Measurement of the W boson mass at the Fermilab Tevatron

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on behalf of the CDF and DØ Collaborations
Motivation

W mass is a key parameter in the Standard Model. This model does not predict the value of the W mass, but it predicts this relation between the W mass and other experimental observables:

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

**Radiative corrections** ($\Delta r$) depend on $M_t$ as $\sim M_t^2$ and on $M_H$ as $\sim \log M_H$. They include diagrams like these:

Precise measurements of $M_W$ and $M_{\text{top}}$ constrain SM Higgs mass.

For equal contribution to the Higgs mass uncertainty need:

$\Delta M_W = 0.006 \Delta M_{\text{top}}$ \Rightarrow current Tevatron average: $\Delta M_{\text{top}} = 1.1$ GeV

would need: $\Delta M_W = 7$ MeV (currently have: $\Delta M_W = 23$ MeV)

Additional contributions to $\Delta r$ arise in various extensions to the Standard Model, e.g. in SUSY:
- p pbar collisions at $\sqrt{s} = 1.96$ TeV
- up to now $\int L \, dt > 10$ fb$^{-1}$ delivered/experiment

- $MW$ measurement (Run IIa peak lumi $\sim 10^{32}$ cm$^{-2}$ s$^{-1}$):
  CDF 200 pb$^{-1}$  
  $\text{Phys. Rev. D 77, 112001 (2008)}$
  DØ 1 fb$^{-1}$  
  $\text{Phys. Rev. Lett. 103, 141801 (2009)}$

- in progress ( Run IIb peak luminosity $\sim 3 \times 10^{32}$ cm$^{-2}$ s$^{-1}$):
  CDF 2.4 fb$^{-1}$
  DØ 4.3 fb$^{-1}$
Signature in the detector

In a nutshell, measure two objects in the detector:
- lepton (in principle e or µ), need energy measurement with 0.2 per-mil precision
- hadronic recoil, need ~ 1% precision

$Z \rightarrow \text{ee/µµ}$ used for calibration/recoil modeling
kinematics in transverse plane
Experimental observables

$P_T(e)$ most affected by $P_T(W)$

$P_T(\nu)$ measured by $\not E_T$

$$M_T = \sqrt{2E_T^l \not E_T (1 - \cos \Delta \phi)}$$

$M_T$ most affected by measurement of missing transverse momentum

Need Monte Carlo simulation to predict shapes of these observables for given mass hypothesis. Use ResBos [Balazs, Yuan; Phys Rev D56, 5558] + Photos/WGRAD for W/Z production and decay, plus parameterised detector model.
Momentum and Energy calibration of $\mu/e$

Momentum scale using $J/\Psi \rightarrow \mu\mu$ (600 K) and $Y \rightarrow \mu\mu$ data extrapolated to $Z \rightarrow \mu\mu$

Tracker calibration $\rightarrow$ precise tracker simulation

Momentum scale
$\Delta M_W = 19$ MeV

absolute $M_W$ is measured in CDF

Material $X_0$ tuned to 2.5 parts in $10^4$ $E/p$ and $Z_{ee}$ combined

Energy scale + non-lin.
$\Delta M_W = 30$ MeV

Resolution
$\Delta M_W = 9$ MeV
Electrons: energy scale

After having corrected for the effects of the uninsstrumented material, use $M_Z$ from LEP and energy spread of electrons in Z decay to constrain $\alpha$ and $\beta$. $E_{\text{measured}} = \alpha \times E_{\text{LEP}} + \beta$

$M_W/M_Z$ is measured in DØ

$m(Z) = 91.185 \pm 0.033$ GeV (stat)

This corresponds to the dominant systematic uncertainty (by far) in the W mass measurement (but this is really just Z statistics ... more data will reduce it):

* $\Delta M_W = 34$ MeV, 100% correlated between all three observables
Recoil calibration

Final adjustment of free parameters in the recoil model is done \textit{in situ} using balancing in $Z \rightarrow e^+ e^-$ events and the standard UA2 observables.

UA2 observables: in transverse plane, use a coordinate system defined by the bisector of the two electron momenta.

recoil: $u_T = u_T^{\text{Hard}} + u_T^{\text{soft}} + u_T^{\text{Elec}} + u_T^{\text{FSR}}$

$\eta$-imbalance: $(\mathbf{p}_{t e}^{ee} + \mathbf{p}_{t e}^{\text{rec}}) \cdot \hat{\eta}$

$\xi$-imbalance: $(\mathbf{p}_{t e}^{ee} + \mathbf{p}_{t e}^{\text{rec}}) \cdot \hat{\xi}$
Mass Fits

Transverse mass fits $P(\chi^2) = 7\%$

CDF combined results $(m_T(e,\mu), p_T(e,\mu), p_T(\nu(e,\mu)))$

$M_W = (80349 \pm 54_{\text{stat}}) \pm 34_{\text{syst}} \text{ MeV}$

$= 80413 \pm 48 \text{ MeV}$

Combination of all six fits yields $P(\chi^2) = 44\%$
m(W) = 80.401 ± 0.023 GeV (stat)  
m(W) = 80.400 ± 0.027 GeV (stat)  
m(W) = 80.402 ± 0.023 GeV (stat)

