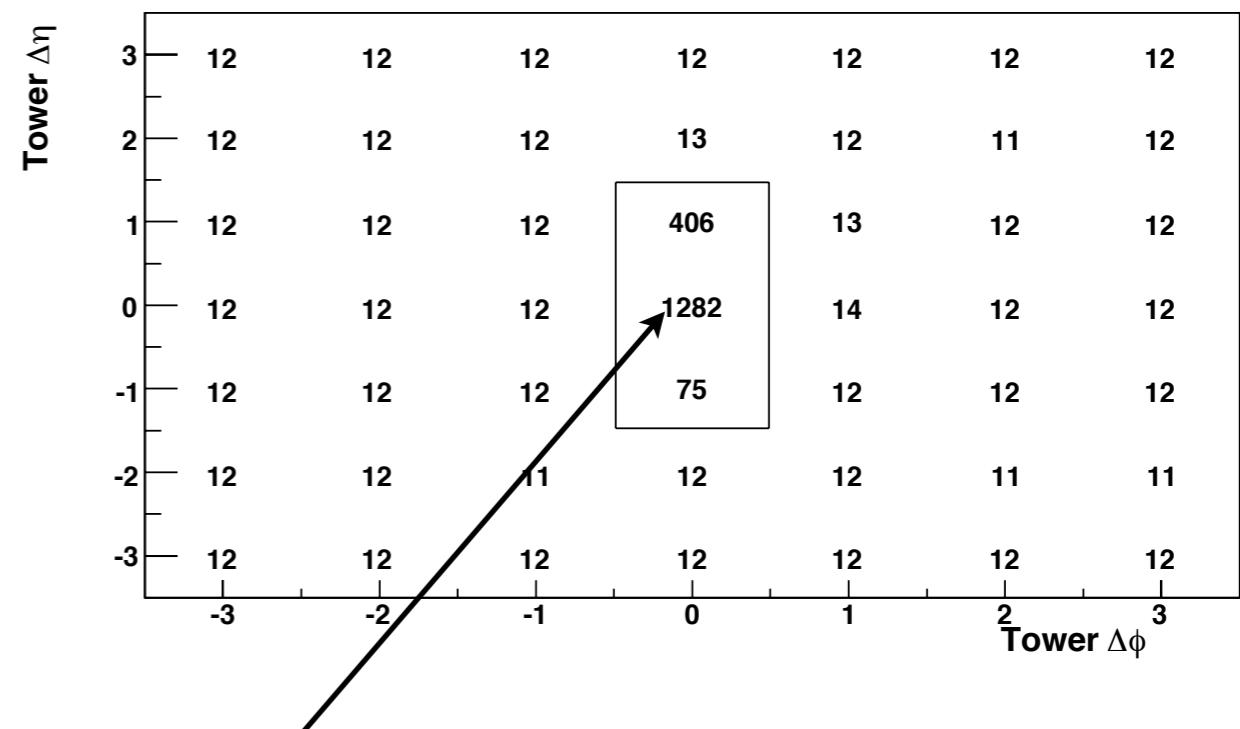
Hadronic recoil: lepton removal

- Hadronic recoil \mathbf{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 $\Delta M_W = 2 \text{ MeV}$

Electron channel W data:
Mean EM calorimeter deposition

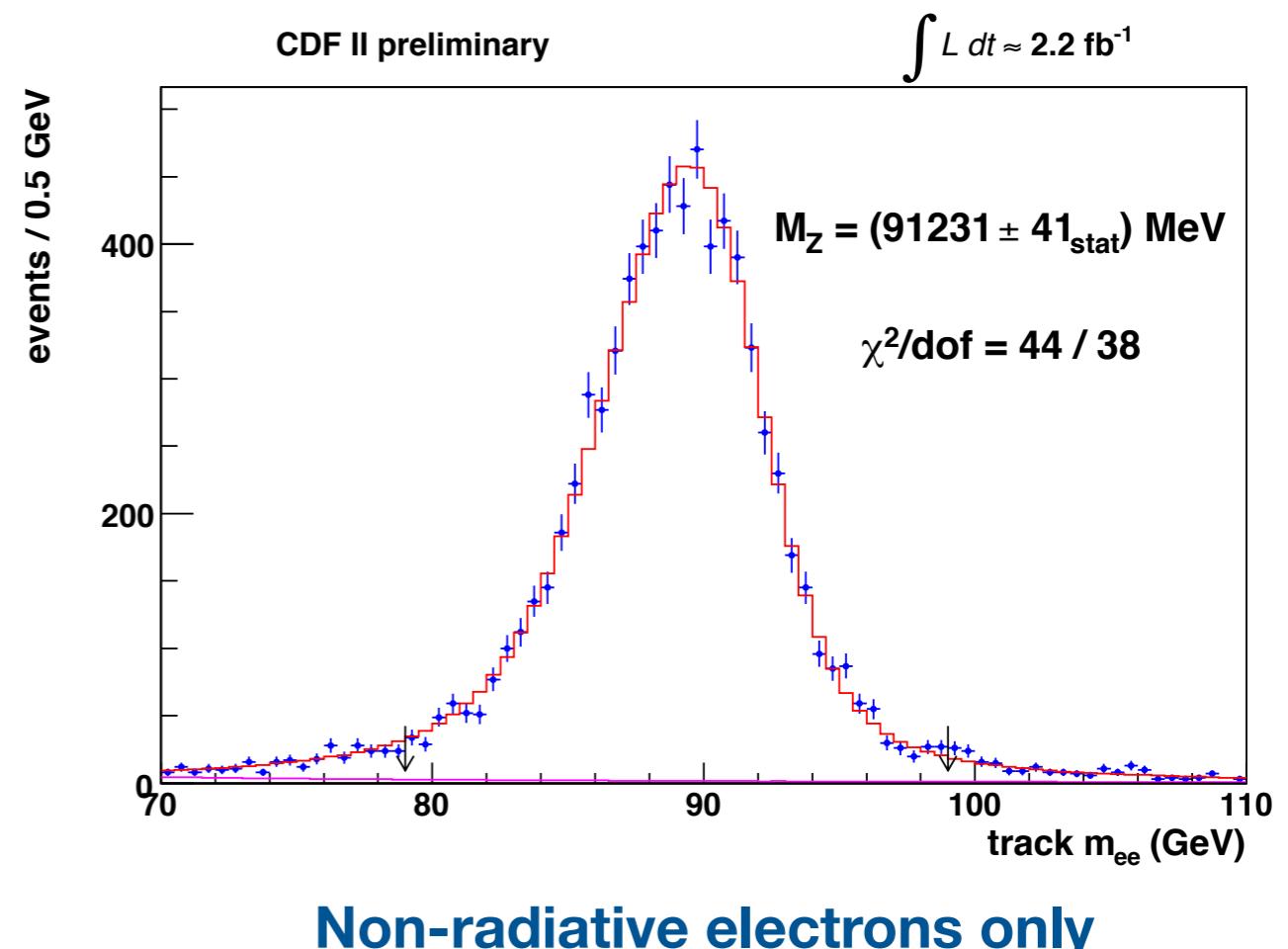
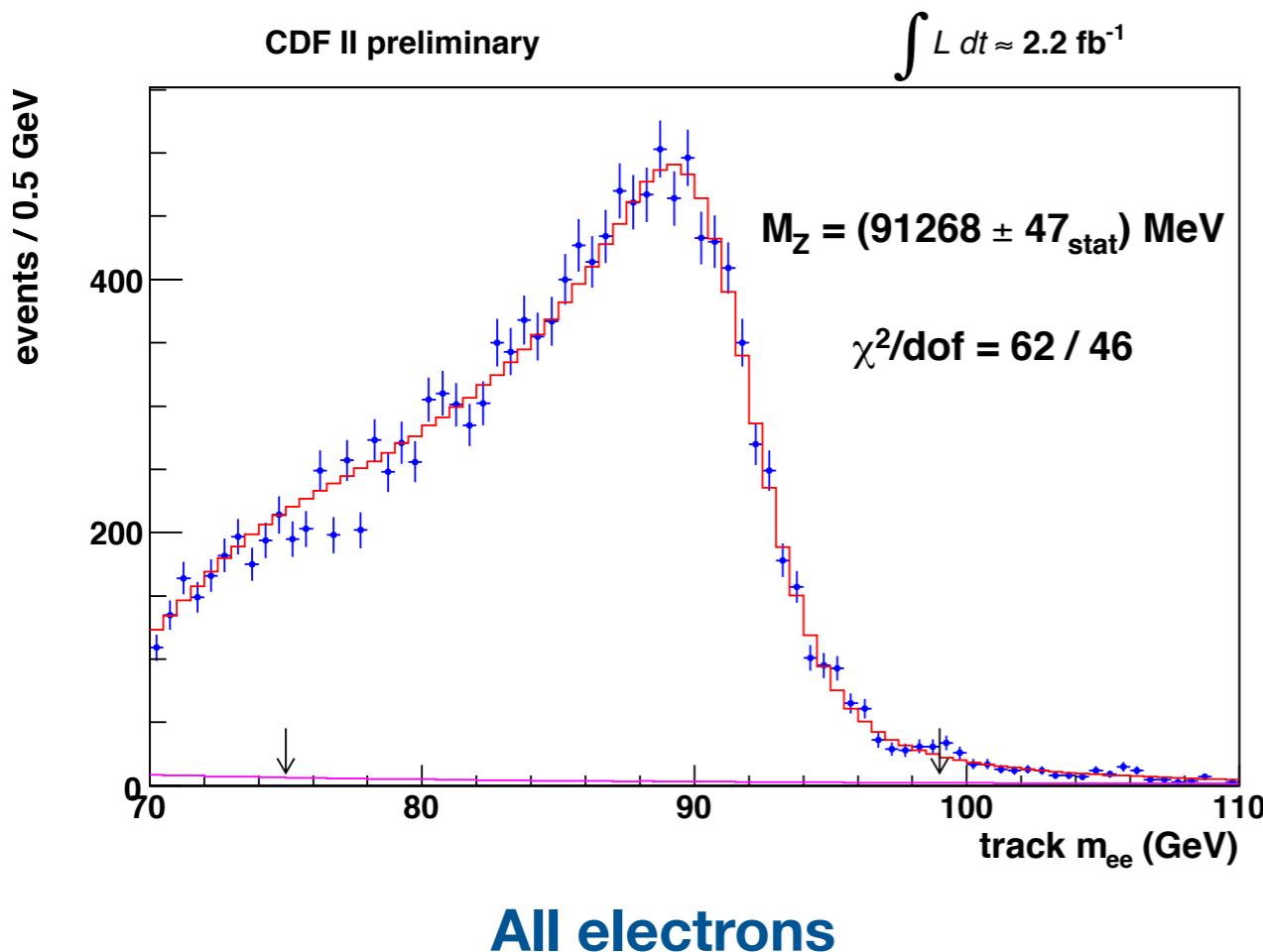


