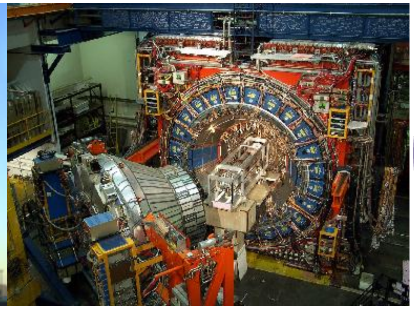


The Mass of the W Boson

(and, maybe, a few other selected topics)

Dave Waters

on behalf of the UCL-CDF group :

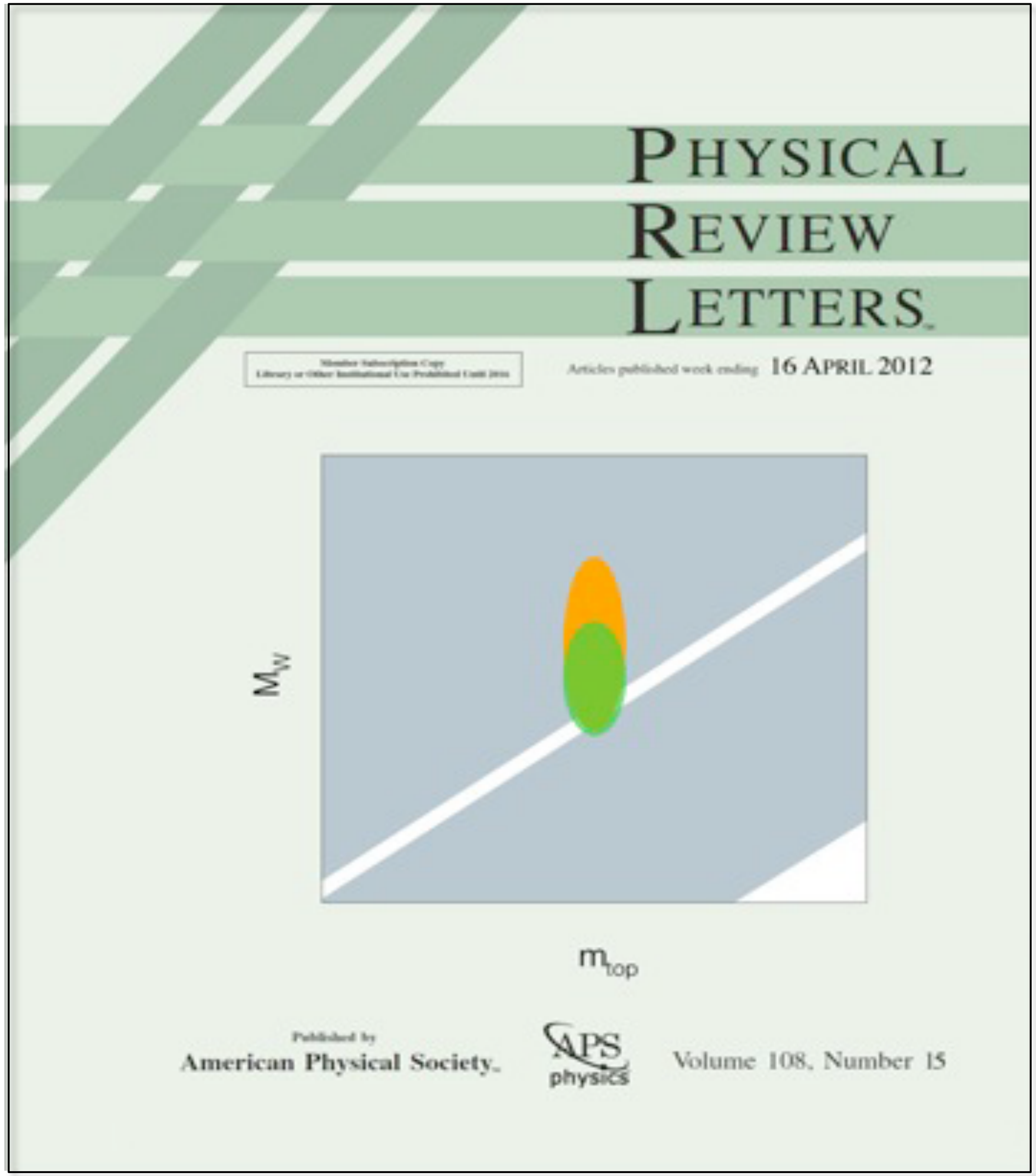
Dan Beecher, Ilija Bizjak, Ben Cooper, Mark Lancaster, Sarah Malik, Emily Nurse, Tom Riddick, Troy Vine

Tevatron Run II

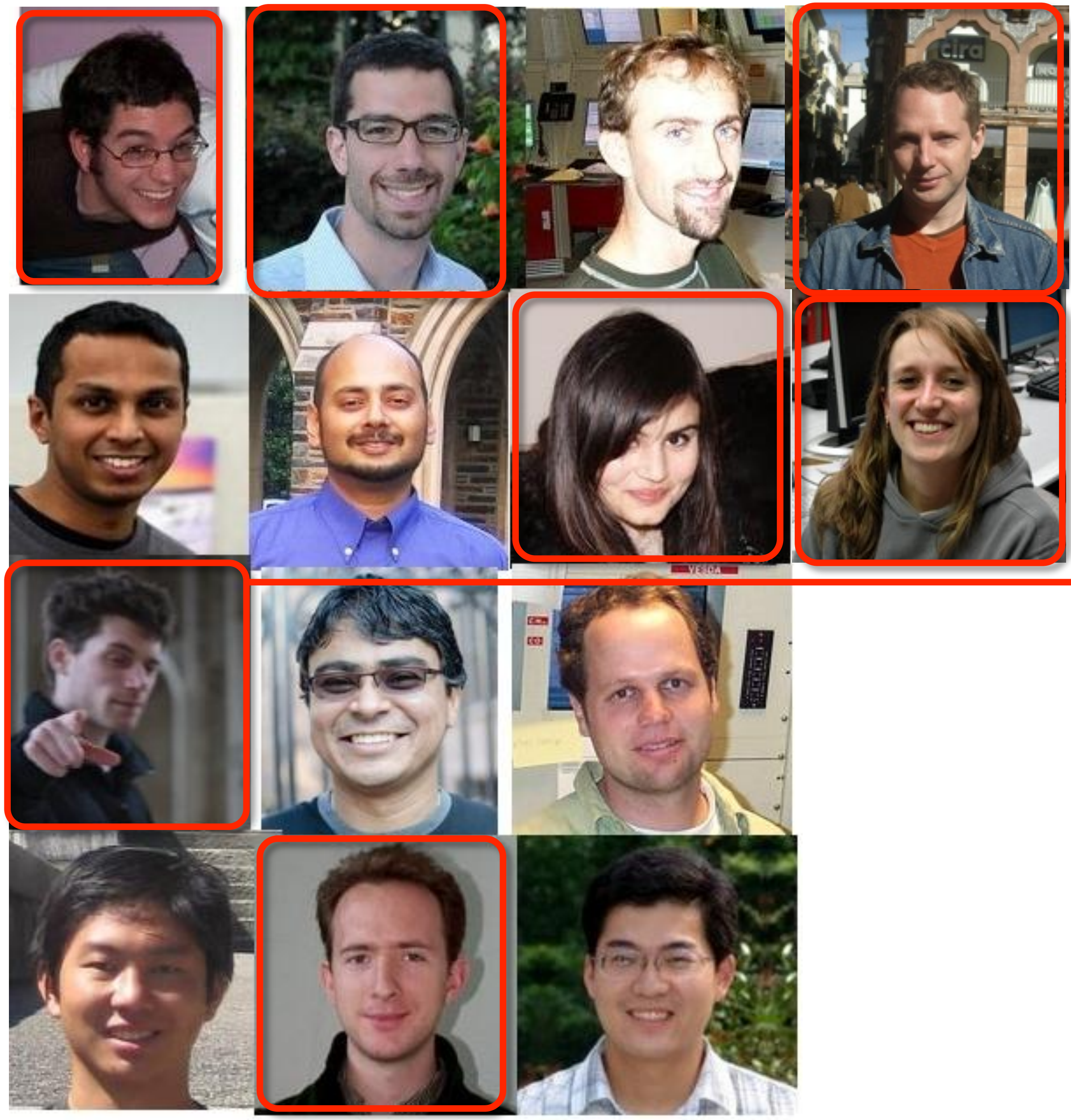
<u>1st March 2001 – 30th September 2011</u>

- 12 fb^{-1} delivered to CDF and DØ ➔ ~10 fb^{-1} good data on tape.

W Mass


PHYSICAL
REVIEW
LETTERS
Articles published week ending 16 APRIL 2012
M_W
m_top
Published by
American Physical Society.
APS
physics
Volume 108, Number 15

W Mass



Afghanistan
Kabul
Islamabad
Borders of Kashmir are in dispute; India, Pakistan and China have differing claims.
China
Pakistan
Srinagar
Jammu
Amritsar
Chandigarh
Simla
New Delhi
Nepal
Kathmandu
Bhutan
Bangladesh
Dhaka
Jaipur
Agra
Lucknow
Kanpur
Allahabad
Varanasi
Gandhinagar
Ahmadabad
Bhopal
Jabalpur
Calcutta
Jamshedpur
India
Raipur
Bhubaneshwar
Cuttack
Puri
Myanmar (Burma)
Mumbai
Pune
Hyderabad
Vishakhapatnam
Yangon (Rangoon)
Arabian Sea
Bay of Bengal
Panaji
Marmagao
Bangalore
Chennai
Mangalore
Pondicherry
Cuddalore
Calicut (Khozikode)
Kavaratti
Madurai
Tiruvanantapuram
Sri Lanka
Andaman Islands (India)
Port Blair
Nicobar Islands (India)
©1997 MAGELLAN Geographix (805) 685-3100 www.maps.com

W Width

Γ_W = 2032 ± 73 MeV (CDF-UCL 2007)

How Well do we Know our Forces ?

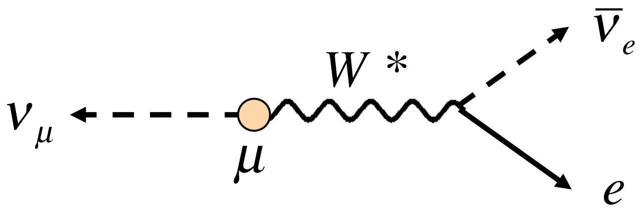
Force	Carrier	Mass	Lifetime
EM	Photon	$< 10^{-16}$ eV	stable
Strong	Gluon	< few MeV	stable
Weak NC	Z^0	91.1876 ± 0.0021 GeV	$1/\tau$ = 2.4952 ± 0.0023 GeV
Weak CC	$W^\pm$	80.399 ± 0.023 GeV	$1/\tau$ = 2.085 ± 0.042 GeV **(directly measured : UCL CDF 2008)**

2011

$$\frac{\Delta M_W}{M_W} \Big/ \frac{\Delta M_Z}{M_Z} \approx 12 \qquad \frac{\Delta \Gamma_W}{\Gamma_W} \Big/ \frac{\Delta \Gamma_Z}{\Gamma_Z} \approx 22$$

EWK Precision Measurements : Big Picture

- Electroweak standard model relates precisely known parameters and less well known parameters through radiative corrections :



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

$\alpha_{em}(0) = 1/137.03599911(46)$

$M_Z = 91.1876(21)\ \text{GeV}$

$$G_F = \frac{\pi \alpha_{em}}{\sqrt{2} M_W^2 (1 - M_W^2 / M_Z^2)} \cdot \frac{1}{(1 - \Delta r)}$$

Δr : **radiative corrections (zero at tree level)**

rearranging

$$M_W = f(\alpha_{em}(0), G_F, M_Z, \Delta r)$$

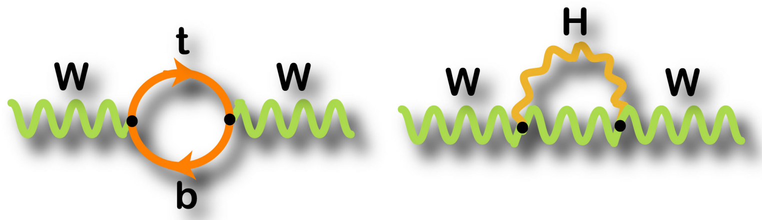
extremely well known

what goes into Δr ?

W Mass : Playing Precision Catch-Up

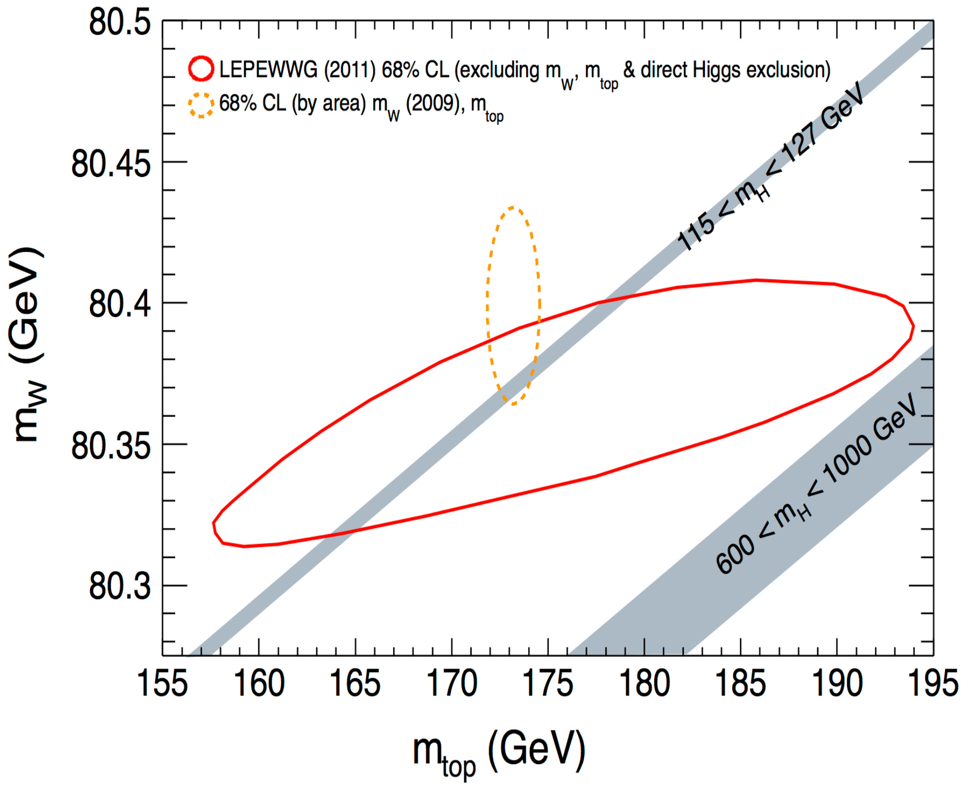
- Radiative corrections to **M_W** include those due to **top** and **Higgs** :

$$\Delta M_W \propto M_{top}^2$$



$$\Delta M_W \propto \ln M_H$$

- Equivalently, measuring **M_W** and **M_{top}** places constraints on the missing piece, **M_H**.



