Precision Measurement of the W Boson Mass at CDF

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Duke University

45th Annual Fermilab Users Meeting
Tollestrup Award Presentation

June 13, 2012

Photo: Reidar Hahn/Fermilab

Introduction: a testament to insanity

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"A low mass bison at Fermilab"
*-**The Guardian** (J. Butterworth)*
from "W Marks the Spot" (2-Mar-2012)

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- A true end-to-end analysis
  - Detailed understanding of theoretical model, detector response, and experimental environment
  - Bespoke tools
  - Convincing collaborators to read 400+ pages of documentation

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- This measurement did take nearly five years
- A true end-to-end analysis
  - Detailed understanding of theoretical model, detector response, and experimental environment
  - Bespoke tools
  - Convincing collaborators to read 400+ pages of documentation
- End result: **single most precise** measurement of the W boson mass

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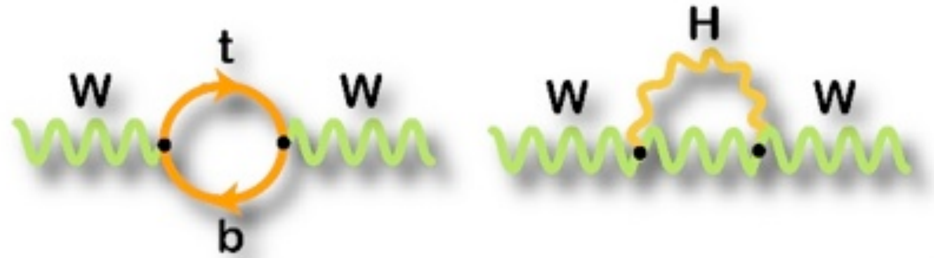
The electroweak sector and M_W

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}\frac{1}{(1-\Delta r)}$$

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

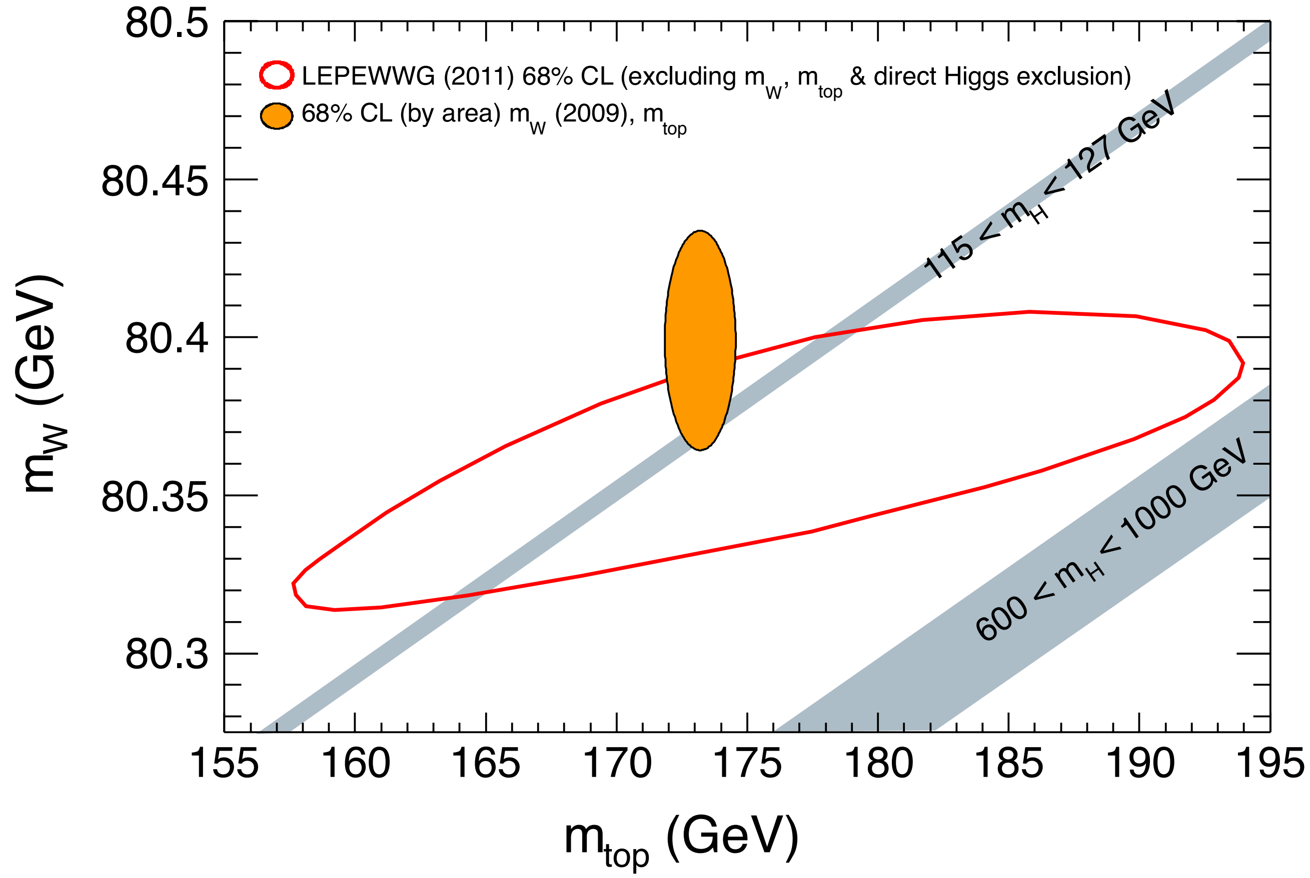
- Radiative corrections Δr dominated by top and Higgs loops



$\Delta r \sim m_t^2$ $\Delta r \sim \ln M_H$

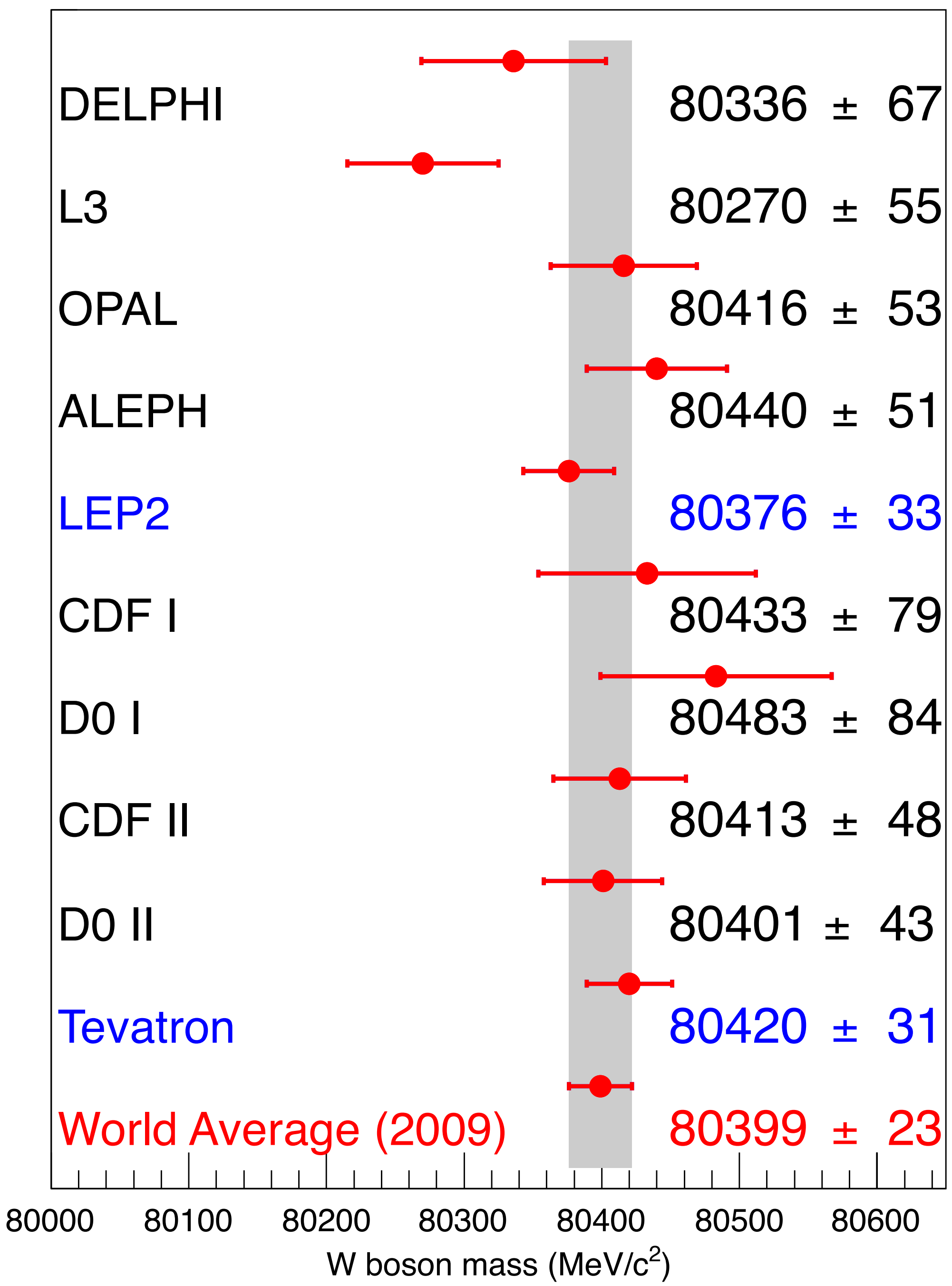
- Precision measurements in M_W and m_t constrain SM Higgs mass

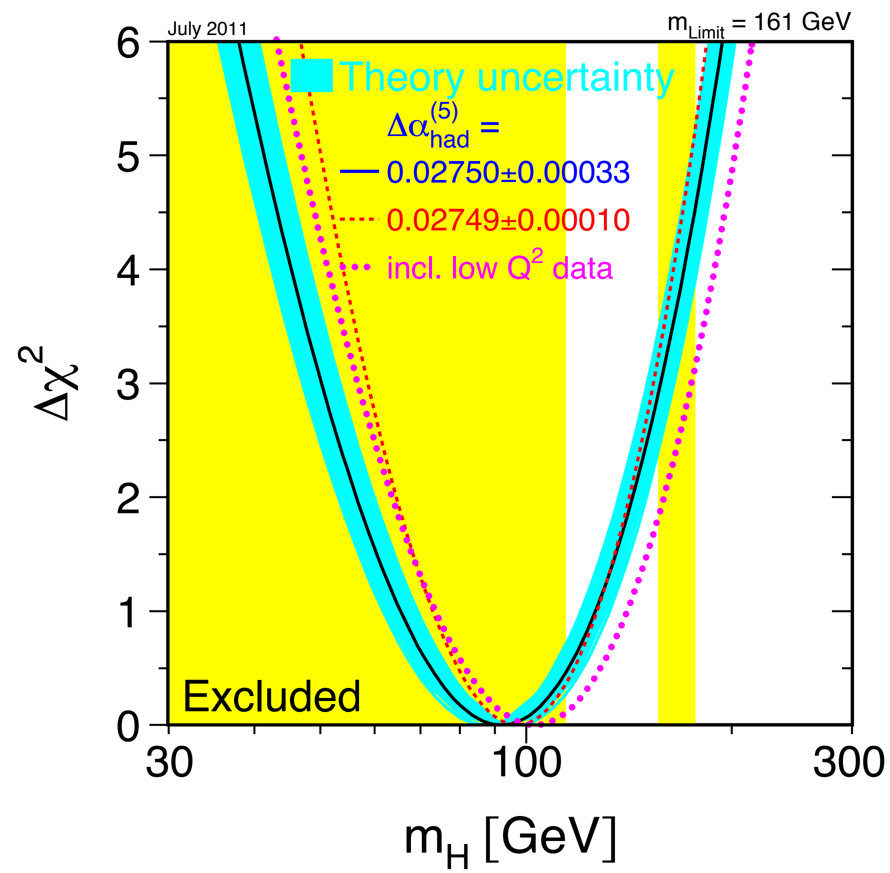
Where should the Higgs be?



M_W history and Higgs mass constraint

As of January 2012





$m_t = 173.2 \pm 0.9$ GeV

$M_W = 80.399 \pm 0.023$ GeV

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

$m_H < 161$ GeV @95% CL

Δm_t of 0.9 GeV equivalent to ΔM_W of 6 MeV

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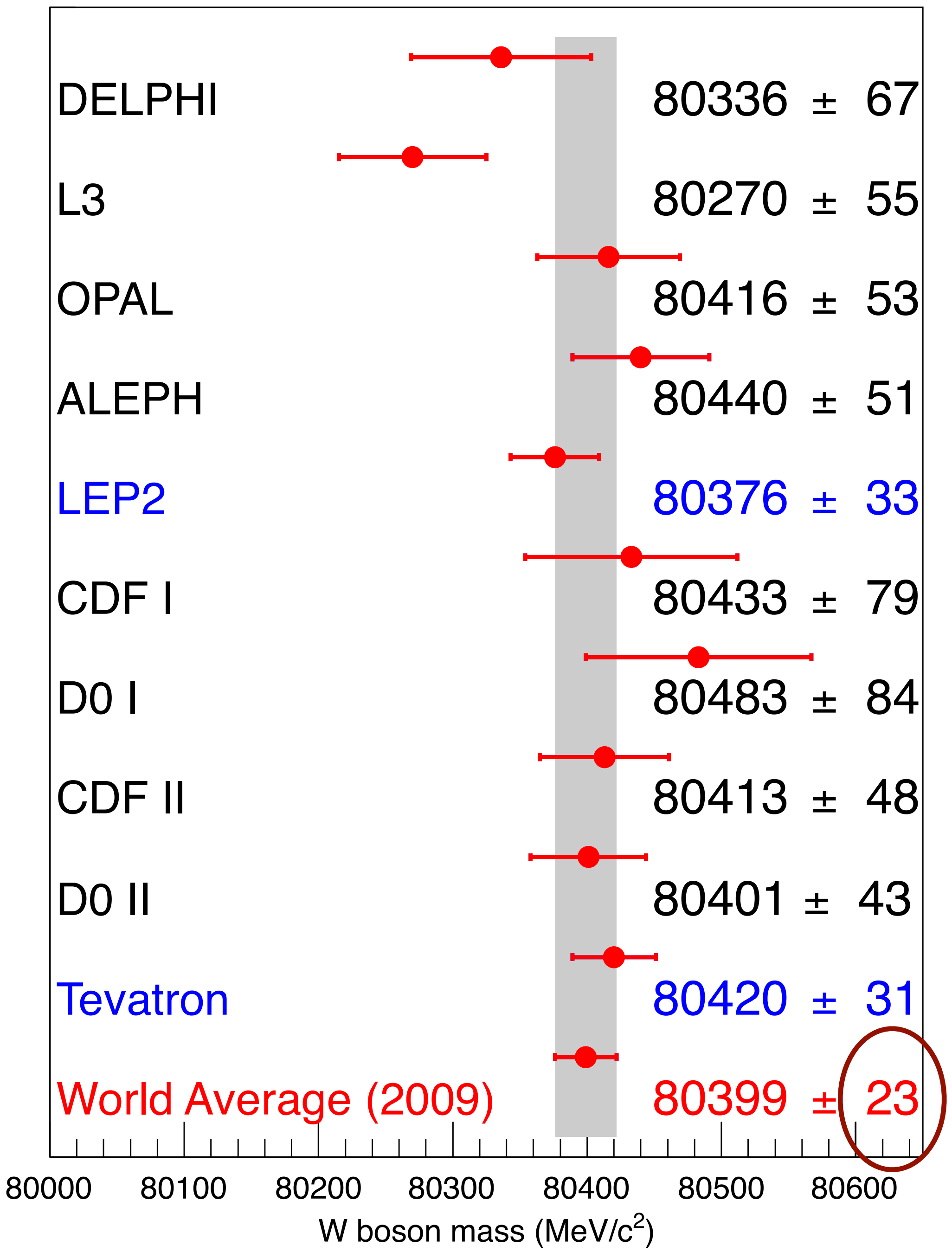

