Measurement of the W Boson Mass using 2.2 fb^{-1} of CDF II Data

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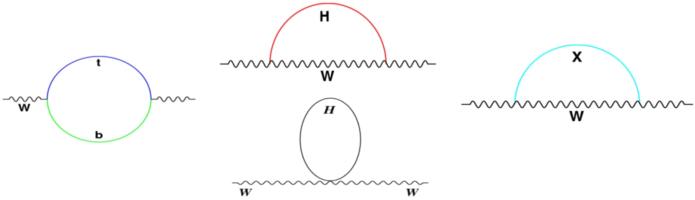
Motivation



ρ parameter $\Longrightarrow M_W^2 = \rho M_{W\ tree}^2$

$\Delta\rho = \rho - 1 \sim M_{top}^2$

$\Delta\rho \sim \ln M_H$

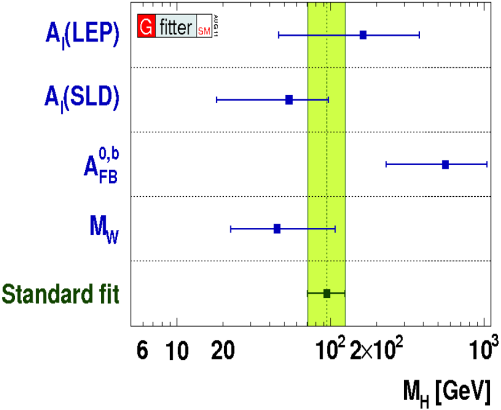
M_W and M_{top} costrain M_H and possibly new particles beyond SM

Motivation

$\Longrightarrow$

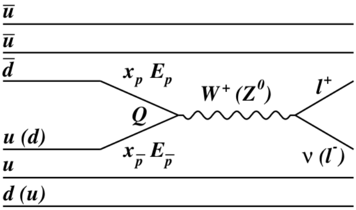
$\Longrightarrow$

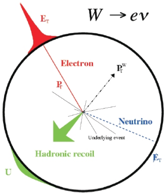
$\sim 3\sigma$



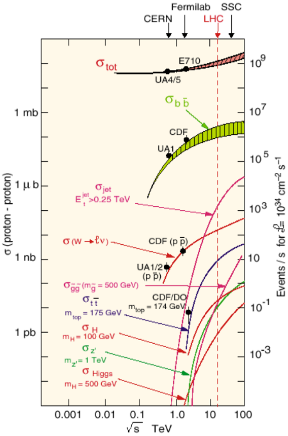
Other precision mesurements costrain M_H, equivalent to $\delta M_W = 15\ MeV$

Leading order annihilation





- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ *TeV*
  W and Z decay to lepton or quark pairs:
  - ~~$q\bar{q}$~~ large direct background (μb)
  - ~~$\tau\nu_\tau$~~ decays $\tau \longrightarrow \nu_\tau + had$
  - electronic decay $W \longrightarrow e\nu$, $Z \longrightarrow ee$ $\Longleftarrow$ (*nb*)
  - muonic decay $W \longrightarrow \mu\nu$, $Z \longrightarrow \mu\mu$ $\Longleftarrow$ (*nb*)



Measurement strategy

$$W \longrightarrow l\nu$$

- transverse lepton momentum $\vec{p}_T(l)$
- total transverse recoil $\vec{u}_T$

Transverse Mass

As neutrino escapes detection and initial unknown partonic p_z precludes usage of p_z conservation:

$$m_T = \sqrt{2p_T(l)p_T(\nu)[1 - \cos(\phi_l - \phi_\nu)]}$$

Jacobian peaks

$$\frac{dn}{dp_T} = \frac{1}{\sqrt{\left(\frac{m_W}{2}\right)^2 - p_T^2}} \frac{dn}{d\theta^*}$$

Peak for $p_T(l) = M_W/2$ and for $p_T(\nu) = M_W/2$

Very sharp for $p_T(W) = 0$

W has to be at rest

Jacobian peaks

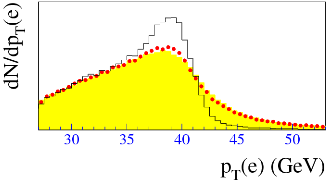


Figure 1: The effects of resolution and the finite p_T^W on $p_T(e)$ in W boson decay. The histogram shows p_T^W without detector smearing and for $p_T^W = 0$. The dots include the effects of adding finite p_T^W, while the shaded histogram includes the effects of detector resolutions. The effects are calculated for the DØ Run I detector resolutions.

