$M_W, Z A_{fb},$ and $W/Z$ Production

Bodhitha Jayatilaka
Fermilab
on behalf of the ATLAS, CDF, CMS, and DØ collaborations

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W/Z physics at hadron colliders

- Long history dating back to the discovery of the W and Z (1983)
- From discovery to standard candle: Tevatron, LHC
  - Crucial for understanding detectors at each new energy
- Important for constraining PDFs
- Background to many new physics searches
- Essential quantities in the SM
  - Precision measurements
  - Can shed light on potential new physics

1. W/Z production measurements
2. W boson mass
3. Asymmetry measurements
W and Z production
Inclusive W and Z production at 8 TeV

- May 2012 run with greater bunch spacing
  - Average 4 interactions per crossing (vs. 21 for rest of 2012)
  - Int. luminosity of 18.2/pb
- First inclusive W and Z cross-section measurement at 8 TeV

\[
\begin{align*}
\text{CMS} & \quad L = 18.2 \text{ pb}^{-1}, \sqrt{s} = 8 \text{ TeV} \\
\nu^+ l \rightarrow +W & \quad 7.11 \pm 0.03_{\text{stat}} \pm 0.14_{\text{syst}} \pm 0.18_{\text{lum}} \text{ nb} \\
\nu^- l \rightarrow -W & \quad 7.12 \pm 0.20 \text{ nb} \\
\text{PRL 112, 191802 (2014)}
\end{align*}
\]
Hadron collider W and Z cross sections as $\sqrt{s}$

- Hadron collider W/Z cross-sections measured as predicted at 0.6, 1.8, 1.96, 7, and 8 TeV
  - Looking forward to 13-14 TeV!
\[ \frac{d^2 \sigma}{dP_T(Z) d|Y(Z)|} \]

- Explore \( \sigma(Z) \) in high granularity up to high \( p_T \)
  - Full 8 TeV dataset
  - 10 bins in \( p_T(Z) \)
  - 8 bins in \( Y(Z) \)
- Test of QCD dynamics
  - Sensitive to gluon PDF
- Compare to Madgraph + Pythia and RESBOS
  - Shape not well-predicted at high \( p_T(Z) \)
**Z/γ* p_T measurement**

- Essential for tuning model in W mass measurement
- \( p_{T,l} > 20 \text{ GeV}, 66 < m_{ll} < 116 \text{ GeV}, |\eta| < 2.4 \)
- \(~0.5\%\) precision up to \( p_T(Z) \sim 30 \text{ GeV} \)
Direct W Boson Mass Measurements
Measuring the W boson mass

- Electroweak sector of the standard model (SM) relates $m_W$ to well-measured constants
  \[ m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2}G_F \sin^2 \theta_W (1 - \Delta r)} \sin \theta_W^2 = 1 - \frac{m_W^2}{m_Z^2} \]
  - Radiative corrections $\Delta r$ dominated by top and Higgs loops

- Precision measurements in $m_W$ and $m_{top}$ tell us if the Higgs is SM or not
- Measuring requires precise measurement of Lepton $p_T$ and transverse hadronic recoil (infer neutrino energy)
- Develop parametrized detector simulation to model detector effects and underlying physics
  - Tune using data
W mass: track momentum scale

• Foundation of CDF analysis is track $p_T$ measurement with drift chamber (COT)
• Perform alignment using cosmic ray data: $\sim 50\mu m \rightarrow \sim 5\mu m$ residual
• Calibrate scale using large sample of dimuon resonances ($J/\psi$, $Y$, $Z$)
  • Span a large range of $p_T$
  • Flatness is a test of $dE/dx$ modeling
• Final scale error of $9 \times 10^{-5}$: $\Delta M_W = 7$ MeV
• Confirm by measuring $M_Z$. Add as further constraint.
**W mass: calorimeter energy scale**

**CDF**
- Apply calibrated p-scale and set EM scale using $E/p$ of $W$ and $Z$ events
  - Overall scale from peak
  - Radiative tail used to tune material model
- Confirm by measuring $M_Z$

**DØ**
- Use $Z\rightarrow ee$ events and LEP $M_Z$ to calibrate scale
- Use subsamples to calibrate material model and response to pileup

---

$E_{\text{meas}} = \alpha E_{\text{true}} + \beta$

Z subsamples of inst. L

[36e30]
W mass: recoil calibration

- Measured recoil: 1) hard recoil from hadronic activity in W/Z event, 2) underlying event/spectator interaction energy
- Tune using Z and minimum-bias data
- Validate using measured recoil in W events

Tuning with Z→ll

\[
\left( \vec{p}_T^Z + \vec{u}_T \right) \cdot \hat{\eta}
\]

Validating with W→lv

\[
\begin{align*}
\mu & \approx 0.321 \text{ GeV} \\
\sigma & \approx 4.665 \text{ GeV}
\end{align*}
\]

\[
\begin{align*}
\mu & = -0.313 \pm 0.006 \text{ GeV} \\
\sigma & = 4.664 \pm 0.004 \text{ GeV}
\end{align*}
\]
W mass: results