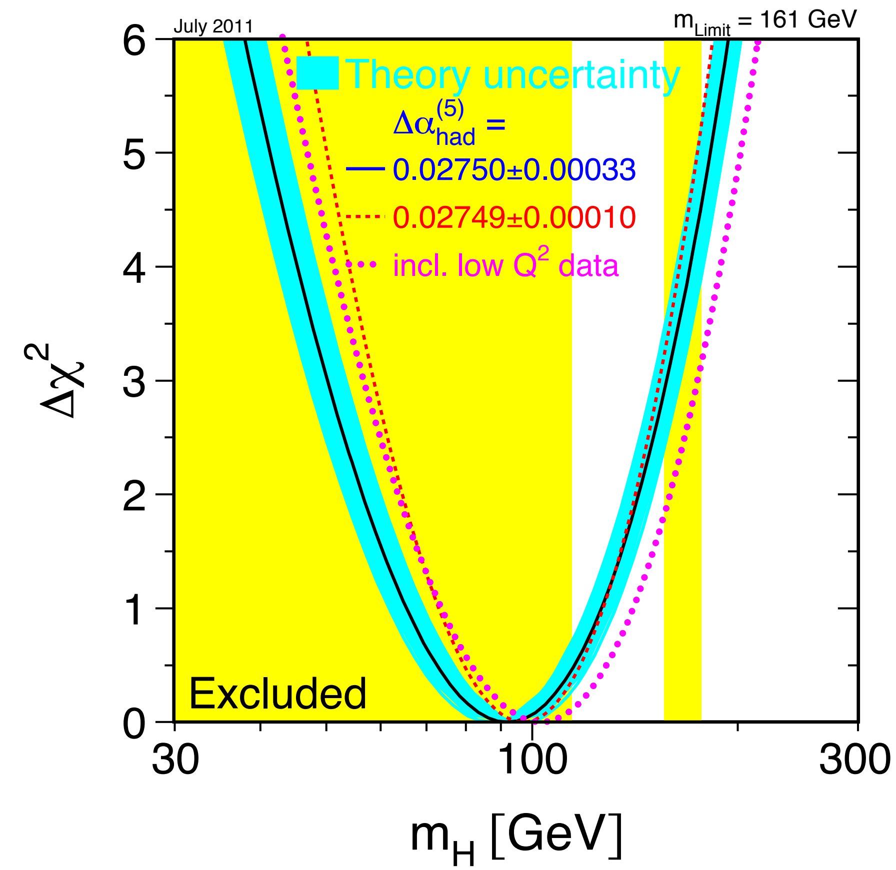

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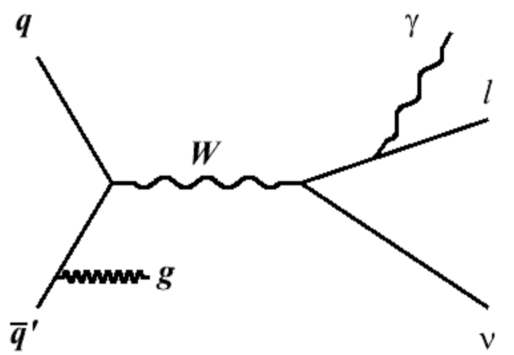
Can we exceed this precision with a single measurement?

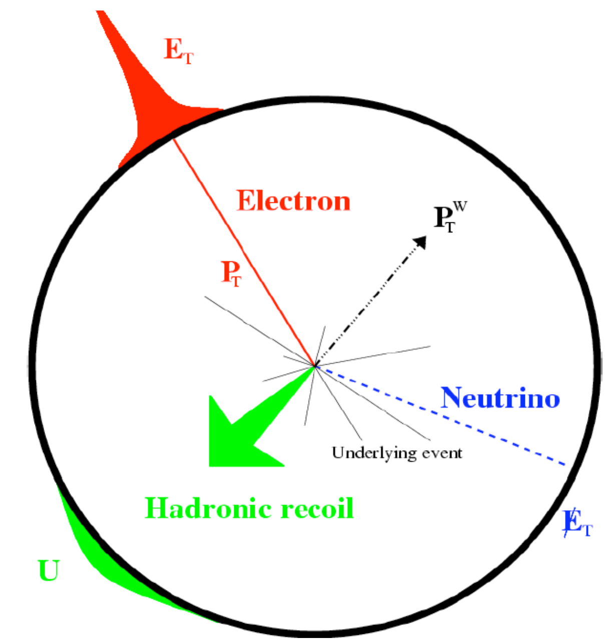
Measuring M_W

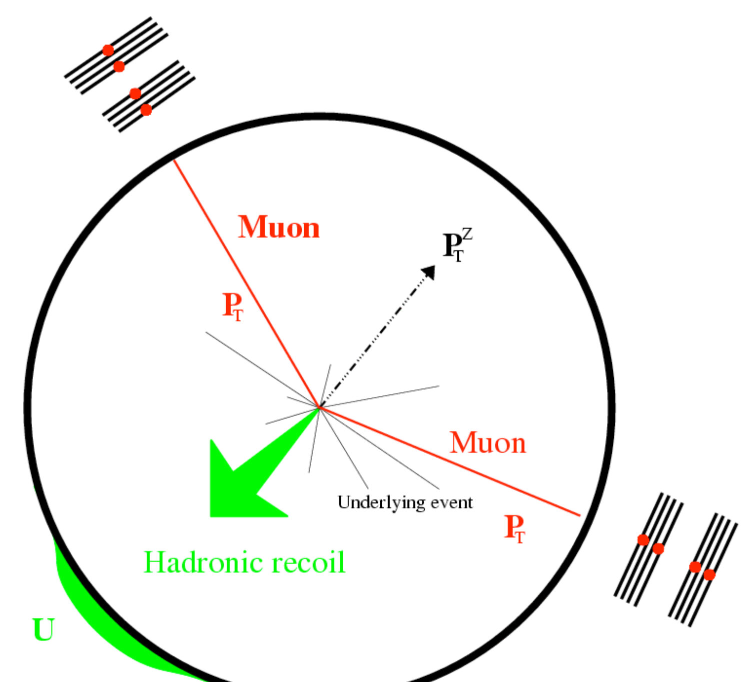
- Use electron and muon decays of *W* bosons
- Lepton p_T^l carries most information: measure as precisely as possible (*e.g.* 0.01% at CDF)
  - Calibrate using dimuon resonances
- Measure transverse hadronic recoil
  - Sum of all transverse energy minus lepton
  - Calibrate using *Z* boson events
- Infer neutrino energy $p_T^\nu = -(p_T^l + u_T)$
  - Perform mass fits using transverse quantities (p_T^l, p_T^ν, and m_T)

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

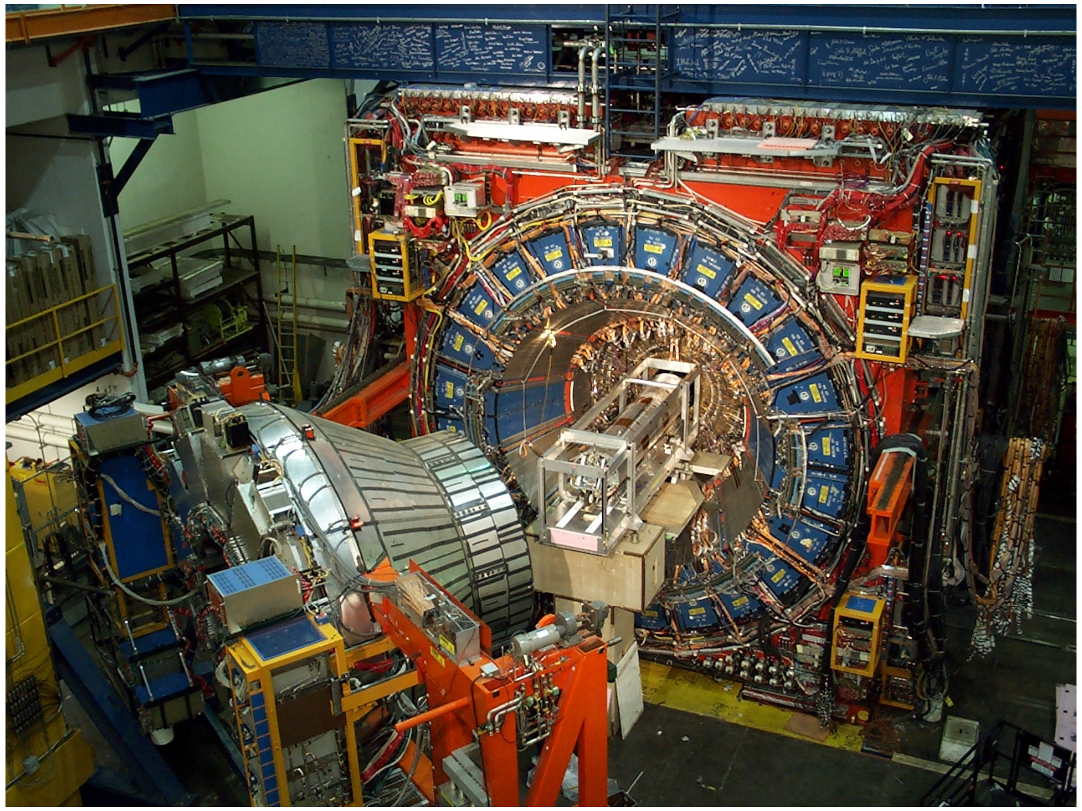
- Build parameterized (tunable) detector model
  - Accurate production model (incl. QED rad. corr.)
  - Calibrate tunable parameters using data (*e.g.* J/ψ, *Z*)

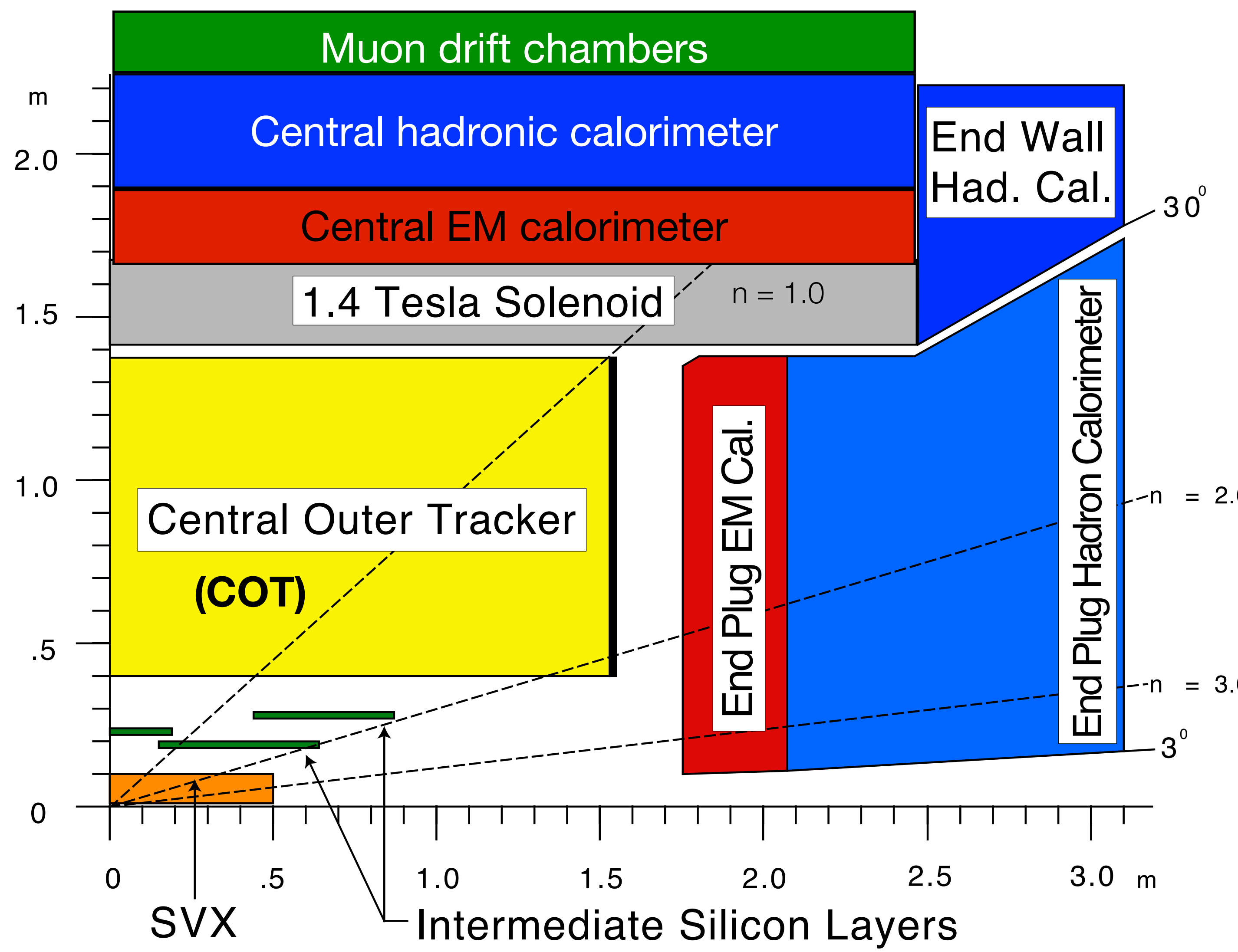






CDF II (2001-2011)





