Measurement of the W Boson Mass at CDF
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Riken Brookhaven Research Center Workshop
June 24-25, 2010
Spontaneous Symmetry Breaking

- **2008 Nobel Prize in Physics**

  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"

  Yoichiro Nambu

- Experimentally, jury is still out on Higgs mechanism of Electroweak Symmetry Breaking in the Standard Model of Particle Physics
From the Tevatron, $\delta M_{\text{top}} = 1.3 \text{ GeV} \Rightarrow \delta M_H / M_H = 11\%$

equivalent $\delta M_W = 8 \text{ MeV}$ for the same Higgs mass constraint

Current world average $\delta M_W = 23 \text{ MeV}$

- progress on $\delta M_W$ now has the biggest impact on Higgs constraint!
Motivation II

- SM Higgs fit: $M_H = 83^{+30}_{-23}$ GeV (gfitter.desy.de)

- LEPII direct searches: $M_H > 114.4$ GeV @ 95% CL (PLB 565, 61)

In addition to the Higgs, is there another missing piece in this puzzle?

$\left( A_{FB}^b \text{ vs } A_{LR} : 3.2\sigma \right)$

Must continue improving precision of $M_W$, $M_{top}$...

Other precision measurements constrain Higgs, equivalent to $\delta M_W \sim 15$ MeV

Motivate direct measurement of $M_W$ at the 15 MeV level and better
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Motivate direct measurement of $M_W$ at the 15 MeV level and better
Can the $\chi^2$ parabola in $\ln M_H$ be narrowed?

Where will it minimize in the future?

Will Tevatron exclude the Higgs in the preferred ($M_H < 200$ GeV) range?

Will LHC see the (SM or non-SM) Higgs inside or outside the preferred mass range?
W Mass Analysis Strategy
Quark-antiquark annihilation dominates (80%)

Lepton $p_T$ carries most of $W$ mass information, can be measured precisely (achieved 0.03%)

Initial state QCD radiation is $O(10 \text{ GeV})$, measure as soft 'hadronic recoil' in calorimeter (calibrated to ~1%)
Pollutes $W$ mass information, fortunately $p_T(W) \ll M_W$
W Boson Production at the Tevatron

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Quadrant of Collider Detector at Fermilab (CDF)

Select W and Z bosons with central (|\eta| < 1) leptons
Collider Detector at Fermilab (CDF)

- Muon detector
- Central hadronic calorimeter
- Central outer tracker (COT)
CDF W & Z Data Samples

- **W, Z, J/ψ** and Upsilon decays triggered in the dilepton channel

- Analysis of 2.3 fb$^{-1}$ data in progress

  
  - Electron channel: $L = 218$ pb$^{-1}$
  
  - Muon channel: $L = 191$ pb$^{-1}$

- Event selection gives fairly clean samples
  
  - W boson samples' mis-identification backgrounds ~ 0.5%

<table>
<thead>
<tr>
<th>Sample</th>
<th>Candidates</th>
</tr>
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<td>$W \rightarrow e\nu$</td>
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<tr>
<td>$W \rightarrow \mu\nu$</td>
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<tr>
<td>$Z \rightarrow e^+e^-$</td>
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<td>$Z \rightarrow \mu^+\mu^-$</td>
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Outline of CDF Analysis

*Energy scale measurements drive the W mass measurement*

- **Tracker Calibration**
  - alignment of the central drift chamber (COT with ~2400 cells) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\gamma \rightarrow \mu\mu$ mass fits
    - Confirmed using $Z \rightarrow \mu\mu$ mass fit

- **EM Calorimeter Calibration**
  - COT momentum scale transferred to EM calorimeter using a fit to the peak of the $E/p$ spectrum, around $E/p \sim 1$
  - Calorimeter energy scale confirmed using $Z \rightarrow ee$ mass fit

