Precision Electroweak Measurements with the ATLAS Detector

Tony Kwan
on behalf of the ATLAS Collaboration

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The Weak Mixing Angle

- The electroweak sector of the Standard Model can be tested via precision measurements of fundamental observables such as the *weak mixing angle*, θ_W.

- By rotating electroweak boson fields W^3 and B by θ_W, the Z and photon (A) fields are obtained:

$$\begin{pmatrix} Z \\ A \end{pmatrix} = \begin{pmatrix} \cos\theta_\mathrm{W} & -\sin\theta_\mathrm{W} \\ \sin\theta_\mathrm{W} & \cos\theta_\mathrm{W} \end{pmatrix} \begin{pmatrix} W^3 \\ B \end{pmatrix}.$$

- At leading order (LO), the weak mixing angle also relates the masses of the Z and $W^\pm$: $\sin^2\theta_\mathrm{W} = 1 - m_W^2/m_Z^2$.

- The value of θ_W is not predicted by the Standard Model; hence, it must be experimentally determined.

- Higher-order electroweak radiative corrections affect such LO relations.

- In practice, these higher-order corrections are absorbed into an *effective* weak mixing angle:

$$\sin^2\theta_\mathrm{eff} = \kappa \sin^2\theta_\mathrm{W}.$$

- $\kappa = 1 + \delta\kappa$, and $\delta\kappa$ contains the higher-order corrections.

- $\delta\kappa$, therefore $\sin^2\theta_\mathrm{eff}$, is a function of invariant mass and $\cos\theta$ and also depends on fermion flavour.

- This analysis measures $\sin^2\theta_\mathrm{eff}^\ell$ for leptons at the Z-pole.

The Drell-Yan Cross Section

- Drell-Yan process **[1]**:
  $q(P_1) + \bar{q}(P_2) \to Z/\gamma^* \to \ell^+\ell^-$.

- A 5-dimensional differential cross section can describe the kinematics of the two leptons produced from the process:

$$\frac{d\sigma}{dp_{\mathrm{T}}^{\ell\ell}\,dy^{\ell\ell}\,dm^{\ell\ell}\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_{\mathrm{T}}^{\ell\ell}\,dy^{\ell\ell}\,dm^{\ell\ell}}$$

$$\left\{ (1 + \cos^2\theta) + \frac{1}{2}A_0(1 - 3\cos^2\theta) + A_1\,\sin 2\theta\,\cos\phi \right.$$

$$+ \frac{1}{2}A_2\,\sin^2\theta\,\cos 2\phi + A_3\,\sin\theta\,\cos\phi + A_4\,\cos\theta$$

$$\left. + A_5\,\sin^2\theta\,\sin 2\phi + A_6\,\sin 2\theta\,\sin\phi + A_7\,\sin\theta\,\sin\phi \right\}$$

- The cross section can be decomposed into $1 + 8$ harmonic polynomials, $P_i(\cos\theta, \phi)$, with coefficients $A_i(p_T^{\ell\ell}, y^{\ell\ell}, m^{\ell\ell})$.

- Angular coefficients A_i have been measured by ATLAS at $\sqrt{s}$ = 8 TeV **[2]**.

- Electroweak parameters can be extracted from measurements of A_i, one being the *effective leptonic weak mixing angle*.
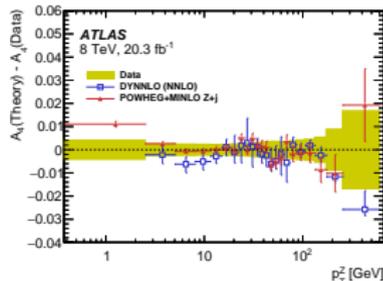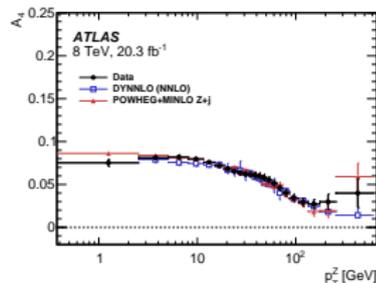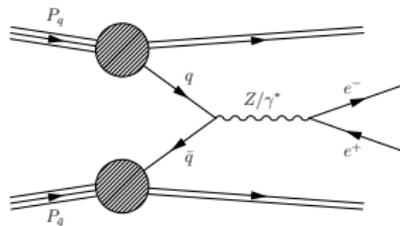
ATLAS Effective Weak Mixing Angle at 8 TeV

