Precision Measurement of the W Boson Mass at CDF

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High Energy Physics Seminar
University of California, Davis

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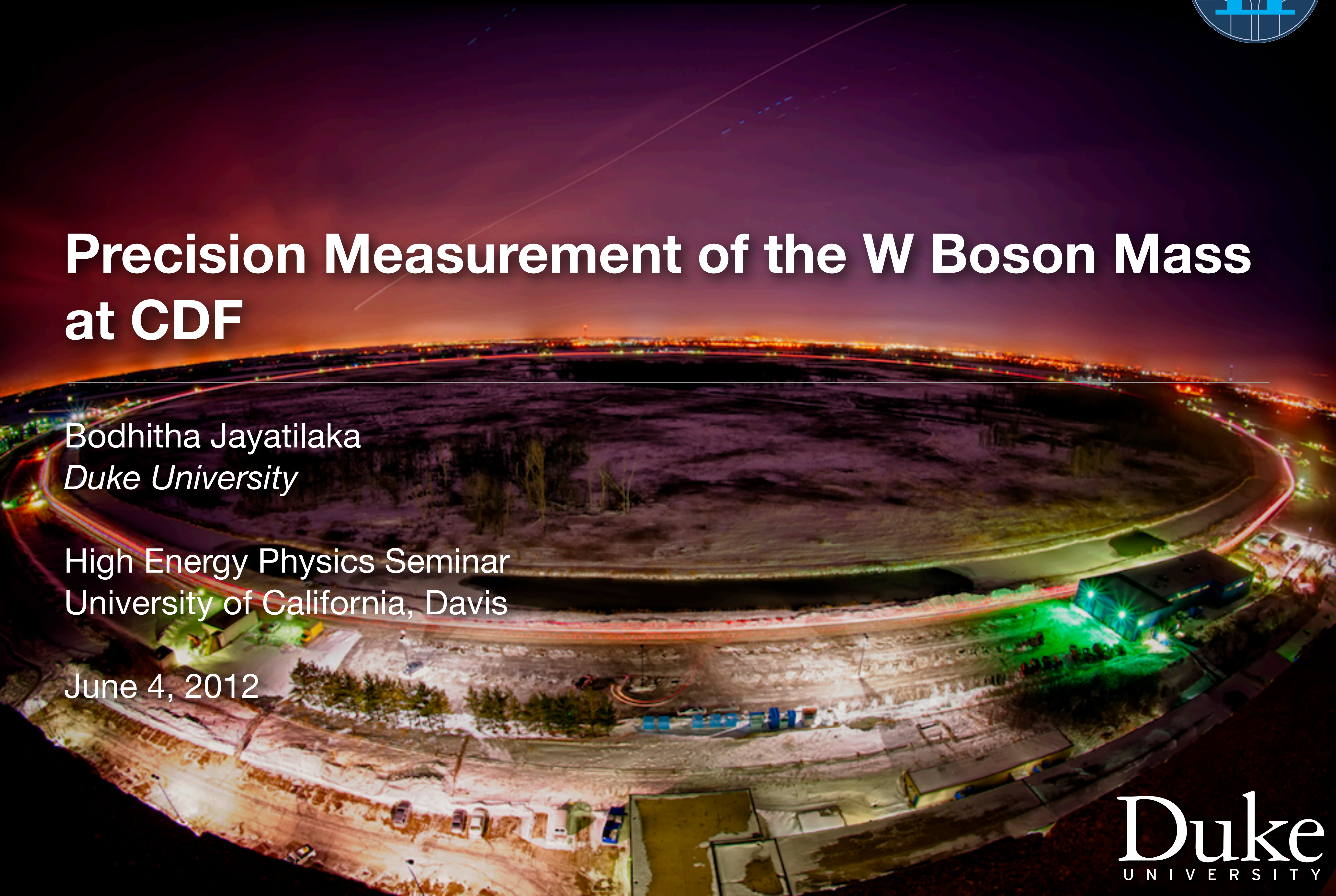

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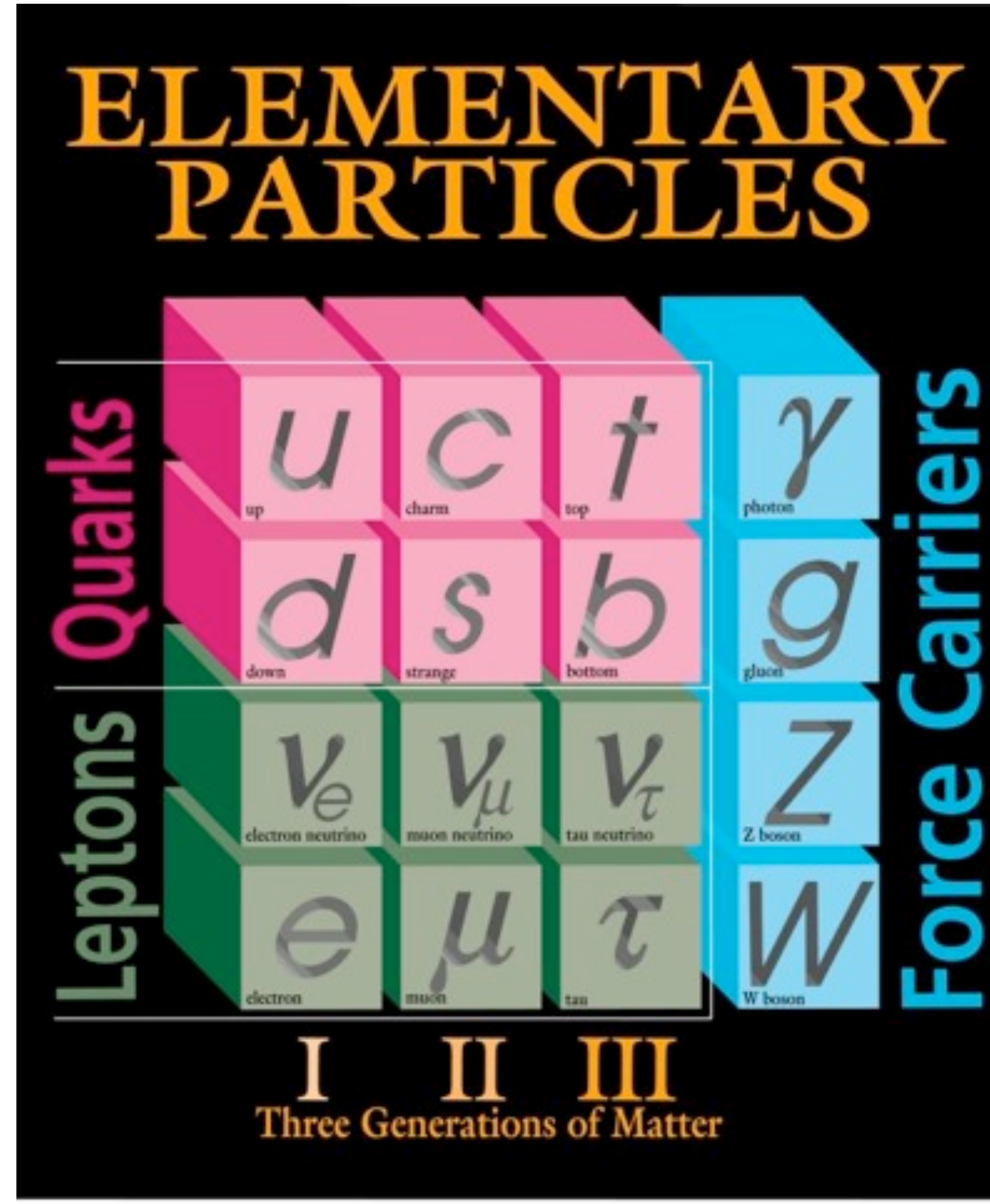
Motivation: a picture to start with

- The standard model
  - Describes known particles and interactions
  - Does not (verifiably) describe
    - Spontaneous symmetry breaking of U(1)×SU(2)
    - Fermion masses



Fermilab 95-759

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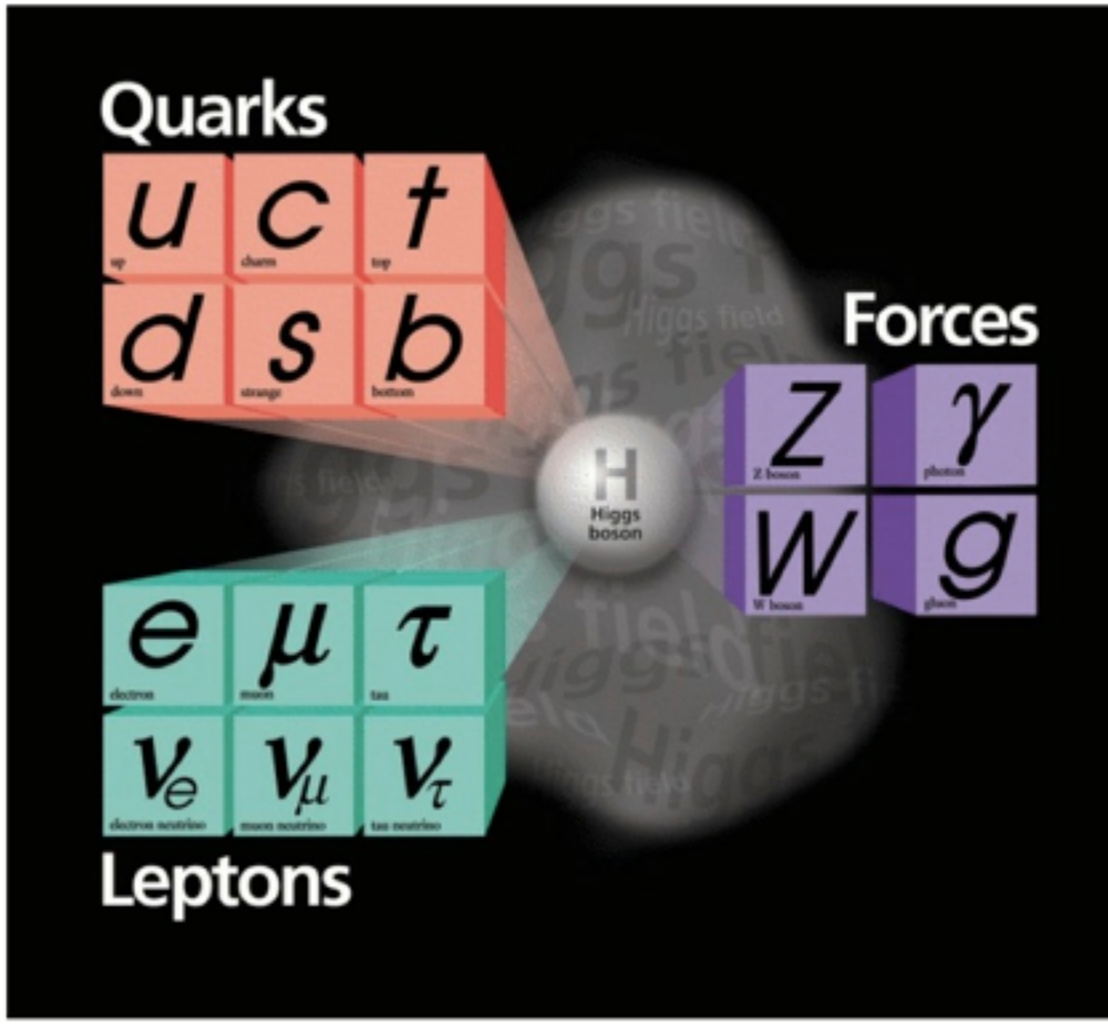
- Simple explanation: **Higgs mechanism**
  - Explains EWSB and fermion masses
  - Physical manifestation of Higgs boson



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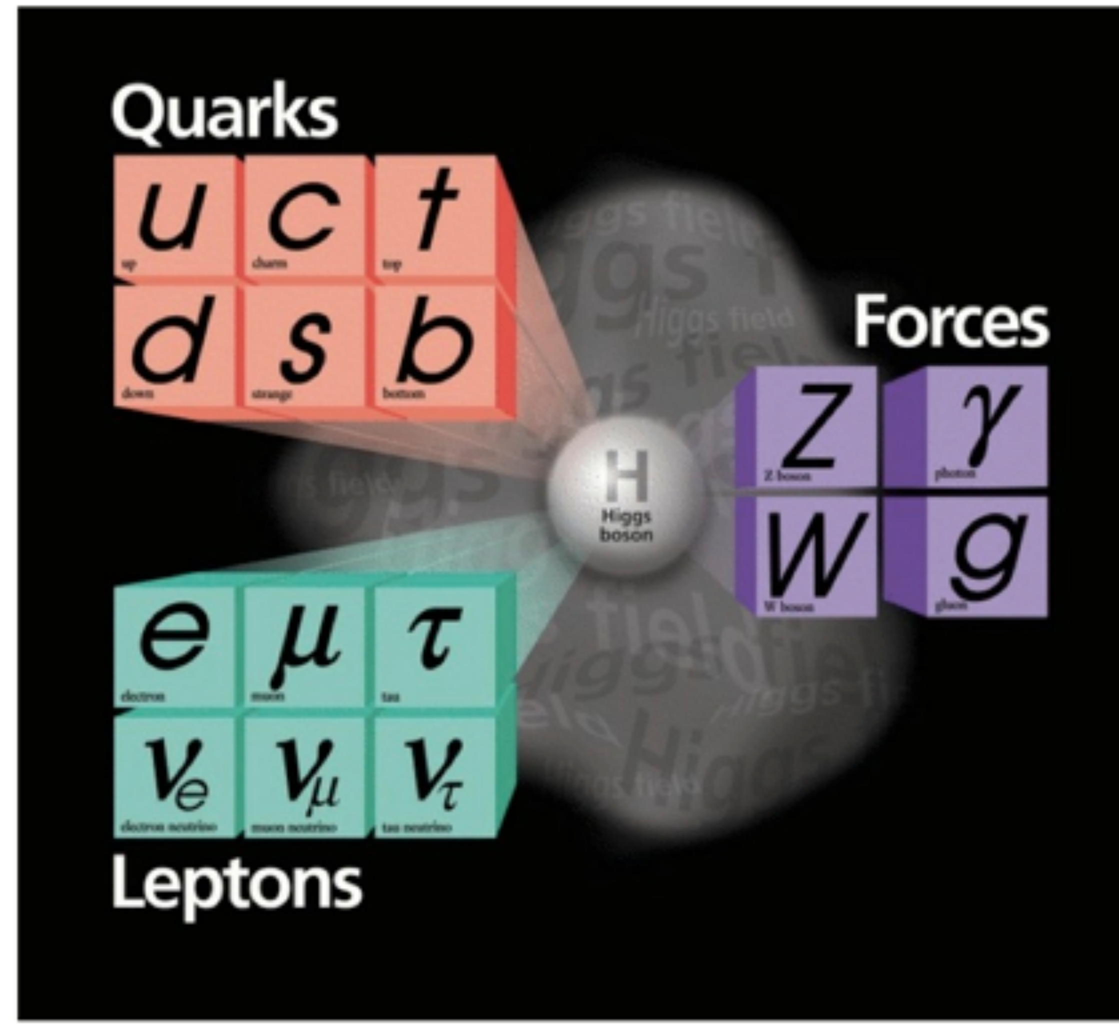
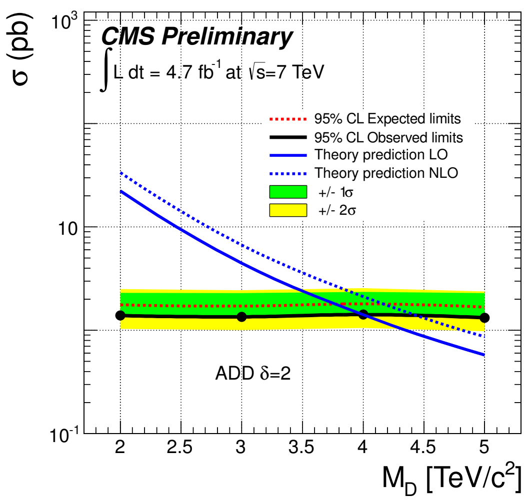
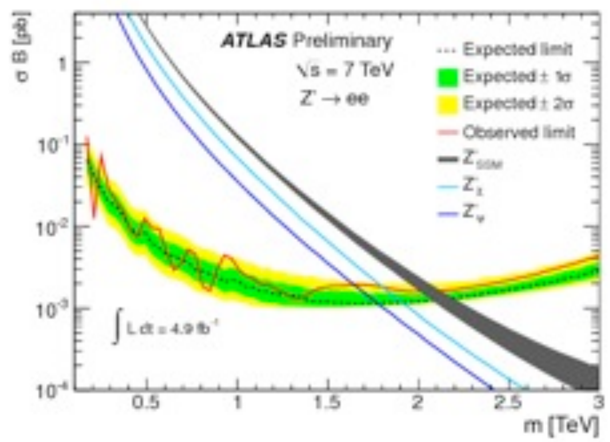
- Alternatively: *????*

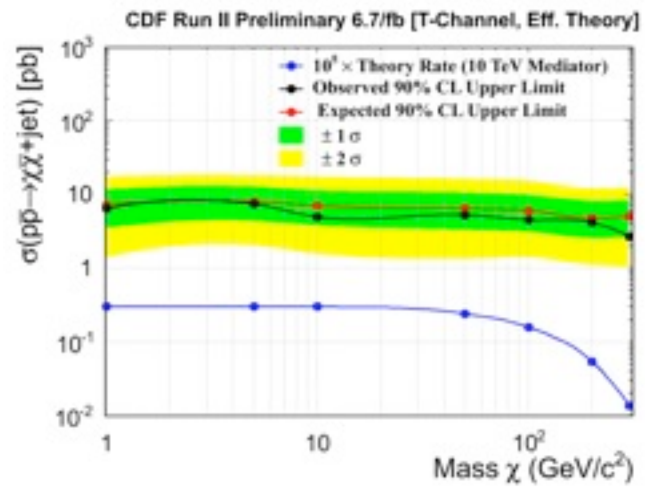


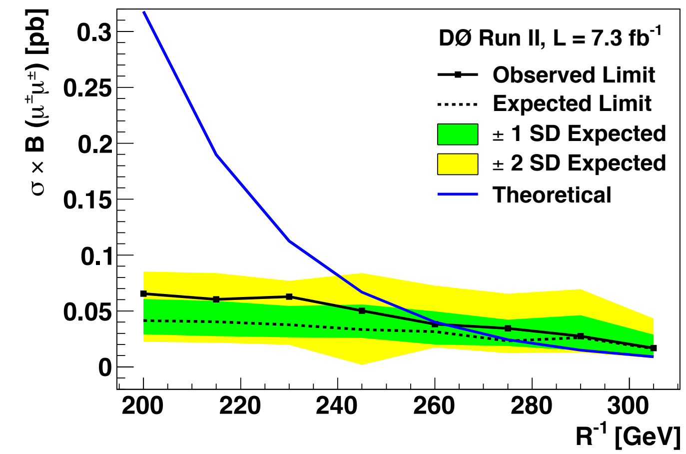
Cracking/checking the picture with colliders

1. Direct searches. *e.g.:*

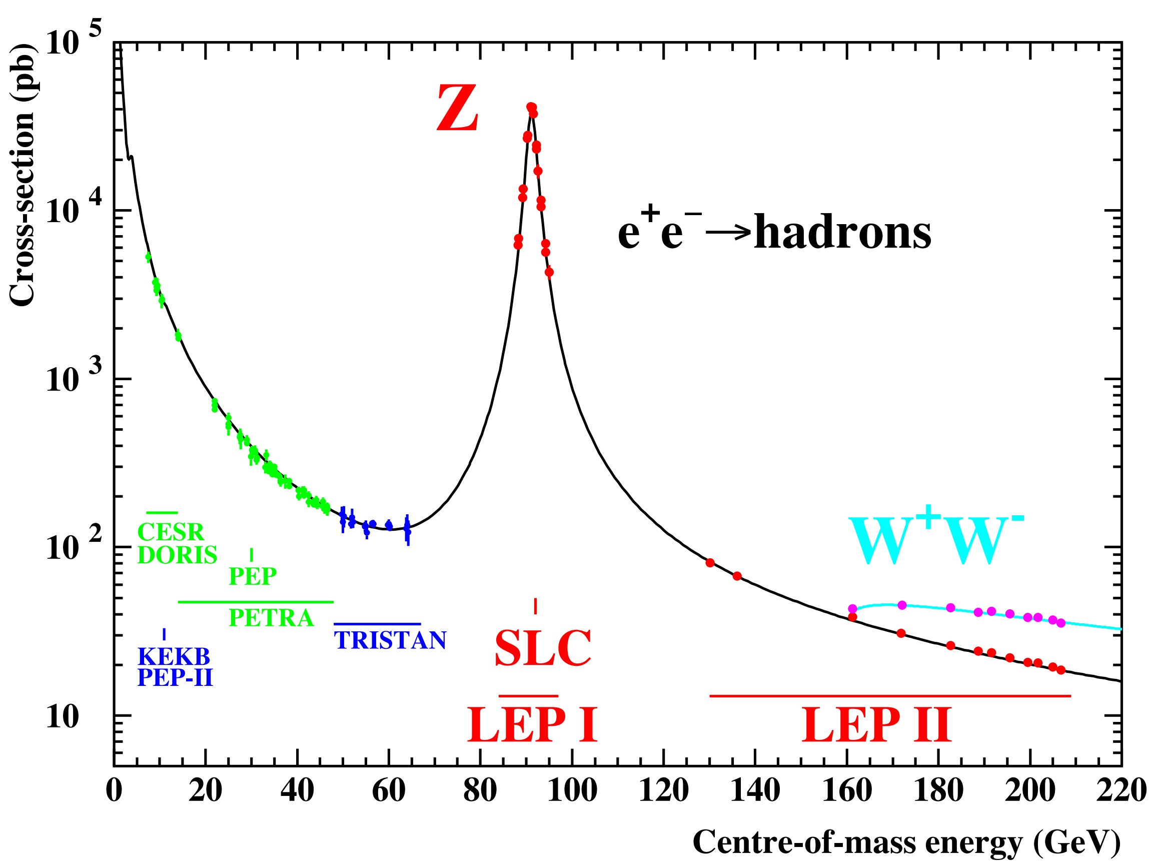


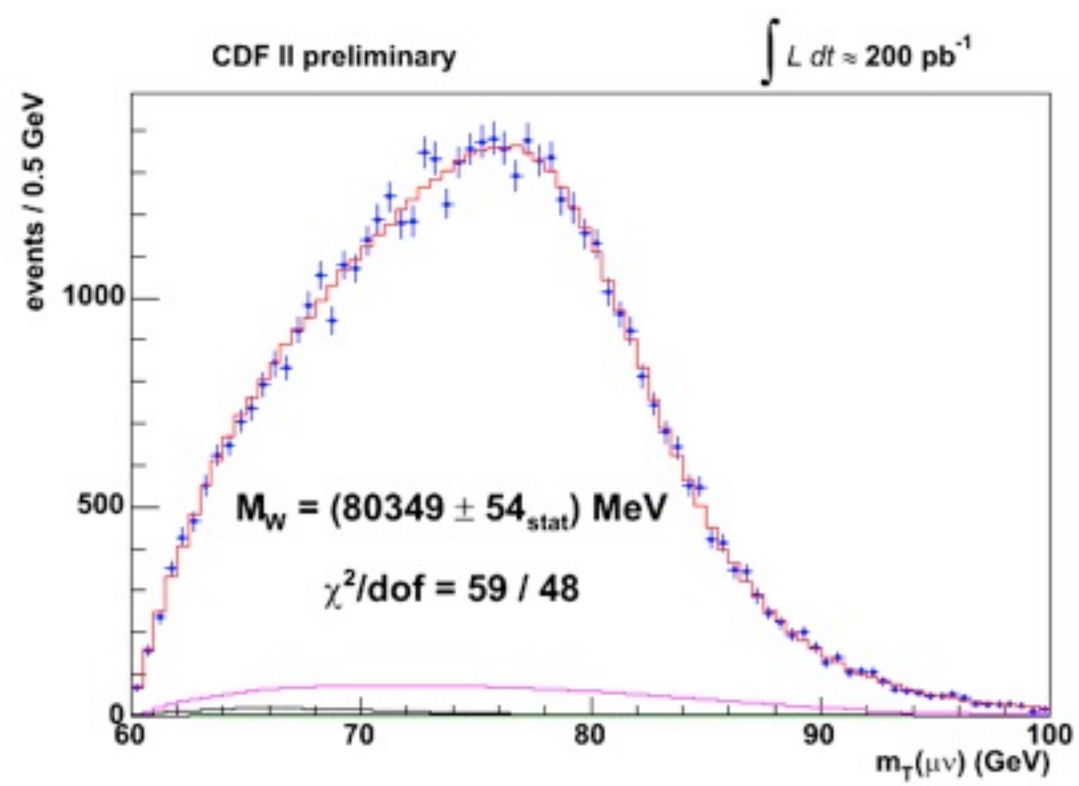






2. Precision measurements





What the W mass tells us

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

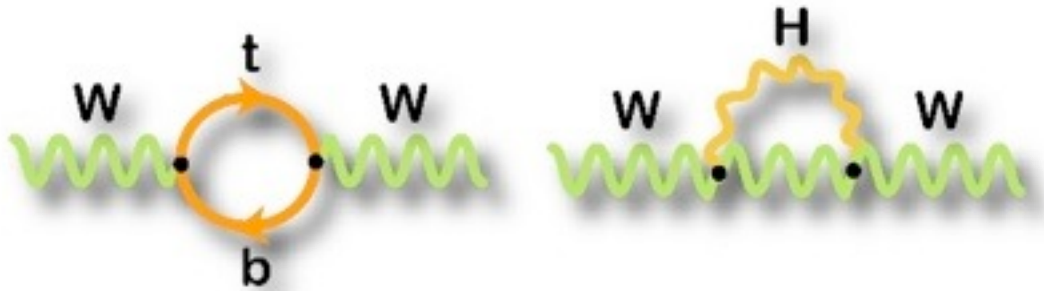
$$G_F = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2} \qquad \alpha_{EM}(Q^2 = M_Z^2) = 1/127.918(18)$$

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

- These inputs give a prediction of m_W

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

- Radiative corrections Δr dominated by top and Higgs loops



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

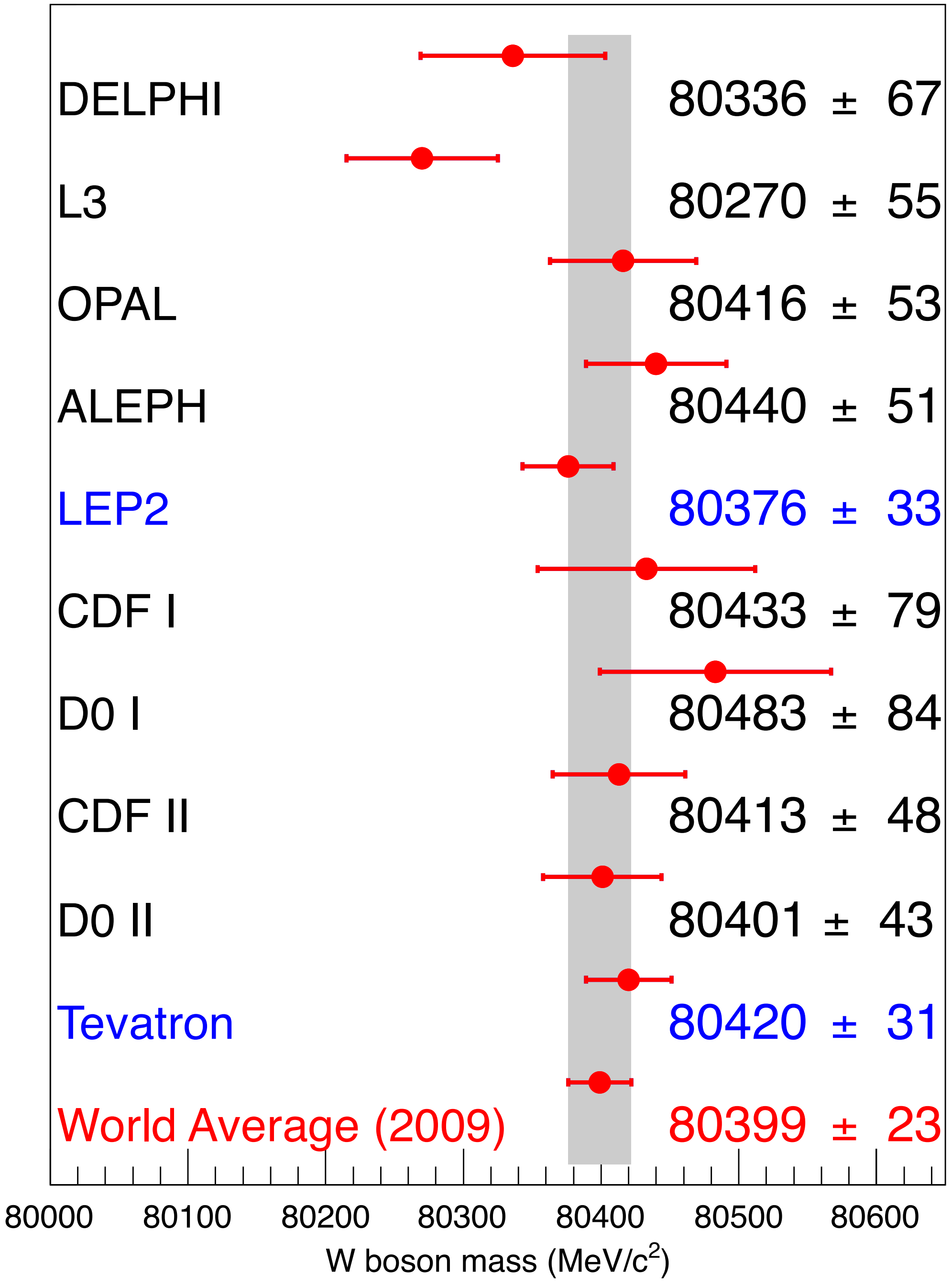
Where should the Higgs be?

Measurements of M_W

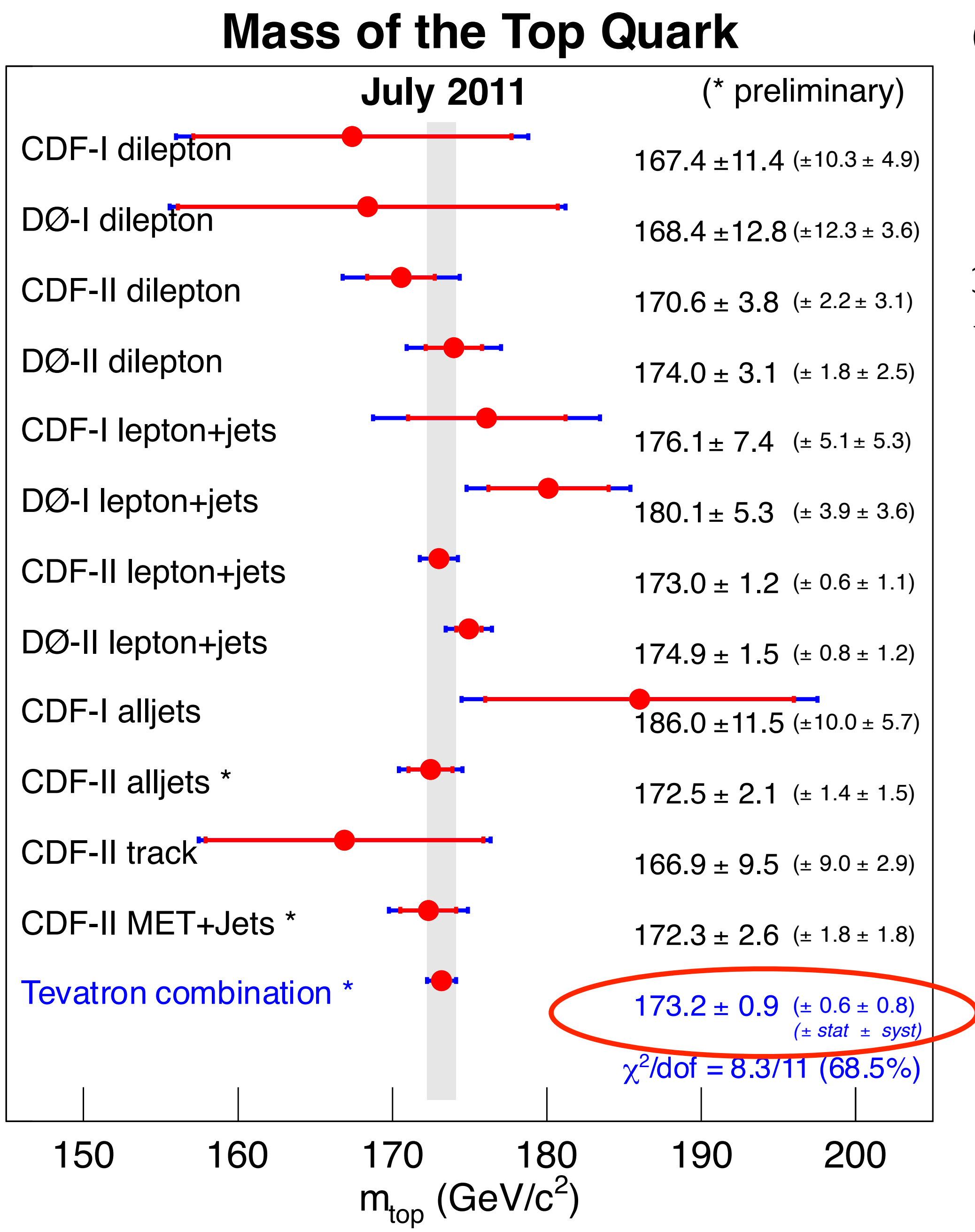
- State-of-the-art (Jan 2012)
  - DØ M_W=80401±43 MeV [1 fb^{-1}, *e*]
    *PRL **103**:141801 (2009)*
  - CDF M_W=80413±48 MeV [200 pb^{-1}, *e+μ*]
    *PRL **99:**151801 (2007)*
    *PRD **77:**112001 (2008)*
  - Combining with LEP ΔM_W = 23 MeV

- *Achieved:* exceed precision of e^+e^- machine measurements with hadron collider

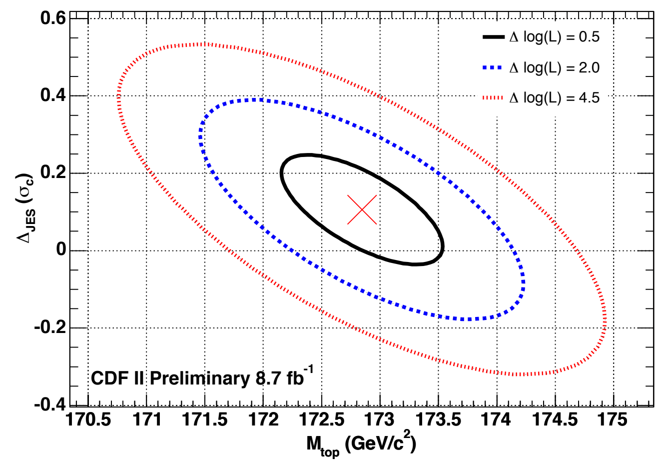
- *Goal:* match precision of all previous measurements with single CDF measurement