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

Candidate events:

W: 470,126 (*e*); 624,708 (μ)

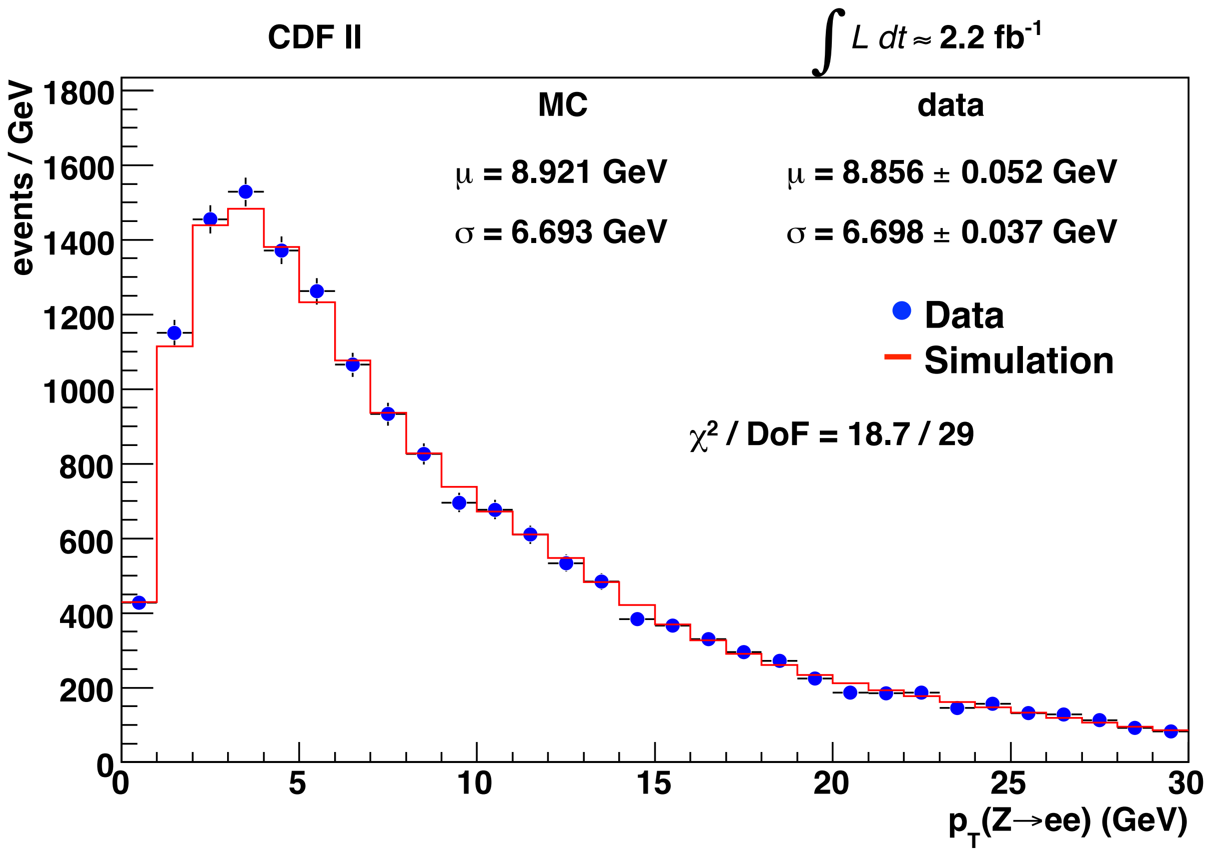
Theoretical model

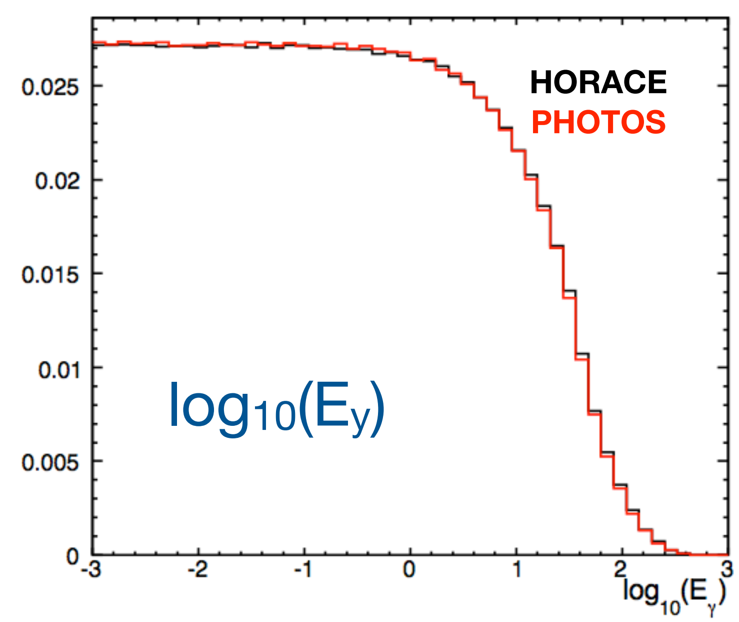
Boson p_T

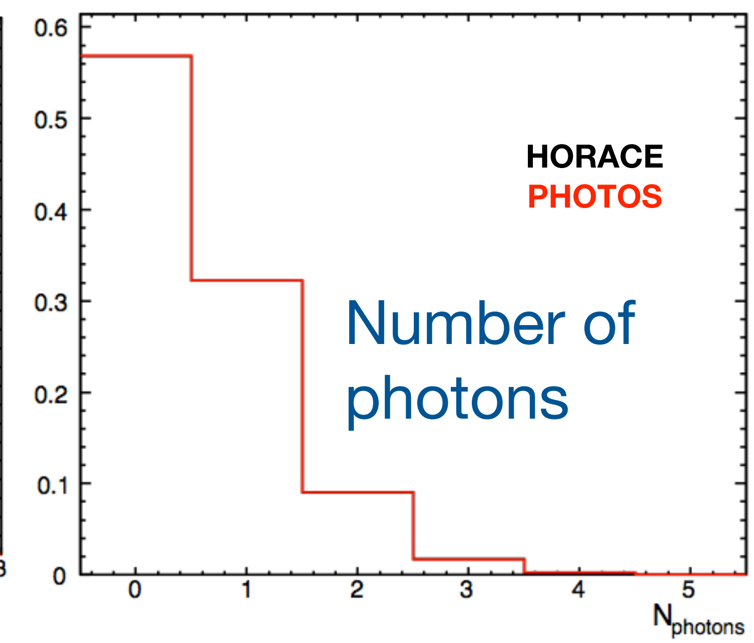
- Calculate at NNLO using RESBOS
- Non-perturbative QCD controlled by tunable parameters
  - Fit parameters with measured Z boson p_T spectrum
- Uncertainty results in ΔM_W = 5 MeV

QED radiation

- Simulate LL FSR photons using PHOTOS
- Cross-check against HORACE
  - Study ISR/FSR, pair creation, etc.
- Uncertainty results in ΔM_W = 4 MeV

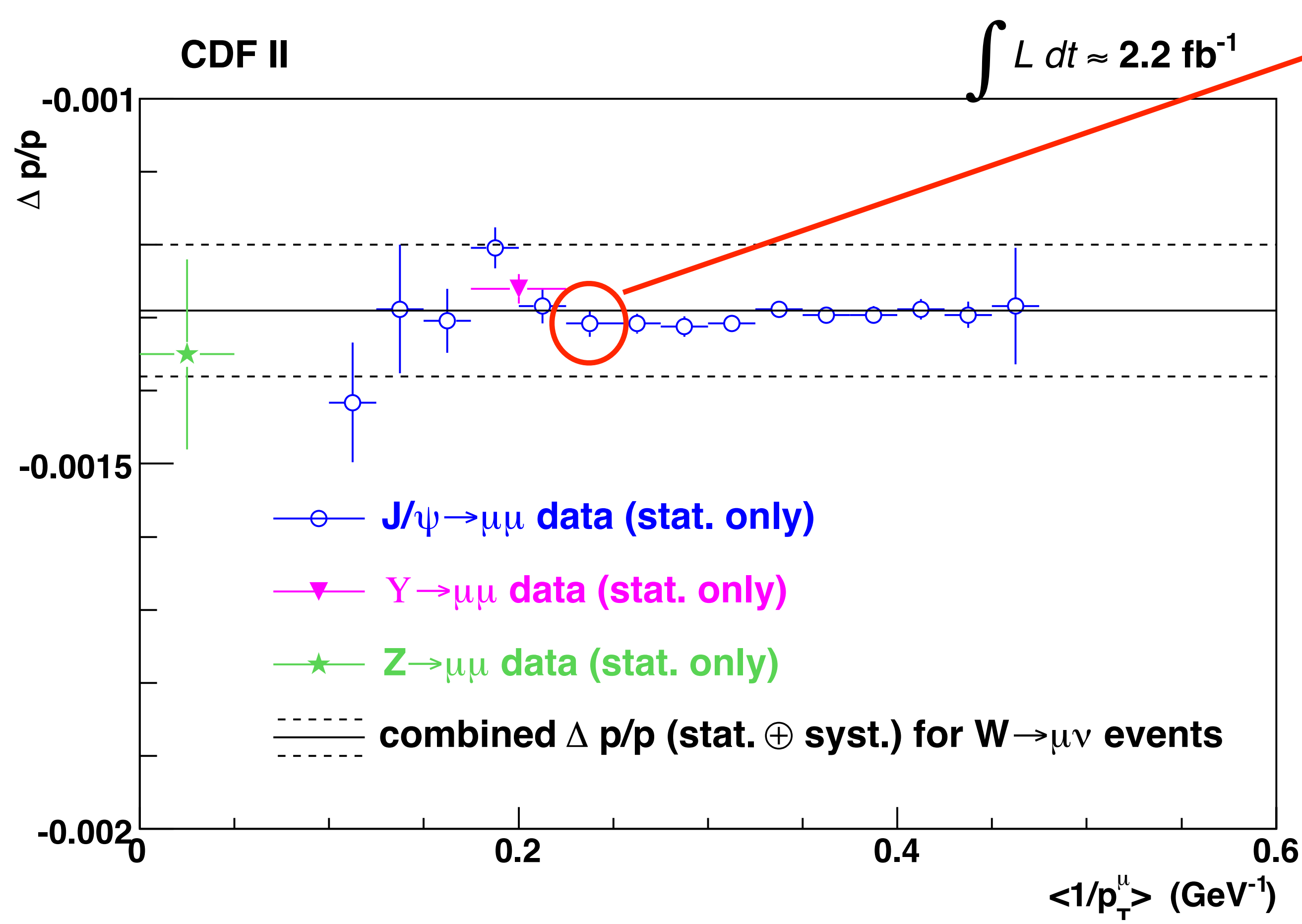


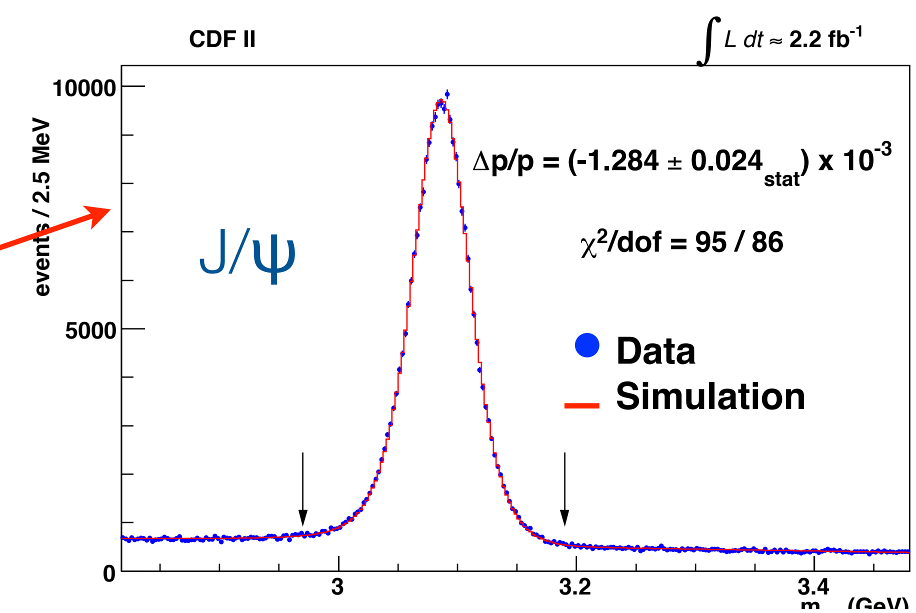


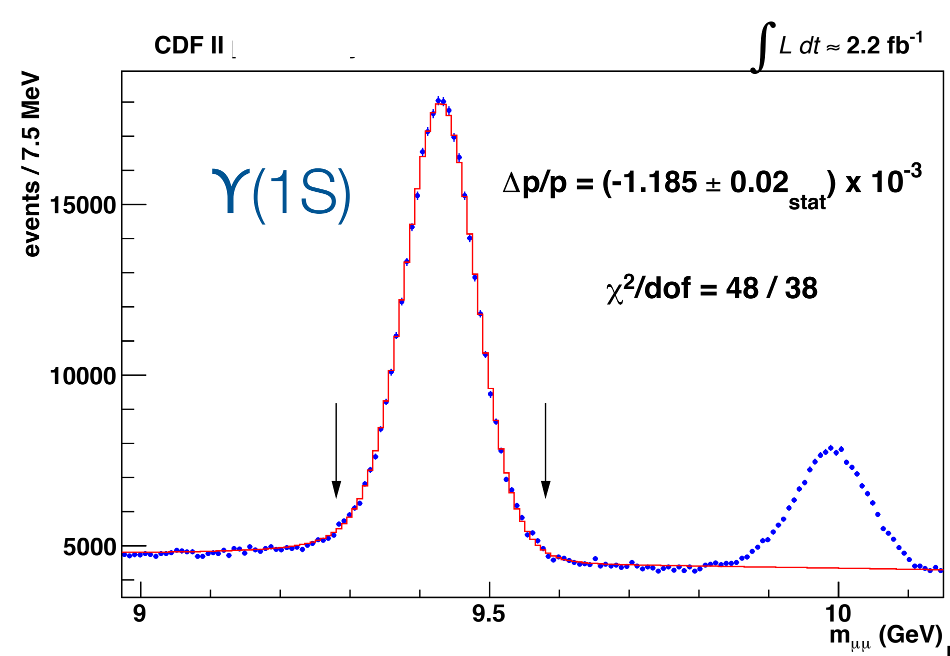


Track momentum scale

- Foundation of analysis is track p_T measurement with the COT
- Perform alignment using cosmic ray data: ~50μm→~5μm residual
- Calibrate scale using large sample of dimuon resonances (J/ψ, ϒ)
  - Span a large range of p_T
  - Flatness is a test of dE/dx modeling
  - Final scale error of 9×10^{-5}

