Precision electroweak measurements with ATLAS

N. Andari (CEA Saclay)

On behalf of the ATLAS Collaboration
EW precision measurements

3 precision observables define the EW sector of the SM for example: $\alpha_{EM}, G_F, m_Z$

--> define the other EW observables at tree-level:

$$m_W^2 \left( 1 - \frac{m_W^2}{m_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_F}$$

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$$
EW precision measurements

3 precision observables define the EW sector of the SM for example: $\alpha_{EM}, G_F, m_Z$

$\Rightarrow$ define the other EW observables at tree-level $\Rightarrow$ loop-level:

$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi \alpha}{\sqrt{2}G_F} (1 + \Delta r)$$

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} \Rightarrow \sin^2 \theta_{\text{eff}} = \kappa^l \sin^2 \theta_W$$

EW precision measurements:

- Test the self consistency of the SM
- Complementary approach for New Physics discovery
- Probe very high energy scale via radiative corrections
3 precision observables define the EW sector of the SM for example: $\alpha_{EM}$, $G_F$, $m_Z$ --> define the other EW observables at tree-level loop-level:

$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F} (1 + \Delta r)$$

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

$$\sin^2 \theta_{\text{eff}}^l = \kappa^l \sin^2 \theta_W$$

$\kappa^l$ and $\Delta r$ reflects loop corrections and depends on $m_t^2$ and $\ln(m_H)$

**EW fit:**

$$\sin^2 \theta_{\text{eff}}^l = 0.23149 +/- 0.00007$$

$$m_W = 80358 +/- 8 \text{ MeV}$$

**Focus of this talk:**

- Weak mixing angle: $\sin^2 \theta_W$
- W-boson mass: $m_W$
Part I: Weak mixing angle

Data: 20.2 fb⁻¹ of 8TeV

Neutral current: \( q \bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+ \ell^- \)

\( Z \) couples differently with left and right handed fermions \( \rightarrow \) Forward-backward asymmetry

Drell-Yan cross-section factorisation in full lepton phase space:

\[
\frac{d\sigma}{dp_T^\ell d\phi_d \ell \ell \ell d \cos \theta d \phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^\ell d\phi_d \ell \ell \ell} \\
\left\{ (1 + \cos^2 \theta) + \frac{1}{2} A_0(1 - 3 \cos^2 \theta) + A_1 \sin 2\theta \cos \phi \right. \\
+ \frac{1}{2} A_2 \sin^2 \theta \cos 2\phi + A_3 \sin \theta \cos \phi + A_4 \cos \theta \\
+ A_5 \sin^2 \theta \sin 2\phi + A_6 \sin 2\theta \sin \phi + A_7 \sin \theta \sin \phi \right\}
\]

Fold angular polynomials and fit to reco angular distributions binned in \( m_Z \) and \( |y_Z| \)

- \( y_Z \rightarrow 0 \) \( u(x) \sim \bar{u}(x) \) \( \Rightarrow \) maximal dilution
- \( y_Z \gg 0 \) \( u(x) \gg \bar{u}(x) \) \( \Rightarrow \) unambiguous

3 decay channels: \( \mu\mu_{CC} \), \( ee_{CC} \), \( ee_{CF} \)
Uncertainties dominated by statistics (including MC stat) and PDFs

Most precise channel $ee_{\text{CF}}$ – less dilution for high dilepton rapidity

Spread between different recent PDFs~$6 \times 10^{-5}$ (only CT10: $22 \times 10^{-5}$ away from MMHT14)

Similar PDF uncertainties from eigenvectors / replicas

<table>
<thead>
<tr>
<th>Channel</th>
<th>$ee_{CC}$</th>
<th>$\mu\mu_{CC}$</th>
<th>$ee_{CF}$</th>
<th>$ee_{CC} + \mu\mu_{CC}$</th>
<th>$ee_{CC} + \mu\mu_{CC} + ee_{CF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central value</td>
<td>0.23148</td>
<td>0.23123</td>
<td>0.23166</td>
<td>0.23119</td>
<td>0.23140</td>
</tr>
<tr>
<td>Total</td>
<td>68</td>
<td>59</td>
<td>43</td>
<td>49</td>
<td>36</td>
</tr>
<tr>
<td>Stat.</td>
<td>48</td>
<td>40</td>
<td>29</td>
<td>31</td>
<td>21</td>
</tr>
<tr>
<td>Syst.</td>
<td>48</td>
<td>44</td>
<td>32</td>
<td>38</td>
<td>29</td>
</tr>
</tbody>
</table>
Part I: Weak mixing angle

Data: 20.2 fb$^{-1}$ of 8TeV

- ATLAS results consistent with the mean value of LEP and SLD (~3σ discrepancy) and other available measurements.

