A New Precise Measurement of the W Boson Mass at CDF

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For the CDF Collaboration

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The electroweak gauge sector of the standard model, defined by \((g, g', \nu)\), is constrained by three precisely known parameters:

- \(\alpha_{\text{EM}}(M_Z) = 1 / 127.918(18)\)
- \(G_F = 1.16637 (1) \times 10^{-5} \text{ GeV}^{-2}\)
- \(M_Z = 91.1876 (21) \text{ GeV}\)

At tree-level, these parameters are related to other electroweak observables, e.g. \(M_W\):

- \(M_W^2 = \pi \alpha_{\text{EM}} / \sqrt{2} G_F \sin^2 \vartheta_W\)

  - where \(\vartheta_W\) is the Weinberg mixing angle, defined by
    \[\cos \vartheta_W = M_W / M_Z\]
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 $M_{\text{top}}$, the $W$ boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model
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

- From the Tevatron, $\Delta M_{\text{top}} = 0.9$ GeV => $\Delta M_H / M_H = 8\%$
- equivalent $\Delta M_W = 6$ MeV for the same Higgs mass constraint
- Current world average $\Delta M_W = 23$ MeV
  - progress on $\Delta M_W$ has the biggest impact on Higgs constraint
Motivation

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

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

$M_H \sim 120$ GeV

$M_H > 600$ GeV

(from P. Langacker, 2012)

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

Select $W$ and $Z$ bosons with central ($|\eta| < 1$) leptons

EM calorimeter provides precise electron energy measurement

Drift chamber provides precise lepton track momentum measurement

Calorimeters measure hadronic recoil particles
Analysis Strategy

Maximize the number of internal constraints and cross-checks

Driven by two goals:

1) Robustness: constrain the same parameters in as many different ways as possible

2) Precision: combine independent measurements after showing consistency
Internal Alignment of COT

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

- Fit COT 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'
Custom 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-granularity 3-D lookup table of material properties for silicon detector and COT
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

$$\Delta p/p = (-1.284 \pm 0.024) \times 10^{-3}$$

**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

$J/\psi \rightarrow \mu\mu$ mass fit (bin 5)

$\chi^2$/dof = 95 / 86
Tracking Momentum Scale

$\gamma \rightarrow \mu\mu$ resonance provides

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

Data
Simulation

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

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

NBC $\gamma \rightarrow \mu\mu$

mass fit

\[ \int L \, dt = 2.2 \text{ fb}^{-1} \]
Z→μμ  Mass Cross-check & Combination

- Using the J/ψ and Y momentum scale, performed “blinded” measurement of Z mass

  - Z mass consistent with PDG value (91188 MeV) (0.7σ statistical)
  - \( M_Z = 91180 \pm 12_{\text{stat}} \pm 9_{\text{momentum}} \pm 5_{\text{QED}} \pm 2_{\text{alignment}} \) MeV

\[ \int L \, dt = 2.2 \, \text{fb}^{-1} \]
Tracker Linearity Cross-check & Combination

- Final calibration using the J/ψ, Υ 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 Scale

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

$$\Delta S_E = (9_{\text{stat}} \pm 5_{\text{non-linearity}} \pm 5_{X0} \pm 9_{\text{Tracker}}) \times 10^{-5}$$

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

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

Tail of E/p spectrum used for tuning model of radiative material
Z→ee Mass Cross-check and Combination

- 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

\[ \Delta M_W = 10 \text{ MeV} \]
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 $\alpha_S$
$W$ Transverse Mass Fit