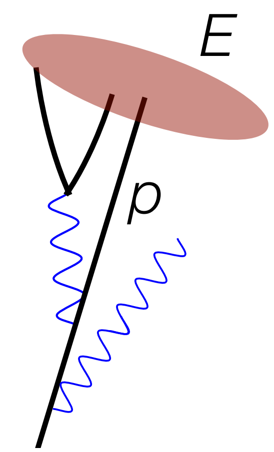


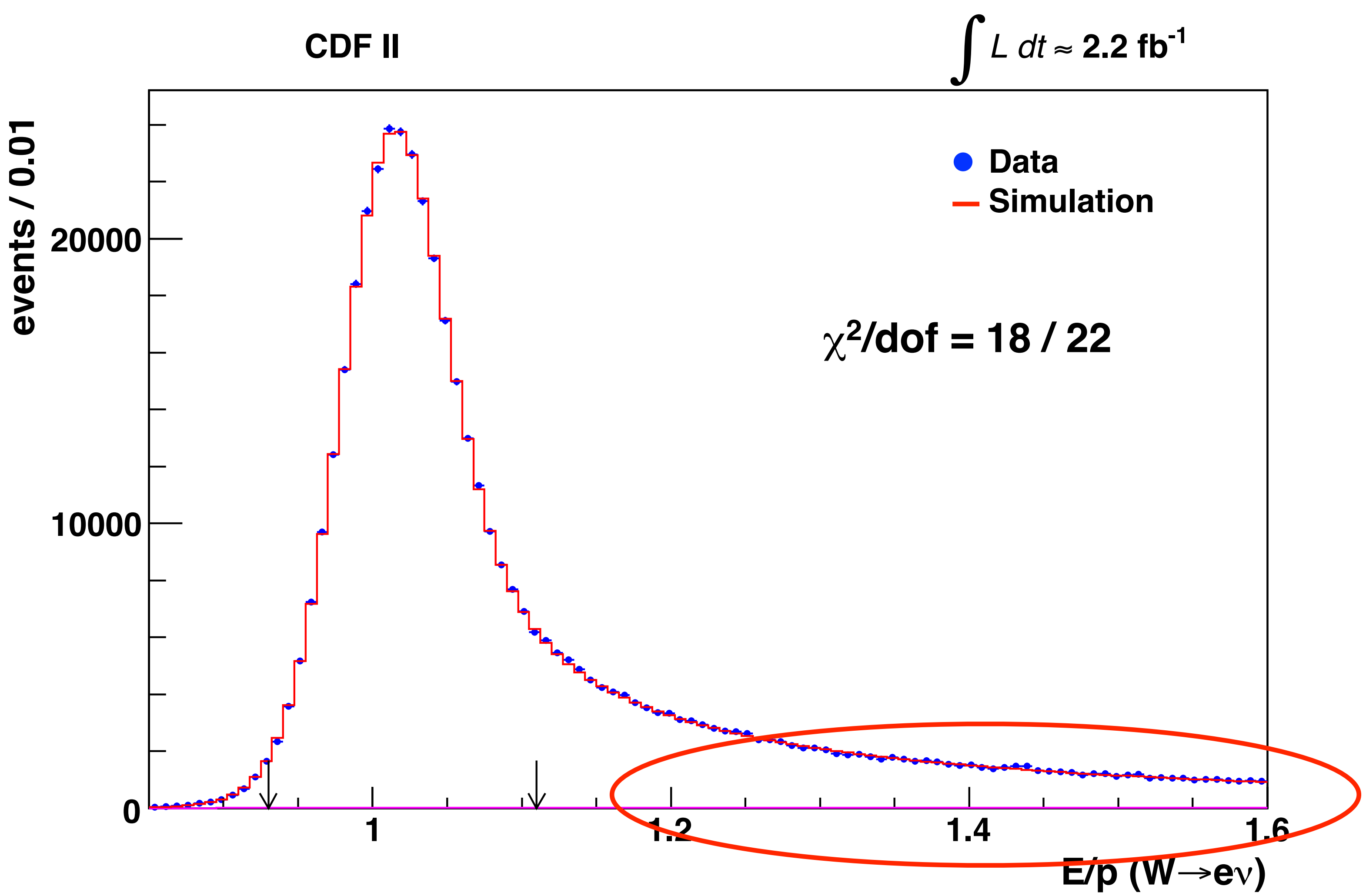


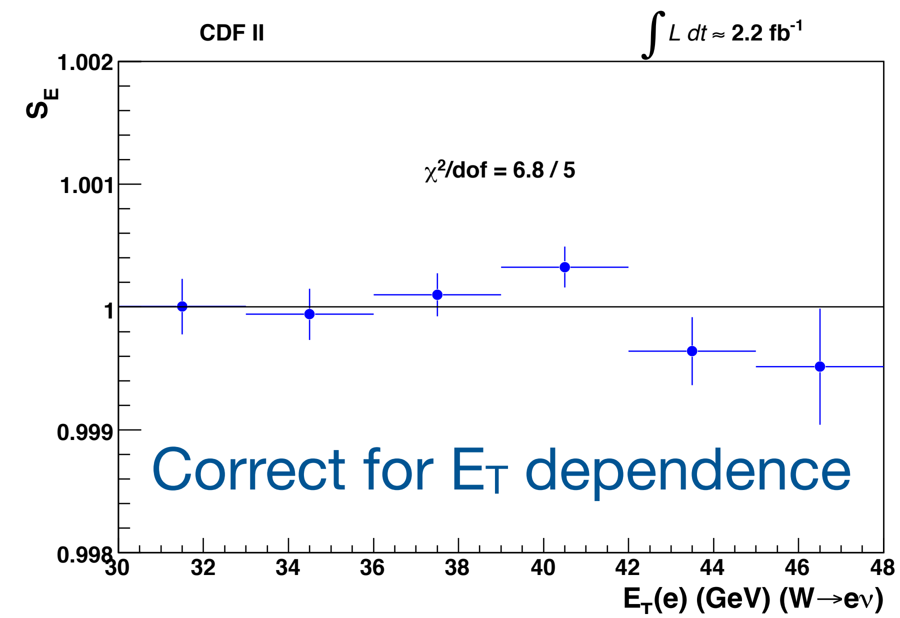


EM energy scale

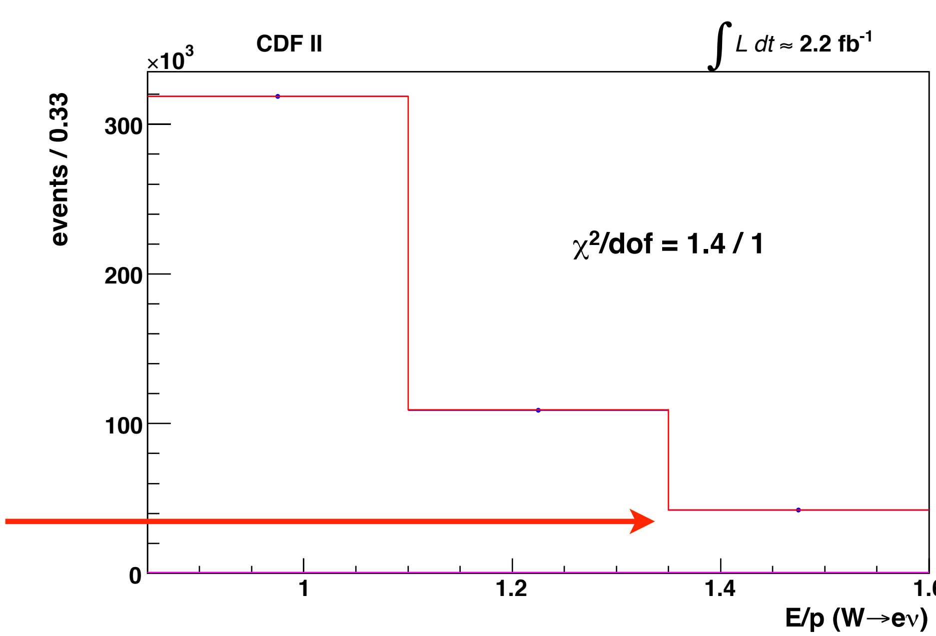
- Apply calibrated track momentum scale to set EM scale
- ***E/p*** of *W* and *Z* events
  - Overall scale from peak
  - Radiative tail used to tune material model





