Precision Electroweak Measurements at the Tevatron

- The W mass @ Tevatron
- Effective weak mixing angle
- The Top Mass @ Tevatron

Iain Bertram, Lancaster University
for the D0 Collaboration
DIS 2017 - 6 April 2017
Motivations

- Consistency tests of electroweak symmetry breaking mechanism

Over-constrained: 3 free parameters in the SM are constrained by 7 experimental measurements.

\[ \alpha_{em}, G_F, M_Z, M_W, \sin^2 \theta_W, m_{top}, M_H \]
Tevatron @ Fermilab

- Multi-purpose, high acceptance, well understood detectors.
  \[ \mathcal{L} \, dt \sim 10 \, \text{fb}^{-1} \]
The W mass @ Tevatron

**Strategy:**
- Analyse the $p_T^l$, $E_T^l$, $m_T^l$ distributions in $W \rightarrow l\nu$ ($l=e/\mu$) channels
- Likelihood fits of $M_W$-parameterized simulation templates
- Lepton E/p scale and recoil calibration with $Z \rightarrow ll$ data

**Results**
- Dominant systematic are the lepton E/p scale and PDFs.
- Tevatron results are combined using BLUE

\[ M_W = 80387 \pm 16 \text{ MeV}/c^2 \]

Consistent with the latest ATLAS result of 80370±19 MeV
arXiv:1701.07240

CDF and D0 are working on finalising measurements with the full data set.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$M_W$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF (2.2 fb$^{-1}$, $\mu$&amp;e)</td>
<td>80387 ± 12 ± 15</td>
</tr>
<tr>
<td>D0 (5.3 fb$^{-1}$, e)</td>
<td>80375 ± 11 ± 20</td>
</tr>
</tbody>
</table>


**Mass of the W Boson**

- CDF 1988-1995 (107 pb$^{-1}$) 80432 ± 79
- D0 1992-1995 (95 pb$^{-1}$) 80478 ± 83
- CDF 2002-2007 (2.2 fb$^{-1}$) 80387 ± 19
- D0 2002-2009 (5.3 fb$^{-1}$) 80376 ± 23
- Tevatron 2012 80387 ± 16
- LEP 80376 ± 33
- World average 80385 ± 15
Effective weak mixing angle

- The forward-backward asymmetry $A_{fb}$ arises from the interference of the vector and axial vector couplings.

$$
-i \frac{g}{2 \cos \theta_W} \bar{f} \gamma^\mu (g_V^f - g_A^f \gamma_5) f Z_\mu
$$

\[
\begin{align*}
  g_V^f &= I_3^f - 2Q_f \sin^2 \theta_W \\
  g_A^f &= I_3^f \\
  \sin^2 \theta_W &= 1 - \frac{M_W^2}{M_Z^2} \\
  &\quad \text{("on-shell")}
\end{align*}
\]

- Convert $\sin^2 \theta_{\text{eff}}^{ll}$ to $\sin^2 \theta_W$ using conversion factor calculated using ZFitter (depends on well known $M_Z$): $\text{Re}(\kappa) \sim 1.037$

$$
\sin^2 \theta_{\text{eff}}^{\text{Lept}} = \text{Re}[\kappa_l(M_Z)] \cdot \sin^2 \theta_W
$$

("effective", Zfitter)

Can be directly measured via Parity-violating observables at Z-pole

Can be directly measured via Parity-violating observables at Z-pole
The effective weak mixing angle

- The best current measurements differ by 3.2σ
  - LEP b-quark $A^{0,b}_{\text{fb}}$
  - SLD beam LR-polarization $A_{lr}$

The LEP/SLD Average $0.23153 \pm 0.00016$

$\sin^2 \theta_{\text{eff}}$
Weak mixing angle @ the Tevatron

- Measure background-subtracted $A_{fb}$ as function of invariant mass in Collins-Soper frame

$$A_{fb} = \frac{N(\cos \theta^* > 0) - N(\cos \theta^* < 0)}{N(\cos \theta^* > 0) + N(\cos \theta^* < 0)}$$

$$\cos \theta^* = \frac{2(p_l^+ p_{l^-} - p_{l^-} p_l^+)}{m(l\bar{l}) \sqrt{m^2(l\bar{l}) + p_T^2(l\bar{l})}}$$

$$p_{l^\pm} = p_0 \pm p_3$$
Previous Results

- $\chi^2$ fits between data $A_{FB}$ and MC templates for a series of different Pythia values of $\sin^2\theta_W$