Peak very sensitive to non zero $p_T(W)$

Jacobian peaks

In hadronic colliders, m_T is preferred

$$\sigma^{-1}\frac{d\sigma}{d\mu} = \mu(1-\mu^2)^{-1/2}\sigma^{-1}\frac{d\sigma}{d\cos\theta}$$

where $\mu = m_T/m_W$.

Sharp peak at $\mu = 1$

Effect of a finite $p_T(W)$ determined by applying a boost along x axis

$$\sigma^{-1}\frac{d\sigma}{d\mu} = \mu\frac{(1-\mu^2)^{-1/2}}{(2\pi)}\int_0^{2\pi} d\varphi\, I(\mu,\varphi,\alpha)\sigma^{-1}\frac{d\sigma}{d\cos\theta}\,, \tag{5}$$

where the function I is

$$I(\mu,\varphi,\alpha) = (\mu^4+\mu^4\alpha^2\cos^2\varphi+2\mu^2\alpha^2\sin^2\varphi+\mu^4\sin^2\varphi)(\mu^2+\alpha^2\sin^2\varphi)^{-1/2}(\mu^2+\mu^2\alpha^2\cos^2\varphi+\alpha^2\sin^2\varphi)^{-3/2}. \tag{6}$$

$\alpha = (\gamma^2-1)^{1/2}$

At $\mu = 1$, $I(\mu,\phi,\alpha)$ is finite for all α

m_T peak less sensistive to non zero $p_T(W)$

Jacobian peaks

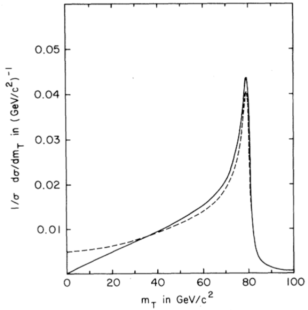


FIG. 1. $\sigma^{-1}d\sigma/dm_T$ for $M = 80$ GeV/c^2 and $\Gamma = 2.5$ GeV/c^2. The solid line is for $p_T{}^W = 0$ GeV/c, while the dashed line is for $p_T{}^W = 50$ GeV/c.

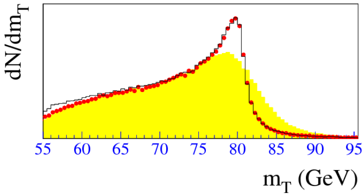


Figure 2: The effects of resolution and the finite p_T^W on M_T in $W \to e\nu$. The histogram shows M_T without detector smearing and for $p_T^W = 0$. The dots include the effects of adding finite p_T^W, while the shaded histogram includes the effects of detector resolutions. The effects are calculated for the DØ Run I detector resolutions.

Jacobian peaks

- m_T fits are
  - most **insensitive** to $p_T(W) \neq 0$
  - worse resolution to hadron and electron response

- p_T fits are
  - most **sensistive** to $p_T(W) \neq 0$
  - better experimental resolution

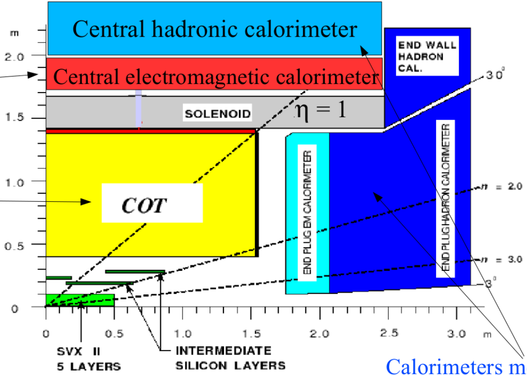
With high statistics → better cuts on hadronic recoil → $p_T(W)$ model better controlled → p_T can compete with m_T

Measurement strategy

Monte Carlo simulation is used to predict shape of these distribution as a function of M_W, including:

- kinematic distributions
  - QED radiation
  - PDFs
- detector effects
  - external Bremsstrahlung
  - ionization energy loss in material
  - tracker momentum scale
  - calorimeter energy scale
  - resolutions
  - acceptance

