First Run II Measurement of the W Boson Mass with CDF

Chris Hays,
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University of Edinburgh
January 31, 2007
The Standard Model

“Electromagnetic” charge
Interact via $\gamma$

“Weak” charge
Interact via $W, Z$

“Strong” charge
Interact via $g$

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Electroweak Symmetry Breaking

Non-zero particle mass breaks the weak symmetry

QUARK MASSES

Quarks

Mass (GeV/c²)

0 50 100 150 200

up down strange charm bottom top

175

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Particle mass determined by viscosity in the Higgs sea

Top quark

Up quarks

Higgs Vacuum Energy
Higgs Boson

Vacuum expectation value determined by effective weak coupling:

\[ \langle \phi \rangle = \frac{1}{(\sqrt{8G_F})^{1/2}} = 174 \text{ GeV} \]

\((G_F\) measured from muon decay to 0.0009\%)

Higgs mass and self-couplings not predicted by Standard Model

→ However, Higgs mass indirectly affects gauge boson masses via loop corrections:

\[ \Delta m_W \propto \ln \left( \frac{m_H}{m_Z} \right) \]

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W Boson Mass

Given precise measurements of $m_Z$ and $\alpha_{EM}(m_Z)$, we can predict $m_W$:

$$m_W^2 = \frac{\pi \alpha_{EM}}{\sqrt{2} G_F (1 - m_W^2 / m_Z^2)(1 - \Delta r)}$$

(“on-shell scheme”)

$\Delta r$: O(3%) radiative corrections dominated by $t\bar{b}$ and Higgs loops

$\Delta m_W \propto m_t^2$
**Measured Top Mass**

**Best Tevatron Run II (Preliminary)**
- **D0 Dilepton** $(L = 370 \text{ pb}^{-1})$:
  - $178.1 \pm 6.7 \pm 4.8$
- **D0 Lepton+Jets** $(L = 370 \text{ pb}^{-1})$:
  - $170.3 \pm 2.5 \pm 3.8$
- **CDF Dilepton** $(L = 1030 \text{ pb}^{-1})$:
  - $164.5 \pm 3.9 \pm 3.9$
- **CDF Lepton+Jets** $(L = 940 \text{ pb}^{-1})$:
  - $170.9 \pm 1.6 \pm 2.0$
- **CDF All hadronic** $(L = 1020 \text{ pb}^{-1})$:
  - $174.0 \pm 2.2 \pm 4.8$
- **Tevatron July'06** (CDF+D0 Run I+II Average):
  - $171.4 \pm 1.2 \pm 1.8$ (stat) $\pm$ (syst)

**Top mass now measured to 2.1 GeV (1.2%)**

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W Mass Prediction and Measurement

W mass uncertainty from input parameters:

<table>
<thead>
<tr>
<th>Parameter Shift</th>
<th>$m_W$ Shift (MeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_H = +100$ GeV/c$^2$</td>
<td>-41.3</td>
</tr>
<tr>
<td>$\Delta m_t = +2.1$ GeV/c$^2$</td>
<td>12.8</td>
</tr>
<tr>
<td>$\Delta m_Z = +2.1$ MeV/c$^2$</td>
<td>2.6</td>
</tr>
<tr>
<td>$\Delta \alpha_{EM} = +0.00013$</td>
<td>-2.3</td>
</tr>
</tbody>
</table>

Direct W mass measurement

<table>
<thead>
<tr>
<th></th>
<th>W-Boson Mass [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEVATRON</td>
<td>80.452 ± 0.059</td>
</tr>
<tr>
<td>LEP2</td>
<td>80.376 ± 0.033</td>
</tr>
<tr>
<td>Average</td>
<td>80.392 ± 0.029</td>
</tr>
</tbody>
</table>

$\chi^2$/DoF: 1.3 / 1

W mass predicted much more precisely (13 MeV) than measured (29 MeV)