Muon channel W data:
Mean hadronic calorimeter deposition



Z mass with electron tracks

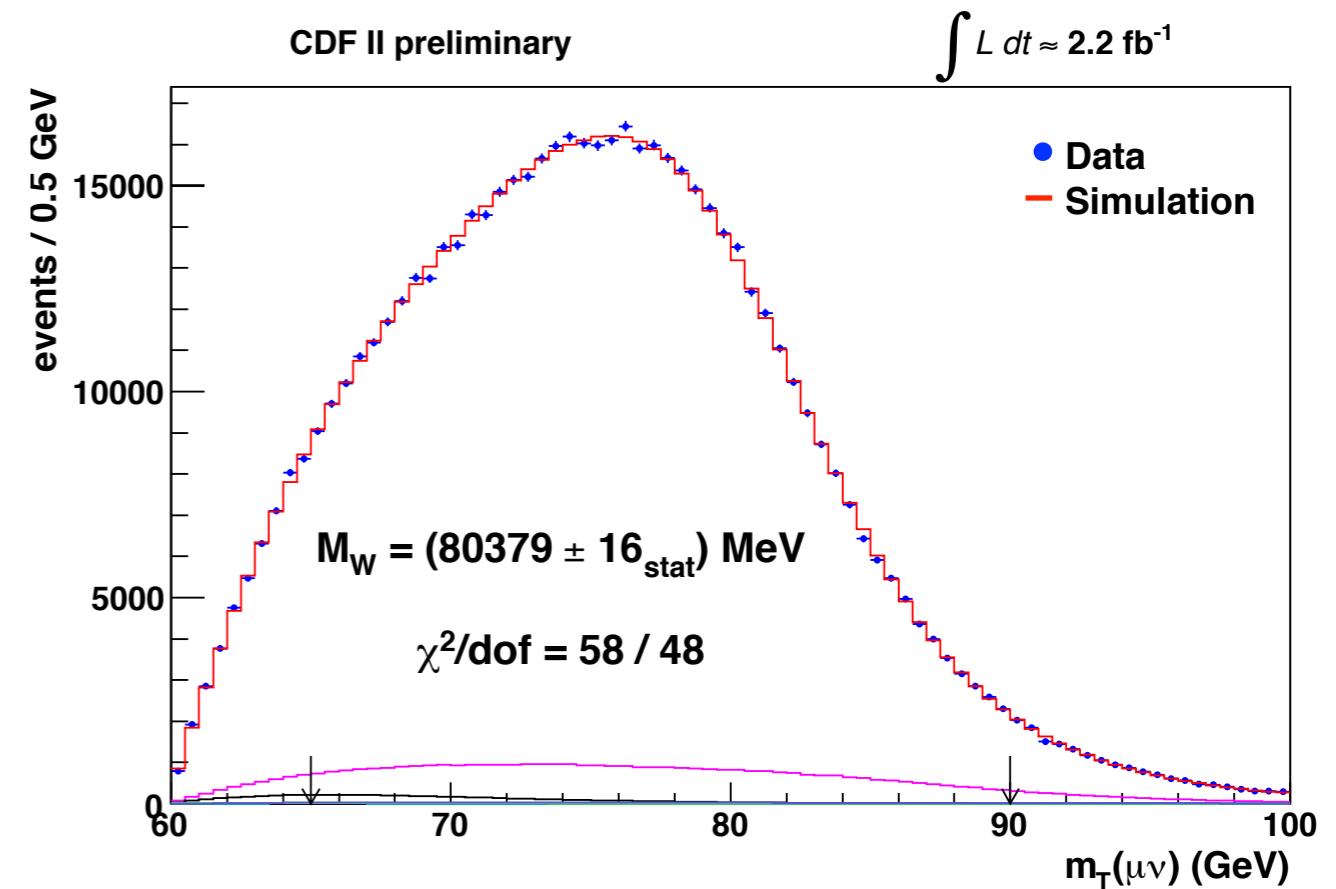
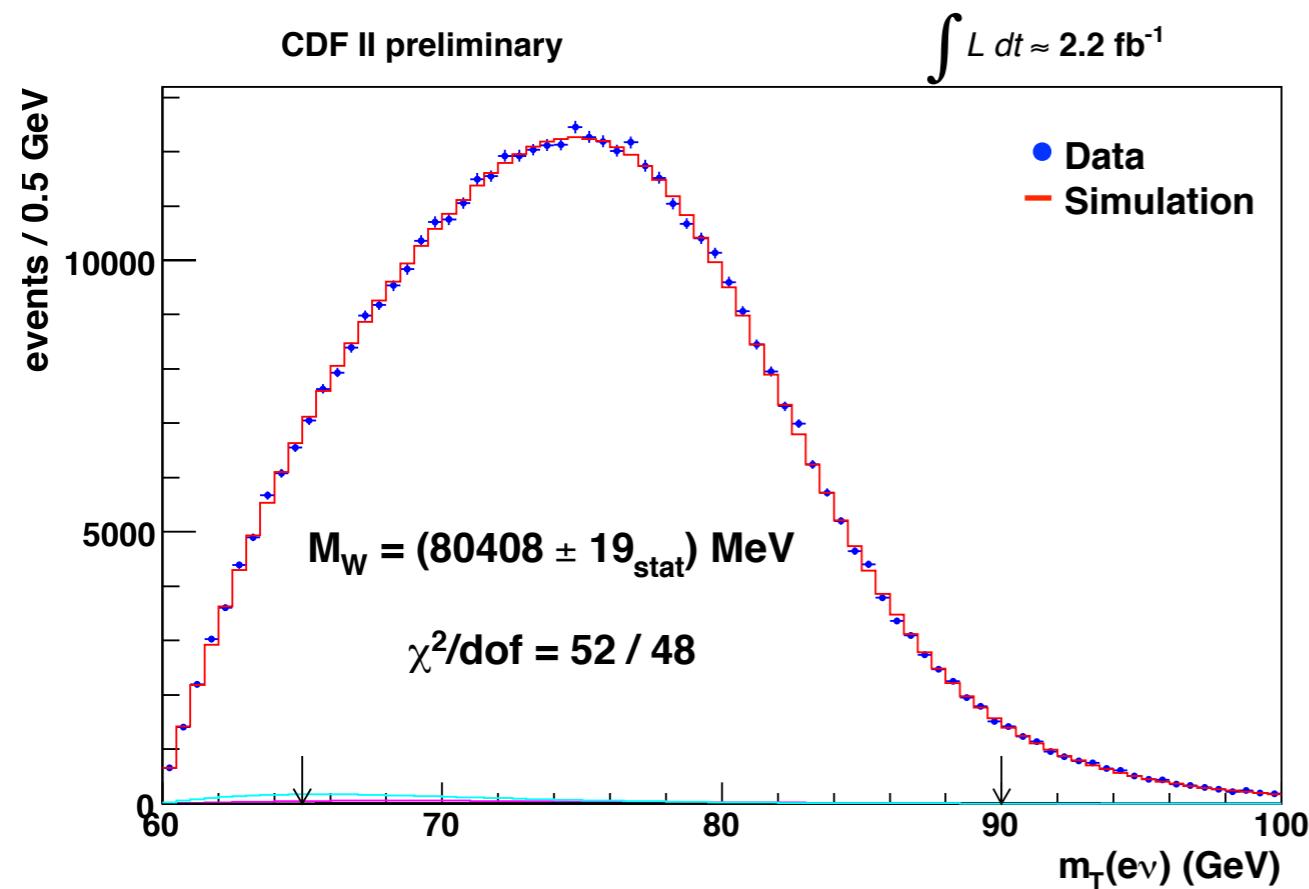
- Measurement made with only track momenta of Z electrons
- Validates application of momentum scale to high- p_T electron tracks