<table>
<thead>
<tr>
<th>Data Source</th>
<th>$\sin^2\theta_W \pm $ stat. $\pm$ syst. $\pm$ PDF</th>
<th>Total uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF $Z\mu\mu$ 9fb$^{-1}$</td>
<td>$0.2315 \pm 0.0009 \pm 0.0002 \pm 0.0004$</td>
<td>$\pm 0.0010$</td>
</tr>
<tr>
<td>DØ Zee 9.7fb$^{-1}$</td>
<td>$0.23147 \pm 0.00043 \pm 0.00008 \pm 0.00017$</td>
<td>$\pm 0.00047$</td>
</tr>
<tr>
<td>CDF Zee 9fb$^{-1}$</td>
<td>$0.23248 \pm 0.00049 \pm 0.00004 \pm 0.00019$</td>
<td>$\pm 0.00053$</td>
</tr>
</tbody>
</table>
Previous Tevatron Combination

• Combination of CDF $Z\mu\mu+Z\text{ee}$ and D0 $Z\text{ee}$ results
• Using ZFITTER and NNPDF3.0

$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.23179 \pm 0.00030 \pm 0.00017$$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sin^2 \theta_{\text{eff}}^{\text{lept}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP-1 and SLD: Z-pole</td>
<td>0.23149 ± 0.00016</td>
</tr>
<tr>
<td>LEP-1 and SLD: $A_F^{0,b}$</td>
<td>0.23098 ± 0.00026</td>
</tr>
<tr>
<td>SLD: $A_f$</td>
<td>0.23098 ± 0.00026</td>
</tr>
<tr>
<td>CMS $\mu\mu$ 1 fb$^{-1}$</td>
<td>0.2287 ± 0.0032</td>
</tr>
<tr>
<td>ATLAS $ee+\mu\mu$ 5 fb$^{-1}$</td>
<td>0.2308 ± 0.0012</td>
</tr>
<tr>
<td>LHCb $\mu\mu$ 3 fb$^{-1}$</td>
<td>0.23142 ± 0.00107</td>
</tr>
<tr>
<td>CDF $\mu\mu$ 9 fb$^{-1}$</td>
<td>0.2315 ± 0.0010</td>
</tr>
<tr>
<td>CDF $ee$ 9 fb$^{-1}$</td>
<td>0.23248 ± 0.00053</td>
</tr>
<tr>
<td>CDF $ee+\mu\mu$ 9 fb$^{-1}$</td>
<td>0.23221 ± 0.00046</td>
</tr>
<tr>
<td>D0 $ee$ 10 fb$^{-1}$</td>
<td>0.23137 ± 0.00047</td>
</tr>
</tbody>
</table>

- Translate into $M_W$
  Tevatron from $\sin^2 \theta_W$
  $M_W = 80351 \pm 18 \text{ MeV}/c^2$

- Compare with Tevatron and LEP direct measurements
  $M_W = 80385 \pm 15 \text{ MeV}/c^2$

FERMILAB-CONF-16-295-E
New: D0 $Z\mu\mu$

- Last channel @ Tevatron:
  - 8.6 fb$^{-1}$ $Z\mu\mu$ events, $p_T$$>$$15$ GeV/c, $|\eta|$$<$$1.8$; opposite charge, $74 < M_{\mu\mu} < 110$ GeV/c$^2$
  - Modified Resbos + NNPDF3.0
  - The D0 $Z\mu\mu$ result is less precise than Zee due to the more central muon acceptance and the less precise muon momentum measurement.

- We reweight the MC to data separately as a function of eta for each muon charge and solenoid polarity so as to correct for residual mis-alignments.

$$P(\eta, q, S) = \alpha(\eta, q, S) \times P_{\text{obs}}(\eta, q, S)$$
MC—Data Comparison

- Check agreement in multiple kinematic distributions
  - Muon $p_T/\eta$, and di-muon $p_T/\eta/M/cos\theta^*$ distribution
  - Good agreement

\[ \chi^2/\text{dof} = 1.1 \]

$\sin^2 \theta_W^B$ in Pythia in a mass region of $74 < M_{\mu\mu} < 110$ GeV

\[ \sin^2 \theta_W^B = 0.22994 \pm 0.00059 \text{ (stat)} \pm 0.00011 \text{ (syst)} \pm 0.00027 \text{ (pdf)} \]

\[ = 0.22994 \pm 0.00066 \]
Systematics

- Dominated by uncertainty due to the PDF and modelling the background.