CDF Detector



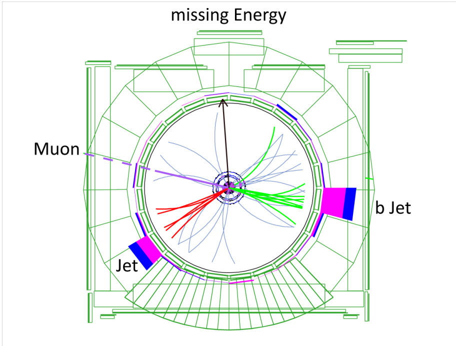
EM calorimeter provides precise electron energy measurement

COT provides precise lepton track momentum measurement

Calorimeters measure hadronic recoil particles

Inner silicon tracker, outer tracking drift chamber, COT, 1.4 *T* m. f. inside trackers, EM and Had calorimeters, muon system (CMU, CMP, CMX)

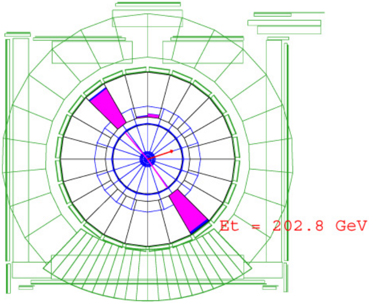
Experimental signatures: muon



Event selection

- minimum ionizing energy in calorimeter ($< 2\ GeV$ in EM, $< 6\ GeV$ in had)
- COT track, production vertex, $d_0 < 1\ mm$, $z_0 < 60\ cm$, $p_T > 30\ GeV$
- track segment in CMU and CMP or in CMX, compatible with COT track

Experimental signatures: electron



Event selection

- COT track: same for muon
- $E/p < 1.6$, $\frac{E_{had}}{E_{EM}} < 0.1$
- track matching with calorimeter energy and positions

Event Selection

Goal: select events with high $p_T(l)$ and small hadronic recoil activity
$p_T(l)$ carries most of M_W information

For Z candidates:

- 66 $GeV < m_{ll} <$ 116 GeV for leptons of both flavors

For W candidates

- recoil energy in calorimeter $<$ 15 GeV
- transverse missing energy $>$ 30 GeV
- 60 $GeV < m_T <$ 100 GeV

Data collected between February 2002 and September 2007 $\longmapsto$ 2.2 fb^{-1}

- 470 126 $W \longrightarrow e\nu$ candidates $\Longleftarrow$ in 2007 only 63 964
- 624 708 $W \longrightarrow \mu\nu$ candidates $\Longleftarrow$ in 2007 only 51 128

Momentum calibration

High statistics from

$J/\psi \longrightarrow \mu\mu$	large cross section, precise mass, narrow width
$\Upsilon(1s) \longrightarrow \mu\mu$	invariant mass 3 times larger than J/ψ, produced promptly
$Z \longrightarrow \mu\mu$	crosscheck

Momentum Calibration

***A priori* momentum scale**: $mv^2/R = evB$, $p_T = eB/(2|c|)$ where $c \equiv q/(2R)$
AP scale $eB/2 = 2.11593 \cdot 10^{-3} GeV/cm$, 0.15% accuracy

J/ψ **decays**, fitting dimuon mass $\Longrightarrow$ 0.025% accuracy

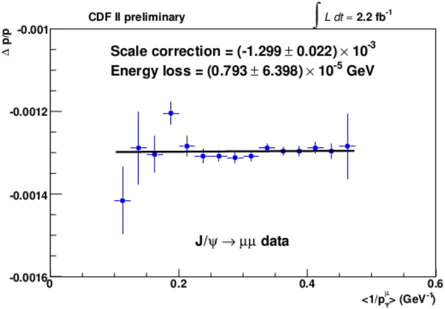
Accurate modelling of muon ionization energy loss required $\Longrightarrow$ $\Delta p/p$ as a function of $< 1/p_T^{\mu} >$ to improve model