Need to reduce $\delta m_W$ to further constrain Higgs mass
Predicted Higgs mass from W loop corrections:

\[ m_H = 85^{+39}_{-28} \text{ GeV} \] (< 166 GeV at 95% CL)

Direct search from LEP II: \( m_H > 114.4 \text{ GeV} \) at 95% CL
Projection with 2 fb$^{-1}$ of data:

$\delta m_W = 40$ MeV per experiment
## Tevatron Run I Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>CDF $\mu$</th>
<th>CDF $e$</th>
<th>DØ $e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$ statistics</td>
<td>100</td>
<td>65</td>
<td>60</td>
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<tr>
<td>Lepton energy scale</td>
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<tr>
<td>Lepton resolution</td>
<td>20</td>
<td>25</td>
<td>19</td>
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<tr>
<td>Recoil model</td>
<td>35</td>
<td>37</td>
<td>35</td>
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<tr>
<td>$p_T(W)$</td>
<td>20</td>
<td>15</td>
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<tr>
<td>Selection bias</td>
<td>18</td>
<td>-</td>
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<tr>
<td>Backgrounds</td>
<td>25</td>
<td>5</td>
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<tr>
<td>Parton dist. functions</td>
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<td>8</td>
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<tr>
<td>QED rad. corrections</td>
<td>11</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>$\Gamma(W)$</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>144</strong></td>
<td><strong>113</strong></td>
<td><strong>84</strong></td>
</tr>
</tbody>
</table>
Each experiment has collected >1.5 $fb^{-1}$ of 1.96 TeV $\sqrt{s}$ pp collisions

Current Run II: 15x Run I data set

Today: First Run II W mass measurement

(CDF 200 pb$^{-1}$)

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W & Z Boson Production and Decay

Dominant production mechanism: $q\bar{q}^{(s)}$ annihilation

$\sigma(W \rightarrow l\nu) = 2775 \text{ pb}$

After event selection ($l, \nu E_T > 30 \text{ GeV}$):
51,128 $W \rightarrow \mu\nu$ candidates
63,964 $W \rightarrow e\nu$ candidates

$\sigma(Z \rightarrow ll) = 254.9 \text{ pb}$

After event selection ($l E_T > 30 \text{ GeV}$):
4,960 $Z \rightarrow \mu\mu$ candidates
2,919 $Z \rightarrow ee$ candidates
Measurement Strategy

Calibrate $l^\pm$ track momentum with mass measurements of $J/\psi$ and $Y$ decays to $\mu$

Calibrate calorimeter energy using track momentum of $e$ from $W$ decays

Cross-check with $Z$ mass measurement, then add $Z$'s as a calibration point

Cross-check with $W$ recoil distributions

Combine information into transverse mass:

$$m_T = \sqrt{E_T \hat{E}_T (1 - \cos \Delta \phi)}$$

Statistically most powerful quantity for $m_W$ fit

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Transverse Mass Distribution

Distribution peaks just below $m_W$ and falls sharply just above $m_W$

$m_W = 80$ GeV

$m_W = 81$ GeV
High-precision tracking drift chamber
\[ \frac{\delta p_T}{p_T} = 0.05\% \quad p_T : 2\% \text{ for } 40 \text{ GeV } \mu \]

High-precision electromagnetic calorimeter
\[ \frac{\delta E_T}{E_T} = 13.5\% / \sqrt{E_T} \oplus 1.7\% : \]
\[ 3\% \text{ for } 40 \text{ GeV } e \]

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Momentum Scale Calibration

Magnetic field along z-axis causes curvature in transverse plane:
\[ \frac{mv^2}{R} = evB, \]
\[ p_T = eBR \]

CDF: Insufficient precision on B and R for W mass measurement

**In-situ calibration:**
(1) Apply relative alignment of drift chamber wires
(2) Determine momentum scales such that \( J/\psi, Y, \) and Z mass measurements result in the world-average values