<table>
<thead>
<tr>
<th>sin$^2 \theta_W^B$</th>
<th>0.22994</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty</td>
<td>0.00059</td>
</tr>
<tr>
<td>Systematic uncertainties</td>
<td></td>
</tr>
<tr>
<td>Momentum calibration</td>
<td>0.00002</td>
</tr>
<tr>
<td>Momentum resolution</td>
<td>0.00004</td>
</tr>
<tr>
<td>Background</td>
<td>0.00010</td>
</tr>
<tr>
<td>Efficiencies</td>
<td>0.00001</td>
</tr>
<tr>
<td>Total systematic</td>
<td>0.00011</td>
</tr>
<tr>
<td>PDF</td>
<td>0.00027</td>
</tr>
<tr>
<td>Total</td>
<td>0.00066</td>
</tr>
</tbody>
</table>
Result

\[
\sin^2 \theta_W^B = 0.22994 \pm 0.00059 \text{ (stat)} \pm 0.00011 \text{ (syst)} \pm 0.00027 \text{ (pdf)} \\
= 0.22994 \pm 0.00066
\]

- Convert \(\sin^2 \theta_W^B\) to \(\sin^2 \theta_{\text{eff}}\) using comparison of LO Pythia and NLO Resbos:
  \(\sin^2 \theta_{\text{eff}} = \sin^2 \theta_W^B + 0.00008\)

\[
\sin^2 \theta_{\text{eff}} = 0.23002 \pm 0.00066
\]

- This is converted to the on-shell normalisation for \(\sin^2 \theta_W\) using ZFitter:
  \(\sin^2 \theta_W (\text{on-shell}) = 0.22181 \pm 0.0064\)

\[
M_W = 80441 \pm 33 \text{ MeV/c}^2
\]

- D0’s Zμμ and Zee results agree to 1.4\(\sigma\) (when referred to the same PDF set).
Direct Top Mass from D0

- Full D0 combination of Run1 0.1 fb\(^{-1}\) and Run2 9.7 fb\(^{-1}\) results
- Systematic uncertainties and correlations among channels have been taken into account

\[
m_t = 174.9 \pm 0.75 \text{ GeV}/c^2
\]

Top pole mass from differential cross sections

- Top quark momentum, $t\bar{t}$ invariant mass distributions, etc. are sensitive to the top quark mass
  - Expect improvement vs extraction from total cross-section
  - Use the D0 lepton+jets measurement: Phys. Rev. D 90, 092006 (2014)
  - Compare differential distributions to NNLO QCD calculation of TOP++ using the pole mass:
    Czakon, Fiedler, Heymes and Mitov, JHEP 1605, 034 (2016)

See D Heymes talk on Tuesday
Top pole mass from differential cross sections

NNLO QCD scale uncertainties < 5% for $p_T^{\text{top}}$
c.f. 10% maximum for $m(t\bar{t})$
Top pole mass from differential cross sections

- Use $\chi^2$ fit to measure the mass
- Include full 2-D correlation matrix in $m(t\bar{t})$, $p_T^{\text{top}}$

$m_t = 169.1 \pm 1.4 \text{ (theo)} \pm 2.2 \text{ (exp)} \text{ GeV}/c^2$

Precision: 1.5% ~ 25% improvement over using inclusive XS
Summary

• **W Mass**
  • Current Tevatron combination is $80387 \pm 16$ MeV
  • Analysis of full data sample is ongoing.

• **Weak Mixing Angle**
  • Preliminary Tevatron combination of $0.23179 \pm 0.00035$ using CDF $Z(ee/\mu\mu)$ and D0 $Z(ee)$
  • **NEW** preliminary result of $0.23002 \pm 0.00066$ with D0 $Z(\mu\mu)$ measurement
  • Once the D0 $Z(\mu\mu)$ result is finalised the full Tevatron combination will be completed.
  • Will make a significant contribution to improving the world average.

• **Top Mass**
  • New D0 combination of all direct measurements from Run I and Run II.
  • New D0 preliminary measurement of top quark pole mass using $d\sigma/dp_T$ and $d\sigma/M_{tt}$. 