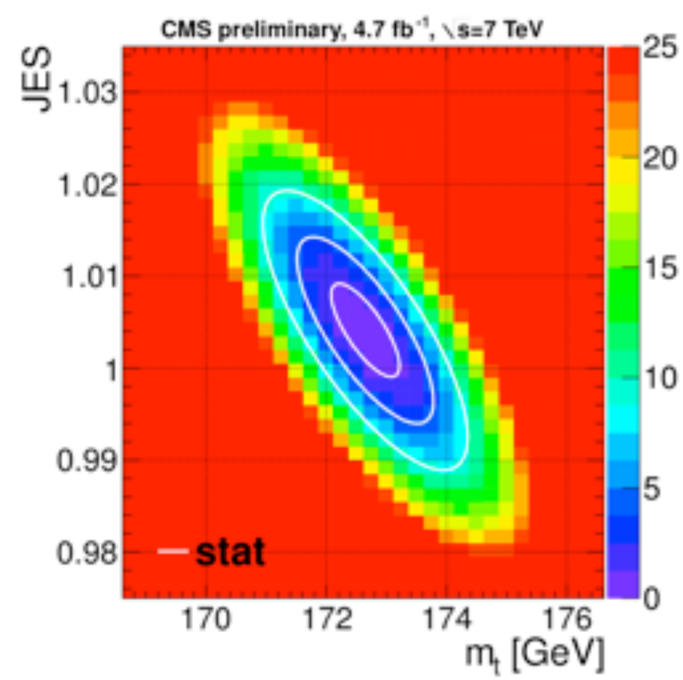
The top quark mass



Combination does not (yet) include



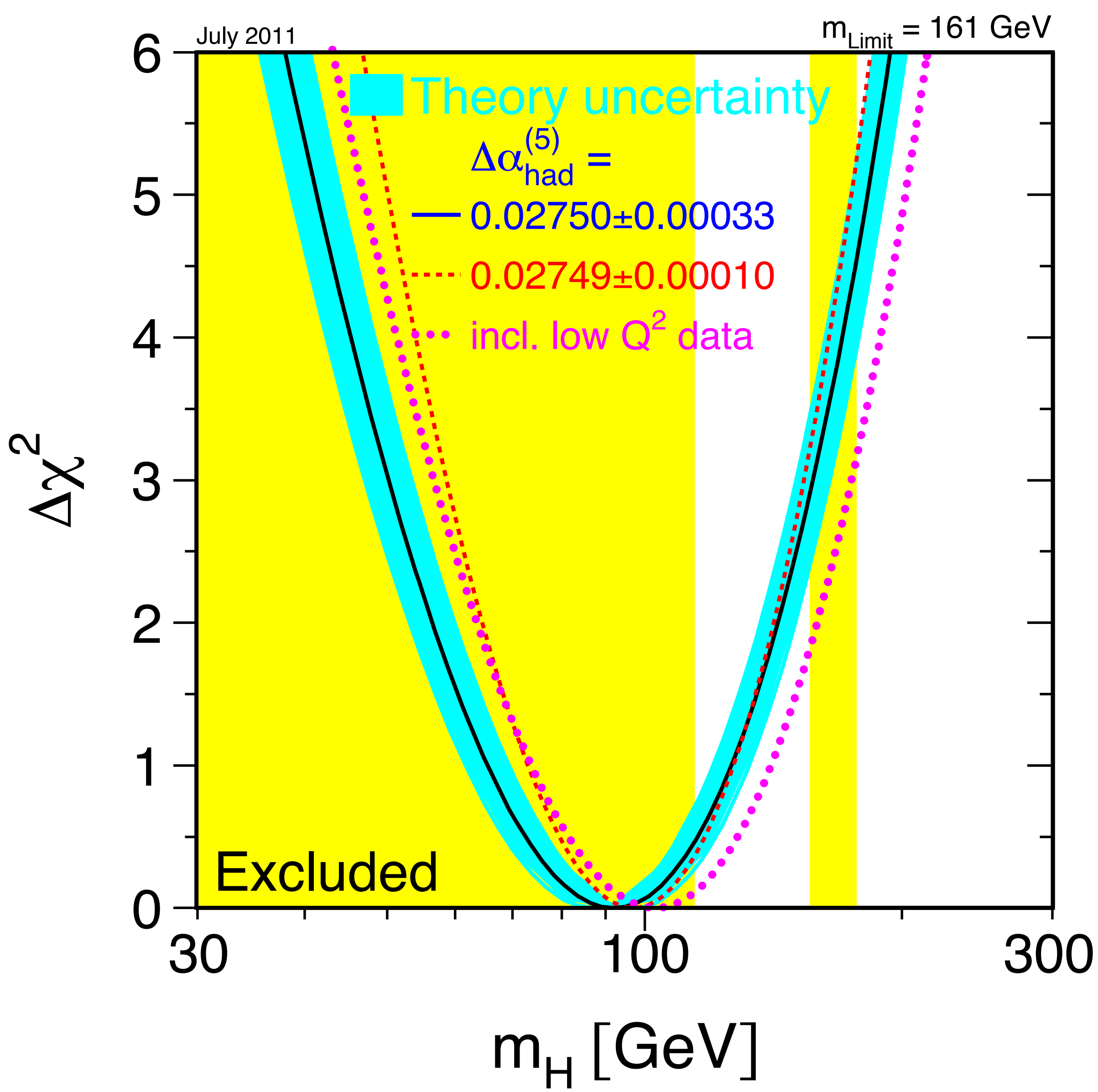
Single best measurement
m_{top} = 172.8±1.1 GeV [CDF]

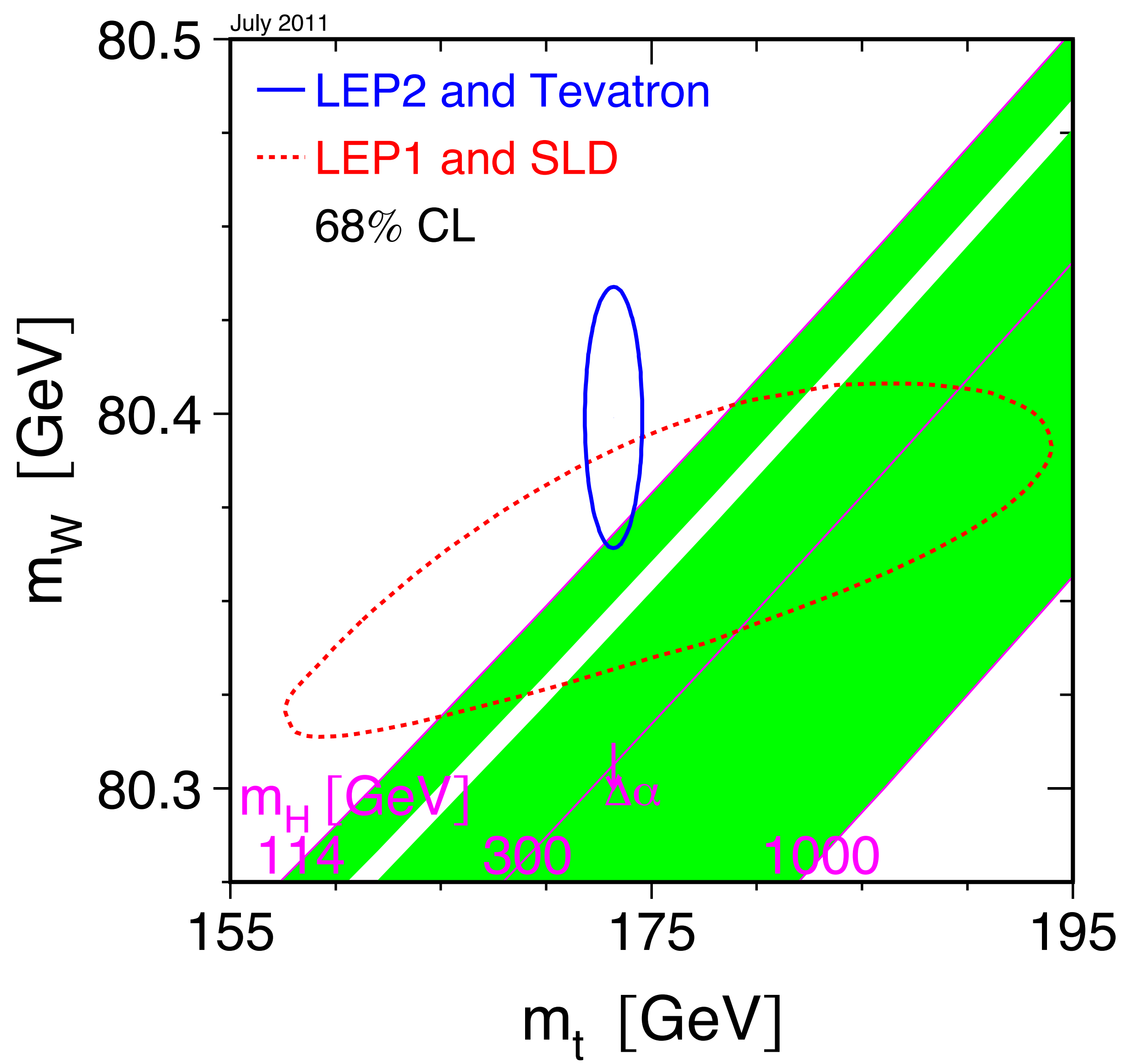


Impressive results from LHC
e.g. (single best LHC meas.)
m_{top} = 172.6±1.3 GeV [CMS]

- m_{top} = 173.2 ± 0.9 GeV
  - Equivalent to Δm_W = 6 MeV on m_H fit
  - m_W is limiting factor on m_H prediction!

Putting it together





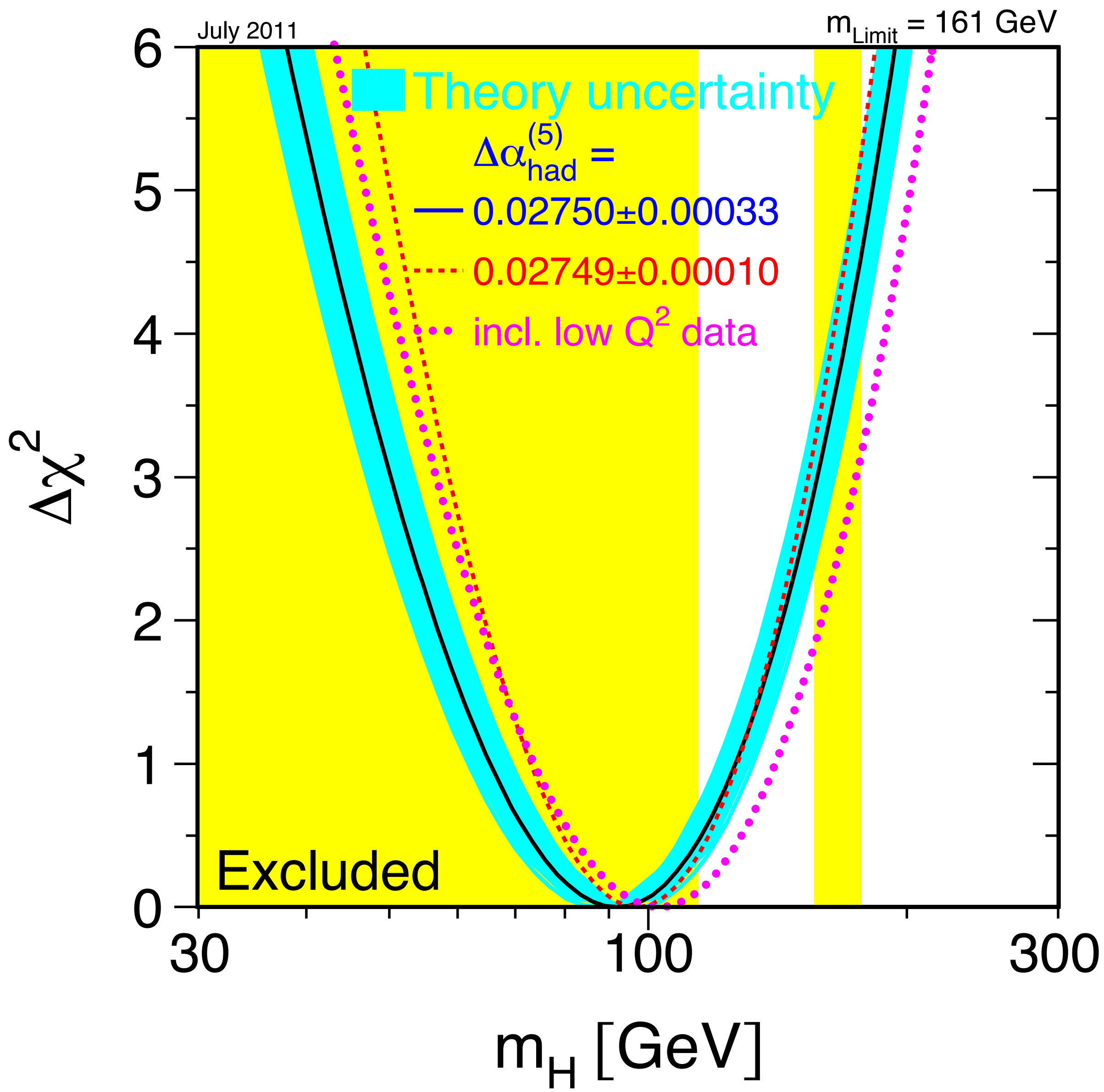
As of July 2011:

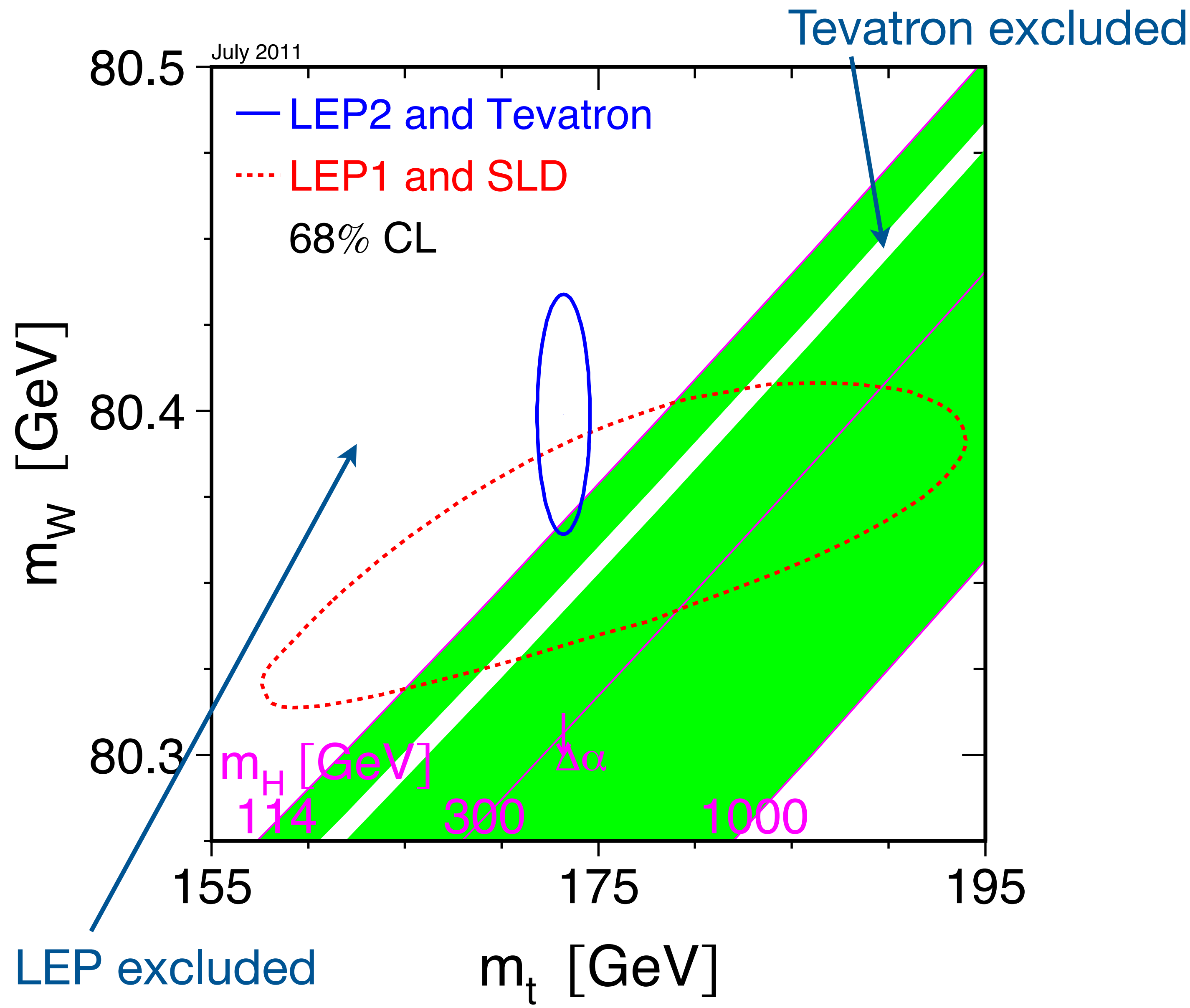
$m_H = 92^{+34}_{-26}$ GeV

$m_H < 161$ GeV @95% CL

Fits and plots from LEPEWWG

Putting it together





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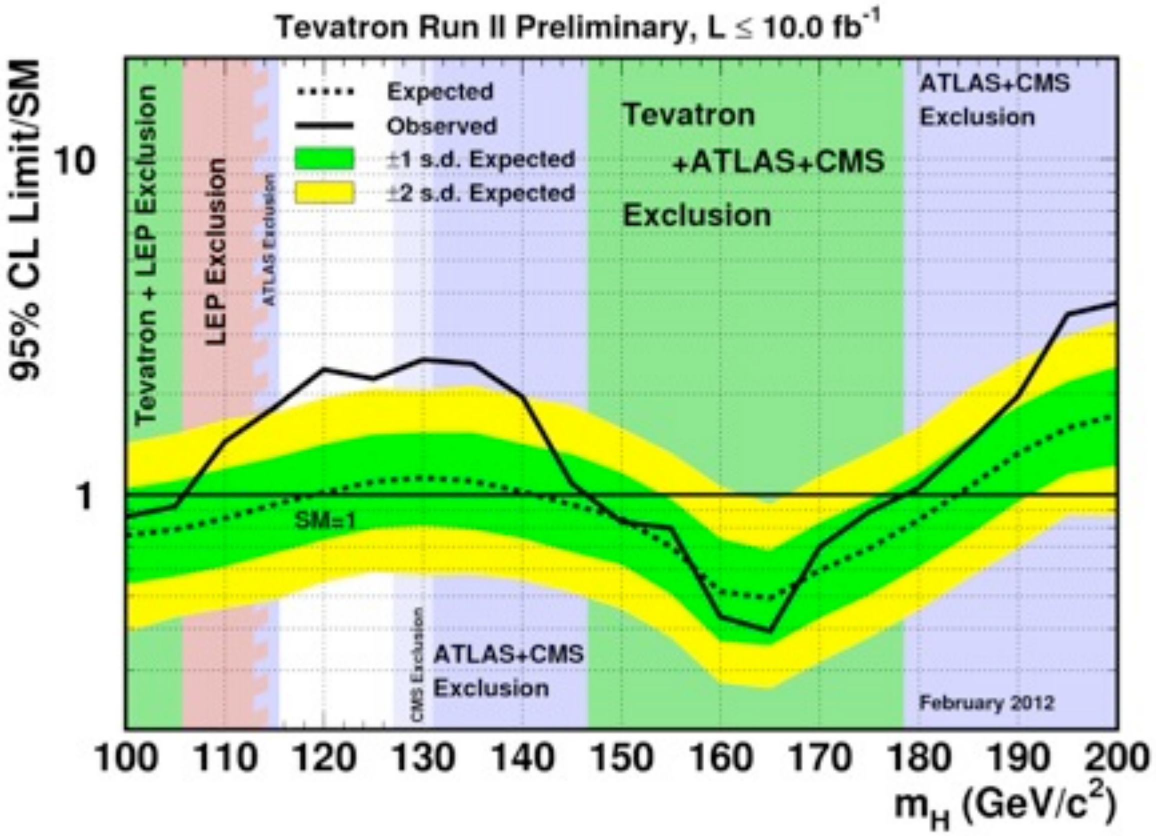
Since then...



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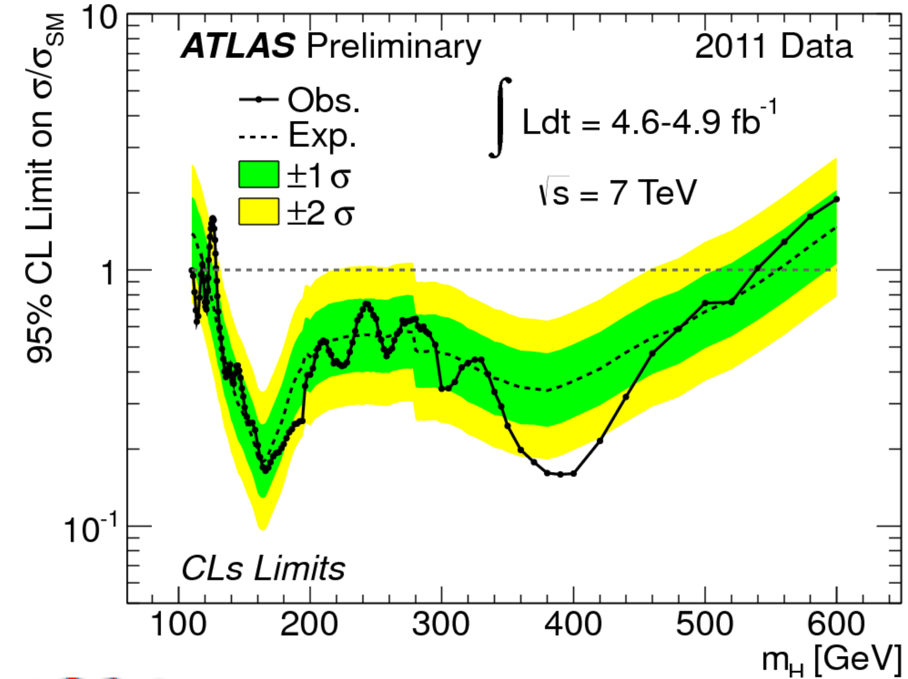
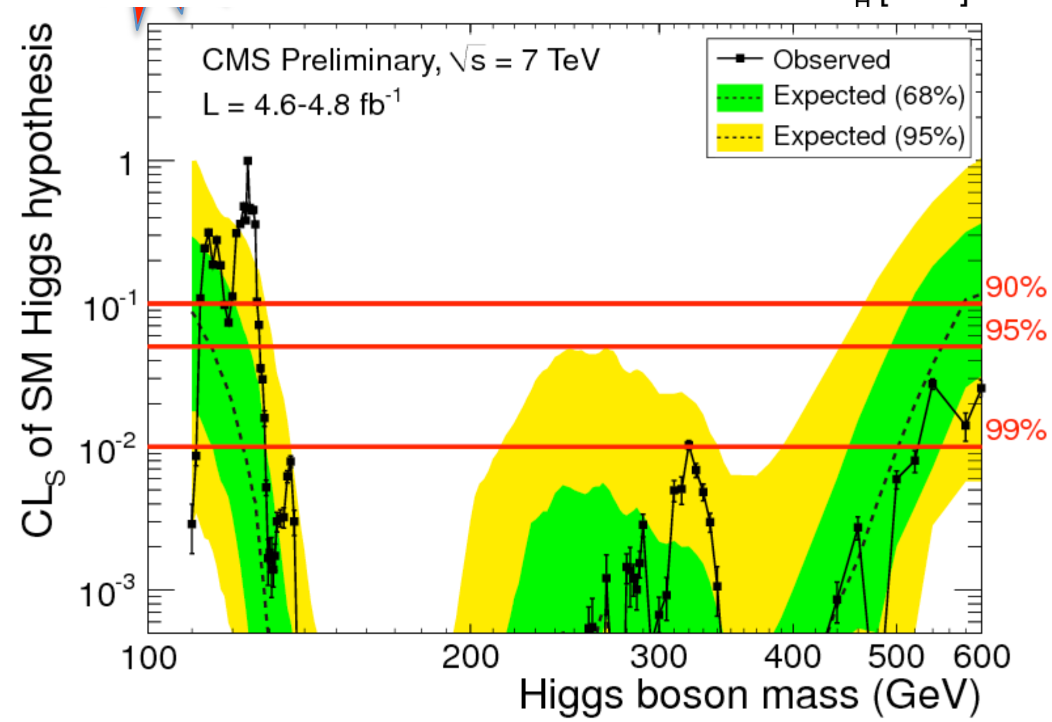




- Direct searches at the LHC and Tevatron restrict SM Higgs to narrow range
  - $m_H \sim$ 118-127 GeV

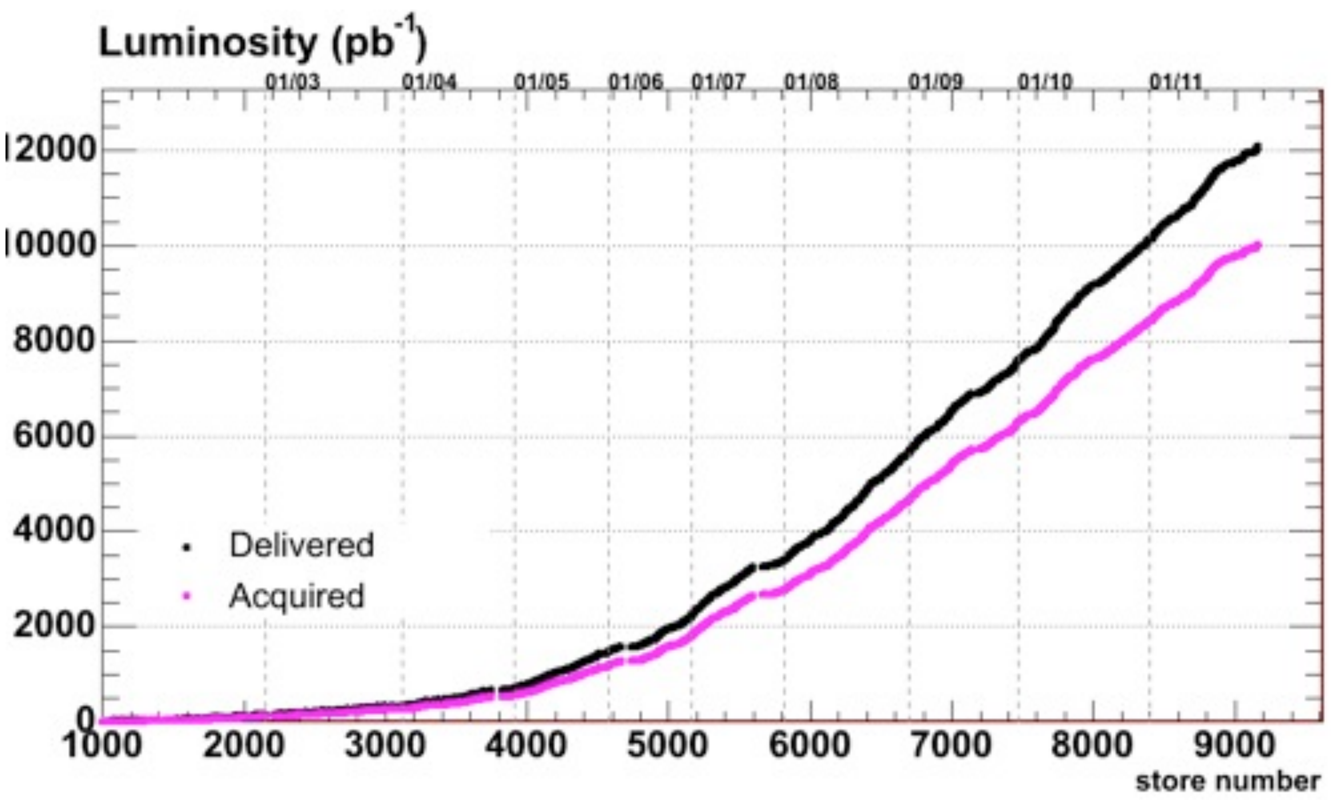
Analysis strategy

The Tevatron at Fermilab

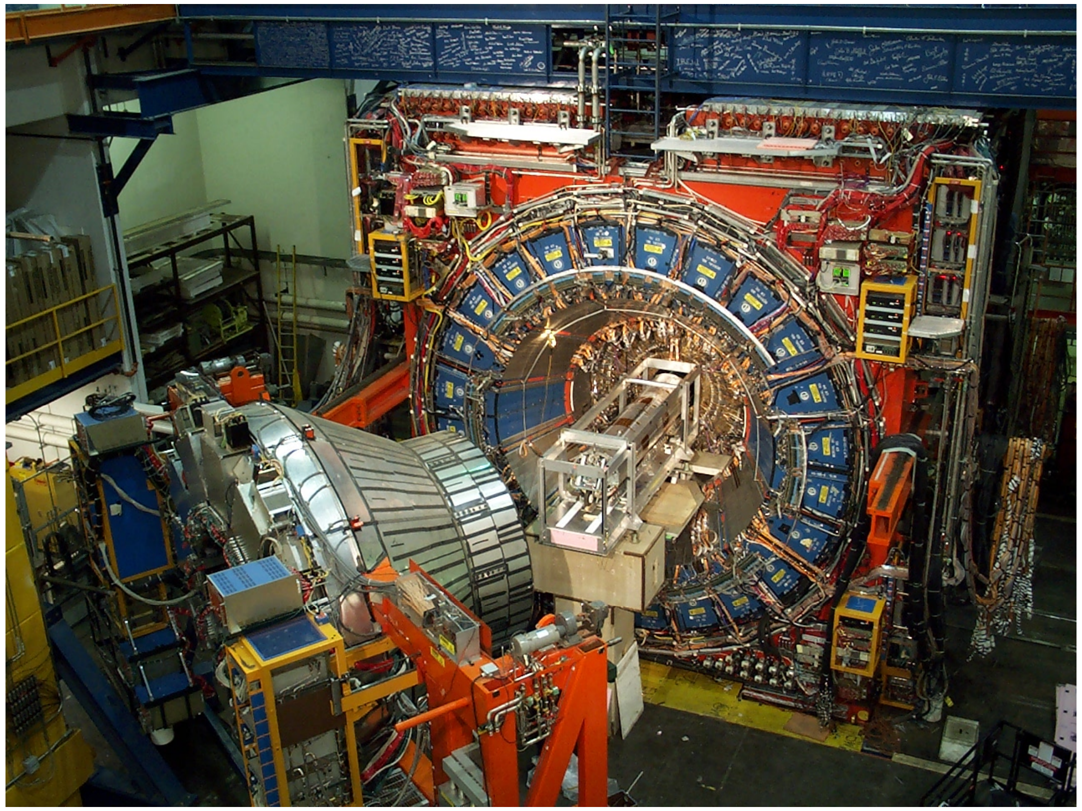
- 1.96 TeV ppbar collider
  - Highest ^p-pbar^ energy collider in the world
  - Typical inst. lumi.: 3×10^{32} $cm^{-2}s^{-1}$
    - 2011 LHC: ~3×10^{33} $cm^{-2}s^{-1}$
  - Bunch spacing: 396 ns
    - 2011 LHC: 50 ns

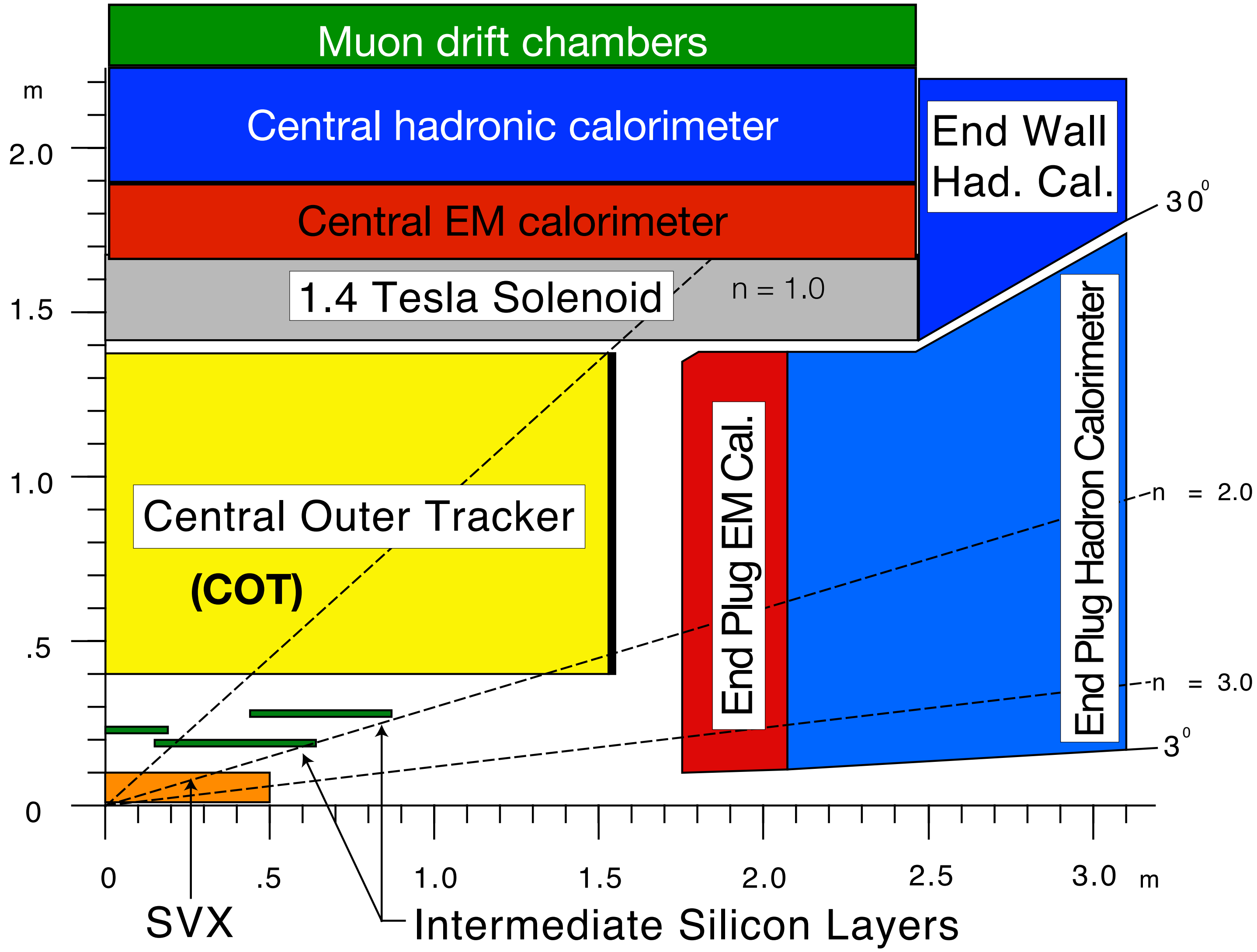
- Ceased operations Sep 30, 2011
  - ~12 fb^{-1} delivered to CDF and DØ

- Analysis presented utilizes 2.2 fb^{-1}



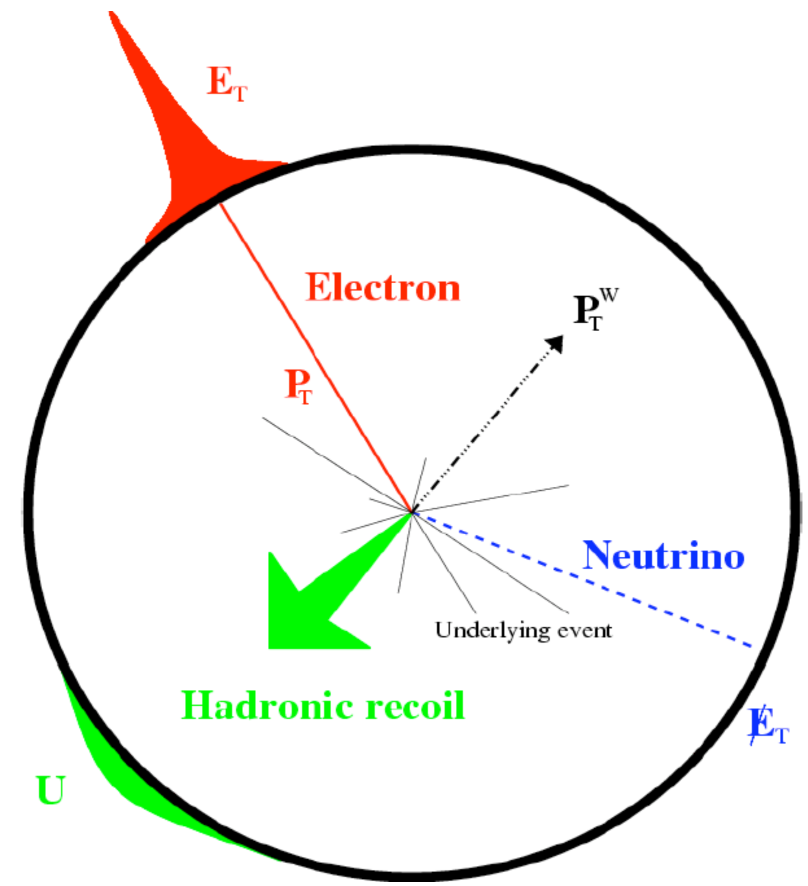
CDF II (2001-2011)





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%
  - 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)

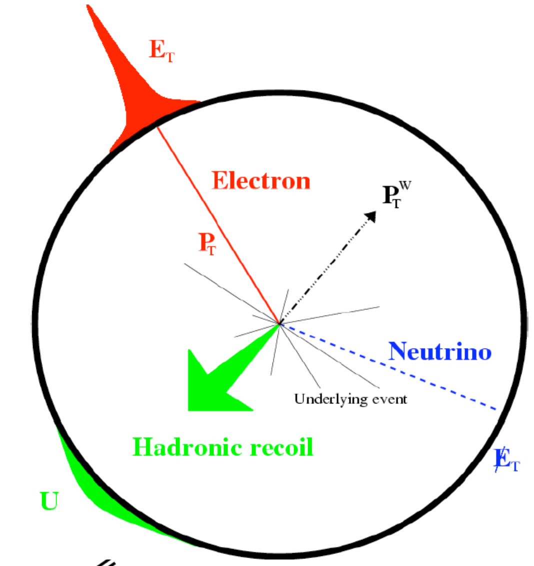
- Maximize internal constraints and cross-checks
- Why?
  1. **Robustness**: Constrain the same parameter multiple ways
  2. **Precision**: After demonstrating 1), combine independent measurements