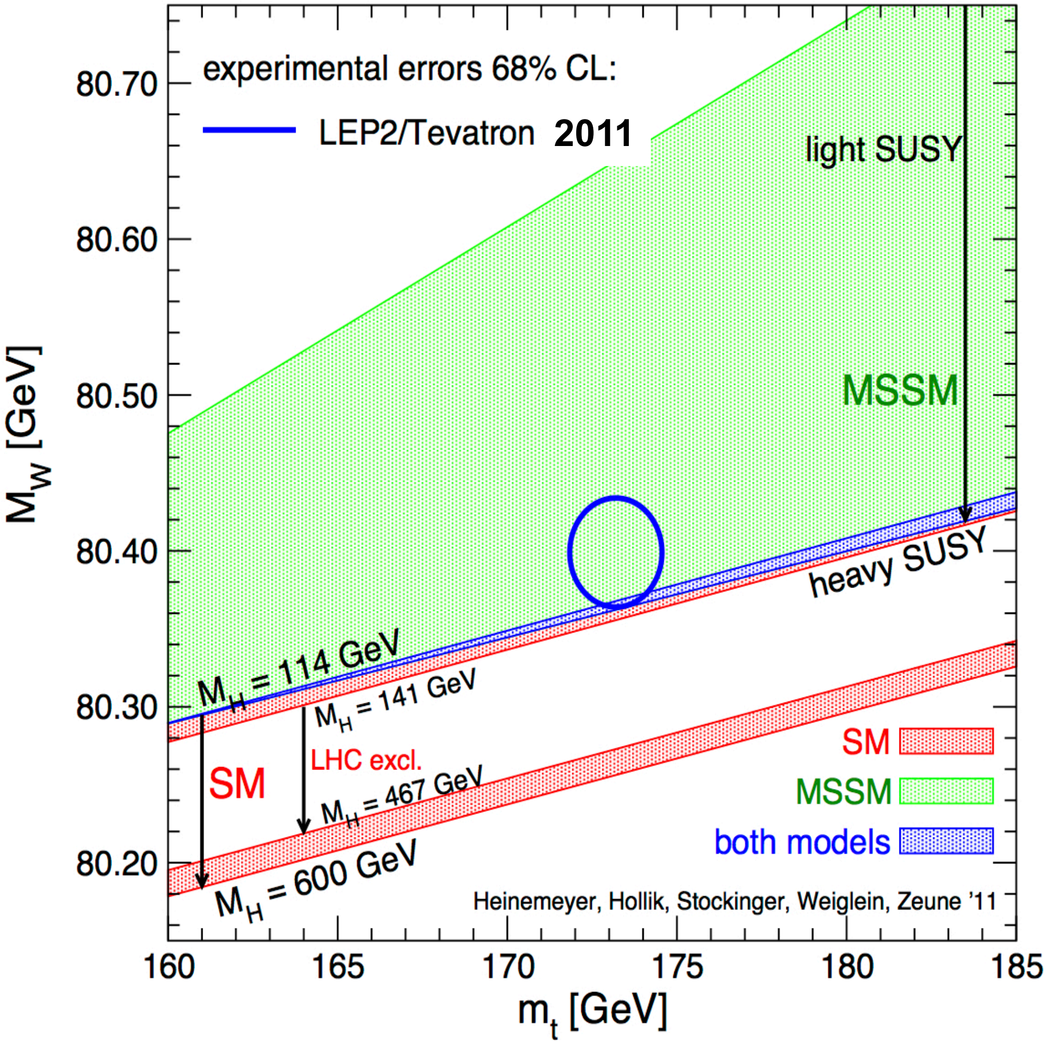
$$M_H = 92^{+34}_{-26}\ \text{GeV} \quad \text{(LEP EWWG, 2011)}$$

- How do **M_W** and **M_{top}** inputs compare ?
- Current top mass precision :

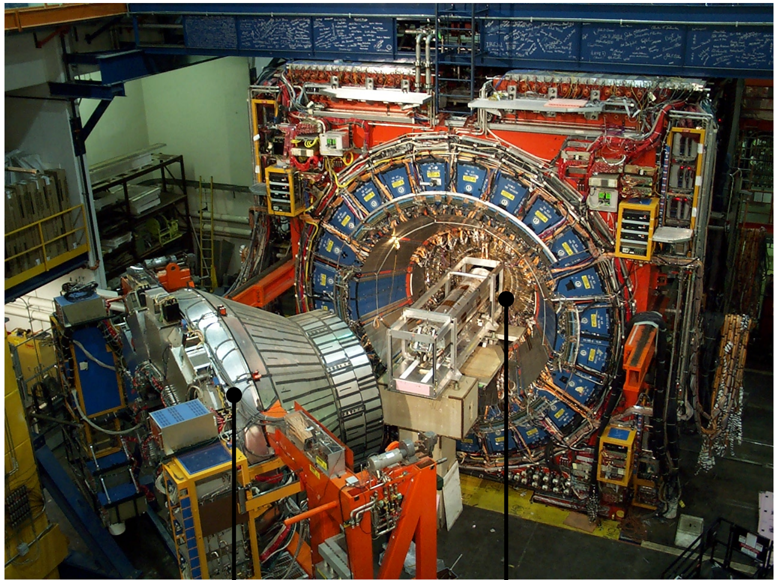
  $\Delta(M_{TOP})$ = 0.9 GeV (0.54%)
- Equivalent constraint on **M_H** would come from:

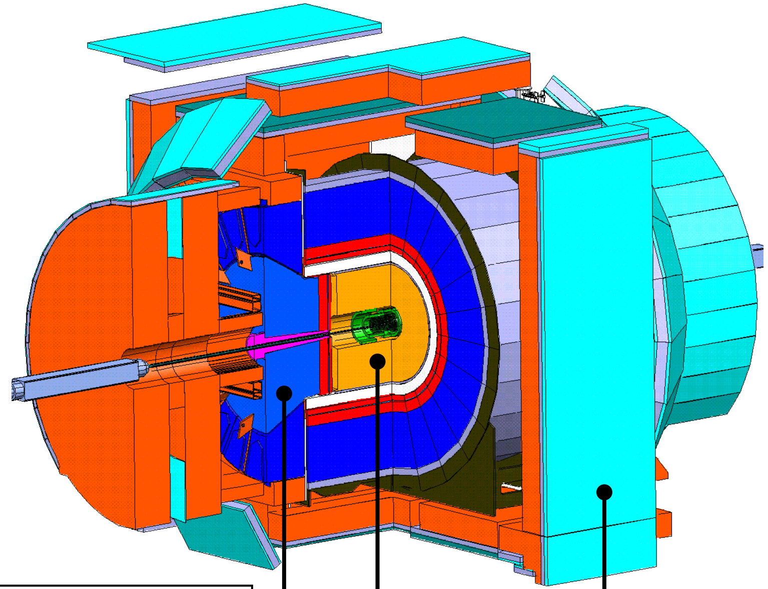
  $\Delta(M_W)$ = 6 MeV (0.001%)
- The most important measurement for us to improve now is the W mass !

Triangulating New Physics



- Even after a Higgs discovery at the LHC, precision EWK measurements will enable powerful Standard Model consistency fits.
- May be possible to distinguish SM from MSSM and in general constrain the properties of new physics at higher mass scales.





Drift chamber outer tracker :
$\delta p_T / p_T \approx 0.0005 \times p_T$ [GeV/c; beam constrained]; $|\eta| < 1$

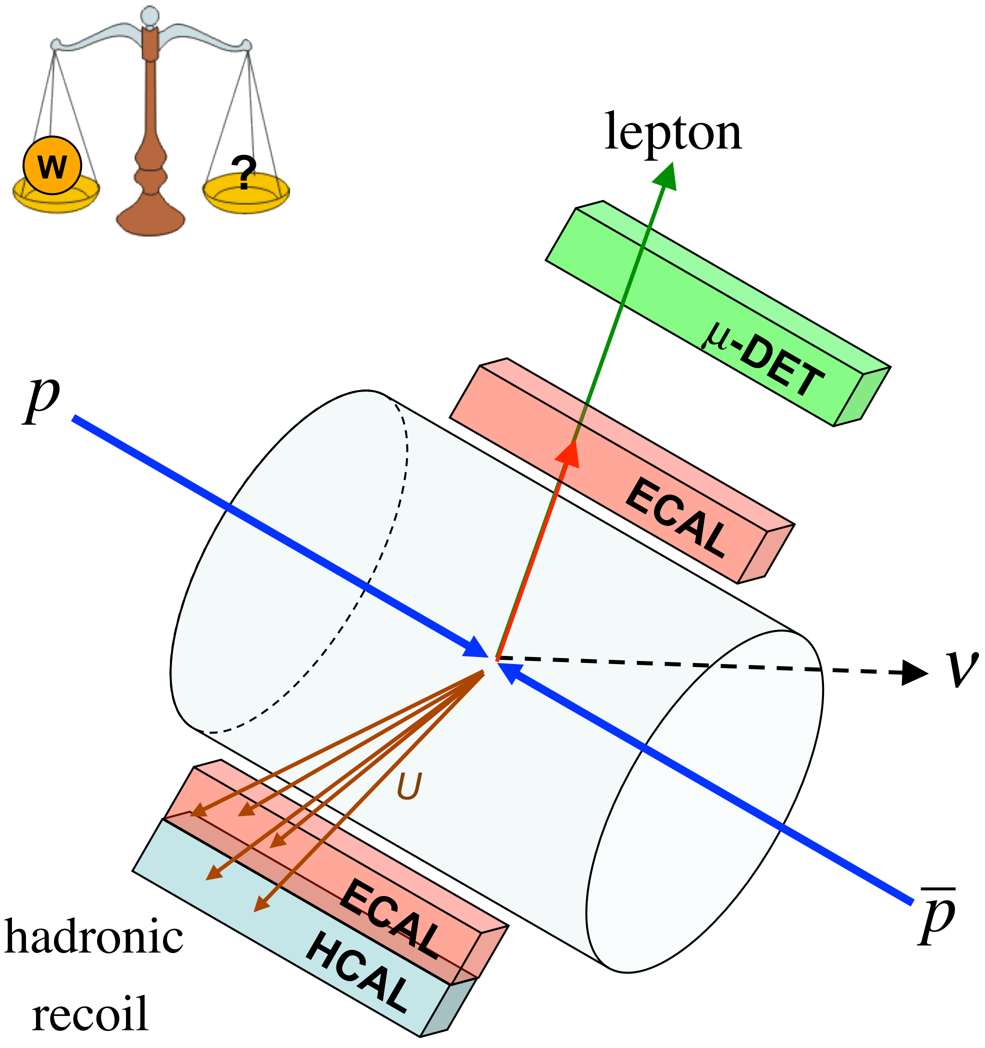
Silicon vertex detector :
tracking coverage out to $|\eta| < 2.8$

Central calorimeter : $\delta E_T / E_T \approx 13.5\% / \sqrt{E_T} \oplus 1.5\%$ $|\eta| < 1.1$

Plug calorimeter : coverage out to $|\eta| < 3.0$

Muon chambers : coverage out to $|\eta| < 1.0$

W Mass : Observables



$$p\bar{p} \rightarrow W(\rightarrow l\nu) + X$$

Lepton :
Measure 4-vector as precisely as possible.

Hadronic Recoil :
Measure in transverse plane only

$$\vec{u}_T = \{u_x, u_y\}$$

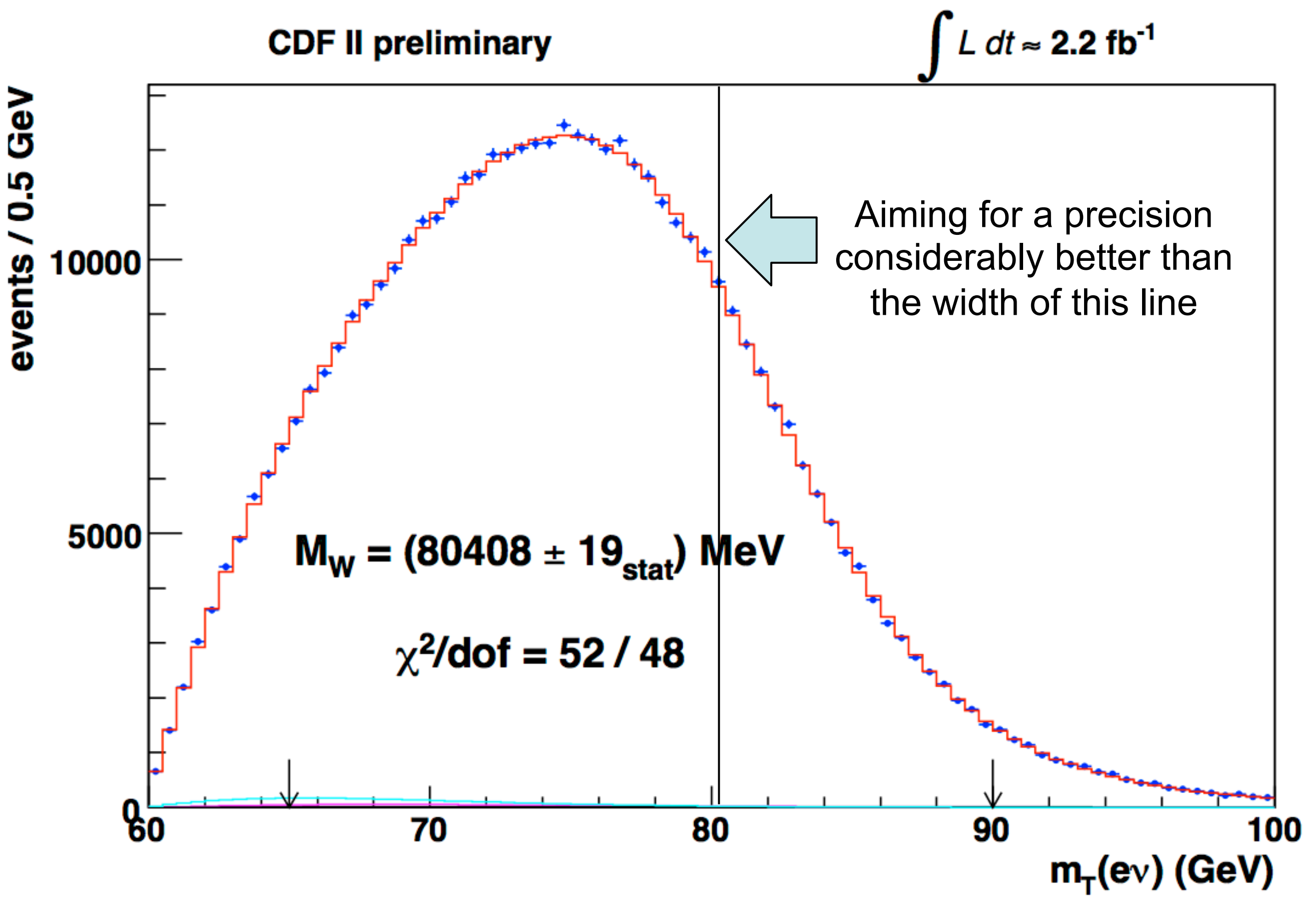
Neutrino :
Infer transverse momentum :

$$\vec{p}_T^{\,\nu} = -(\vec{p}_T^{\,l} + \vec{u}_T)$$

Transverse Mass :

$$M_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos(\Delta\phi^{l\nu}))}$$

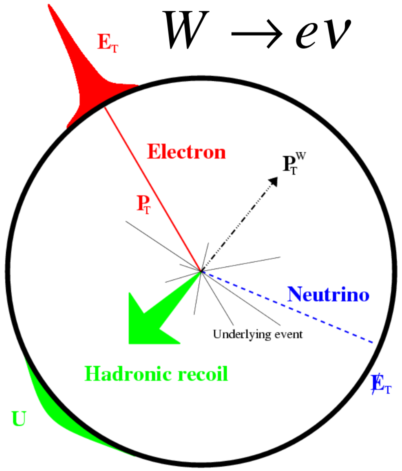
Measurement Strategy



- Fit to M_T around the Jacobian peak.
- Extremely good control of signal modelling, backgrounds & instrumental effects.
- Also extract independent information from lepton and neutrino p_T distributions.