- $ee_{CF}$ is unique to ATLAS and is more sensitive than combined $ee_{CC} + \mu\mu_{CC}$ ($49 \times 10^{-5}$ ~ similar sensitivity to CMS measurement).
Prospects at HL-LHC:
- Reduction of statistical uncertainty (3000 fb⁻¹)
- Extended pseudo-rapidity coverage (|η|<4)
- Expected reduction of PDF uncertainties
  Including LHeC data: reduction of PDF (total) uncertainties by a factor of ~5
  wrt to HL-LHC PDFs.
Part II: W-boson mass

Very challenging: aim precision of 10 MeV using 40 GeV leptons —> knowledge of peak position $@ 2 \times 10^{-4}$

High experimental precision & accurate theory modelling

Not possible to fully reconstruct the invariant mass

Sensitive final state distributions: $p_T^\ell$, $m_T$, $p_T^{\text{miss}}$

\[
p_T^{\text{miss}} = - \left( \vec{p}_T^\ell + \vec{u}_T \right), \quad m_T = \sqrt{2p_T^\ell p_T^{\text{miss}} (1 - \cos \Delta \phi)}
\]

$u_T$ being the recoil

Sensitive to $p_T^W$ & PDFs

Sensitive to pile-up and UE

Data: 4.6 fb$^{-1}$ of 7 TeV


arXiv:0901.0512
Part II: W-boson mass

Data: 4.6 fb\(^{-1}\) of 7 TeV

Lepton and Recoil calibration

Use Z-boson sample for experimental and theoretical constraints $\rightarrow$ Address Z to W extrapolation
Part II: W-boson mass

Data: $4.6 \text{ fb}^{-1}$ of 7 TeV

Consistent with the SM expectation, compatible with the world average and comparable in precision to the currently leading measurements by CDF

Dominated by PDF and QCD model uncertainties (mainly $p_T^W$)
Part II: W-boson mass

Impact of W-boson transverse momentum modelling

**ATLAS Simulation**

<table>
<thead>
<tr>
<th>$\sqrt{s} = 7$ TeV, pp→$W^\pm + X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pythia 8 AZ</td>
</tr>
<tr>
<td>Powheg + Pythia 8 AZNLO</td>
</tr>
<tr>
<td>DYRes</td>
</tr>
<tr>
<td>Powheg MiNLO + Pythia 8</td>
</tr>
</tbody>
</table>

**Low pile-up data:** collected at $\sqrt{s} = 5$ TeV ($\sim 250$ pb$^{-1}$) and at 13 TeV ($\sim 340$ pb$^{-1}$)

Target 1% uncertainty in bins of 5 GeV for low $p_T^W$  

$\rightarrow$ decrease $p_T^W$ uncertainty in the W-boson mass measurement

**ATLAS Online, 13 TeV**

<table>
<thead>
<tr>
<th>$\int L dt = 136.4$ fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015: $\langle \mu \rangle = 13.4$</td>
</tr>
<tr>
<td>2016: $\langle \mu \rangle = 25.1$</td>
</tr>
<tr>
<td>2017: $\langle \mu \rangle = 37.8$</td>
</tr>
<tr>
<td>2018: $\langle \mu \rangle = 37.3$</td>
</tr>
<tr>
<td>Total: $\langle \mu \rangle = 34.0$</td>
</tr>
</tbody>
</table>

$m_W = 7$ TeV
Potential low pile-up runs at HL-LHC (14 TeV) and HE-LHC (27 TeV): 200 pb\(^{-1}\) per week

- Extended coverage with new tracking detector: |\(\eta\)| < 4 \(\rightarrow\) 30% reduction of PDF uncertainties

- The PDF uncertainties can be reduced to about 4 MeV using HL-LHC PDF sets and to 2 MeV using LHeC PDF sets.
Conclusions

- Precision measurement of the effective leptonic weak mixing angle:
  \[ \sin^2 \theta_W = 0.23140 \pm 0.00036 \]
dominated by PDF and statistical uncertainties.

- In preparation for full Run 2 measurements of \( \sin^2 \theta_W \): reduction of statistical uncertainty, higher level of dilution effects.

- Prospects of \( \sin^2 \theta_W \)@HL-LHC: \( 15 \times 10^{-5} \) uncertainty can be achieved (at each experiment ATLAS, CMS and LHCb). \( 8 \times 10^{-5} \) using LHeC.

- First LHC measurement of the W-boson mass: \( m_W = 80370 \pm 19 \) MeV comparable to precision at the Tevatron.

- **Low pile-up data**: improve precision and measure transverse momentum up to 1% level.

- Prospects of \( m_W \)@HL-LHC: 30% reduction of PDF uncertainty with extended tracker. \( 4 \) MeV with HL-LHC PDF sets. \( 2 \) MeV with LHeC.

More interesting results to come!