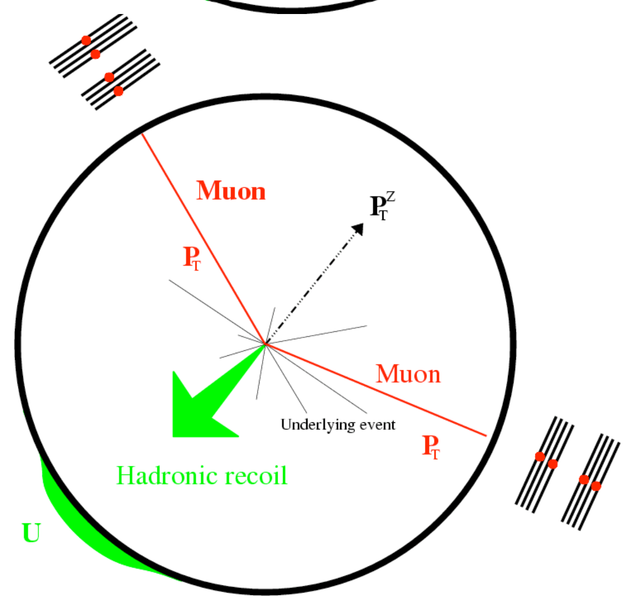
Measurement strategy (more specifically)

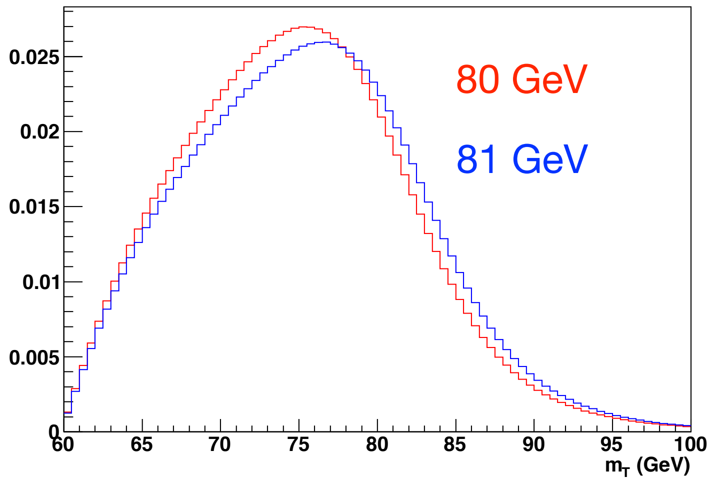
- Perform COT alignment with cosmic ray data
- Calibrate track momentum scale using dimuon resonances (J/ψ, Υ).
  - **Cross-check** with Z mass measurement and add as further calibration point
- Calibrate calorimeter energy using E/p of W and Z decays
  - **Cross-check** with Z mass measurement
- Calibrate hadronic recoil with Z decays to μ, e
  - **Cross-check** with W recoil distributions
- 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

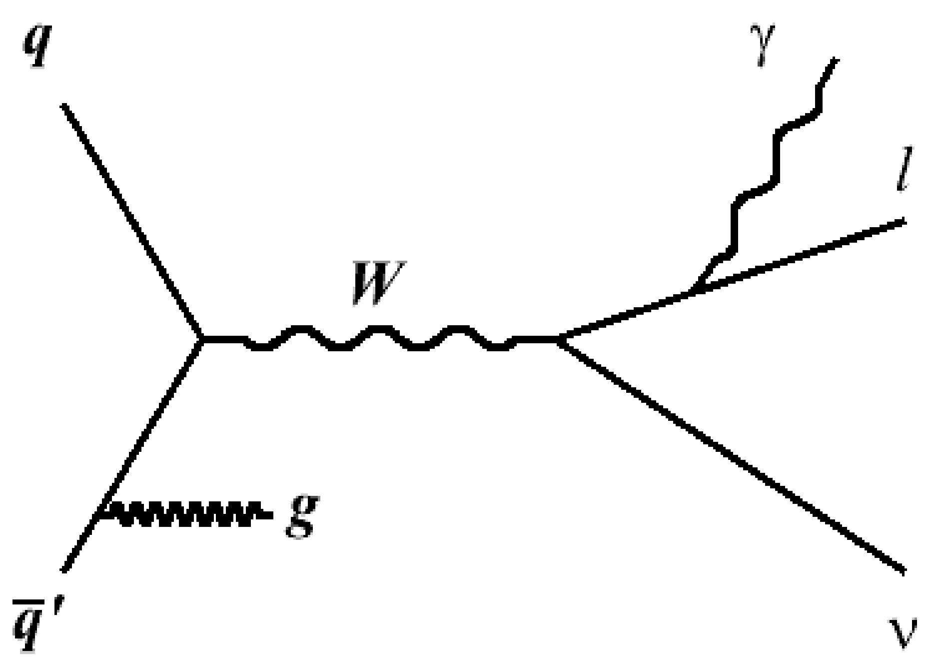






Selecting W (and Z) bosons at CDF

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



Select $e\nu$ and $\mu\nu$ 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

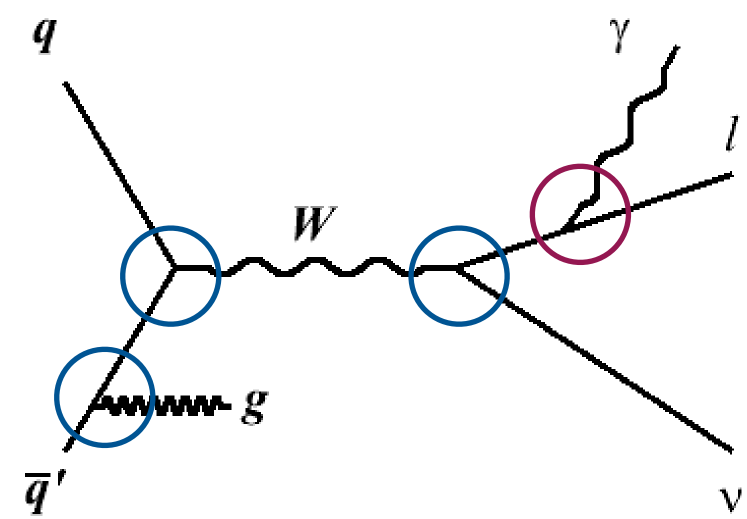
Analysis dataset: **2.2 fb^{-1}**

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

Theoretical model

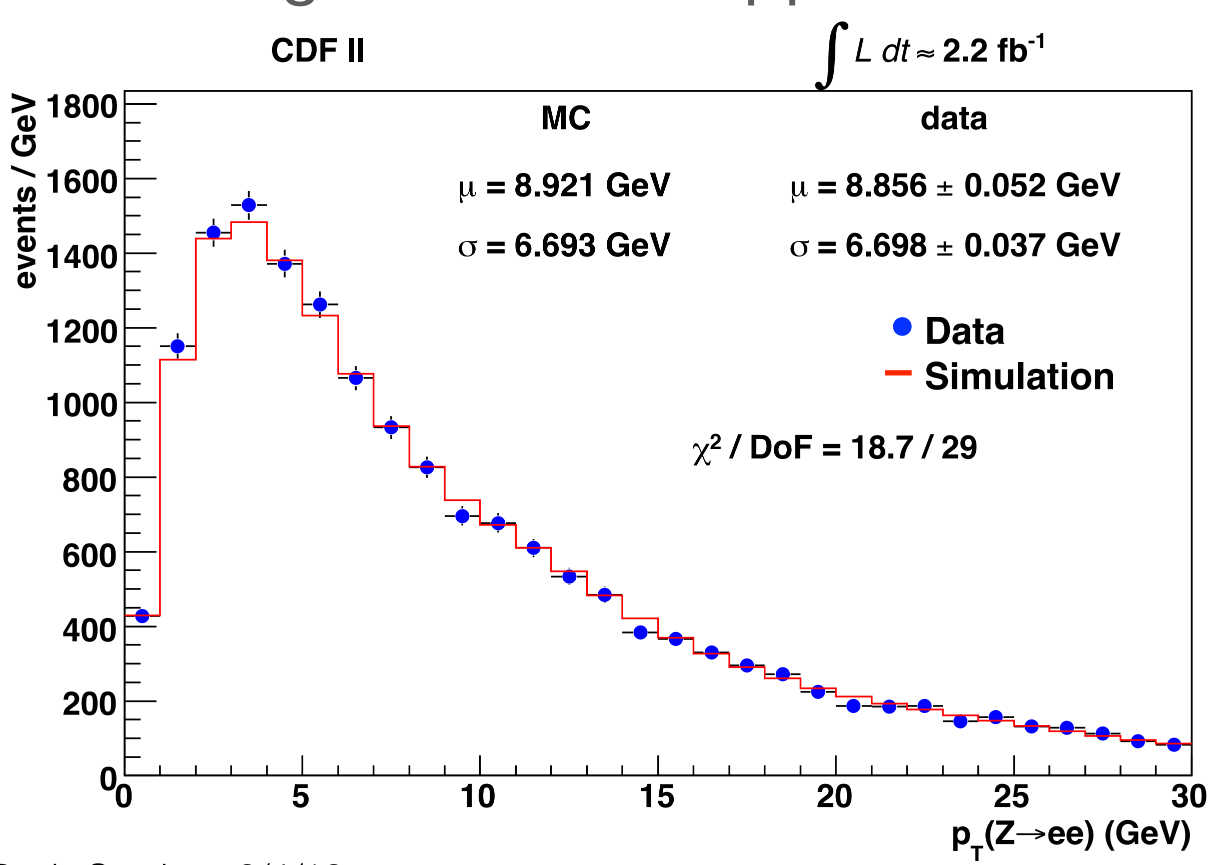
Event generation and boson p_T

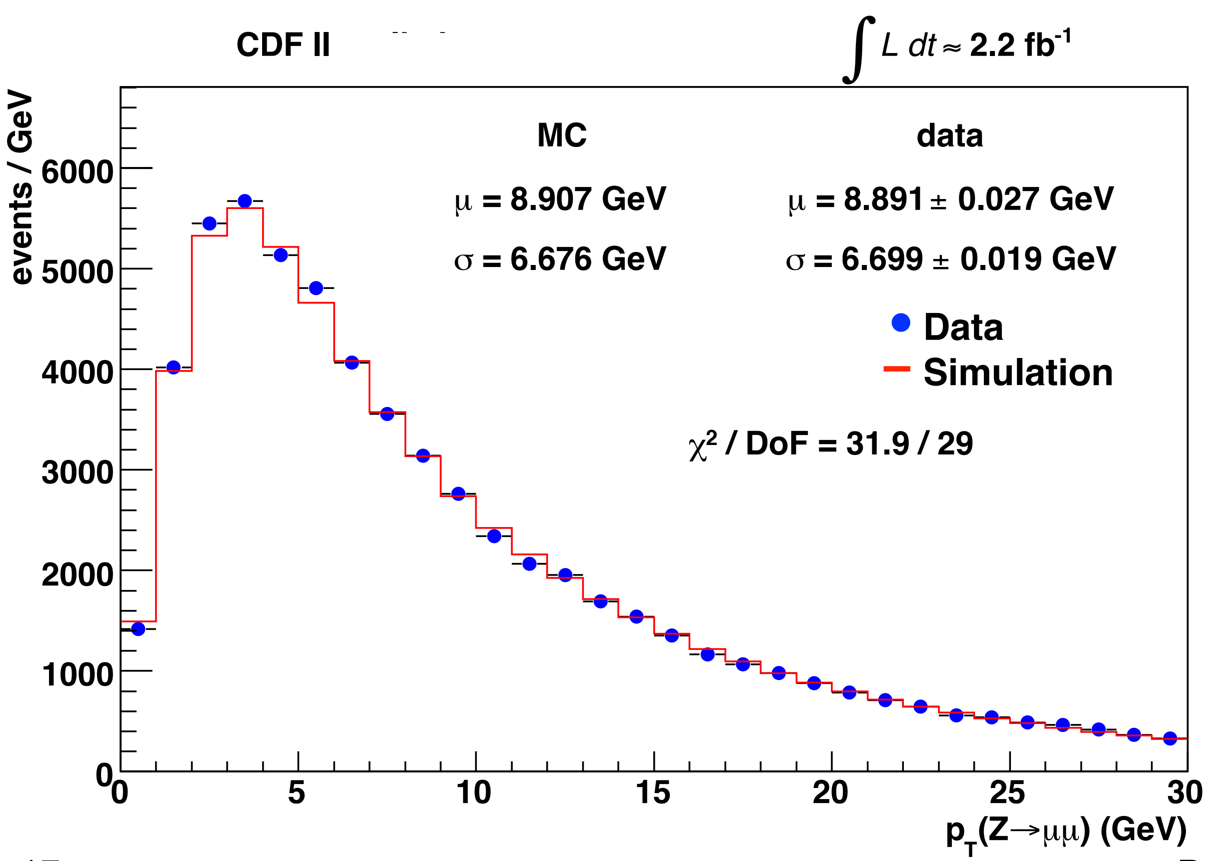
- Generator level simulation from **RESBOS**[1]
  - QCD effects, tunable parameters for non-perturbative regime (low-p_T)
- QED radiation simulated by **PHOTOS**[2]
  - FSR multiphoton simulation
- Fit parameters in boson p_T shape
  - Low p_T sensitive to g_2
  - Intermediate-high p_T sensitive to α_s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



[1] *C Balazs and C-P Yuan, PRD* ***55****, 5558 (1997)*
[2] *P. Golonka and Z. Was, Eur. J. Phys. C* ***45****, 97 (2006)*

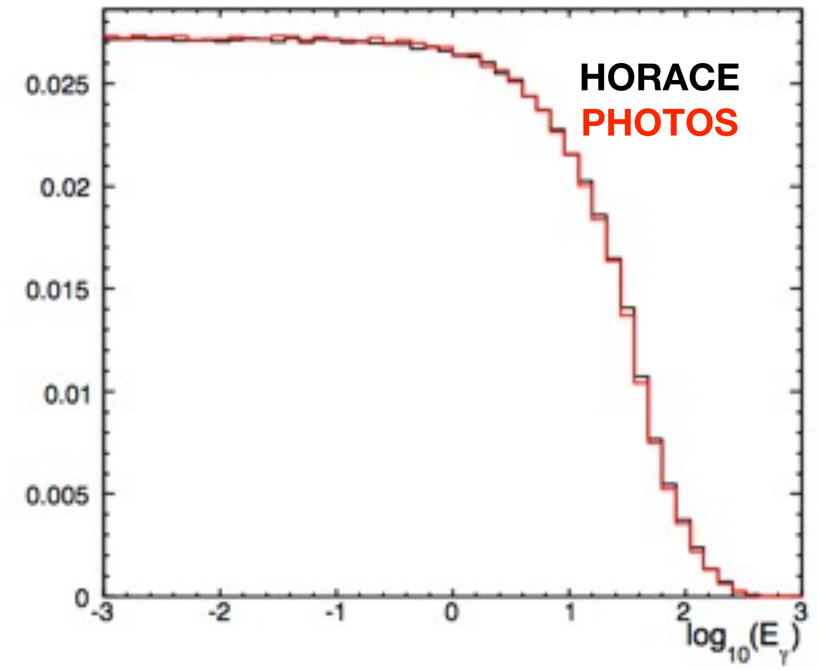
} ΔM_W = 5 MeV

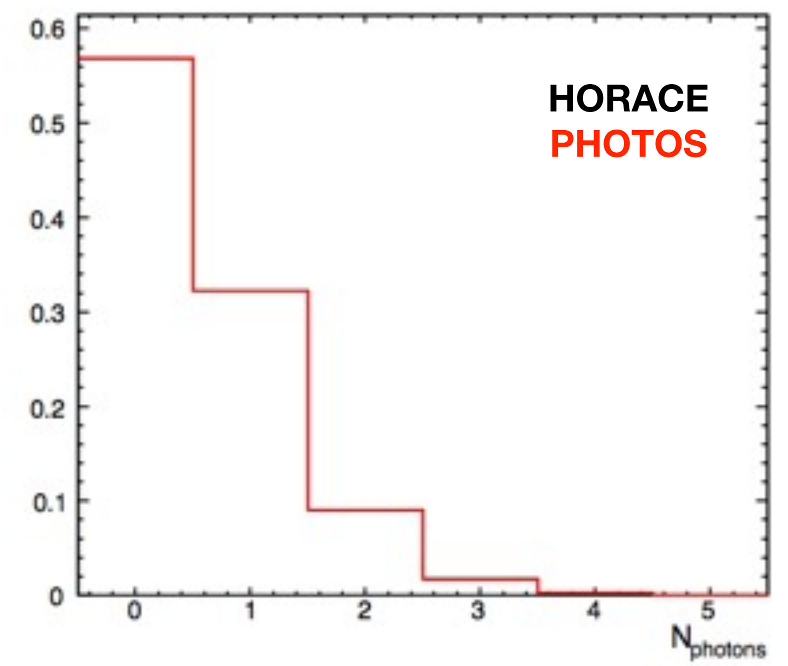




QED Radiation

- Extensive studies of 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)

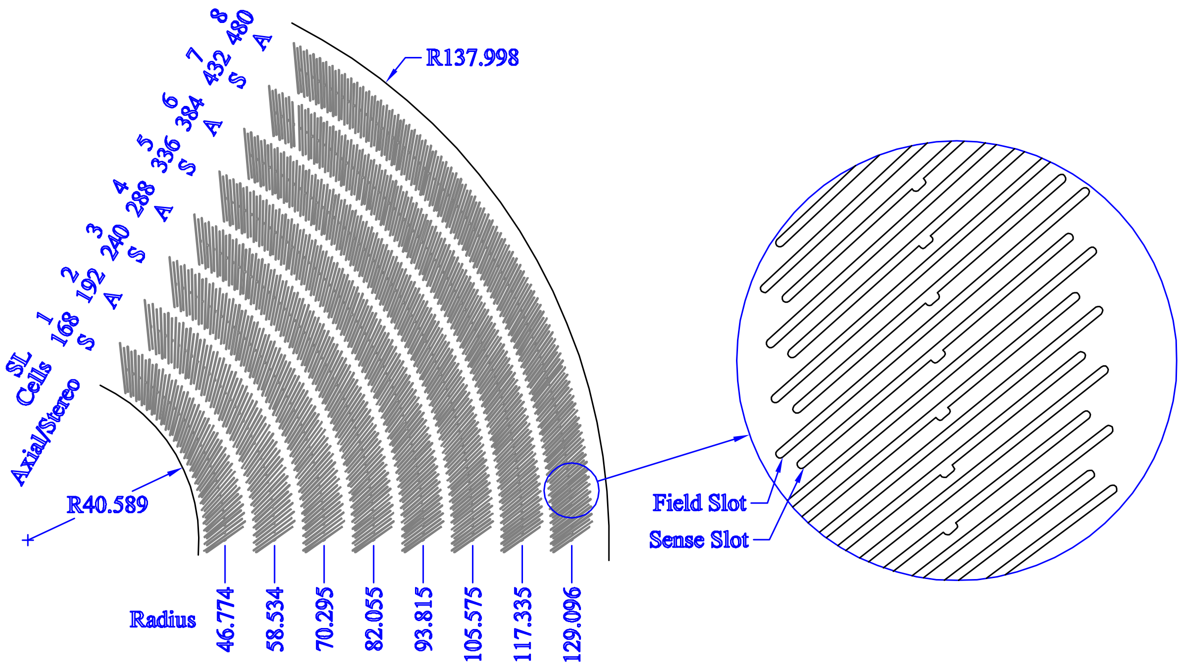


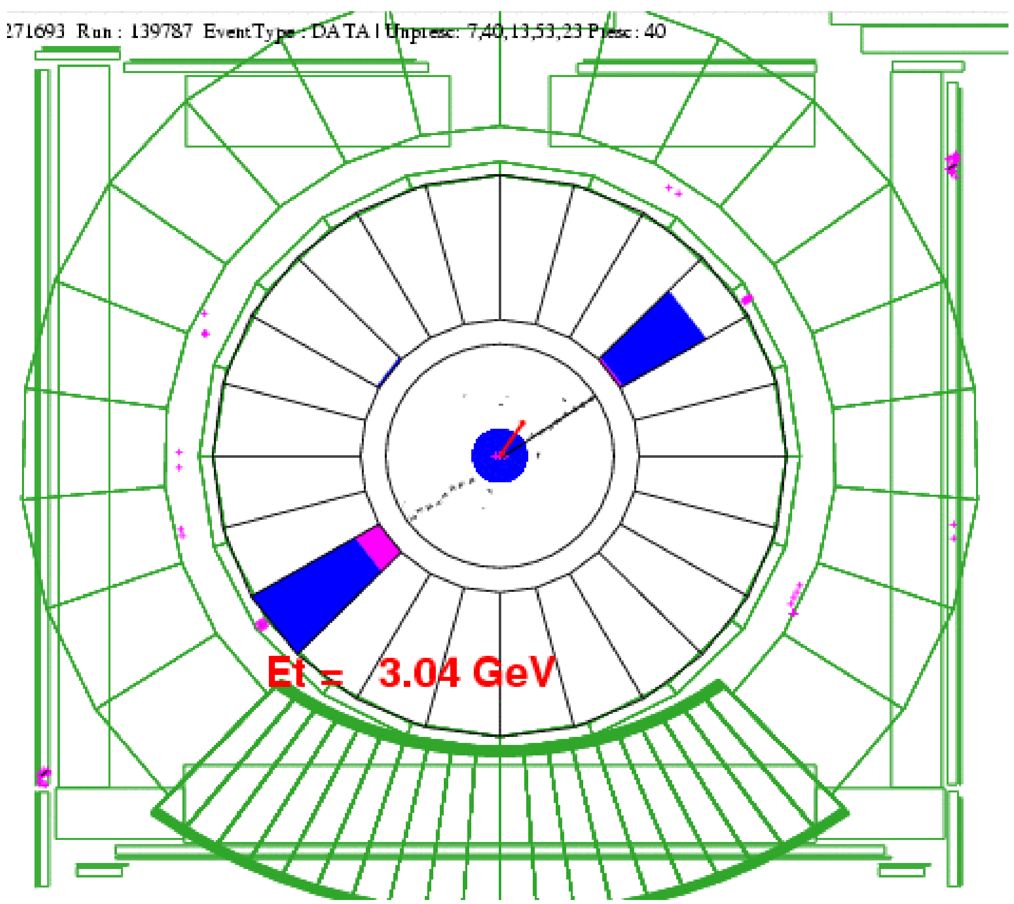


[1]*C.M. Carloni Calame, G. Montagna, O. Nicrosini and A. Vicini, JHEP* ***0710****:109 (2007)*

Tracker alignment

COT alignment with cosmic rays

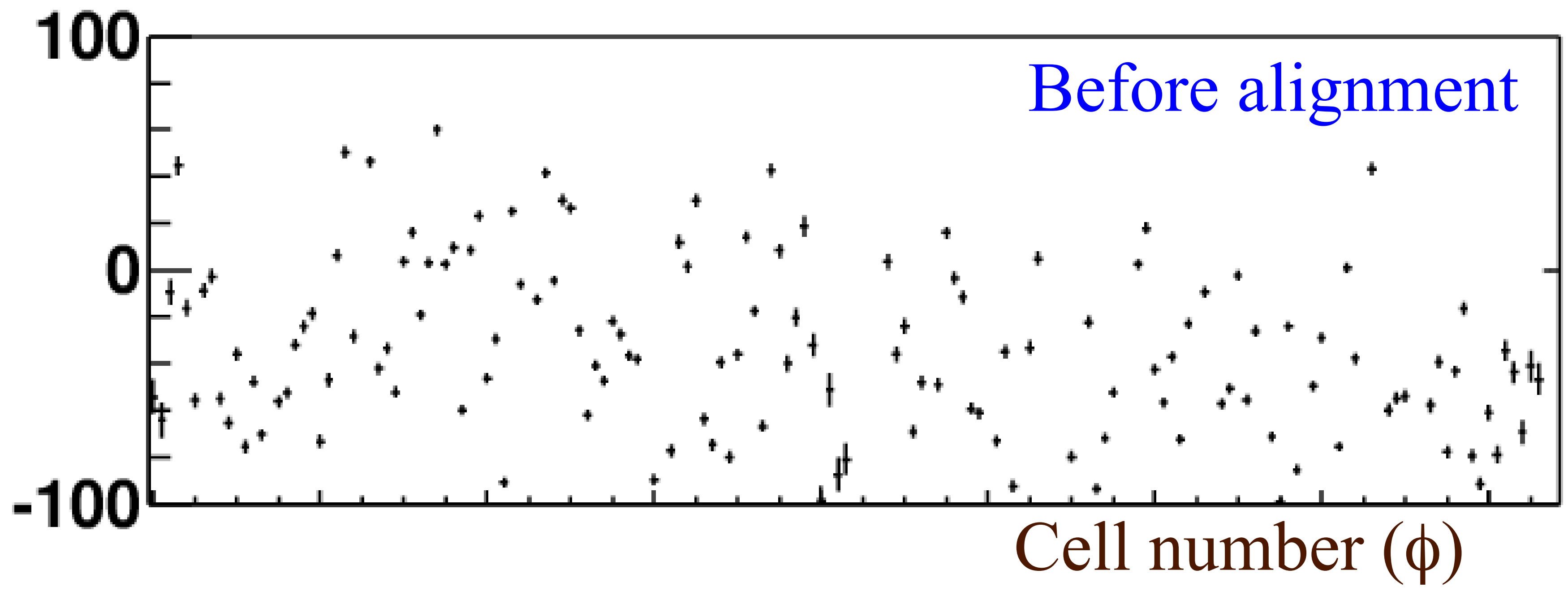


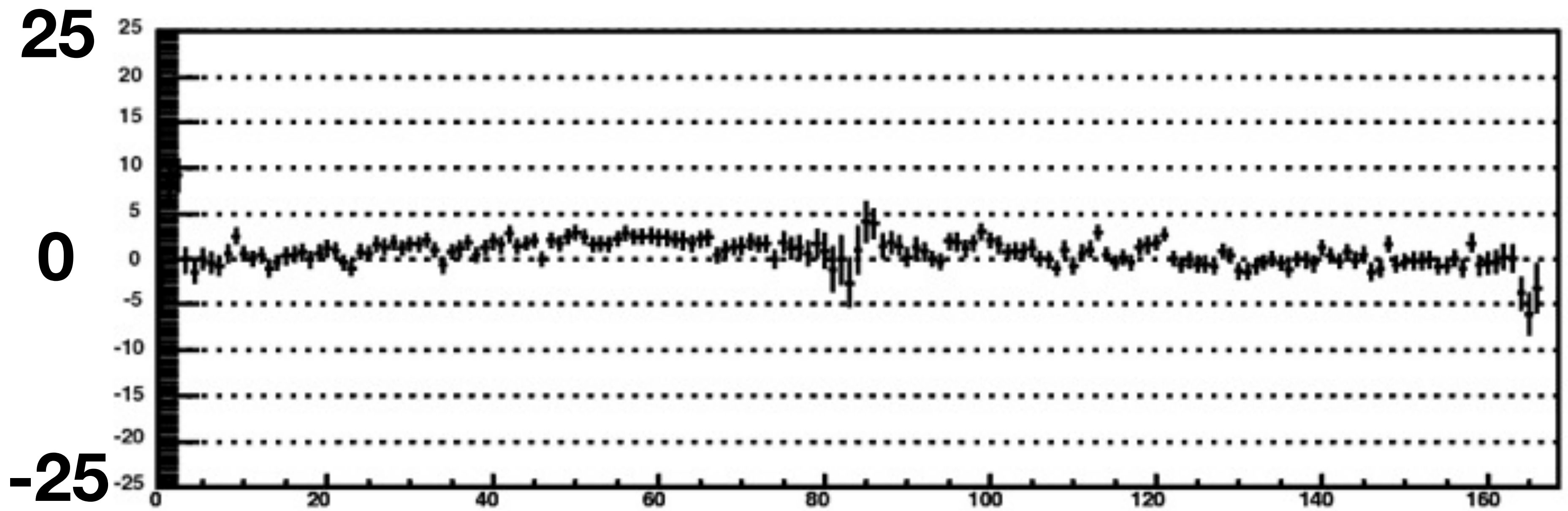


- COT consists of ~30k wires organized into ~2400 “cells”
- Accurate measure of wire positions crucial for precision track p_T
- Use *in-situ* cosmic ray data for alignment
  - Fit of COT hits on either side of vertex to single helix
  - A. Kotwal, H. Gerberich, C. Hays, NIM A **506**, 110 (2003)

Tracker alignment

- Improve relative alignment precision from ~50μm to ~2μm

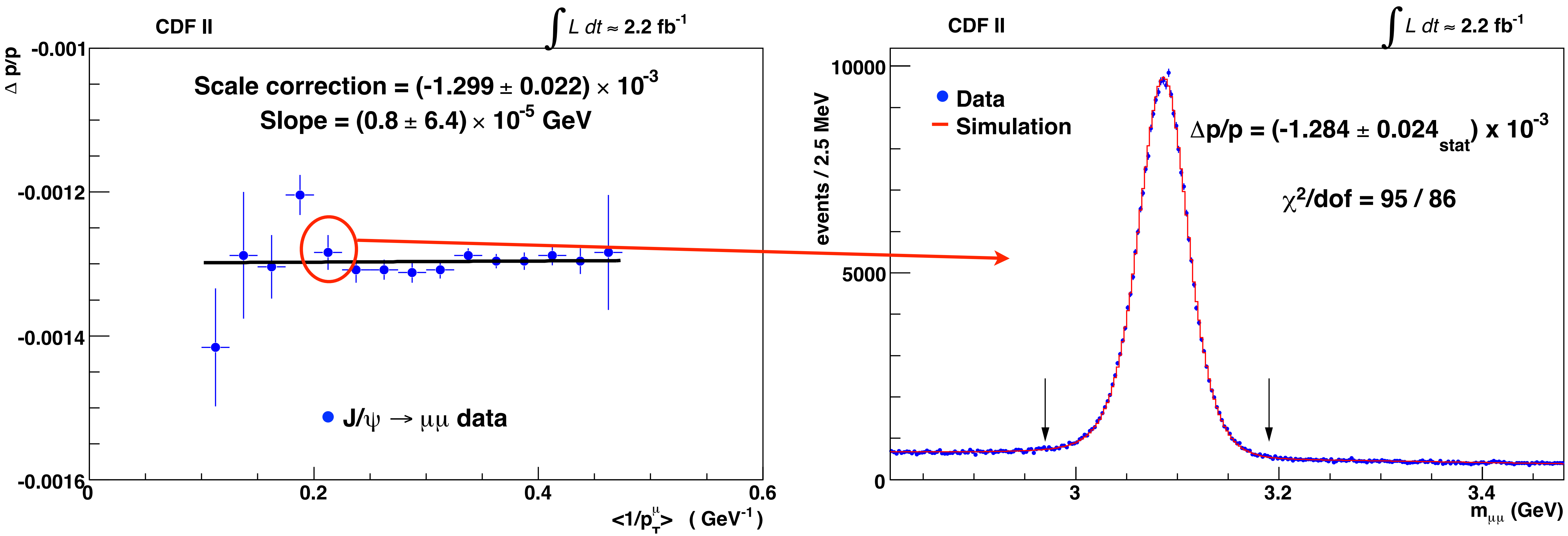




Track momentum scale

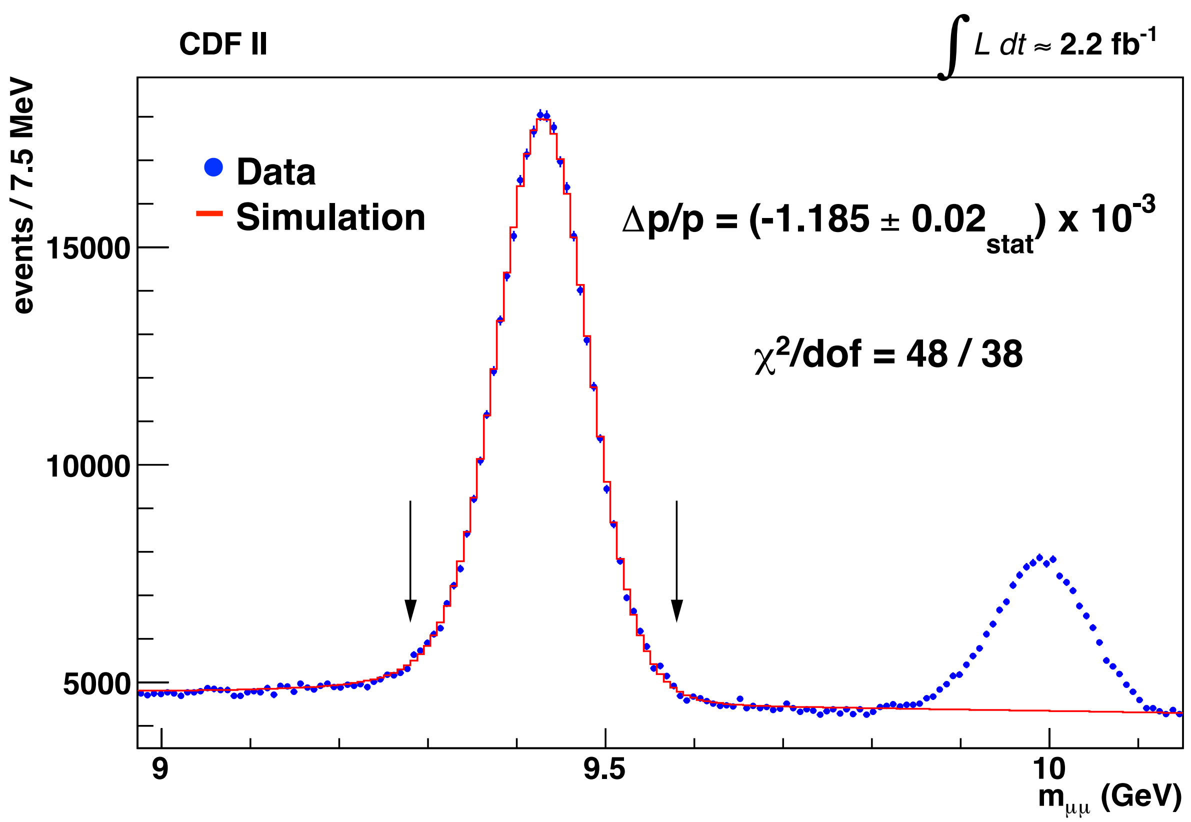
Track momentum scale: J/ψ

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

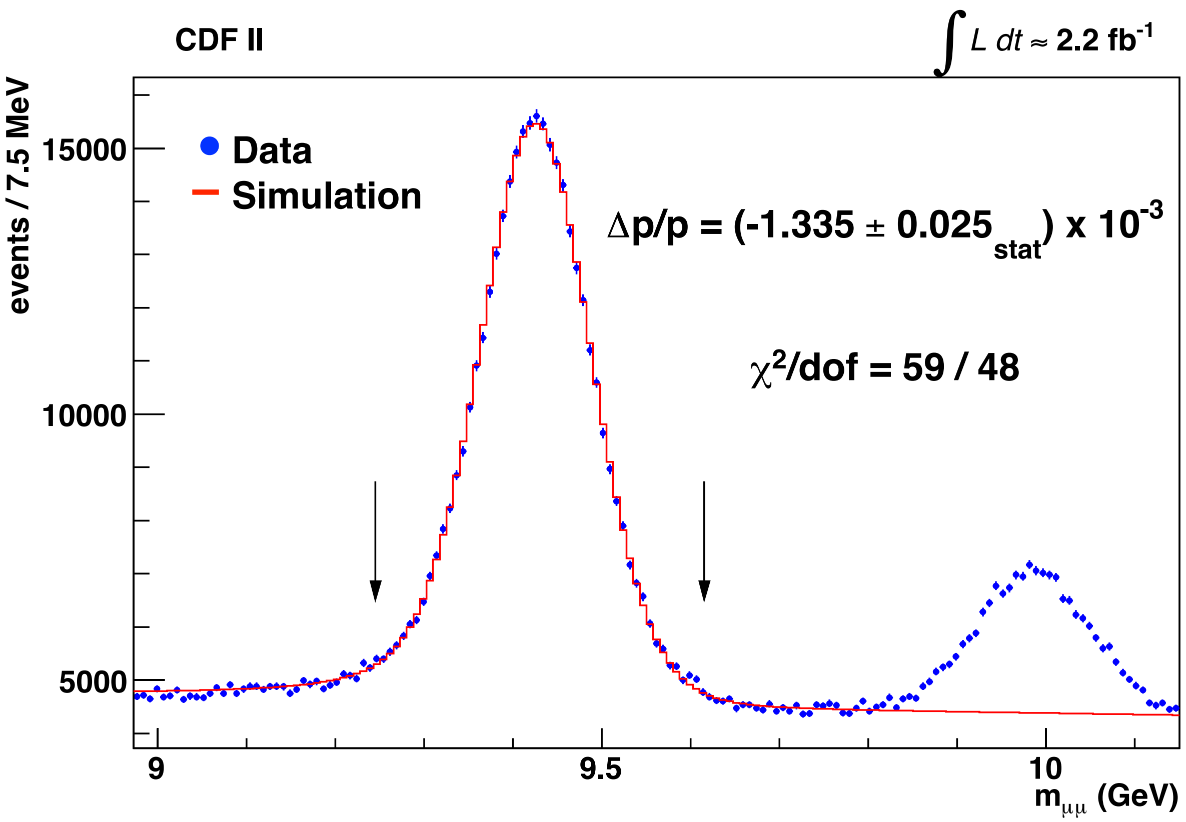


Track momentum scale: Υ

- Υ sample provides higher-p_T sample
- 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