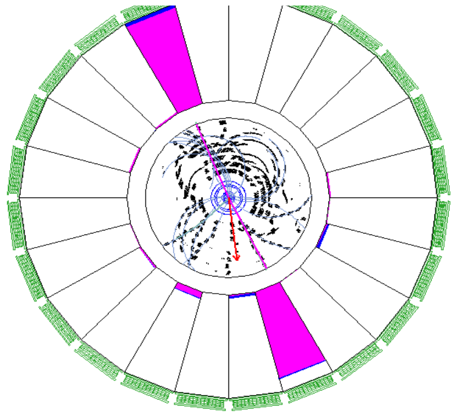
W Mass : Samples

$W \to e\nu$



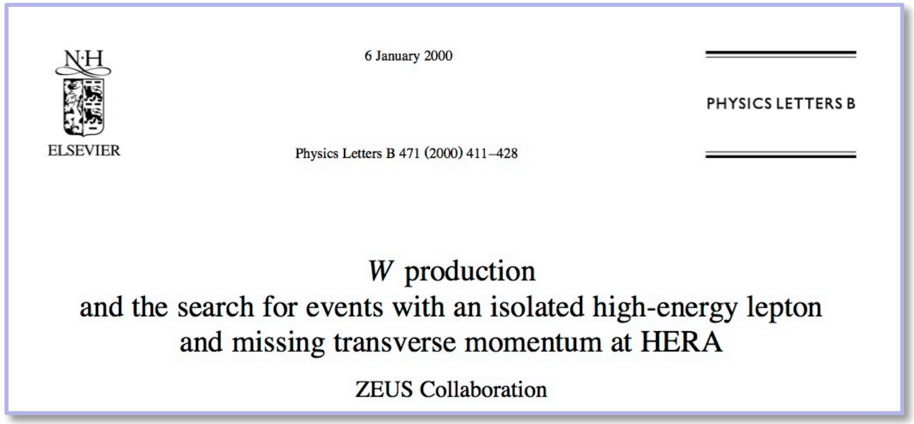
Channel (Exp.)	Luminosity	#Events
$W \to e\nu$	2.2 fb^{-1}	470, 126
$W \to \mu\nu$	2.2 fb^{-1}	624, 708
$Z \to ee$	2.2 fb^{-1}	16,134
$Z \to \mu\mu$	2.2 fb^{-1}	59,738

$Z \to e^+e^-$



$W \to \ell\nu$ Kinematic Cuts ⇒ $30 < p_T^\ell, p_T^\nu < 55$ GeV, $|\vec{u}| < 15$ GeV

- Selection efficiencies are *small* compared to cross-section analyses : 3% (Z) - 12% (W).
- We are trading statistics for systematics - tight fiducial and ID cuts.



N·H ELSEVIER

6 January 2000

PHYSICS LETTERS B

Physics Letters B 471 (2000) 411–428

W production
and the search for events with an isolated high-energy lepton
and missing transverse momentum at HERA

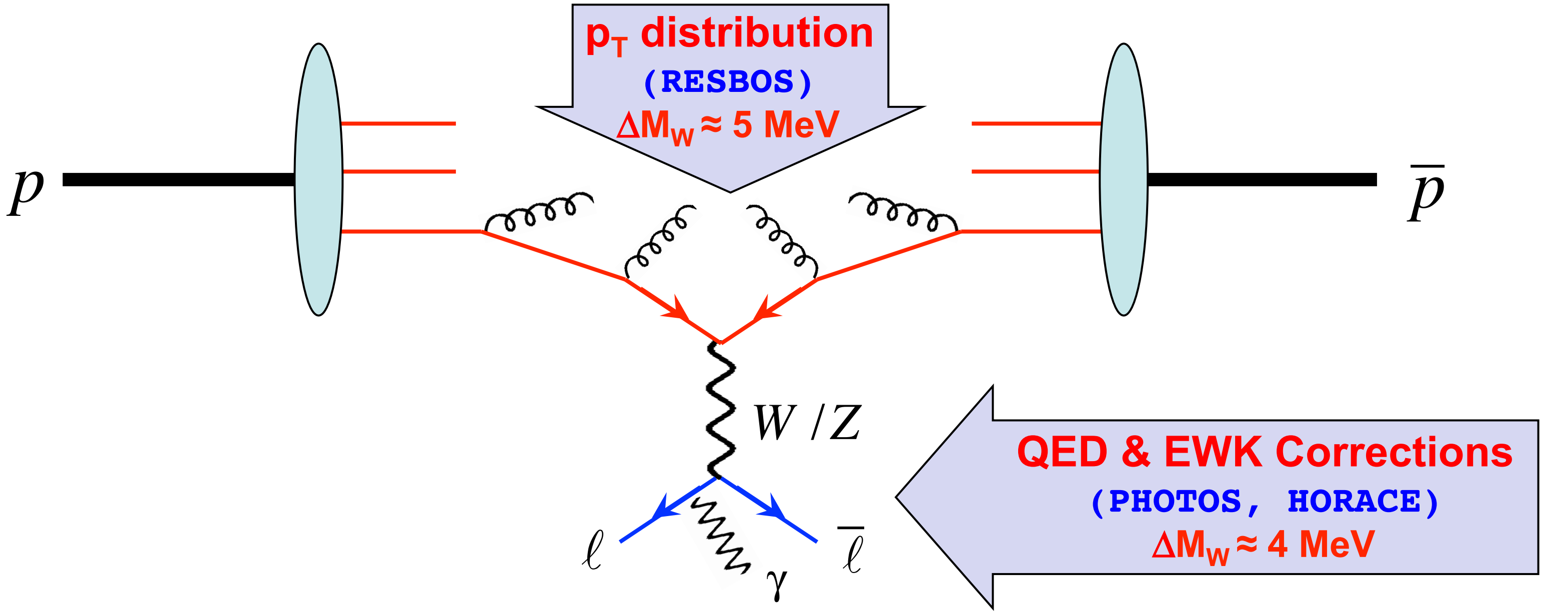
ZEUS Collaboration

<u>My Ph.D. Thesis</u>

3 $W \to e\nu$ events in 48 pb^{-1}

$$\sigma\left(e^+p \to e^+W^\pm X\right) = 0.9^{+1.0}_{-0.7} \pm 0.2 \text{ pb}$$

W Mass : Production Modelling



$$d\sigma_{p\bar{p}\to W/Z\to\ell\bar{\ell}} = \int \sum_{i,j=u,d,s,(c,b)} [f_i^q(x_p) f_j^{\bar{q}}(x_{\bar{p}}) + f_i^{\bar{q}}(x_p) f_j^q(x_{\bar{p}})] \times d\sigma_{q\bar{q}\to W/Z\to\ell\bar{\ell}} \; dx_p dx_{\bar{p}}$$

y-distribution
(MSTW2008, CTEQ6.6)
$\Delta M_W \approx 10$ MeV

angular & mass distributions (RESBOS)

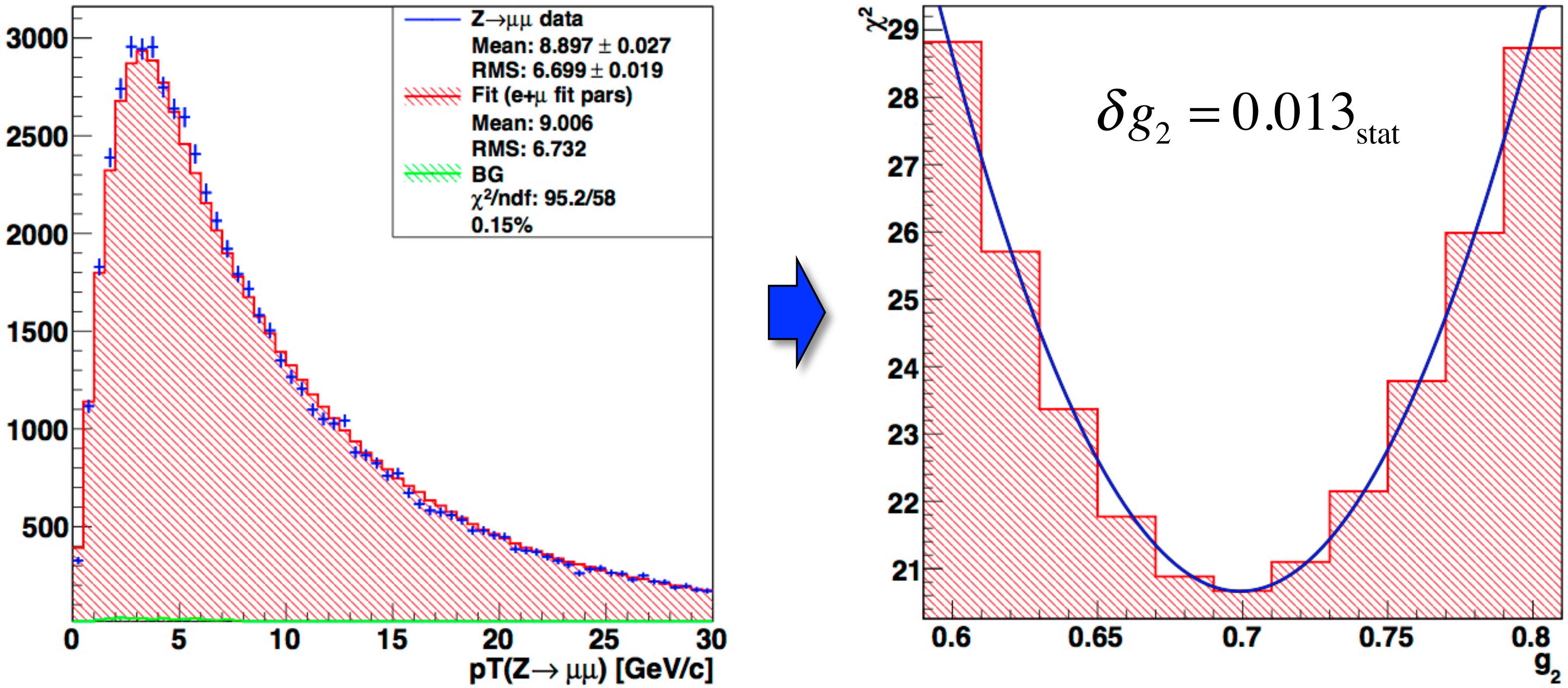
$$d\sigma_{q\bar{q}\to W/Z\to l\bar{l}}(\hat{s},\theta_l,\phi_l) \propto \text{couplings} \times \left[\frac{1}{(\hat{s} - M_{W/Z}^2)^2 + (\Gamma_{W/Z}\hat{s}/M_{W/Z})^2}\right]$$

W Production Modelling : p_T

- Use the best model on the market : RESBOS **Landry et al. (2003)**

$$\frac{d\sigma}{dp_T^{W/Z}} \sim f^{\text{PETURBATIVE}}(\alpha_S) \times f^{\text{NON-PETURBATIVE}}(\alpha_S, g_1, g_2, g_3)$$

- Constrain parameters using *our own* Z data :

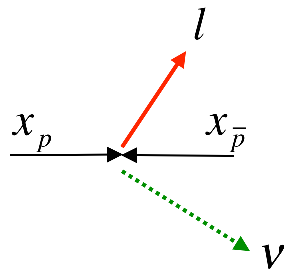


- Vary g_2 and α_S taking into account correlations ➔ **M_W ~ 3 MeV**

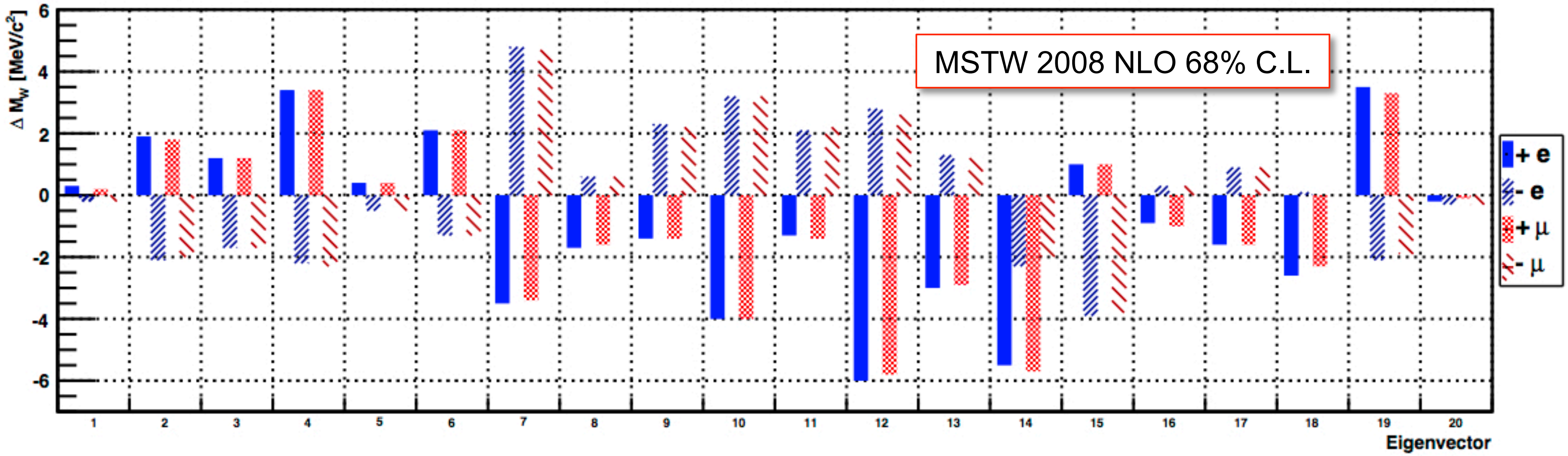
Dan Beecher Ph.D. Thesis

W Production Modelling : p_Z

- PDF's sculpt kinematic distributions through the requirement that the charged lepton be central :



- Generate weighted event ensembles using PDF error sets :

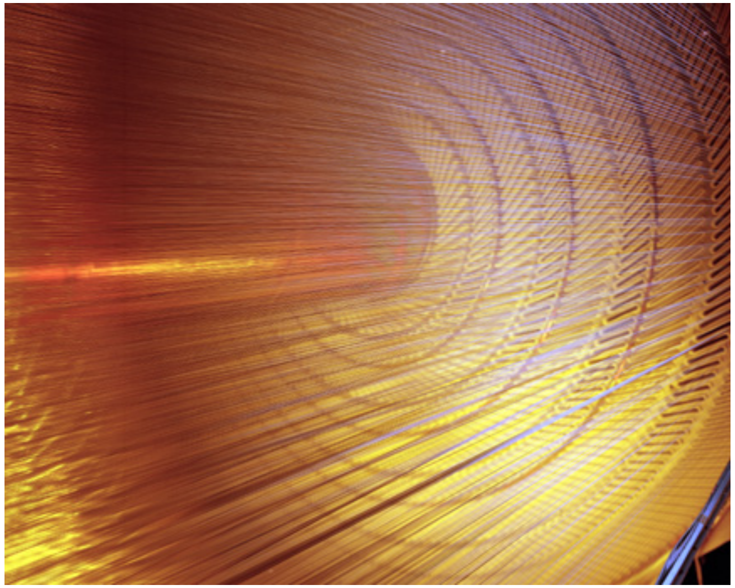


$$\Delta M_W = \frac{1}{2}\sqrt{\sum_i (\Delta M_W^{i,+} - \Delta M_W^{i,-})^2}$$ (special treatment for shifts with the same sign)

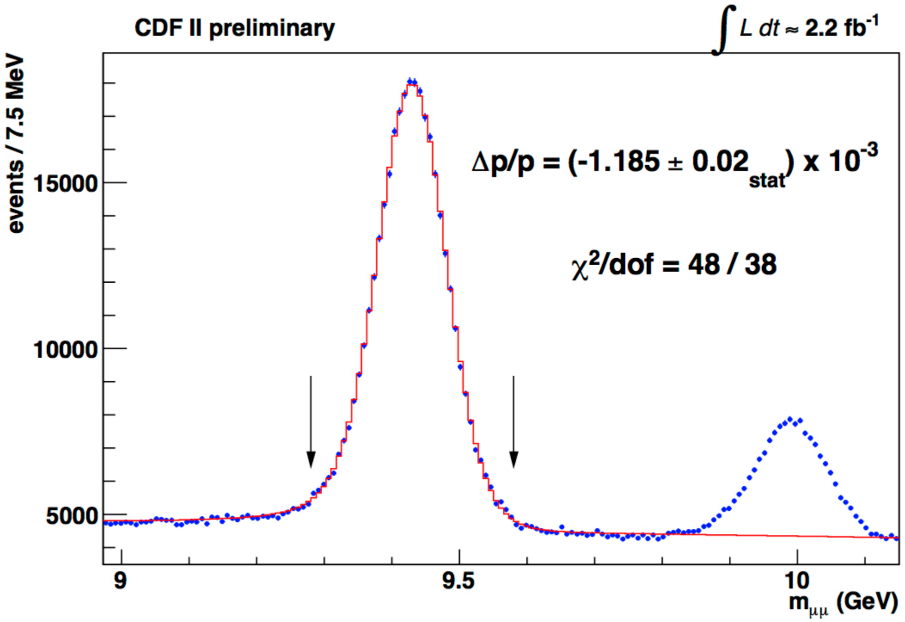
➔ **M_W ~ 10 MeV** (validated using CTEQ6, NNLO etc.)