DØ RunII 1fb⁻¹
80.401 ± 0.021(stat.) ± 0.038(syst.) GeV
80.401 ± 0.043 GeV
this new result is the
single most precise measurement
of the W boson mass to date
## Summary of uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>(\sigma(m_W)) MeV</th>
<th>(m_T)</th>
<th>(\sigma(m_W)) MeV (p_T^e)</th>
<th>(\sigma(m_W)) MeV (E_T)</th>
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<td><strong>Experimental</strong></td>
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<td>Boson (p_T)</td>
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<td>14</td>
<td>17</td>
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<tr>
<td><strong>Total</strong></td>
<td>37</td>
<td>40</td>
<td>44</td>
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</table>

**statistical**

23 27 23

**total**

44 48 50
For the first time the total uncertainty of 31 MeV from Tevatron is smaller than that of 33 MeV from LEP II.

World average is now: \(80.399 \pm 0.023\) GeV

Combination performed with B.L.U.E. method
Higgs mass constraints

\[ M_{\text{top}} = 173.3 \pm 1.3 \text{ GeV} \]
\[ M_W = 80.399 \pm 0.023 \text{ GeV} \]

without LEP/Tevatron limits
\[ M_H = 84^{+30}_{-23} \text{ GeV} \]

with LEP/Tevatron limits
\[ M_H = 120^{+17}_{-6} \text{ GeV} \]

The 95% upper limits are 159 GeV without Tevatron limits and 155 GeV with Tevatron limits

in a near future \( \Delta M_{\text{top}} = 1 \text{ GeV} \) and \( \Delta M_W = 0.015 \text{ GeV} \)
Challenges in Run IIb

Run IIb instantaneous luminosity results in much higher energy flow from additional collisions which complicates the modeling of detector effects. The impact of these additional collisions necessitates changes in all parts of the parametrized detector models both for CDF and DØ.

Inst. luminosity

Scalar Et : sum of the total transverse energy deposited in the DØ calorimeter (electron energy removed)
from 54 MeV to 16 meV (stat)

fit with 2.3 fb⁻¹

from 48 MeV to 15 meV (stat)

fit with 2.4 fb⁻¹
DØ 4.3 fb⁻¹
55K Z→ee
1.7 M W→ee

Statistical error : 13 MeV
Electron energy scale : 15 MeV
Total error about: 25 MeV

PDF uncertainty: ~15 MeV (new estimation with RESBOS)

• close contacts with theorists: different event generators (PYTHIA, RESBOS, POWHEG) are studied
• Found including EC electrons can reduce the PDF uncertainties by half
• Including Tevatron RunII W asymmetry results in PDF constraints (CT10W set), can reduce the PDF uncertainties by ~ 20%

Work in progress
Summary

- $M_W$ world average is $80.399 \pm 0.023$ GeV ($80.420 \pm 0.031$ GeV from Tevatron)

- CDF analysis in progress with $2.4 \, (\mu\nu)/2.3 \, (\nu e)$ fb$^{-1}$

- DØ expected Run IIb (4.3 fb-1) accuracy: ~25 MeV: Stat. ~13 MeV + Syst. ~22 MeV
- + Run IIa 1 fb-1, Total Run II (5.3fb-1): ~22MeV

- difficulties resulting from a larger instantaneous luminosity in the RunIIb make the analysis very challenging.

- on the road of 15 MeV uncertainty (CDF and DØ combined)
- with more statistics (10 fb$^{-1}$ in the can already !) 10 MeV ??

- but theoretical errors (PDF) have to be reduced !

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Backup Slides
Consistency

Direct measurement:
LEP and Tevatron

Indirect measurement:
Z-Pole measurements: constrain EW radiative corrections allow to predict $M_W$ and $M_{top}$ within SM

Good agreement: Successful SM test
Both data prefer light Higgs boson
Motivation

NLO QCD

Higgs

New Physics
Detectors

DZero Run II upgrades
2T solenoid
inner tracking
Preshower
extended µ coverage
and shielding
Trigger, DAQ
recorded 10 fb⁻¹
data taking efficiency ~ 85%

CDF Run II upgrades
1.7 T solenoid
Inner tracking
Forward calorimeter
extended µ coverage
Trigger, DAQ
Electrons: energy scale

**After** having corrected for the effects of the uninstrumented material: final energy response calibration, using $Z \rightarrow e\,e$, the known $Z$ mass value from LEP, and the standard “$f_Z$ method”:

$$E_{\text{measured}} = \alpha \times E_{\text{true}} + \beta$$

Use energy spread of electrons in $Z$ decay to constrain $\alpha$ and $\beta$.