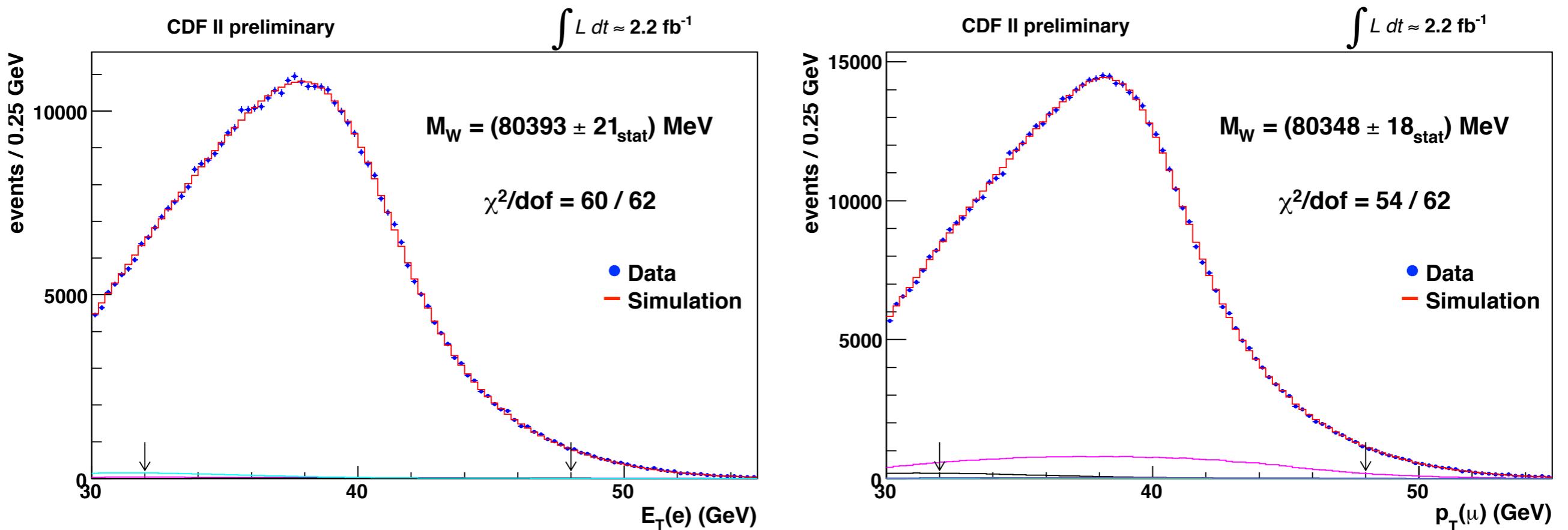
A word on blinding

- 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

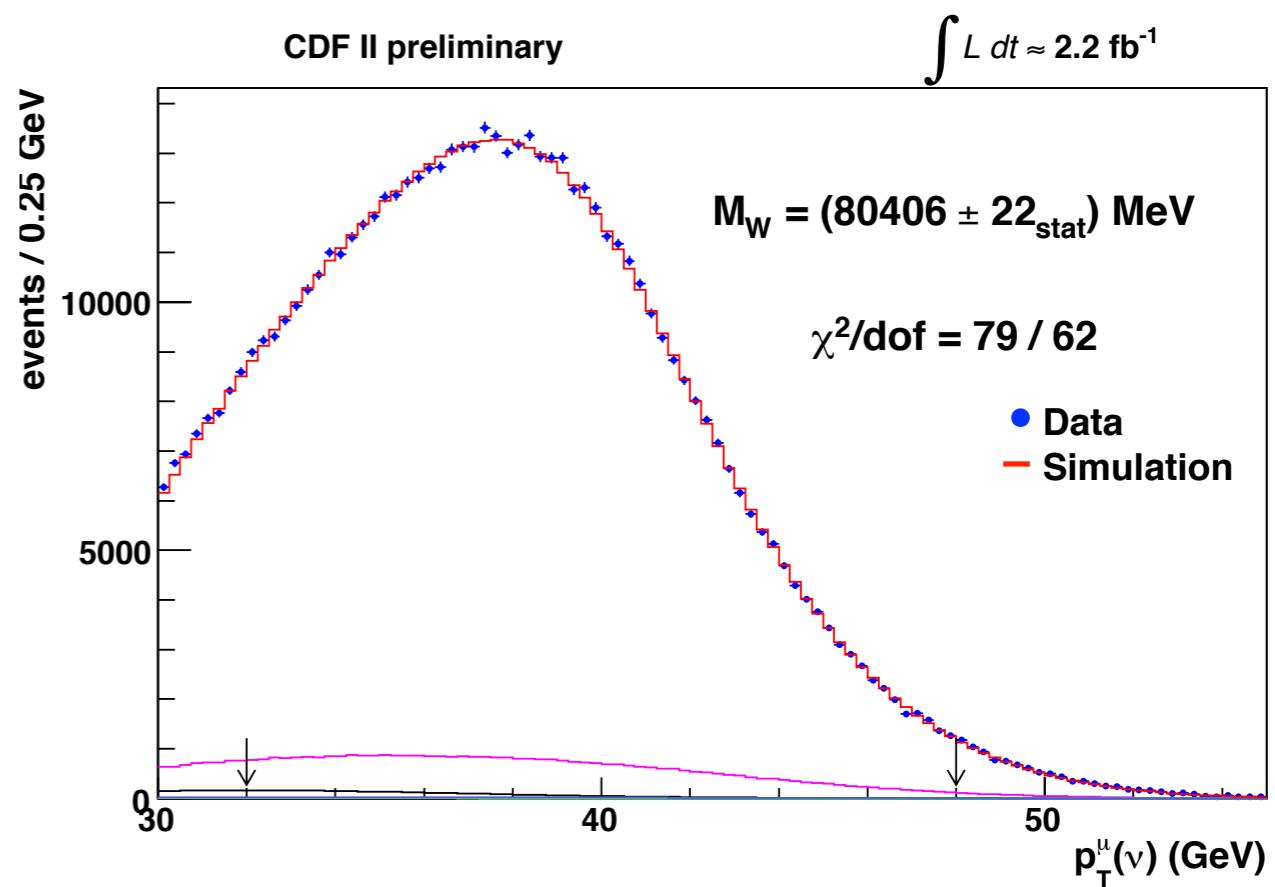
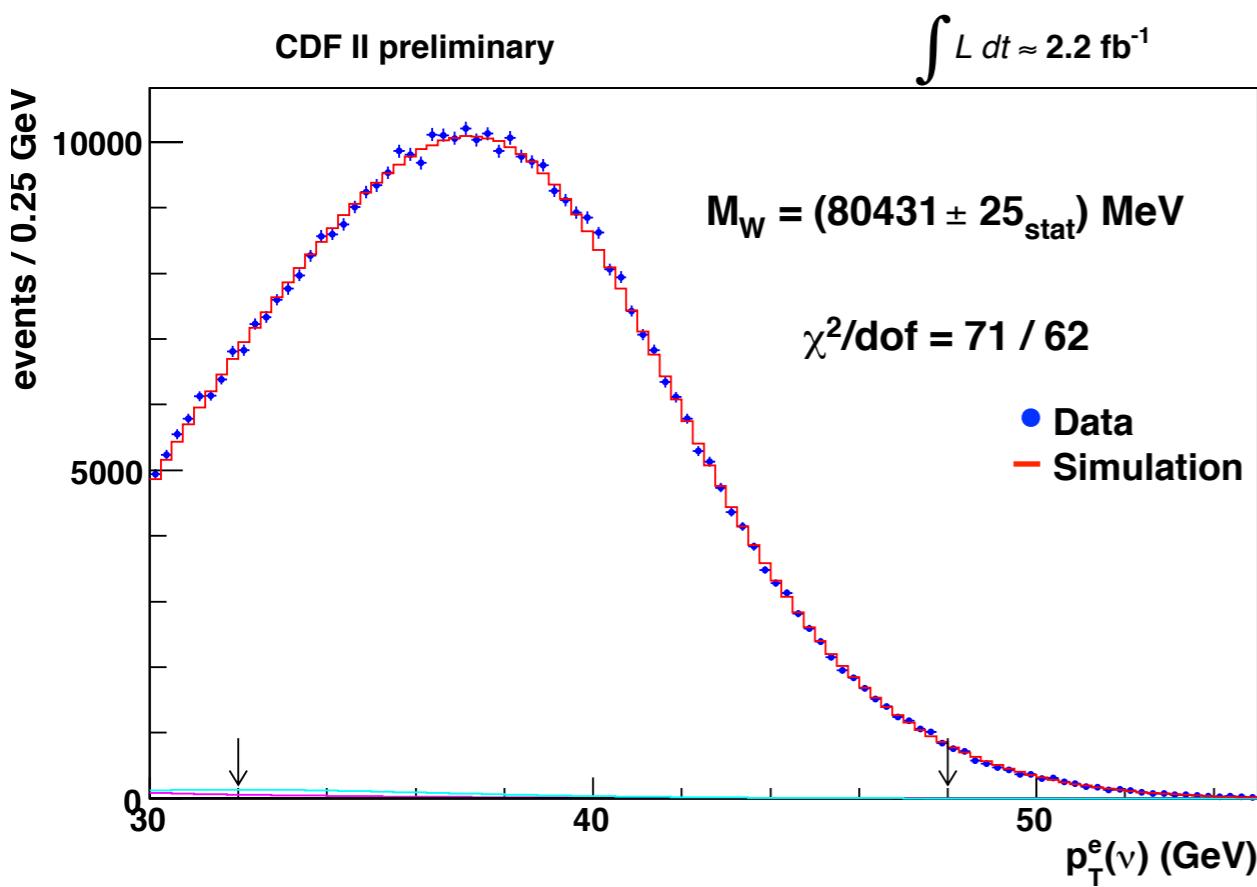
W mass fits: m_T