Dan Beecher Ph.D. Thesis

Momentum Scale

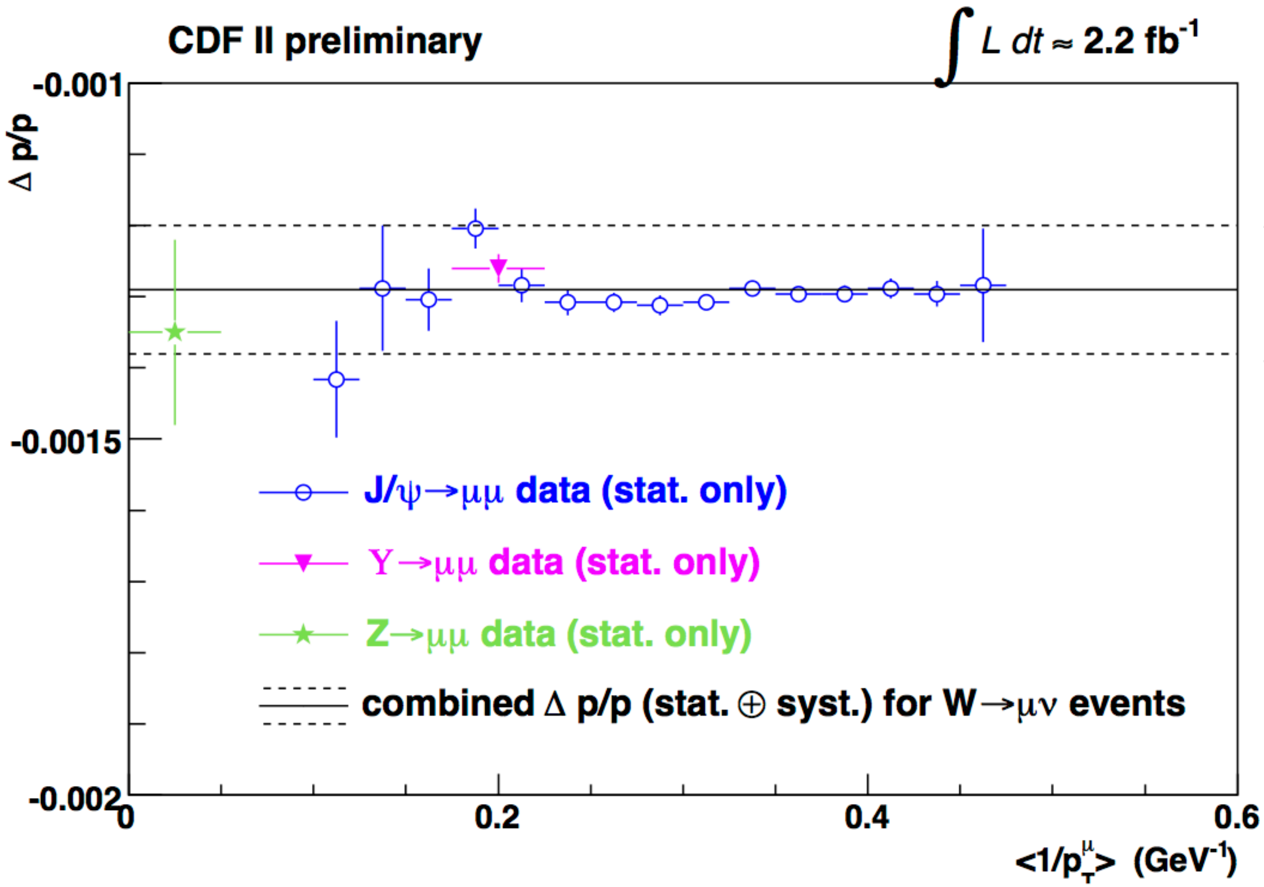


- The heart of the CDF analysis is the extremely good p_T measurement from the tracker.
- Start with a detailed cosmic ray internal alignment of the 30,240 sense wires of the COT to an accuracy of **~5 μm**



- Use fits to precisely known J/Ψ and Υ resonances spanning a large range of curvature.
- Fit the single hit resolution **~150 μm** and the effect of the beam constraint.

Momentum Scale



$$\Rightarrow \frac{\delta p}{p} = 0.00009$$

$\Delta M_W(\mu)$ = 7 MeV

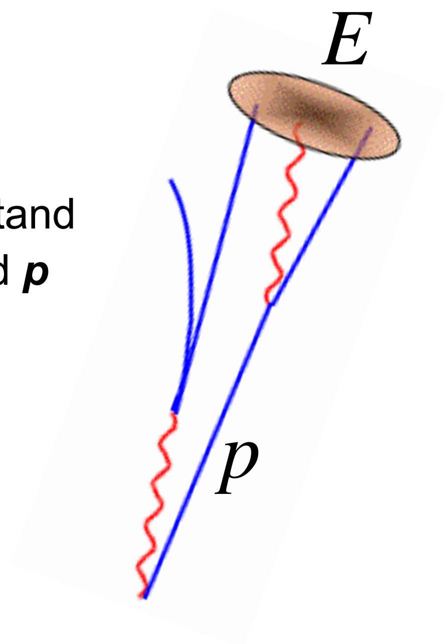
Flatness over a large p_T range
is also a test of dE/dx modelling

Electron Energy Scale

- How do we precisely determine the electromagnetic calorimeter energy scale ?

[1] Transfer the precise momentum scale to the calorimeter by fitting the ratio ***E/p*** for electrons.

- Statistically precise.
- Hard ! Need to understand reconstruction of **E** and ***p*** in minute detail.



[2] Extract directly by fitting to precisely known **Z→ee** resonance.

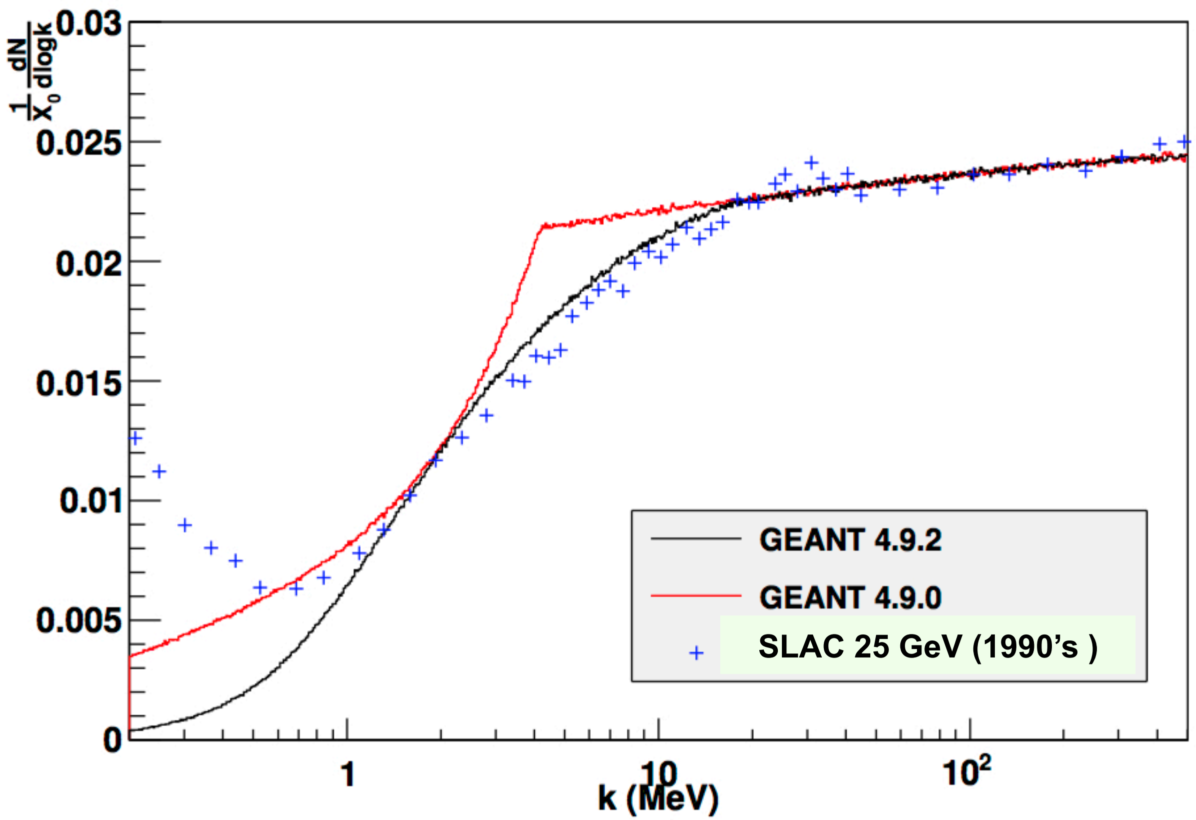
- Relatively easy. No tracking.
- Statistically poorer.

- Do the 2 methods agree ?
- A very powerful cross-check .
- Run 1 : 3.9σ discrepancy never resolved.

Electron Energy Loss Mechanisms

- Precise control over all possible energy loss mechanisms is required.
- For example Landau-Pomeranchuk-Migdal (LPM) suppression of Bremsstrahlung for low-energy photons :

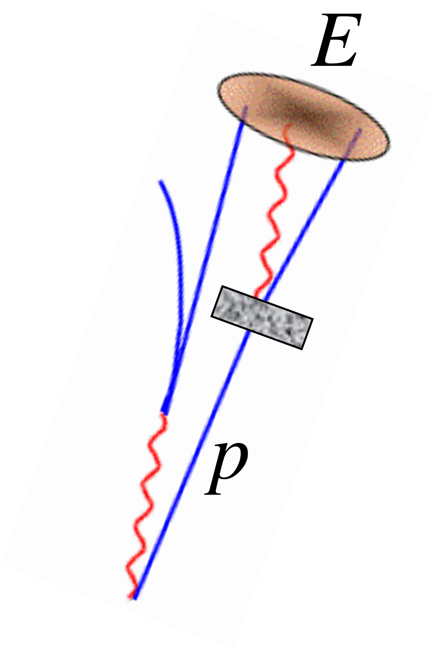
$$k(E_\gamma) < \frac{E^2}{E + E_{\mathrm{LPM}}} \quad \text{where} \quad E_{LPM} \sim 72\ \mathrm{TeV}\ \ (\mathrm{Si})$$



- Go back and systematically validate GEANT-4 against original test-beam data.
- Assess systematic uncertainty from all sources : **~ few MeV**

Tom Riddick Ph.D. Thesis

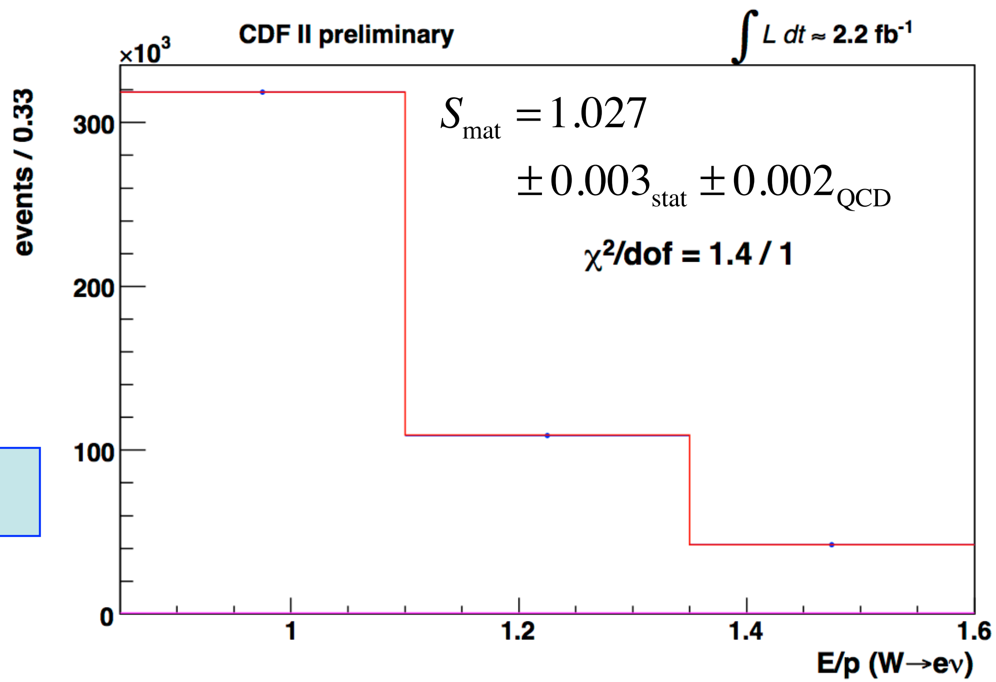
Simulating Electrons : Material



- Start from a detailed, tuned material map.
- Very detailed Brem. & energy loss treatment.
- Compare E/P tails in data and simulation :

$E/p \sim 1$
No Brem.

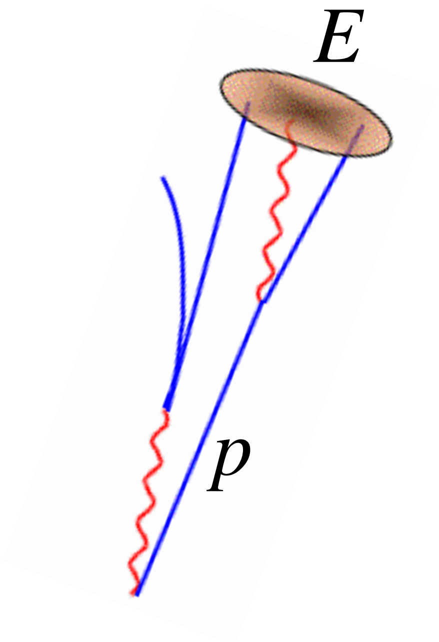
$E/p \sim 1.5$
Hard Brem.

