W Boson Mass Measurements at the Tevatron
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Motivation for Precision Electroweak Measurements

- Radiative corrections due to heavy quark and Higgs loops and exotica

Motivate the introduction of the $\rho$ parameter:
\[ M_W^2 = \rho [M_W({\text{tree}})]^2 \]
with the predictions $\Delta \rho = (\rho - 1) \sim M_{\text{top}}^2$ and $\Delta \rho \sim \ln M_H$

- In conjunction with $M_{\text{top}}$ and the Higgs boson mass, the W boson mass stringently tests the SM
- A discrepancy with the SM can be used to test new physics models
Contributions from Supersymmetric Particles

- Radiative correction depends on mass splitting ($\Delta m^2$) between squarks in SU(2) doublet

- After folding in limits on SUSY particles from direct searches, SUSY loops can contribute 100 MeV to $M_W$
Progress on $M_{\text{top}}$ at the Tevatron and LHC

- From the Tevatron and LHC (which is approaching Tevatron precision), $\Delta M_{\text{top}} < 0.9 \text{ GeV} \Rightarrow \Delta M_H / M_H < 8\%$
- equivalent $\Delta M_W < 6 \text{ MeV}$ for the same Higgs mass constraint
- Current world average $\Delta M_W = 15 \text{ MeV}$
  - progress on $\Delta M_W$ has the biggest impact on precision electroweak fit
Motivation

- Generic parameterization of new physics contributing to W and Z boson self-energies: $S, T, U$ parameters (Peskin & Takeuchi)

$M_W$ and Asymmetries are the most powerful observables in this parameterization

Additionally, $M_W$ is the only measurement which constrains $U$

$M_H \sim 120$ GeV

$M_H > 600$ GeV

(from P. Langacker, 2012)
W Boson Production at the Tevatron

Quark-antiquark annihilation dominates (80%)

Lepton $p_T$ carries most of $W$ mass information, can be measured precisely (achieved 0.01%)

Initial state QCD radiation is $O(10 \text{ GeV})$, measure as soft 'hadronic recoil' in calorimeter (calibrated to $\sim 0.5\%$)
Quadrant of Collider Detector at Fermilab (CDF)

EM calorimeter provides precise electron energy measurement

Drift chamber provides precise lepton track momentum measurement

Calorimeters measure hadronic recoil particles

Select W and Z bosons with central (|\eta| < 1) leptons
D0 Detector at Fermilab

Highly-segmented, stable Uranium+liquid Argon EM calorimeter provides precise electron energy measurement.

Silicon and Scintillating fiber trackers provides precise lepton track position measurement.

Calorimeters measure hadronic recoil particles.
Electron Energy Scale at D0

- Correct for low-energy non-linearity
  - Energy loss due to upstream dead material (ionization, bremsstrahlung)
  - Modeling of underlying event energy flow in electron towers
  - Electronics noise and pileup
- Straight-line model for calorimeter response
  \[ R_{EM}(E_{true}) = \alpha \cdot (E_{true} - \bar{E}_{true}) + \beta + \bar{E}_{true} \]

Tune on \( Z \rightarrow ee \) mass exploiting electron energy spread

\[ \Rightarrow \text{measure } m_W/m_Z \]

Calibration procedure checked with closure test performed with GEANT pseudo-data
$Z \rightarrow ee$ data at D0

- 54.5k events
- $m(ee)$
- $p_T(e)$

Good agreement between data and parameterised Monte Carlo.
CDF Electron and Muon Measurement

- A complete detector simulation of all quantities measured in the data
- First-principles simulation of tracking
  - Tracks and photons propagated through a high-granularity 3-D lookup table of material properties for silicon detector and drift chamber

![Diagram of electron and muon measurement with tracks and photons propagating through a calorimeter.](Image)
Internal Alignment of CDF Drift Chamber

- Use a clean sample of \(~400k\) cosmic rays for cell-by-cell internal alignment

- Fit hits on both sides simultaneously to a single helix (A. Kotwal, H. Gerberich and C. Hays, NIMA 506, 110 (2003))
  - Time of incidence is a floated parameter in this 'dicosmic fit'
CDF Tracking Momentum Scale

Set using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ resonance and $Z \rightarrow \mu\mu$ masses

- Extracted by fitting $J/\psi$ mass in bins of $1/p_T(\mu)$, and extrapolating momentum scale to zero curvature
- $J/\psi \rightarrow \mu\mu$ mass independent of $p_T(\mu)$ after 4% tuning of energy loss

$$\int L \, dt = 2.2 \, fb^{-1}$$

Scale correction = $(-1.299 \pm 0.022) \times 10^{-3}$
Slope = $(0.8 \pm 6.4) \times 10^{-5}$ GeV

