Precision Measurement of the W Boson Mass with CDF

Chris Hays, University of Oxford

Les Rencontres de Physique de la Vallee d’Aoste
March 7, 2007
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 $tb$ and Higgs loops

$\Delta m_W \propto m_t^2$

$\Delta m_W \propto \ln (m_H/m_Z)$

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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>$80.452 \pm 0.059$</td>
</tr>
<tr>
<td>LEP2</td>
<td>$80.376 \pm 0.033$</td>
</tr>
<tr>
<td>Average</td>
<td>$80.392 \pm 0.029$</td>
</tr>
</tbody>
</table>

W mass predicted much more precisely (13 MeV) than measured (29 MeV)
Need to reduce $\delta m_W$ to further constrain $m_H$ and other new physics

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Tevatron Run II

Each experiment has collected $>2 \text{ fb}^{-1}$ of 1.96 TeV $\sqrt{s}$ pp collisions

Current Run II: $>15 \times$ Run I data set

First Run II W mass measurement uses 200 pb$^{-1}$ of CDF data
$W & Z$ Boson Production and Decay

Dominant production mechanism: $q\bar{q}^{(*)}$ 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
CDF Detector

High-precision tracking drift chamber
\[ \delta p_T / p_T = 0.05\% p_T : 2\% \text{ for } 40 \text{ GeV } \mu \]

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

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

Cross-check with $W$ recoil distributions

Combine information into transverse mass:

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

Statistically most powerful quantity for $m_W$ fit

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Alignment and Corrections

Align tracker using cosmic-ray data
Determine track-level 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

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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
Momentum Scale Calibration

Constrain tracks to originate from the beam line
Improves resolution by a factor of \( \approx 3 \)

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

Use calibrated momentum scale to measure Z mass

Constrain tracks to originate from the beam line
Improves resolution by a factor of \( \approx 3 \)
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
- Energy loss in solenoid

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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%

CDF Run II Preliminary

Calorimeter Energy $<$ Track Momentum:
Energy loss in hadronic calorimeter

Calorimeter Energy $>$ Track Momentum:
Energy loss in tracker

Energy loss in

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Scale Energy Dependence

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
Z Mass Measurement

**Fit Z mass using scale from E/p calibration**

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

- 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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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
\[ \delta m_W = 8 \ (5) \text{ MeV for } e \ (\mu) \]
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

\[ \delta m^{}_{W} = 11 \text{ MeV} \]
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*
Production, Decay, Background

Boson $p_z$ determined by parton distribution functions

\[ \text{Vary PDFs according to uncertainties} \]

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

\[ \begin{array}{c}
\text{q'} \\
\gamma \\
W \\
g \\
q
\end{array} \]

Bremstrahlung reduces charged lepton $p_T$

\[ \text{Predict using NLO QED calculation, apply NNLO correction} \]

\[ \delta m_W = 11 \text{ (12) MeV for } e (\mu) \]

Background affects fit distributions

QCD: Measure with data

Electroweak: Predict with MC

\[ \delta m_W = 8 \text{ (9) MeV for } e (\mu) \]

<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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Mass fit results blinded with $[-100,100]$ MeV offset throughout analysis

Upon completion, offset removed to determine final result

Transverse mass fits:

$\mathcal{M}_W = 80417 \pm 48 \text{ MeV (stat + sys)}$

for $e + \mu$ combination ($P(\chi^2) = 7\%$)

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Fit $E_T$, $E_T^T$ distributions and combine with $m_T$ to extract most precise result

**Electron $E_T$ fit:**

CDF II preliminary

$\int L \, dt \approx 200 \text{ pb}^{-1}$

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

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

$\mu$ distribution

**Muon $p_T$ fit:**

CDF II preliminary

$\int L \, dt \approx 200 \text{ pb}^{-1}$

$M_W = (80321 \pm 66_{\text{stat}}) \text{ MeV}$

$\chi^2/\text{dof} = 72/62$

$e^+ \mu$ combination

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

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:

Muon $E_T$ fit:

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

for six-fit combination ($P(\chi^2) = 44\%$)
### 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>
<td>9</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Recoil Scale</td>
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<tr>
<td>Recoil Resolution</td>
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<tr>
<td>$u_\parallel$ Efficiency</td>
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<td>1</td>
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<tr>
<td>Lepton Removal</td>
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<td>Backgrounds</td>
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<tr>
<td>$p_T(W)$</td>
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<td>QED</td>
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<tr>
<td><strong>Total Systematic</strong></td>
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<td>26</td>
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<tr>
<td><strong>Statistical</strong></td>
<td>48</td>
<td>54</td>
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<tr>
<td><strong>Total</strong></td>
<td>62</td>
<td>60</td>
<td>26</td>
</tr>
</tbody>
</table>

*CDF II preliminary, $L = 200$ pb$^{-1}$*
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)
Previous Higgs Mass Prediction

**Predicted Higgs mass from global electroweak data:**

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

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

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New Higgs Mass Prediction

Predicted Higgs mass from global electroweak data:
\[ m_H = 80^{+36}_{-26} \text{ GeV} \ (< 153 \text{ GeV at 95\% CL}) \]

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

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Effect on New Physics Models

Supersymmetry now preferred at 1σ level...