Track momentum scale: systematic uncertainties

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

- Dominated by QED and B-field non-uniformity
    - BC vs NBC comparison contributes additional 0.036×10^{-3}

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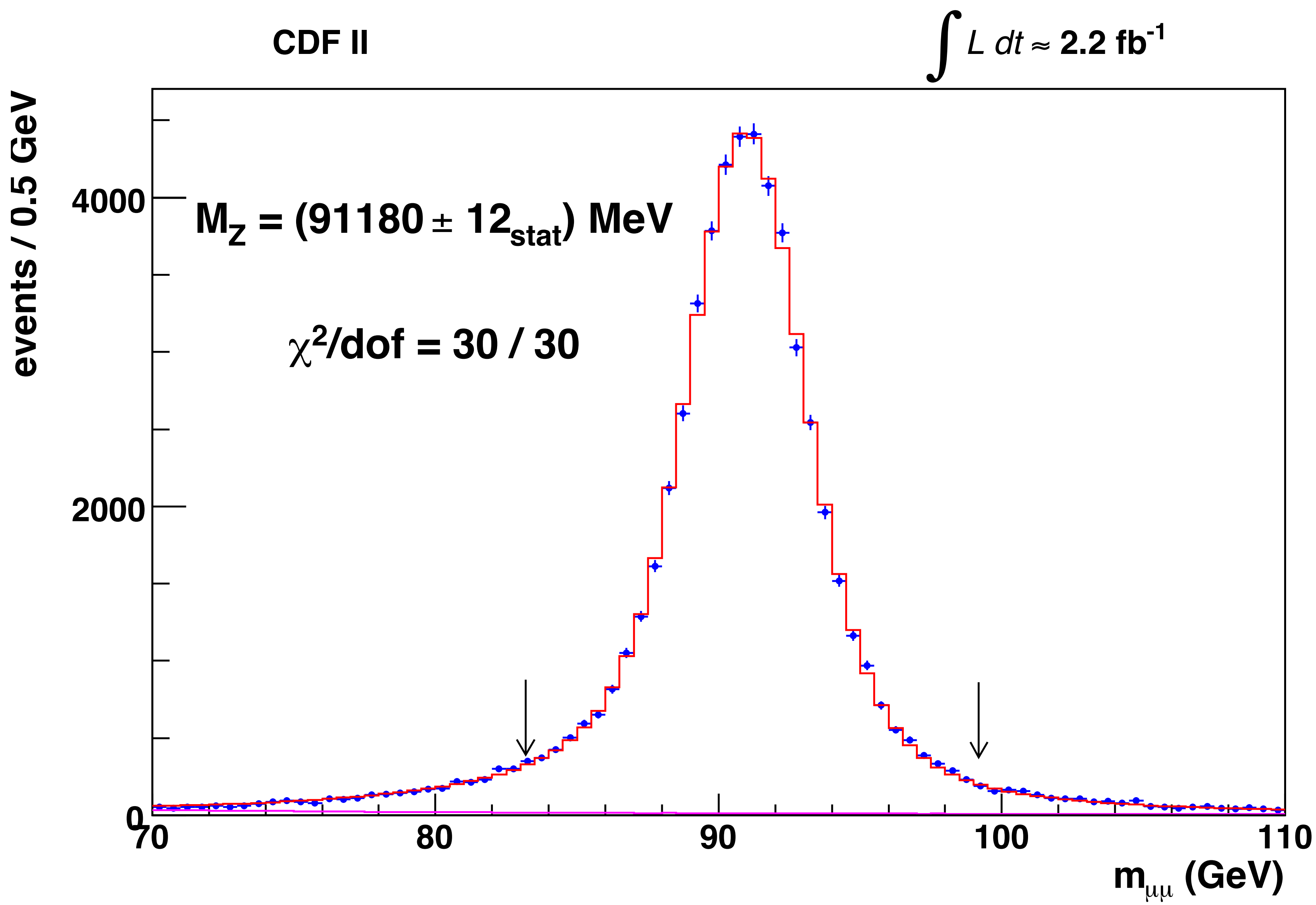
$\Delta M_W \sim 6$ MeV

- Dominated by QED and B-field non-uniformity
  - BC vs NBC comparison contributes additional 0.036x10^{-3}

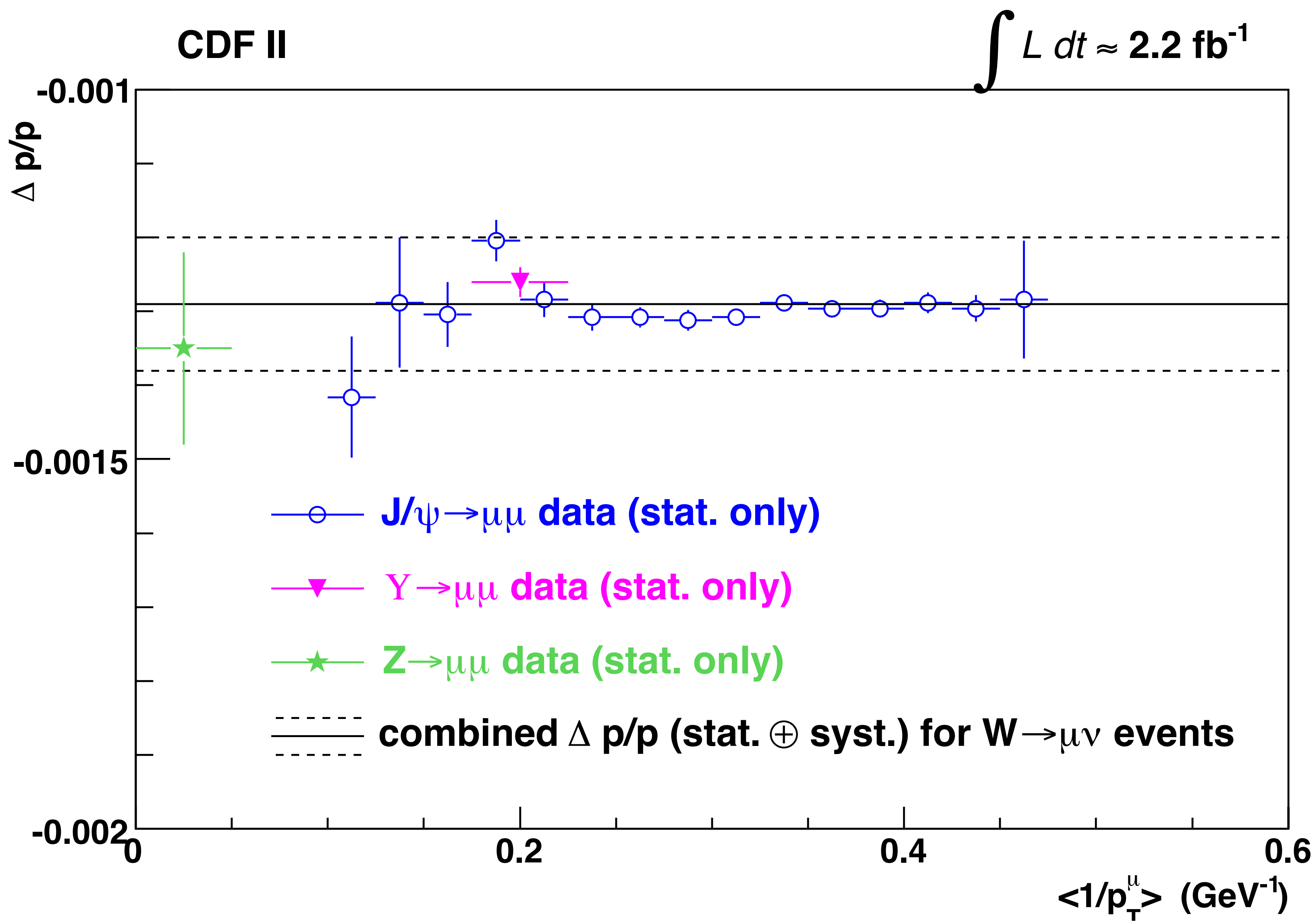
Muon Z mass measurement

- Perform **independent** measurement of Z mass using tuned momentum scale
  - Fit central value kept blind during scale calibration
  - $M_Z = 91180 \pm 12_{stat} \pm 9_{p\text{-}scale} \pm 5_{QED} \pm 2_{alignment} = 91180 \pm 16$ MeV
  - Excellent agreement with world average (91188±2 MeV)



Final momentum scale

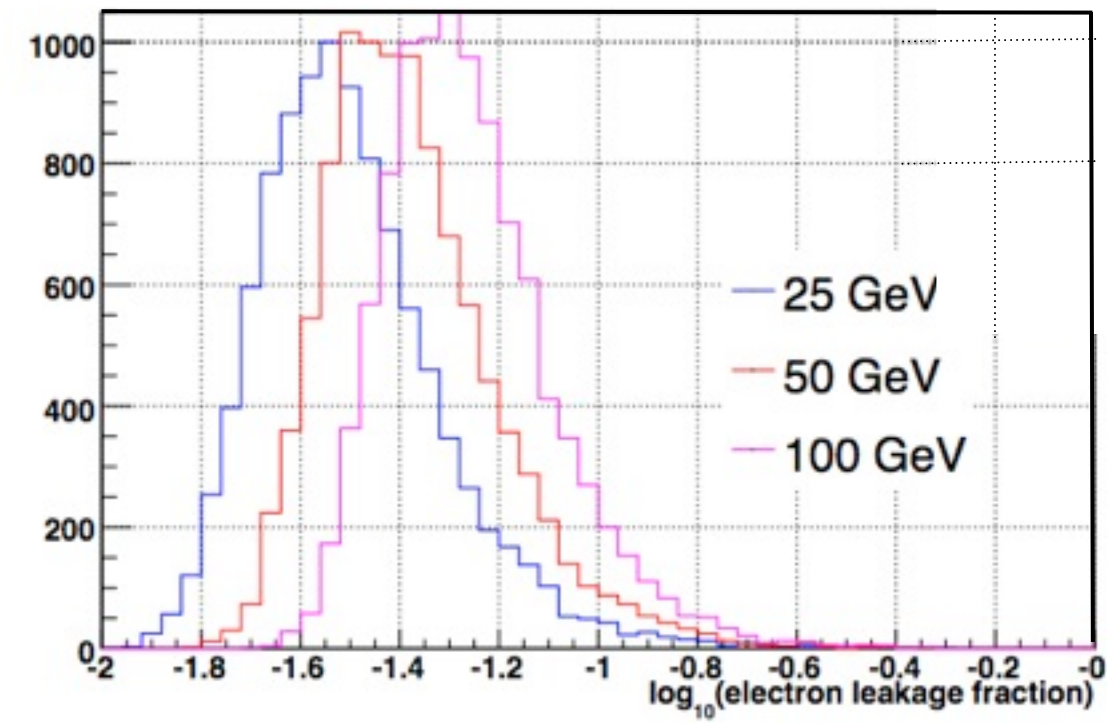
- Add Z data as final calibration point for momentum scale
  - $\Delta p/p_{final}$ = $(-1.29 \pm 0.07_{stat} \pm 0.05_{QED} \pm 0.02_{align}) \times 10^{-3}$
  - Apply scale to *W* muons and *E/p* calibration
  - Systematic uncertainty ΔM_W = 7 MeV



EM calorimeter scale

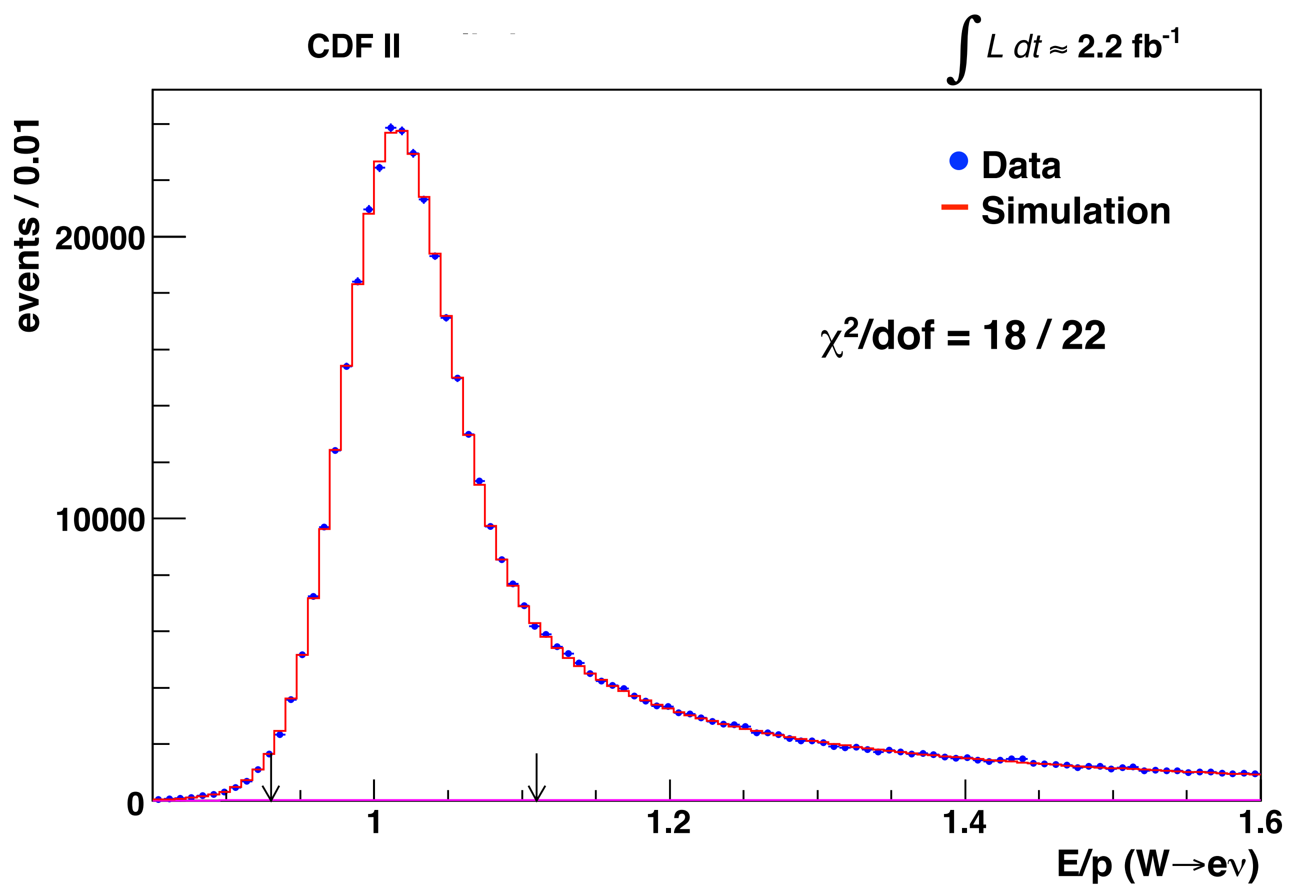
Simulation for electrons and photons

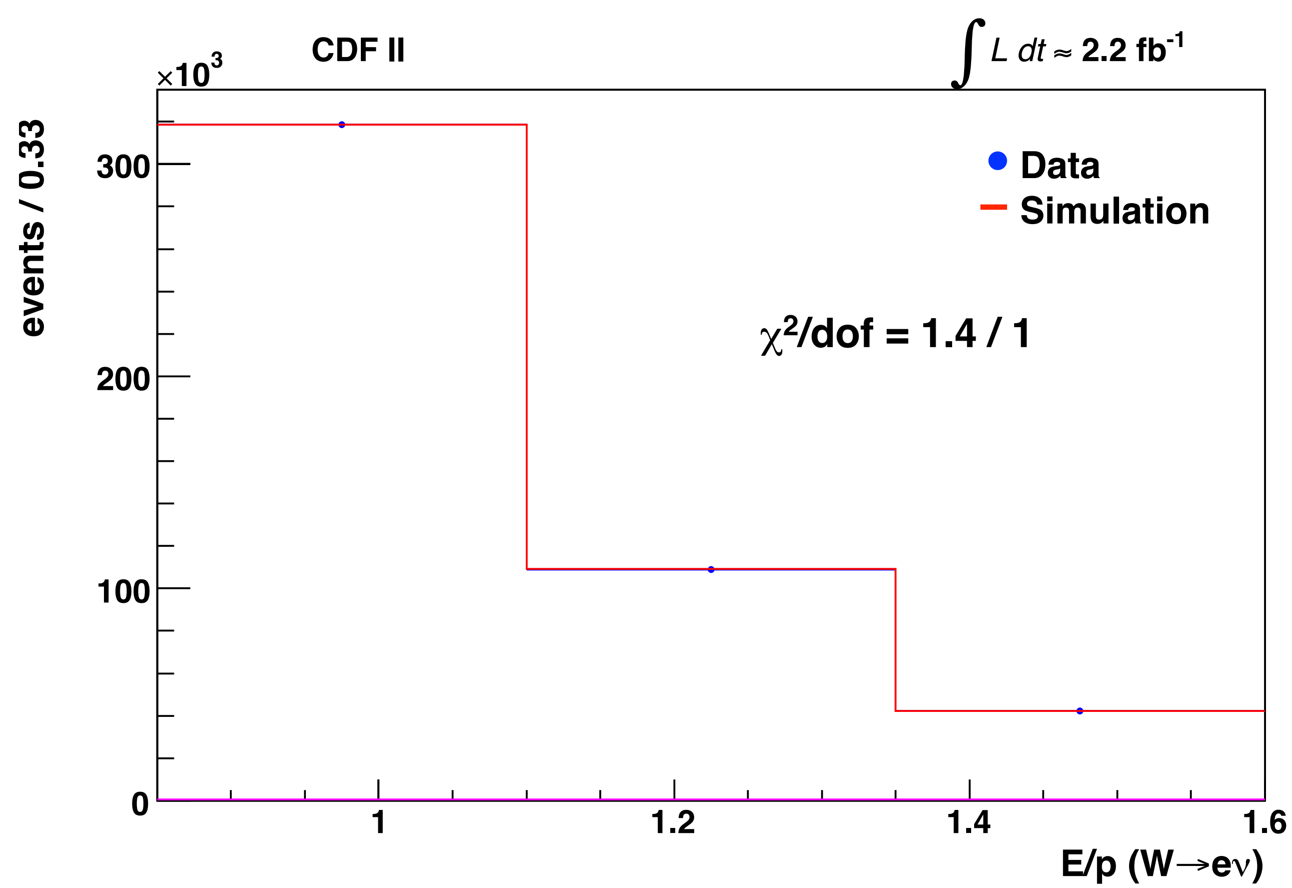
- EM energy loss studied using detailed GEANT4-based simulation
  - Leakage into hadronic calorimeter
  - Absorption into coil
  - Dependence on incident angle and E_T
- Improved model of Landau-Pomeranchuk-Migdal (LPM) suppression of bremsstrahlung
  - Sophisticated material map for tracker region of detector



Energy scale calibration

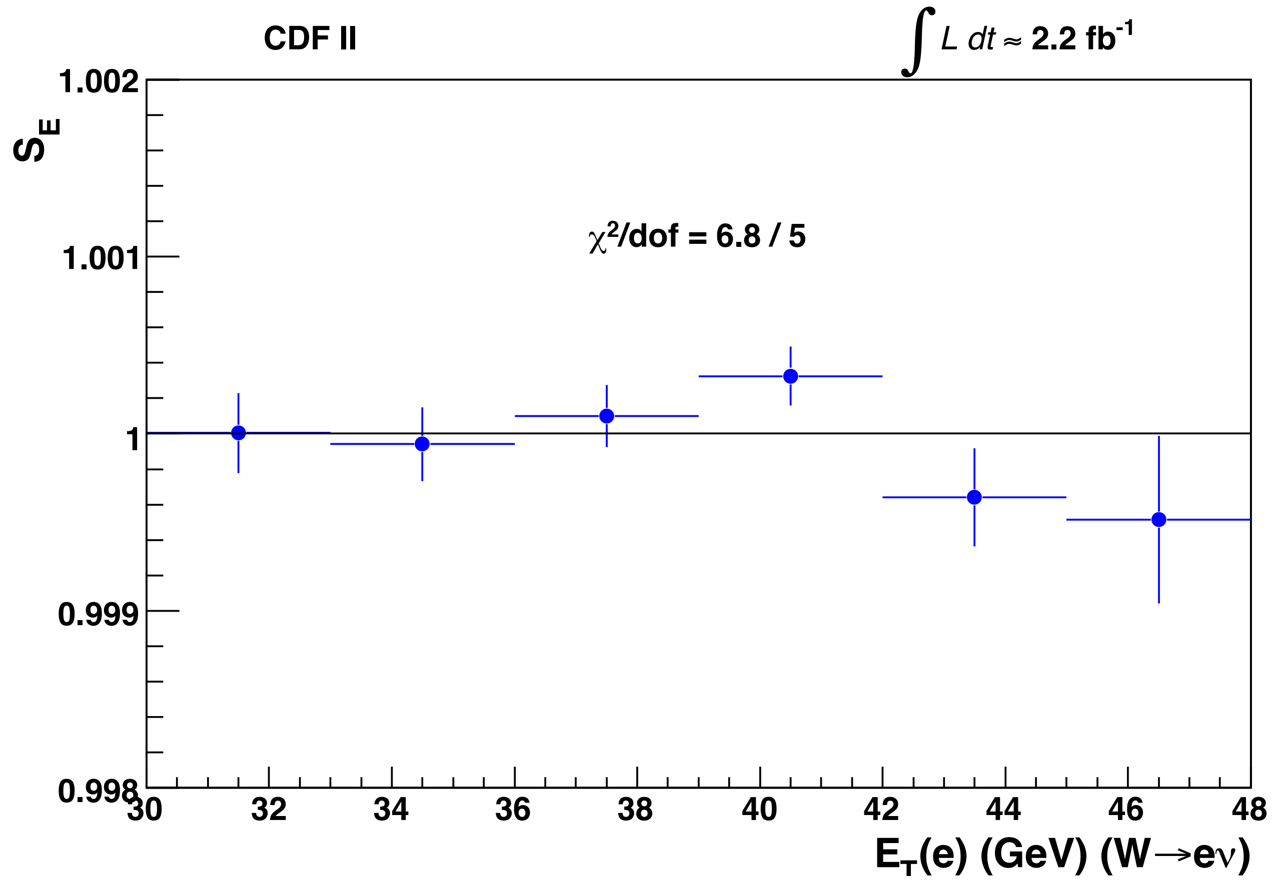
- Calibrate EM calorimeter response using *W* and *Z E/p* distributions
  - Fit to peak to obtain scale (central value of 1 by construction)
    - $\Delta S_E = (9_{stat} \pm 5_{non\text{-}linearity} \pm 5_{mat} \pm 9_{p\text{-}scale}) \times 10^{-5}$
  - Fit to tail to tune amount of radiative material
    - Apply scale factor to material model $S_{X0} = 1.026 \pm 0.003_{stat} \pm 0.002_{bkg}$
- Systematic uncertainty $\Delta M_W = 13$ MeV

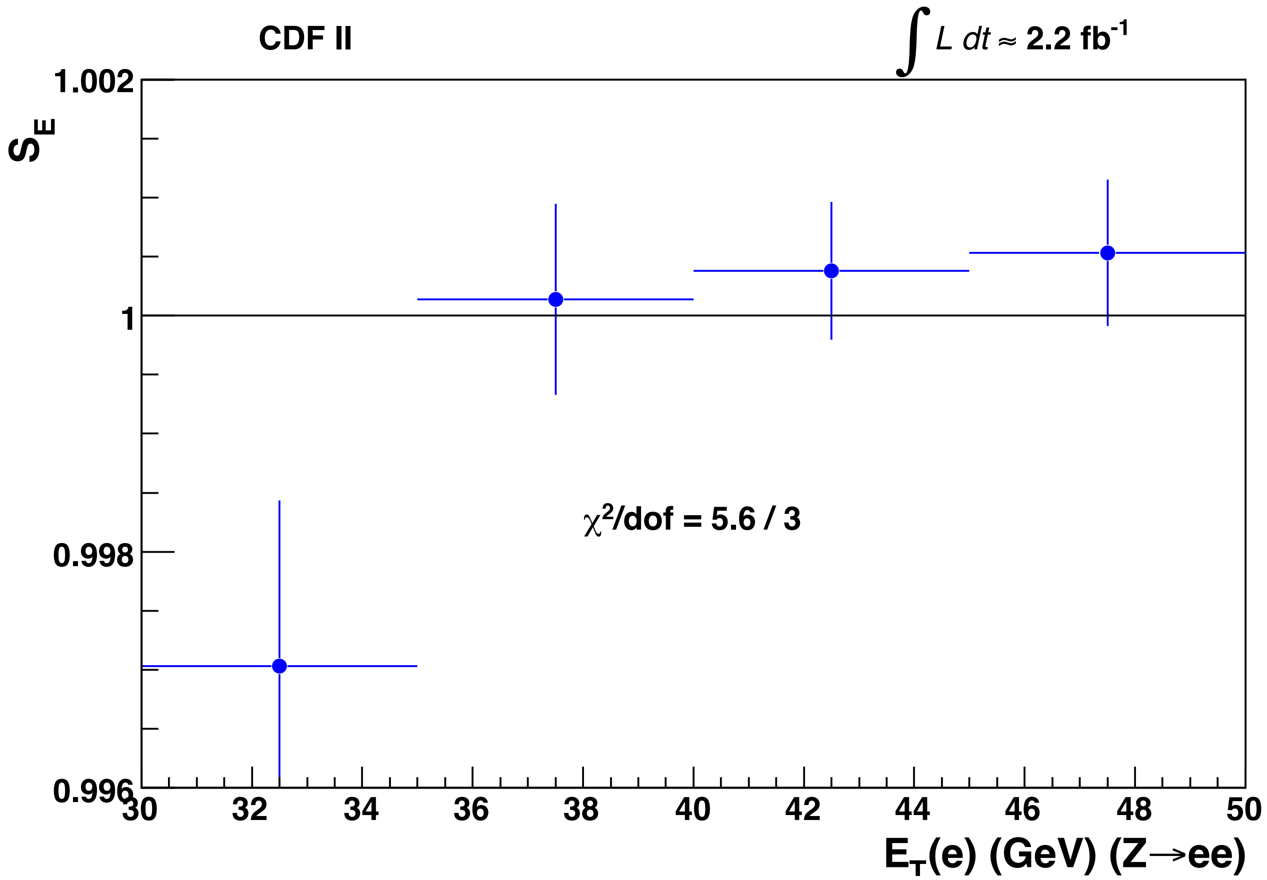




EM scale non-linearity

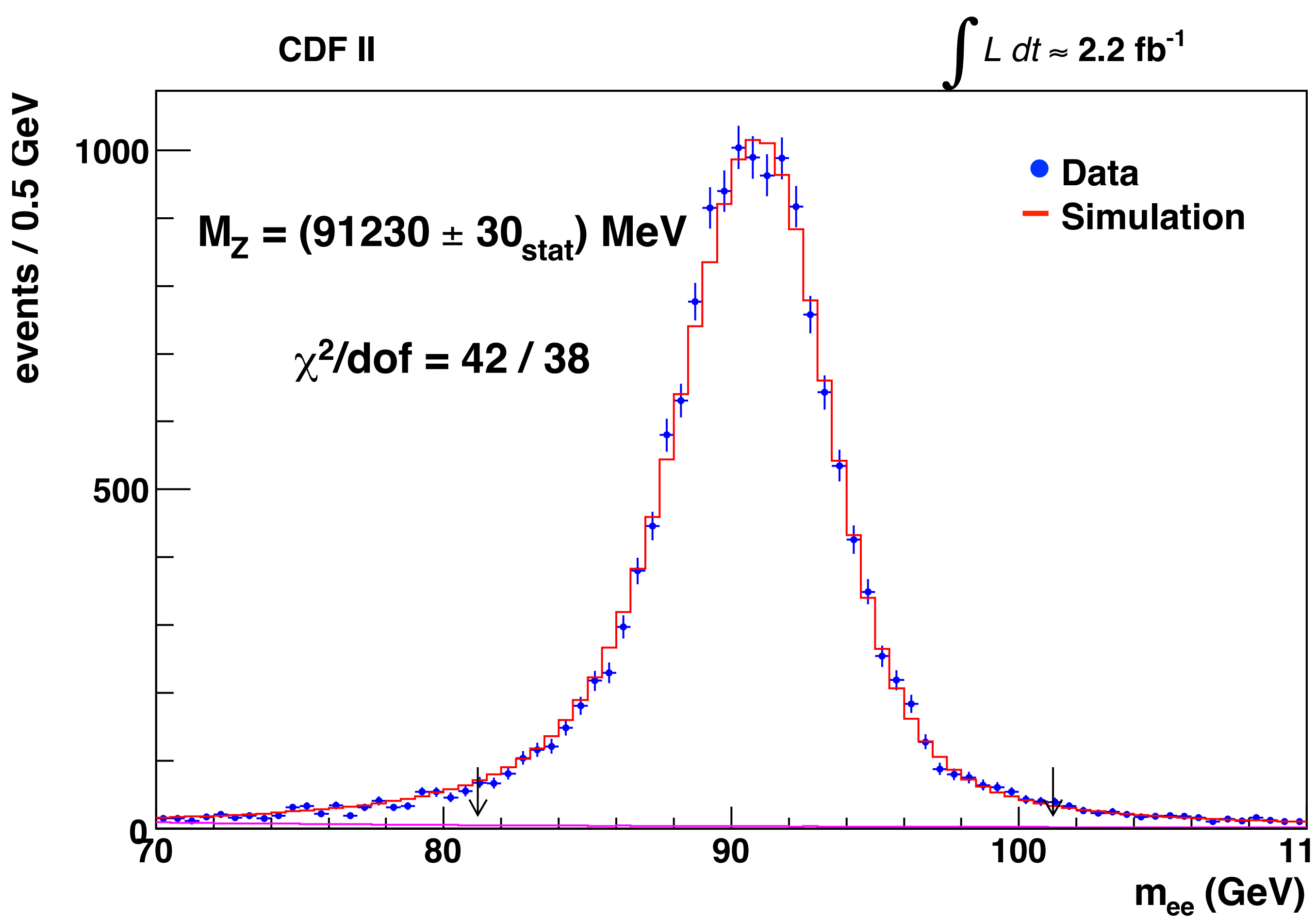
- Fit E/p in bins of electron E_T
  - Parameterize non-linearity as $S_E = 1 + \beta \log(E_T/39 \text{ GeV})$
- Tune using W and Z data and obtain $\beta = (5.2 \pm 0.7_{stat}) \times 10^{-3}$
  - ΔM_W = 4 MeV
- Obtain flat response in E_T after tuning





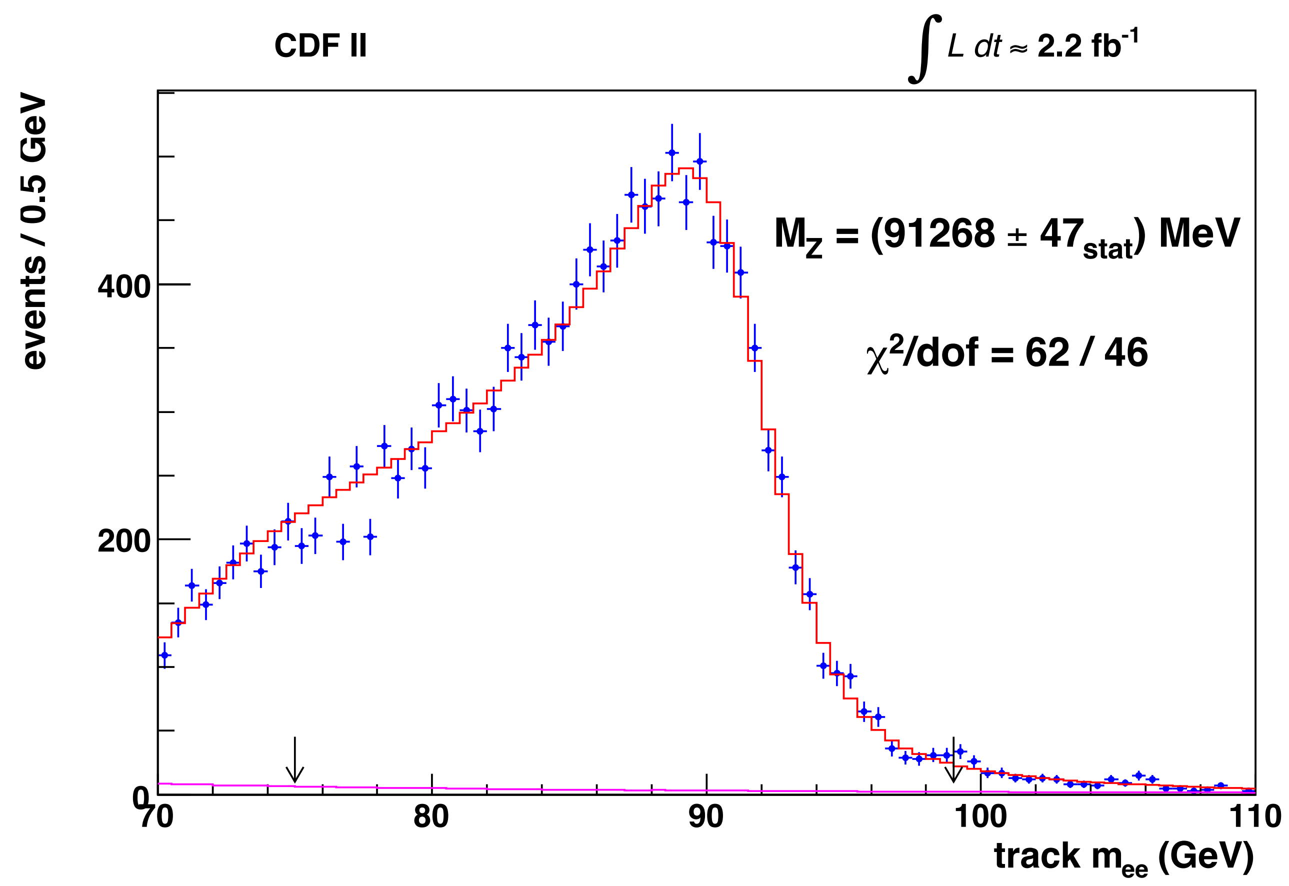
Electron Z mass and final EM energy scale

- Perform **independent** measurement of Z mass using calibrated EM scale
  - $M_Z = 91230 \pm 30_{stat} \pm 10_{E/p} \pm 8_{p\text{-}scale} \pm 5_{QED} \pm 2_{alignment} = 91230 \pm 33$ MeV
  - Excellent agreement with world average $M_Z = 91188 \pm 2$ MeV
- Combine E/p calibration with M_Z to obtain final EM calibration
  - Systematic uncertainty $\Delta M_W = 10$ MeV



Z mass with electron tracks

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



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 $\kappa = (0.58 \pm 0.05)\%$
  - Apply secondary constant term for radiative electrons (E/p > 1.1)
    - $\kappa_\gamma = (7.4 \pm 1.8)\%$
- Resolution terms total $\Delta M_W = 4$ MeV

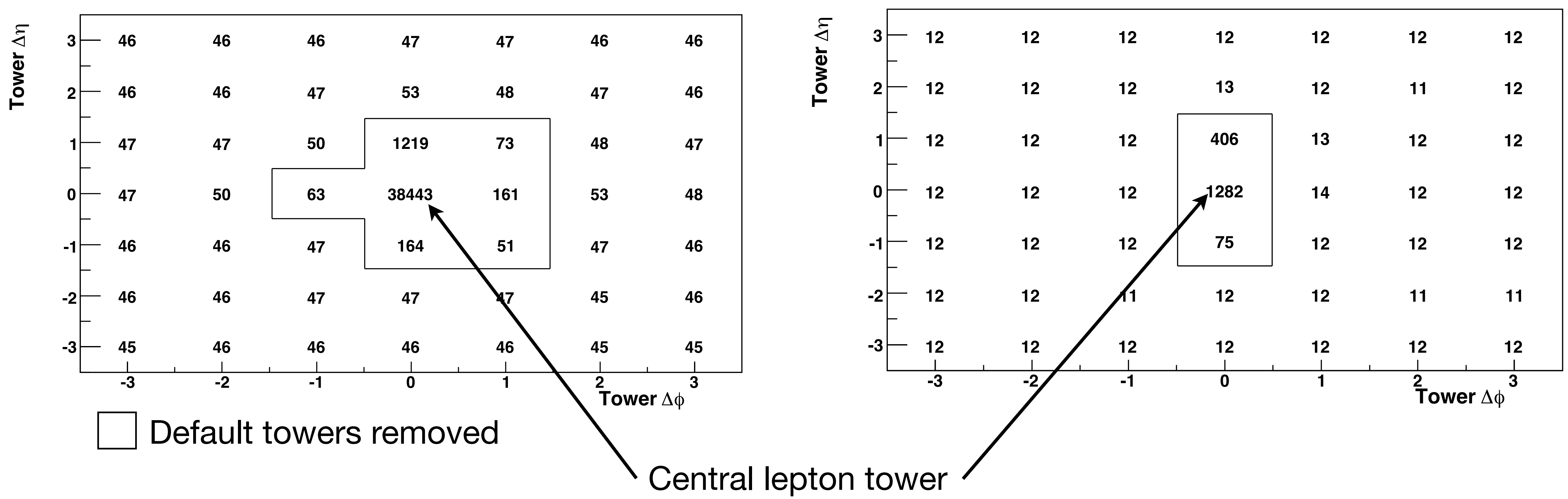
Hadronic recoil

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 (MeV)