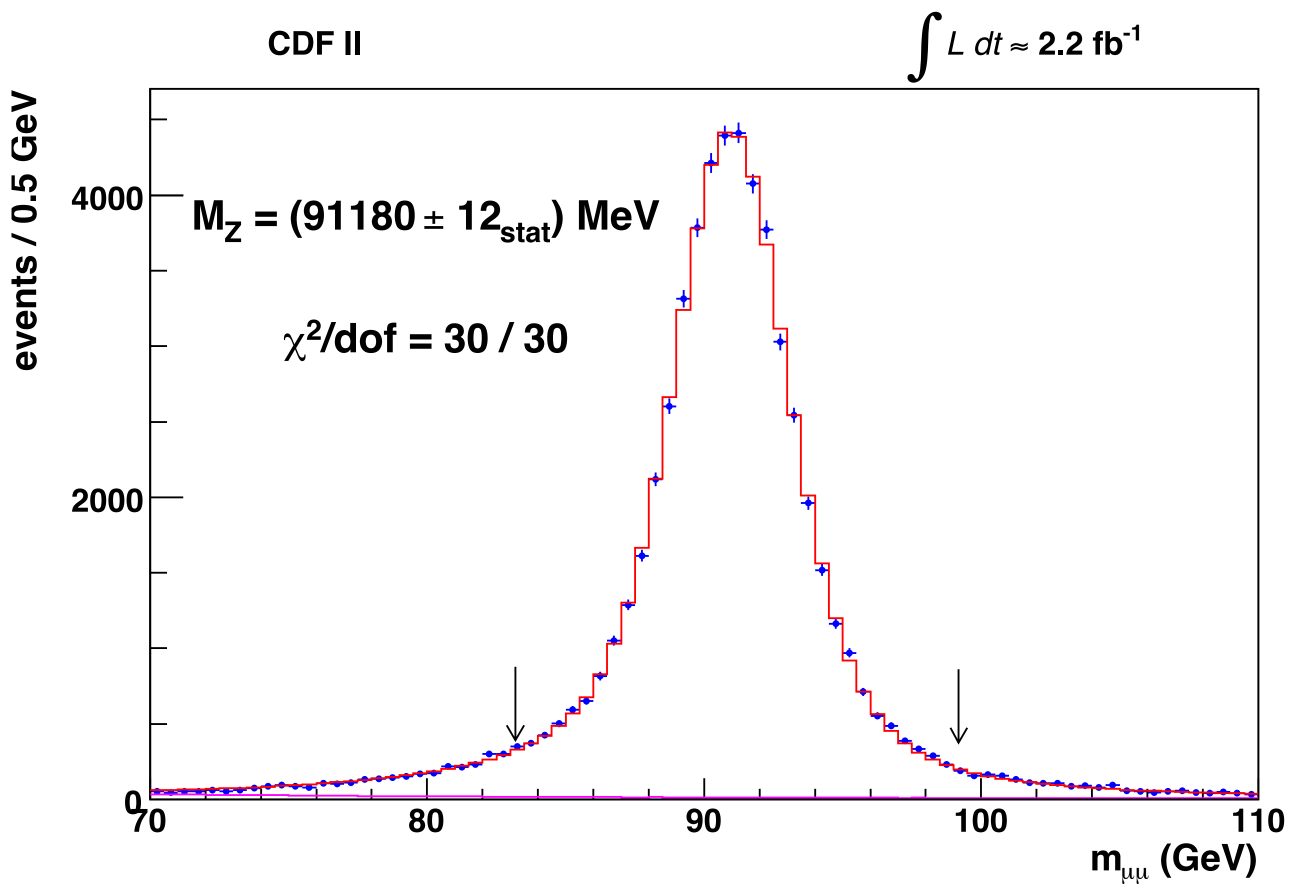


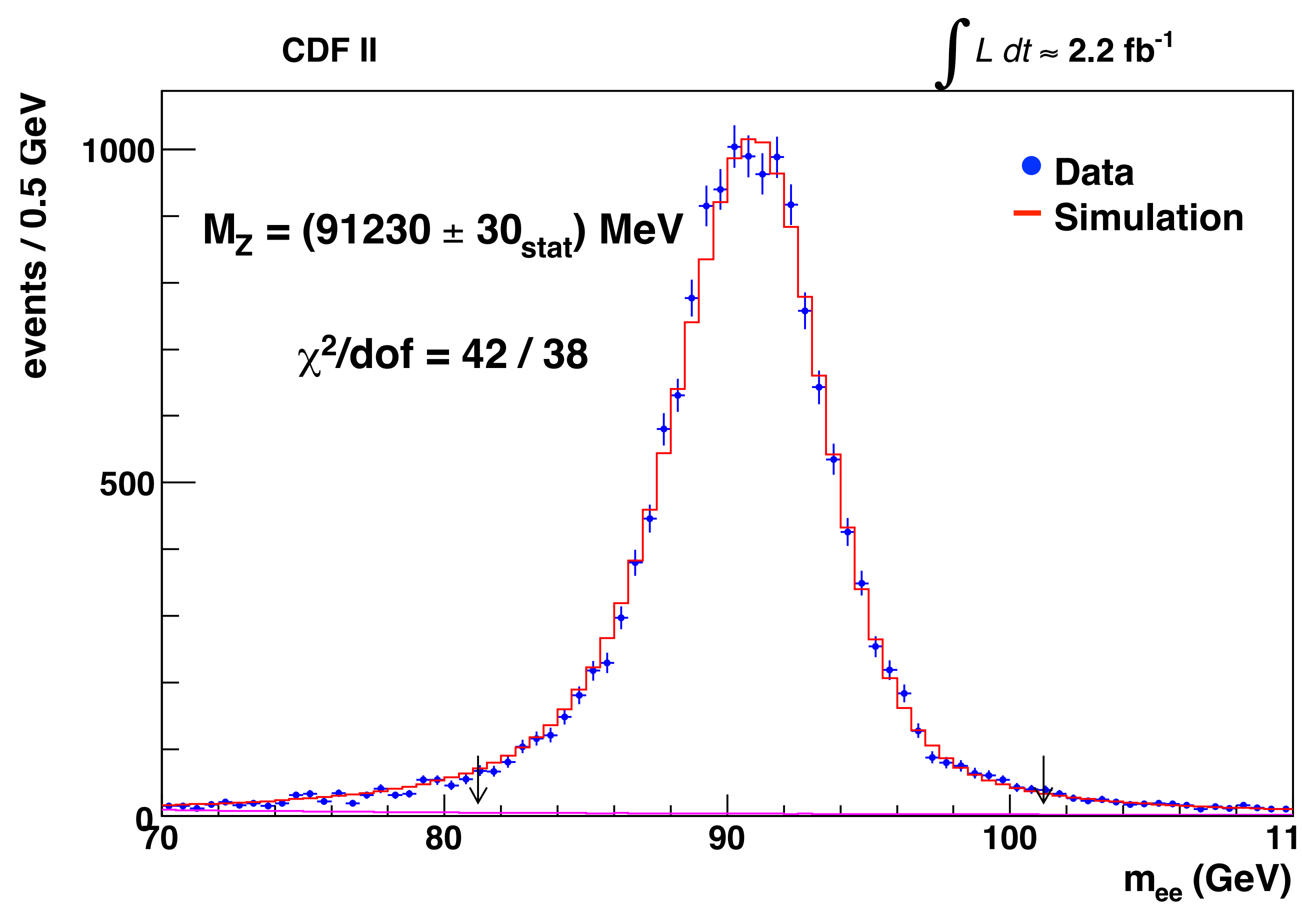
Scale radiative material in simulation



Cross-check and further calibration with M_Z

- Perform blinded measurement of Z mass using scales not calibrated to M_Z
- Most precise measurement of M_Z at a hadron collider!
  - Comparison to LEP value of M_Z=91188±2 MeV is a powerful cross-check of calibration
- After unblinding, M_Z added as further calibration to both track momentum and EM energy scales
  - Combined: $\Delta M_W = 7$ MeV (momentum scale), $\Delta M_W = 10$ MeV (EM scale)

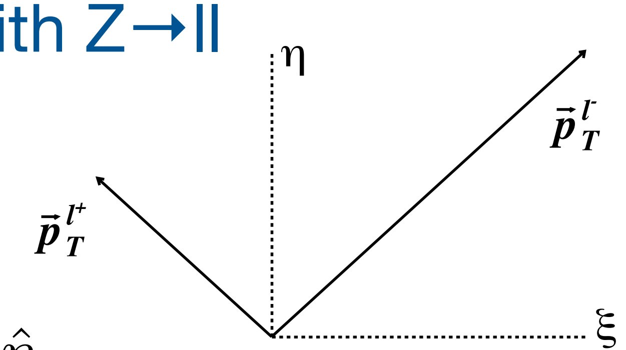




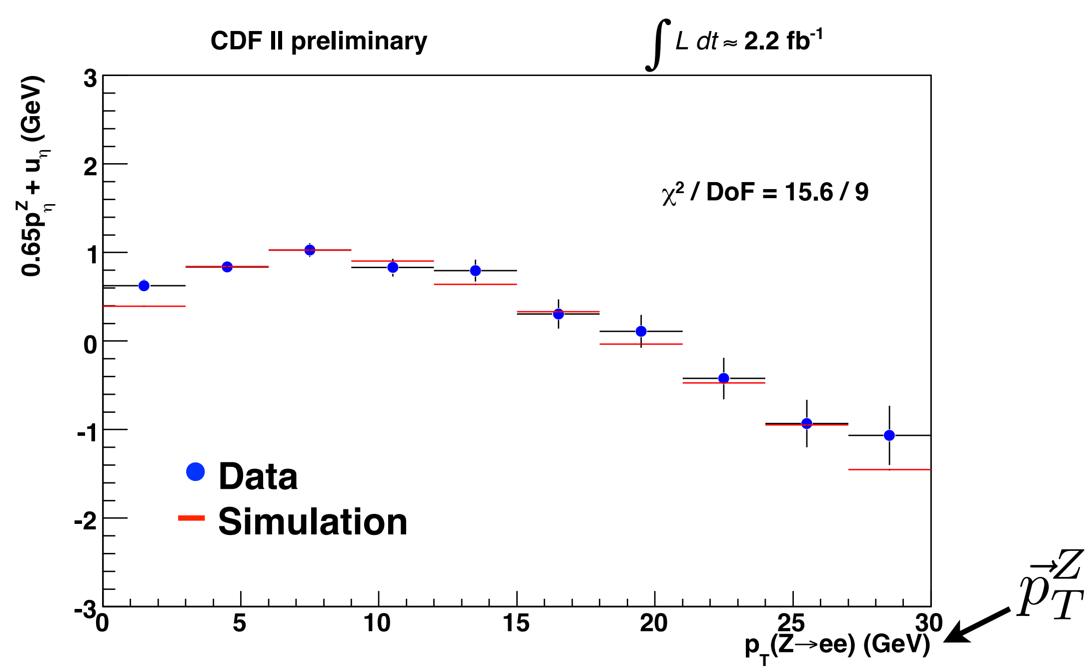
Recoil

- Measured recoil: all calorimeter energy minus measured lepton
  - Contains 1) hard recoil from hadronic activity in W/Z event, 2) underlying event/spectator interaction energy
- Tune using Z and minimum-bias data
- Validate using measured recoil in W events