New world average:

![Graph showing the effect on new physics models with a preference for supersymmetry at the 1σ level.](image)

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New W Mass Projections

New projected Tevatron precision as a function of luminosity:

*New projection with 1.5 fb\(^{-1}\) of data:*

\(\delta m_W < 25\) MeV with CDF

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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 \( \delta m_W < 25 \text{ MeV with 1.5 fb}^{-1} \) already collected

Will squeeze SM in conjunction with Tevatron Higgs results

Electroweak data will probe more new physics after the Higgs
Backup
Filling in the Pieces

Precision electroweak data will continue to guide us to the next physics

**Today:** $\delta m_W = 25$ MeV, $m_H < 153$ GeV at 95% CL

![Diagram showing SM measurement and $m_W$]

**After Higgs:** $\delta m_W = 15$ MeV, SUSY predicted at 95% CL?

![Diagram showing SM measurement and $m_W$ with SUSY excluded]

**After SUSY:** $\delta m_W = 10$ MeV, more new physics?

![Diagram showing $m_W$ measurement and MSSM]

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Electron $m_T$ Signed $\chi$

High $\chi^2$ dominated by a few bins with large fluctuations
## Tevatron Run I Uncertainties

<table>
<thead>
<tr>
<th>Source of Uncertainty</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>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>85</td>
<td>75</td>
<td>56</td>
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<tr>
<td>Lepton resolution</td>
<td>20</td>
<td>25</td>
<td>19</td>
</tr>
<tr>
<td>Recoil model</td>
<td>35</td>
<td>37</td>
<td>35</td>
</tr>
<tr>
<td>$pT(W)$</td>
<td>20</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Selection bias</td>
<td>18</td>
<td>-</td>
<td>12</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>25</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Parton dist. functions</td>
<td>15</td>
<td>15</td>
<td>8</td>
</tr>
<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>Total</td>
<td>144</td>
<td>113</td>
<td>84</td>
</tr>
</tbody>
</table>
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))
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
Alignment Example

Inner 'Superlayer:'

Before alignment

CDF Run II preliminary

Cell Shift (microns)

Cell number (\(\phi\))

After alignment
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
Electron Track Model Validation

*Fit Z mass reconstructed from electron track momenta*

\[ \langle \sigma \rangle = 200 \text{ pb}^{-1} \quad \text{CDF Run II Preliminary} \]

![Graph showing the reconstructed Z mass distribution.](image)

\[ m_Z = (91282 \pm 143) \text{ MeV} \]

\[ \chi^2/\text{dof} = 30 / 22 \]

Measured value consistent with world average value (91188 MeV)

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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*
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>
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<td>0.12</td>
<td>0.10</td>
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<tr>
<td>Beam constraint bias</td>
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<td>Ionizing material scale</td>
<td>0.06</td>
<td>0.03</td>
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<tr>
<td>COT alignment corrections</td>
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<tr>
<td>Fit range</td>
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<td>0.02</td>
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<tr>
<td>( p_T ) threshold</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
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<td>0.03</td>
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<td>0.03</td>
<td>0.02</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>
</tr>
<tr>
<td>Statistical</td>
<td>0.01</td>
<td>0.06</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0.25</td>
<td>0.21</td>
<td>0.17</td>
</tr>
</tbody>
</table>

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Transverse Mass Distribution

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

$\ m_w = 80 \text{ GeV}$ $\ m_w = 81 \text{ GeV}$
Energy Loss Model

Use GEANT to parametrize energy loss in solenoid and hadronic calorimeter

Energy loss in hadronic calorimeter:
Previous $W$ Mass Projections

Previously projected Tevatron precision as a function of luminosity:

Projection with 2 $fb^{-1}$ of data:
\[ \delta m_W = 40 \text{ MeV per experiment} \]
Predicted Higgs mass from global electroweak data:

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

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

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

$\frac{\Delta p}{p} = (-1.38 \pm 0.06) \times 10^3$

$\chi^2/\text{dof} = 26 / 18$

Tracks with beam constraint

34,618 $Y \rightarrow \mu\mu$ 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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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
Effect on New Physics Models

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

Previous world average:

![Graph showing the effects of various models on the $M_W$ mass](chart.png)

- Experimental errors 68% CL:
  - LEP2/Tevatron (today)

- Models:
  - SM
  - MSSM
  - Light SUSY
  - Heavy SUSY

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Supersymmetry now preferred at $1\sigma$ level...

New world average:

![Graph showing effect on new physics models]