Combine results to obtain scale for \( m_W \) measurement
Tracker Alignment

Central Outer Tracker: Open-cell drift chamber

Wires strung under tension between two endplates

Model endplate distortions and constructional variations using a cell-to-cell endplate alignment

Determine individual cell tilts & shifts using cosmic-ray data

Fit a single 'dicosmic' to track segments on opposite sides of the chamber

Measure cell displacement

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(Kotwal, Gerberich, Hays, NIM A 506, 110 (2003))
Alignment Example

Inner 'Superlayer:'

Before alignment

Cell Shift (microns)

After alignment

CDF Run II preliminary

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Wire Alignment

Wire shape along z-axis determined by:
- Gravitational sag
- Electrostatic effects

Apply additional correction based on cosmic ray study
- Compare parameters of incoming and outgoing tracks from a cosmic ray muon

Final correction removes $z$-dependent curvature biases
Track-Level Corrections

Determine curvature corrections from electron-positron differences
Use ratio of calorimeter energy to track momentum
*Curvature biases affect* $e^+$, $e^-$ *differently, but calorimeter measurement independent of charge*

Statistical uncertainty of track-level corrections leads to $\delta m_W = 6$ MeV
Mass Measurements

Template mass fits to $J/\psi$, $Y$, $Z$ resonances in muon decay channels

Fast detector simulation models relevant physical processes

- internal bremsstrahlung
- ionization energy loss
- multiple scattering

Simulation includes event reconstruction and selection

Detector material model

Map energy loss and radiation lengths in each detector layer

One material parameter determined from data:

Overall material scale
**$J/\psi$ Mass Measurement**

**606,701 $J/\psi \rightarrow \mu\mu$ candidates**

Fit mass as a function of mean inverse $p_T$

Slope affected by energy loss modelling

Scale detector material by 0.94 to remove slope

Measurement dominated by systematic uncertainties

QED and energy loss model:

$$0.20 \times 10^{-3}$$

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Mass Measurement

34,618 $\text{Y} \rightarrow \mu\mu$ candidates

Short lifetime allows a track constraint to the beam line

*Improves resolution by a factor of $\approx 3$*

Test beam constraint by measuring mass using unconstrained tracks

Correct by half the difference between fits

Take correction as a systematic uncertainty

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Combined Momentum Scale

\[ \Delta p/p = (1.50 \pm 0.19) \times 10^{-3} \]

**Systematic uncertainties:**

<table>
<thead>
<tr>
<th>Source</th>
<th>( J/\psi \times 10^{-3} )</th>
<th>( \Upsilon \times 10^{-3} )</th>
<th>Common ( \times 10^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>QED and energy loss model</td>
<td>0.20</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Magnetic field nonuniformities</td>
<td>0.10</td>
<td>0.12</td>
<td>0.10</td>
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<tr>
<td>Beam constraint bias</td>
<td>N/A</td>
<td>0.06</td>
<td>0</td>
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<tr>
<td>Ionizing material scale</td>
<td>0.06</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>COT alignment corrections</td>
<td>0.05</td>
<td>0.03</td>
<td>0.03</td>
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<tr>
<td>Fit range</td>
<td>0.05</td>
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<td>0.02</td>
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<tr>
<td>( p_T ) threshold</td>
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<td>0.02</td>
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<tr>
<td>Resolution model</td>
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<td>0.03</td>
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<td>Background model</td>
<td>0.03</td>
<td>0.02</td>
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<tr>
<td>World-average mass value</td>
<td>0.01</td>
<td>0.03</td>
<td>0</td>
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<tr>
<td>Statistical</td>
<td>0.01</td>
<td>0.06</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.25</strong></td>
<td><strong>0.21</strong></td>
<td><strong>0.17</strong></td>
</tr>
</tbody>
</table>
Momentum Scale Cross-Check

Use calibrated momentum scale to measure Z mass

All measurements consistent
Measurement Strategy

Calibrate $l^\pm$ track momentum with mass measurements of $J/\psi$ and $Y$ decays to $\mu$.