Each muon passing through silicon and COT detectors loses on average 9 MeV

Momentum calibration

Measure of J/ψ mass as a function of inverse muon p_T

Non zero intercept : scale correction relevant for Z and W decays

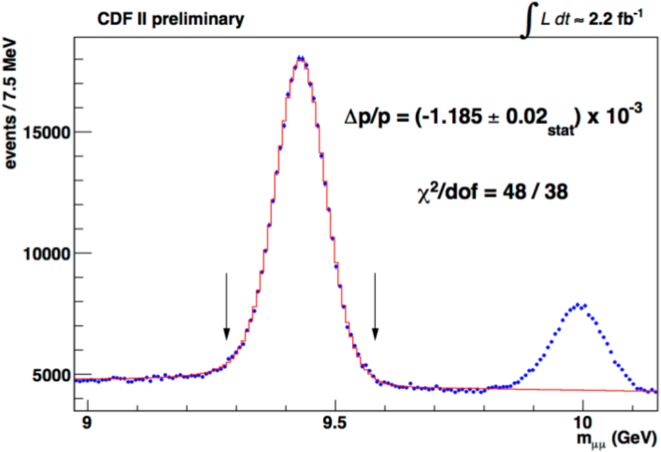


Non zero slope: remaining unmodeled IEL even after material tuning

$$\delta M_W = 7\ MeV$$

- non uniformities in tracker m.f. corrected removing dependence of J/ψ mass from muon mean polar angle
- scale dependence on $< 1/p_T >$ removed scaling tracker material

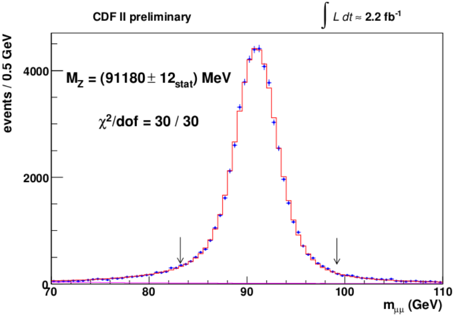
Momentum calibration



$\Upsilon(1s)$ $\Upsilon(2s)$

Momentum calibration

Combined momentum scale from J/ψ and $\Upsilon(1s)$ applied to Z and W samples



Consistent with world average $m_Z = 91188 \pm 2\ MeV$

Overall momentum scale $\Delta p/p = (-129 \pm 9)10^{-5}$

In 2007 was $\Delta p/p = (-150 \pm 21)10^{-5}$

Energy calibration

- Electron's energy is measured from its shower in EM calorimeters
- E/p distribution would result, for calibrated data mesurement, of unity for non radiating electrons
- at this energy scale, Bremsstrahlung is favoured with photons collinear to the electron:

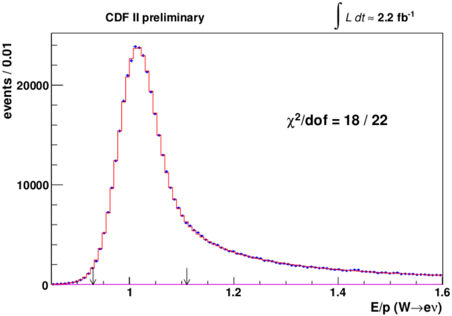
photons invisible in tracker: electron momentum softened

$\Longrightarrow E/p > 1$ (tails)

narrow EM shower: E completely reconstruted

Energy calibration

EM calorimeter energy scale is set using E/p electron distribution



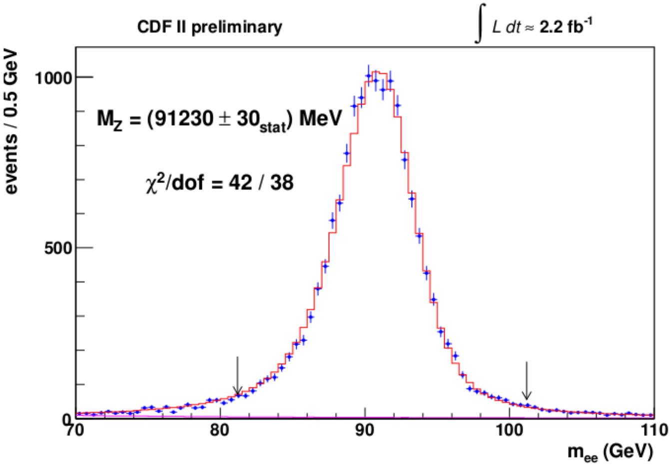
$$\boxed{\delta M_W = 13\ MeV}$$

- EM calorimeter non-linearity from E/p fits as a transverse energy
- tail to tune absolute number of X_0 in tracker

Same with $Z \longrightarrow ee$ samples

Energy calibration

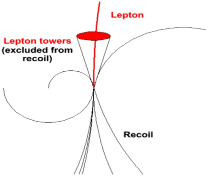
m_Z fit, crosscheck confirms consistency



$$\boxed{\delta M_W = 10\ MeV}$$

Recoil calibration

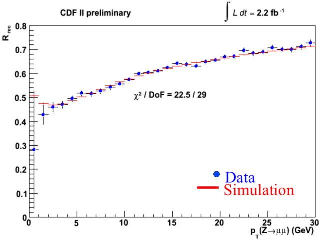
Recoil $\vec{u}$: vector sum of transverse energy over all EM and Had towers for $|\eta| < 2.4$, explicitly removing lepton towers.