Muon channel W data:
Mean hadronic calorimeter deposition (MeV)



Recoil model

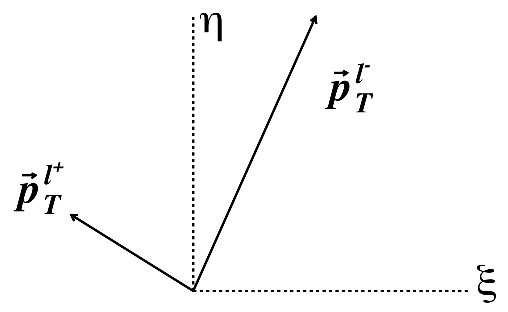
- Parametrize recoil model and tune using data

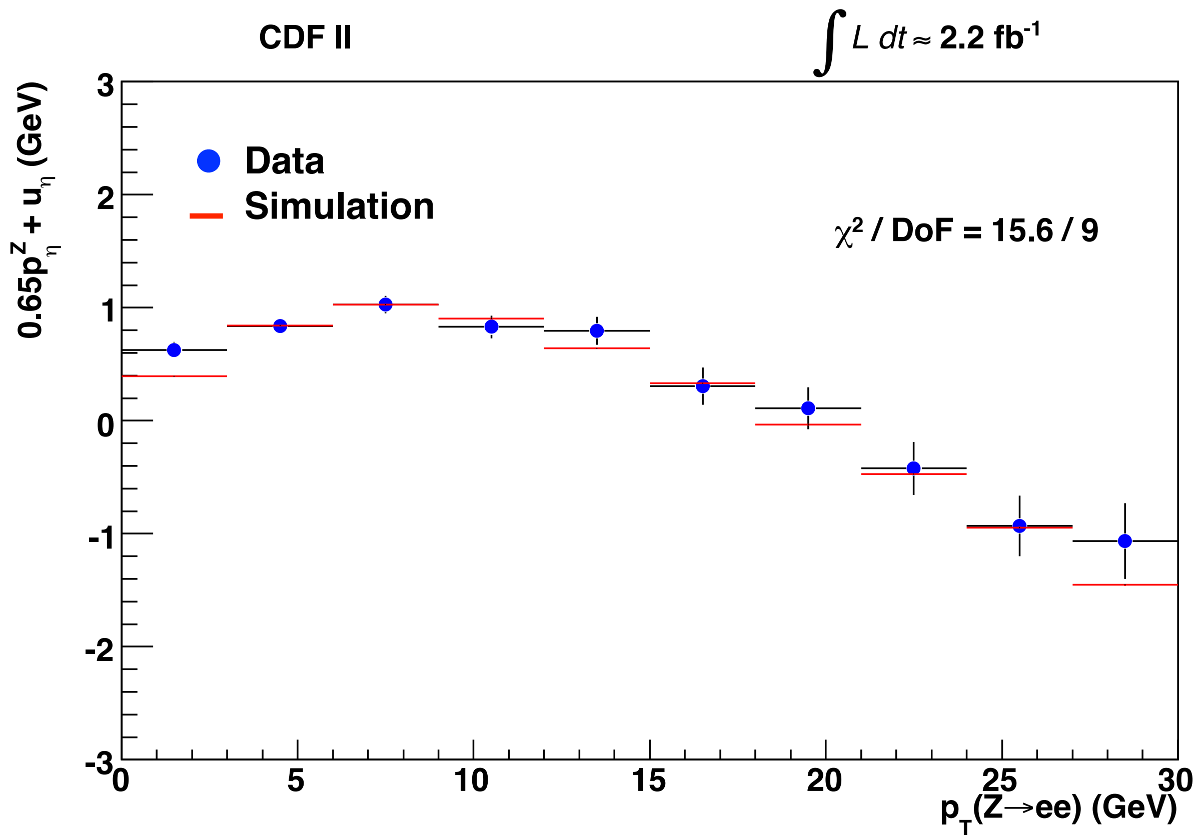
- Two components
  1. Soft “spectator interaction” component
     - Randomly oriented (~2 additional interactions per event)
     - Model using minimum-bias data

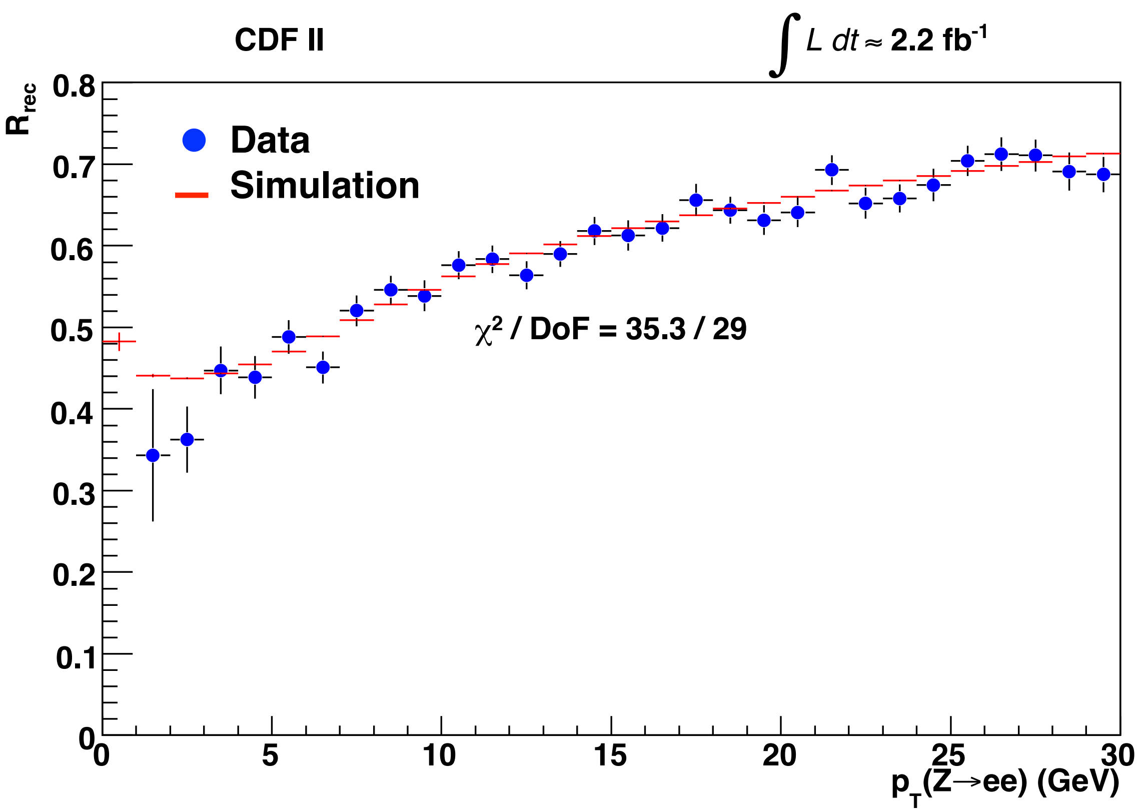
  2. Hard “jet” component
     - Boson p_T dependent response and resolution
     - Tune by balancing boson p_T and recoil

Calibrating recoil response

- Recoil scale $R = u_{meas}/u_{true}$
  - Calibrate by balancing Z p_T against $p_T + u$ along eta axis $\Delta M_W = 4$ MeV

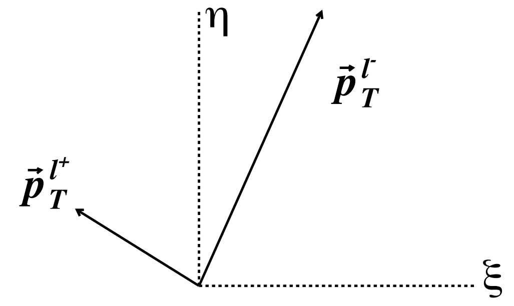


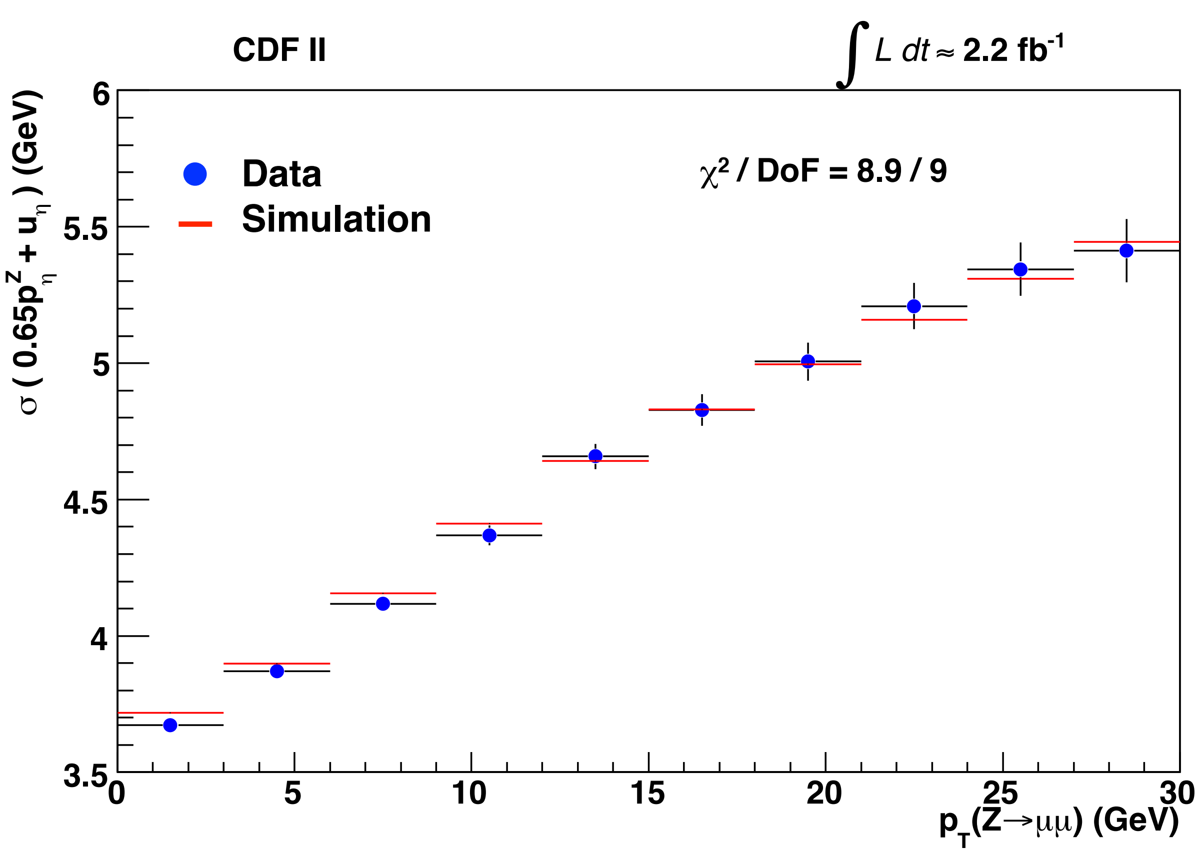


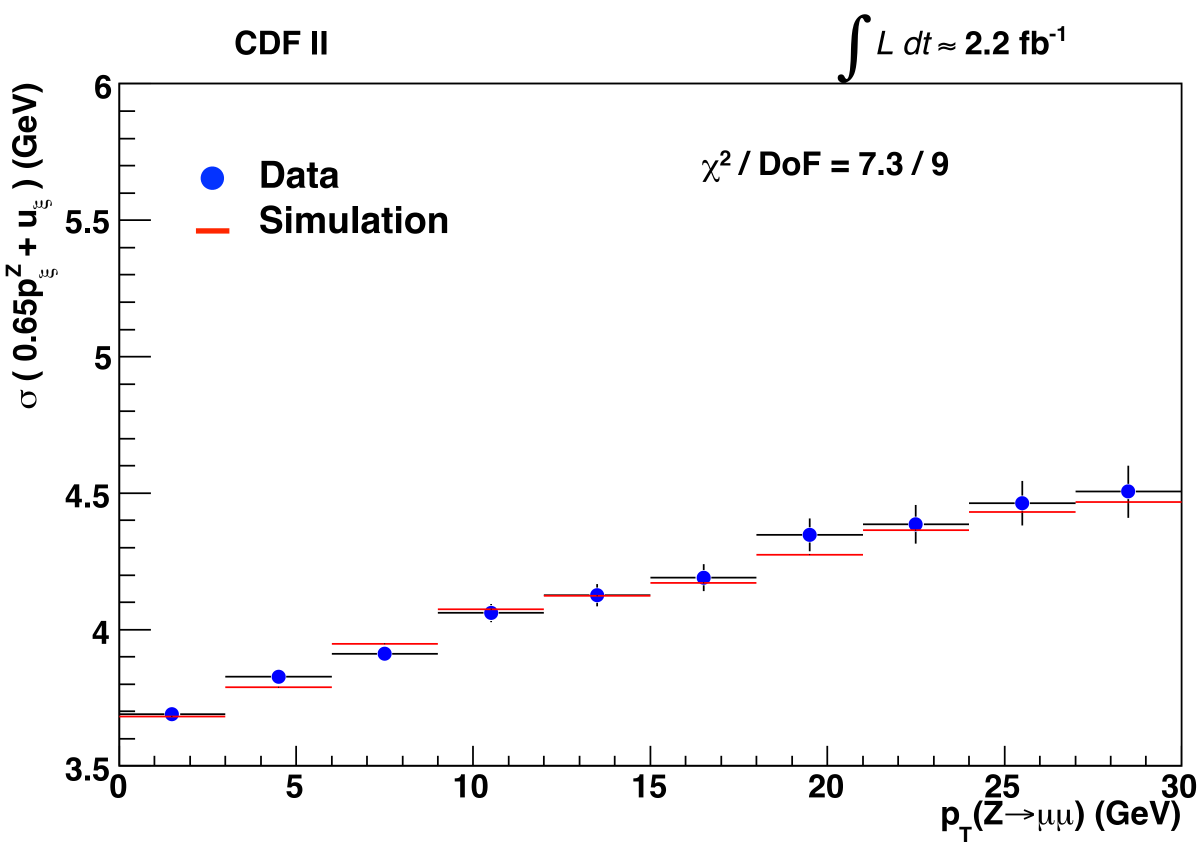


Calibrating recoil resolution

- Recoil resolution
  - Calibrate balancing Z p_T against rms(p_T+u) along both axes ΔM_W = 4 MeV

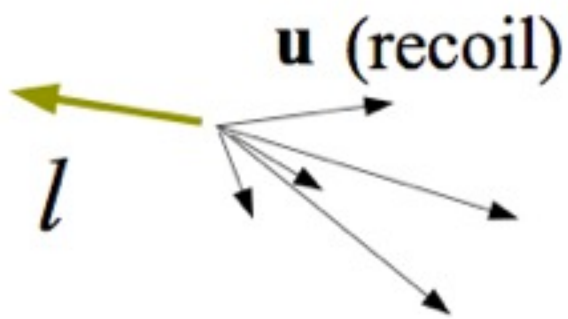


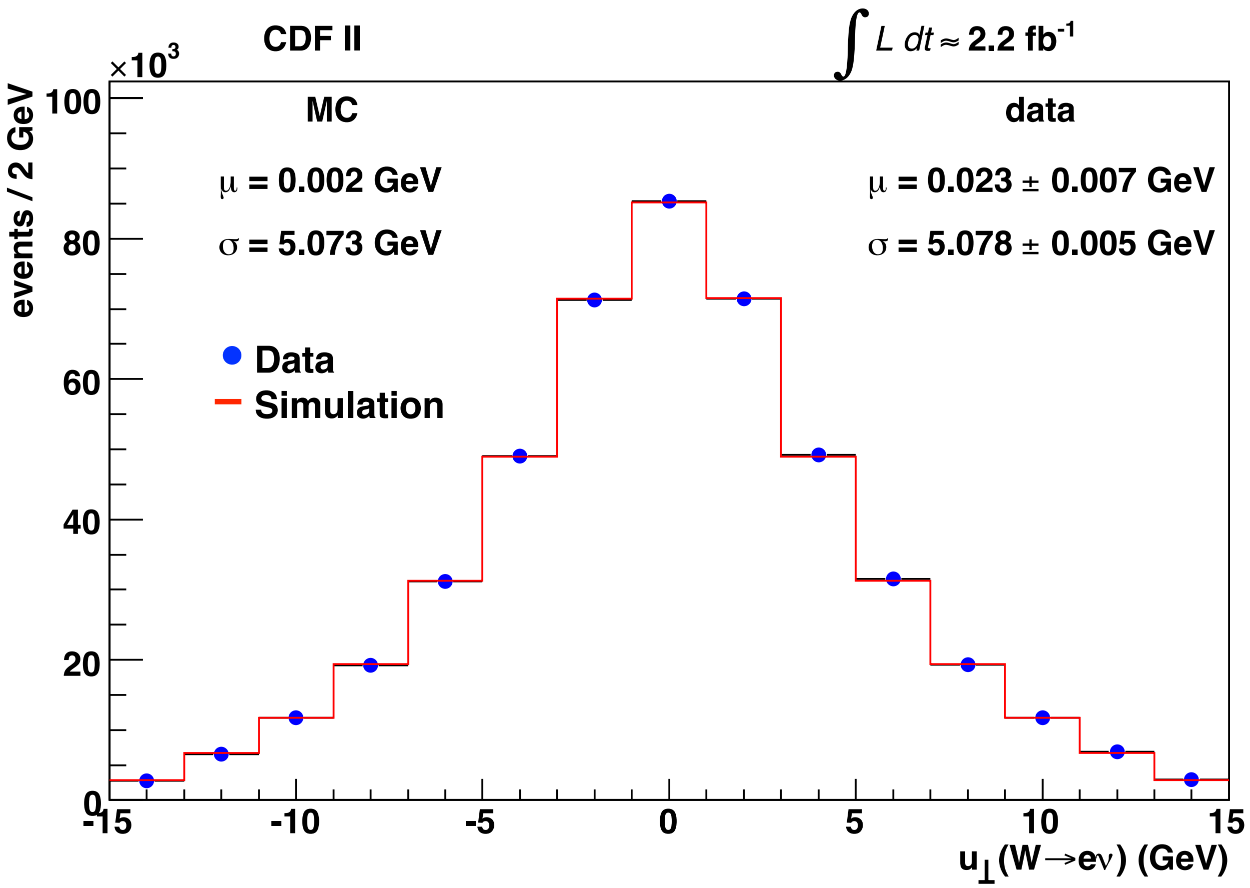




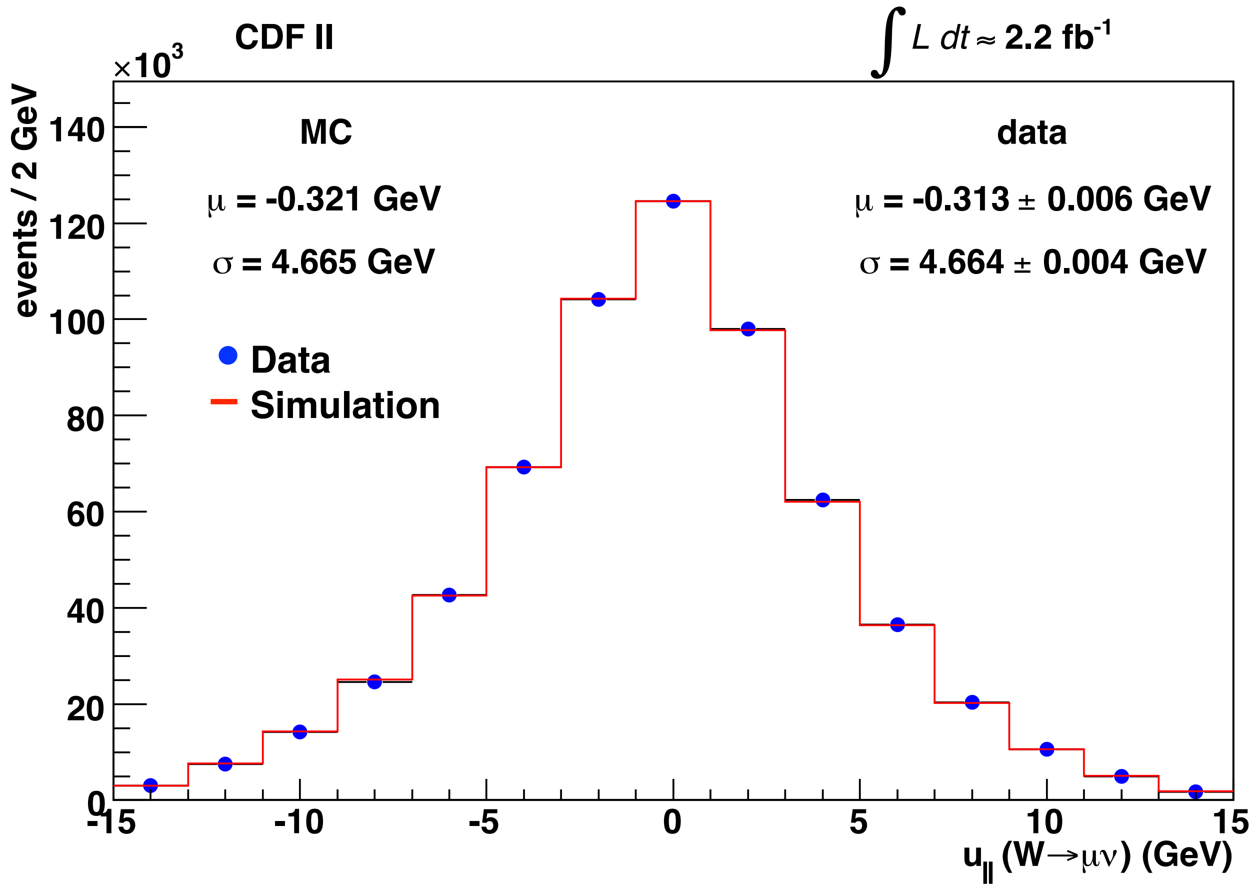
Recoil validation

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





Recoil projection perpendicular to lepton (electrons)



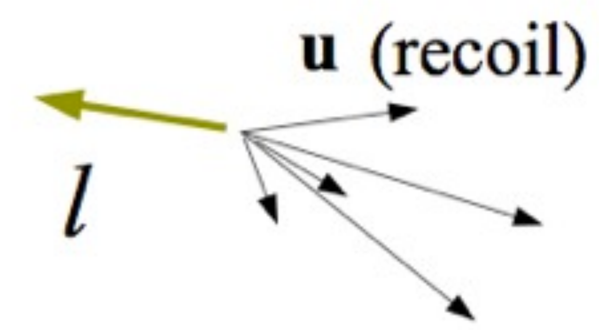
Recoil projection in direction of lepton (muons)

for $u \ll p_T^l$:

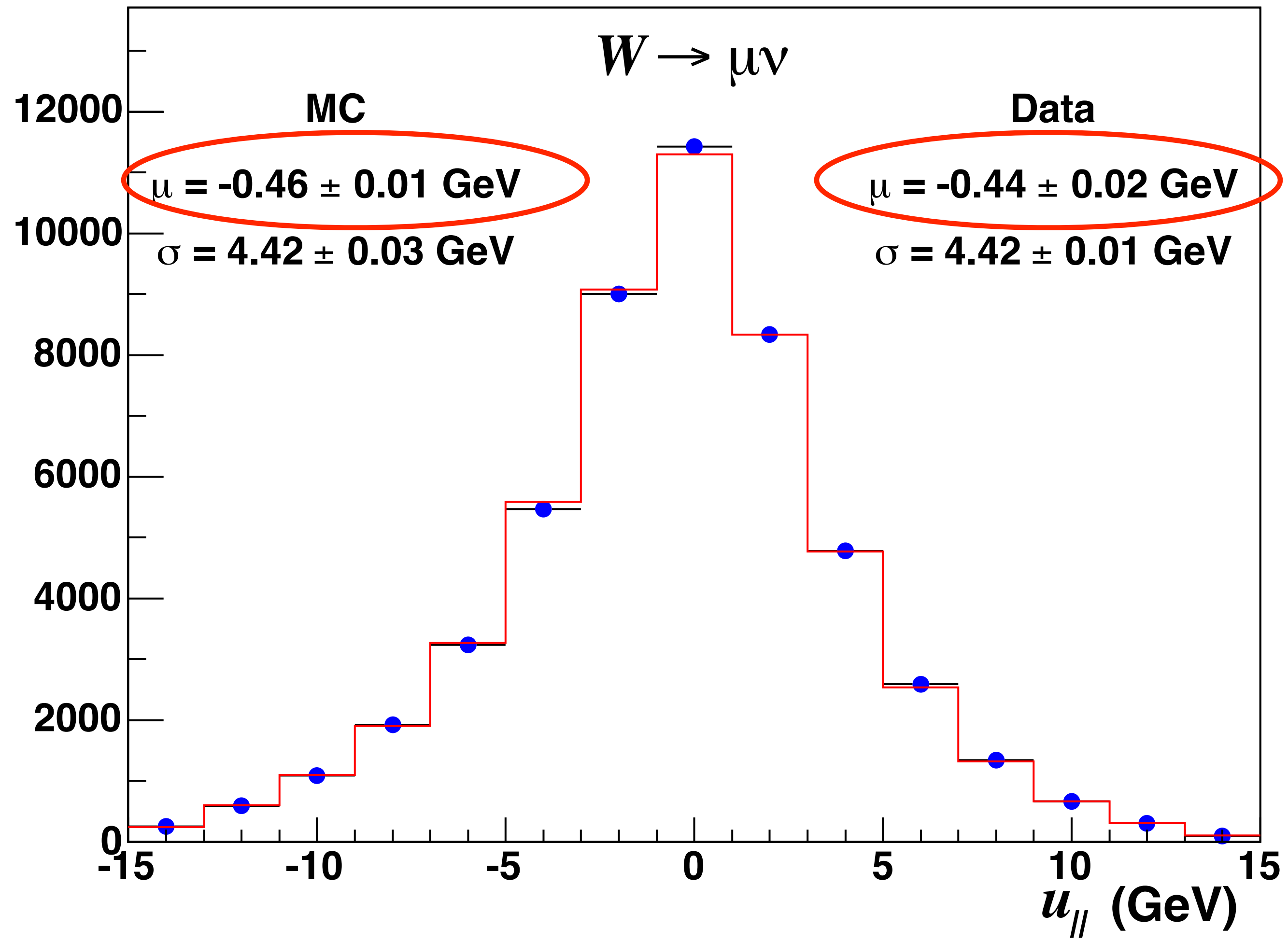
$m_T \approx 2p_T^l + u_{||}$, $p_T^\nu \approx 2p_T^l + 2u_{||}$

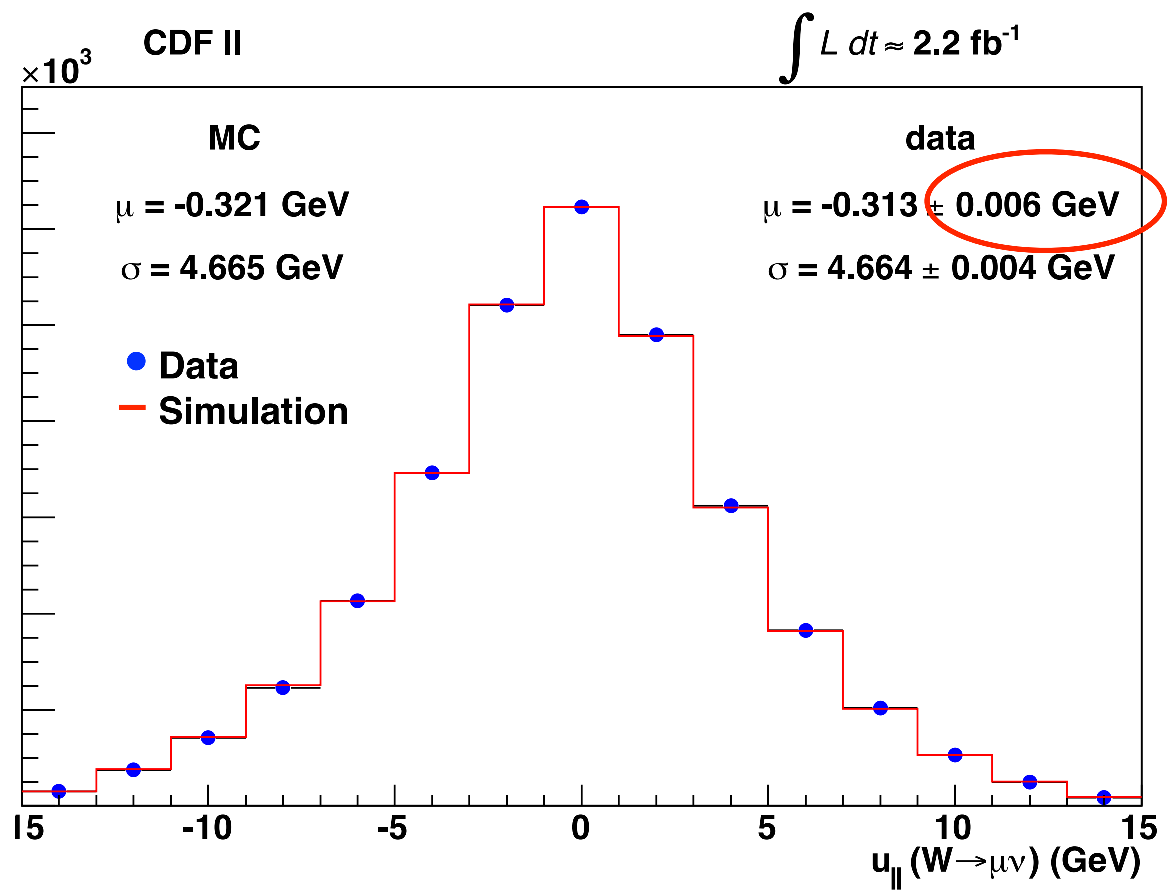
Recoil validation

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



*200 pb^{-1} [PRD**77**:112001,2008]*





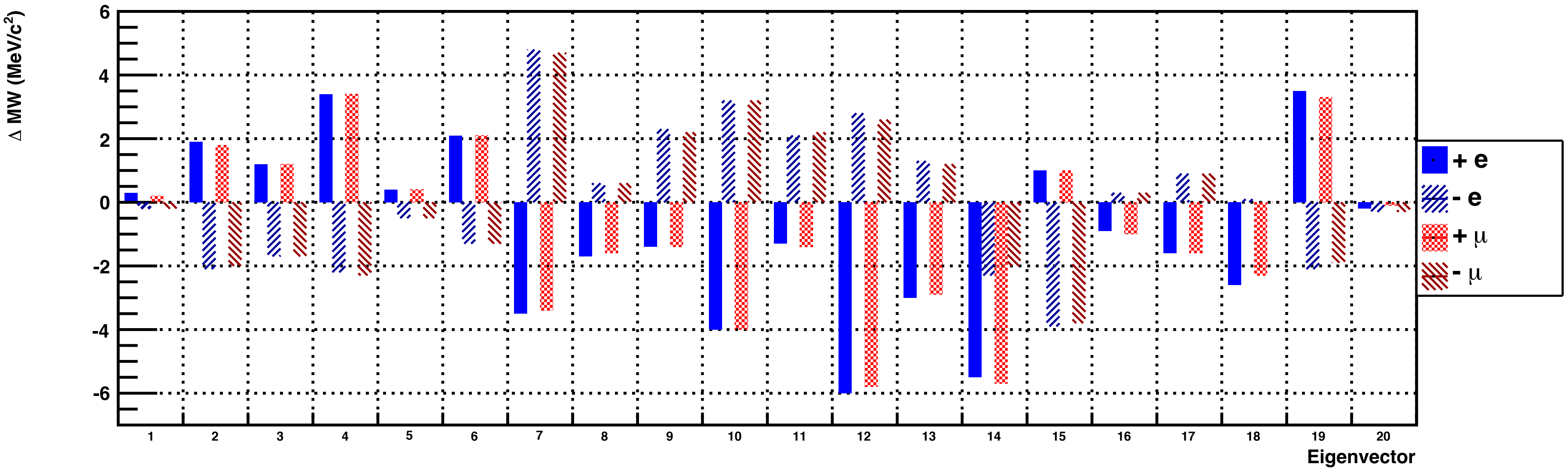
Recoil projection in direction of lepton (muons)

for $u \ll p_T^l$:

$m_T \approx 2p_T^l + u_{||}$, $p_T^\nu \approx 2p_T^l + 2u_{||}$

Parton distribution functions

- 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

- Electroweak backgrounds ($Z \to ll$, $W \to \tau\nu$)
  - Model using standard CDF detector simulated MC
  - Tune recoil model and lepton response
- QCD backgrounds (hadronic jets, meson decay-in-flight)
  - Model using control regions in data
- 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**	
$Z \to ll$	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