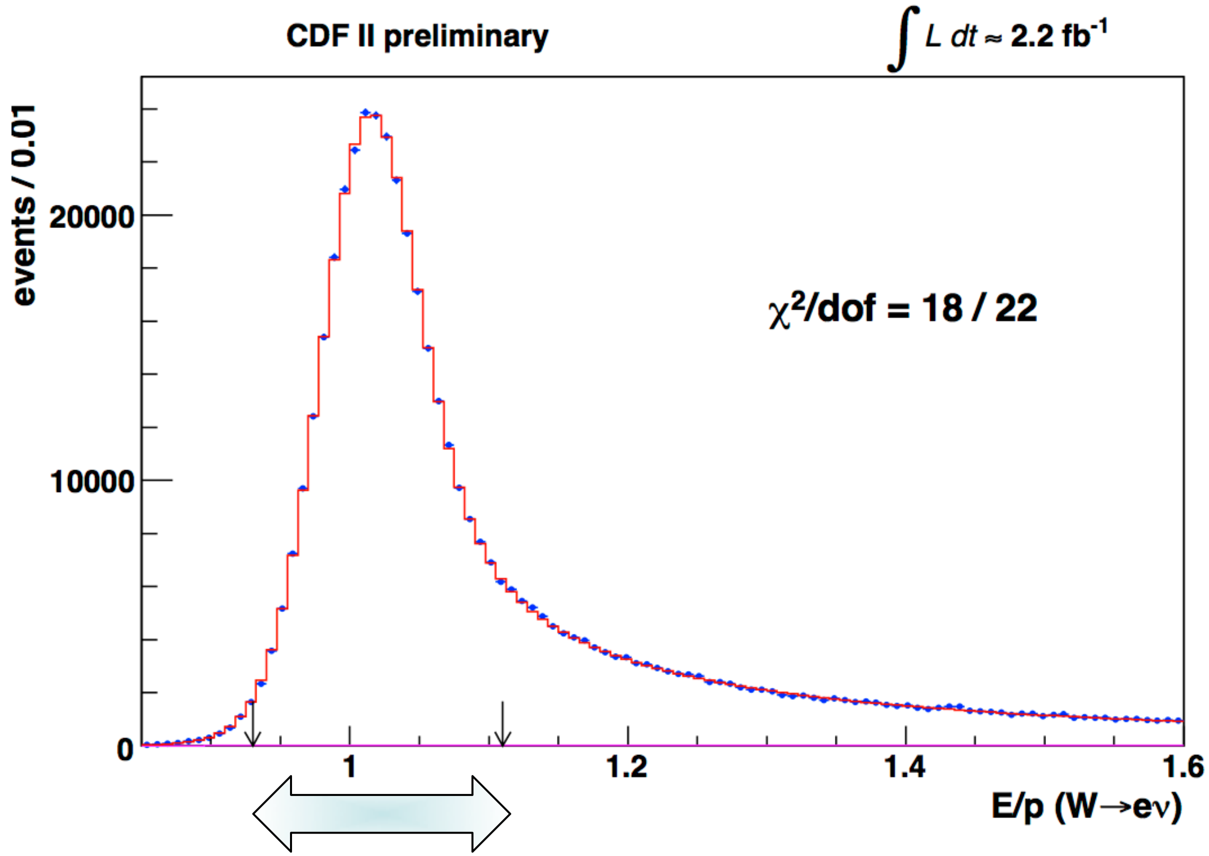


Determine amount of radiating material to better than 0.5%

Electron Energy Scale

- Transfer p-scale to E-scale using E/p :





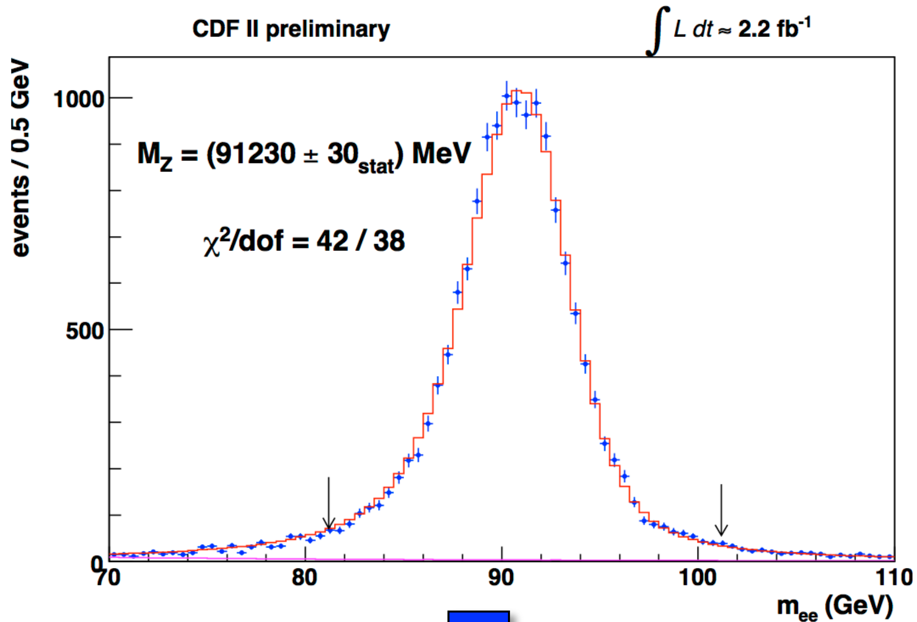
Fit Region for Energy Scale

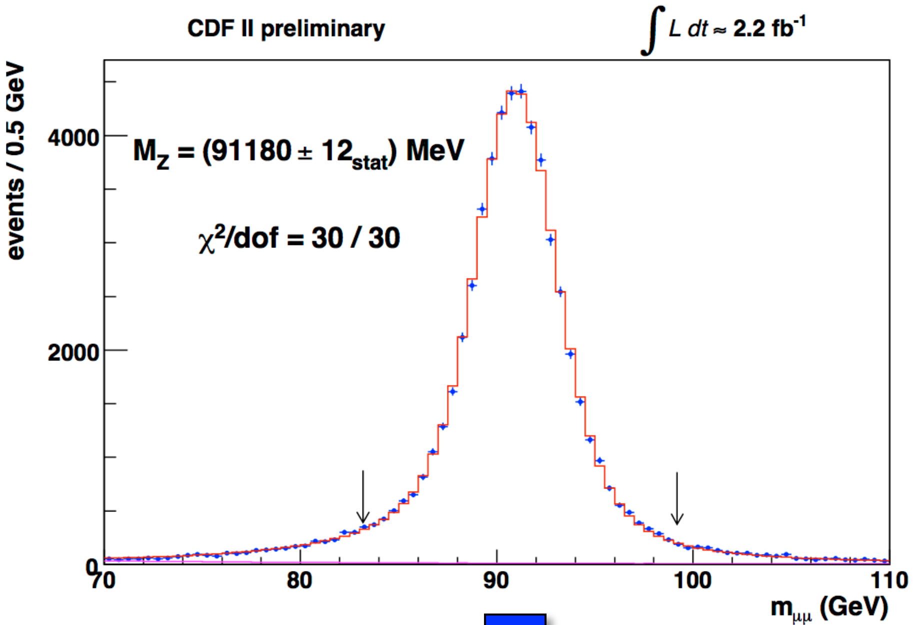
- Need to worry about *non-linearity* when comparing scales determined from W's and Z's

Tom Riddick Ph.D. Thesis

M_Z Cross-Checks

- Z mass fits blinded until the p-scale (from J/ψ and Υ) and E-scale (from E/p) were finalised.
- Compare Z mass fits with PDG .
- Subsequently Z constraints are included in p/E-scale determinations.





combined with E/p to give :

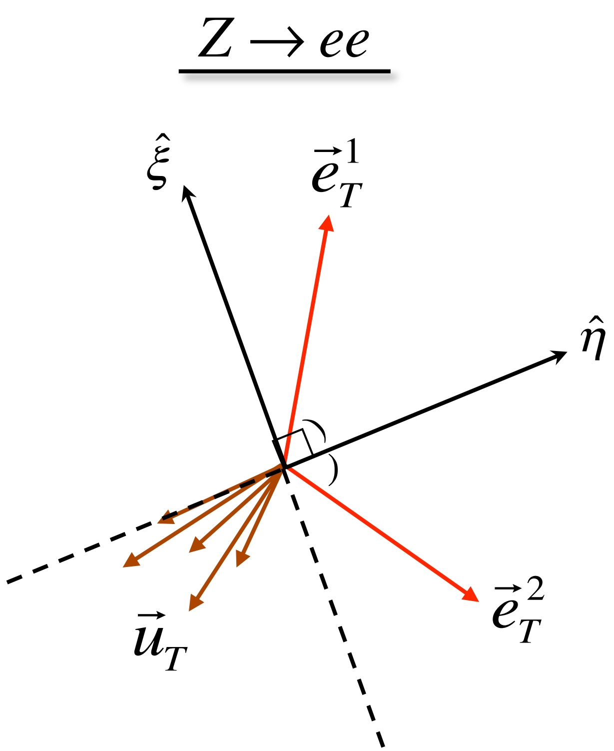
$\Delta M_W(e)$ = 10 MeV

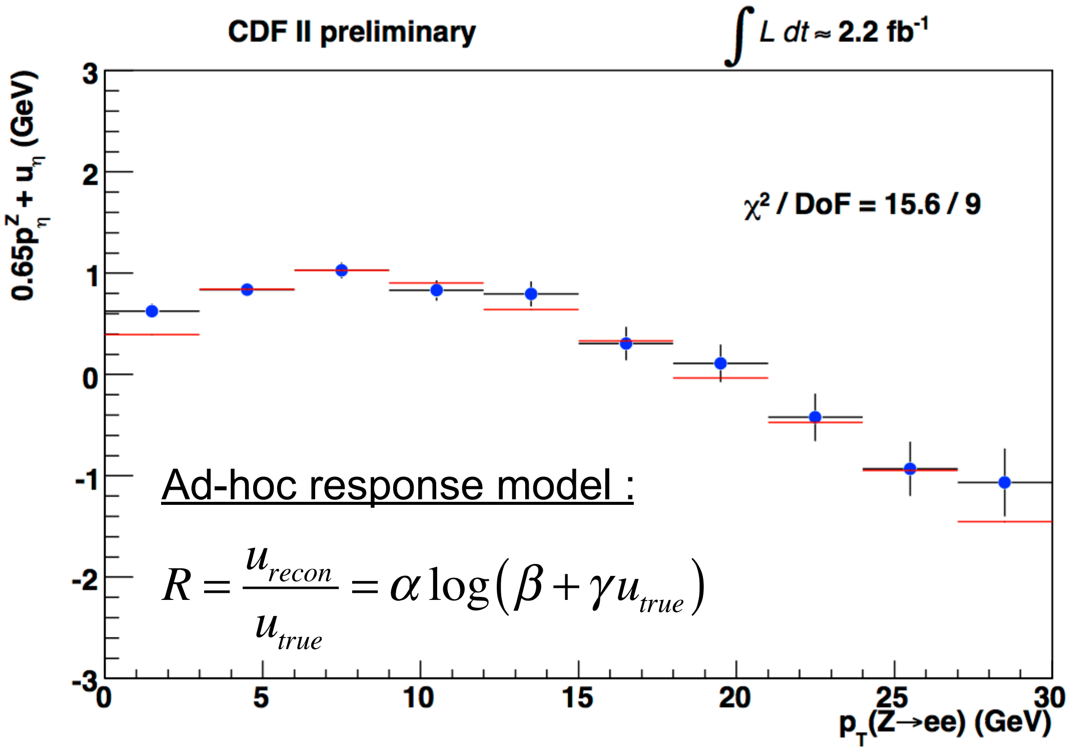
combined with J/ψ and Υ to give :

$\Delta M_W(\mu)$ = 7 MeV

Recoil Modelling

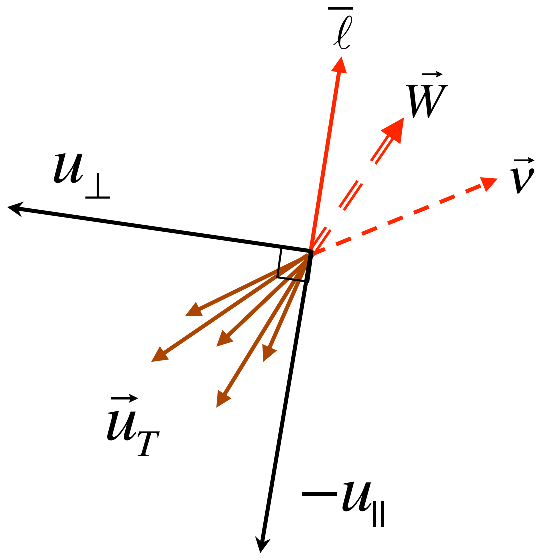
- "Recoil" from **(1)** W/Z p_T **(2)** UE **(3)** overlapping MB events **(4)** lepton energy leakage/FSR.
- Tune using Z data and minimum-bias data.

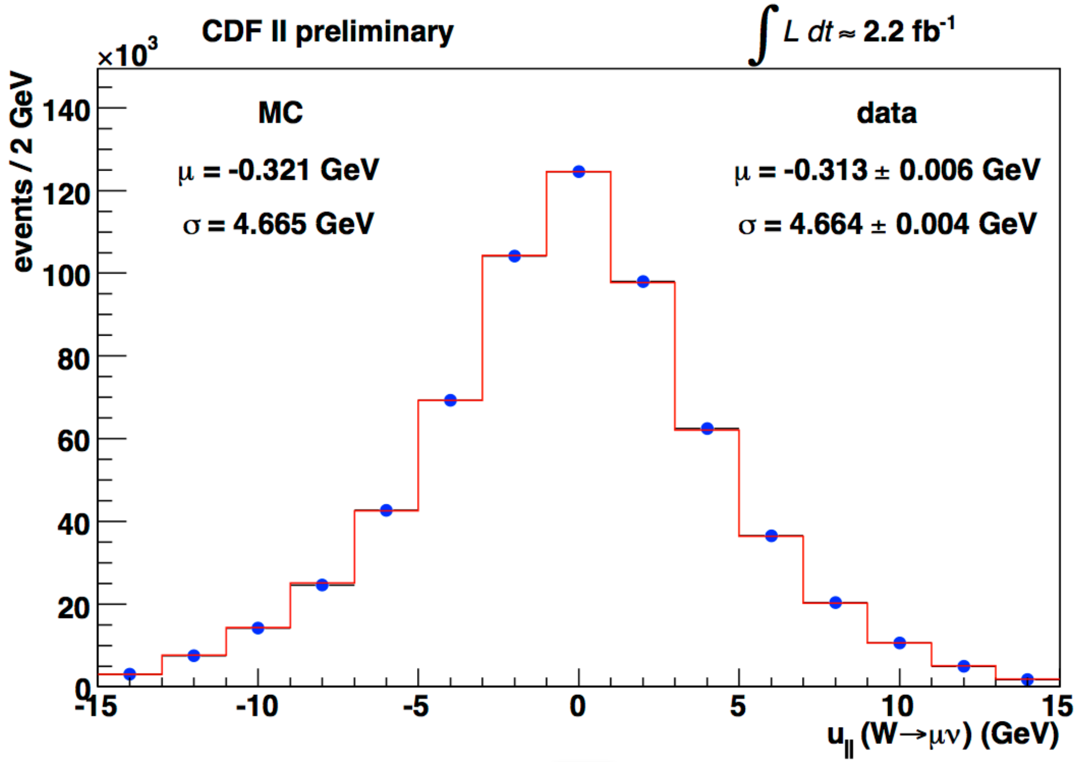




Recoil Modelling

$W \to e\nu$



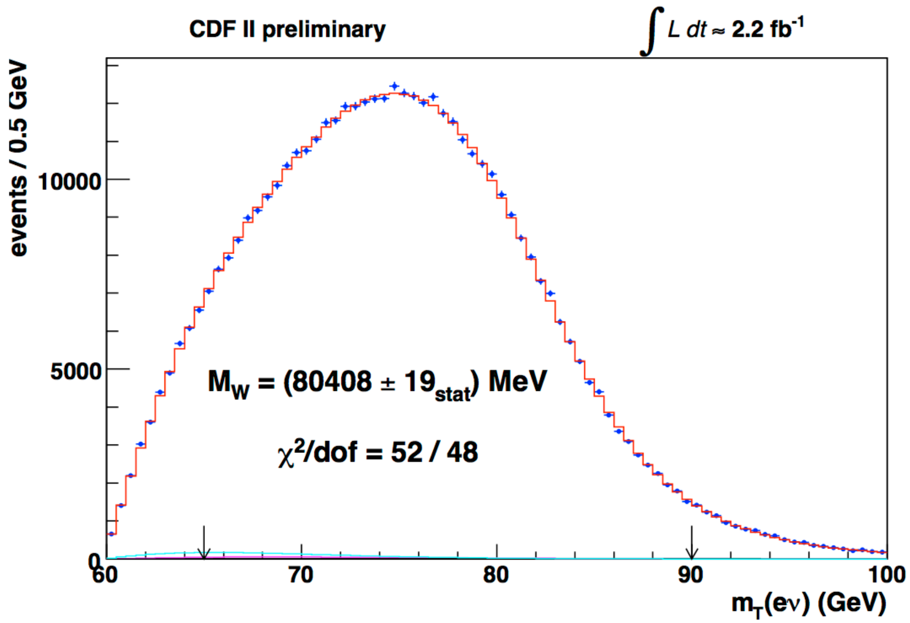


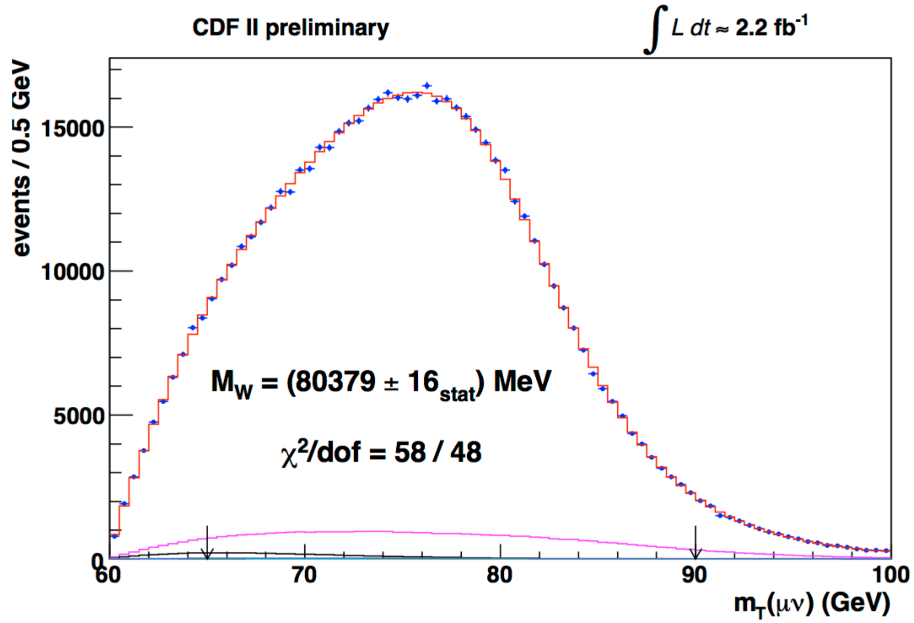
$$M_T \sim 2p_T^\ell + u_\parallel$$

direct bias on M_W if mis-modelled

- Good agreement between W data and simulation.
- Residual recoil modelling systematic **~ 6 MeV**