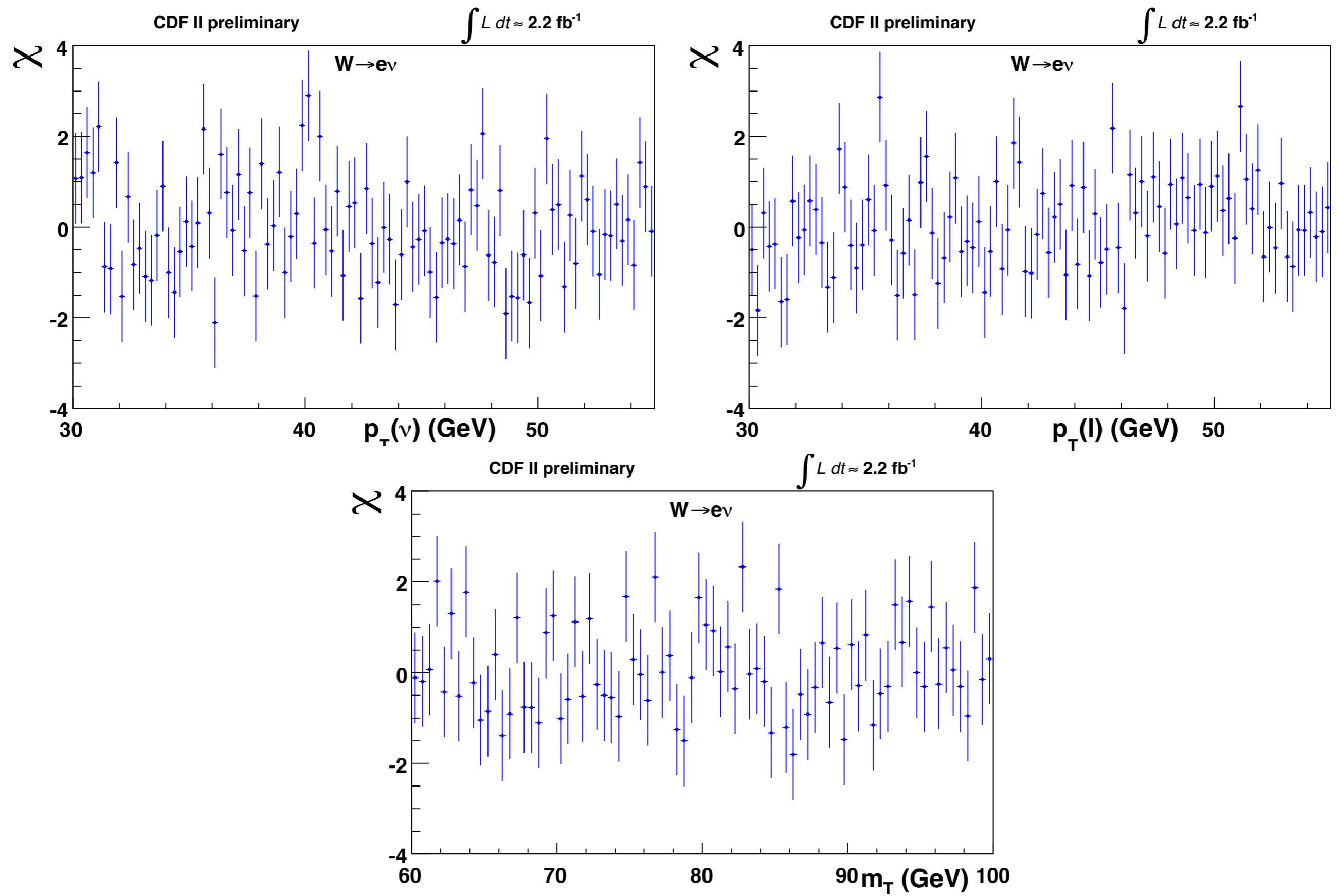
W mass fits: lepton p_T



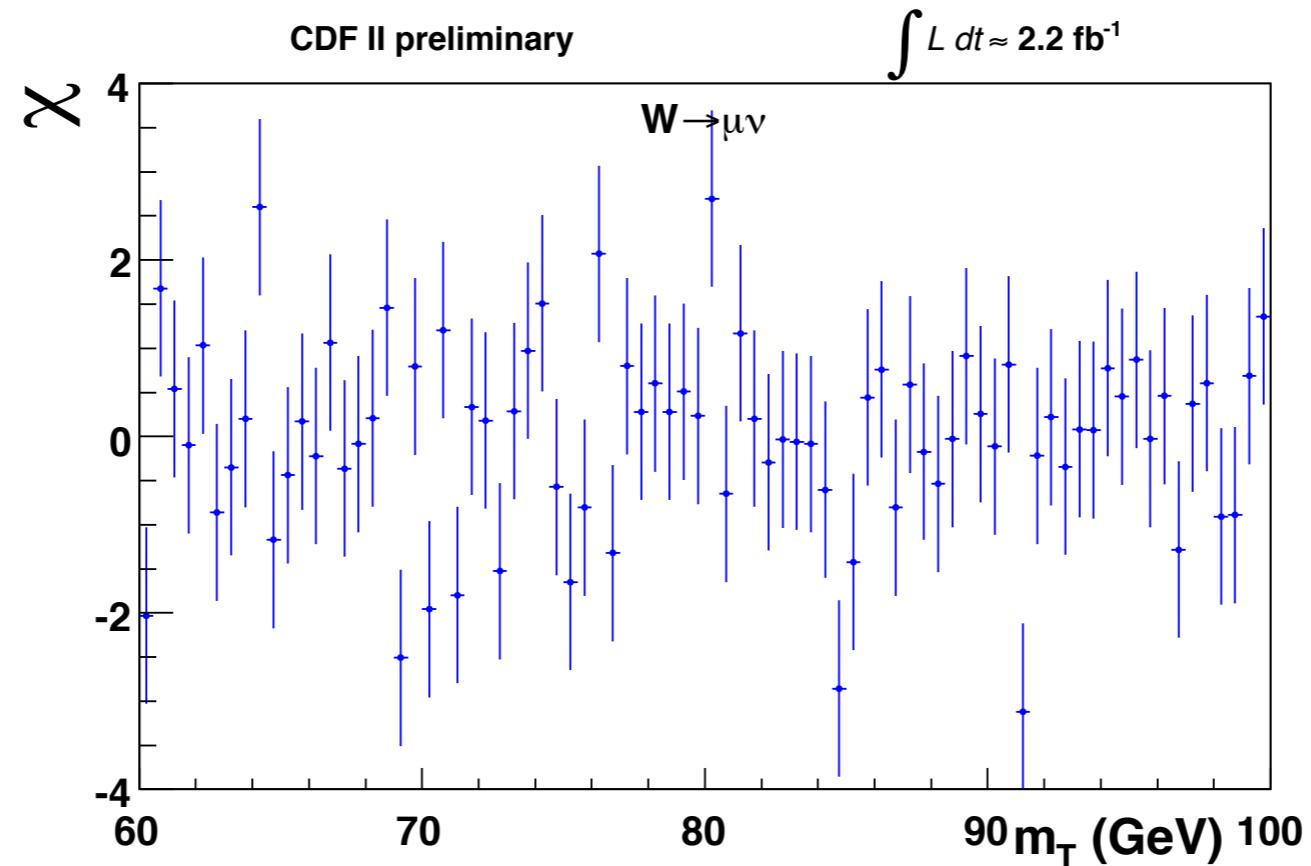