Two components

- soft “spectator interaction” component, randomly oriented $\Longrightarrow$ minimum bias event with tunable magnitude
- hard jet component, opposite to $p_T(W)$ $\Longrightarrow$ p_T dependent, logarithmically increasing in p_T, following Z data

$$R \equiv u_{rec}/u_{true} = a\log(u_{true} + b)/\log(15 + b)$$

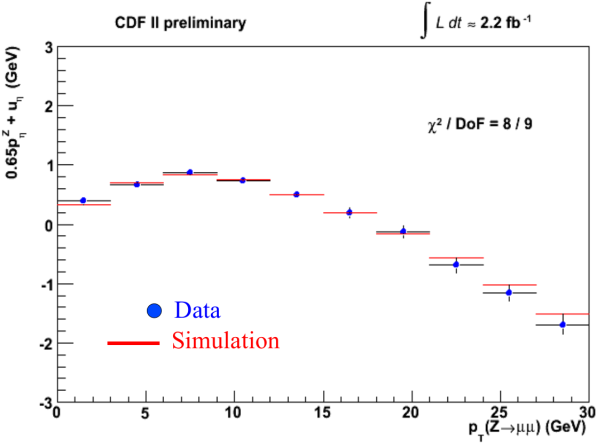


Recoil calibration

$Z \longrightarrow ll$ because we need to reveal both decay products

η axis defined as the geometric bisector of two leptons, ξ axis $\perp$ η

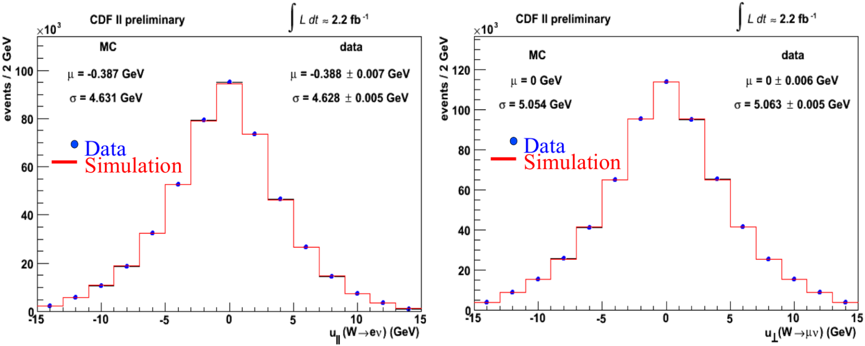
Mean and rms of recoil projection as a function of $p_T(ll)$



Tuning of hadronic model parameters (minimum χ^2)

Recoil calibration

Tuned hadronic recoil model tested on $W \longrightarrow l\nu$



Substantial improvement in model accuracy led to

$$\boxed{\delta M_W = 7\ MeV}$$

In 2007 was **20 MeV**

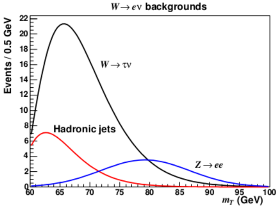
Backgrounds

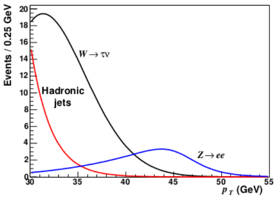
Both in $W \longrightarrow e\nu$ and in $W \longrightarrow \mu\nu$

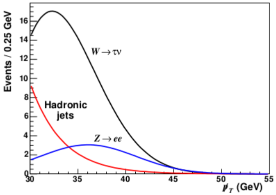
- $Z/\gamma* \longrightarrow ll$ with one l not detected
- $W \longrightarrow \tau\nu$ with τ decay products reconstructed as charged lepton
- multijet, where one jet is misreconstructed

In $W \longrightarrow \mu\nu$ sample

- cosmic rays, where a μ through COT is reconstructed on only one side
- long-lived hadrons $\longrightarrow \mu\nu X$, where μ misreconstructed