CDF II

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

$M_W = (80379 \pm 16_{\text{stat}}) \, \text{MeV}$

$\chi^2/\text{dof} = 58/48$

Muons

Data

Simulation
$W$ Mass Fit using Lepton $p_T$

CDF II

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

$M_W = (80393 \pm 21_{\text{stat}}) \text{ MeV}$

$\chi^2/\text{dof} = 60 / 62$

Electrons

Data

Simulation
## Summary of $W$ Mass Fits

<table>
<thead>
<tr>
<th>Charged Lepton</th>
<th>Kinematic Distribution</th>
<th>Fit Result (MeV)</th>
<th>$\chi^2$/DoF</th>
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</thead>
<tbody>
<tr>
<td>Electron</td>
<td>Transverse mass</td>
<td>80408 ± 19</td>
<td>52/48</td>
</tr>
<tr>
<td>Electron</td>
<td>Charged lepton $p_T$</td>
<td>80393 ± 21</td>
<td>60/62</td>
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<tr>
<td>Electron</td>
<td>Neutrino $p_T$</td>
<td>80431 ± 25</td>
<td>71/62</td>
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<tr>
<td>Muon</td>
<td>Transverse mass</td>
<td>80379 ± 16</td>
<td>57/48</td>
</tr>
<tr>
<td>Muon</td>
<td>Charged lepton $p_T$</td>
<td>80348 ± 18</td>
<td>58/62</td>
</tr>
<tr>
<td>Muon</td>
<td>Neutrino $p_T$</td>
<td>80406 ± 22</td>
<td>82/62</td>
</tr>
</tbody>
</table>

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

- Muons: $p_T^\gamma$  
  80406 ± 22
- Muons: $p_T^l$       
  80348 ± 18
- Muons: $m_T$         
  80379 ± 16
- Electrons: $p_T^\gamma$  
  80431 ± 25
- Electrons: $p_T^l$    
  80393 ± 21
- Electrons: $m_T$      
  80408 ± 19

W boson mass (MeV/c$^2$)
Combined Results

- Combined electrons (3 fits): $M_W = 80406 \pm 25$ MeV, $P(\chi^2) = 49\%$

- Combined muons (3 fits): $M_W = 80374 \pm 22$ MeV, $P(\chi^2) = 12\%$

- All combined (6 fits): $M_W = 80387 \pm 19$ MeV, $P(\chi^2) = 25\%$
New CDF Result (2.2 fb\(^{-1}\))
Transverse Mass Fit Uncertainties (MeV)

<table>
<thead>
<tr>
<th>Source</th>
<th>Electrons</th>
<th>Muons</th>
<th>Common</th>
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<tbody>
<tr>
<td>W statistics</td>
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<td>Recoil energy scale</td>
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<td>pT(W) model</td>
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<td>Total systematic</td>
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<tr>
<td>Total</td>
<td>26</td>
<td>23</td>
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</tr>
</tbody>
</table>

Systematic uncertainties shown in green: statistics-limited by control data samples.
Combined W Mass Result, Error Scaling
Previous $M_W$ vs $M_{\text{top}}$
Updated $M_W$ vs $M_{\text{top}}$
W Boson Mass Measurements from Different Experiments

Previous world average = 80399 ± 23 MeV

new CDF result is significantly more precise than other measurements
PDF Uncertainties – scope for improvement

- Factor of 5 bigger samples of W and Z bosons available

- 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
Summary

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

- New CDF W mass result from 2.2 fb$^{-1}$ is the most precise in the world

  \[ M_W = 80387 \pm 12_{\text{stat}} \pm 15_{\text{syst}} \text{ MeV} \]
  \[ = 80387 \pm 19 \text{ MeV} \]

- New global electroweak fit $M_H = 94^{+29}_{-24} \text{ GeV} \at 68\% \text{ CL} \text{ (LEPEWWG)}$

  - SM Higgs prediction is pinned in the low-mass range
  - confront mass of new particle from direct search result ~ 125 GeV

- Looking forward to $\Delta M_W < 10 \text{ MeV}$ from 10 fb$^{-1}$ of CDF data
Backup
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:
  \[ S_E = 1 + \beta \log\left(\frac{E_T}{39 \text{ GeV}}\right) \]
- Tune on $W$ and $Z$ data: $\beta = (5.2 \pm 0.7_{\text{stat}}) \times 10^{-3}$
  \[ \Rightarrow \Delta M_W = 4 \text{ MeV} \]
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

$\Delta M_W = 4$ 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
$\int L \, dt \approx 2.2 \, fb^{-1}$

MC

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.387 GeV</td>
<td>4.631 GeV</td>
</tr>
</tbody>
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Data