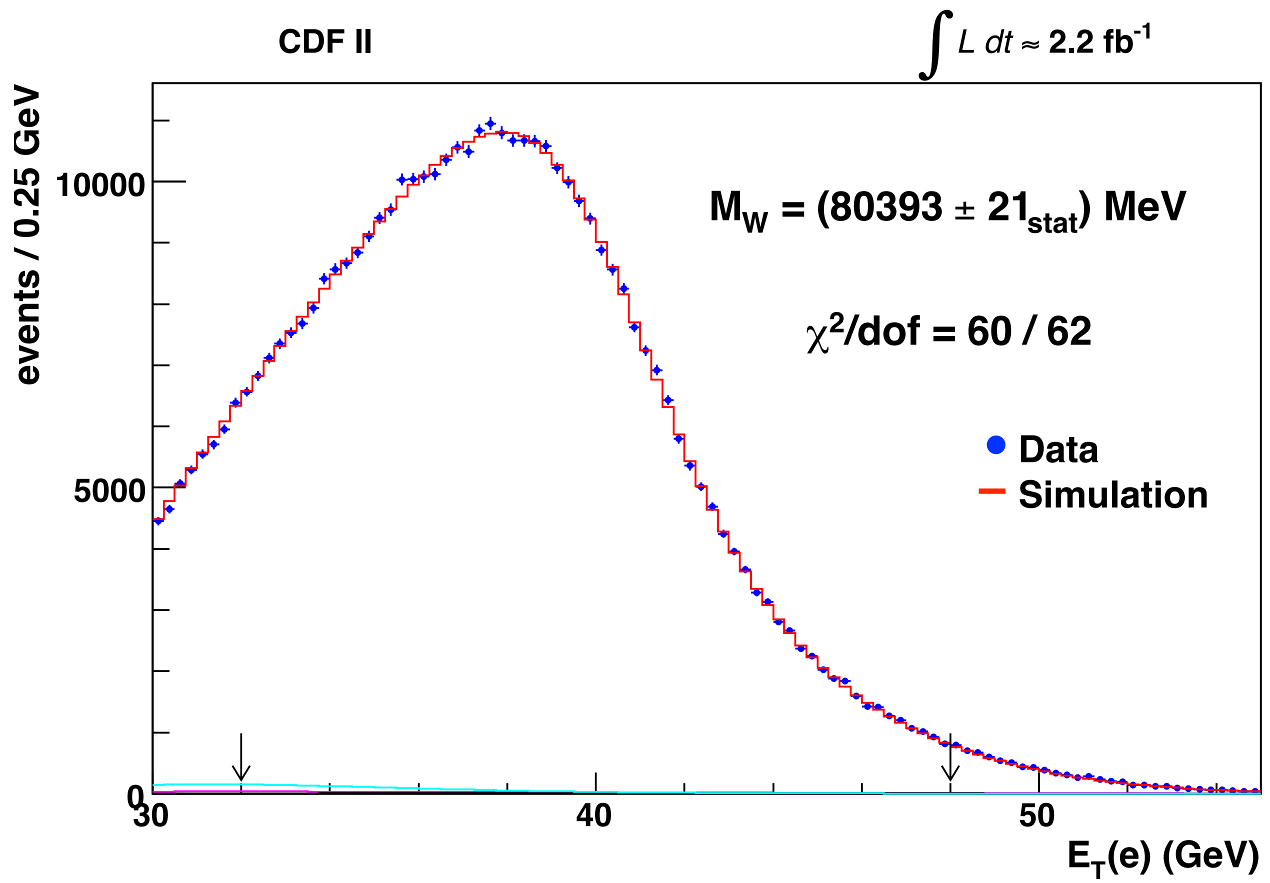
electrons

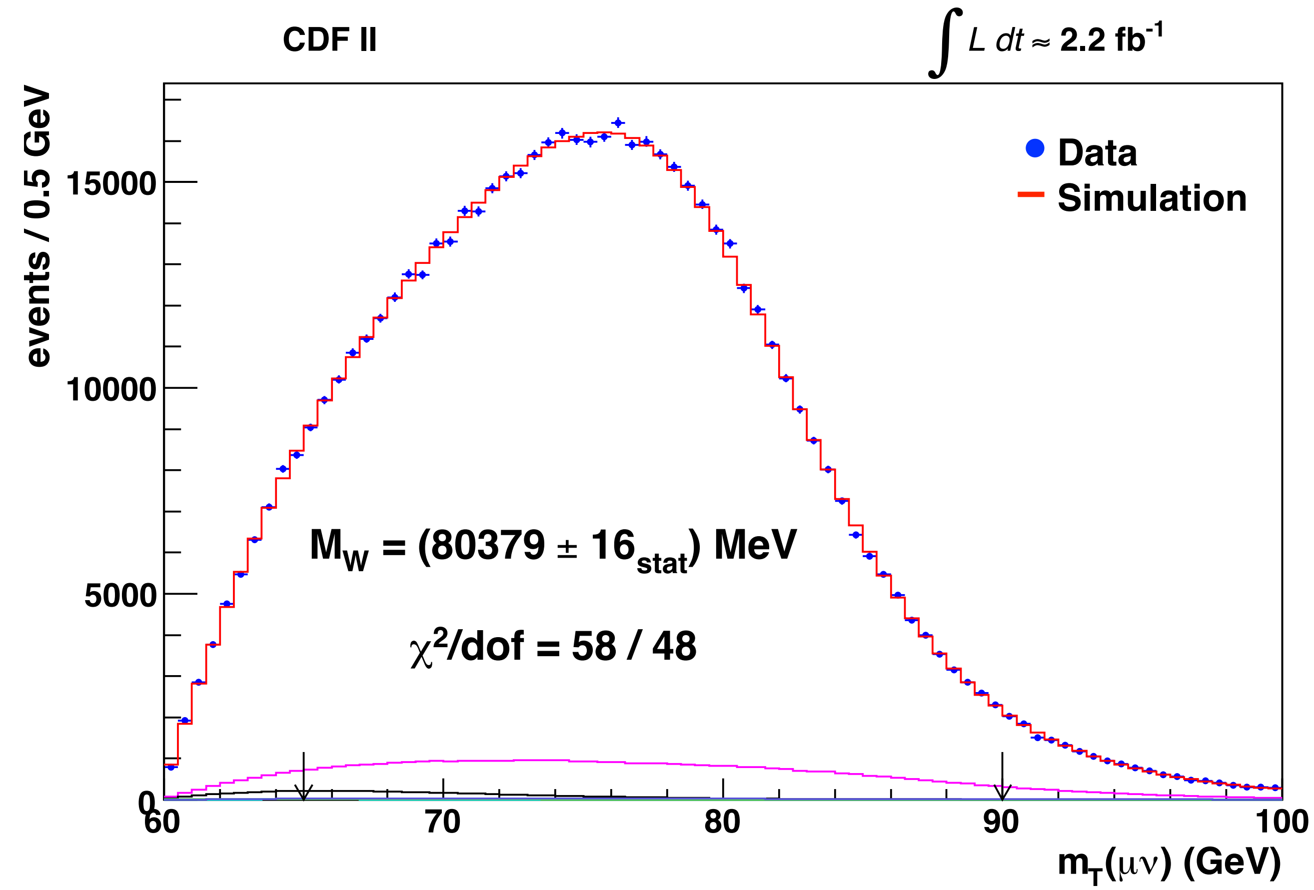
Results

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



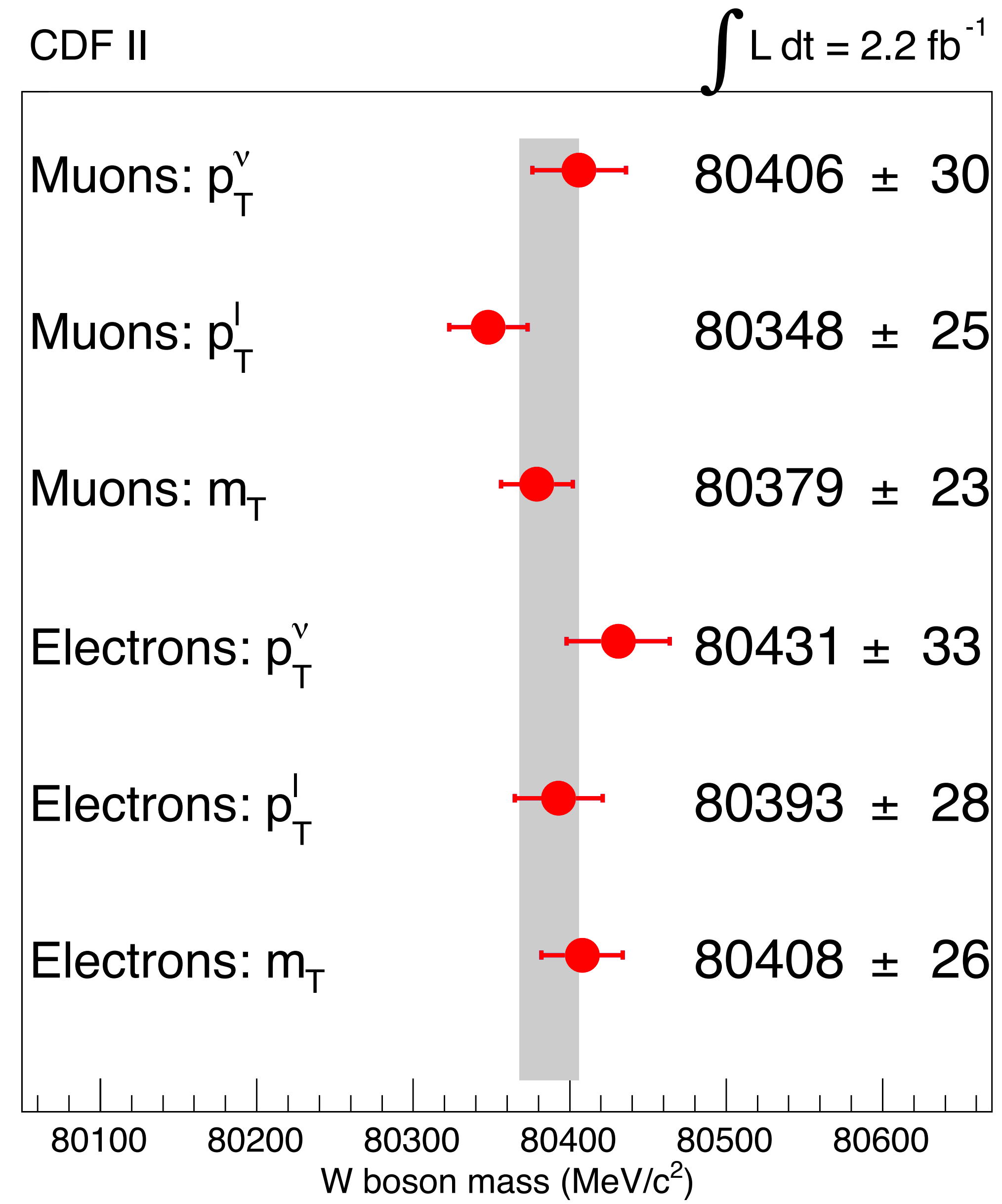


p_T^l: electrons

m_T: muons

All fits

Fit	Fit result (MeV)	χ^2/dof
$W \to e\nu$ (m_T)	$80408 \pm 19_{stat} \pm 18_{syst}$	52/48
$W \to e\nu$ (p_T^l)	$80393 \pm 21_{stat} \pm 19_{syst}$	60/62
$W \to e\nu$ (p_T^ν)	$80431 \pm 25_{stat} \pm 22_{syst}$	71/62
$W \to \mu\nu$ (m_T)	$80379 \pm 16_{stat} \pm 16_{syst}$	58/48
$W \to \mu\nu$ (p_T^l)	$80348 \pm 18_{stat} \pm 18_{syst}$	54/62
$W \to \mu\nu$ (p_T^ν)	$80406 \pm 22_{stat} \pm 20_{syst}$	79/62



Combined results

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

Combined results

- All electron fits combined

  M_W **= 80406 ± 25 MeV,** χ^2/dof = 1.4/2 (49%)

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

Combined results

- All electron fits combined

  $\boldsymbol{M_W}$ **= 80406 ± 25 MeV,** χ^2/dof = 1.4/2 (49%)

- All muon fits combined

  $\boldsymbol{M_W}$ **= 80374 ± 22 MeV,** χ^2/dof = 4/2 (12%)

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

Combined results

- All electron fits combined

  $\boldsymbol{M_W}$ **= 80406 ± 25 MeV,** χ^2/dof = 1.4/2 (49%)

- All muon fits combined

  $\boldsymbol{M_W}$ **= 80374 ± 22 MeV,** χ^2/dof = 4/2 (12%)

- All fits combined

  $\boldsymbol{M_W}$ **= 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

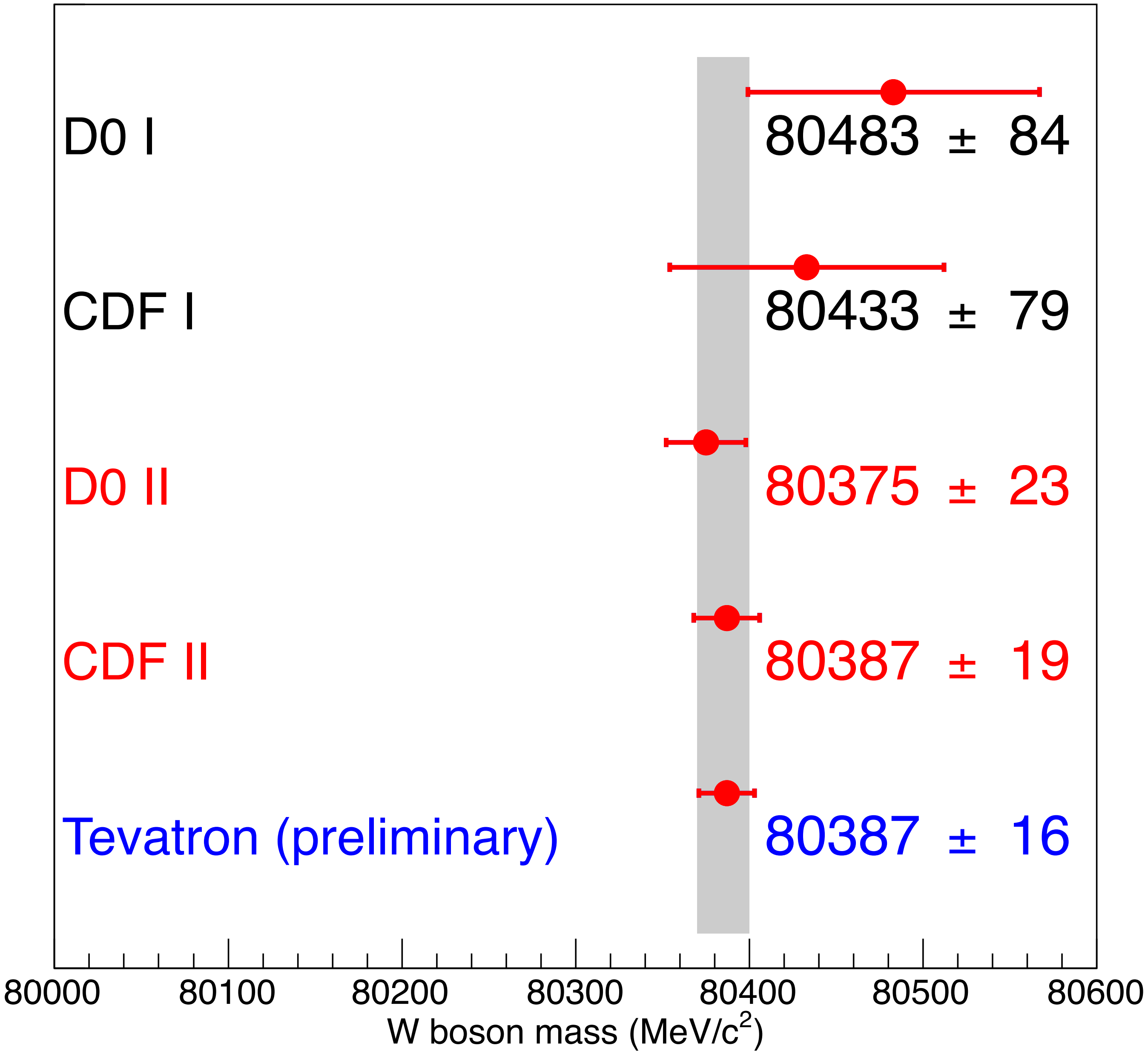
Statistics limited by control data

Theory based (external inputs)

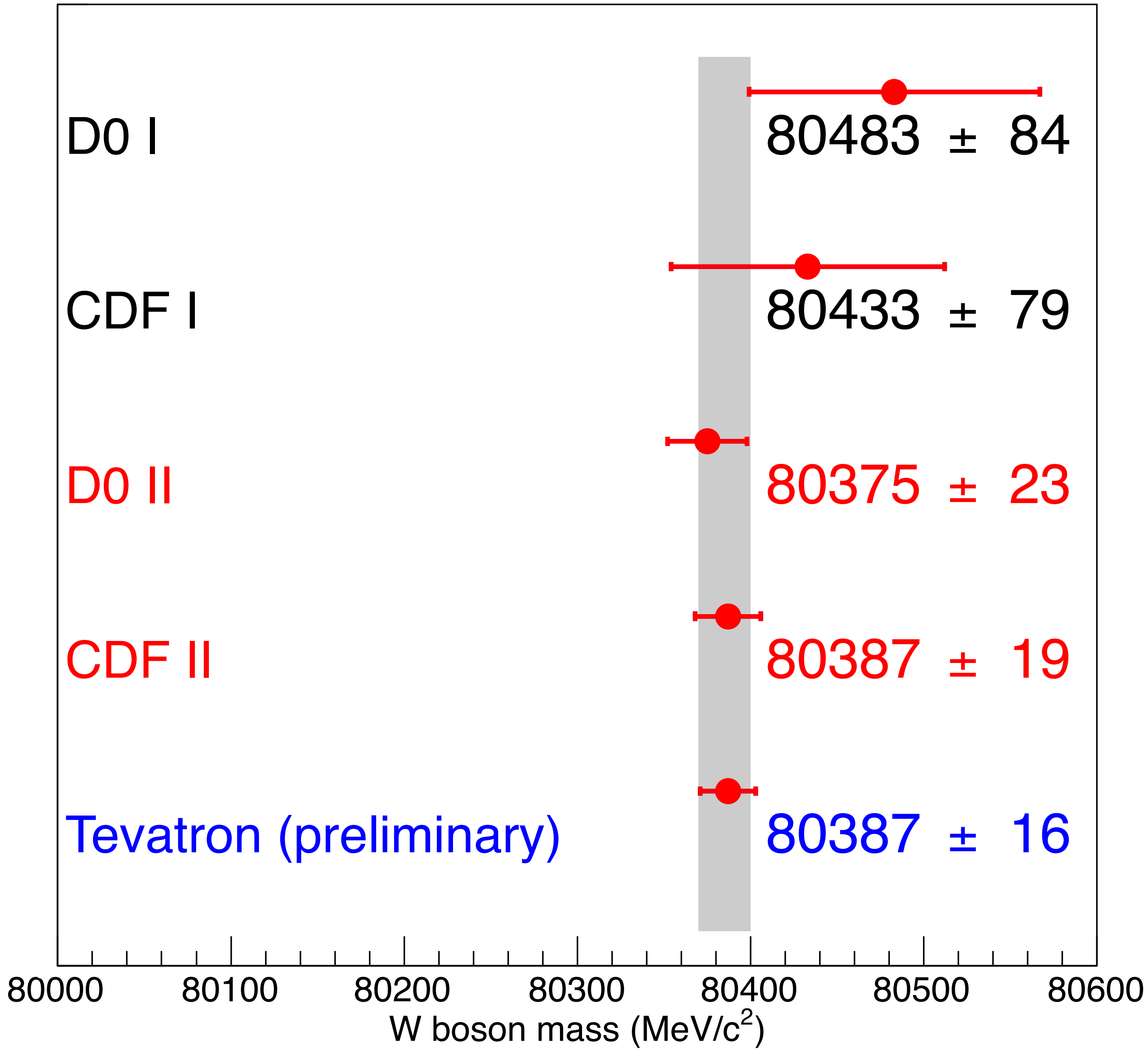
Source	Uncertainty 2.2 fb^{-1} (MeV)	Uncertainty 0.2 fb^{-1} (MeV)
Lepton energy scale	7	23
Lepton energy resolution	2	4
Recoil energy scale	4	8
Recoil energy resolution	4	10
Lepton removal	2	6
Backgrounds	3	6
p_T (W) model	5	4
PDFs	10	11
QED radiation	4	10
Total systematics	*15*	*34*
W statistics	12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

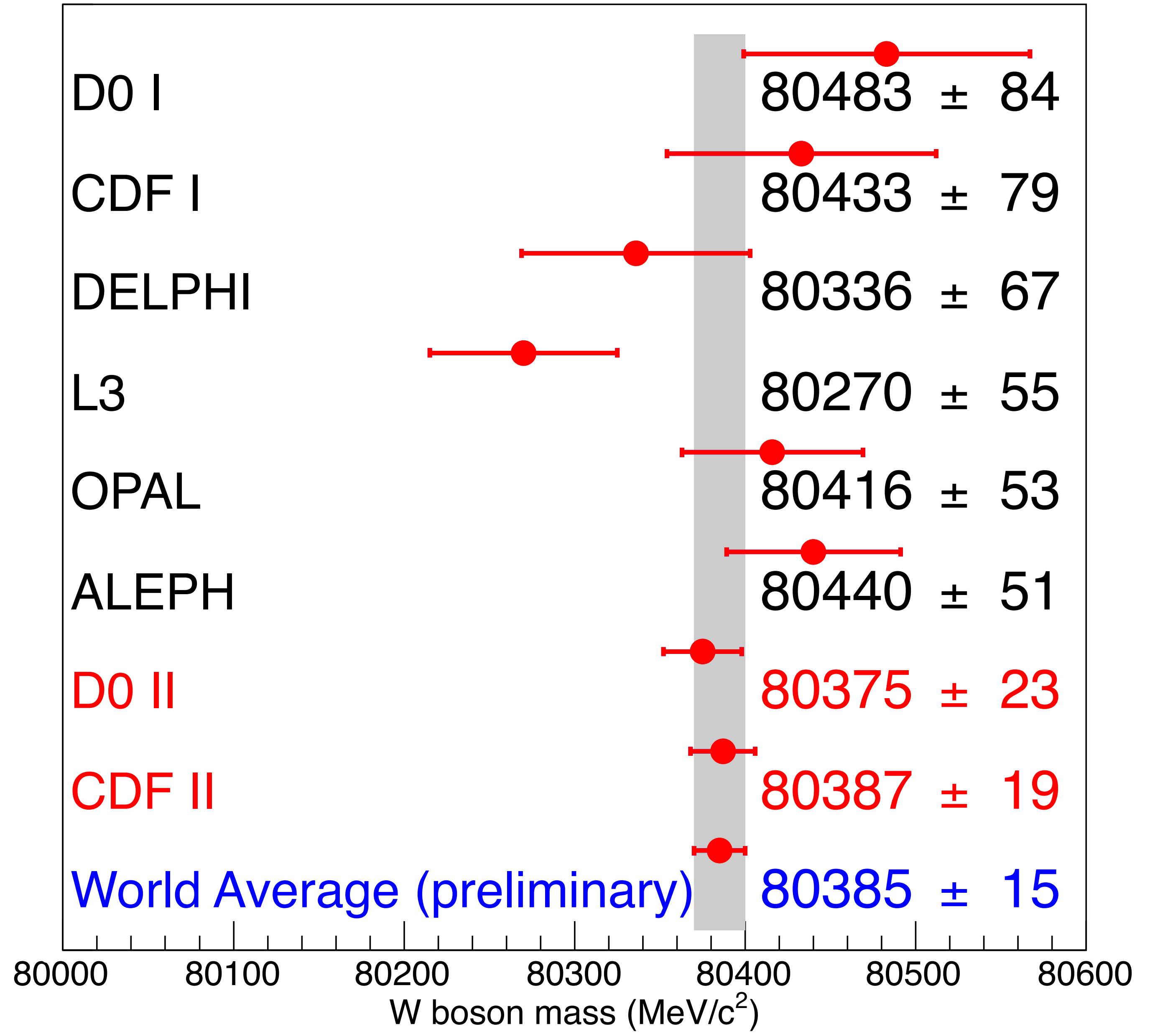
$M_W = 80387 \pm 12_{stat} \pm 15_{syst}$ MeV/c^2

Tevatron and world combinations

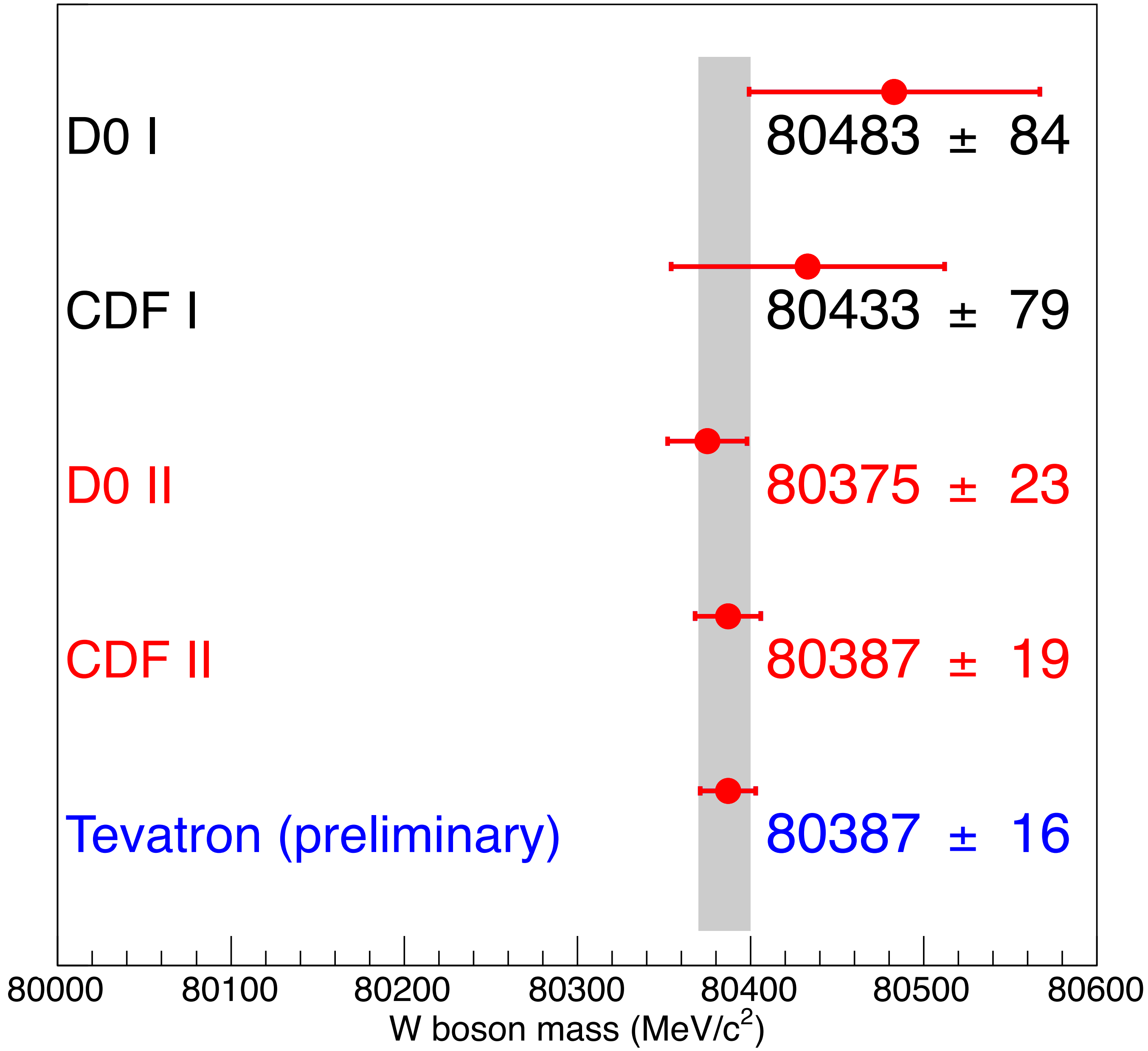


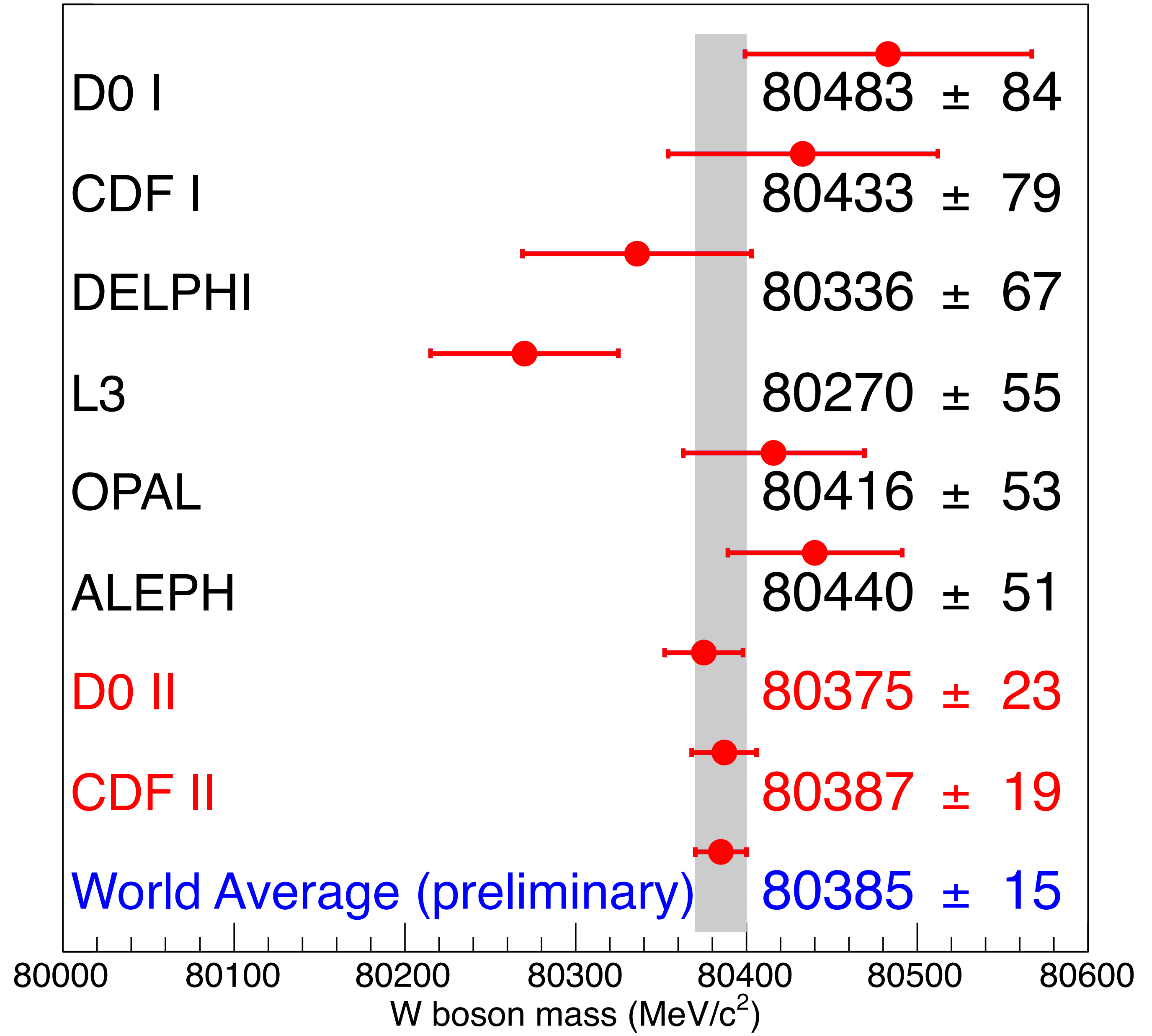
Tevatron and world combinations





Tevatron and world combinations

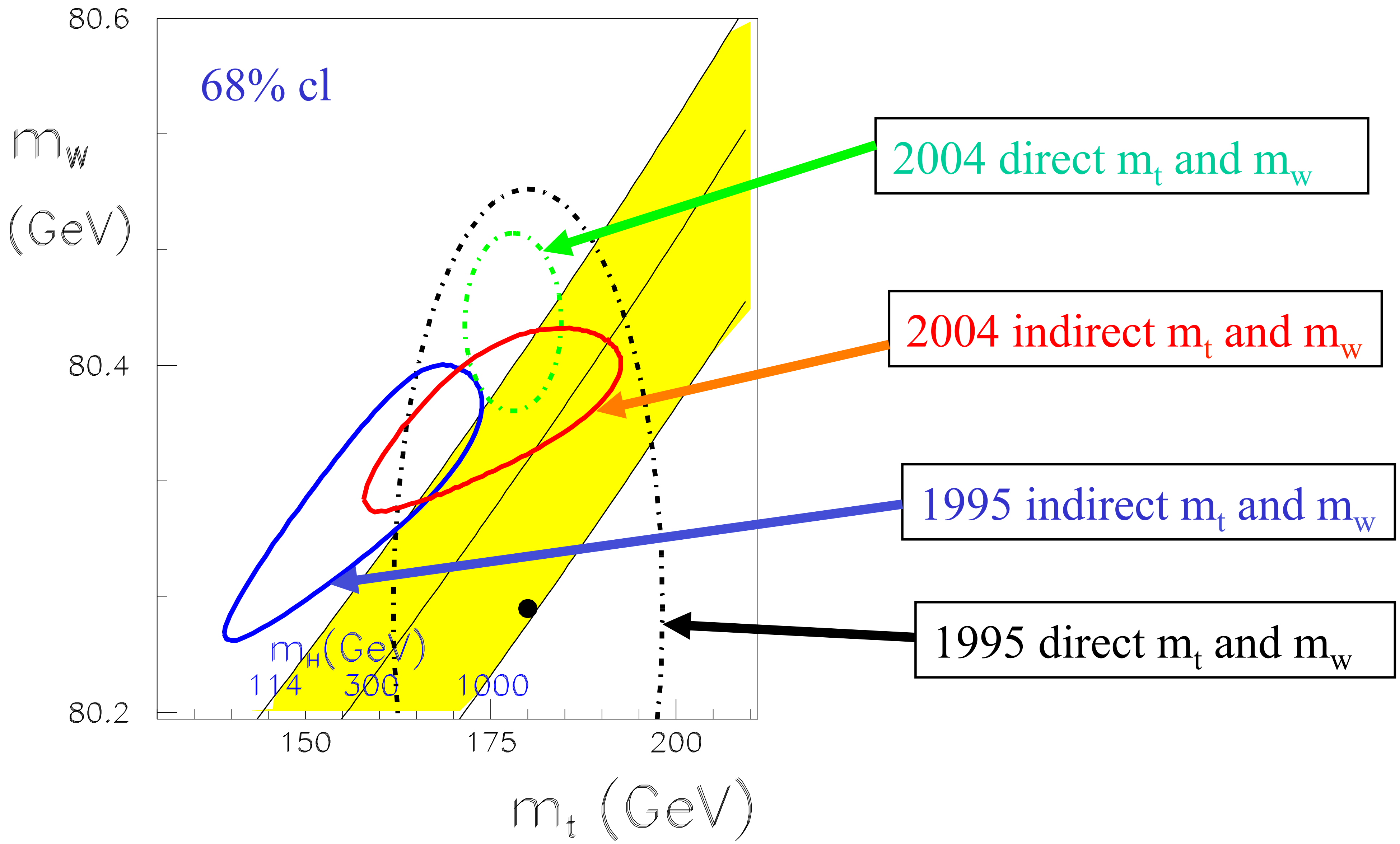




nb: 2009 world average
M_W = 80399±23 MeV

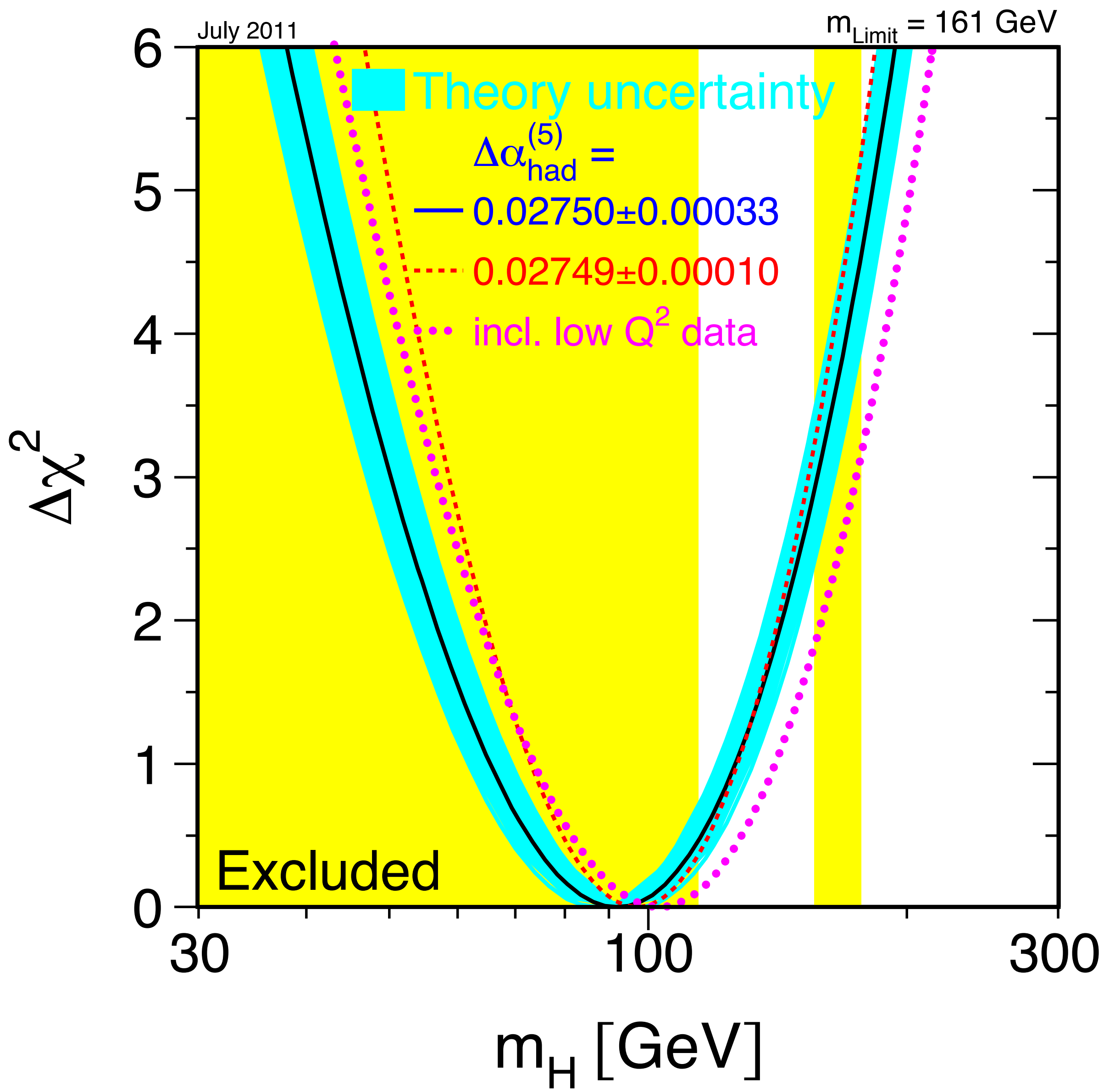
New CDF measurement significantly exceeds precision of all previous measurements of M_W combined!