Results





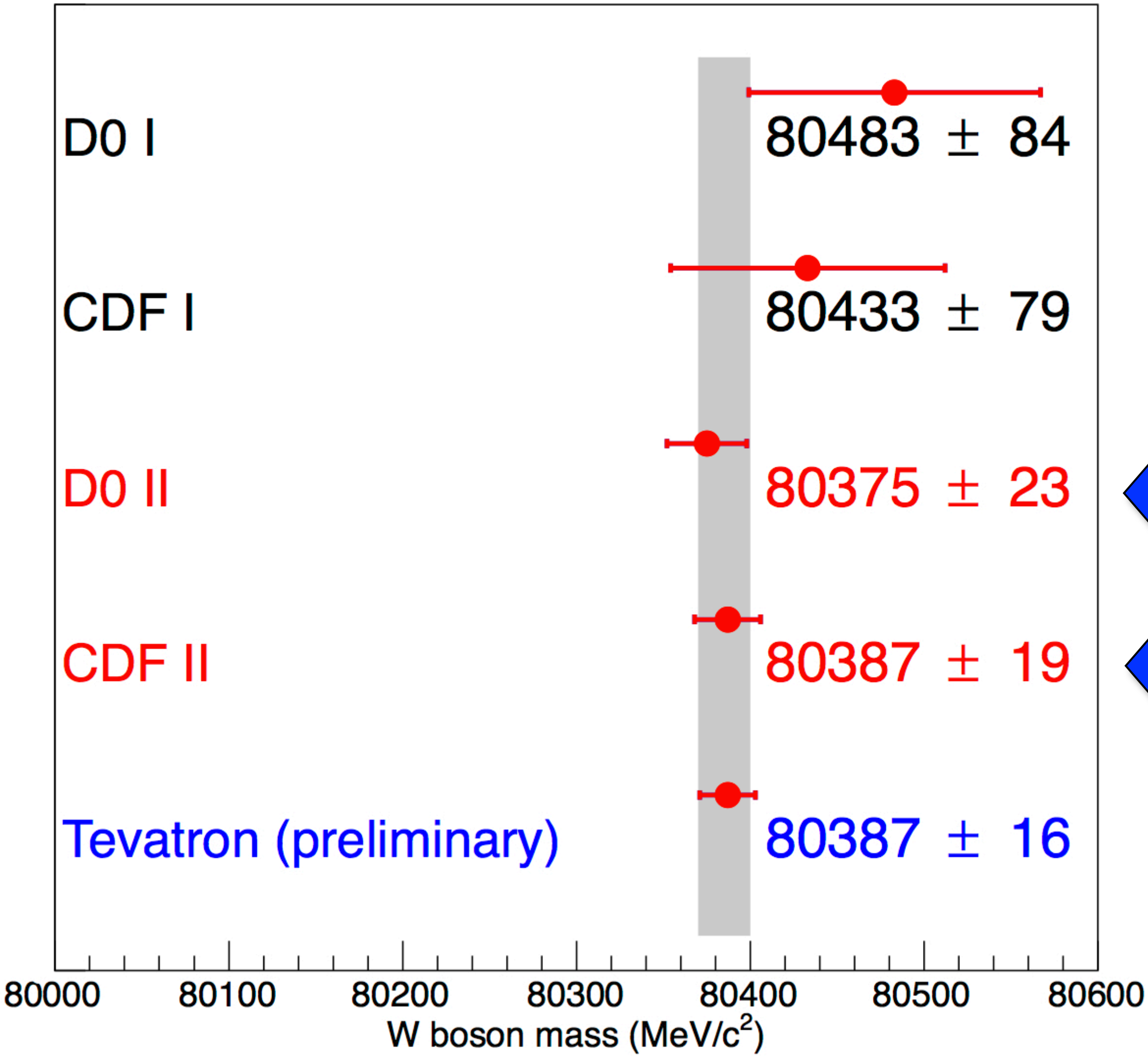
Kinematic Distribution	Electron (MeV)	Muon (MeV)	P(χ^2) (stat + syst)
Transverse Mass	80408 ± 19	80379 ± 16	28%
Lepton Transverse Momentum	80393 ± 21	80348 ± 18	13%
Neutrino p_T	80431 ± 25	80406 ± 22	49%
P(χ^2) (stat + syst)	49%	12%	

Systematic Uncertainties

- All 6 fits are combined taking into account correlations : P(χ^2) = 25%

Source	Uncertainty (MeV)	
Lepton Energy Scale	7	← Tom, Ilija
Lepton Energy Resolution	2	
Recoil Energy Scale	4	← Sarah
Recoil Energy Resolution	4	← Sarah
Recoil Corrections	2	
Backgrounds	3	
p_T(W) Model	5	← Dan
PDFs	10	← Dan
QED Radiation	4	← Ilija
Total Systematic	**15**	
Statistical	12	
Total Uncertainty	**19**	

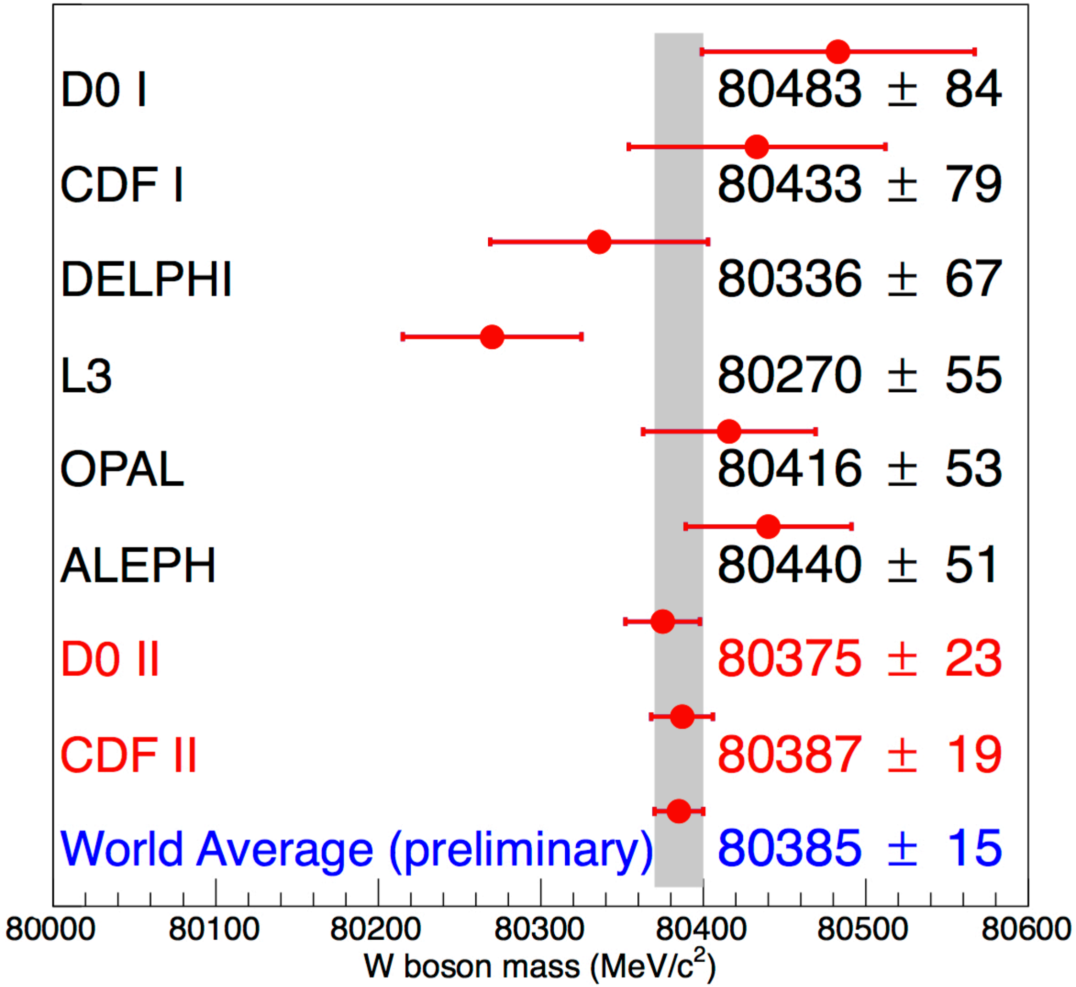
New Tevatron Average



Phys.Rev.Lett. 108 (2012) 151804

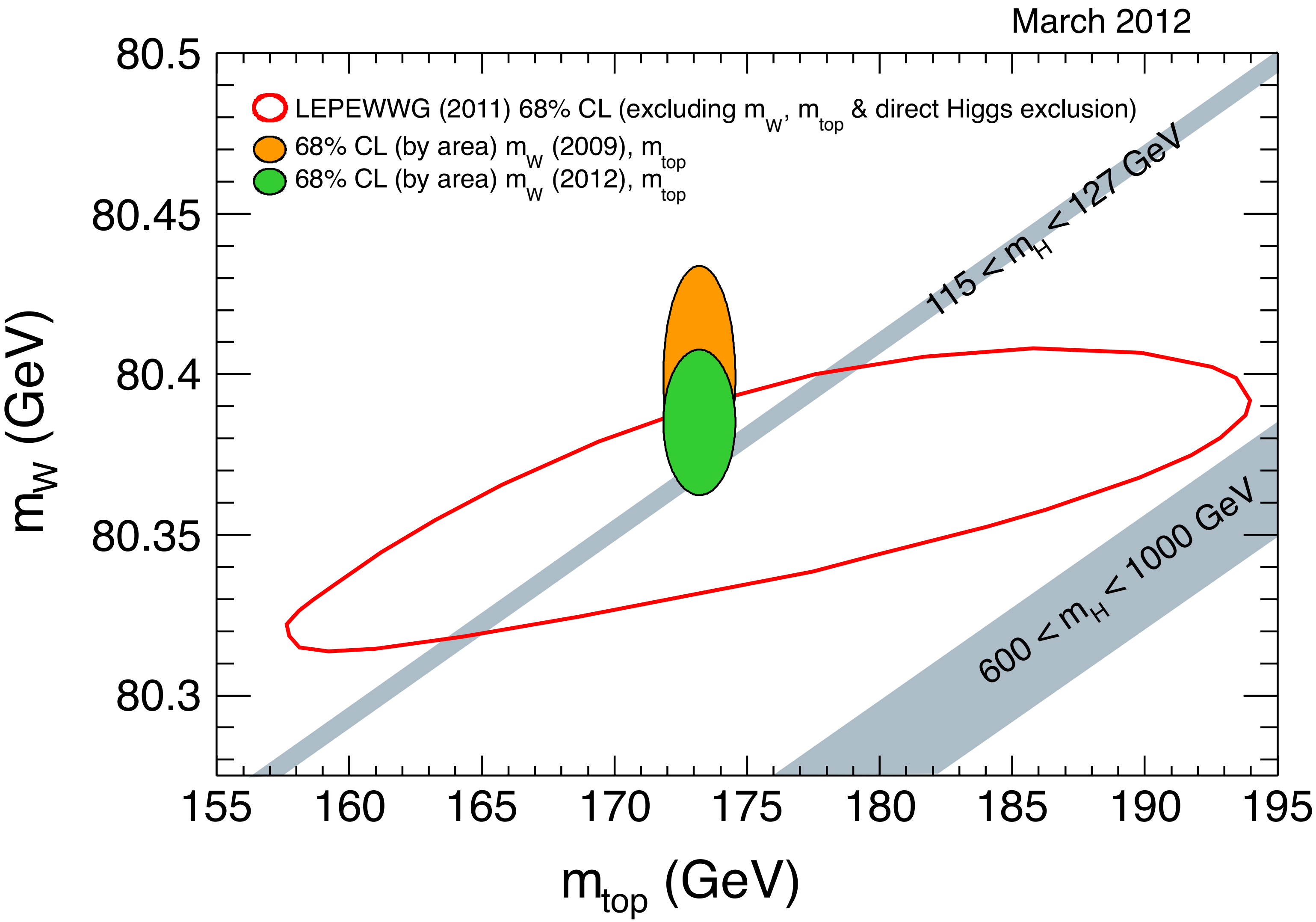
Phys.Rev.Lett. 108 (2012) 151803

New World Average

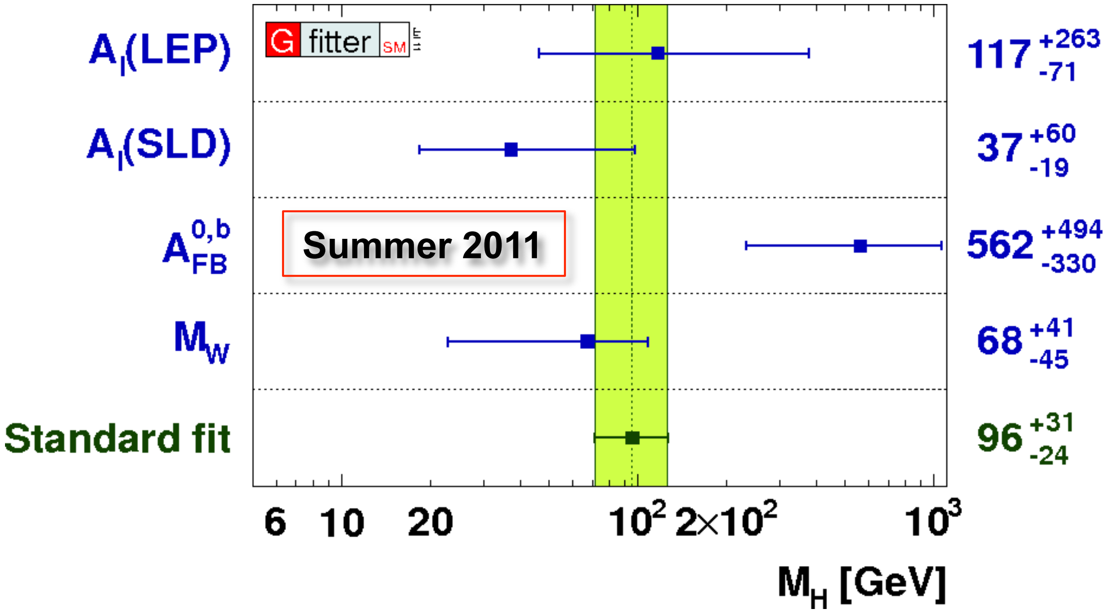


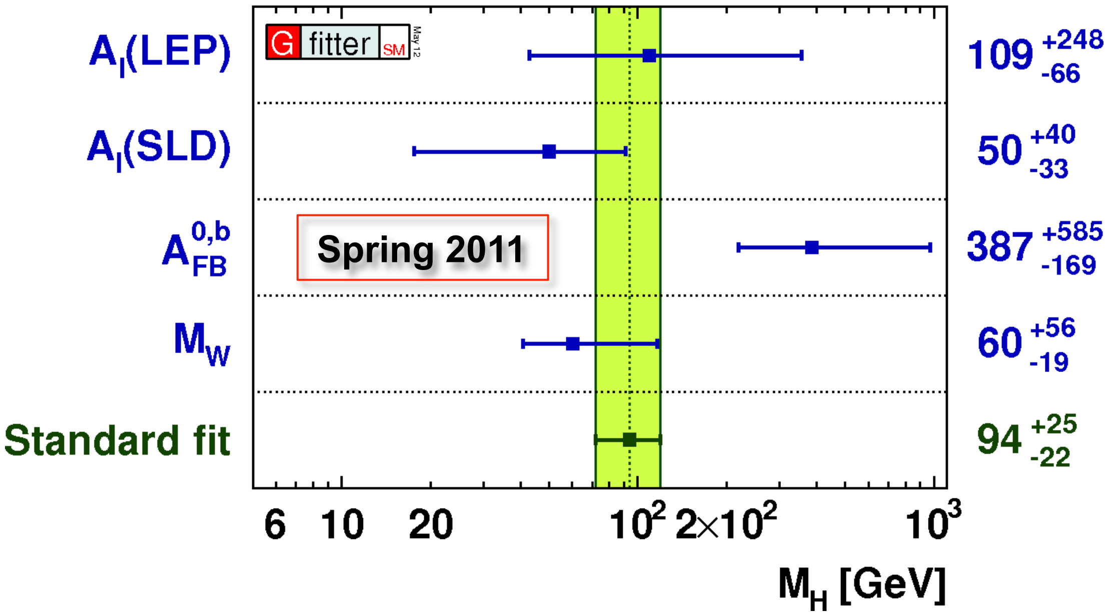
- Previous World Average (2009) : **M_W = 80399 ± 23 MeV**
- Error reduced by ⅓