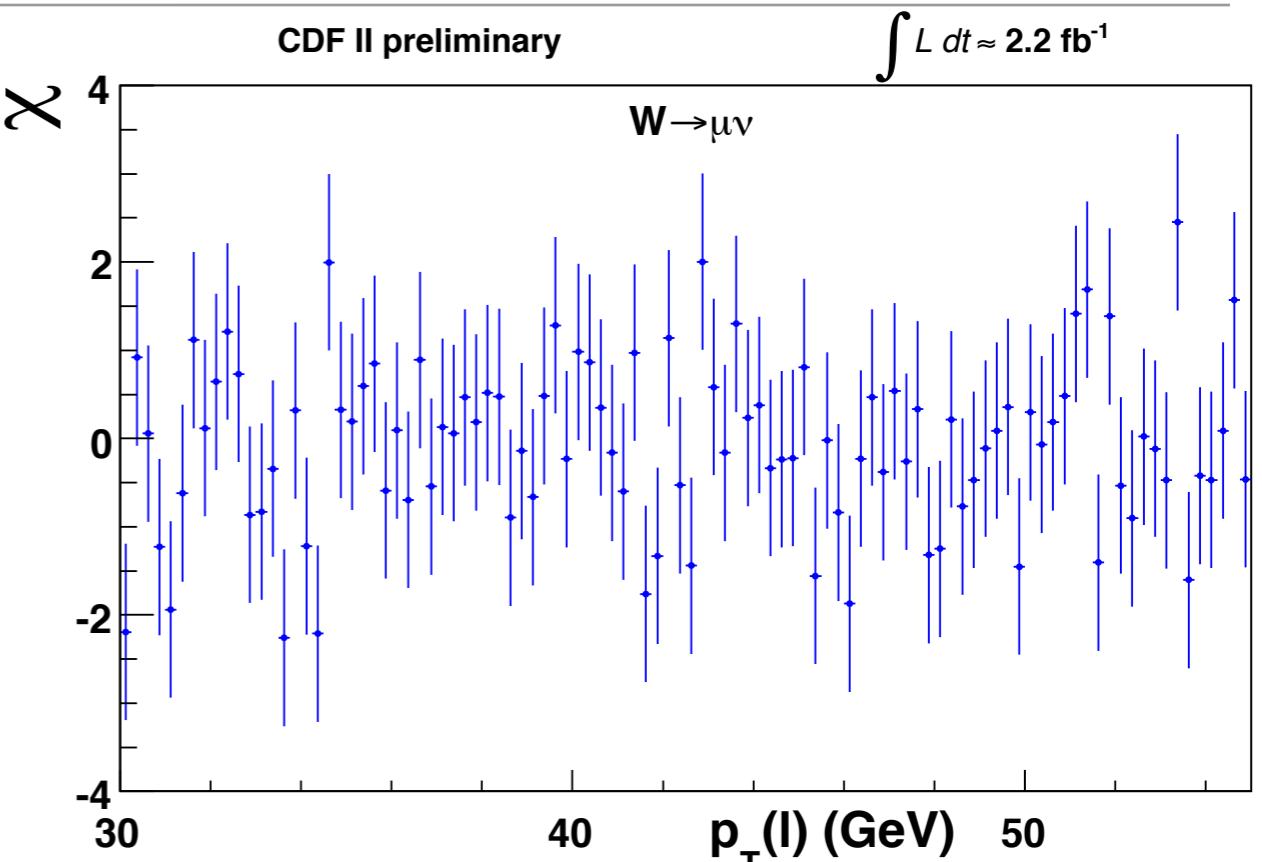
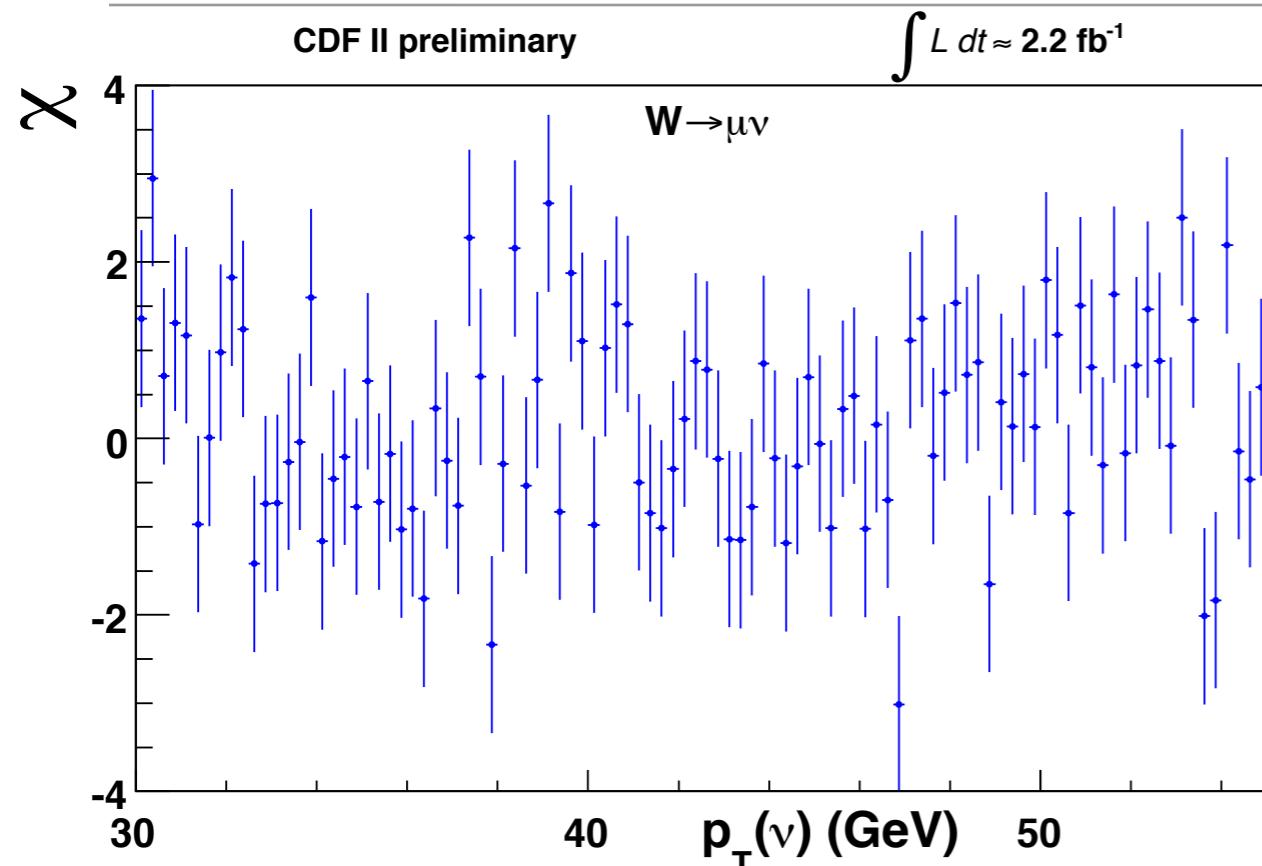
W mass fits: neutrino p_T



