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

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on behalf of the CDF Collaboration

Lake Louise Winter Institute
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Outline

1. Motivation
2. W Production at the Tevatron
3. Analysis Strategy
4. Detector Calibration
   - Momentum Scale
   - Energy Scale
   - Recoil
5. Event Simulation
6. Results
7. Summary/Outlook
Motivation

- Derive $W$ mass from precisely measured electroweak quantities

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

$$\cos \theta_W = \frac{m_W}{m_Z}$$

- Radiative corrections $r$ dominated by top quark and Higgs loop
  ⇒ allows constraint on Higgs mass

Current top mass uncertainty 1.2%
(2.1 GeV)
→ contributes 0.016%
(13 MeV) to $\delta m_W$

Current $W$ mass uncertainty 0.036%
(29 MeV)
→ Higgs mass predicted: $85^{+39}_{-28}$ GeV

- Progress on $W$ mass uncertainty now has the biggest impact on Higgs mass constraint

- With improved precision also sensitive to possible exotic radiative corrections
Recoil measurement allows inference of neutrino $E_T$ (restricted to $u<15$ GeV)

Quark-antiquark annihilation dominates (80%)

precise charged lepton measurement is the key (achieved ~0.03%)

Combine information into transverse mass: $m_T = \sqrt{2p_T^l p_T^\nu (1 - \cos \phi_{lv})}$

Use $Z\to \mu\mu$ and $Z\to ee$ events to derive recoil model
Measurement Strategy

W mass is extracted from transverse mass, transverse momentum and transverse missing energy distribution

Detector Calibration
- Tracking momentum scale
- Calorimeter energy scale
- Recoil

Fast Simulation
- NLO event generator
- Model detector effects

W Mass templates

Data
Binned likelihood fit
W Mass

81 GeV
80 GeV

+ Backgrounds
- Silicon tracking detectors
- Central drift chambers (COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding

CDF Detector
Tracker Alignment

- Internal alignment is performed using a large sample of cosmic rays → Fit hits on both sides to one helix

- Determine final track-level curvature corrections from electron-positron E/p difference in $W \rightarrow e\nu$ decays

- Statistical uncertainty of track-level corrections leads to systematic uncertainty $\Delta M_W = 6$ MeV
**Momentum Scale Calibration**

Exploit large J/ψ and Upsilon datasets to set tracker scale

- Tune model of energy loss \( \rightarrow J/\psi \) independent of muon \( p_T \)
  \[ \Delta M_{W} = 17 \text{ MeV} \]

Apply momentum scale to Z’s

- Tune resolution on width of di-muon mass peaks
  \[ \Delta M_{W} = 3 \text{ MeV} \]

- Good agreement with PDG (91187±2 MeV)

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Transfer momentum calibration to calorimeter using $E/p$ distribution of electrons from $W$ decay by fitting peak of $E/p$

Tune number of radiation lengths with $E/p$ radiative tail

Correct for calibration $E_T$ dependence

Add $Z$ Mass fit to calibration (30% weight) $\Delta M_W = 30$ MeV

Apply energy scale to $Z$’s

Tune resolution on $E/p$ and $Z$ mass peak $\Delta M_W = 9$ MeV

$W \rightarrow e\nu$

$Z \rightarrow ee$

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

S_E = $1 \pm 0.00025_{\text{stat}}$

$\chi^2/\text{dof} = 17/16$

$M_Z = (91190 \pm 67_{\text{stat}})$ MeV

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

good agreement with PDG $(91187 \pm 2$ MeV)
Hadronic Recoil Definition

Recoil definition:
→ Vector sum over all calorimeter towers, excluding:
  - lepton towers
  - towers near beamline ("ring of fire")

Electrons: Remove 7 towers keystone
\[ \Delta M_W = 8 \text{ MeV} \]

Muons: Remove 3 towers (MIP)
\[ \Delta M_W = 5 \text{ MeV} \]

Model tower removal in simulation
• Use Z balancing to calibrate recoil energy scale and to model resolution

• Calibrate scale \( R = u_{\text{meas}} / u_{\text{true}} \) with balance along bisector axis \( \Delta M_W = 9 \text{ MeV} \)

• Resolution has two components
  - soft (underlying event)
  - hard (jets)

• Calibrate along both axes, \( \eta \) & \( \xi \)
  \( \Delta M_W = 7 \text{ MeV} \)
Recoil Model Checks