- **Tracker and EM Calorimeter resolutions**

- **Hadronic recoil modelling**
  - Characterized using $p_T$-balance in $Z \rightarrow ll$ events
Drift Chamber (COT) Alignment

COT endplate geometry
Internal Alignment of COT

- Use a clean sample of ~200k cosmic rays for cell-by-cell internal alignment

- Fit COT hits on both sides simultaneously to a single helix (AK, H. Gerberich and C. Hays, NIMA 506, 110 (2003))
  - Time of incidence is a floated parameter

- Same technique being used on ATLAS and CMS
Residuals of COT cells after alignment

CDFII

Before alignment

after alignment

Final relative alignment of cells ~5 μm (initial alignment ~50 μm)
Cross-check of COT alignment

- Final cross-check and correction to track curvature based on difference of \( \langle E/p \rangle \) for positrons vs electrons (red points)
- Smooth ad-hoc curvature corrections applied \( \Rightarrow \delta M_w = 6 \text{ MeV} \)
- Systematic effects also relevant for LHC trackers
Signal Simulation and Fitting
Signal Simulation and Template Fitting

- All signals simulated using a custom Monte Carlo
  - Generate finely-spaced templates as a function of the fit variable
  - Perform binned maximum-likelihood fits to the data
- Custom fast Monte Carlo makes smooth, high statistics templates
  - And provides analysis control over key components of the simulation

- CDF and D0 extract the W mass from three kinematic distributions: Transverse mass, charged lepton $p_T$ and neutrino $p_T$
Generator-level input for W & Z simulation provided by RESBOS (C. Balazs & C.-P. Yuan, PRD56, 5558 (1997) and references therein), which

- Calculates triple-differential production cross section, and p_T-dependent double-differential decay angular distribution

- Calculates boson p_T spectrum reliably over the relevant p_T range: includes tunable parameters in the non-perturbative regime at low p_T

Radiative photons generated according to energy vs angle lookup table from WGRAD (U. Baur, S. Keller & D. Wackerroth, PRD59, 013002 (1998))
Constraining Boson $p_T$ Spectrum

- Fit the non-perturbative parameter $g_2$ in RESBOS to $p_T(ll)$ spectra:
  
  $g_2 = 0.685 \pm 0.048$

  - Consistent with global fits (Landry et al, PRD67, 073016 (2003))

- Negligible effect of second non-perturbative parameter $g_3$

  Position of peak in boson $p_T$ spectrum depends on $g_2$
Fast Monte Carlo Detector Simulation

- A complete detector simulation of all quantities measured in the data

- First-principles simulation of tracking
  - Tracks and photons propagated through a high-resolution 3-D lookup table of material properties for silicon detector and COT
  - At each material interaction, calculate
    - Ionization energy loss according to complete Bethe-Bloch formula
    - Generate bremsstrahlung photons down to 4 MeV, using detailed cross section and spectrum calculations
    - Simulate photon conversion and compton scattering
    - Propagate bremsstrahlung photons and conversion electrons
    - Simulate multiple Coulomb scattering, including non-Gaussian tail
  - Deposit and smear hits on COT wires, perform full helix fit including optional beam-constraint
Fast Monte Carlo Detector Simulation

- A complete detector simulation of all quantities measured in the data
- First-principles simulation of tracking
  - Tracks and photons propagated through a high-resolution 3-D lookup table of material properties for silicon detector and COT
Tracking Momentum Scale
Tracking Momentum Calibration

- Set using $\Upsilon \rightarrow \mu \mu$ and $\gamma \rightarrow \mu \mu$ resonances
  - Consistent within total uncertainties

- Use $\Upsilon$ to study and calibrate non-linear response of tracker

- Systematics-dominated, improved detector modelling required

\[
\langle \frac{1}{p_T(\mu)} \rangle \text{(GeV}^{-1})
\]