Calibrate calorimeter energy using track momentum of $e$ from $W$ decays.

Cross-check with $Z$ mass measurement, then add $Z$'s as a calibration point.

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Cross-check with $W$ recoil distributions.

Combine information into transverse mass:

$$m_T = \sqrt{E_T \hat{E}_T (1 - \cos \Delta \phi)}$$

Statistically most powerful quantity for $m_W$ fit.

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Calorimeter Energy Calibration

Calibrate electron energy using electron track momentum
   First step: validate model of electrons in tracker

Additional physical effects beyond those associated with muons:
   Photon radiation and conversion in tracker
Electron Track Model Validation

*Fit Z mass reconstructed from electron track momenta*

$\mathcal{L} = 200 \text{ pb}^{-1}$  CDF Run II Preliminary

Measured value consistent with world average value (91188 MeV)

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Full Electron Simulation

Response and resolution in EM calorimeter

Energy loss into hadronic calorimeter

Track reconstruction in outer tracker

Energy loss in solenoid

Bremstrahlung and conversions in silicon

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Energy Loss Model

Use GEANT to parametrize energy loss in solenoid and hadronic calorimeter

Energy loss in hadronic calorimeter:
Energy Scale Calibration

Calibrate calorimeter energy with peak of $W$ electron $E/p$ distribution

One free parameter for $X_0$ scale (set with high $E/p$ region)

Material scale: $1.004 \pm 0.009$

Energy scale uncertainty: 0.034%
Apply energy-dependent scale to each simulated electron and photon

Determine energy dependence from $E/p$ fits as functions of electron $E_T$

Scale: $1 + (6 \pm 7) \times 10^{-5} [E_T/\text{GeV} - 39]$  

($\delta m_W = 23 \text{ MeV}$)

Most energy dependence implicitly accounted for by detector model

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$\mathcal{L} = 200 \text{ pb}^{-1}$  
CDF Run II Preliminary

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Z Mass Measurement

Fit Z mass using scale from E/p calibration

$\mathcal{L} = 200 \text{ pb}^{-1}$ CDF Run II Preliminary

$\frac{\chi^2}{\text{dof}} = 34 / 38$

$E = (91190 \pm 67) \text{ MeV}$

Measured value consistent with world average value (91188 MeV)

Incorporate mass fit into calibration to reduce scale uncertainty

$\delta m_w = 30 \text{ MeV}$

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Measurement Strategy

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Cross-check with $W$ recoil distributions

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$$m_T = \sqrt{E_T E_T (1 - \cos \Delta \phi)}$$

Statistically most powerful quantity for $m_W$ fit

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Boson $p_T$ Model

Model boson $p_T$ using RESBOS generator with tunable non-perturbative parameters

"$g_2$" parameter determines position of peak in $p_T$ distribution

Measure $g_2$ with Z boson data (other parameters have negligible effect on $W$ mass)

$$g_2 = 0.685 \pm 0.048; \; \delta m_W = 3 \text{ MeV}$$

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Recoil Measurement

Calculate recoil by summing over calorimeter towers, excluding:

- Towers with lepton energy deposits
- Towers near the beam line

Electron: Remove 7 towers (shower)
Muon: Remove 3 towers (MIP)

Model tower removal in simulation

$$\delta m_w = 8 \pm 5 \text{ MeV for } e (\mu)$$
Recoil Model

Components:

- Recoil scale \( R = \frac{u_{\text{meas}}}{u_{\text{true}}} \)
- Recoil resolution
- Spectator and additional interactions (contribute to resolution)

Calibrate scale with momentum balance along bisector axis (\( \eta \))

Calibrate models of recoil resolution and spectator interactions using momentum resolution along both axes

\[ \delta m_w = 11 \text{ MeV} \]