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.388 ± 0.007 GeV</td>
<td>4.628 ± 0.005 GeV</td>
</tr>
</tbody>
</table>

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

MC

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.918 GeV</td>
<td>3.522 GeV</td>
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Data

<table>
<thead>
<tr>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.925 ± 0.004 GeV</td>
<td>3.519 ± 0.003 GeV</td>
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</table>

$p_T(W)$, muon channel
## Backgrounds in the W sample

### Muons

<table>
<thead>
<tr>
<th>Background</th>
<th>% of $W \rightarrow \mu\nu$ data</th>
<th>$\delta m_W$ (MeV)</th>
<th>$m_T$ fit</th>
<th>$p_T^\mu$ fit</th>
<th>$p_T^\nu$ fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>$7.35 \pm 0.09$</td>
<td>2</td>
<td>4</td>
<td>5</td>
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<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>$0.880 \pm 0.004$</td>
<td>0</td>
<td>0</td>
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<tr>
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<td>1</td>
<td>1</td>
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<tr>
<td>DIF</td>
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<td>3</td>
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<td>Cosmic rays</td>
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<tr>
<td>Total</td>
<td></td>
<td>3</td>
<td>5</td>
<td>6</td>
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### Electrons

<table>
<thead>
<tr>
<th>Background</th>
<th>% of $W \rightarrow e\nu$ data</th>
<th>$\delta m_W$ (MeV)</th>
<th>$m_T$ fit</th>
<th>$p_T^e$ fit</th>
<th>$p_T^\nu$ fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow ee$</td>
<td>$0.139 \pm 0.014$</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>$0.93 \pm 0.01$</td>
<td>1</td>
<td>1</td>
<td>1</td>
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</tr>
<tr>
<td>QCD</td>
<td>$0.39 \pm 0.14$</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Backgrounds are small (except $Z \rightarrow \mu\mu$ with a forward muon)
Z → ee Mass Cross-check using Electron Tracks

- Performed “blind” measurement of Z mass using electron tracks
  - Consistent with PDG value within 1.8σ (statistical)
- Checks tracking for electrons vs muons, and model of radiative energy loss

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

\[
M_Z = (91268 \pm 47_{\text{stat}}) \text{ MeV}
\]

\[
\chi^2/\text{dof} = 62/46
\]

Data
Simulation
$W$ Transverse Mass Fit

CDF II

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

Electrons

$M_W = (80408 \pm 19_{\text{stat}}) \text{ MeV}$

$\chi^2/\text{dof} = 52 / 48$

Data

Simulation
$W$ Lepton $p_T$ Fit

CDF II

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

**Muons**

\[ M_W = (80348 \pm 18_{\text{stat}}) \, \text{MeV} \]

\[ \chi^2/\text{dof} = 54 / 62 \]

- **Data**
- **Simulation**
$W$ Missing $E_T$ Fit

CDF II

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

$M_W = (80431 \pm 25_{\text{stat}}) \, \text{MeV}$

$\chi^2/\text{dof} = 71/62$

**Electrons**

- **Data**
- **Simulation**

(events / 0.25 GeV)

$p_T^e(v) \, (\text{GeV})$
$W$ Missing $E_T$ Fit

CDF II

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

Muons

$M_W = (80406 \pm 22_{\text{stat}}) \, \text{MeV}$

$\chi^2/\text{dof} = 79 / 62$

- **Data**
- **Simulation**

$\text{events / 0.25 GeV}$

$p_T^\mu(v) \, (\text{GeV})$
$W$ Mass Fit Residuals, Electron Channel
$W$ Mass Fit Residuals, Muon Channel
$W$ Mass Fit Window Variation, $m_T$ Fit
$W$ Mass Fit Window Variation, $p_T(l)$ Fit

![Graphs showing variation in $\Delta M_W$ with respect to $p_T(l)$ over different fit windows.](image-url)
$W$ Mass Fit Window Variation, $p_T(\nu)$ Fit
$W$ Mass Fit Results