$\Upsilon$ mass independent of $p_T(\mu)$

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

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

Data

Simulation
# Tracking Momentum Scale Systematics

## Systematic uncertainties on momentum scale

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<thead>
<tr>
<th>Source</th>
<th>$J/\psi \times 10^{-3}$</th>
<th>$\Upsilon \times 10^{-3}$</th>
<th>Common $\times 10^{-3}$</th>
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<tr>
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<td>0.25</td>
<td>0.21</td>
<td>0.17</td>
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Uncertainty dominated by QED radiative corrections and magnetic field non-uniformity.
EM Calorimeter Response
Electromagnetic Calorimeter Calibration

- E/p peak from $W \rightarrow e\nu$ decays provides EM calorimeter calibration relative to the tracker
  - Calibration performed in bins of electron energy

![Graph showing data and simulation comparison with statistical uncertainty]

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

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

Tail region of E/p spectrum used for tuning model of radiative material
Calorimeter Simulation for Electrons and Photons

- Distributions of energy loss calculated based on expected shower profiles as a function of $E_T$
  - Leakage into hadronic calorimeter
  - Absorption in the coil
  - Relevant for $E/p$ lineshape
Consistency of Radiative Material Model

- Excellent description of E/p spectrum tail
- Radiative material tune factor: $S_{X0} = 1.004 \pm 0.009_{\text{stat}} \pm 0.002_{\text{background}}$
  achieves consistency with E/p spectrum tail
  - CDF detector geometry confirmed as a function of pseudorapidity: $S_{\text{MAT}}$, independent of $|\eta|$

![CDF data vs simulation](image)

Default energy loss * 1.004
Measurement of EM Calorimeter Non-linearity

- Perform E/p fit-based calibration in bins of electron $E_T$
- Parameterize non-linear response as: $S_E = 1 + \zeta \left( \frac{E_T}{\text{GeV}} - 39 \right)$
- Tune on W and Z data: $\zeta = (6 \pm 7_{\text{stat}}) \times 10^{-5}$

$\Rightarrow \Delta M_W = 23$ MeV
Z → ll Mass Cross-checks

- Z boson mass fits consistent with tracking and E/p-based calibrations

CDF II, $L \sim 200$/pb

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

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

$M_Z = (91184 \pm 43)$ MeV

$\chi^2/\text{dof} = 32 / 30$
Hadronic Recoil Model
Constraining the Hadronic Recoil Model

Exploit similarity in production and decay of $W$ and $Z$ bosons

Detector response model for hadronic recoil tuned using $p_T$-balance in $Z \rightarrow ll$ events

Transverse momentum of Hadronic recoil ($u$) calculated as 2-vector-sum over calorimeter towers
Tuning Recoil Response Model with Z events

Project the vector sum of $p_T(ll)$ and $u$ on a set of orthogonal axes defined by lepton directions.

Mean and rms of projections as a function of $p_T(ll)$ provide information on hadronic model parameters.

Hadronic model parameters tuned by minimizing $\chi^2$ between data and simulation.

$\Delta M_W = 9$ MeV
Tuning Recoil Resolution Model with $Z$ events

At low $p_T(Z)$, $p_T$-balance constrains hadronic resolution due to underlying event.

At high $p_T(Z)$, $p_T$-balance constrains jet resolution.

Resolution of $p_T$-balance (GeV)

CDF II

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

$\chi^2 / \text{DoF} = 4.8 / 10$

Data

Simulation

$\Delta M_W = 7 \, \text{MeV}$
Testing Hadronic Recoil Model with $W$ events

Compare recoil distributions between simulation and data

Recoil projection (GeV) on lepton direction

$p_T(W)$ comparison
W Mass Fits
$W$ Transverse Mass Fits

CDF II

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

**Muons**

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

$\chi^2/\text{dof} = 59 / 48$
$W$ Lepton $p_T$ Fits

CDF II

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

Electrons

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

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

- Data
- Simulation

events / 0.25 GeV

$E_T(e)$ (GeV)
## Transverse Mass Fit Uncertainties (MeV)