Electron fit residuals

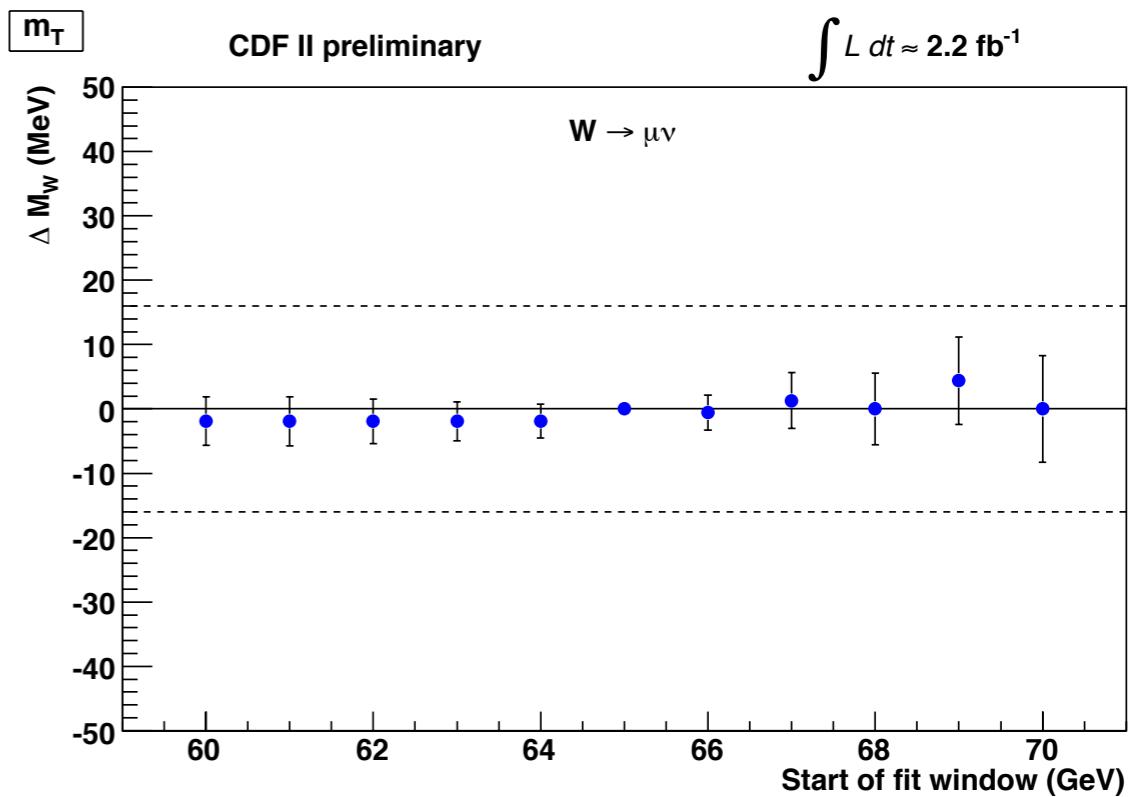
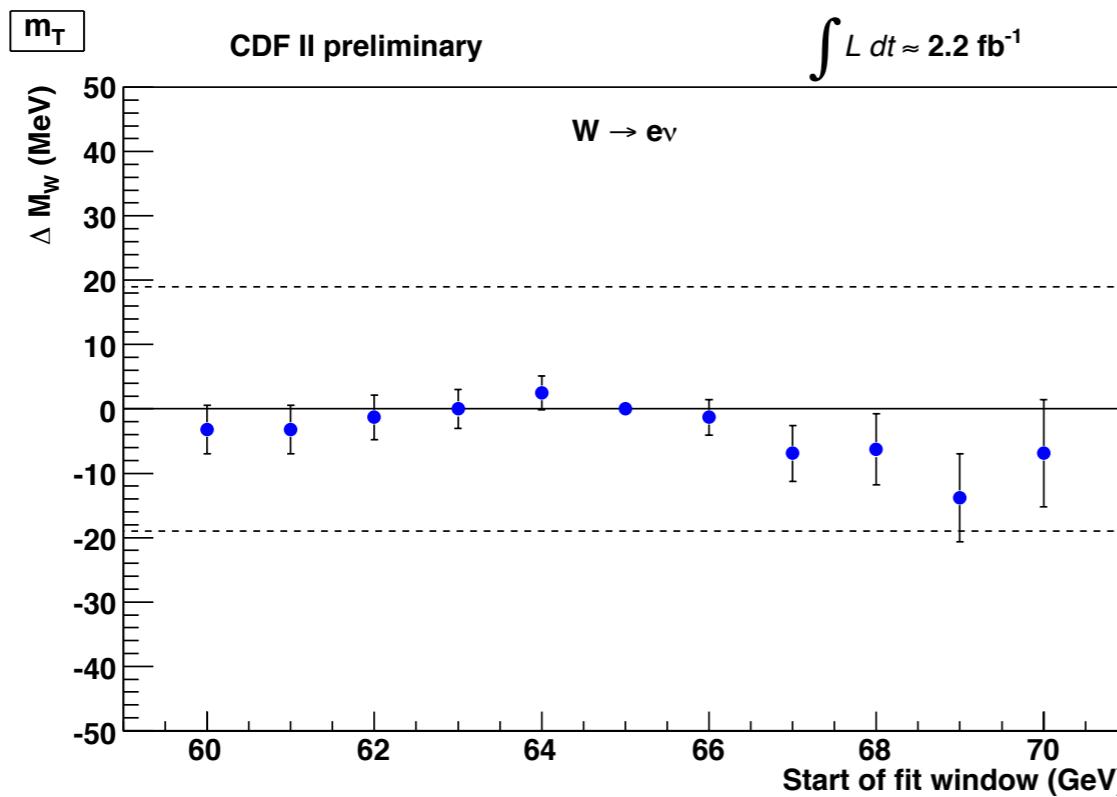