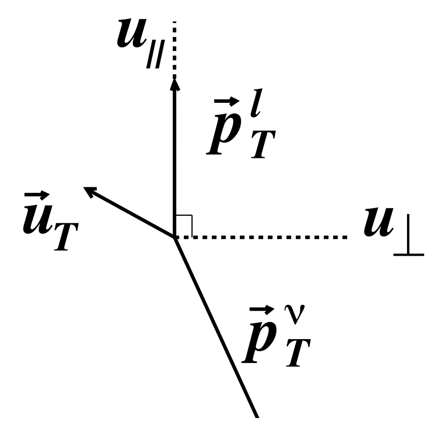
Tuning with Z→ll



$$(\vec{p}_T^{\,Z} + \vec{u}_T) \cdot \hat{\eta}$$



Validating with W→lν

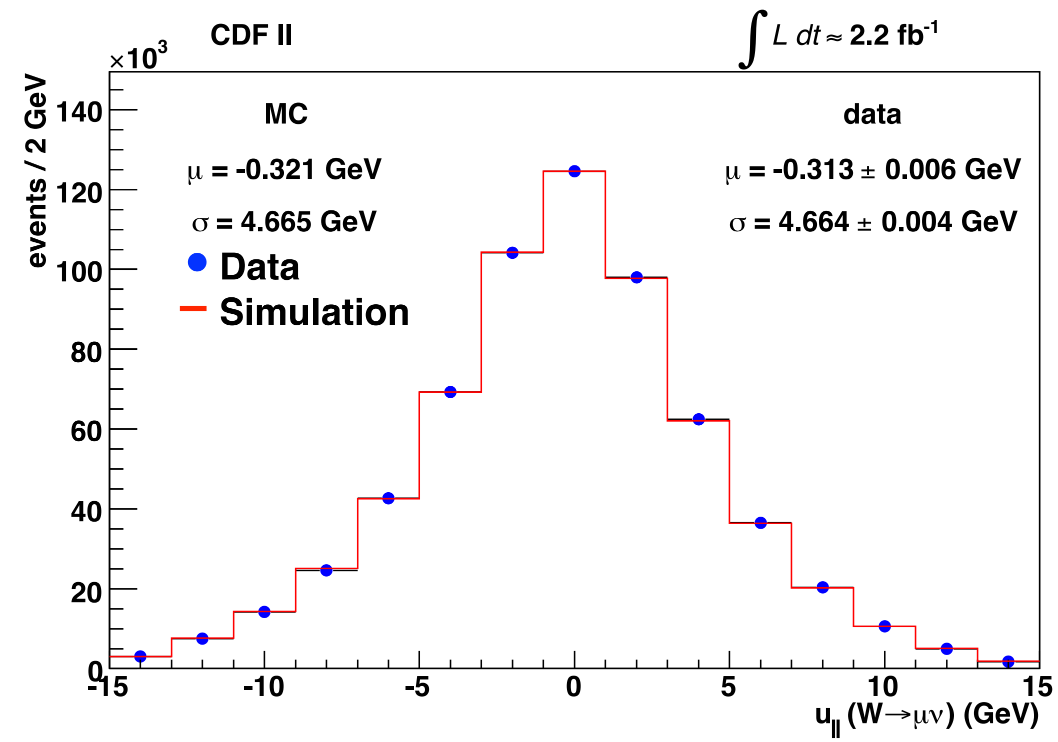


for $u \ll p_T^l$ *:*

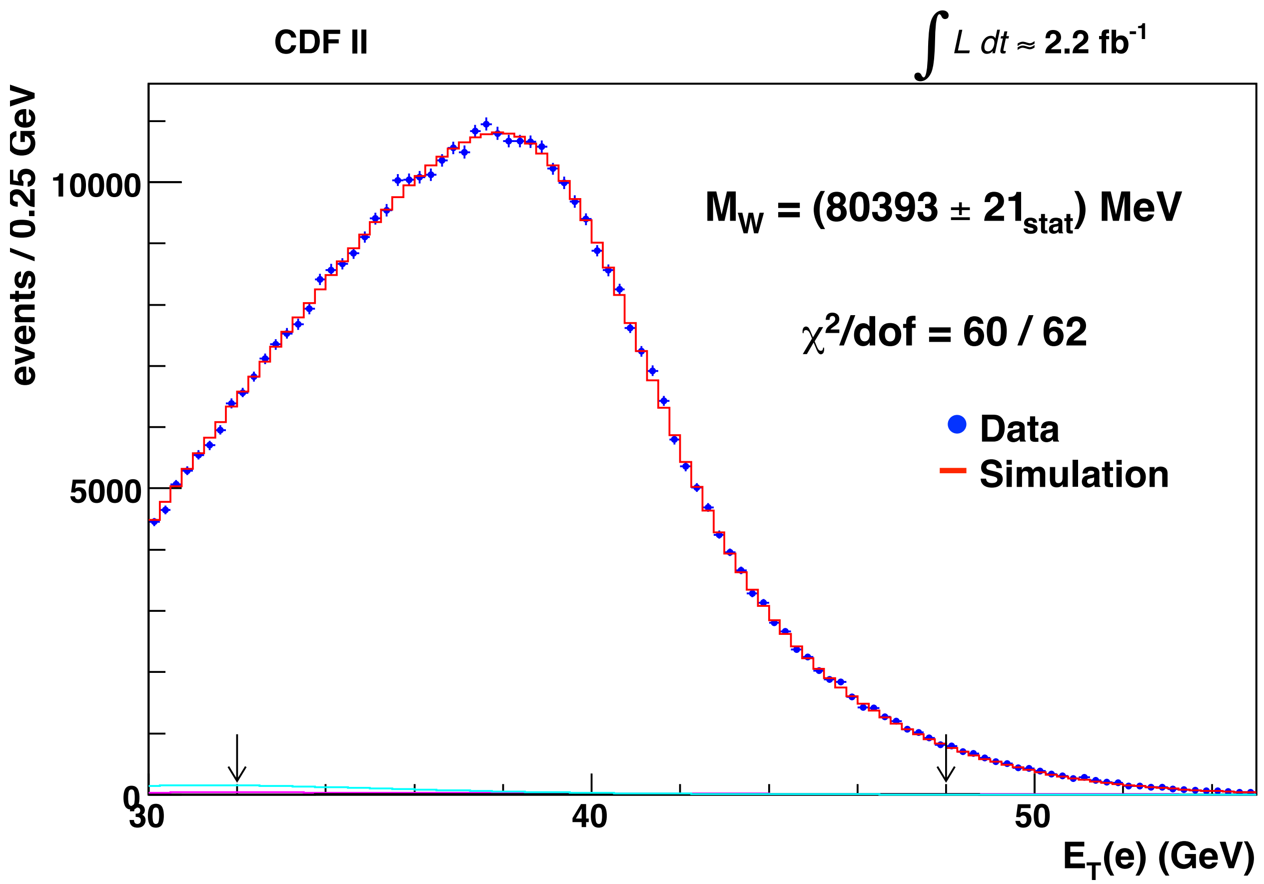
$m_T \approx 2p_T^l + u_{||}$

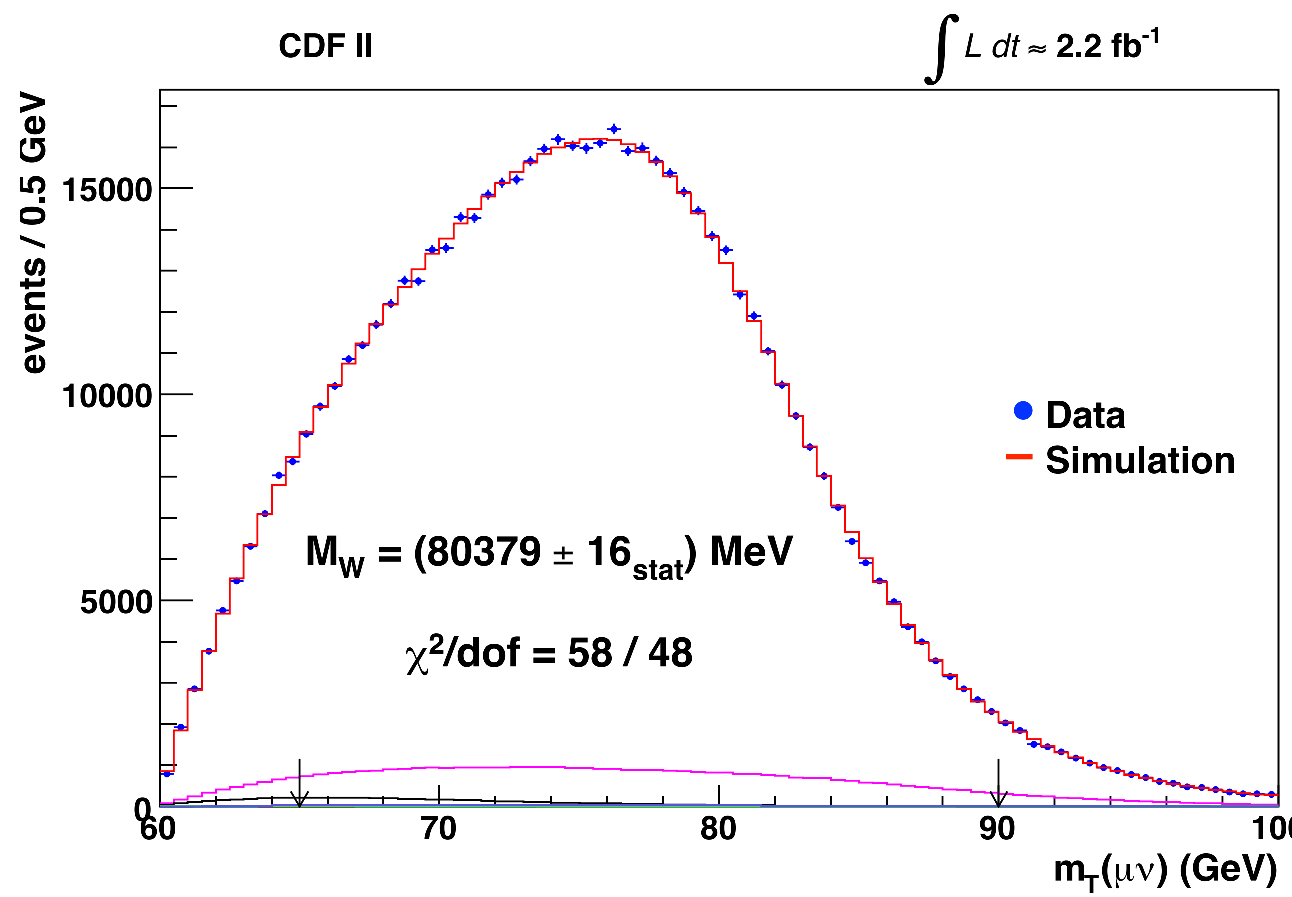
$p_T^\nu \approx 2p_T^l + 2u_{||}$

mis-modeled $u_{||}$ directly biases measured M_W



Example mass fits



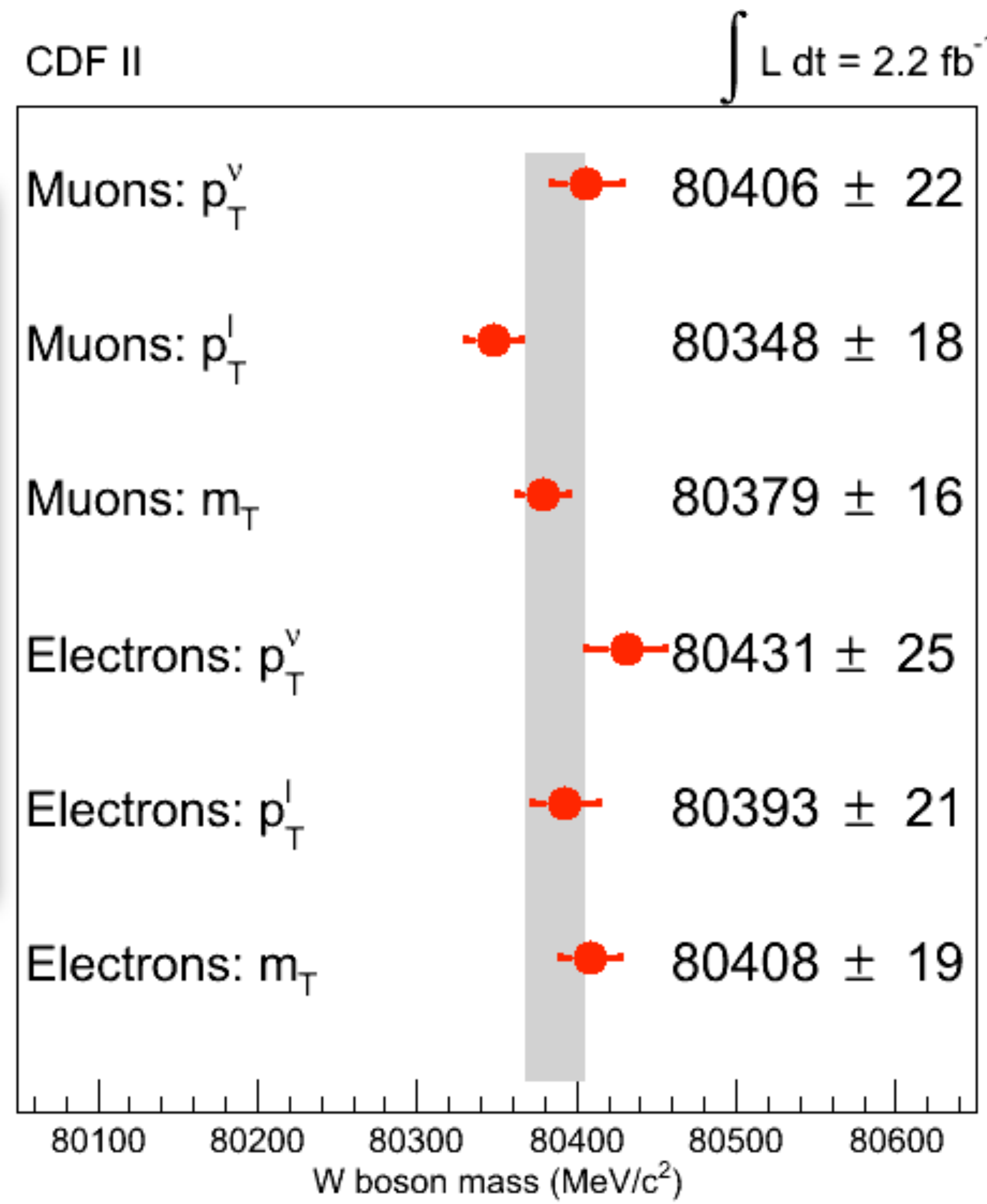


p_T^l: electrons **m_T: muons**

- All fits kept **blinded** during analysis
  - Random, common, offset from [-75,+75] MeV added to all fits
  - Offset only removed after analysis is frozen