<table>
<thead>
<tr>
<th></th>
<th>electrons</th>
<th>muons</th>
<th>common</th>
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<tbody>
<tr>
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<td><strong>Total systematic</strong></td>
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<tr>
<td><strong>Total</strong></td>
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</tbody>
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*Systematic uncertainties shown in green: statistics-limited by control data samples*

*W charge asymmetry from Tevatron helps with PDFs*
Tevatron Run 1 (100 pb⁻¹) W Mass Systematic Uncertainties (MeV)

<table>
<thead>
<tr>
<th></th>
<th>CDF m</th>
<th>CDF e</th>
<th>D0 e</th>
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<td><strong>Total</strong></td>
<td><strong>144</strong></td>
<td><strong>113</strong></td>
<td><strong>84</strong></td>
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</table>

For comparison to run 2 analysis
W Boson Mass Measurements

CDF: 200 pb\(^{-1}\), electron and muon channels
D0: 1 fb\(^{-1}\), electron channel

(D0 Run II: PRL 103:141801, 2009)
Pre-Run 2 $M_W$ vs $M_{\text{top}}$

Experimental errors 68% CL:

- LECP2/Tevatron (1998)

- Light SUSY
- MSSM
- Heavy SUSY

- SM
- $M_H = 114$ GeV
- $M_H = 400$ GeV

Heinemeyer, Hollik, Stockinger, Weber, Weiglein
Post-Run 2 $M_W$ $\nu$ $M_{\text{top}}$
Improvement of $M_W$ Uncertainty with Sample Statistics

Next target: 15-20 MeV measurement of $M_W$ from the Tevatron
Preliminary Studies of 2.3 fb\(^{-1}\) Data from CDF

CDF has started the analysis of 2.3 fb\(^{-1}\) of data, with the goal of measuring \(M_W\) with precision better than 25 MeV.

Lepton resolutions as good as they were in 200 pb\(^{-1}\) sample.
Preliminary Studies of 2.3 fb$^{-1}$ Data

Statistical errors on all lepton calibration fits have scaled with statistics

Detector and data quality maintained over time

detailed calibrations in progress
Preliminary Studies of 2.3 fb$^{-1}$ Data

Recoil resolution not significantly degraded at higher instantaneous luminosity

CDF II preliminary $\int L \, dt = 2.4$ fb$^{-1}$

W$\rightarrow$e$\nu$

$\Delta m_W^{\text{stat}} = 15$ MeV/c$^2$
$\chi^2$/dof = 70 / 48

CDF II preliminary $\int L \, dt = 2.3$ fb$^{-1}$

W$\rightarrow$\mu$\nu$

$\Delta m_W^{\text{stat}} = 16$ MeV/c$^2$
$\chi^2$/dof = 72 / 48

statistical errors on transverse mass fits are scaling with statistics
$M_W$ Measurement at LHC

- Very high statistics samples of $W$ and $Z$ bosons
  - 10 fb$^{-1}$ at 14 TeV: 40 million $W$ boson and 4 million $Z$ boson candidates per decay channel per experiment

- Statistical uncertainty on $W$ mass fit $\sim$ 2 MeV

- Calibrating lepton energy response using the $Z \rightarrow ll$ mass resonance, best-case scenario of statistical limit $\sim$ 5 MeV precision on calibrations

- Calibration of the hadronic calorimeter based on transverse momentum balance in $Z \rightarrow ll$ events also $\sim$ 2 MeV statistical limit

- Total uncertainty on $M_W$ $\sim$ 5 MeV if $Z \rightarrow ll$ data can measure all the $W$ boson systematics
**$M_W$ Measurement at LHC**

- Can the $Z \rightarrow ll$ data constrain all the relevant $W$ boson systematics?