Muon fit residuals

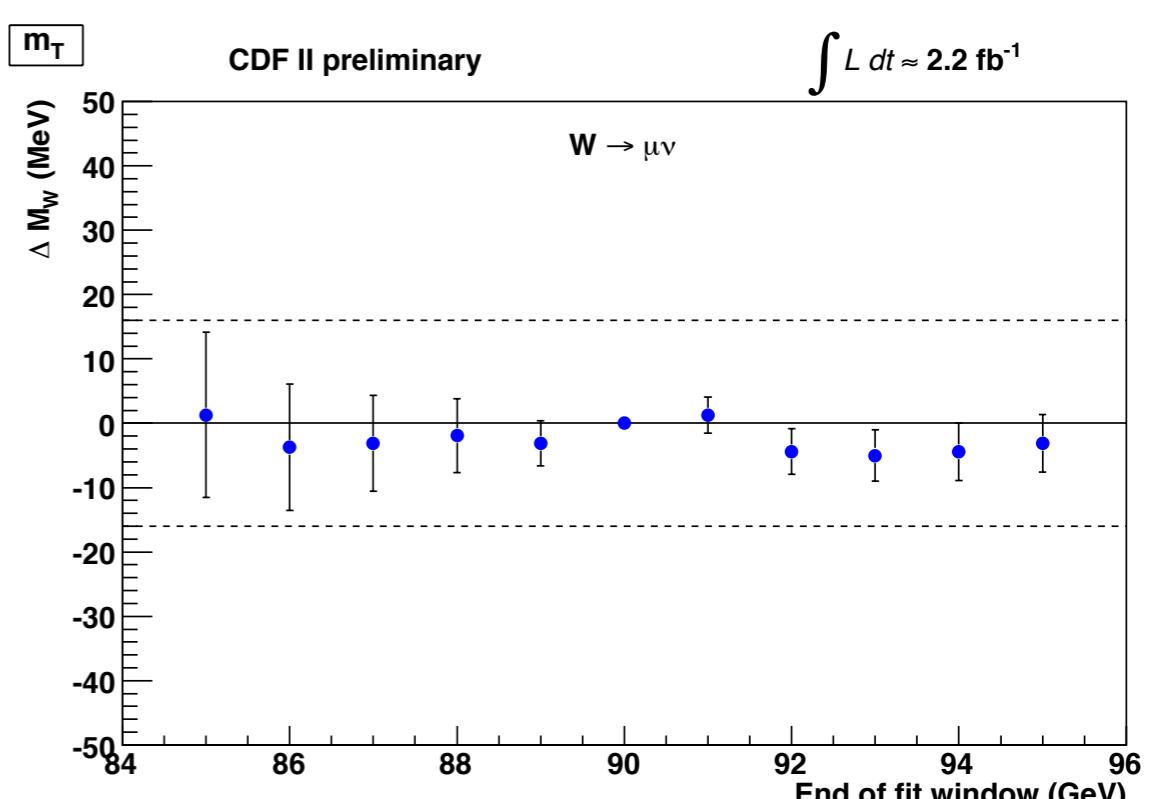
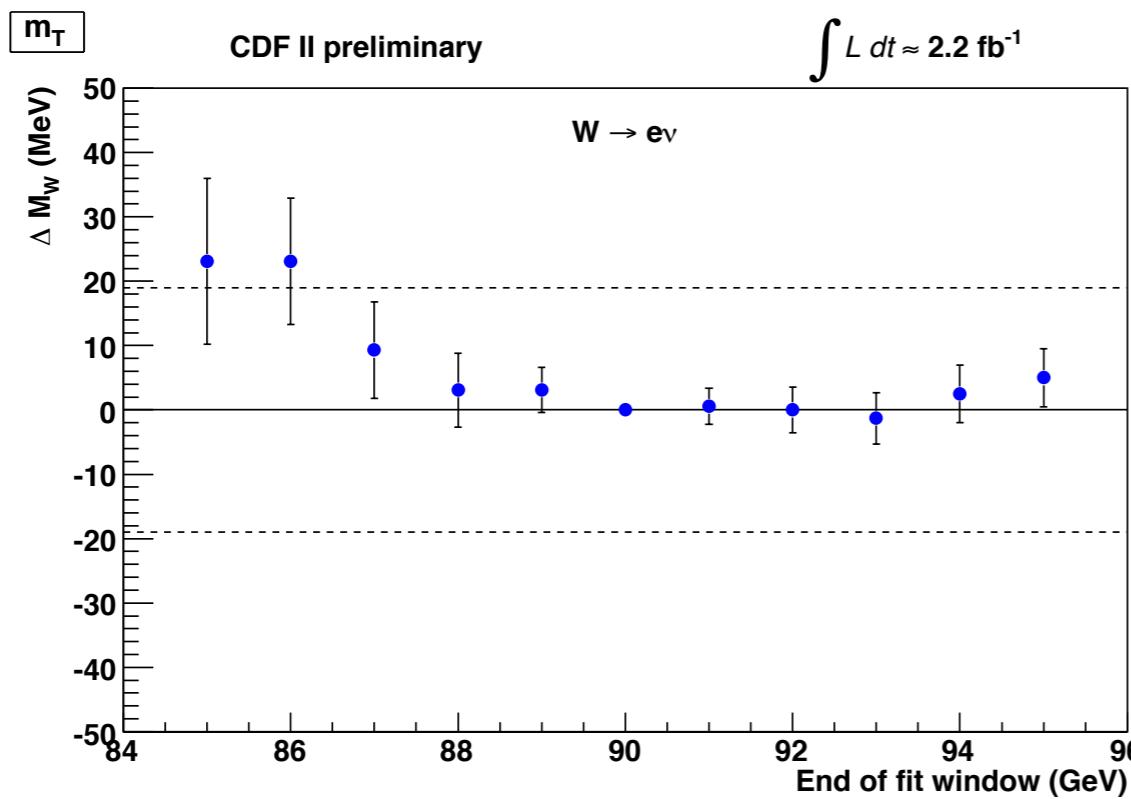


Fit window variation: m_T

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

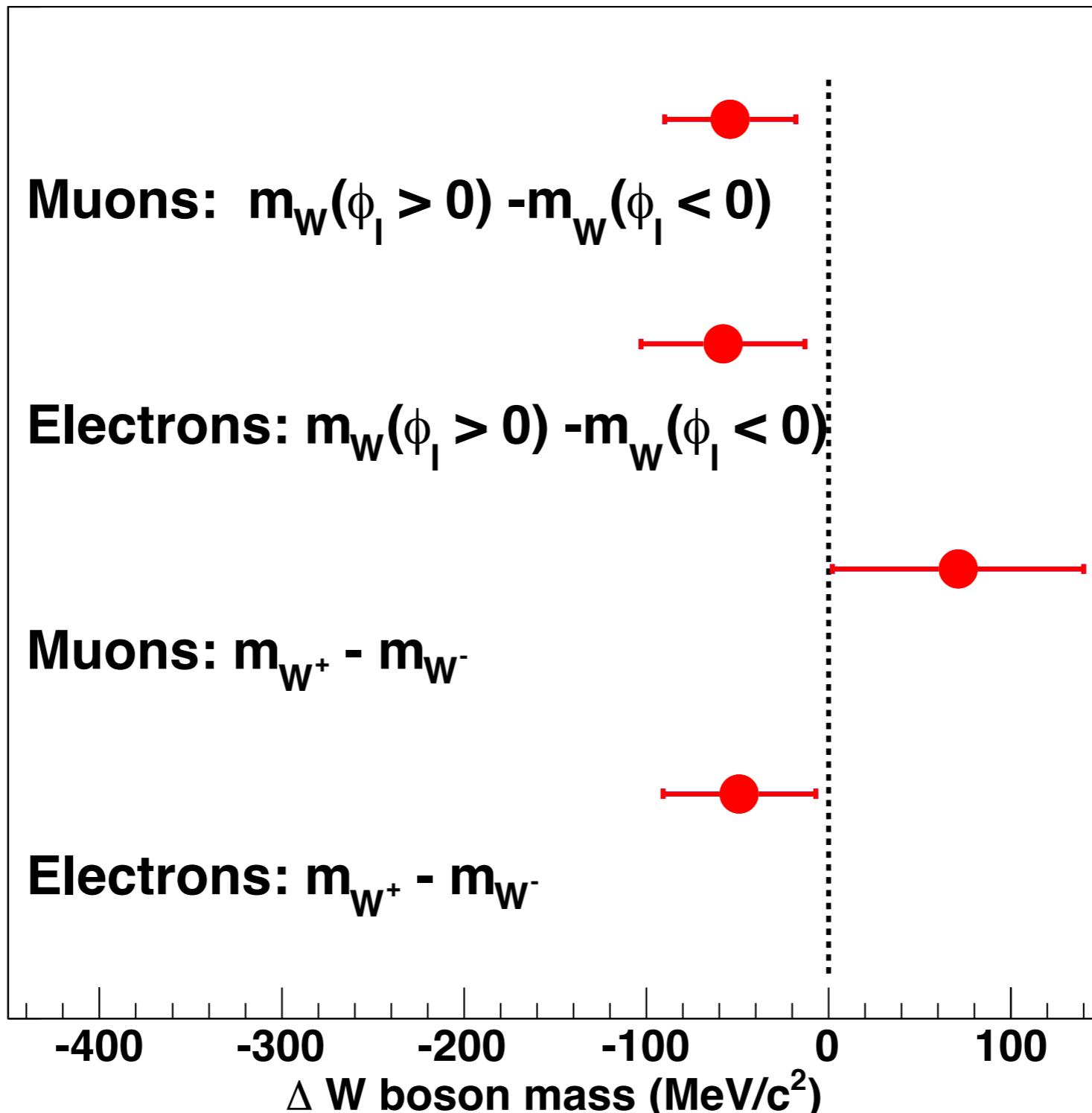
Systematic (MeV)	Electrons	Muons	Common
Lepton Energy Scale	10	7	5
Lepton Energy Resolution	4	1	0
Recoil Energy Scale	6	6	6
Recoil Energy Resolution	5	5	5
$u_{ }$ efficiency	2	1	0
Lepton Removal	0	0	0
Backgrounds	3	5	0
$p_T(W)$ model (g_2, g_3, α_s)	9	9	9
Parton Distributions	9	9	9
QED radiation	4	4	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