Default energy loss * 1.04

Data
Simulation

$\Delta p/p = (-1.284 \pm 0.024_{\text{stat}}) \times 10^{-3}$
$\chi^2/\text{dof} = 95 / 86$

$J/\psi \rightarrow \mu\mu$
mass fit (bin 5)
CDF Tracking Momentum Scale

\( \Upsilon \rightarrow \mu\mu \) resonance provides

- Momentum scale measurement at higher \( p_T \)
- Validation of beam-constraining procedure (upsilons are promptly produced)
- Cross-check of non-beam-constrained (NBC) and beam-constrained (BC) fits

\[ \int L \, dt = 2.2 \, fb^{-1} \]

\[ \Delta p/p = \left( -1.335 \pm 0.025 \text{ stat} \right) \times 10^{-3} \]

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

NBC \( \Upsilon \rightarrow \mu\mu \) mass fit
$Z \rightarrow \mu\mu$ Mass Cross-check & Combination at CDF

- Using the $J/\psi$ and $\Upsilon$ momentum scale, performed “blinded” measurement of $Z$ mass

  $M_Z = 91180 \pm 12_{\text{stat}} \pm 9_{\text{momentum}} \pm 5_{\text{QED}} \pm 2_{\text{alignment}}$ MeV

\[ \int L \, dt = 2.2 \text{ fb}^{-1} \]

$\chi^2/\text{dof} = 30/30$
CDF Tracker Linearity Cross-check & Combination

- Final calibration using the J/ψ, Y and Z bosons for calibration
- Combined momentum scale correction:

\[ \frac{\Delta p}{p} = ( -1.29 \pm 0.07_{\text{independent}} \pm 0.05_{\text{QED}} \pm 0.02_{\text{align}} ) \times 10^{-3} \]

\[ \Delta M_W = 7 \text{ MeV} \]
EM Calorimeter Energy Calibration at CDF

- E/p peak from $W \rightarrow \nu e$ decays provides measurements of EM calorimeter scale and its ($E_T$-dependent) non-linearity

$$\Delta S_E = (\text{9 stat} \pm 5 \text{ non-linearity} \pm 5 X_0 \pm 9 \text{Tracker}) \times 10^{-5}$$

Setting $S_E$ to 1 using E/p calibration from combined $W \rightarrow \nu e$ and $Z \rightarrow \nu \nu$ samples

$\int L dt = 2.2 \text{ fb}^{-1}$

$\Delta M_W = 13 \text{ MeV}$

Tail of E/p spectrum used for tuning model of radiative material

\[ \chi^2/\text{dof} = 18 / 22 \]
Z→ee Mass Cross-check and Combination at CDF

- Performed “blind” measurement of Z mass using E/p-based calibration
  - Consistent with PDG value (91188 MeV) within 1.4σ (statistical)
  - \( M_Z = 91230 \pm 30_{\text{stat}} \pm 10_{\text{calorimeter}} \pm 8_{\text{momentum}} \pm 5_{\text{QED}} \pm 2_{\text{alignment}} \) MeV

- Combine E/p-based calibration with Z→ee mass for maximum precision

\[ \Delta M_W = 10 \text{ MeV} \]
Recoil Response Model at D0 (similar to CDF)

- Hadronic response model motivated from “first principles”
  - “jet response” + spectator interaction + additional interactions and noise

Tuned on $p_T$ balance in Z boson events
$W$ Mass Fits at D0

1.677 $M_W$ events

Fitted result:

$m_W = 80371 \pm 13$ (stat) MeV

$m_W = 80343 \pm 14$ (stat) MeV
**W Mass Fits at CDF**

- **625k events**
  - Muons
    - $M_W = (80379 \pm 16_{stat})$ MeV
    - $\chi^2$/dof = 58 / 48
  - Electrons
    - Neutrino $p_T$ fits also performed by both experiments to check consistency

- **470k events**
  - $M_W = (80393 \pm 21_{stat})$ MeV
  - $\chi^2$/dof = 60 / 62
  - Electron-channel lepton $p_T$ fit
# Transverse Mass Fit Uncertainties (MeV)

<table>
<thead>
<tr>
<th>Source</th>
<th>CDF $m_T(\mu, \nu)$</th>
<th>CDF $m_T(e, \nu)$</th>
<th>DØ $m_T(e, \nu)$</th>
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Combined W Mass Result, Error Scaling (CDF)
W Boson Mass Measurements from Different Experiments

World average computed by TeVEWWG
ArXiv: 1204.0042

<table>
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<th>Experiment</th>
<th>Mass (MeV/c^2) ± Error</th>
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<td>D0 I</td>
<td>80483 ± 84</td>
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<tr>
<td>CDF I</td>
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<td>5.3 fb^{-1} D0 II (PRL 108, 151804)</td>
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<td>2.2 fb^{-1} CDF II (PRL 108, 151803)</td>
<td>80387 ± 19</td>
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<tr>
<td>World Average</td>
<td>80385 ± 15</td>
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PDF Uncertainties – scope for improvement