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

  $\boldsymbol{M_W}$ **= 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***

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

Combined uncertainties

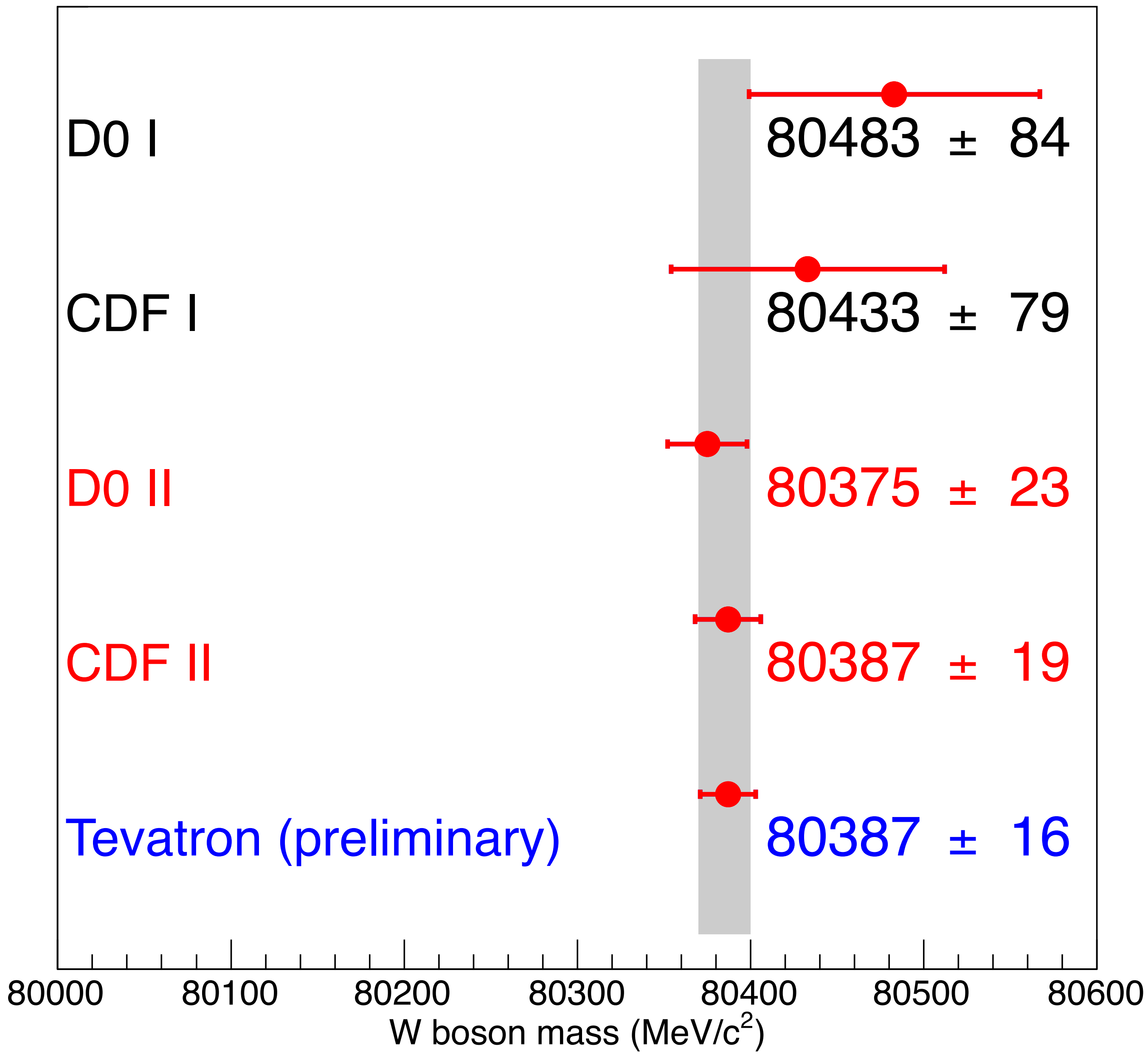
Statistics limited by control data

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***

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

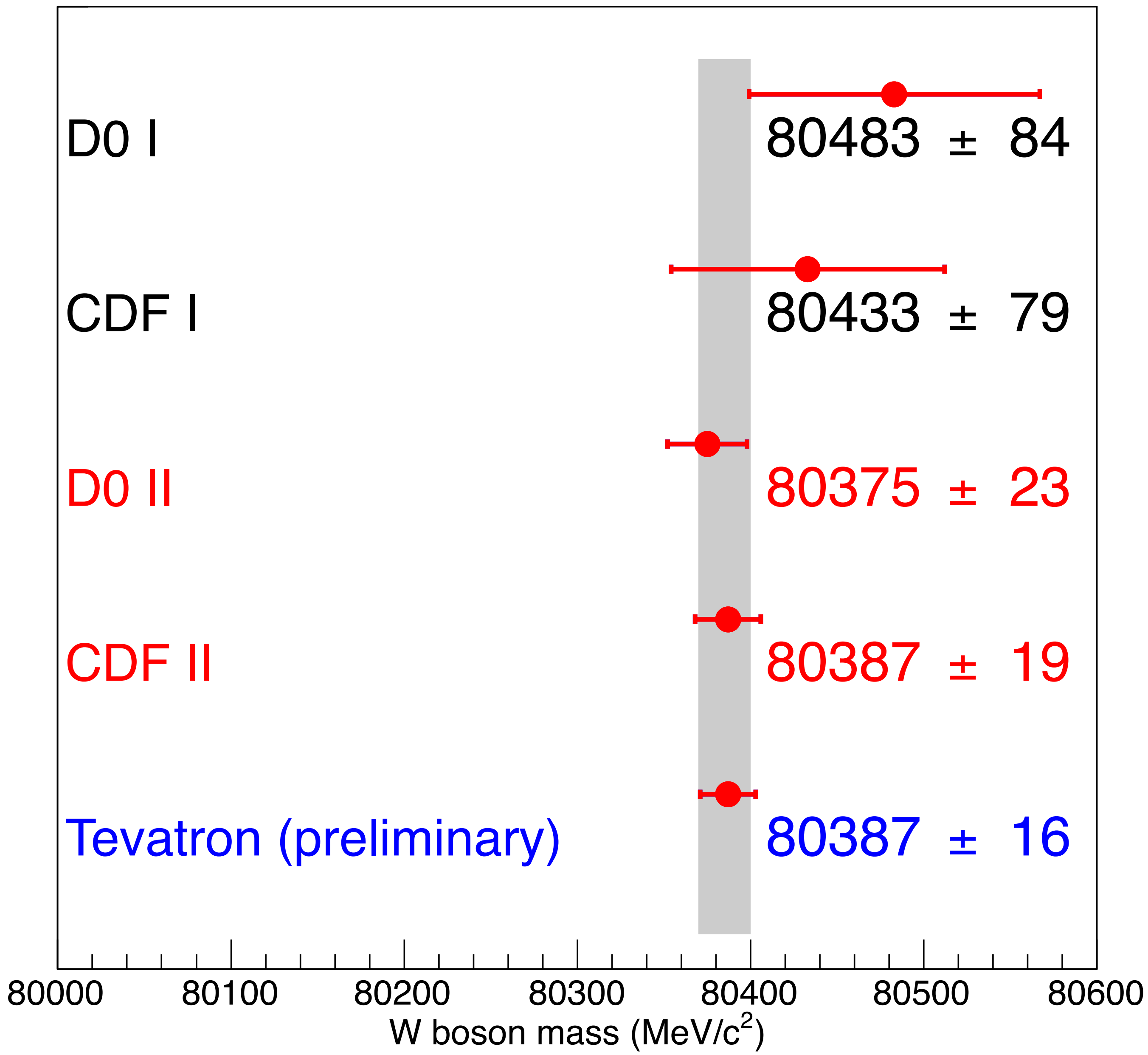
Tevatron and world combinations

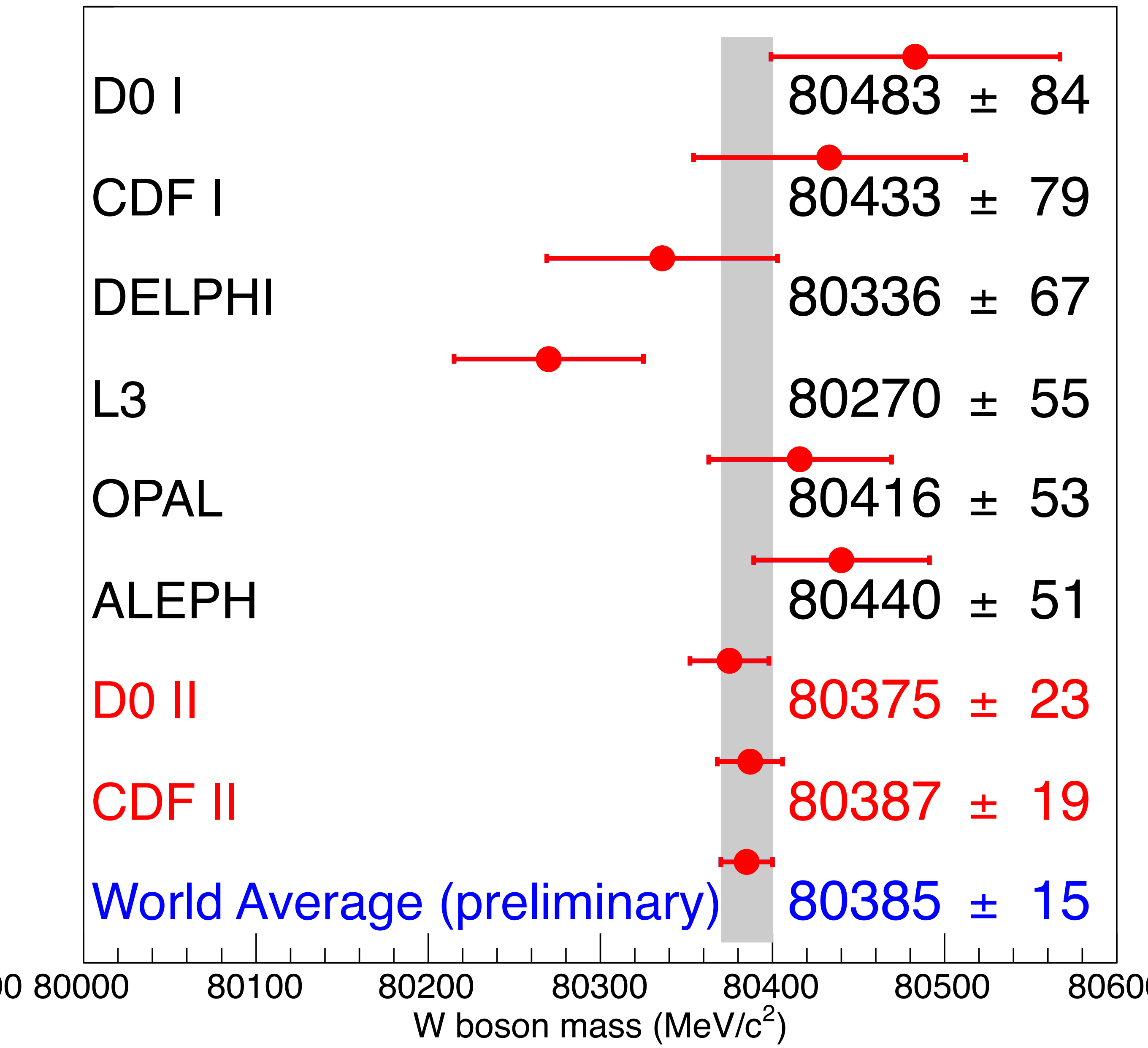


nb: 2009 world average

M_W = 80399±23 MeV

Tevatron and world combinations





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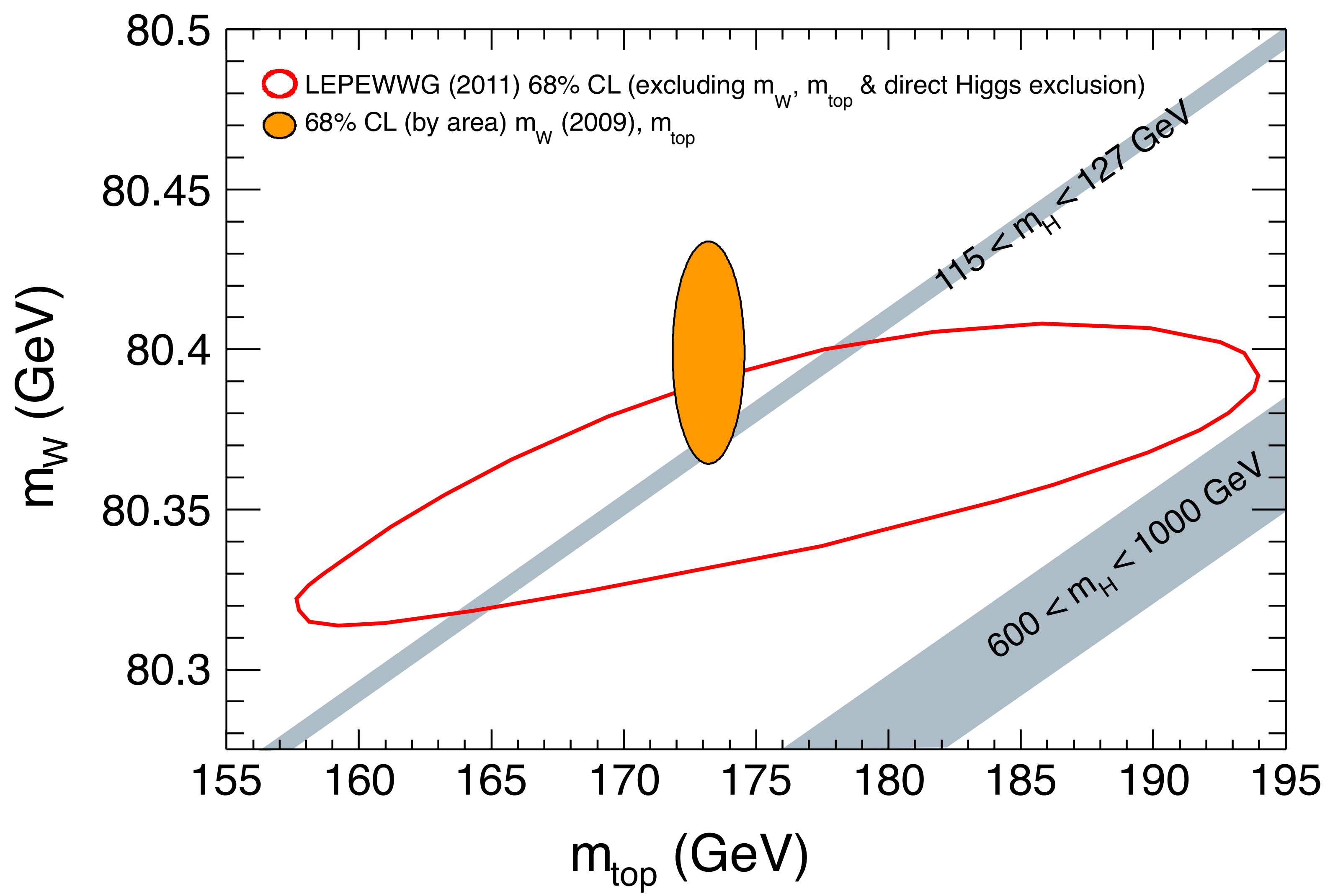
M_W = 80399±23 MeV