- As an extension to the A_i analysis, the leptonic weak mixing angle, $\sin^2 \theta_{\text{eff}}^{\ell}$, is extracted from the measurement of A_4 by comparing predicted angular ($\cos \theta$ and ϕ) distributions to measured ones **[3]**.

- $A_4 \propto$ product of vector and axial-vector couplings of the Z to the q and $\ell \propto \sin^2 \theta_{\text{eff}}^{\ell}$.

- LO in EW and NLO in QCD predictions of A_4 as a function of $\sin^2 \theta_{\text{eff}}^{\ell}$ are computed using DYTurbo, an optimized version of DYRES/DYNNLO.

- EW corrections are applied to the predictions enhancing their accuracy.

- To further improve the agreement with data, NNLO QCD corrections are also applied to the A_4 predictions.

- A_4 is then parametrized: $A_4 = a \sin^2 \theta_{\text{eff}}^{\ell} + b$.

- A likelihood function $\mathcal{L}(A_4, \sigma, \theta \mid \text{data}) = \mathcal{L}(\sin^2 \theta_{\text{eff}}^{\ell}, \sigma, \theta \mid \text{data})$ is constructed, where θ are nuisance parameters representing systematic uncertainties.

- The $\sin^2 \theta_{\text{eff}}^{\ell}$ that maximizes the likelihood function (or best describes the data) is taken as the measurement.
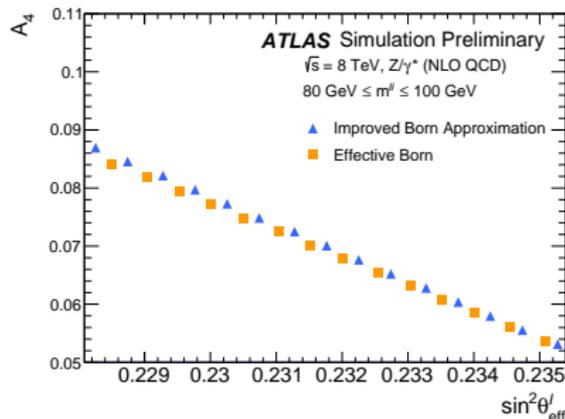
Analysis Channels

- The 2012 ATLAS dataset is used for this measurement which corresponds to $\sqrt{s}$ = 8 TeV and $\mathcal{L}$ = 20.2 fb^{-1}.
- Extraction of $\sin^2\theta_{\text{eff}}^{\ell}$ is made using measurements from 3 analysis channels.

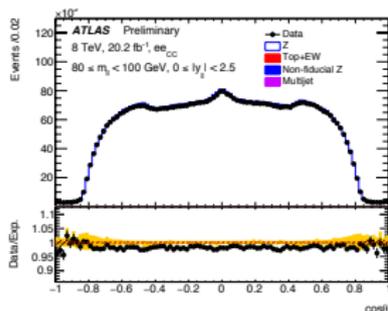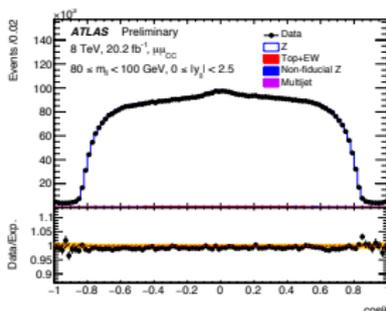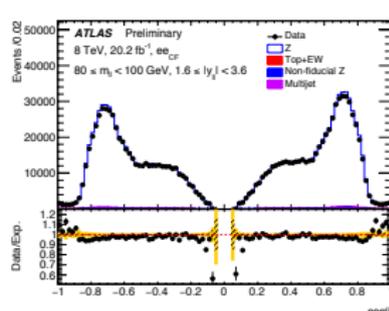"ee$_{\text{CC}}$": $q\bar{q} \rightarrow Z/\gamma^* \rightarrow e^+e^-$:   "$\mu\mu_{\text{CC}}$": $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-$:   "ee$_{\text{CF}}$": $q\bar{q} \rightarrow Z/\gamma^* \rightarrow e^+e^-$:

- $m_{\ell\ell} \in$ [70, 80, 100, 125] GeV;
- $|y_{\ell\ell}| \in$ [0, 0.8, 1.6, 2.5]

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- $m_{\ell\ell} \in$ [80, 100] GeV;
- $|y_{\ell\ell}| \in$ [1.6, 2.5, 3.6]

Table of Results

Results determined using predictions calculated with parton distribution function (PDF) set MMHT14:

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
			Uncertainties		
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
			Uncertainties in measurements		
PDF (meas.)	8	9	7	6	4
p_T^Z modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
			Uncertainties in predictions		
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

- Dominant uncertainties on the fully combined result include signal Monte Carlo statistics and the PDF uncertainty on the prediction.
- The ee_{CF} measurement yields the most precise measurement of $\sin^2 \theta_{\text{eff}}^\ell$.
  - Sensitivity to $\sin^2 \theta_{\text{eff}}^\ell$ is at its greatest for large values of $|y^{\ell\ell}|$, which the inclusion of a forward electron allows to be measured.

Comparing the Three Channels


ATLAS Preliminary
8 TeV, 20.2 fb⁻¹
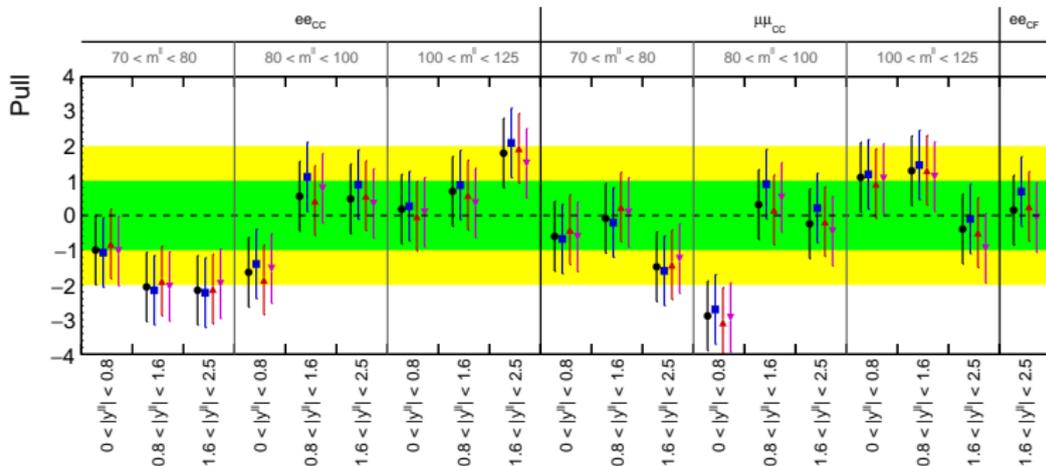
- The ee_{CC}, $\mu\mu_{CC}$, and ee_{CF} $\sin^2\theta^\ell_{eff}$ measurement results are compared to each other in every analysis bin.
- The pulls are plotted with respect to the bin with the greatest sensitivity, namely $2.5 < |y^{\ell\ell}| < 3.6$ of the ee_{CF} channel.
- Results are shown separately using 4 different PDF sets.
- A p-value of 3.4% is obtained, due primarily to a 3.0 standard deviation pull from the $\mu\mu_{CC}$ measurement in $80 < m^{\ell\ell} < 100$ GeV, $0 < |y^{\ell\ell}| < 0.8$.

Cross-Check using Forward-Backward Asymmetry

- With the 2012 dataset, a triple-differential Drell-Yan cross section, $d\sigma/dm^{\ell\ell}d|y^{\ell\ell}|d\cos\theta$, has been published by ATLAS **[4]**.

