Measurement of the W boson mass with 1 fb$^{-1}$ of DØ Run II data

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on behalf of the DØ Collaboration
Motivation for precise W mass

- Precise measurements of $m_W$ and $m_t$ can constrain SM Higgs mass

$$m_W = \sqrt{\frac{\pi \alpha}{\sqrt{2} G_F}} \cdot \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}}$$

$\Delta r \propto m_t^2$  
$\Delta r \propto \log m_H$

- $\Delta m_W$ has same impact on $\Delta m_H$ for $\Delta m_W/\Delta m_t \approx 0.006$
  - for recent $\Delta m_t = 1.3$ GeV would need: $\Delta m_W = 8$ MeV (0.01%)  
  - current world average: $\Delta m_W = 25$ MeV (0.03%)

- Additional contributions to $\Delta r$ arise in SM extensions...

*EPS 2009, Cracow, Poland*

Mikolaj Cwiok, 17 July 2009
Signatures & observables

- **Signatures of W events:**
  - isolated, high $p_T$ lepton (e or $\mu$)
  - missing $E_T$

- **Use 3 kinematic variables:** (Jacobian edge)
  \[
  m_T = \sqrt{2 \, E_T^\ell \, E_T \, (1 - \cos \Delta \phi_{\ell \nu})}
  \]
  - affected by detector resolution (MET)

  \[ p_T^\ell \]
  - affected by motion of W boson ($p_T^W$)

  \[ p_T^\nu = E_T \]
  - sensitive to both effects, but is not 100% correlated with other 2 measurements

- **25 MeV precision on $m_W$ requires:**
  - accuracy of lepton (e or $\mu$) energy scale: $\sim 0.02\%$
  - accuracy of hadronic recoil scale: $\sim 1\%$
Analysis overview

• This analysis exploits $W \rightarrow e\nu$ channel only
  electron energy resolution $\sim 4\%$, muon momentum scale $\sim 10\%$ @ $p_T=50$ GeV

• Compare $m_T, p_T^e, \not{E}_T$ data spectra with template spectra from MC

• Fast Monte Carlo for templates generation:
  ResBos – $W$ and $Z/\gamma^*$ boson production, decay kinematics
  perturbative NLO at high boson $p_T$, gluon resummation at low boson $p_T$
  PHOTOS – FSR radiation of $\leq 2$ photons
  effect of full QED corrections assessed from WGRAD and ZGRAD

Parametric MC Simulation (PMCS) – detector efficiencies, energy response & resolution for electrons and hadronic recoil
  parametric functions and binned look-up tables based on detailed GEANT simulation
  and fine-tuned from control data samples: $Z\rightarrow ee$, Zero Bias, Minimum Bias

• Blind analysis – $m_W$ returned by fits was deliberately shifted by some unknown offset before the final fitting
  results were unblinded after completing all consistency checks for $W$ and $Z$ events
Event selection

- **1 fb⁻¹ of data (Run Ila, 2002-2006)**
- **W→ev sample – 499,830 evts:**
  - Electron: |η| < 1.05, spatial track match, \( p_T^e > 25 \text{ GeV} \)
  - Missing \( E_T > 25 \text{ GeV} \)
  - Recoil \( u_T < 15 \text{ GeV} \)
  - 50 < \( m_T < 200 \text{ GeV} \)

  96% purity, main backgrounds: \( Z\rightarrow ee \), QCD multijet, \( W\rightarrow \tau v\rightarrow ev\nu\nu \)

- **Z→ee sample for calibration – 18,725 evts:**
  - calibrate EM energy scale from Z pole
  - tune fast PMCS
Electron efficiency

Fast MC models various electron selection efficiencies:

- **Electron-only**: trigger, CAL-based ID, tracking from Z data; tag & probe; parameterized using: $\eta^e$, $p_T^e$, $z_{vtx}$

- **W event topology**: spatial proximity recoil ↔ electron from Z data; parameterized using: $p_T^e$, $u_\parallel$

- **Additional hadronic energy** in CAL at high luminosity from full MC + ZB data; parameterized using: Scalar $E_T$, $u_\parallel$
Electron model