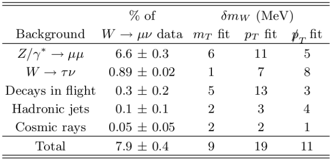




Backgrounds

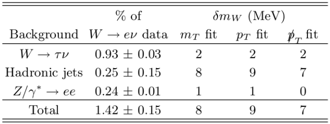
2007

Muons



Background	% of $W \to \mu\nu$ data	δm_W (MeV) m_T fit	p_T fit	$\not{p}_T$ fit
$Z/\gamma^* \to \mu\mu$	6.6 ± 0.3	6	11	5
$W \to \tau\nu$	0.89 ± 0.02	1	7	8
Decays in flight	0.3 ± 0.2	5	13	3
Hadronic jets	0.1 ± 0.1	2	3	4
Cosmic rays	0.05 ± 0.05	2	2	1
Total	7.9 ± 0.4	9	19	11

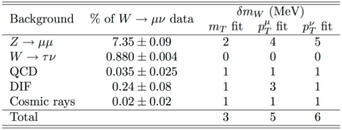
Electrons



Background	% of $W \to e\nu$ data	δm_W (MeV) m_T fit	p_T fit	$\not{p}_T$ fit
$W \to \tau\nu$	0.93 ± 0.03	2	2	2
Hadronic jets	0.25 ± 0.15	8	9	7
$Z/\gamma^* \to ee$	0.24 ± 0.01	1	1	0
Total	1.42 ± 0.15	8	9	7

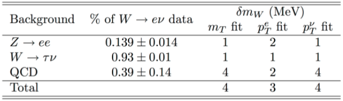
2012

Muons



Background	% of $W \to \mu\nu$ data	δm_W (MeV) m_T fit	p_T^μ fit	p_T^ν fit
$Z \to \mu\mu$	7.35 ± 0.09	2	4	5
$W \to \tau\nu$	0.880 ± 0.004	0	0	0
QCD	0.035 ± 0.025	1	1	1
DIF	0.24 ± 0.08	1	3	1
Cosmic rays	0.02 ± 0.02	1	1	1
Total		3	5	6

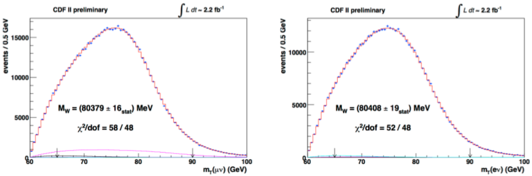
Electrons



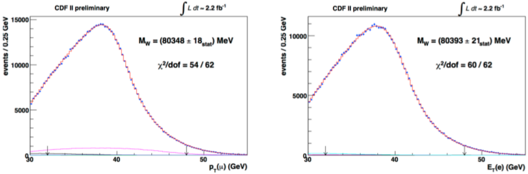
Background	% of $W \to e\nu$ data	δm_W (MeV) m_T fit	p_T^e fit	p_T^ν fit
$Z \to ee$	0.139 ± 0.014	1	2	1
$W \to \tau\nu$	0.93 ± 0.01	1	1	1
QCD	0.39 ± 0.14	4	2	4
Total		4	3	4

Mass fits

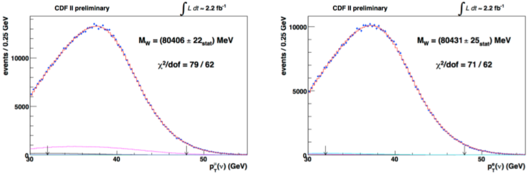
Binned maximum-likelihood fit to $p_T(l)$, $p_T(\nu)$, m_T for each lepton channel



Charged Lepton Fits (muons) **(electrons)**



Neutrino Fits (muons) **(electrons)**



Mass fits

- Statistical correlation between fits measured through fits of simulated data to MC templates
- Different fits combined, calculating full covariance matrix for uncertainities

Combined m_T fits
$M_W = 80390 \pm 20\ MeV$

Combined $p_T(l)$ fits
$M_W = 80366 \pm 22\ MeV$

Combined $p_T(\nu)$ fits
$M_W = 80416 \pm 25\ MeV$

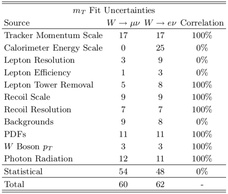
Combined m_T, $p_T(l)$, $p_T(\nu)$ for electron
$M_W = 80406 \pm 25\ MeV$