- Derived from the cross section are measurements of forward-backward asymmetry (A_{FB}) which is sensitive to $\sin^2\theta_{eff}^\ell$.

- As a check of the tools and corrections used in the A_4 analysis, measured and predicted values (calculated using $\sin^2\theta_W = 0.23148$) of A_{FB} are compared.

- Additionally, $\sin^2\theta_{eff}^\ell$ obtained from A_{FB} is comparable to the result obtained with A_4.

- A formal extraction of the effective leptonic weak mixing angle using A_{FB} is ongoing.
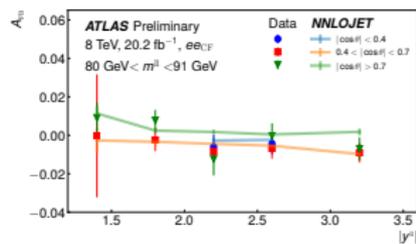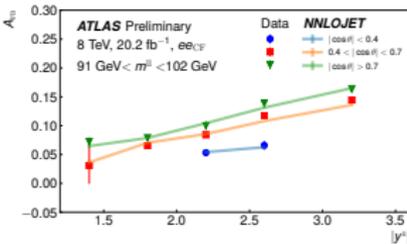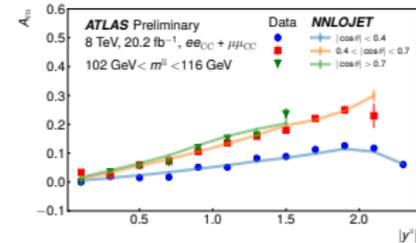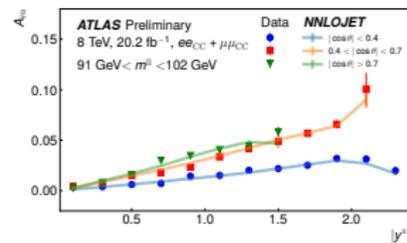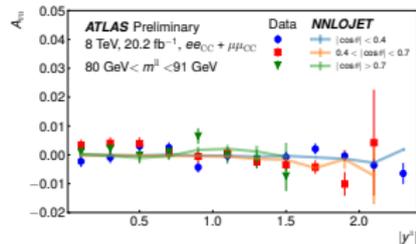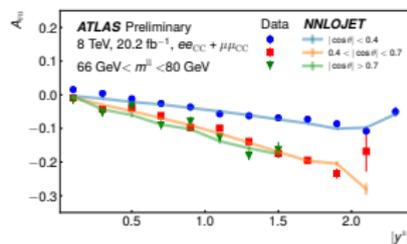
Comparison of $\sin^2\theta^{\ell}_{\text{eff}}$ with Past Measurements

$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23140 \pm 0.0021\,(\text{stat.}) \pm 0.00024\,(\text{PDF}) \pm 0.00016\,(\text{syst.})$$

ATLAS Preliminary

LEP-1 and SLD: Z-pole	0.23152 ± 0.00016
LEP-1 and SLD: $A^{0,b}_{FB}$	0.23221 ± 0.00029
SLD: A_l	0.23098 ± 0.00026
Tevatron	0.23148 ± 0.00033
LHCb: 7+8 TeV	0.23142 ± 0.00106
CMS: 8 TeV	0.23101 ± 0.00053
ATLAS: 7 TeV	0.23080 ± 0.00120
ATLAS: $ee_{CC}+\mu\mu_{CC}$	0.23119 ± 0.00049
ATLAS: ee_{CF}	0.23166 ± 0.00043
ATLAS: 8 TeV	0.23140 ± 0.00036