W mass vs. top mass

With M_W = 80399±23 MeV

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

LEPEWWG/ZFitter

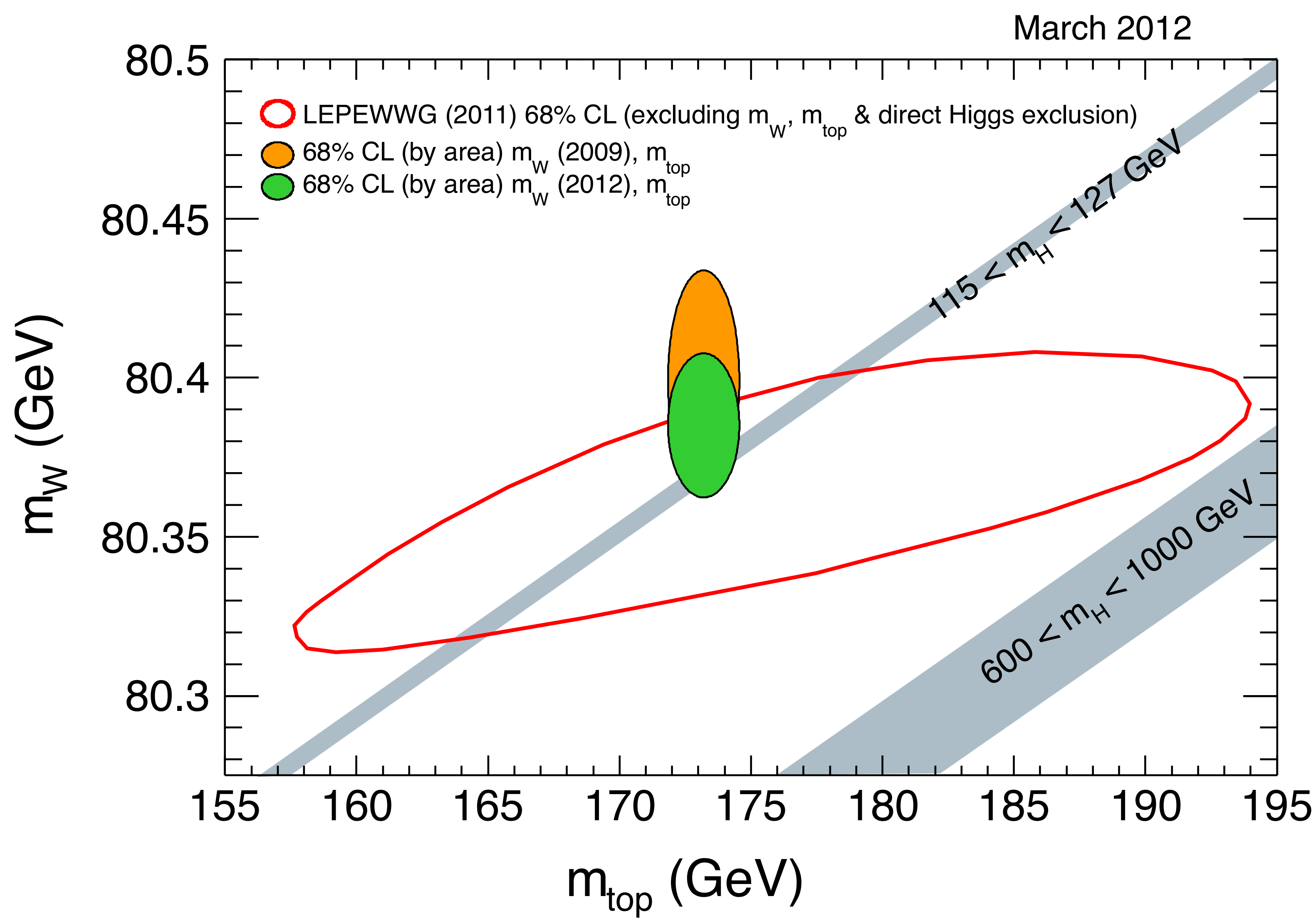


W mass vs. top mass

With M_W = 80385±15 MeV

$M_H = 94^{+29}_{-24}$ GeV
M_H < 152 GeV @95% CL

LEPEWWG/ZFitter



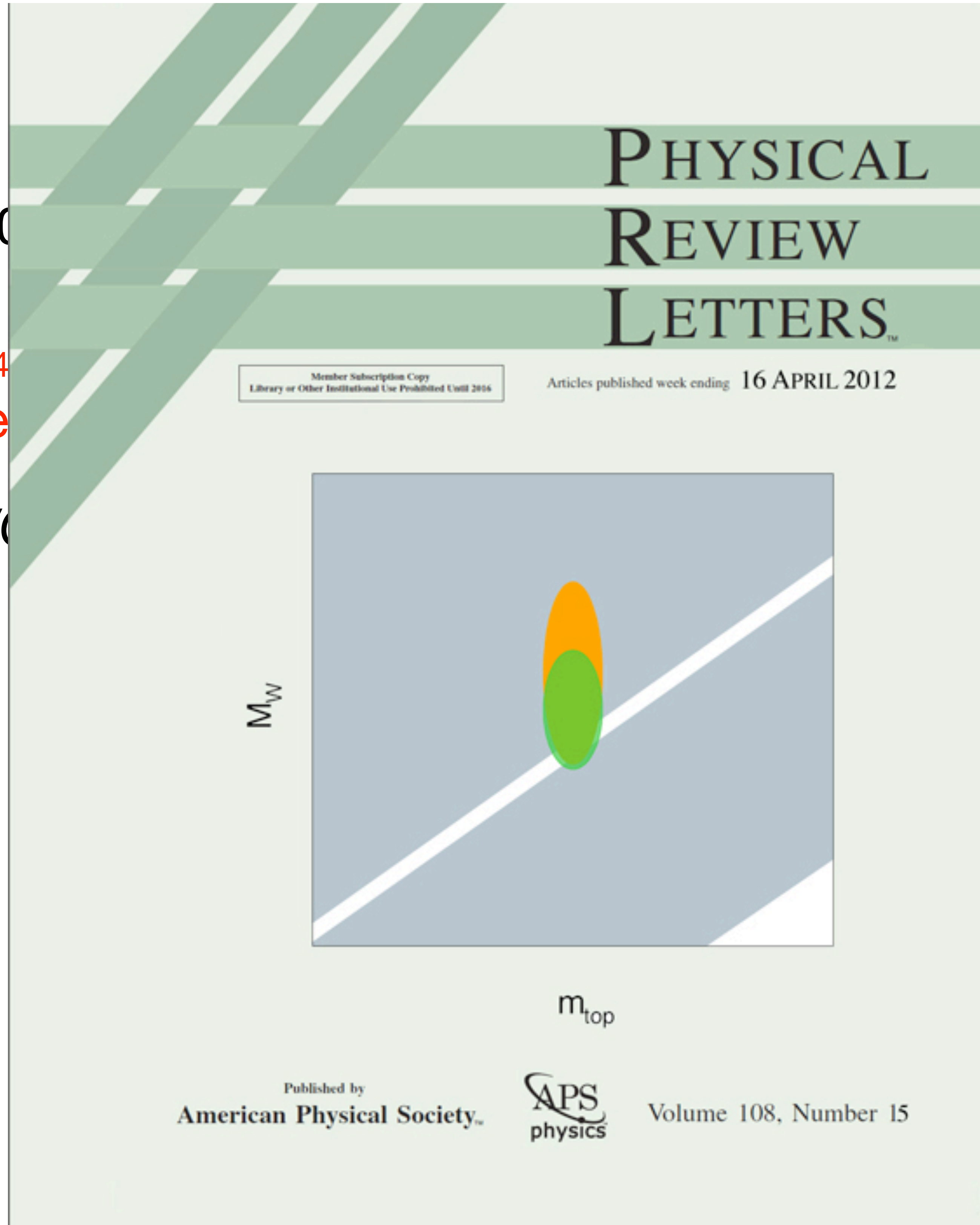
W mass vs. top mass

With M_W = 80

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

M_H < 152 Ge

LEPEWWG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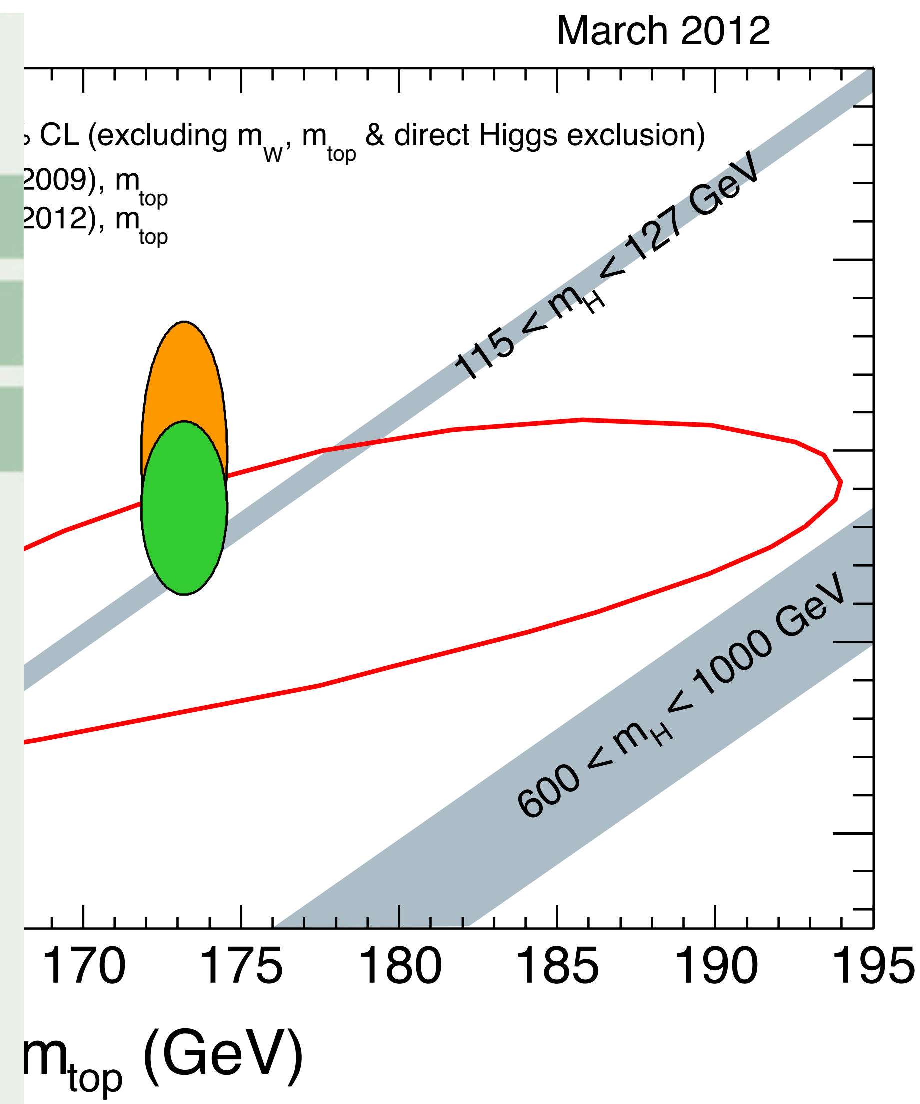

CDF: PRL **105**, 151803 (2012)
DØ: PRL **105**, 151804 (2012)
PRL Editors' Suggestions

And finally...

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    - ΔM_W = 16 MeV is a true legacy measurement

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http://www-cdf.fnal.gov/physics/ewk/2012/wmass/

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Review committee: F. Bedeschi, M. Shochet, B. Ashmanskas, K. Hatakeyama

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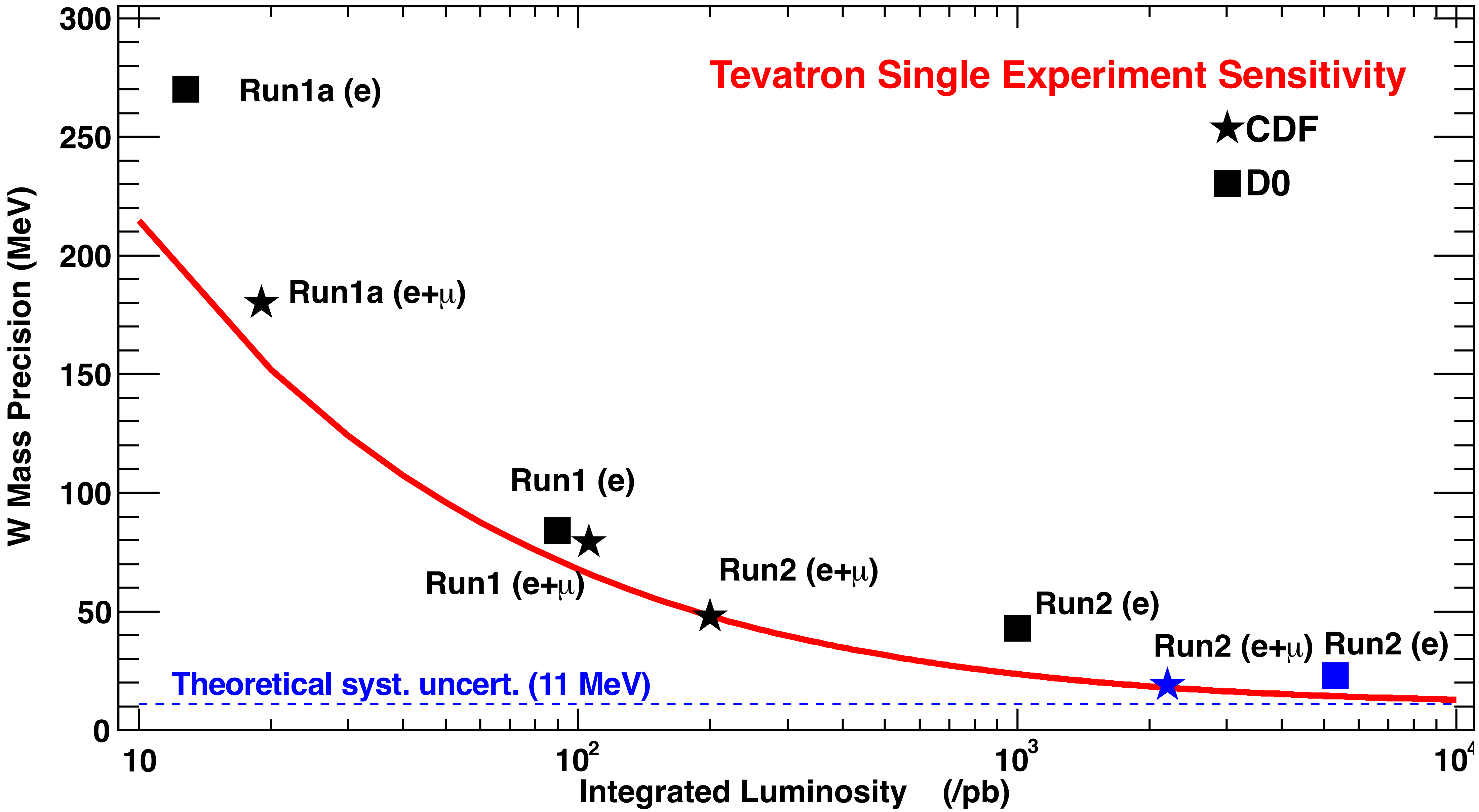
- Thanks to the URA, Tollestrup award committee, and UEC

Backup

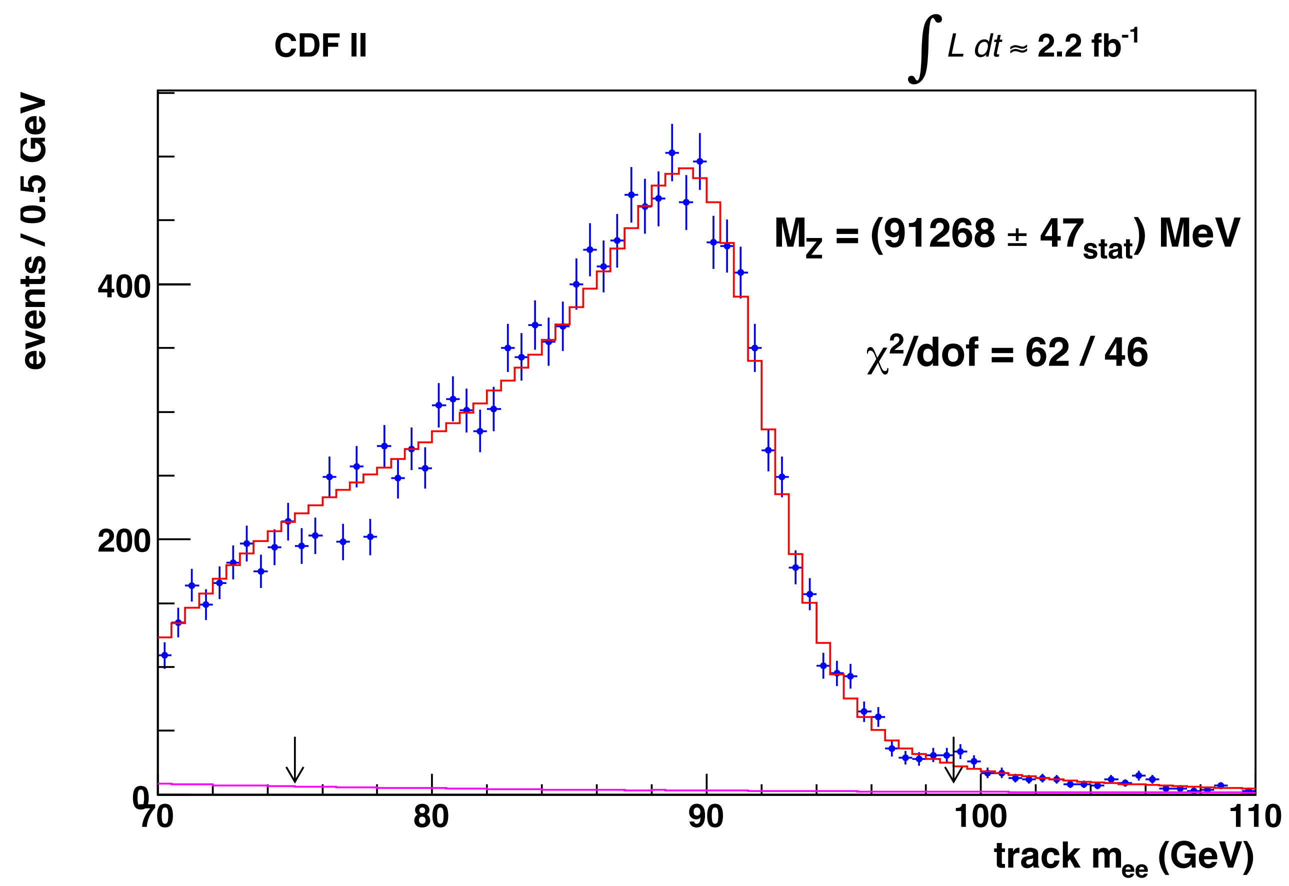
Uncertainty projections



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

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



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	
$Z \to ll$	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 (blue columns) / electrons (yellow columns)

Uncertainty progress