Consequences of the New M_W Measurement



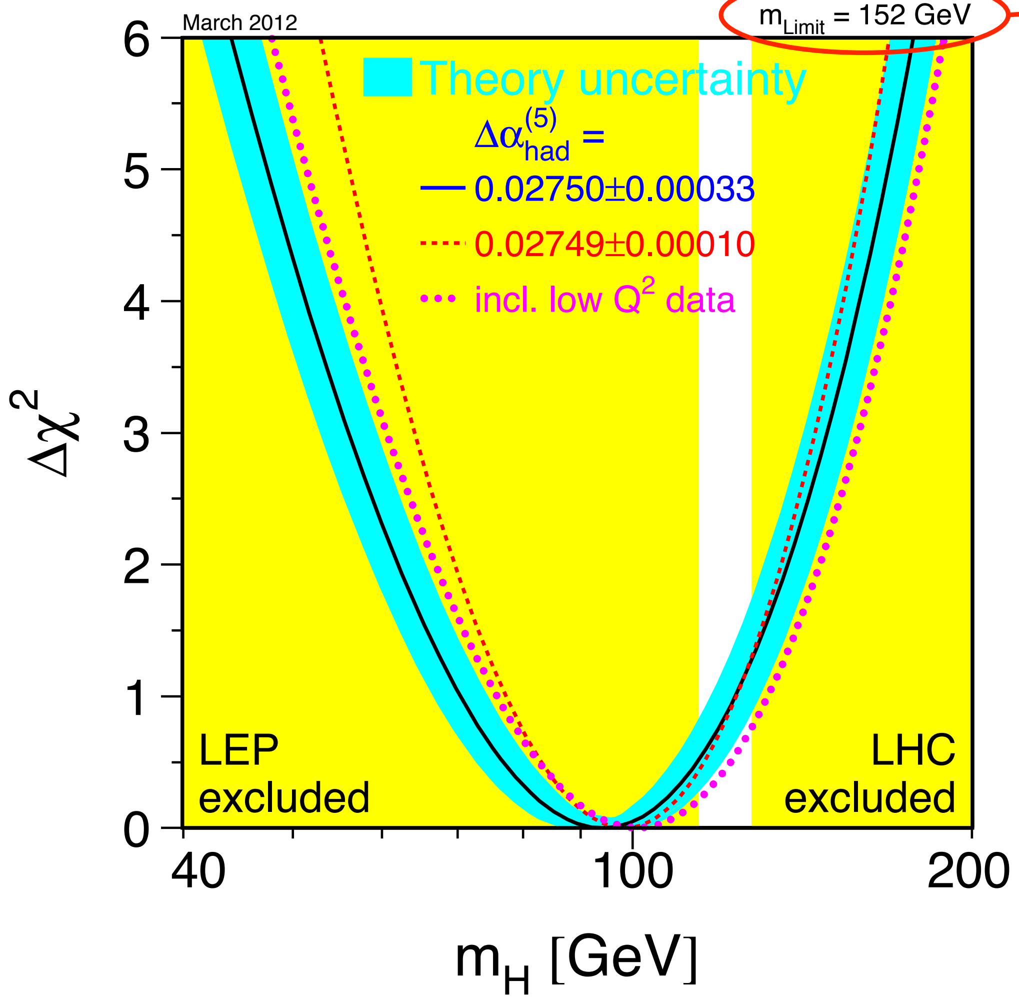
Consequences of the New M_W Measurement





- Small decrease in central Higgs value.
- Tighter constraint on m_H

Consequences of the New M_W Measurement



from 161 GeV

$$M_W = 80385 \pm 15 \text{ MeV}$$

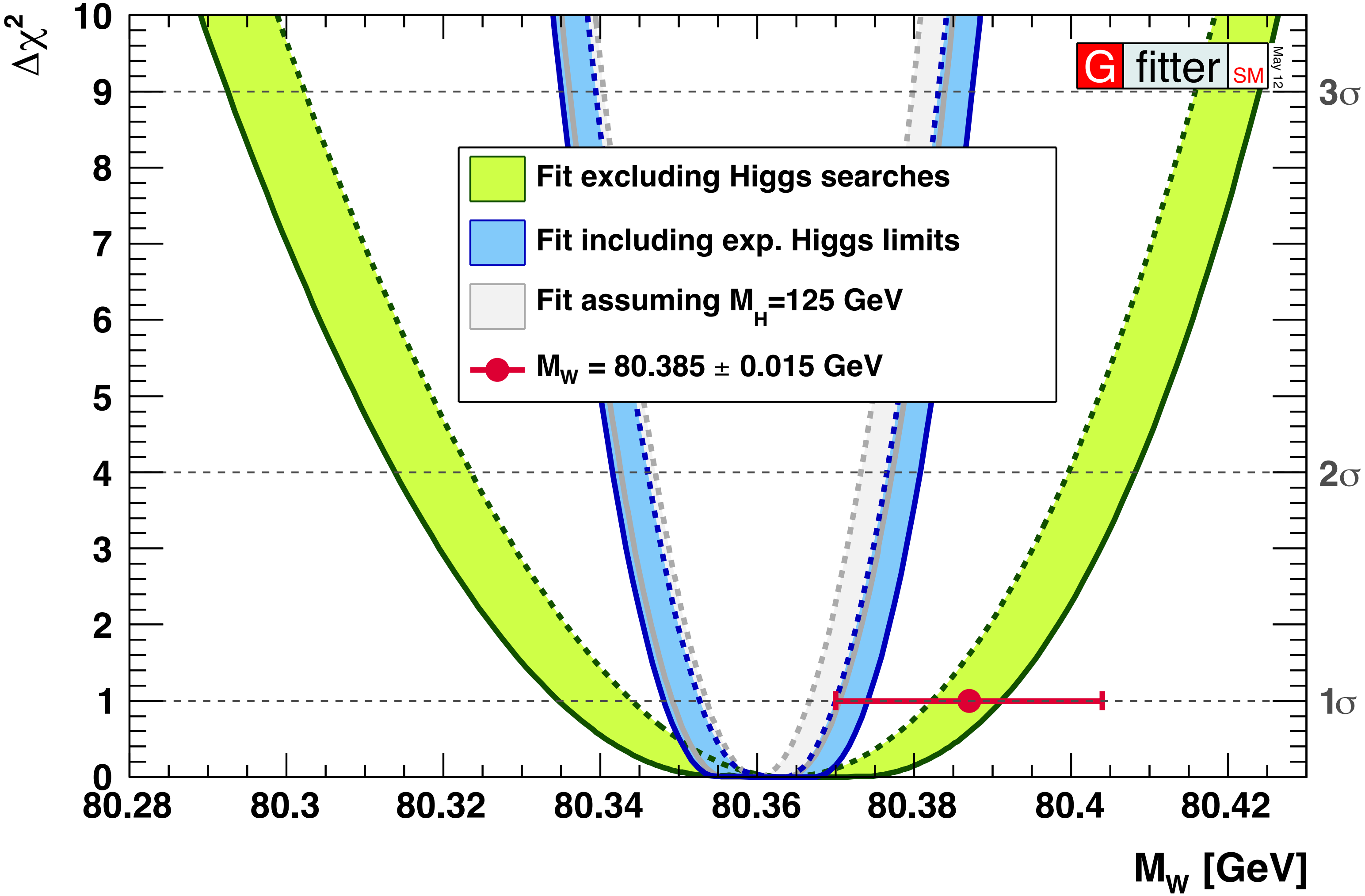
$$M_{top} = 173.2 \pm 0.9 \text{ GeV}$$

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

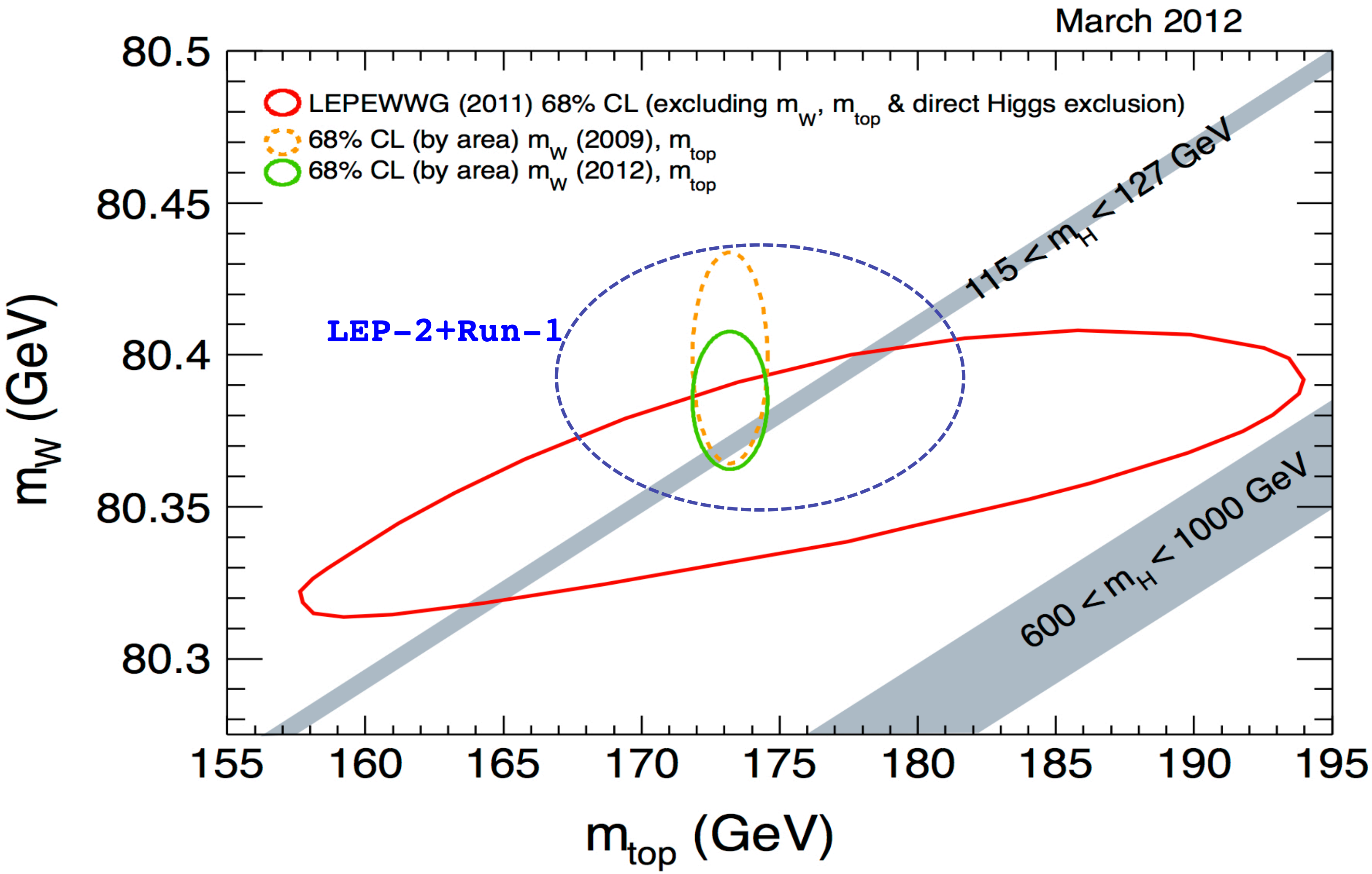
$$M_H < 152 \text{ GeV@95\% C.L.}$$

(LEPEWWG/Zfitter)

Consequences of the New M_W Measurement

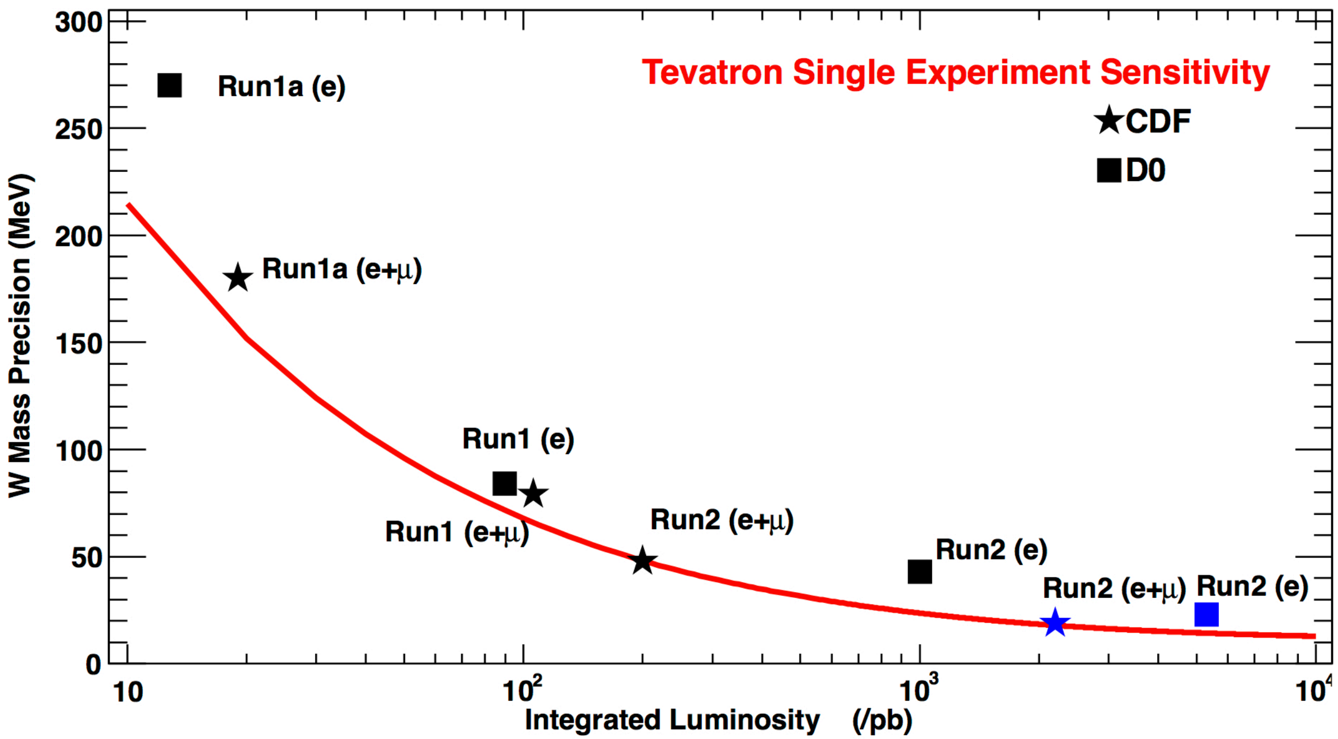


- Impact of Run 2 precision measurements of m_W and m_{top} :



Outlook

- The W mass measurement can be further improved – for CDF only ¼ of the final dataset has been analysed. By how much ?