- Electron and muon $m_T$ fits combined
  \[ m_W = 80390 \pm 20 \text{ MeV}, \frac{\chi^2}{\text{dof}} = 1.2/1 \ (28\%) \]

- Electron and muon $p_T$ fits combined
  \[ m_W = 80366 \pm 22 \text{ MeV}, \frac{\chi^2}{\text{dof}} = 2.3/1 \ (13\%) \]

- Electron and muon MET fits combined
  \[ m_W = 80416 \pm 25 \text{ MeV}, \frac{\chi^2}{\text{dof}} = 0.5/1 \ (49\%) \]

- All electron fits combined
  \[ m_W = 80406 \pm 25 \text{ MeV}, \frac{\chi^2}{\text{dof}} = 1.4/2 \ (49\%) \]

- All muon fits combined
  \[ m_W = 80374 \pm 22 \text{ MeV}, \frac{\chi^2}{\text{dof}} = 4/2 \ (12\%) \]

- All fits combined
  \[ m_W = 80387 \pm 19 \text{ MeV}, \frac{\chi^2}{\text{dof}} = 6.6/5 \ (25\%) \]
<table>
<thead>
<tr>
<th>Systematic (MeV/c²)</th>
<th>Electrons</th>
<th>Muons</th>
<th>Common</th>
</tr>
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<tr>
<td>Lepton Energy Scale</td>
<td>10</td>
<td>7</td>
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<tr>
<td>Lepton Energy Resolution</td>
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<td>Recoil Energy Scale</td>
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<tr>
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<td>Parton Distributions</td>
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<td>QED radiation</td>
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<td><strong>Total</strong></td>
<td><strong>19</strong></td>
<td><strong>18</strong></td>
<td><strong>16</strong></td>
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### $p_T(\nu)$ Fit Systematic Uncertainties

<table>
<thead>
<tr>
<th>Systematic (MeV/c²)</th>
<th>Electrons</th>
<th>Muons</th>
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</table>
## Combined Fit Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton Energy Scale</td>
<td>7</td>
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<tr>
<td>Lepton Energy Resolution</td>
<td>2</td>
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<tr>
<td>Recoil Energy Scale</td>
<td>4</td>
</tr>
<tr>
<td>Recoil Energy Resolution</td>
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<tr>
<td>$u_{</td>
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<tr>
<td>Lepton Removal</td>
<td>2</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>3</td>
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<tr>
<td>$p_T(W)$ model</td>
<td>5</td>
</tr>
<tr>
<td>Parton Distributions</td>
<td>10</td>
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<tr>
<td>QED radiation</td>
<td>4</td>
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<tr>
<td>$W$ boson statistics</td>
<td>12</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>19</strong></td>
</tr>
</tbody>
</table>
## Systematic Uncertainties in QED Radiative Corrections

<table>
<thead>
<tr>
<th>Effects:</th>
<th>CDF0</th>
<th>CDF1a</th>
<th>CDF1b</th>
<th>CDFII 200pb⁻¹</th>
<th>CDFII 2.3fb⁻¹</th>
<th>DØ 1fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single photon</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Exact $O(\alpha)$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Multi-photon</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ISR</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Uncertainties:</th>
<th>CDF0</th>
<th>CDF1a</th>
<th>CDF1b</th>
<th>CDFII 200pb⁻¹</th>
<th>CDFII 2.3fb⁻¹</th>
<th>DØ 1fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\gamma$ emission</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>ISR</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>$\alpha\alpha$s</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>✓</td>
<td>—</td>
</tr>
<tr>
<td>SV cut-off</td>
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<td>—</td>
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<td>✓</td>
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<tr>
<td>Z/W correl.</td>
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<td>—</td>
<td>—</td>
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<td>✓</td>
<td>✓</td>
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<tr>
<td>Beyond $2\gamma$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>H.O. SV corr.</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Pair creation</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Breit-Wigner</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>EWK scheme</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>✓</td>
<td>—</td>
</tr>
</tbody>
</table>
EM Calorimeter Uniformity