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Recoil Model Checks

Apply model to $W$ boson sample, test consistency with data

Recoil distribution

*Sensitive to scale, resolution, boson $p_T$*

$u_{||}$ distribution

*Sensitive to lepton removal, efficiency model, scale, resolution, $W$ decay*

*Directly affects $m_T$ fit result*

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Production, Decay, Background

Boson $p_z$ determined by parton distribution functions

Vary PDFs according to uncertainties

$\delta m_W = 11$ MeV

Bremstrahlung reduces charged lepton $p_T$

Predict using NLO QED calculation, apply NNLO correction

$\delta m_W = 11$ (12) MeV for $e$ ($\mu$)

Background affects fit distributions

QCD: Measure with data

Electroweak: Predict with MC

$\delta m_W = 8$ (9) MeV for $e$ ($\mu$)

<table>
<thead>
<tr>
<th>Background</th>
<th>% ($\mu$)</th>
<th>% ($e$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic Jets</td>
<td>0.1 ± 0.1</td>
<td>0.25 ± 0.15</td>
</tr>
<tr>
<td>Decays in Flight</td>
<td>0.3 ± 0.2</td>
<td>-</td>
</tr>
<tr>
<td>Cosmic Rays</td>
<td>0.05 ± 0.05</td>
<td>-</td>
</tr>
<tr>
<td>$Z \rightarrow ll$</td>
<td>6.6 ± 0.3</td>
<td>0.24 ± 0.04</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>0.89 ± 0.02</td>
<td>0.93 ± 0.03</td>
</tr>
</tbody>
</table>

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Calibrate $l^\pm$ track momentum with mass measurements of $J/\psi$ and $\Upsilon$ decays to $\mu$.

Calibrate calorimeter energy using track momentum of $e$ from $W$ decays.

Cross-check with $Z$ mass measurement, then add $Z$'s as a calibration point.

Calibrate recoil measurement with $Z$ decays to $e, \mu$.

Cross-check with $W$ recoil distributions.

Combine information into transverse mass:

$$m_T = \sqrt{E_T^T (1 - \cos \Delta \phi)}$$

Statistically most powerful quantity for $m_W$ fit.
Mass fit results blinded with [-100,100] MeV offset throughout analysis. Upon completion, offset removed to determine final result.

Transverse mass fits:

- **Muon channel**: $m_W = 80417 \pm 48$ MeV (stat + sys) for $e + \mu$ combination ($P(\chi^2) = 7\%$)

- **Electron channel**: $m_W = 80493 \pm 48$ MeV (stat)
Fit $E_T$, $\not{E}_T$ distributions and combine with $m_T$ to extract most precise result

**Electron $E_T$ fit:**

$M_W = (80451 \pm 58_{\text{stat}}) \text{ MeV}$

$\chi^2/\text{dof} = 63/62$

**Muon $p_T$ fit:**

$M_W = (80396 \pm 66_{\text{stat}}) \text{ MeV}$

$\chi^2/\text{dof} = 44/62$

$m_W = 80388 \pm 59 \text{ MeV} \text{ (stat + sys)}$

for lepton $p_T$ $e + \mu$ combination ($P(\chi^2) = 18\%$)

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W Mass Fits

\[ m_W = 80434 \pm 65 \text{ MeV (stat + sys)} \]

for neutrino \( p_T e + \mu \) combination \((P(\chi^2) = 43\%)\)

**Electron \( E_T \) fit:**

CDF II preliminary

\[ \int L dt \approx 200 \text{ pb}^{-1} \]

\[ M_W = (80451 \pm 58_{\text{stat}}) \text{ MeV} \]

\[ \chi^2/\text{dof} = 63 / 62 \]