- Factor of 5 bigger samples of $W$ and $Z$ bosons available at Tevatron

- Newer PDF sets, e.g. CT10W include more recent data, such as Tevatron $W$ charge asymmetry data

- Dominant sources of $W$ mass uncertainty are the $d_{\text{valence}}$ and $\bar{d}-\bar{u}$ degrees of freedom
  - Understand consistency of data constraining these d.o.f.
  - PDF fitters increase tolerance to accommodate inconsistent datasets

- Tevatron and LHC measurements that can further constrain PDFs:
  - $Z$ boson rapidity distribution
  - $W \rightarrow l\nu$ lepton rapidity distribution
  - $W$ boson charge asymmetry
The top quark mass, the W boson mass and the mass of the Higgs boson provides a stringent test of the standard model at loop level.
Current $M_W$ vs $M_{top}$

![Graph showing the relationship between $M_W$ and $m_t$ with experimental errors and theoretical predictions.](image)
Improved $M_W$ vs $M_{\text{top}}$ (half the current uncertainties)

$\delta M_W \sim 7 \text{ MeV}$

$\delta m_{\text{top}} \sim 0.5 \text{ GeV}$
Summary

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

- New Tevatron W mass result from $2.2 \text{ fb}^{-1} - 5.3 \text{ fb}^{-1}$ (PRL 108, 151803 & 151804)
  - $M_W = 80385 \pm 15 \text{ MeV}$

- New global electroweak fit $M_H = 94^{+29}_{-24} \text{ GeV} @ 68\% \text{ CL}$ (LEPEWWG)
  - Consistent with directly measured $M_H \sim 125 \text{ GeV}$

- Looking forward to $\Delta M_W < 10 \text{ MeV}$ from $10 \text{ fb}^{-1}$ of Tevatron data
  - Could LHC achieve $\Delta M_W \sim 5 \text{ MeV}$ given huge statistics?
Backup
Constraining Boson $p_T$ Spectrum

- Fit the non-perturbative parameter $g_2$ and QCD coupling $\alpha_S$ in RESBOS to $p_T(ll)$ spectra:

$$\Delta M_W = 5 \text{ MeV}$$

Position of peak in boson $p_T$ spectrum depends on $g_2$

Tail to peak ratio depends on $\alpha_S$
Measurement of EM Calorimeter Non-linearity

- Perform E/p fit-based calibration in bins of electron $E_T$
- GEANT-motivated parameterization of non-linear response:
  $S_E = 1 + \beta \log(E_T / 39 \text{ GeV})$
- Tune on W and Z data: $\beta = (5.2\pm0.7_{\text{stat}}) \times 10^{-3}$
  $\Rightarrow \Delta M_W = 4 \text{ MeV}$
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.

$\Delta M_W = 4 \text{ MeV}$
Testing Hadronic Recoil Model with $W$ events

Compare recoil distributions between simulation and data

Recoil projection (GeV) on lepton direction

Data
Simulation

CDF II $\int L \, dt = 2.2 \text{ fb}^{-1}$

$\mu = -0.387 \text{ GeV}$
$\sigma = 4.631 \text{ GeV}$

MC
$\mu = -0.388 \pm 0.007 \text{ GeV}$
$\sigma = 4.628 \pm 0.005 \text{ GeV}$

Data
$\mu = 5.918 \text{ GeV}$
$\sigma = 3.522 \text{ GeV}$

Simulation
$\mu = 5.925 \pm 0.004 \text{ GeV}$
$\sigma = 3.519 \pm 0.003 \text{ GeV}$

$p_T(W)$, muon channel
# Systematic Uncertainties in QED Radiative Corrections

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<th>CDF0</th>
<th>CDF1a</th>
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Parton Distribution Functions

- Affect W kinematic lineshapes through acceptance cuts
- We use CTEQ6 as the default PDF
- Use ensemble of 'uncertainty' PDFs
  - Represent variations of eigenvectors in the PDF parameter space
  - Compute $\delta M_W$ contribution from each error PDF
- Using MSTW2008 PDF ensemble defined for 68% CL, obtain systematic uncertainty of 10 MeV
- Comparing CTEQ and MSTW at 90% CL, yield similar uncertainty (CTEQ is 10% larger)
  - Cross-check: default MSTW2008 relative to default CTEQ6 yields 6 MeV shift in W mass
Generator-level Signal Simulation

- 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 $p_T$
- Multiple radiative photons generated according to PHOTOS (P. Golonka and Z. Was, Eur. J. Phys. C 45, 97 (2006) and references therein)