First Measurement of the W Boson Mass with CDF in Run II

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On Behalf of the CDF Collaboration

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Motivation

- W boson mass can be derived from precisely measured quantities

\[ m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_F \sin^2 \theta_W (1 - \Delta r)} \]
\[ \sin \theta_W^2 = 1 - \frac{m_W^2}{m_Z^2} \]

- Radiative corrections \( r \) dominated by top and Higgs loops

- Precise knowledge of top quark and W boson masses help constrain Higgs boson mass

\[ M_{\text{Higgs}} = 85^{+39}_{-28} \text{GeV}/c^2 \]
\[ M_{\text{Higgs}} < 166 \text{ GeV}/c^2 \ (95\% \ CL) \]
W boson production and decay

- W production at Tevatron dominated by $q\bar{q}$ annihilation
- Use events with electron or muon in final state
  - $\sigma \cdot BR = 2.749 \pm 0.174$ nb
  - Dataset of 200 pb$^{-1}$
  - ~100,000 candidate events
Measurement strategy

• Use transverse mass

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

• Precise measurement of charged lepton
  ‣ Calibrate track momentum measurement
  ‣ Calibrate calorimeter energy measurement
  ‣ Use Z boson as cross-check and additional calibration

• Hadronic recoil - allows inference of neutrino
  ‣ Calibrate using Z boson events
  ‣ Cross-check with W boson events

• Perform final fit using W mass templates
  ‣ Parameterized fast simulation to model detector effects
Track momentum scale

- Large sample of $J/\psi$s and $\Upsilon$s are used
  - Tune model of energy loss $\rightarrow J/\psi$ mass independent of muon $p_T$
  - Tune track resolution using $\Upsilon$ decays
- Apply momentum scale to $Z$ decays
  - Use world avg. $Z$ mass as additional calibration

$$\Delta m_W = 17 \text{ MeV}/c^2$$

CDF II preliminary $\int L \, dt = 200 \text{ pb}^{-1}$

Scale correction = $(-1.64 \pm 0.01_{\text{stat}} \pm 0.06_{\text{slope}}) \times 10^{-3}$

$J/\psi \rightarrow \mu \mu$ data

$\Delta p/p = (-1.376 \pm 0.064_{\text{stat}}) \times 10^{-3}$

$\chi^2$/dof = 26 / 18

$M_2 = (91184 \pm 43) \text{ MeV}$

$\chi^2$/dof = 32 / 30

Events / 0.5 GeV

$-3 \times 10^3$ slope $0.06$ stat $0.01$

$\delta_{mW}$ = 17 MeV/c$^2$
Calorimeter energy scale

- Calibration of calorimeter energy scale vital for electron measurement
- Calorimeter energy calibrated using peak of electron $E/p$ distribution from $W$s
  - Apply calibrated track momentum scale
- Energy loss tuned with high $E/p$ tail
- Correct for $E_T$ dependence
- Measure $Z$ mass in electrons using calibrated scale

$$\Delta m_W = 30 \text{ MeV}/c^2$$
Recoil

- Hadronic recoil (u): energy in calorimeter excluding measured lepton
- Calibrate model for u using Z boson events
  - Recoil energy scale $R = u_{\text{meas}} / u_{\text{true}}$
  - Recoil energy resolution

$$\Delta m_W = 11 \text{ MeV}/c^2$$
Recoil validation

• Compare recoil distribution between simulation and data for $W$ boson events

CDF II preliminary

Electrons

Muons

MC

$\mu = 5.44$ GeV
$
\sigma = 3.46$ GeV

data

$\mu = 5.44 \pm 0.01$ GeV
$
\sigma = 3.47 \pm 0.01$ GeV

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

$\int L \, dt = 200$ pb$^{-1}$
### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$W \to \mu\nu$</th>
<th>$W \to e\nu$</th>
<th>Common</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton Scale</td>
<td>17</td>
<td>30</td>
<td>17</td>
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<tr>
<td>Lepton Resolution</td>
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<td>9</td>
<td>0</td>
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<tr>
<td>Lepton Efficiency</td>
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<td>3</td>
<td>0</td>
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<tr>
<td>Lepton Tower Removal</td>
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<td>8</td>
<td>5</td>
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<tr>
<td>Recoil Energy Scale</td>
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<td>9</td>
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<tr>
<td>Recoil Energy Resolution</td>
<td>7</td>
<td>7</td>
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<tr>
<td>Backgrounds</td>
<td>9</td>
<td>8</td>
<td>0</td>
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<tr>
<td>PDFs</td>
<td>11</td>
<td>11</td>
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<tr>
<td>$W$ Boson $p_T$</td>
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</tr>
<tr>
<td>Photon Radiation</td>
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<td>11</td>
<td>11</td>
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<tr>
<td>Statistical</td>
<td>54</td>
<td>48</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>60</td>
<td>62</td>
<td>26</td>
</tr>
</tbody>
</table>