- Fits performed to $m_T$, $p_T$, $p_T^\nu$
- Combine all three in both $e$ and $\mu$ channels (CDF) and $p_T$, $m_T$ in $e$ channel (DØ), taking into account correlations

$M_W = 80387 \pm 19$ MeV (CDF, 2.2 fb$^{-1}$)

PRD 89, 072003 (2014)

$M_W = 80367 \pm 26$ MeV (DØ, 4.3 fb$^{-1}$)

PRD 89, 012005 (2014)
W mass: uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>CDF</th>
<th>CDF</th>
<th>DØ</th>
</tr>
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<tbody>
<tr>
<td>Lepton energy scale</td>
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<td>Lepton energy resolution</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>23</strong></td>
<td><strong>26</strong></td>
<td><strong>26</strong></td>
</tr>
</tbody>
</table>

Modeling uncertainties (PDFs) beginning to dominate c.f. Lepton scale uncertainty for CDF with 200 pb$^{-1}$ was 30 MeV
W mass: combination

Mass of the W Boson

<table>
<thead>
<tr>
<th>Measurement</th>
<th>( M_W ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF 1988-1995 (107 pb(^{-1}))</td>
<td>80432 ± 79</td>
</tr>
<tr>
<td>D0 1992-1995 (95 pb(^{-1}))</td>
<td>80478 ± 83</td>
</tr>
<tr>
<td>CDF 2002-2007 (2.2 fb(^{-1}))</td>
<td>80387 ± 19</td>
</tr>
<tr>
<td>D0 2002-2009 (5.3 fb(^{-1}))</td>
<td>80376 ± 23</td>
</tr>
<tr>
<td>Tevatron 2012</td>
<td>80387 ± 16</td>
</tr>
<tr>
<td>LEP</td>
<td>80376 ± 33</td>
</tr>
<tr>
<td>World average</td>
<td>80385 ± 15</td>
</tr>
</tbody>
</table>

\( M_W = 80385 \pm 15 \) MeV

- Analysis being performed with full Tevatron dataset
  - CDF ~ 10 MeV, DØ ~15 MeV total uncertainty projected
- LHC with further PDF constraints — < 10 MeV?

nb: 2009 world average
\( M_W = 80399\pm23 \) MeV

PRD 88, 052018 (2013)
Asymmetry measurements
W boson charge asymmetry

- $W^+(W^-)$ boosted in direction of (anti)proton
- Difference in $u$, $d$ PDFs results in $W$ charge asymmetry at Tevatron

$$A(y_W) = \frac{d\sigma_{W^+}/dy_W - d\sigma_{W^-}/dy_W}{d\sigma_{W^+}/dy_W + d\sigma_{W^-}/dy_W}.$$  

- No V-A dilution
- DØ measurement uses full dataset in electron channel
  - Use neutrino weighting method [PRD 77, 111301 (2008)]
  - Critical data for improving PDF precision

PRL 112, 151803 (2014)
Muon charge asymmetry

- Greater $W^+$ production rate than $W^-$ rate at pp colliders
  - Difference can help constrain PDFs
- Use 7 TeV dataset
  - Similar event selection as inclusive $W$ cross-section measurement
- Measure asymmetry in bins of $|\eta|$ 
- Measure with two different $p_T$ cuts: 25 and 35 GeV
- Compare with predictions using various PDFs

arXiv:1312.6283
Measuring $\sin^2 \theta_W$

- In the SM:
  \[
  \sin^2 \theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \text{from LEP}
  \]

- Measurement of $\sin^2 \theta_W$ indirectly measures $M_W$

- Obtain from angular distribution of leptons in Drell-Yan ($Z/\gamma^* \rightarrow l^+l^-$) events
  \[
  \frac{dN}{d\theta} \approx 1 + \cos^2 \theta + A_4 \cos \theta
  \]
  - Forward-backward asymmetry
    \[
    A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8} A_4
    \]
  - Measure $A_{FB} \rightarrow \sin^2 \theta_{\text{eff}}^{\text{lep}}$ (effective $Z/\text{lepton coupling}) \rightarrow \sin^2 \theta_W \rightarrow M_W$
Measuring $\sin^2 \theta_W$

- In the SM:
  \[ \sin \theta_W^2 = 1 - \frac{m_W^2}{m_Z^2} \]
  from LEP

- Measurement of $\sin^2 \theta_W$ indirectly measures $M_W$

- Obtain from angular distribution of leptons in Drell-Yan ($Z/\gamma^* \rightarrow l^+ l^-$) events
  \[ \frac{dN}{d\theta} \approx 1 + \cos^2 \theta + A_4 \cos \theta \]

- Forward-backward asymmetry
  \[ A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8} A_4 \]