- Production and decay dynamics are slightly different
  - Different quark parton distribution functions
  - Non-perturbative (e.g. charm mass effects in $cs \rightarrow W$) effects
  - QCD effects on polarization of $W$ vs $Z$ affects decay kinematics

- Lepton energies different by $\sim 10\%$ in $W$ vs $Z$ events
- Presence of second lepton influences the $Z$ boson event relative to $W$
- Reconstructed kinematic quantity different (invariant vs transverse mass)
- Subtle differences in QED radiative corrections
- .......

$M_W$ Measurement at LHC

- Can the $Z \to ll$ data constrain all the relevant $W$ boson systematics?

- Can we add other constraints from other mass resonances and tracking detectors?

- With every increase in statistics of the data samples, we climb a new learning curve on the systematic effects
  - Improved calculations of QED radiative corrections available
  - Better understanding of parton distributions from global fitting groups (CTEQ, MSTW, Giele et al)

- Large sample statistics at the LHC imply the potential is there for 5-10 MeV precision on $M_W$
Summary

- The $W$ boson mass is a very interesting parameter to measure with increasing precision

- CDF Run 2 $W$ mass result with 200 pb$^{-1}$ data:
  
  $$M_W = 80413 \pm 48 \text{ MeV}$$

- D0 Run 2 $W$ mass result with 1 fb$^{-1}$ data:
  
  $$M_W = 80401 \pm 43 \text{ MeV}$$

- Most systematics limited by statistics of control samples
  
  - CDF and D0 are both working on $\delta M_W < 25 \text{ MeV}$ measurements from $\sim 2 \text{ fb}^{-1}$ (CDF) and $\sim 4 \text{ fb}^{-1}$ (D0)

- Learning as we go: Tevatron $\rightarrow$ LHC may produce $\delta M_W \sim 5-10 \text{ MeV}$
A possible Future Scenario

Higgs discovery with a large Higgs mass

\[ \delta M_W = 10 \text{ MeV} \]

\[ \delta m_{\text{top}} = 0.5 \text{ GeV} \]
Combined Results

- Combined electrons (3 fits): $M_W = 80477 \pm 62$ MeV, $P(\chi^2) = 49\%$
- Combined muons (3 fits): $M_W = 80352 \pm 60$ MeV, $P(\chi^2) = 69\%$
- All combined (6 fits): $M_W = 80413 \pm 48$ MeV, $P(\chi^2) = 44\%$

Lepton $p_T$ and Missing $E_T$ Fit Uncertainties

<table>
<thead>
<tr>
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<th>Electrons</th>
<th>Muons</th>
<th>Common</th>
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<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$u_\parallel$ Efficiency</td>
<td>16</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>7</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>$p_T(W)$</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>PDF</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>QED</td>
<td>9</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Total Systematic</td>
<td>54</td>
<td>46</td>
<td>42</td>
</tr>
<tr>
<td>Statistical</td>
<td>57</td>
<td>66</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>79</td>
<td>80</td>
<td>42</td>
</tr>
</tbody>
</table>
## Backgrounds in the W sample

<table>
<thead>
<tr>
<th>Source</th>
<th>Fraction (electrons)</th>
<th>Fraction (muons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z -&gt; ll</td>
<td>0.24 ± 0.04 %</td>
<td>6.6 ± 0.3 %</td>
</tr>
<tr>
<td>W -&gt; τν</td>
<td>0.93 ± 0.03 %</td>
<td>0.89 ± 0.02 %</td>
</tr>
<tr>
<td>Mis-identified QCD jets</td>
<td>0.25 ± 0.15 %</td>
<td>0.1 ± 0.1 %</td>
</tr>
<tr>
<td>Decays-in-flight</td>
<td></td>
<td>0.3 ± 0.2 %</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td></td>
<td>0.05 ± 0.05 %</td>
</tr>
</tbody>
</table>

Backgrounds are small (except Z → μμ with a forward muon)

backgrounds contribute systematic uncertainty of 9 MeV on transverse mass fit