- Apply model to W sample to check recoil model from Z's
- Recoil projection along lepton $u_{||}$ → directly affects $m_T$ fits
  → Sensitive to lepton removal, scale, resolution, W decay

- Recoil distribution → sensitive to recoil scale resolution and boson $p_T$
- Recoil model validation plots confirm consistency of the model
Boson $p_T$ Model

- Model boson $p_T$ using RESBOS generator [Balazs et al. PRD56, 5558 (1997)]

- Non-perturbative regime at low $p_T$ parametrized with $g_1$, $g_2$, $g_3$ parameters

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

- Measure $g_2$ with Z boson data (other parameters negligible)

- Find: $g_2 = 0.685 \pm 0.048$

$\Delta M_W = 3$ MeV
Production, Decay and Backgrounds

• QED radiative corrections:
  - use complete NLO calculation (WGRAD) [Baur et al. PRD59, 013002 (1998)]
  - simulate FSR, apply (10±5)% correction for 2\textsuperscript{nd} γ
  \( \Delta M_W = 11 \ (12) \text{ MeV for e (μ)} \)

• Parton Distribution Functions:
  - affect kinematics through acceptance cuts
  - use CTEQ6 ensemble of 20 uncertainty PDFs
  \( \Delta M_W = 11 \text{ MeV} \)

• Backgrounds:
  - have very different lineshapes compared to W signal
  - distributions are added to template
  - QCD measured with data
  - EWK predicted with Monte Carlo
  \( \Delta M_W = 8 \ (9) \text{ MeV for e (μ)} \)

<table>
<thead>
<tr>
<th>Background</th>
<th>% (Muons)</th>
<th>% (Electrons)</th>
</tr>
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<tbody>
<tr>
<td>Hadronic Jets</td>
<td>0.1±0.1</td>
<td>0.25±0.15</td>
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<tr>
<td>Decay in Flight</td>
<td>0.3±0.2</td>
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<tr>
<td>Cosmic Rays</td>
<td>0.05±0.05</td>
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<tr>
<td>( Z \rightarrow ll )</td>
<td>6.6±0.3</td>
<td>0.24±0.04</td>
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<tr>
<td>( W \rightarrow tn )</td>
<td>0.89±0.02</td>
<td>0.93±0.03</td>
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</table>

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Transverse mass fits:

**Muons**

CDF II preliminary

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

$m_W = (80349 \pm 54_{\text{stat}}) \, \text{MeV}$

$\chi^2/\text{dof} = 59 / 48$

**Electrons**

CDF II preliminary

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

$m_W = (80493 \pm 48_{\text{stat}}) \, \text{MeV}$

$\chi^2/\text{dof} = 86 / 48$

$m_W = 80417 \pm 48 \, \text{MeV (stat + syst)}$

combination yields $P(\chi^2) = 7\%$
W Mass Fits

Also fit $E_T$ and $E_T'$ distributions in muon and electron channel and combine with transverse mass fits:

Electron $E_T$ fit

![Electron $E_T$ fit graph]

Muon $E_T'$ fit

![Muon $E_T'$ fit graph]

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

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

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

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

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

combination of all six fits yields $P(\chi^2) = 44\%$

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## Systematic Uncertainty

Systematic uncertainty on transverse mass fit

<table>
<thead>
<tr>
<th>CDF II preliminary</th>
<th>L = 200 pb(^{-1})</th>
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<tbody>
<tr>
<td>(m_T) Uncertainty [MeV]</td>
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<td>Lepton Scale</td>
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<td><strong>Statistical</strong></td>
<td>48</td>
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<tr>
<td><strong>Total</strong></td>
<td>62</td>
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⇒ Combined Uncertainty: 48 MeV for 200 pb\(^{-1}\)
Results

- New CDF result is the world’s most precise single measurement
- World average increases: 80392 to 80398 MeV
- Uncertainty reduced ~15% (29 to 25 MeV)

- Standard Model Higgs constraint: $80^{+36}_{-26}$ GeV (previous: $85^{+39}_{-28}$ GeV)
Summary/Outlook

- First Run II W mass measurement completed using 200 pb\(^{-1}\) of data
- With a total uncertainty of 48 MeV
  \[\rightarrow \text{worlds most precise single measurement}\]
- Projection from previous Tevatron measurements

\[\Delta M_W < 25 \text{ MeV} \quad \text{with 1.5 fb}^{-1} \text{ already collected}\]
Backup
## Systematic Uncertainty

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Signed $\chi$

CDF II preliminary

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

$m_T (\text{GeV})$ vs. $\chi$