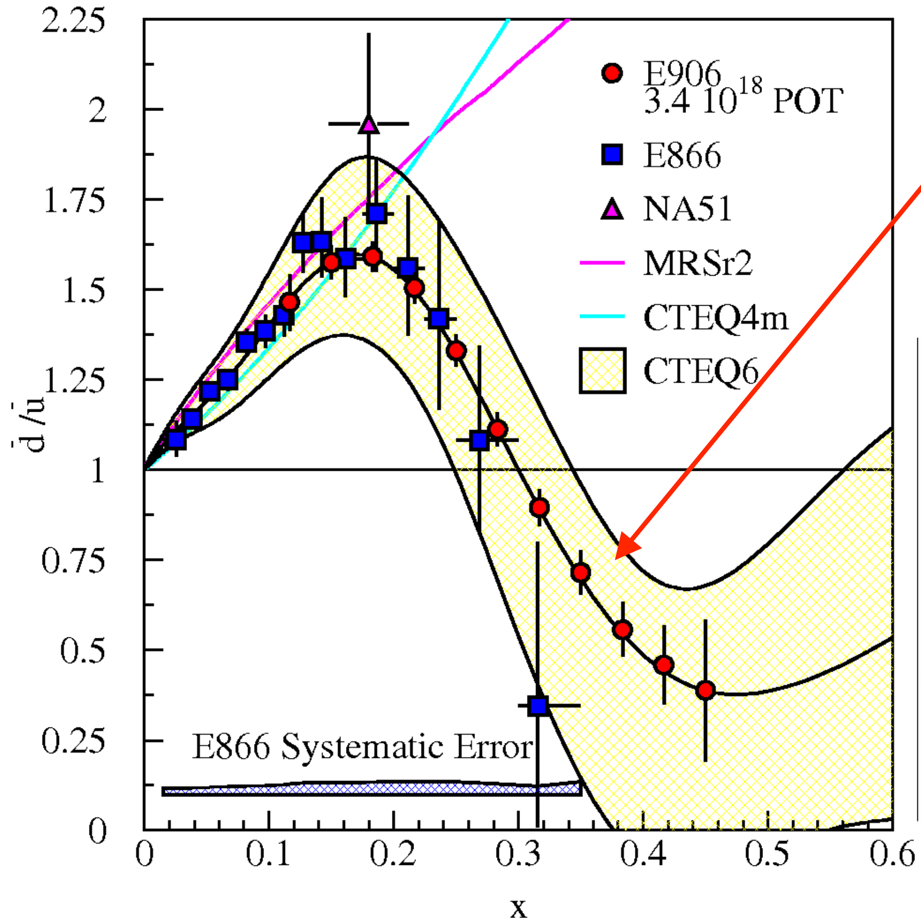
Run 2 Physics Workshop, 1999 → 40 MeV with 2 fb^{-1}

Report of the Working Group on Precision Measurements

Conveners: Raymond Brock[a], Jens Erler[b], Young-Kee Kim[c], and William Marciano[d]
Working Group Members: William Ashmanskas[e], Ulrich Baur[f], John Ellison[g], Mark Lancaster[h], Larry Nodulman[i], John Rha[j], David Waters[k], John Womersley[l]

Systematic Limit ?

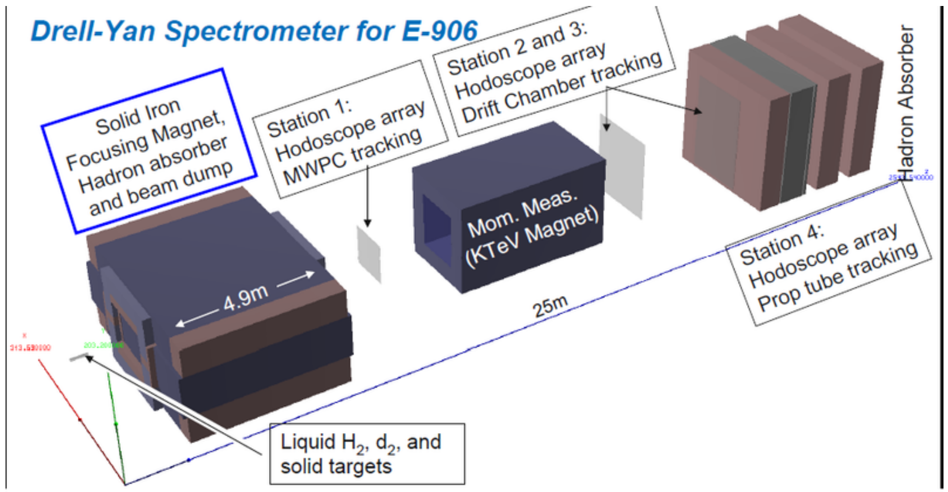
- Model systematics are becoming the limiting factor.
- New techniques or inputs required to reduce the PDF uncertainty on M_W.



- Precision expected from "SeaQuest"

$$pp \to \mu^+\mu^- + X$$

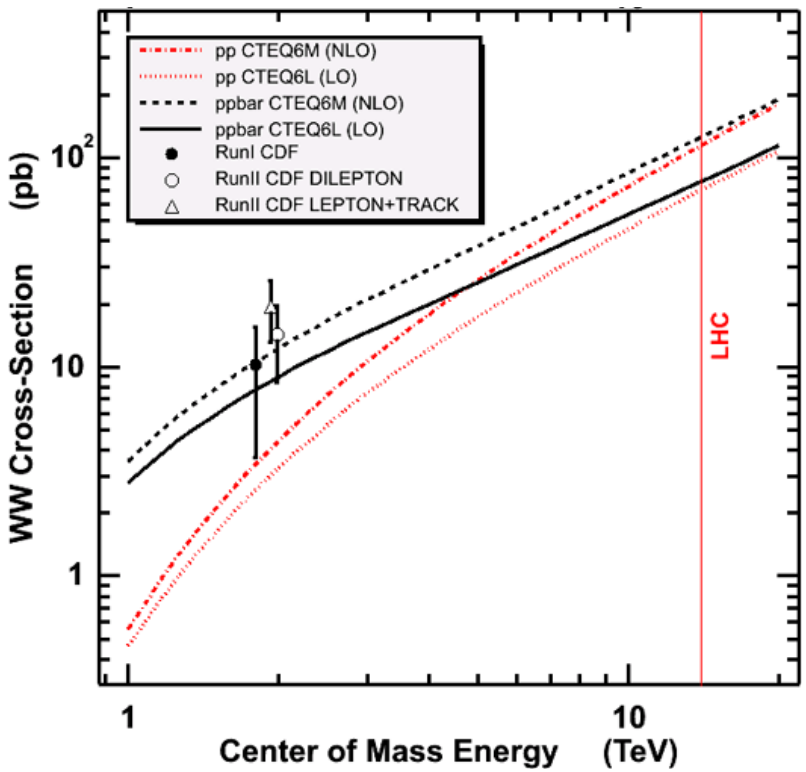
- LHCb/ATLAS/CMS ?



In Other News …

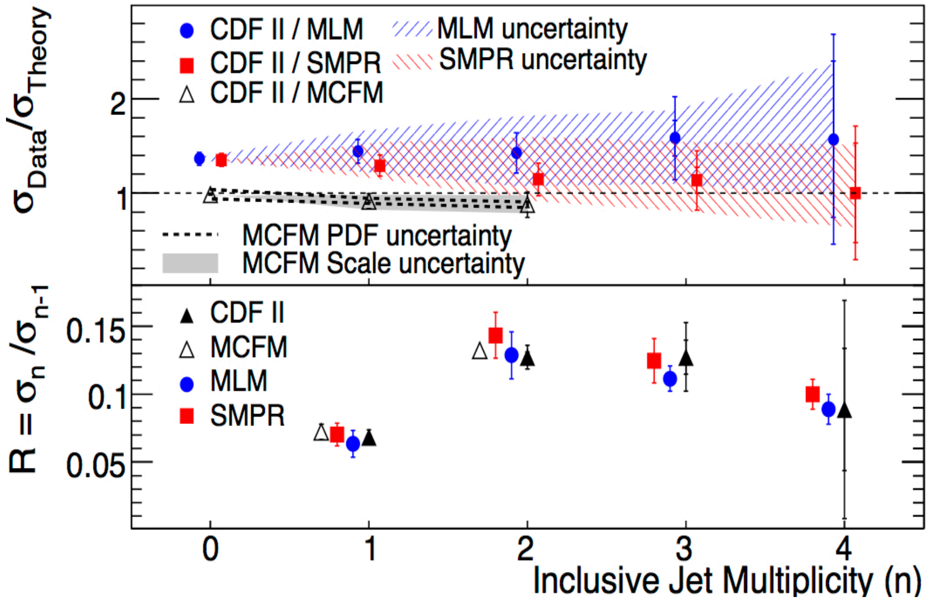
σ(WW) (2004)

- First significant hadron collider measurement.
- Led on to using WW as a Higgs search channel.

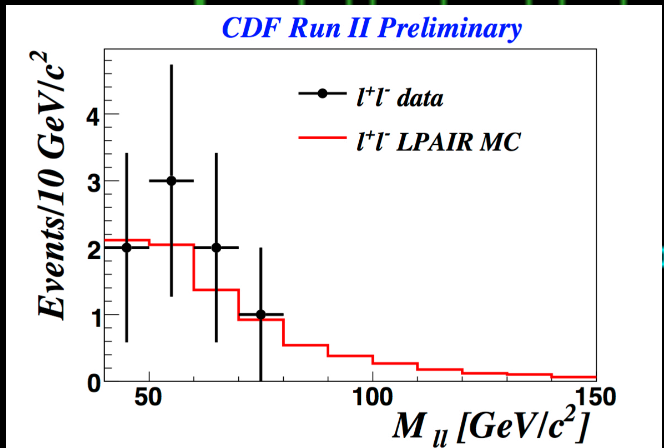


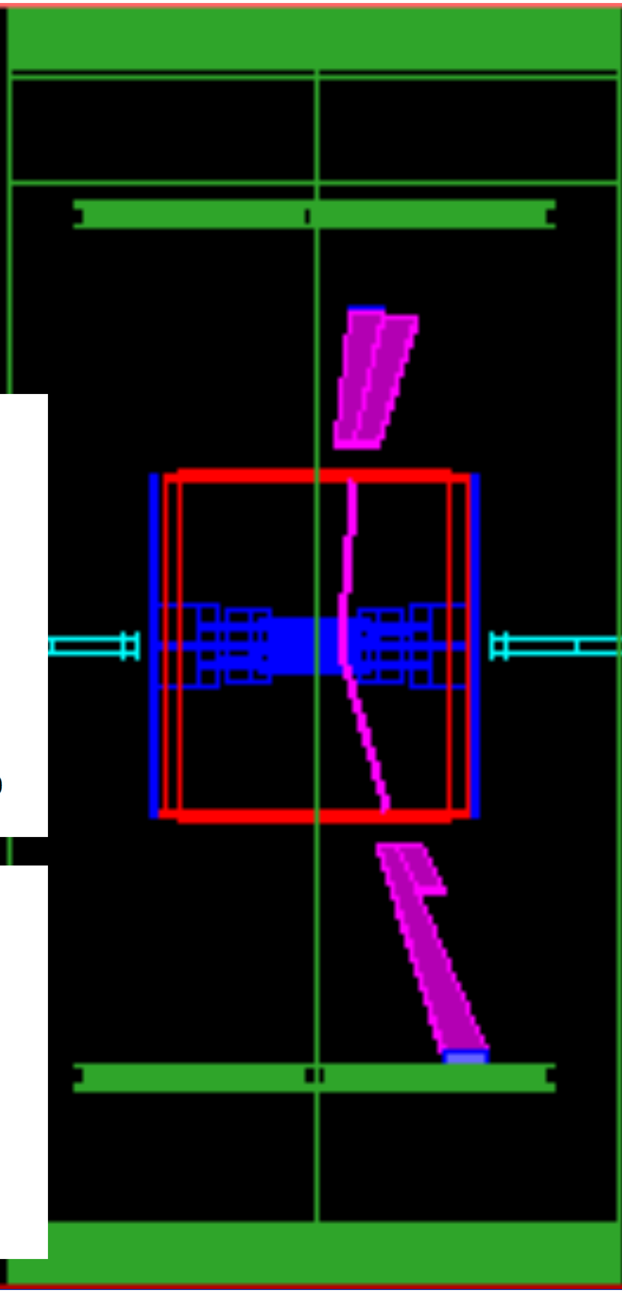
σ(W+jets) (2008)

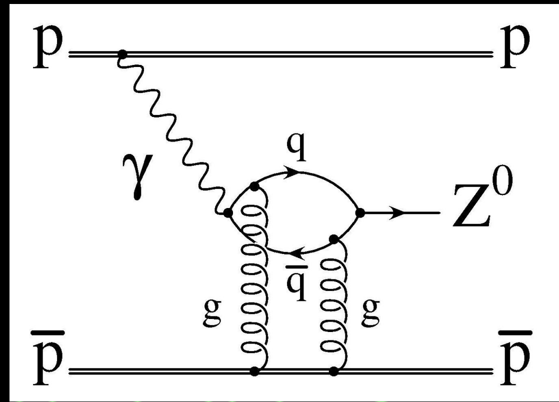
- Total and differential cross-section measurements.
- An early test of "Parton Shower Matching" schemes.
- New experimental methods developed.

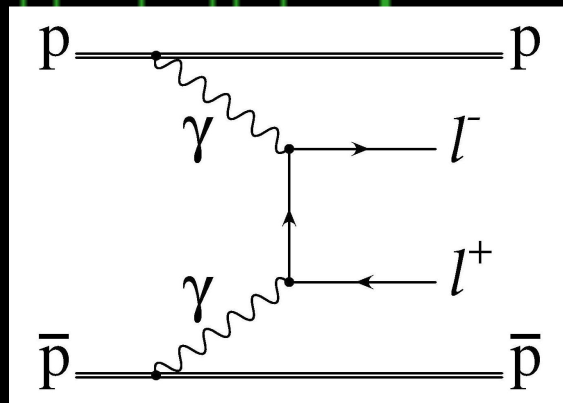


Exclusive Z Production









$$\sigma\left(p\bar{p} \to p\bar{p}\ l^+l^-\right) = 0.24^{+0.13}_{-0.10}\ \text{pb}$$

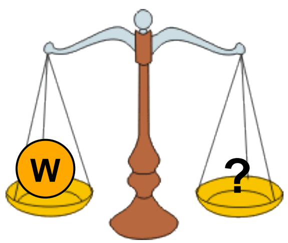
$[M_{ll} > 40\ \text{GeV/c}^2;\ |\eta_l| < 4]$

$$\sigma\left(p\bar{p} \to p\bar{p}\ Z^0\right) < 0.96\ \text{pb}$$

[@ 95% C.L.]

Summary

- Our involvement in CDF is almost over. Mark continues to oversee final Standard Model measurements.
- UCL involvement has been wide and varied, but precision electroweak measurements are a major legacy of CDF :



$$M_W = 80387 \pm 19 \text{ MeV}$$

$$\Gamma_W = 2032 \pm 73 \text{ MeV}$$

The End