- Fit amount of **uninstrumented** material in front of the calorimeter with 0.01X₀ precision
- Use precise Z mass from LEP to calibrate absolute EM energy scale
- **Simulate measured electron energy as:**

\[
E(\text{smear}) = R_{EM}(E) \otimes \sigma_{EM}(E) + \Delta E(L, u_{||})
\]

**Energy response:**

- dominant source in m_{W} systematics: 34 MeV
- fitted from electron energy spread in Z → ee data

**Energy resolution:**

\[
\frac{\sigma_{EM}(E)}{E} = \sqrt{C_{EM}^2 + \frac{S_{EM}(E, \theta)^2}{E}}
\]

- S_{EM} depends on energy and incidence angle, from improved full GEANT simulation featuring: lower energy cut offs, updated interaction x-sections
- C_{EM} = 2.05\% ± 0.10\%; from fit to the m_{ee} distribution from Z → ee data
A candidate event of the process $W \rightarrow e\nu$ is shown in this diagram. The event is characterized by the presence of an electron, a neutrino, and a recoil in the event display. The diagram also includes regions for EM (electromagnetic), HAD (hadronic), and $E_T$ (transverse energy) for analysis.
**Hadronic recoil model**

- Neutrino $p_T$ is simulated as:
  $$\vec{E}_T = -\vec{p}_T^e - \vec{u}_T$$

- Recoil model has HARD and SOFT components:
  $$\vec{u}_T (smear) = \vec{u}_T^{HARD} + \vec{u}_T^{SOFT} + \vec{u}_T^{ELEC} + \vec{u}_T^{FSR}$$

- Model is derived from detailed GEANT simulation ($Z \rightarrow \nu\nu$) and control data samples ($Z \rightarrow ee$, Zero Bias, Minimum Bias)

- Recoil response and resolution are fine-tuned from $Z \rightarrow ee$ data:
  - require balancing of $u_T$ and $p_T^{ee}$
  - mean and width of $\eta_{imb}$ distribution depend on hadronic recoil response and resolution

- Scalar $E_T$ is also modeled for electron selection efficiencies

\[ \chi^2 / \text{ndf} = 3.1 / 7 \]
\[ \chi^2 / \text{ndf} = 4.5 / 8 \]
**W mass fits**

- Templates for different $m_W$ hypotheses at 10 MeV intervals: $W$ signal (PMCS) + background
- Compute binned likelihood between data and template
- Fit $m_W$ for each of 3 observables

$m_W = 80.401 \pm 0.023$ GeV (stat)

Fit range: $65 < m_T < 90$ GeV
**W mass fits**

**Electron $p_T$ method**

\[ m_W = 80.400 \pm 0.027 \text{ GeV (stat)} \]  
Fit range: \( 32 < p_T^e < 48 \text{ GeV} \)

**Neutrino $p_T$ method**

\[ m_W = 80.402 \pm 0.023 \text{ GeV (stat)} \]  
Fit range: \( 32 < E_T < 48 \text{ GeV} \)
## Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>m_T</th>
<th>p_T(e)</th>
<th>Missing E_T</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electron energy response</strong></td>
<td>34</td>
<td>34</td>
<td>34</td>
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<td>3</td>
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<td>Electron energy non-linearity</td>
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<td>7</td>
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<tr>
<td>Electron energy loss differences for W and Z</td>
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<td>4</td>
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</tr>
<tr>
<td>Electron efficiencies</td>
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<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Recoil model</td>
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<td>12</td>
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<tr>
<td>Backgrounds</td>
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<td>5</td>
<td>4</td>
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<tr>
<td><strong>Subtotal Experimental</strong></td>
<td>35</td>
<td>37</td>
<td>41</td>
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<tr>
<td><strong>PDF</strong> CTEQ6.1M</td>
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<td>11</td>
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</tr>
<tr>
<td>QED</td>
<td>7</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Boson p_T</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td><strong>Subtotal Theory (W/Z production &amp; decay)</strong></td>
<td>12</td>
<td>14</td>
<td>17</td>
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<tr>
<td><strong>Total Systematics</strong></td>
<td>37</td>
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<tr>
<td><strong>Total Statistics</strong></td>
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<tr>
<td><strong>TOTAL</strong></td>
<td>44</td>
<td>48</td>
<td>50</td>
</tr>
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</table>
Combined result