In a nutshell: the $f_Z$ observable allows you to split your sample of electrons from $Z \rightarrow e\,e$ into subsamples of different true energy; this way you can **"scan" the electron energy response as a function of energy.**

$$M_Z(\text{measured}) = \alpha \cdot M_Z(\text{true}) + f_Z \cdot \beta + X \cdot \beta^2 + \ldots$$

If $\beta \ll E(e1) + E(e2)$

with $f_Z = (E(e1) + E(e2))(1-\cos(\gamma_{ee}))/M_Z$

$\gamma_{ee}$ is the opening angle between the two electrons

$M_Z(\text{measured})$ vs. $f_Z$ templates generated for range of $\alpha$ and $\beta$ values

**Result:**

$$\alpha = 1.0111 \pm 0.0043$$

$$\beta = -0.404 \pm 0.209 \text{ GeV}$$

**correlation:** -0.997

This corresponds to the dominant systematic uncertainty (by far) in the $W$ mass measurement (but this is really just $Z$ statistics ... more data will reduce it):

$$\Delta m(W) = 34 \text{ MeV}, \quad 100 \% \text{ correlated between all three observables}$$
Electrons: energy resolution

Electron energy resolution is driven by two components: sampling fluctuations and constant term.

**Sampling fluctuations** are driven by sampling fraction of CAL modules (well known from simulation and testbeam) and by uninstrumented material. Amount of material has been quantified with good precision (thanks to Z -> e e decay !).

**Constant term** is extracted from Z -> e e data (essentially fit to observed width of Z peak).

**Result:**

C = (2.05 ± 0.10) %

in excellent agreement with Run II design goal (2%)

**remember that Z mass value from LEP was an input to electron energy scale calibration, PDG: m(Z) = 91.1876 ± 0.0021 GeV**

\[ m(Z) = 91.185 \pm 0.033 \text{ GeV (stat)} \]
A typical W -> ev event

Three observables:

(plots from published RunIIa 1 fb⁻¹ analysis, Phys. Rev. Lett. 103, 141801 (2009).)

Developed a Fast MC model to generate templates of the 3 observables with different W mass hypotheses. Fit the templates to the Data to extract W mass.

The Fast MC model:
- Event Generator: Resbos+Photons
- Parameterized Detector Model

The Parameterized Detector Model is essential in this analysis!
Electron Model:

\[ E_{\text{reco}} = R_{EM}(E_{\text{true}}) \otimes \sigma_{EM}(E_{\text{true}}) + \Delta E_{\text{corr}} \]

Response and Resolution are calibrated using Z invariant mass of Z\(\rightarrow\)ee Data

\(\Delta E_{\text{corr}}\) Model: Model Update in RunIIb

1. Energy Leakage due to FSR
   - Add Inst.Lumi, SET, Eta dependencies
2. Recoil, Mini-Bias and Zero-Bias Contamination inside electron window
3. Effects due to Zero-Suppression and Baseline-Subtraction
   - For modeling 2. and 3., we added Inst. Lumi., SET, electron \(p_T\) and \(U_{\perp}\) dependencies in a very complicated way, based on a new Wenu FullMC production with Electron and Recoil separated.

Recoil Model:

\[ \vec{u}_T = \vec{u}^{\text{Hard}}_{T} + \vec{u}^{\text{Soft}}_{T} + \vec{u}^{\text{Elec}}_{T} + \vec{u}^{\text{FSR}}_{T} \]

Hard Recoil balancing W or Z boson
Soft Recoil: Zero-Bias and Mini-Bias
In the same framework of \(\Delta E_{\text{corr}}\) Modeling
What has been added to (subtracted from) the electron has to be subtracted from (added to) the Recoil.
Stability checks

Changes in the fitted $m_W$ when the fitting range ($m_T$ observable) is varied.

![Graph showing stability checks for $m_W$ with varying fitting ranges](image)

- Upper limit fixed at 90 GeV
- Lower limit fixed at 65 GeV

D0 Preliminary, 1 fb$^{-1}$
Stability checks

**Instantaneous luminosity** (split data into two subsets – high and low inst. luminosity)

Time (i.e. data-taking period)
Electroweak measurements prefer light Higgs, heavy SUSY

- Some tension in both cases
  - Something else?
  - Need increased precision

YES WE CAN!

With > 4 fb$^{-1}$ of data being analyzed currently:
the $\Delta M_W$ per experiment is estimated $\sim$ 25 MeV!
combined $\Delta M_W \sim$ 15 MeV possible by next year

CDF/DØ combined
10 fb$^{-1}$ 2011 (?)
$\Delta m_W \sim$ 10 MeV
$\Delta m_{top} \sim$ 1 GeV
68%, 95%, 99% CL fit contours excl. $M_W$, $m_{\text{top}}$, incl. Higgs searches

1\sigma band for $m_{\text{top}}$ WA

1\sigma band for $M_W$ WA

$M_f = 300 \text{ GeV}$

$M_f = 1000 \text{ GeV}$

$M_f = 1140 \text{ GeV}$
Fits include only the given observable $P$. Pétroff Blois 2011 30 05/31/11