Combined m_T, $p_T(l)$, $p_T(\nu)$ for muon
$M_W = 80374 \pm 22\ MeV$

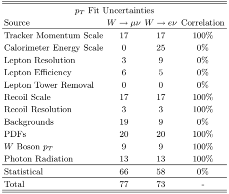
Combination of all fits
$M_W = 80387 \pm 19\ MeV$
Most precise M_W measurement to date

Uncertainities

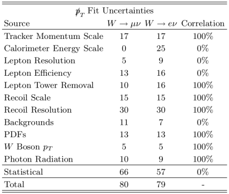
2007



m_T Fit Uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Tracker Momentum Scale	17	17	100%
Calorimeter Energy Scale	0	25	0%
Lepton Resolution	3	9	0%
Lepton Efficiency	1	3	0%
Lepton Tower Removal	5	8	100%
Recoil Scale	9	9	100%
Recoil Resolution	7	7	100%
Backgrounds	9	8	0%
PDFs	11	11	100%
W Boson p_T	3	3	100%
Photon Radiation	12	11	100%
Statistical	54	48	0%
Total	60	62	-

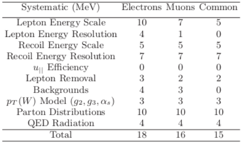


p_T Fit Uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Tracker Momentum Scale	17	17	100%
Calorimeter Energy Scale	0	25	0%
Lepton Resolution	3	9	0%
Lepton Efficiency	6	5	0%
Lepton Tower Removal	0	0	0%
Recoil Scale	17	17	100%
Recoil Resolution	3	3	100%
Backgrounds	19	9	0%
PDFs	20	20	100%
W Boson p_T	9	9	100%
Photon Radiation	13	13	100%
Statistical	66	58	0%
Total	77	73	-



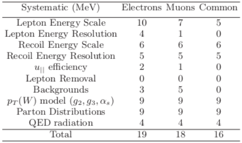
$\not{p}_T$ Fit Uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Tracker Momentum Scale	17	17	100%
Calorimeter Energy Scale	0	25	0%
Lepton Resolution	5	9	0%
Lepton Efficiency	13	16	0%
Lepton Tower Removal	10	16	100%
Recoil Scale	15	15	100%
Recoil Resolution	30	30	100%
Backgrounds	11	7	0%
PDFs	13	13	100%
W Boson p_T	5	5	100%
Photon Radiation	10	9	100%
Statistical	66	57	0%
Total	80	79	-

2012



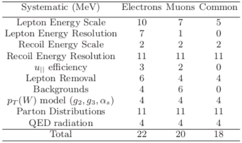
Systematic (MeV)	Electrons	Muons	Common
Lepton Energy Scale	10	7	5
Lepton Energy Resolution	4	1	0
Recoil Energy Scale	5	5	5
Recoil Energy Resolution	7	7	7
$u_{\|\|}$ Efficiency	0	0	0
Lepton Removal	3	2	2
Backgrounds	4	3	0
$p_T(W)$ Model (g_2, g_3, α_s)	3	3	3
Parton Distributions	10	10	10
QED Radiation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

TABLE II: Table of systematic uncertainties for the transverse mass fits.



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

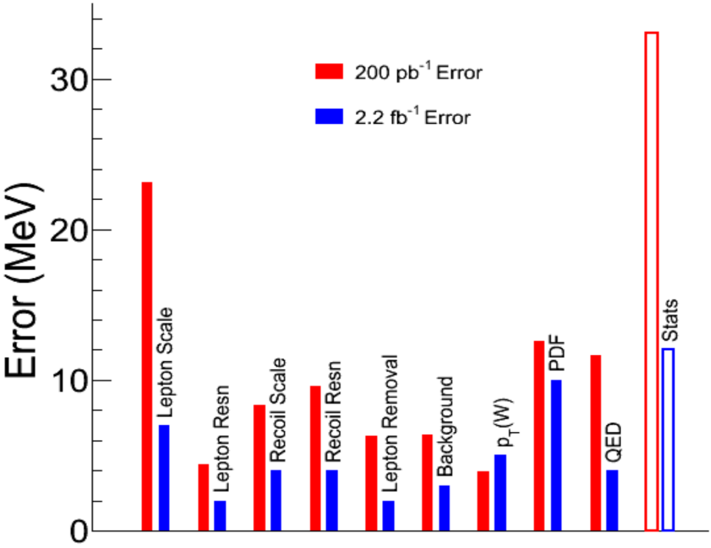
TABLE III: Table of systematic uncertainties for the charged lepton p_T fits.