• Correlation matrix:

<table>
<thead>
<tr>
<th></th>
<th>$m_T$</th>
<th>$p_T(e)$</th>
<th>MET</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_T$</td>
<td>1</td>
<td>0.83</td>
<td>0.82</td>
</tr>
<tr>
<td>$p_T(e)$</td>
<td>1</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>MET</td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Statistics, Electron response, Recoil model, PDF
Other sources: 100% correlated

• DØ Run IIa combination:

$$m_W = 80.401 \pm 0.021 \text{ (stat)}$$
$$\pm 0.038 \text{ (syst) GeV}$$
$$\Delta m_W \text{ (total)} = 0.043 \text{ GeV}$$
Summary & Outlooks

- **Single most precise measurement of** $m_W$ **to date:**

  $$m_W = 80.401 \pm 0.021_{\text{stat}} \pm 0.038_{\text{syst}} \text{ GeV} = 80.401 \pm 0.043 \text{ GeV}$$

  - In good agreement with previous measurements: CDF Run II (0.2 fb$^{-1}$), LEP2 average

- **This DØ analysis exploits 1/6$^{th}$ of the available dataset**

  - Both CDF & DØ are working on larger datasets
  - Total uncertainty of 25 MeV expected at: 2.3 fb$^{-1}$(CDF) and 5 fb$^{-1}$(DØ)

- **Prospects:**

  - Different techniques used by CDF & DØ for lepton energy scale are good for combination and cross checks
  - CDF/DØ/LEP2 combination and W width analysis are currently under Editorial Board review
  - Better constrained PDFs in the future will reduce correlated uncertainties between CDF & DØ
BACKUP
Slides
Tevatron at Fermilab

- Proton-antiproton @ $\sqrt{s}=1.96$ TeV every 396 ns, 36x36 bunches
- Peak luminosity: $3.6 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$
- Recorded: $\sim 6 \text{fb}^{-1}$ / experiment

- By end of 2010: $9 \text{fb}^{-1}$ / experiment
- Running in 2011 is considered
**DØ detector**

- **Tracker:**
  - silicon microstrips + scintillating fibers
  - covers $|\eta| < 2.5$ inside 2T superconducting solenoid

- **Calorimeter:**
  - sampling U/LAr
  - hermetic coverage: $|\eta| < 4.2$

- **Muon system:**
  - wire chambers + scintillators
  - covers $|\eta| < 2$ before and after 1.8T toroid
**DØ LAr calorimeter**

- Active medium: Liquid argon
- Absorber: Uranium (mostly)
- 3 cryostats: Central CAL (CC) and two End CALs (EC)
- Hermetic with full coverage: $|\eta| < 4.2$
- In Run II there is more uninstrumented material in front of the CAL than in Run I

- 46,000 cells
- Segmentation (towers): $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ (0.05 x 0.05 in third EM layer, near shower maximum)
Backgrounds

- **Purity of W sample**: 96%
- **Backgrounds**:
  - $Z \rightarrow ee$: 0.80% (Data)
  - QCD multijet: 1.49% (Data)
  - $W \rightarrow \tau \nu \rightarrow e\nu\nu\nu$: 1.60% (GEANT)
- For 3 observables: estimated backgrounds are added to the simulated signal from $W$ (PMCS)
W production & decay models

Generators for W and Z processes at hadron colliders:

<table>
<thead>
<tr>
<th>Tool</th>
<th>Process</th>
<th>QCD</th>
<th>EW</th>
</tr>
</thead>
<tbody>
<tr>
<td>RESBOS</td>
<td>$W, Z$</td>
<td>NLO</td>
<td>-</td>
</tr>
<tr>
<td>WGRAD</td>
<td>$W$</td>
<td>LO</td>
<td>complete $O(\alpha)$, Matrix Element, $\leq 1$ photon</td>
</tr>
<tr>
<td>ZGRAD</td>
<td>$Z$</td>
<td>LO</td>
<td>complete $O(\alpha)$, Matrix Element, $\leq 1$ photon</td>
</tr>
<tr>
<td>PHOTOS</td>
<td></td>
<td></td>
<td>QED FSR, $\leq 2$ photons</td>
</tr>
</tbody>
</table>