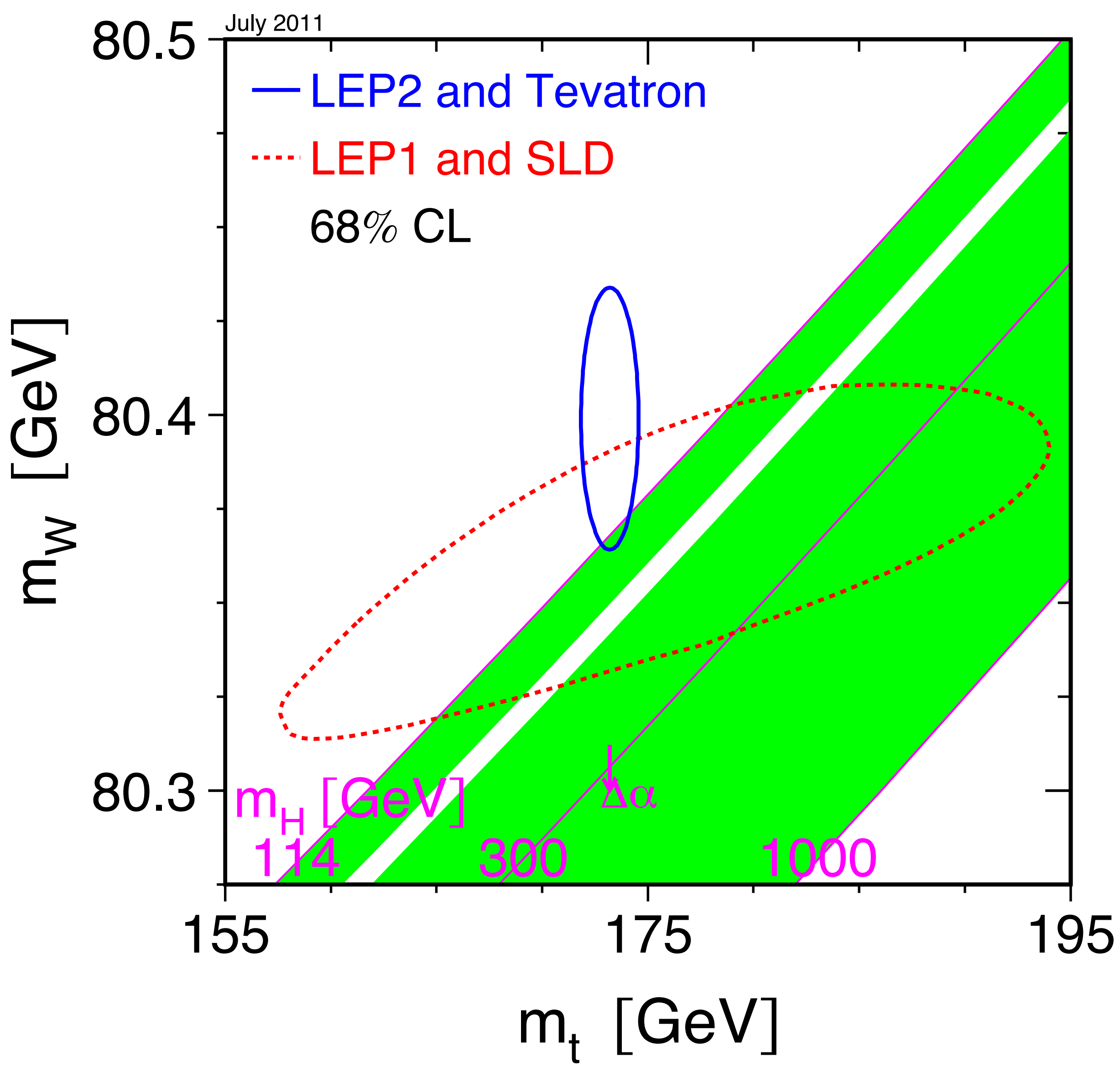
Sidetrack down memory lane



P. Renton, ICHEP 2004

Standard model fit





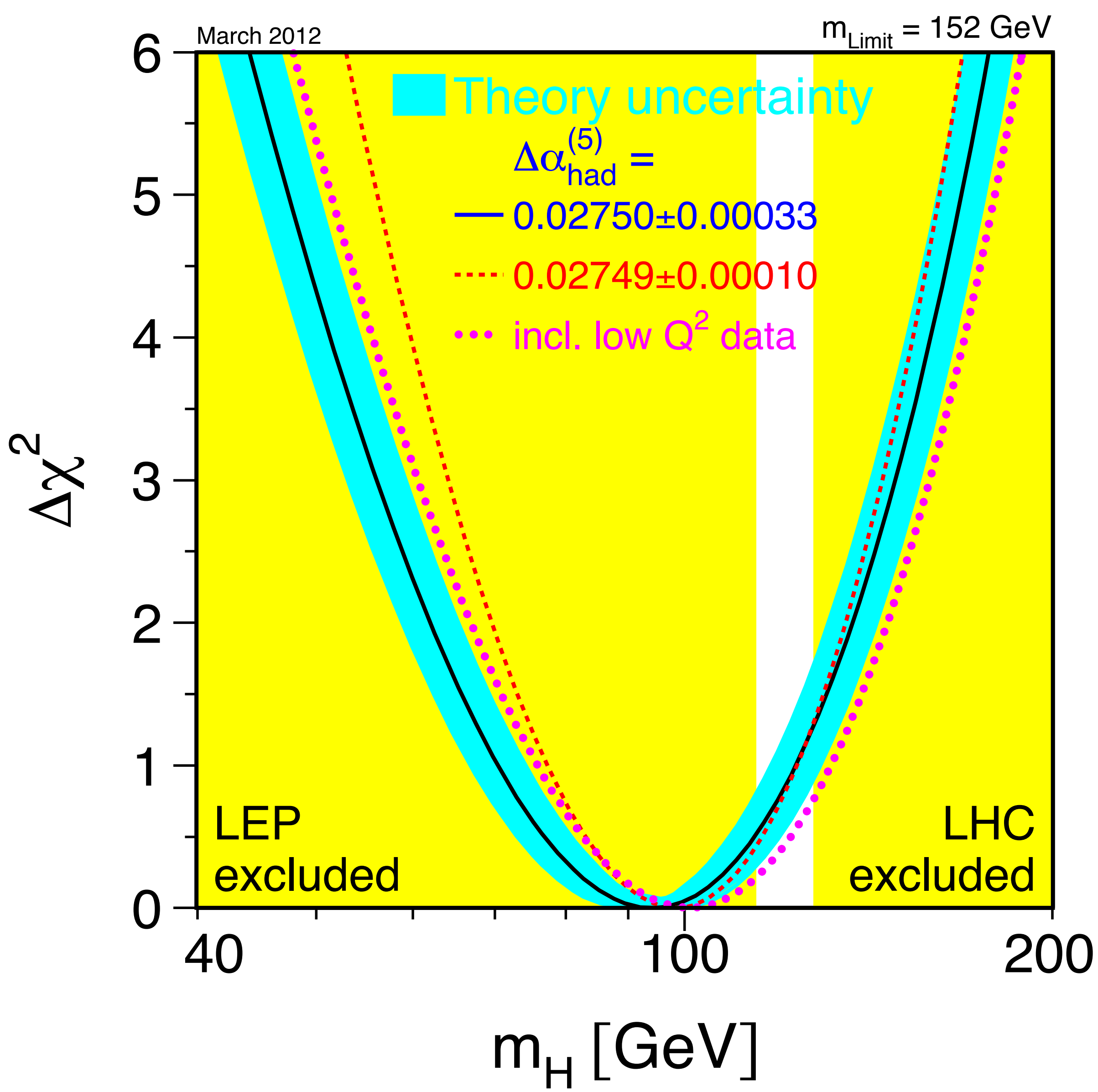
As of July 2011:

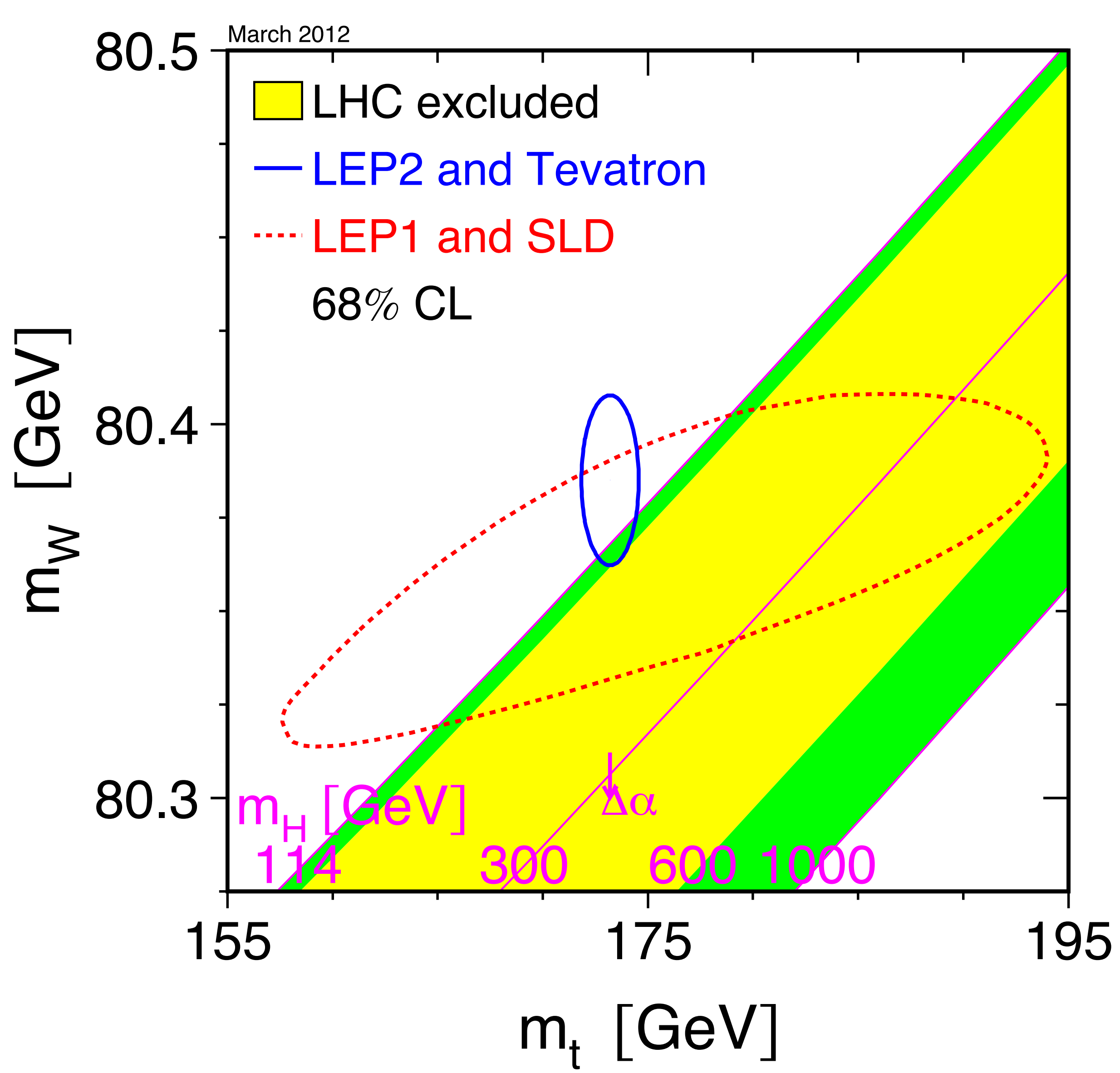
$m_H = 92^{+34}_{-26}$ GeV

$m_H < 161$ GeV @95% CL

Fits and plots from LEPEWWG

Standard model fit





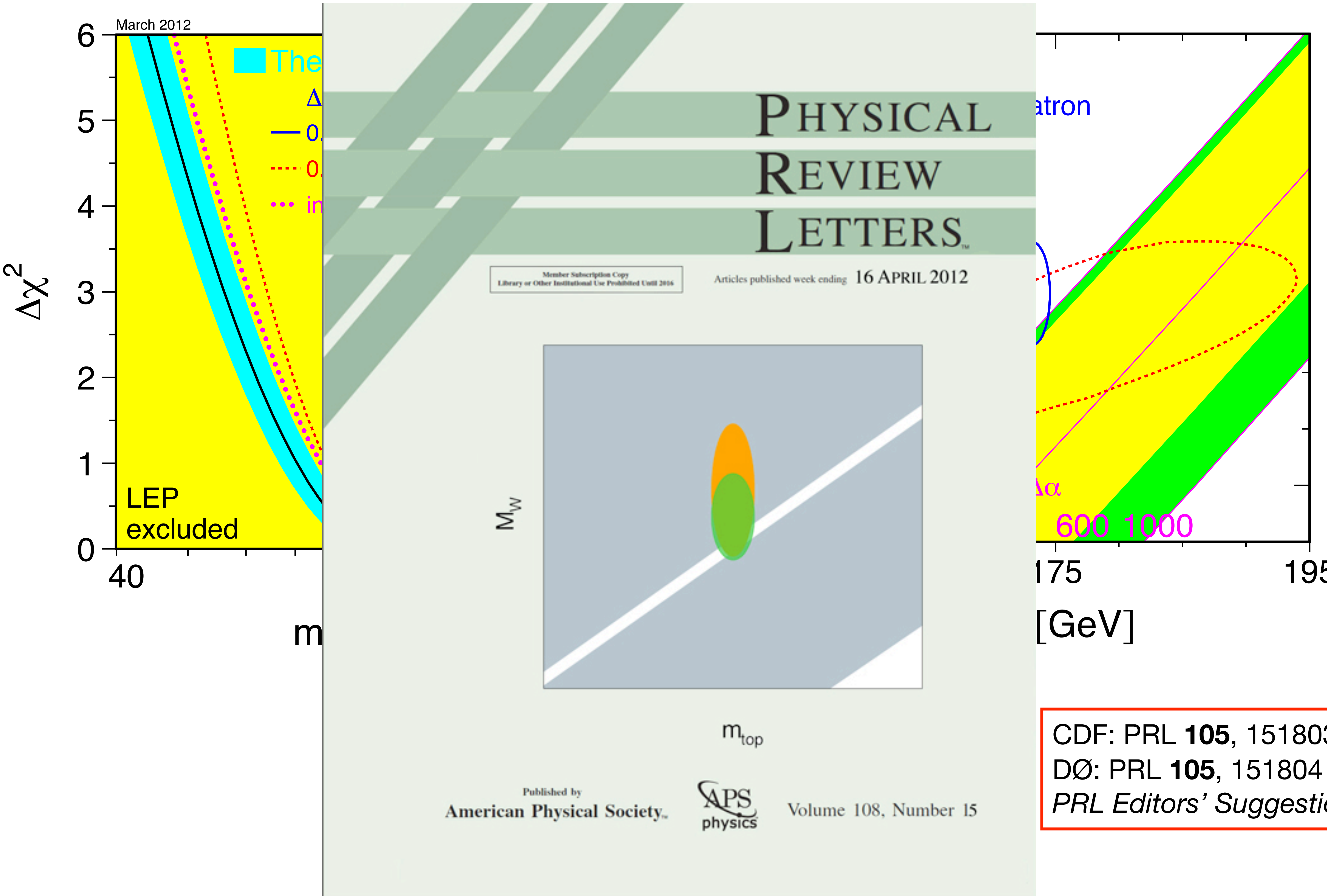
As of March 2012:

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

$m_H < 152$ GeV @95% CL

Fits and plots from LEPEWWG

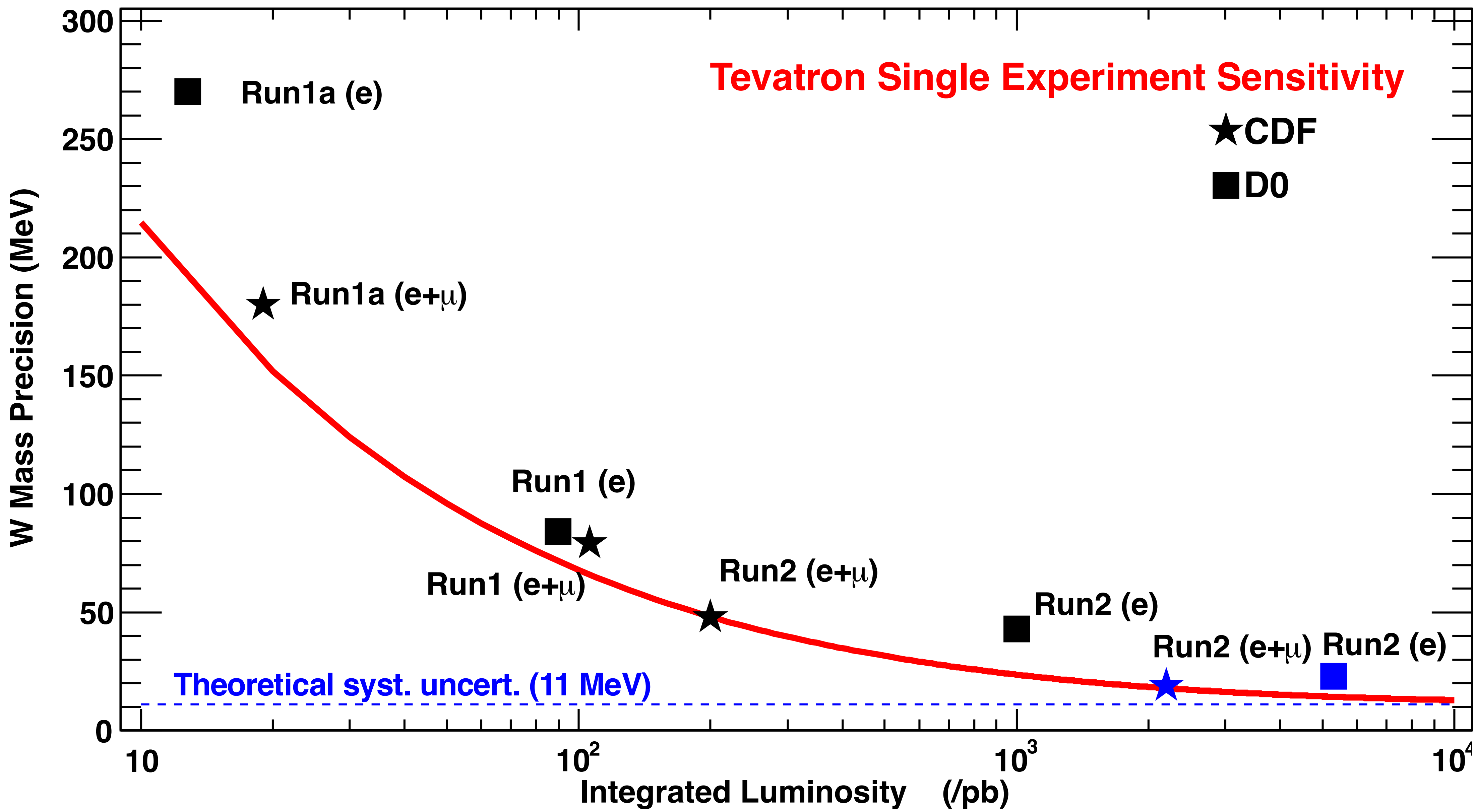
Standard model fit



CDF: PRL **105**, 151803 (2012)
DØ: PRL **105**, 151804 (2012)
PRL Editors' Suggestions

Fits and plots from LEPEWWG

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 *[Phys. Rev. Lett.* ***105****, 158103]*
  - More precise than all previous measurements combined
  - Improves world average uncertainty from 23 MeV to 16 MeV

- New combinations (including DØ [*Phys. Rev. Lett.* ***105****, 158104*])
  - ***Tevatron:*** M_W = 80387±16 MeV (TeVEWWG, preliminary)
  - ***World:*** M_W = 80385±15 MeV (TeVEWWG, preliminary)

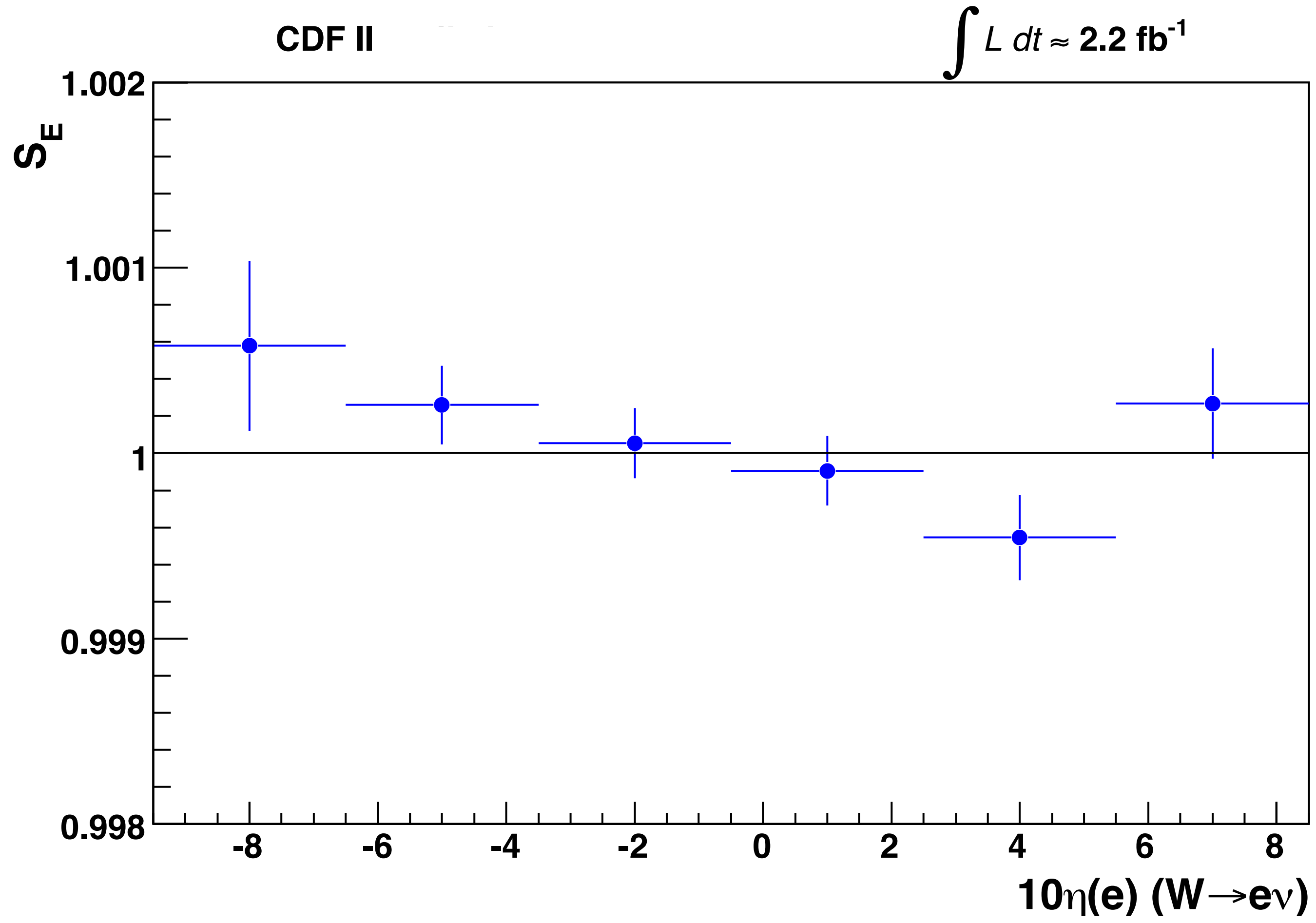
- Results in SM fits of $M_H < 152$ GeV @ 95% CL
  - Previously $M_H < 161$ GeV @ 95% CL
  - M_W still is the limiting factor in M_H prediction

- Full Tevatron dataset (~10 fb^{-1}) on hand
  - $\Delta M_W < 15$ MeV per experiment achievable

Backup

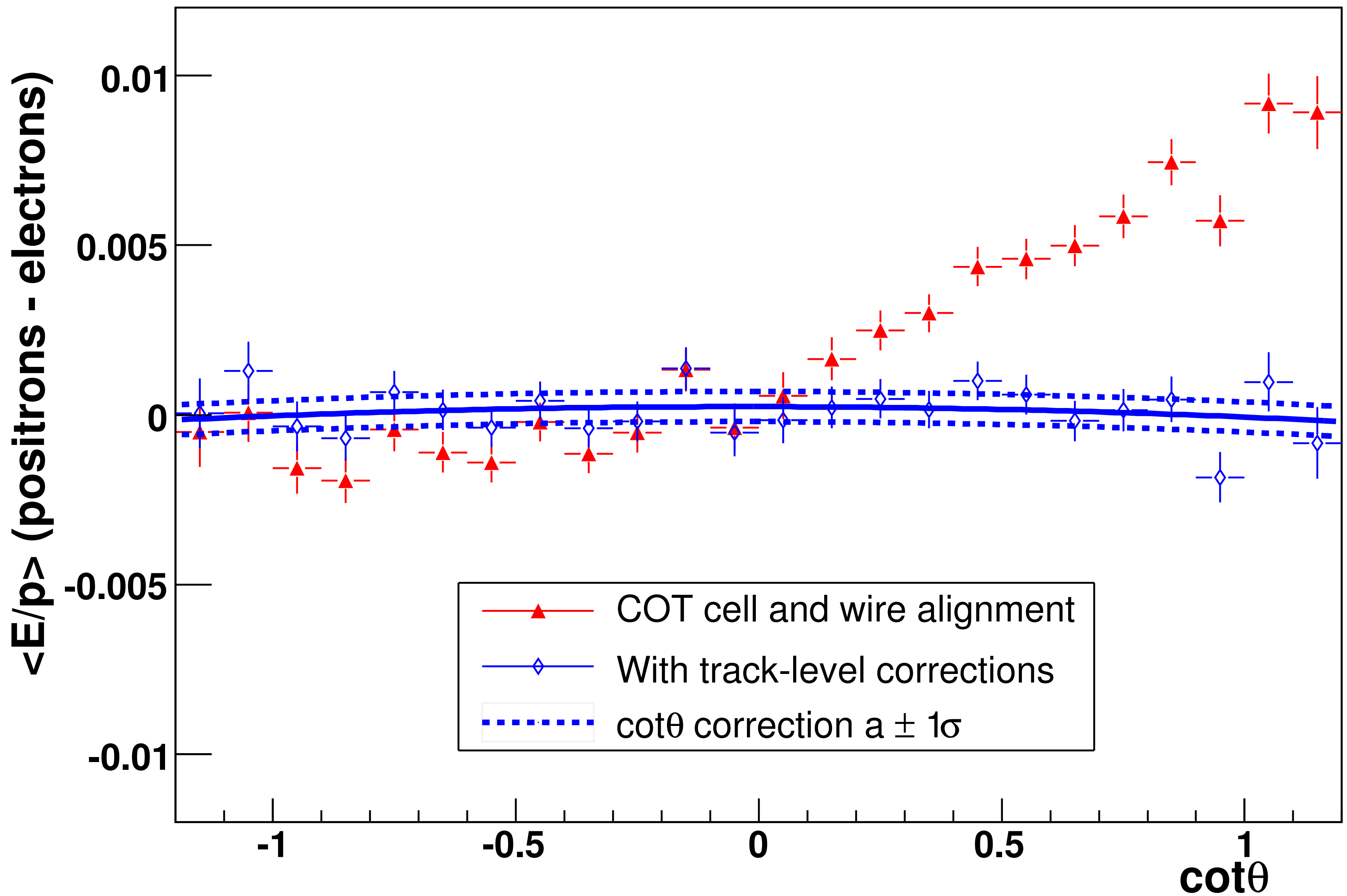
EM calorimeter spatial uniformity

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

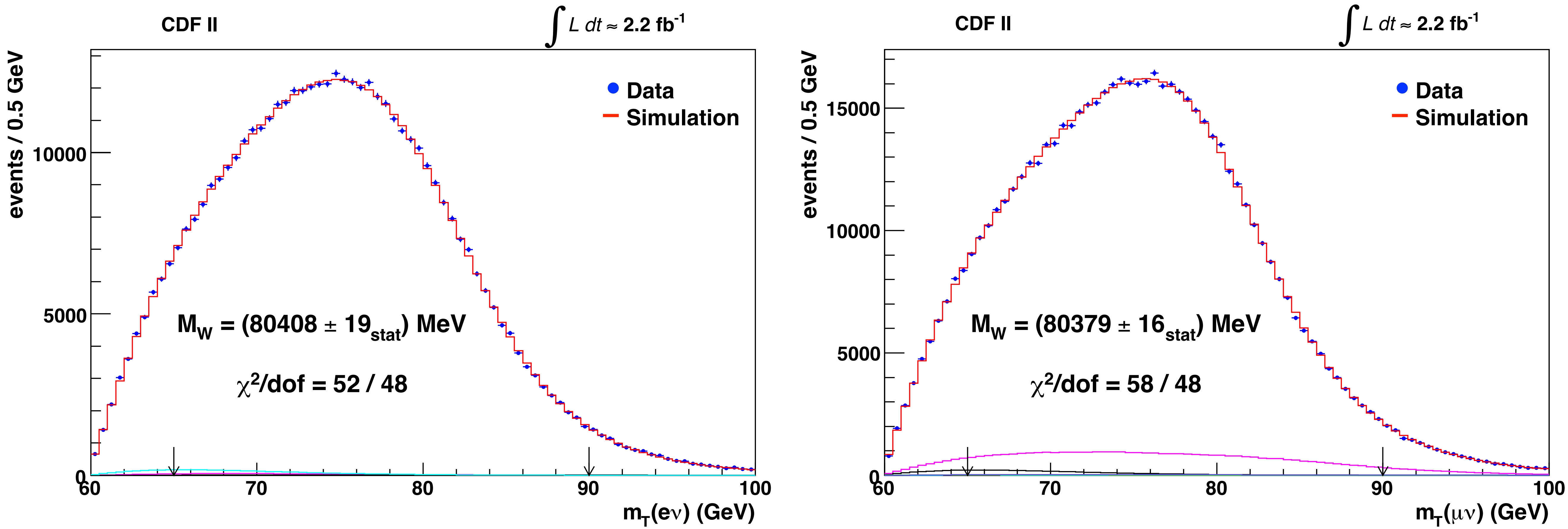


Residual alignment corrections

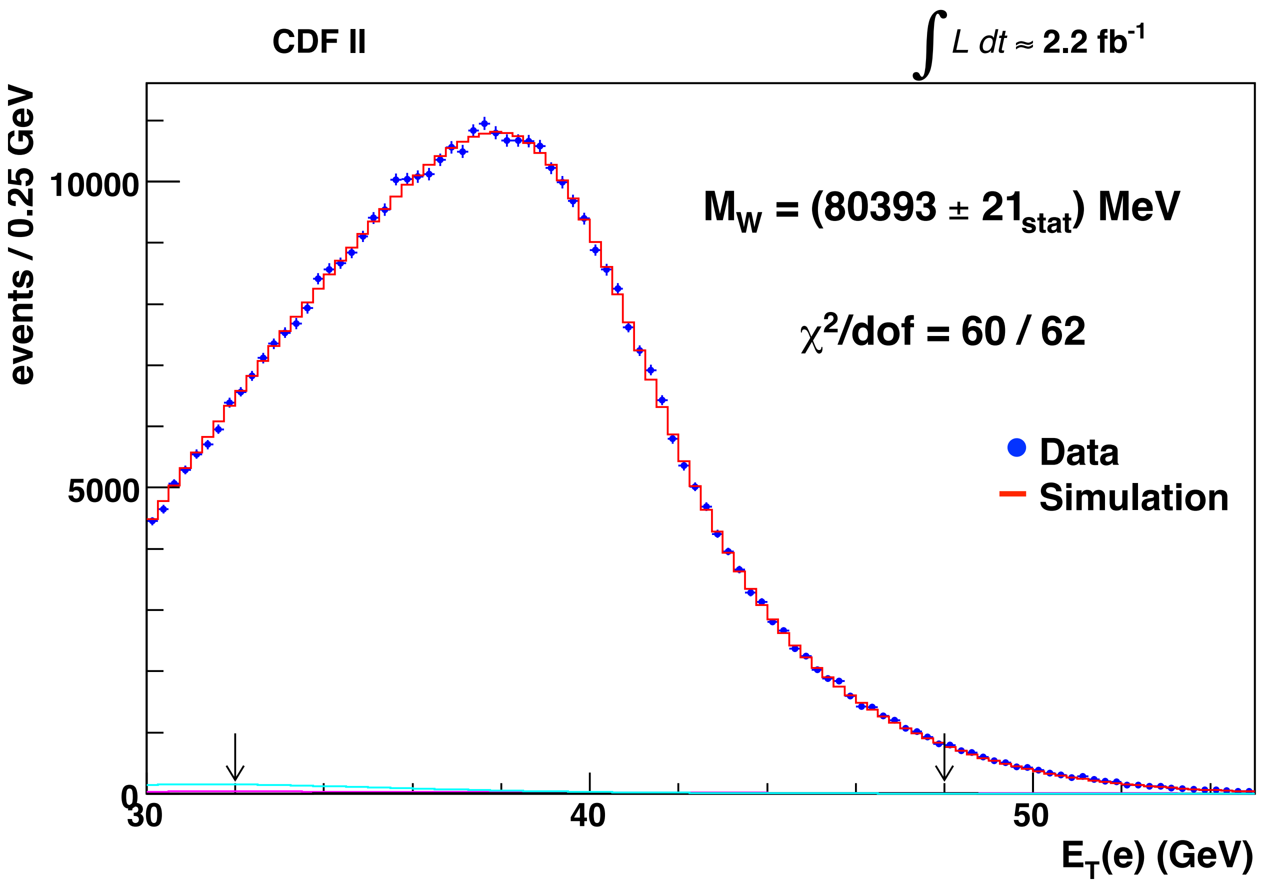
- Some “weakly constrained modes” not corrected by cosmic alignment
- Study these using difference in <E/p> between e^+ and e^- events
    - Apply correction to alignment based on this difference