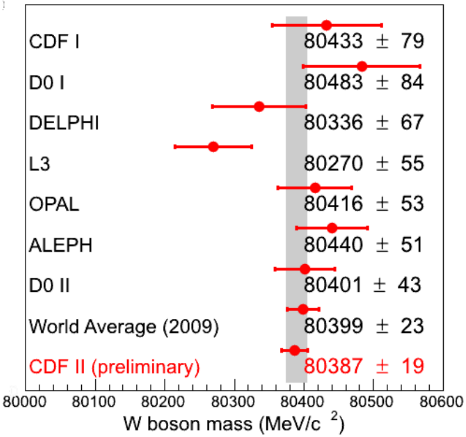
Systematic (MeV)	Electrons	Muons	Common
Lepton Energy Scale	10	7	5
Lepton Energy Resolution	7	1	0
Recoil Energy Scale	2	2	2
Recoil Energy Resolution	11	11	11
$u_{\|\|}$ efficiency	3	2	0
Lepton Removal	6	4	4
Backgrounds	4	6	0
$p_T(W)$ model (g_2, g_3, α_s)	4	4	4
Parton Distributions	11	11	11
QED radiation	4	4	4
Total	22	20	18

TABLE IV: Table of systematic uncertainties for the missing transverse energy fits.

Uncertainities



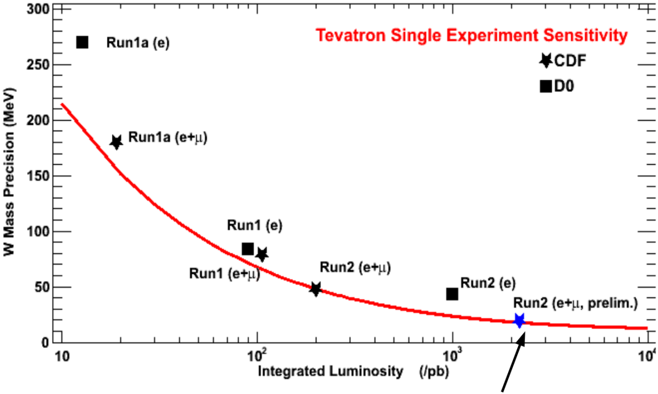
Results


CDF I
80433 ± 79
D0 I
80483 ± 84
DELPHI
80336 ± 67
L3
80270 ± 55
OPAL
80416 ± 53
ALEPH
80440 ± 51
D0 II
80401 ± 43
World Average (2009)
80399 ± 23
CDF II (preliminary)
80387 ± 19
80000
80100
80200
80300
80400
80500
80600
W boson mass (MeV/c 2)

Results

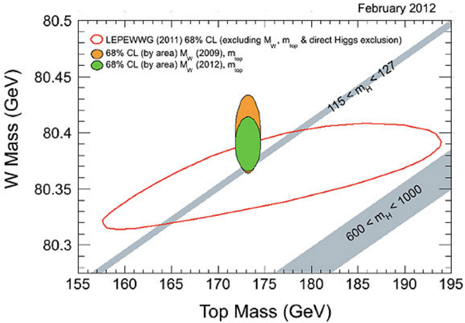
Combining this result with previous CDF measurement $\Longrightarrow$
$M_W = 80394 \pm 18\ MeV$

New world average $M_W = 80390 \pm 16\ MeV$ $\Longrightarrow$ new input for Standard Model global fits



Higher pressure on SM

Results



New Higgs mass estimate $m_H = 90^{+29}_{-23}$ GeV, upper bound 145 GeV 95%C.L.

Excellent agreement with direct searches:

- $m_H < 156$ GeV (Tevatron)
- $m_H < 127$ GeV (LHC)

References

- *First Run II Measurement of the W Boson Mass*, 27 Aug 2007
- *Measurement of the W Boson Mass using 2.2 fb–1 of CDF II Data*, 23 Feb 2012
- *Measuring the W Boson Mass at Hadron Colliders*, U. Baur
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- *A New Precise Measurement of the W Boson Mass by CDF*, A. Kotwal