Some cross-checks

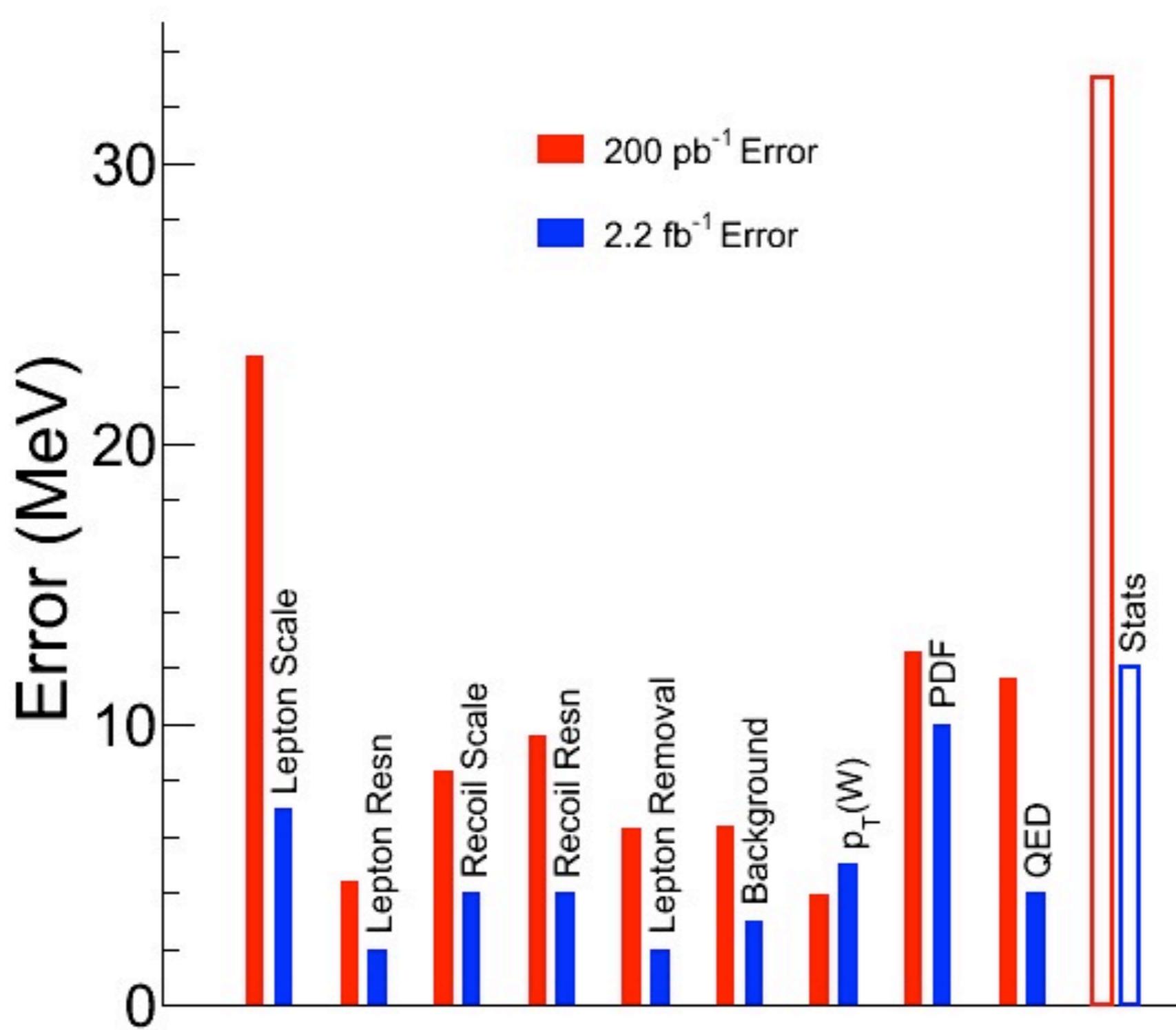
Stat. uncertainty only. p_T^l fits only.



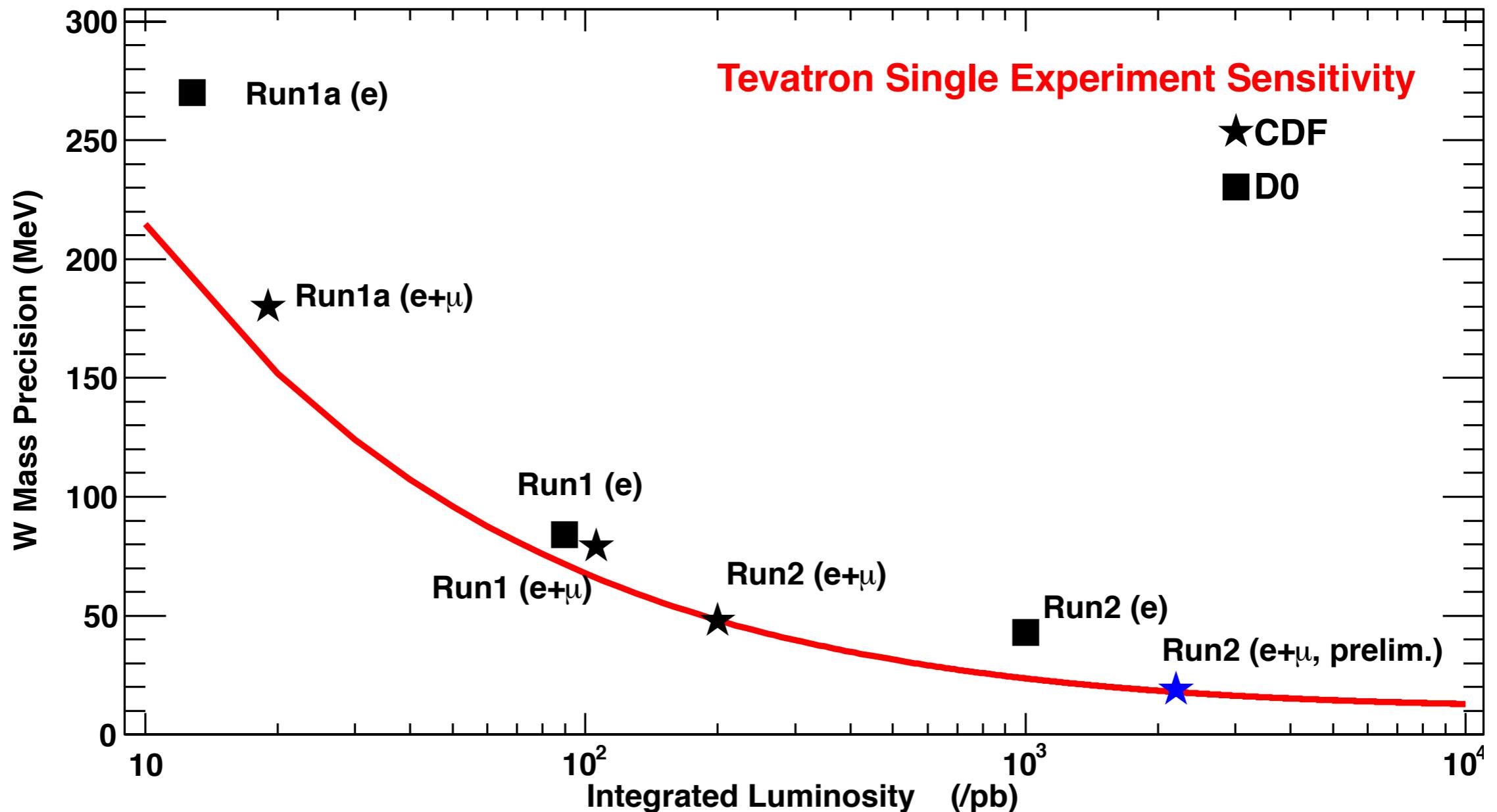
Mass fit combinations

- Electron and muon m_T fits combined
 $m_w = 80390 \pm 20 \text{ MeV}, \chi^2/\text{dof} = 1.2/1 (28\%)$
- Electron and muon p_T fits combined
 $m_w = 80366 \pm 22 \text{ MeV}, \chi^2/\text{dof} = 2.3/1 (13\%)$
- Electron and muon MET fits combined
 $m_w = 80416 \pm 25 \text{ MeV}, \chi^2/\text{dof} = 0.5/1 (49\%)$
- All electron fits combined
 $m_w = 80406 \pm 25 \text{ MeV}, \chi^2/\text{dof} = 1.4/2 (49\%)$
- All muon fits combined
 $m_w = 80374 \pm 22 \text{ MeV}, \chi^2/\text{dof} = 4/2 (12\%)$
- All fits combined
 $m_w = 80387 \pm 19 \text{ MeV}, \chi^2/\text{dof} = 6.6/5 (25\%)$

Uncertainty progress



Uncertainty projections



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