- Systematic uncertainties for transverse mass fits shown (units of MeV/c^2)
Transverse mass fits

**CDF II preliminary**

- Electrons
  - $M_W = (80493 \pm 48_{\text{stat}}) \text{ MeV}$
  - $\chi^2/\text{dof} = 86/48$

- Muons
  - $M_W = (80349 \pm 54_{\text{stat}}) \text{ MeV}$
  - $\chi^2/\text{dof} = 59/48$

- Transverse mass ($m_T$) fits provide most precision
  - Charged lepton $p_T$ and missing $E_T$ (neutrino $p_T$) fits also performed and included in final measurement
Result

- Combined electron and muon fit:
  \[ m_W = 80413 \pm 48 \text{ MeV}/c^2 \]
  - Single most precise measurement of \( W \) boson mass in the world
  - Reduces uncertainty of world avg. by \( \sim 15\% \)

\[\begin{align*}
\text{CDF I} & : 80433 \pm 79 \\
\text{D0 I} & : 80483 \pm 84 \\
\text{DELPHI} & : 80336 \pm 67 \\
\text{L3} & : 80270 \pm 55 \\
\text{OPAL} & : 80416 \pm 53 \\
\text{ALEPH} & : 80440 \pm 51 \\
\text{CDF II (prel.)} & : 80413 \pm 48 \\
\text{World Ave. 2007} & : 80398 \pm 25 \\
\end{align*}\]

Combined with newest \( m_t \) average:

\[ M_{\text{Higgs}} = 76^{+33}_{-24} \text{ GeV}/c^2 \]

\[ M_{\text{Higgs}} < 144 \text{ GeV}/c^2 \text{ (95\% CL)} \]
Result

- Combined electron and muon fit:
  \[ m_W = 80413 \pm 48 \text{ MeV}/c^2 \]
  - Single most precise measurement of $W$ boson mass in the world
  - Reduces uncertainty of world avg. by \( \sim 15\% \)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (MeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF I</td>
<td>80433 \pm 79</td>
</tr>
<tr>
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Combined with newest $m_t$ average:

- $M_{Higgs} = 76^{+33}_{-24} \text{ GeV}/c^2$
- $M_{Higgs} < 144 \text{ GeV}/c^2$ (95% CL)
• CDF has performed single most precise measurement of $W$ boson mass

$$m_W = 80413\pm34\text{(stat)}\pm34\text{(sys)} \text{MeV/c}^2$$

$$= 80413\pm48\text{(stat+sys)} \text{MeV/c}^2$$

▷ Impact on world average has moved most likely Higgs mass further into LEP excluded region

• Expect CDF $\Delta m_W < 25 \text{ MeV/c}^2$ with $\sim2 \text{ fb}^{-1}$ already recorded
Backup Slides
The Tevatron and CDF detector

- Tevatron
  - Peak luminosity $>2.8 \times 10^{32}$ cm$^{-2}$s$^{-1}$
  - 2.5 fb$^{-1}$ delivered to experiments
- CDF Detector - General purpose detector
  - Precision tracking (Silicon + COT)
  - EM and Hadronic calorimeters
  - Muon detectors (extended for Run II)
- $>2.0$ fb$^{-1}$ recorded at CDF
# Backgrounds

## Electrons

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<thead>
<tr>
<th>Source</th>
<th>% of W data</th>
<th>Uncertainty on $m_W$</th>
</tr>
</thead>
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<tr>
<td>Tau decays</td>
<td>0.93±0.02</td>
<td>1 MeV/$c^2$</td>
</tr>
<tr>
<td>Hadronic jets</td>
<td>0.25±0.15</td>
<td>7 MeV/$c^2$</td>
</tr>
<tr>
<td>Z decays</td>
<td>0.24±0.01</td>
<td>2 MeV/$c^2$</td>
</tr>
</tbody>
</table>

## Muons

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</tr>
</thead>
<tbody>
<tr>
<td>Tau decays</td>
<td>0.89±0.02</td>
<td>1 MeV/$c^2$</td>
</tr>
<tr>
<td>Hadronic jets</td>
<td>0.1±0.1</td>
<td>2 MeV/$c^2$</td>
</tr>
<tr>
<td>Z decays</td>
<td>6.6±0.3</td>
<td>6 MeV/$c^2$</td>
</tr>
<tr>
<td>Decays in flight</td>
<td>0.3±0.2</td>
<td>5 MeV/$c^2$</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>0.05±0.05</td>
<td>2 MeV/$c^2$</td>
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