- **ResBos+Photos** as main generator
  - reasonable $p_T^{W,Z}$ spectra
  - leading EWK effects ($1^{st}$ and $2^{nd}$ FSR photon)

- **W/ZGRAD** for estimating effects of full EWK corrections

  Baur, Wackeroth; Phys. Rev D70, 073015

- Final QED $m_W$ uncertainties are 7,7,9 GeV for $m_T$, $p_T^e$, $E_T$
  - comparison of “FSR only” and “full EWK” from W/ZGRAD
  - comparison of “FSR only” W/ZGRAD and Photos

Balazs, Yuan; Phys Rev D56, 5558
Barbiero, Was; Comp Phys Com 79, 291
Hadronic recoil - details

**HARD COMPONENT:**
- hard component balancing $q_T$ of the vector boson
- from $Z\rightarrow nn$ full MC
- fine-tuned from $Z\rightarrow ee$ data

**SOFT COMPONENT:**
- energy not correlated with the vector boson (additional interactions in same BX, spectator partons, detector noise)
- uses ZB & MB event libraries
- fine-tuned from $Z\rightarrow ee$ data

\[
\begin{align*}
\vec{u}_{T,\text{HARD}} &= f(\vec{q}_T) \\
\vec{u}_{T,\text{SOFT}} &= -\sqrt{\alpha_{MB}} \cdot \vec{E}_{T,\text{MB}} - \vec{E}_{T,\text{ZB}} \\
\vec{u}_{T,\text{ELEC}} &= -\sum_e \Delta u_{\parallel} \cdot \hat{p}_{T,e} \\
\vec{u}_{T,\text{FSR}} &= \sum_{\gamma} \vec{p}_{T,\gamma}
\end{align*}
\]

- correction for energy leakage outside electron cones
- from $W$ data (azimuthally separated window)
- FSR photons far away from electron(s) are reconstructed as recoil energy
Consistency checks

• **Vary fitting ranges** for all 3 observables
  
  ![Graph showing consistency checks](image)

  e.g. upper $m_T$ limit
  (yellow = stat. uncert.)

• **Split W & Z data samples into statistically independent categories** or **vary the cuts** and compare relative change in $m_Z/m_W$ ratio:
  
  – Different electron $\eta$ ranges
  – Different EM calorimeter $\phi$ fiducial cuts
  – High and low instantaneous luminosity
  – Different data taking periods
  – High and low scalar $E_T$
  – Different recoil $u_T$ cuts
  – Negative and positive $u_\parallel$

**Result is stable within one standard deviation!**
MC closure test

Test analysis methodology with Full GEANT MC treated as the collider data

Good agreement between Full MC and Fast MC (PMCS)

Fitted W mass and width agree with input values
**W Boson Mass with 1 fb$^{-1}$ of D0 Run II Data**

**EPS 2009, Cracow, Poland**

**M$_{W}$ & $\Gamma_{W}$ – today and future**

### W-Boson Mass [GeV]

**Direct**
- **TEVATRON**
  - 80.432 ± 0.039
- **LEP2**
  - 80.376 ± 0.033
- **Average**
  - 80.399 ± 0.025
  - $\chi^2$/DoF: 1.2 / 1

**Indirect**
- **NuTeV**
  - 80.136 ± 0.084
- **LEP1/SLD**
  - 80.363 ± 0.032
- **LEP1/SLD/m$_{t}$**
  - 80.364 ± 0.020

### W-Boson Width [GeV]

**Direct**
- **TEVATRON**
  - 2.050 ± 0.058
- **LEP2**
  - 2.196 ± 0.083
- **Average**
  - 2.098 ± 0.048
  - $\chi^2$/DoF: 2.1 / 1

**Indirect**
- **p$p$ indirect**
  - 2.141 ± 0.057
- **LEP1/SLD**
  - 2.091 ± 0.003
- **LEP1/SLD/m$_{t}$**
  - 2.091 ± 0.002

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**LEP EW WG**
March 2009

**DIS 2009**
S. Heinemeyer