- Checking uniformity of energy scale in bins of electron pseudo-rapidity

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

$\gamma \rightarrow \mu\mu$ resonance provides

- Cross-check of non-beam-constrained (NBC) and beam-constrained (BC) fits
- Difference used to set additional systematic uncertainty

\[ \Delta p/p = (-1.185 \pm 0.02_{\text{stat}}) \times 10^{-3} \]

$\chi^2$/dof = 48 / 38

BC $\gamma \rightarrow \mu\mu$ mass fit

\[ \int L \, dt \approx 2.2 \text{ fb}^{-1} \]
Lepton Resolutions

• Tracking resolution parameterized in the custom simulation by
  
  - Radius-dependent drift chamber hit resolution $\sigma_h \sim (150 \pm 1_{\text{stat}}) \, \mu m$
  
  - Beamspot size $\sigma_b = (35 \pm 1_{\text{stat}}) \, \mu m$
  
  - Tuned on the widths of the $Z \rightarrow \mu\mu$ (beam-constrained) and $\Upsilon \rightarrow \mu\mu$ (both beam constrained and non-beam constrained) mass peaks

  $\Rightarrow \Delta M_W = 1 \, \text{MeV (muons)}$

• Electron cluster resolution parameterized in the custom simulation by
  
  - $12.6\% / \sqrt{E_T}$ (sampling term)
  
  - Primary constant term $\kappa = (0.68 \pm 0.05_{\text{stat}}) \%$
  
  - Secondary photon resolution $\kappa_{\gamma} = (7.4 \pm 1.8_{\text{stat}}) \%$
  
  - Tuned on the widths of the $E/p$ peak and the $Z \rightarrow ee$ peak (selecting radiative electrons)

  $\Rightarrow \Delta M_W = 4 \, \text{MeV (electrons)}$
Consistency of Radiative Material Model

- Excellent description of E/p spectrum tail
- Radiative material tune factor: $S_{X_0} = 1.026 \pm 0.003_{\text{stat}} \pm 0.002_{\text{background}}$
  achieves consistency with E/p spectrum tail

![Graph showing data and simulation comparison]

$$\chi^2/\text{dof} = 1.4 / 1$$

Default energy loss $\times 1.026$
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)
# Tracking Momentum Scale Systematics

Systematic uncertainties on momentum scale

<table>
<thead>
<tr>
<th>Source</th>
<th>$J/\psi \cdot 10^{-3}$</th>
<th>NBC-$\Upsilon \cdot 10^{-3}$</th>
<th>common $\cdot 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>QED</td>
<td>0.080</td>
<td>0.045</td>
<td>0.045</td>
</tr>
<tr>
<td>B field non-uniformity</td>
<td>0.032</td>
<td>0.034</td>
<td>0.032</td>
</tr>
<tr>
<td>Ionizing material</td>
<td>0.022</td>
<td>0.014</td>
<td>0.014</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.010</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.011</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Misalignment</td>
<td>0.009</td>
<td>0.018</td>
<td>0.009</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.004</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>Fitting window</td>
<td>0.004</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>$\Delta p/p$ step size</td>
<td>0.002</td>
<td>0.003</td>
<td>0</td>
</tr>
<tr>
<td>World-average</td>
<td>0.004</td>
<td>0.027</td>
<td>0</td>
</tr>
<tr>
<td>Total systematic</td>
<td>0.092</td>
<td>0.068</td>
<td>0.058</td>
</tr>
<tr>
<td>Statistical</td>
<td>0.004</td>
<td>0.025</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0.092</td>
<td>0.072</td>
<td>0.058</td>
</tr>
</tbody>
</table>

$\Delta M_{W,z} = 6 \text{ MeV}$

Uncertainty dominated by QED radiative corrections and magnetic field non-uniformity
Cross-check of COT alignment

- Cosmic ray alignment removes most deformation degrees of freedom, but “weakly constrained modes” remain
- Final cross-check and correction to beam-constrained track curvature based on difference of $<E/p>$ for positrons vs electrons
- Smooth ad-hoc curvature corrections as a function of polar and azimuthal angle: statistical errors $\Rightarrow \Delta M_W = 2$ MeV

CDFII preliminary $L = 2.2 \text{ fb}^{-1}$