**Muon \( E_T \) fit:**

CDF II preliminary

\[ \int L dt \approx 200 \text{ pb}^{-1} \]

\[ M_W = (80396 \pm 66_{\text{stat}}) \text{ MeV} \]

\[ \chi^2/\text{dof} = 44 / 62 \]

\[ m_W = 80413 \pm 48 \text{ MeV (stat + sys)} \]

for six-fit combination \((P(\chi^2) = 44\%)\)

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# W Mass Uncertainties

<table>
<thead>
<tr>
<th>$m_T$ Uncertainty [MeV]</th>
<th>Electrons</th>
<th>Muons</th>
<th>Common</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton Scale</td>
<td>30</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>Lepton Resolution</td>
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<tr>
<td>Recoil Scale</td>
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<td>$u_</td>
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<tr>
<td>Lepton Removal</td>
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<tr>
<td>$p_T(W)$</td>
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<td><strong>Total Systematic</strong></td>
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<td><strong>Statistical</strong></td>
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<tr>
<td><strong>Total</strong></td>
<td>62</td>
<td>60</td>
<td>26</td>
</tr>
</tbody>
</table>

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W Mass Result

New CDF result is world's most precise single measurement

Central value increases: 80392 to 80398 MeV
World average uncertainty reduced ~15% (29 to 25 MeV)
Predicted Higgs mass from W loop corrections:

\[ m_H = 85^{+39}_{-28} \text{ GeV} \quad (< 166 \text{ GeV at 95\% CL}) \]

Direct search from LEP II: \( m_H > 114.4 \text{ GeV at 95\% CL} \)

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Predicted Higgs mass from W loop corrections:

\[ m_H = 80^{+36}_{-26} \text{ GeV} \ (< 153 \text{ GeV at 95\% CL}) \]

Direct search from LEP II: \( m_H > 114.4 \text{ GeV at 95\% CL} \)

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Effect on New Physics Models

Additional space-time symmetry (Supersymmetry) would affect the $W$ mass

Previous world average:

![Graph showing experimental errors and different models with mass values and m_t range](image-url)
Effect on New Physics Models

Supersymmetry now preferred at 1σ level...

New world average:

![Graph showing the effect on new physics models with supersymmetry preference at 1σ level. The graph illustrates the calculated new world average for the mass of the top quark, mt, and the mass of the W boson, MW, with experimental errors indicated at the 68% confidence level. The graph includes regions for light and heavy SUSY, as well as the SM models with Mw = 114 GeV and Mw = 400 GeV. The source is Heinemeyer, Hollik, Stockinger, Weber, Weiglein '06.]

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**W Mass Measurement Projections**

Previously projected Tevatron precision as a function of luminosity:

New expectation: $<20$ MeV systematic limit

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Summary

*W mass excellent probe for new particles coupling to the electroweak sector*

CDF has made the single most precise $W$ mass measurement

\[ m_W = 80413 \pm 34 \text{ MeV (stat)} \pm 34 \text{ MeV (sys)} \]
\[ = 80413 \pm 48 \text{ MeV (stat + sys)} \]

*New SM Higgs mass prediction:*) \[ m_H = 80^{+36}_{-26} \text{ GeV} \]

*Mass has moved further into LEP-excluded region*

*Expect CDF $\delta m_W < 25 \text{ MeV with 1.5 fb}^{-1} \text{ already collected})*

*Will continue to squeeze SM in conjunction with Tevatron Higgs results*
Backup
The Standard Model

World without Higgs:

Electroweak charges:
up (0) & down (-1); (0) & (-1)

Strong charges: red, blue, green

Particles

Lepton

Quark

The particle drawings are simple artistic representations.
Electron $m_T$ Signed $\chi$

High $\chi^2$ dominated by a few bins with large fluctuations
Weak Boson Physics

Z boson parameters measured precisely by LEP:

* 17 million measured Z candidates: $\delta m_Z = 2.1$ MeV, $\delta \Gamma_Z = 2.3$ MeV

Tevatron goal:

* World's most precise W boson measurements
* Expect 15 million measured W candidates