- Measure $A_{FB} \rightarrow \sin^2 \theta_{eff}^{lep}$ (effective $Z$/lepton coupling) $\rightarrow \sin^2 \theta_W \rightarrow M_W$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$A_{FB}$</th>
<th>$\sin^2 \theta_{lep eff}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP1+SLD: Combination</td>
<td>$0.23153 \pm 0.00016$</td>
<td></td>
</tr>
<tr>
<td>LEP1+SLD: $A_{FB}^{0,l}$</td>
<td>$0.23099 \pm 0.00053$</td>
<td>$0.226$</td>
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<tr>
<td>LEP1+SLD: $A_{FB}^{0,b}$</td>
<td>$0.23159 \pm 0.00041$</td>
<td>$0.228$</td>
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<tr>
<td>LEP1+SLD: $A_{FB}^{0,s}$</td>
<td>$0.23098 \pm 0.00026$</td>
<td>$0.23$</td>
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<tr>
<td>LEP1+SLD: $A_{FB}^{0,b}$</td>
<td>$0.23221 \pm 0.00029$</td>
<td>$0.232$</td>
</tr>
<tr>
<td>CDF $ee$ 2 fb$^{-1}$</td>
<td>$0.2324 \pm 0.0012$</td>
<td>$0.234$</td>
</tr>
<tr>
<td>D0 $ee$ 5 fb$^{-1}$</td>
<td>$0.2315 \pm 0.0010$</td>
<td></td>
</tr>
</tbody>
</table>
ATLAS $A_{FB}$ measurement

- $ee$ and $\mu\mu$ measurement using $4.8/fb$ of 7 TeV data
  - Electron channel split into CC and CF
    - CF includes one electron $|\eta| < 4.9$
  - Unfold raw $A_{FB}$ to obtain $\sin^2\theta_{eff}$
  - Extract each channel (Muon, CC, CF) separately
    - Final result is combined across all three channels

$$\sin\theta_{eff} = 0.2297 \pm 0.0010$$

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>CC electrons ($10^{-4}$)</th>
<th>CF electrons ($10^{-4}$)</th>
<th>Muons ($10^{-4}$)</th>
<th>Combined ($10^{-4}$)</th>
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<tbody>
<tr>
<td>PDF</td>
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<td>Other sources</td>
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<td>2</td>
</tr>
</tbody>
</table>
CDF $A_{FB} (\mu\mu)$ measurement

- Measured using muon pairs (central)
  - 10 different topologies depending on muon subdetector
  - Use event-weighting method to contend with 10 different $\epsilon A$ [EPJ C 72, 2194 (2012)]
- Extract mixing angle from raw $A_{FB}$

$$\sin^2 \theta_W = 0.2233 \pm 0.0010$$
$$\sin^2 \theta_{eff} = 0.2315 \pm 0.0010$$

PRD 89, 072005 (2014)
DØ $A_{FB}$ (ee) measurement

- Extend $\eta$ coverage of selection, include EC-EC (endcap) events
  - $\sim$85% more statistics than scaling 5/fb to 9.7/fb
- Implement new energy scale calibration
  - Calibrate $E$ as a function of $L_{\text{inst}}$
  - Then calibrate as function of $\eta_{\text{det}}$
- Extract mixing angle from raw $A_{FB}$

\[
sin^2\theta_W = 0.23098 \pm 0.00044 \\
\sin^2\theta_{\text{eff}} = 0.23106 \pm 0.00053
\]

DØ note 6426-conf
\(\sin^2 \theta_W\) summary

**Direct**
- TeV and LEP-2: 80.385 ± 0.015
- LEP-1 and SLD: light quarks: 80.365 ± 0.020
- NuTeV: 80.135 ± 0.085

**Indirect**
- CDF ee 2 fb\(^{-1}\): 80.297 ± 0.048
- CDF \(\mu\mu\) 9 fb\(^{-1}\): 80.365 ± 0.047

Combined CDF+D0 indirect
\(M_W\) in both channels will have ~20 MeV precision

*preliminary*
Summary

• SM holds up well against precision tests
  • Tevatron measurements still yet to come
  • W mass measurements with full dataset to better than 10 MeV precision (theoretical prediction including $m_H$ to 11 MeV now)
  • Many precision measurements to come from LHC experiments
  • W/Z production physics will be verified again at Run 2 energy

• Many results which could not be shown
  • ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  • CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
  • CDF: http://www-cdf.fnal.gov/physics/ewk/
  • DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/ew.htm
  • Parallel talks by H. Yin (CDF+DØ), D. Tsionou (ATLAS), H. Yoo (CMS)
Backup
W Mass: future?

Future Tevatron $m_W$ and Tevatron+LHC $m_t$

or... back to $e^+e^-$?

From CMS Note 2012/003
P. Azzi et al.
“Prospective Studies for LEP3 with the CMS Detector”

Figure 3: The effect of improving the precision of the top mass measurement by a factor 10 (left), or the precision of the Z pole and the W mass measurements by factors of 25 and 10, respectively (right), in the $(m_W, m_{t_{\text{top}}})$ plane.
DØ muon charge asymmetry

- Data reweighted to remove discrepancy between solenoid polarities