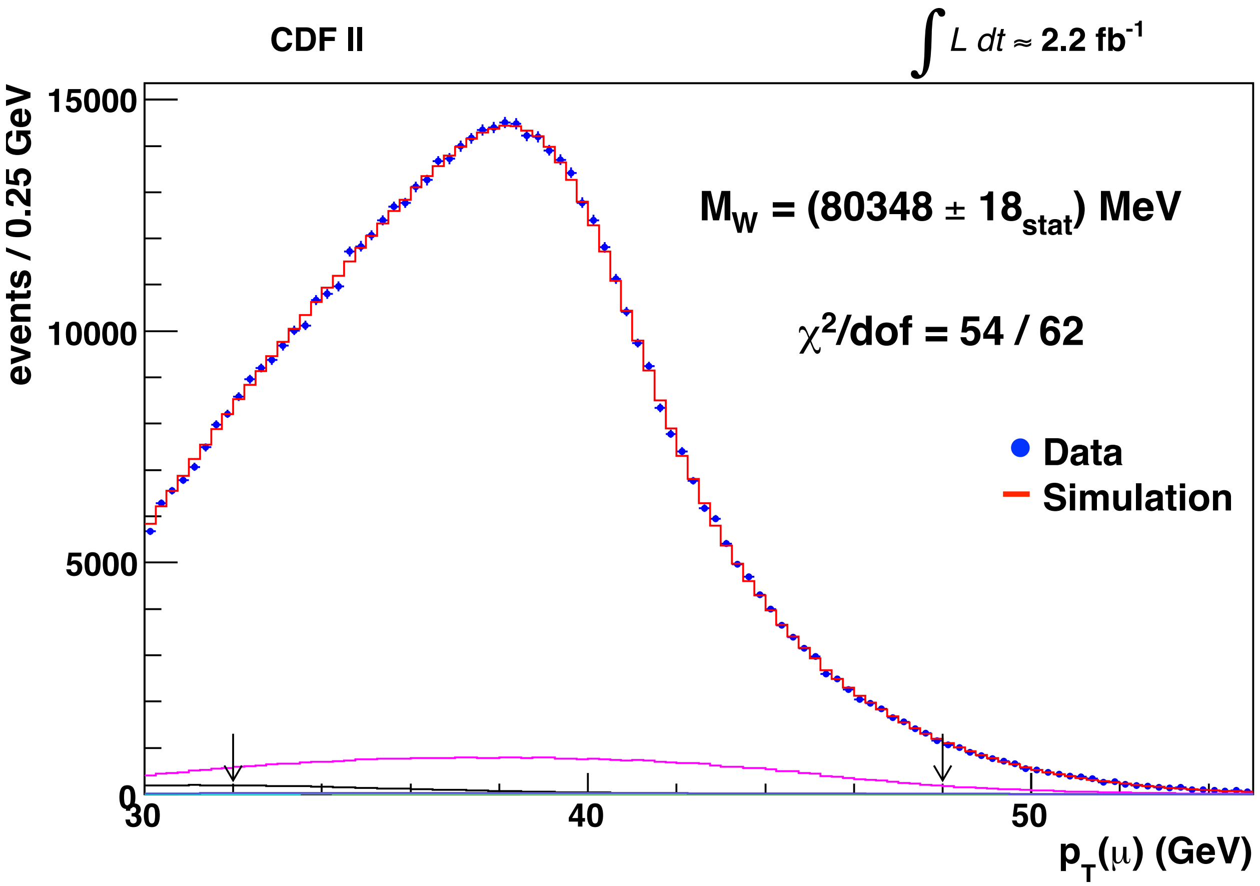


W mass fits: m_T

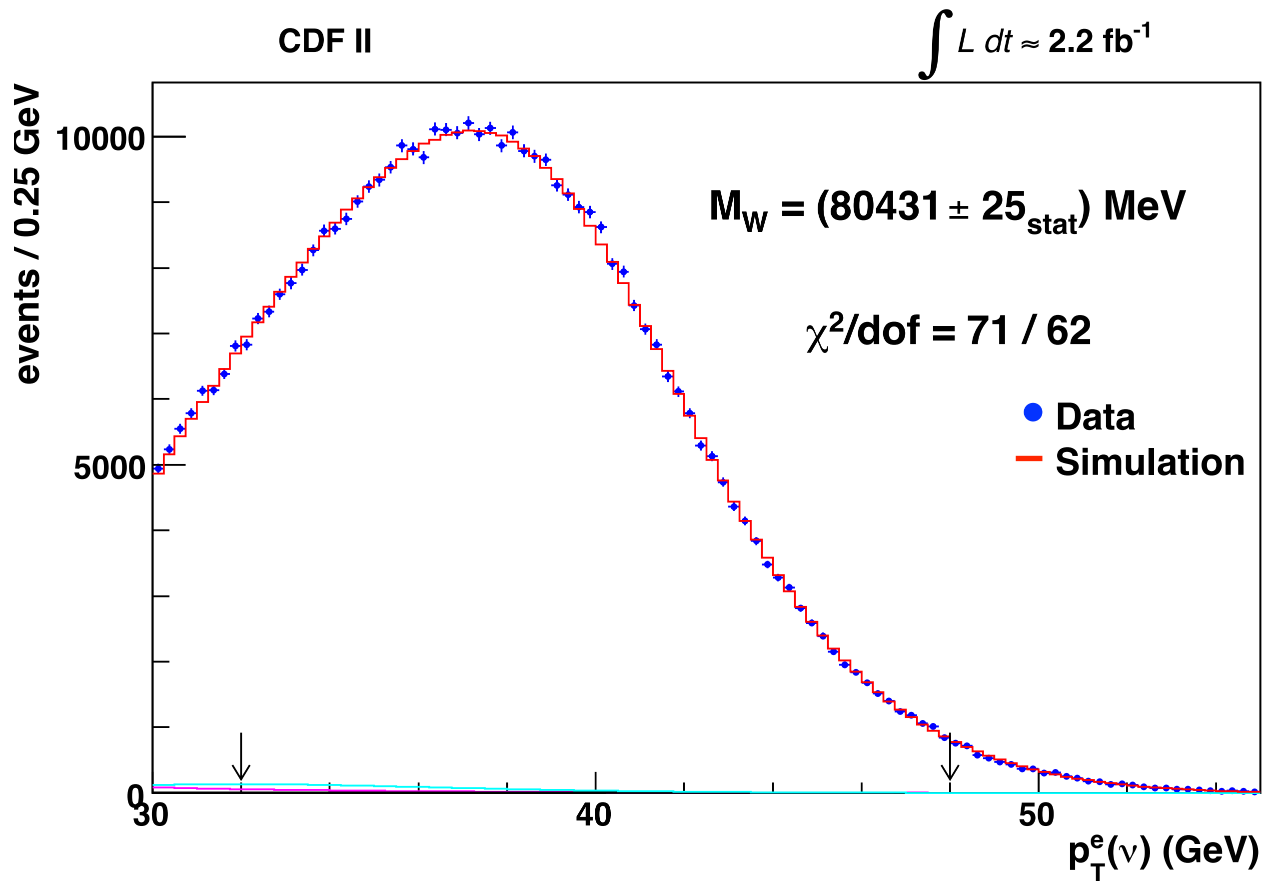


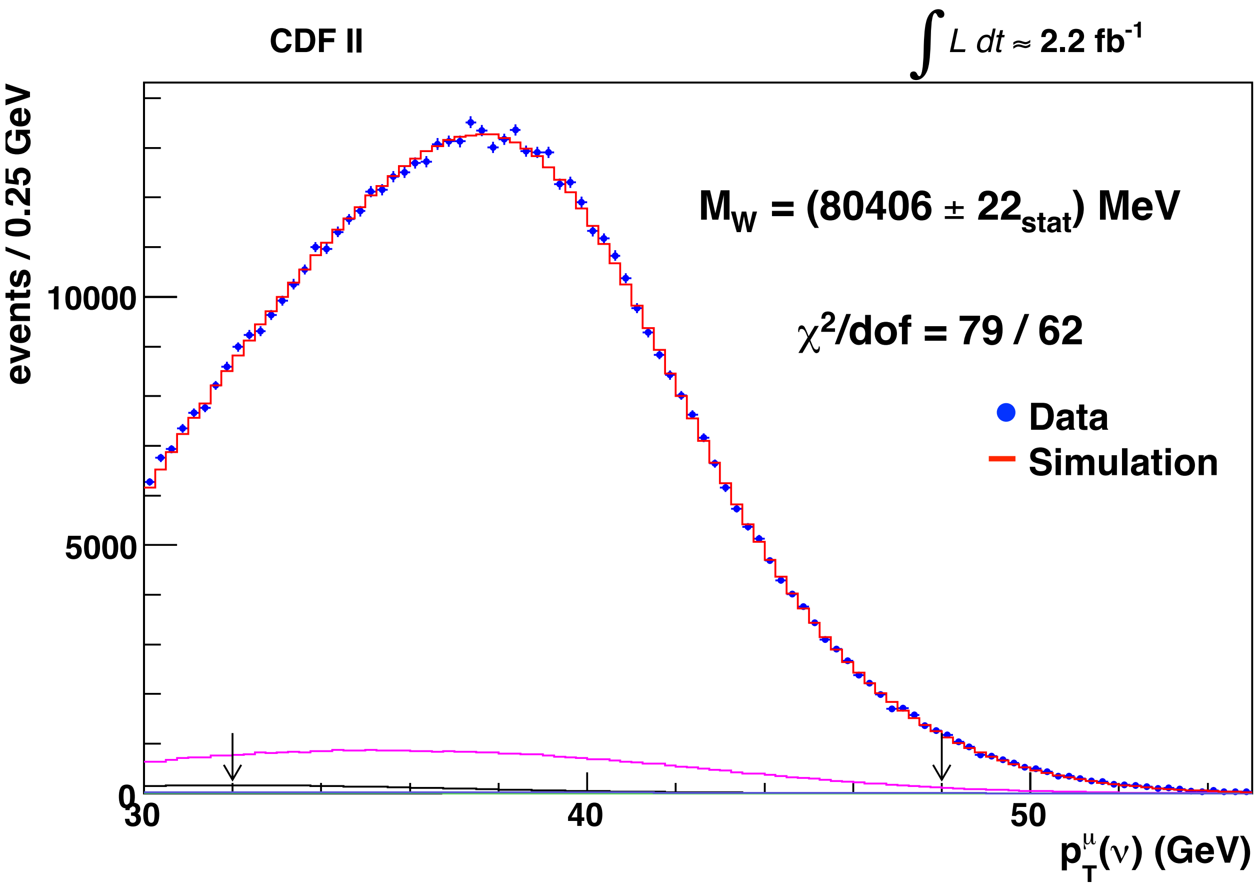
W mass fits: lepton p_T



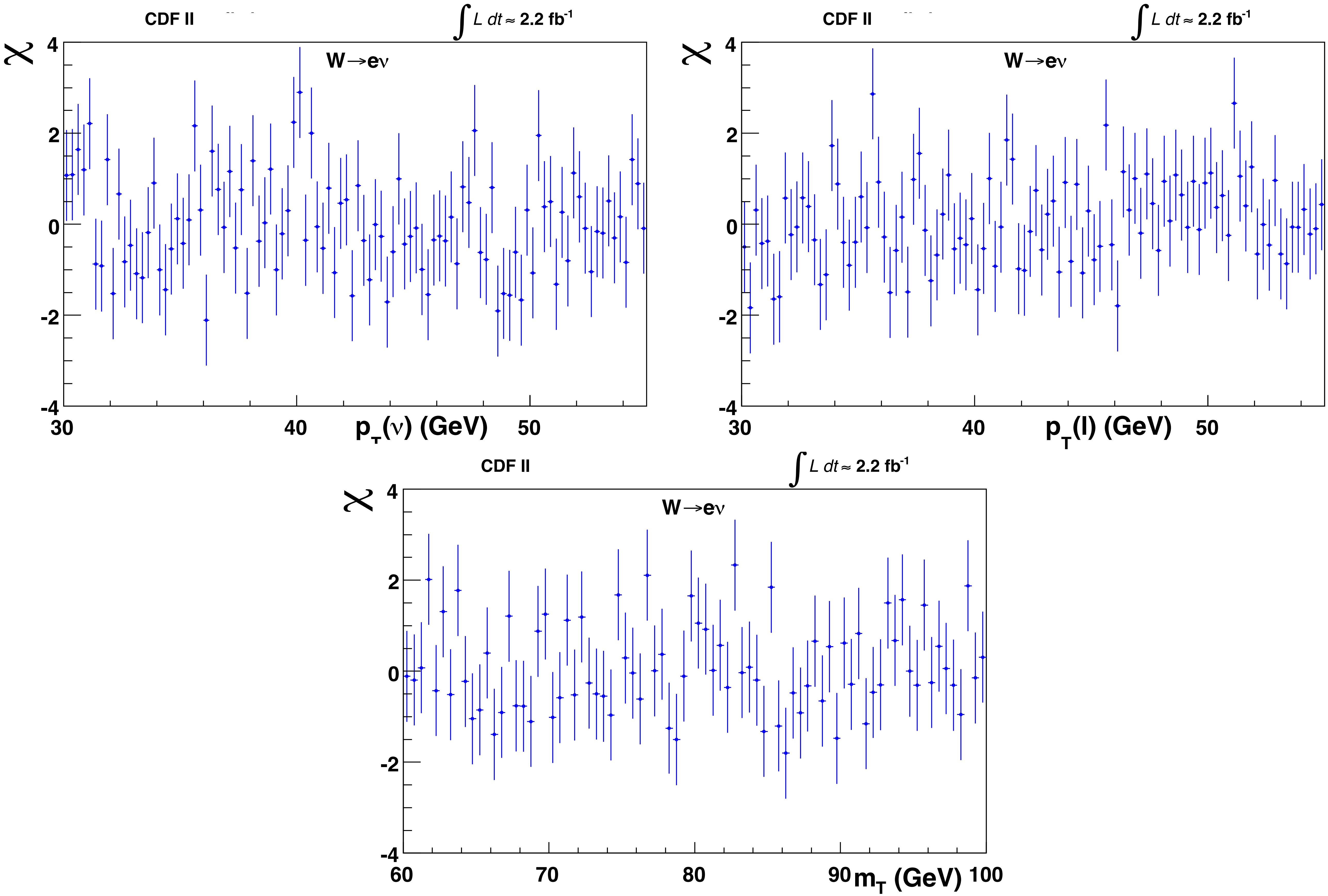


W mass fits: neutrino p_T

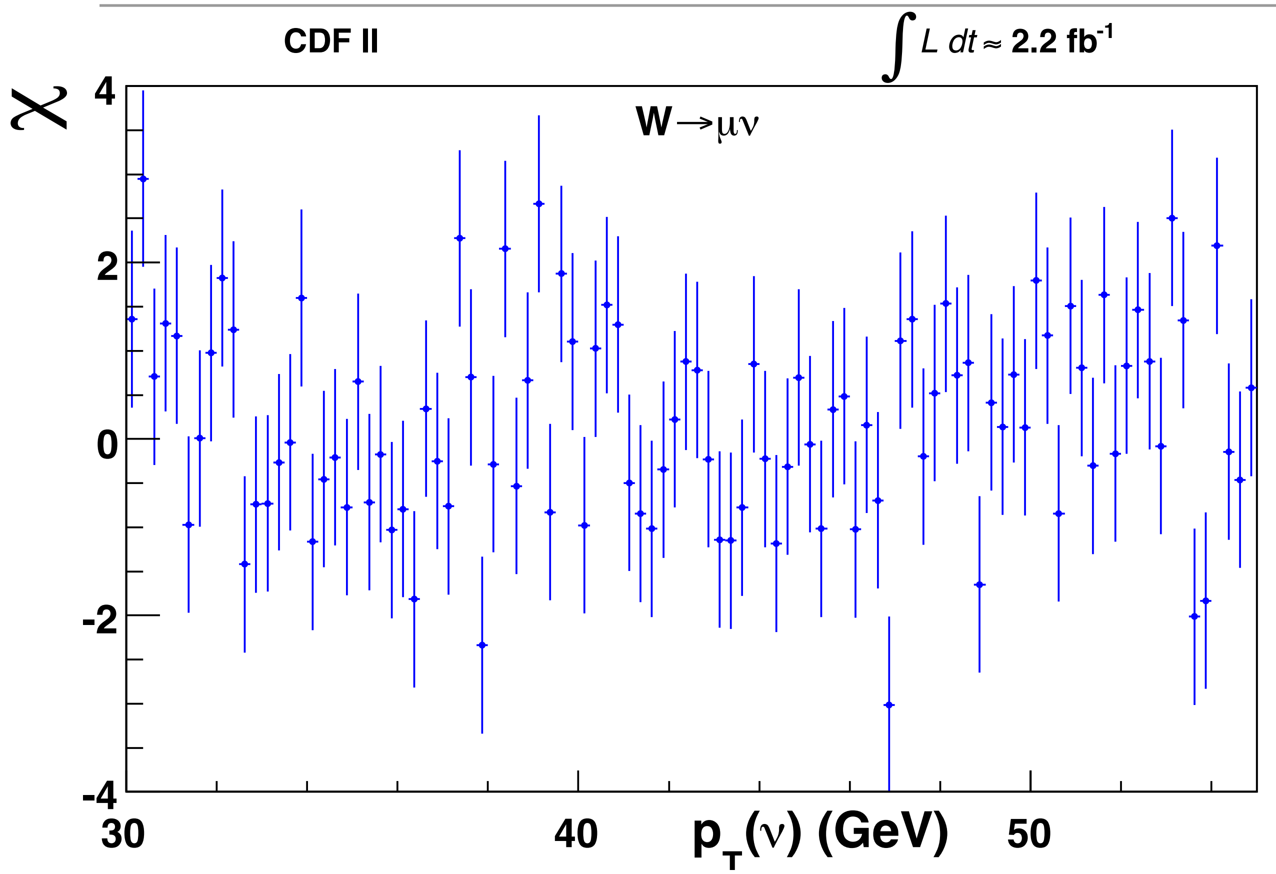


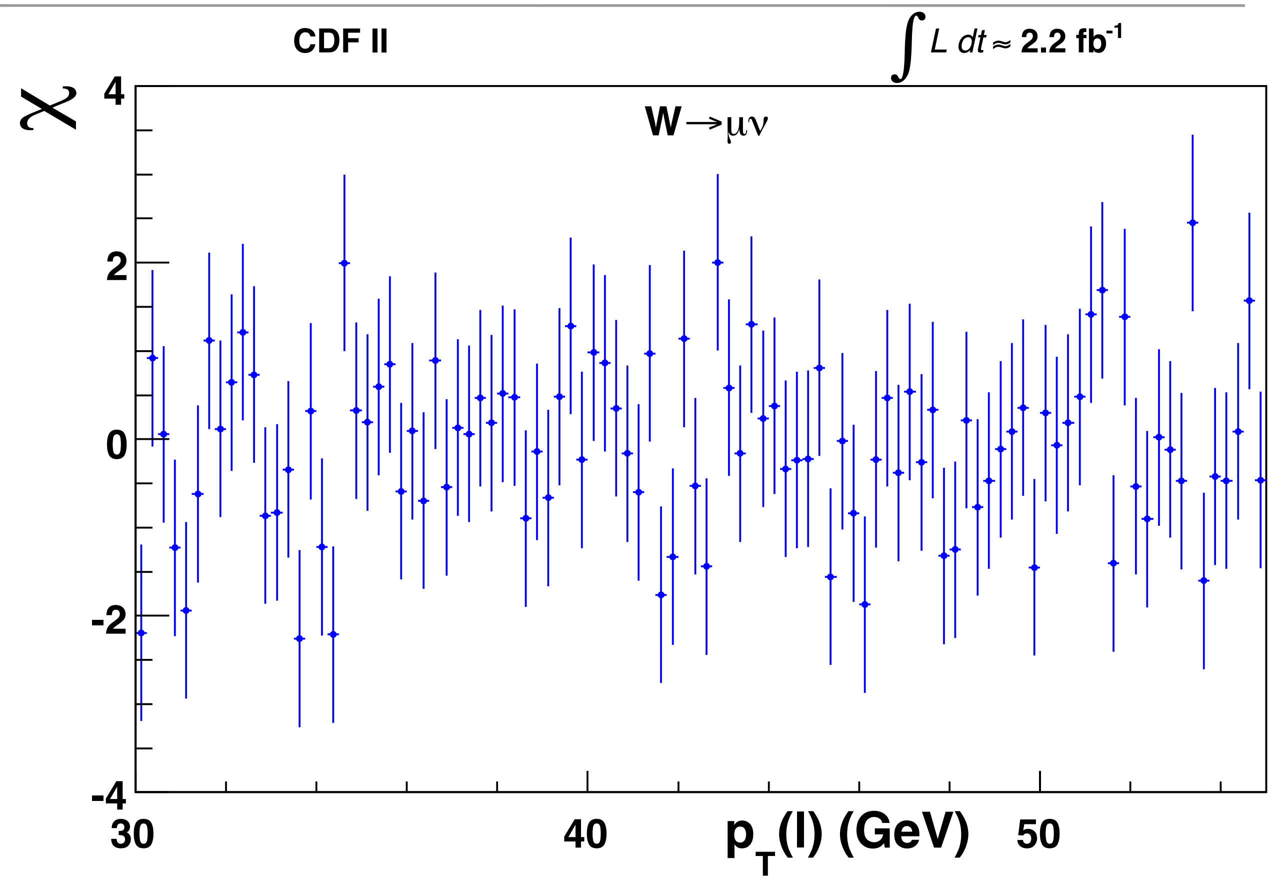


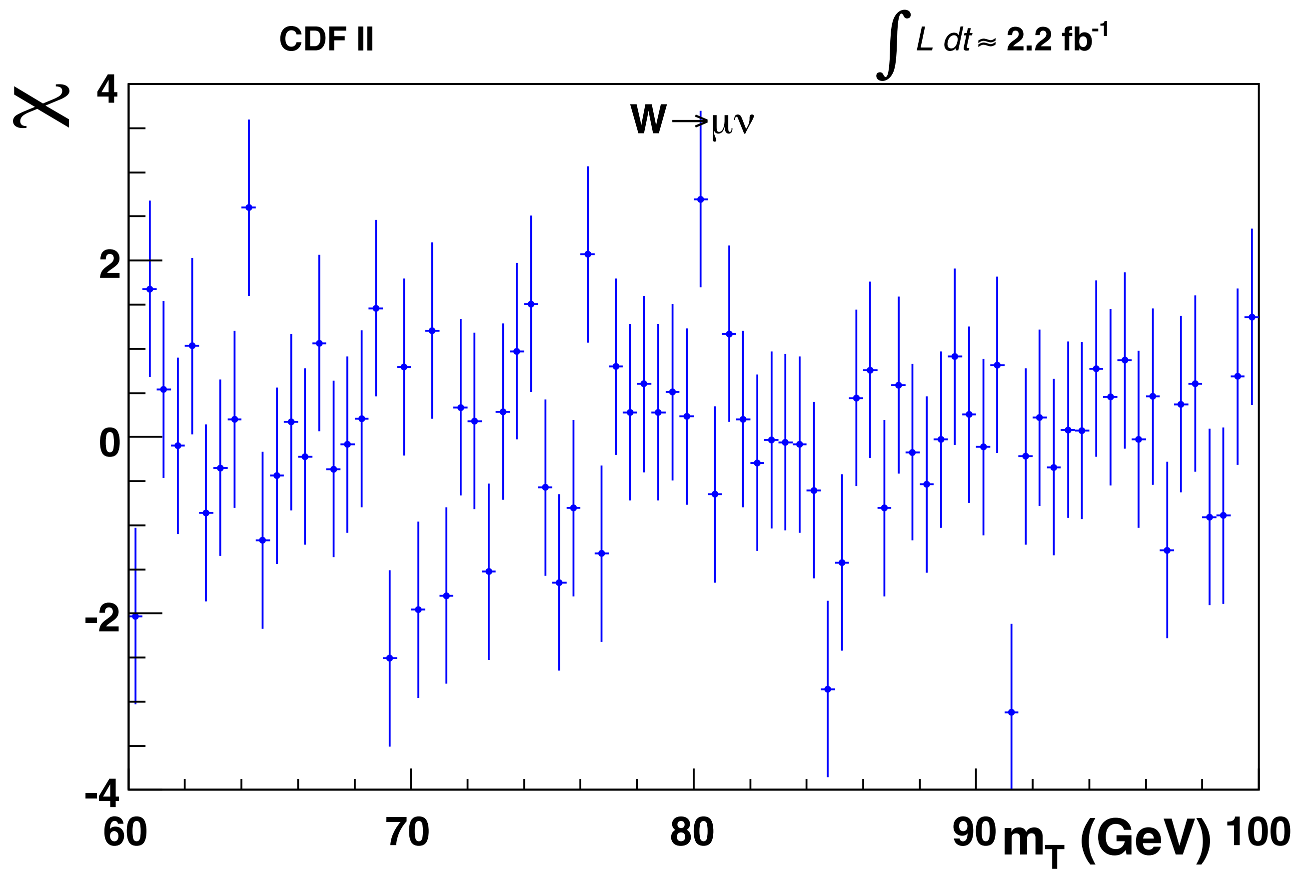
Electron fit residuals



Muon fit residuals

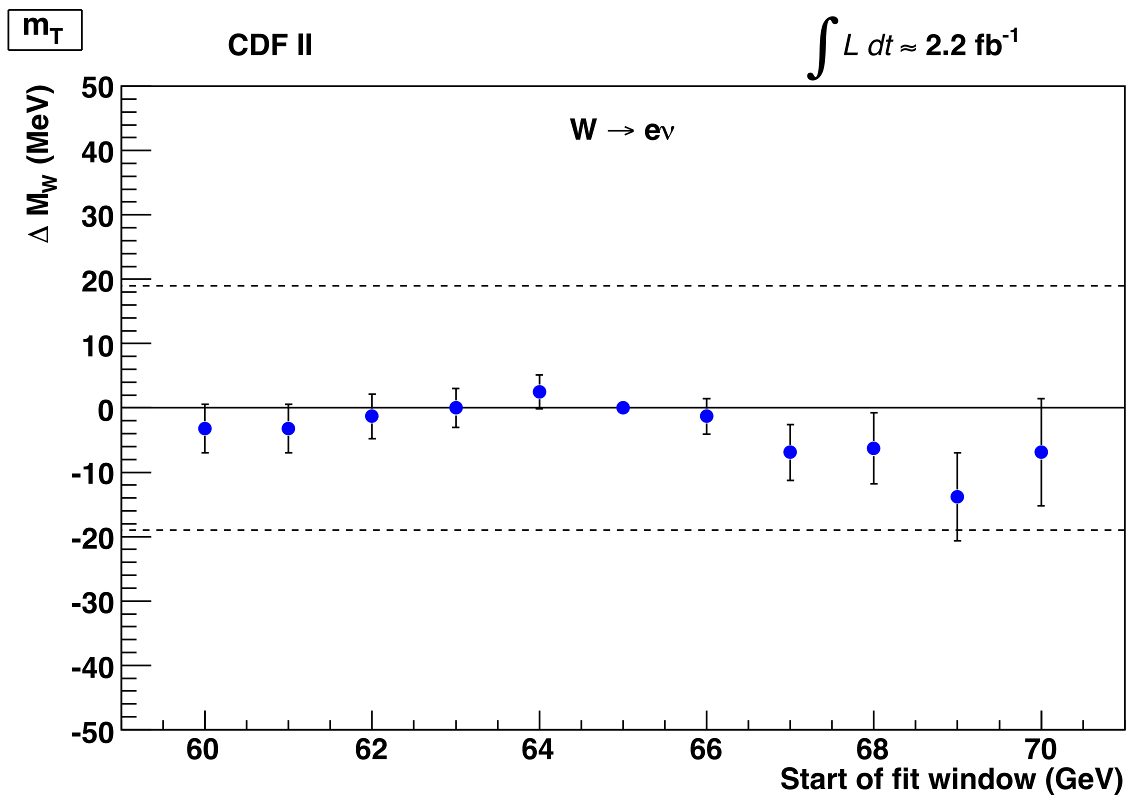


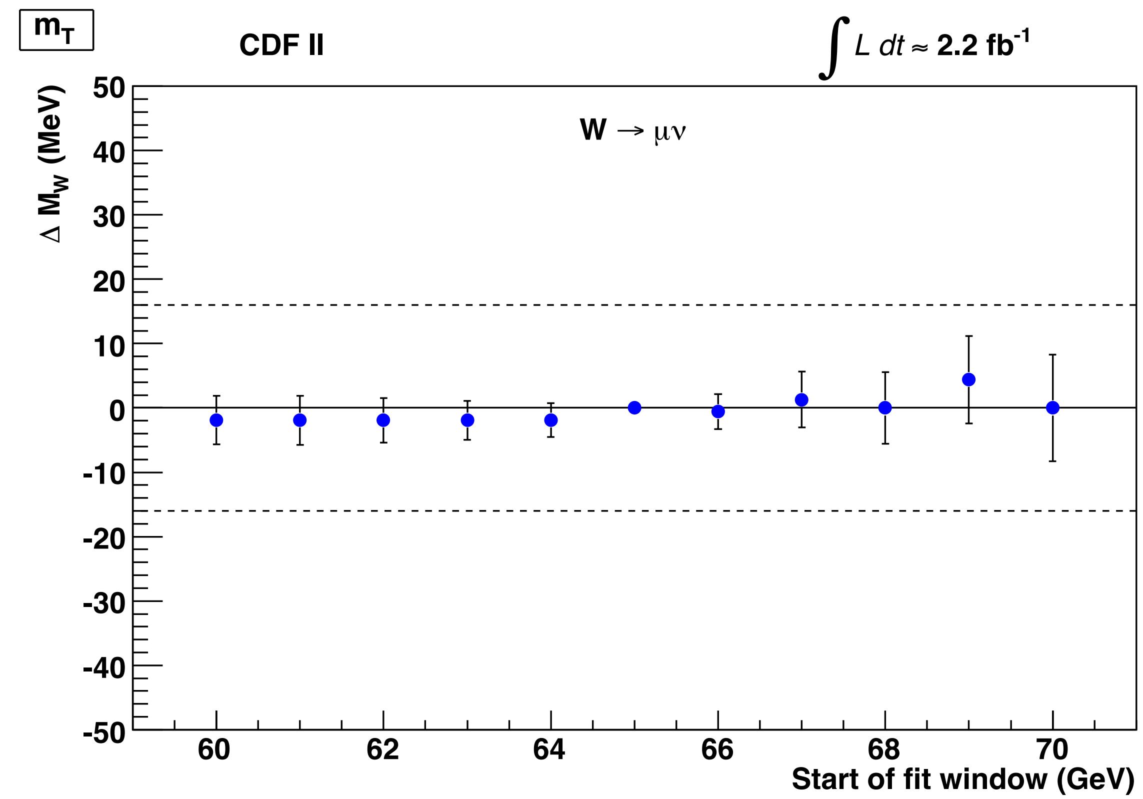




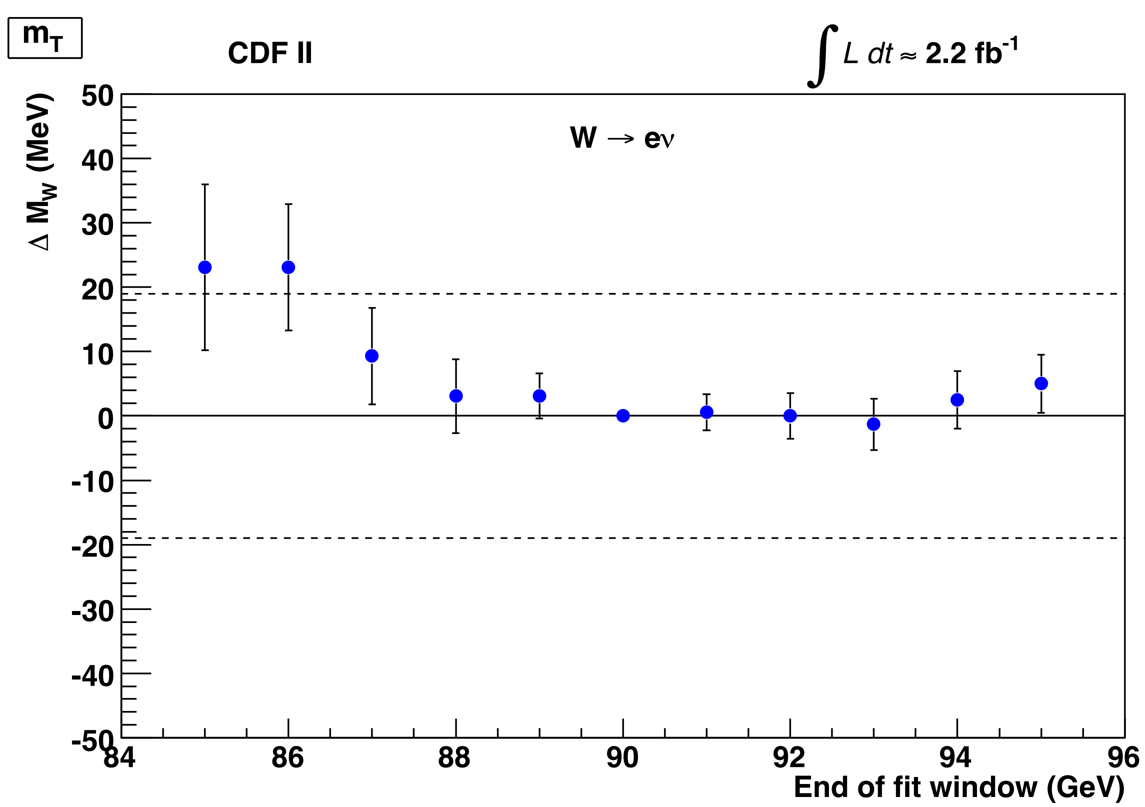
Fit window variation: m_T

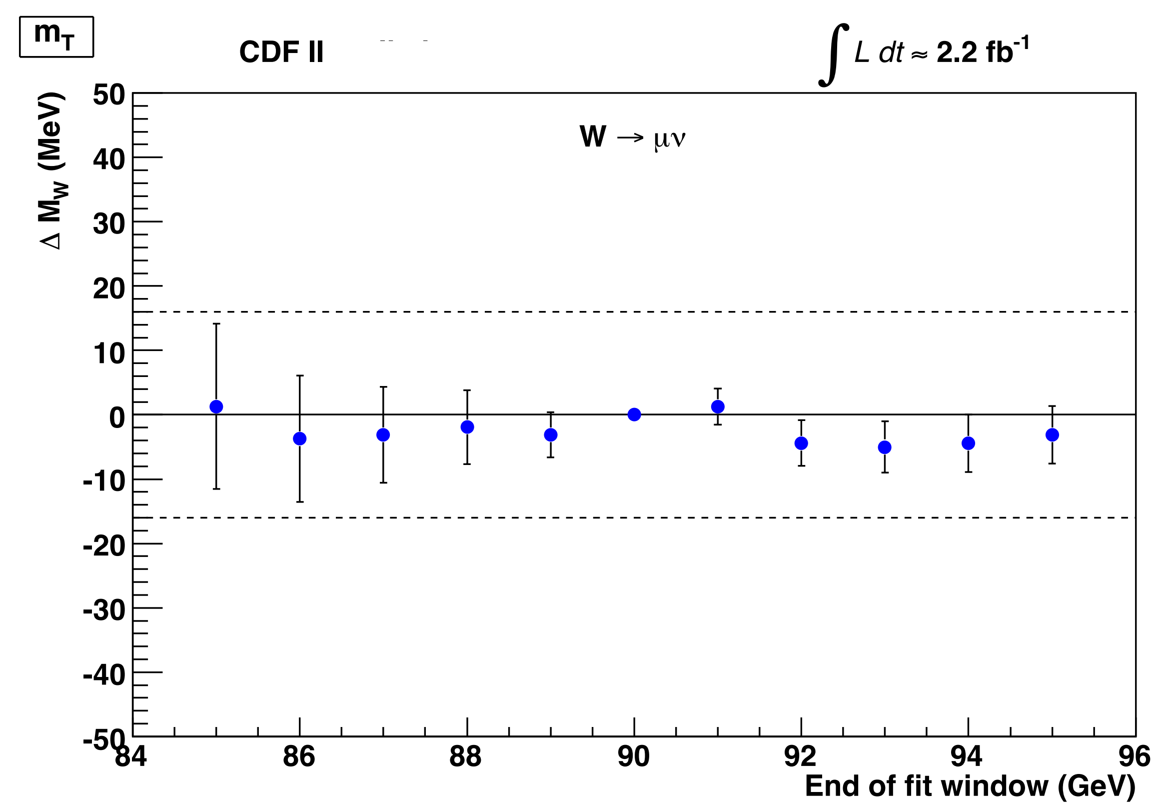
lower





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.

Lepton	Fit	Result (MeV)
Electron	$M_{W^+} - M_{W^-}$	-49±42
Electron	$M_W(\phi>0) - M_W(\phi<0)$	-58±45
Muon	$M_{W^+} - M_{W^-}$	71±69
Muon	$M_W(\phi>0) - M_W(\phi<0)$	-54±36

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

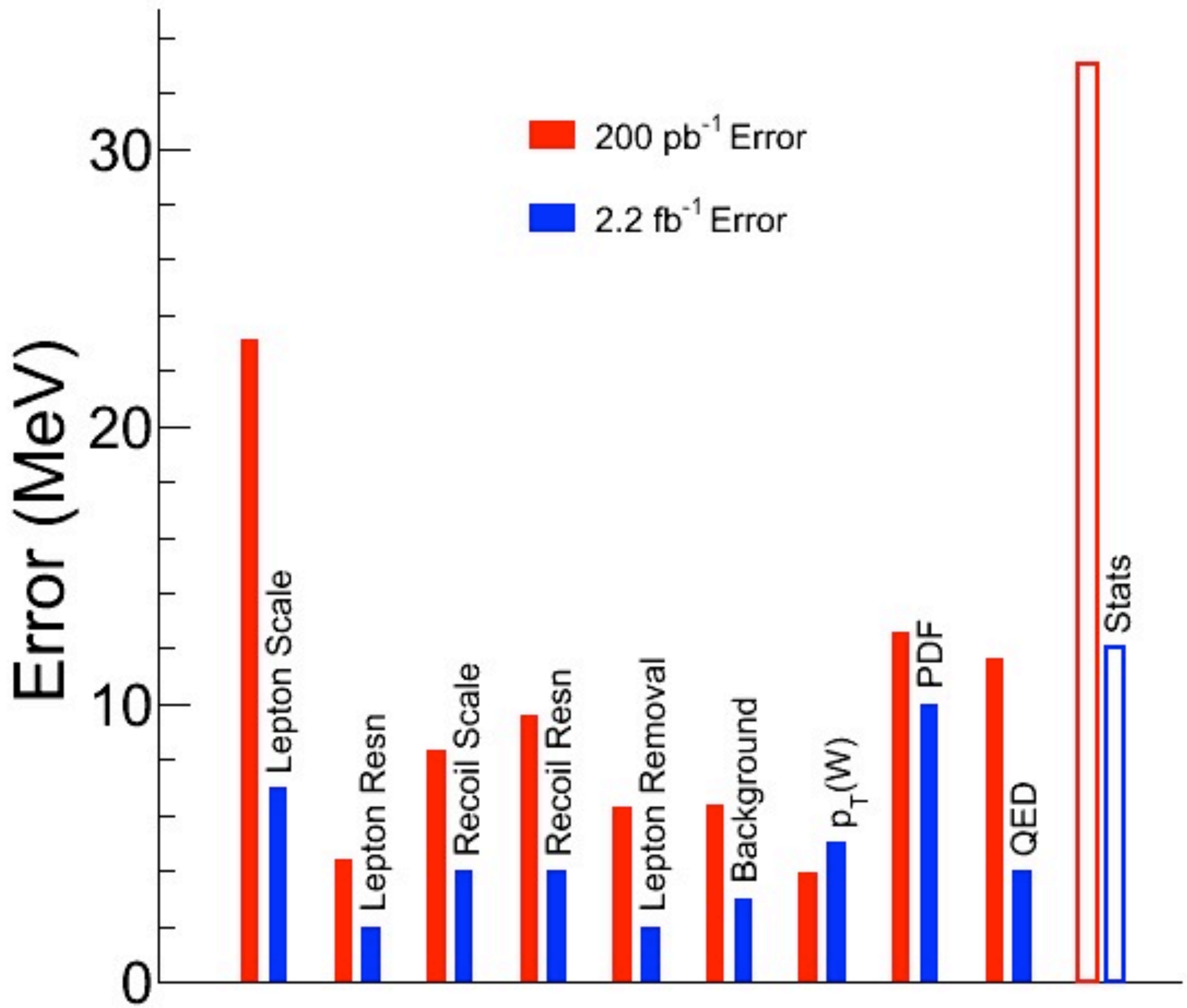
  m_W = 80416 ± 25 MeV, χ^2/dof = 0.5/1 (49%)
- All electron fits combined

  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



MSSM allowed region

Heinemeyer, Hollik, Stockinger, Weiglein, Zeune