$\sin^2\theta^l_{eff}$
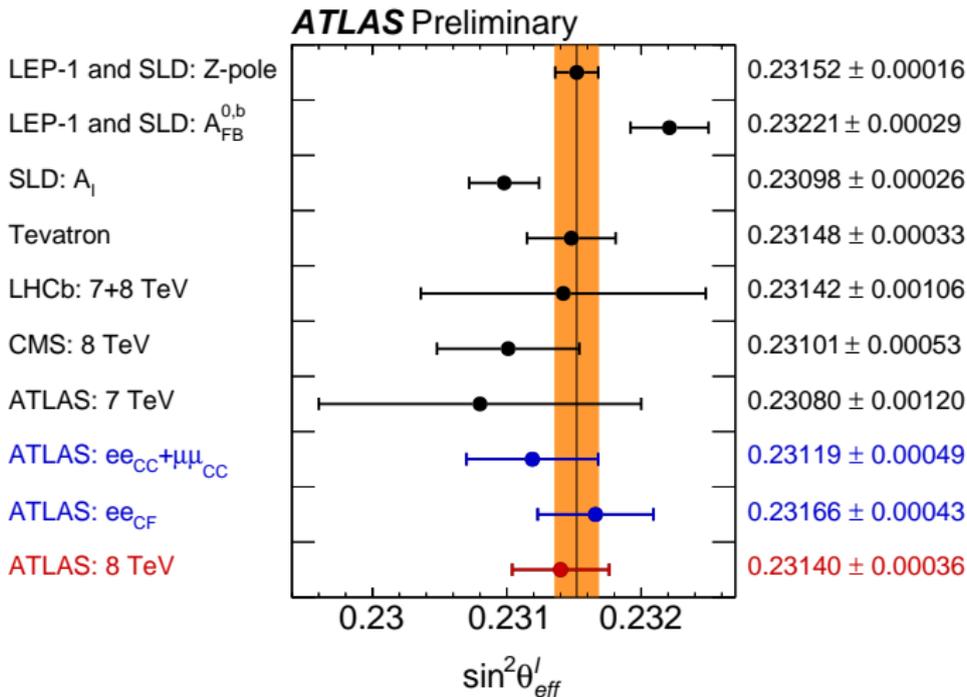
Conclusions

- Using the well-understood ATLAS 2012 dataset, a measurement of the effective leptonic weak mixing angle, $\sin^2 \theta_{\text{eff}}^\ell$, was extracted from the angular coefficient A_4 of the Drell-Yan cross section.

- The analysis consists of three measurement channels: a di-electron and a di-muon channel where both leptons are reconstructed in the central region of the ATLAS detector and a di-electron channel where one of the electrons is reconstructed in the forward region.

- The measured value of $\sin^2 \theta_{\text{eff}}^\ell$ has been cross-checked with the forward-backward asymmetry measurement made by ATLAS using the triple-differential Drell-Yan cross section.

- The following result is achieved:

$$\boxed{\sin^2 \theta_{\text{eff}}^\ell = 0.23140 \pm 0.00036}.$$

- This measurement is consistent with current value of 0.23150 ± 0.00006 from global electroweak fits, and previous measurements such as those from CMS [5] and Tevatron [6].

References

1. S. D. Drell and T. M. Yan, Phys. Rev. Lett. 25 (1970) 316.

2. ATLAS Collaboration, "*Measurement of the angular coefficients in Z-boson events using electron and muon pairs from data taken at $\sqrt{s}$ = 8 TeV with the ATLAS detector*", JHEP 08 (2016) 159, arXiv: 1606.00689 [hep-ex].

3. ATLAS Collaboration, "*Measurement of the effective leptonic weak mixing angle using electron and muon pairs from Z-boson decay in the ATLAS experiment at $\sqrt{s}$ = 8 TeV*", 2018, ATLAS-CONF-2018-037.

4. ATLAS Collaboration, "*Measurement of the Drell-Yan triple-differential cross section in pp collisions at $\sqrt{s}$ = 8 TeV*", JHEP 12 (2017) 059, arXiv: 1710.05167 [hep-ex].

5. CMS Collaboration, "*Measurement of the weak mixing angle using the forward-backward asymmetry of Drell-Yan events in pp collisions at 8 TeV*", submitted to Eur. Phys. J. C. (2018), arXiv: 1806.00863 [hep-ex].

6. CDF Collaboration, "*Measurement of $\sin^2 \theta_{\mathrm{eff}}^{\mathrm{lept}}$ using $e^+ e^-$ pairs from γ^*/Z bosons produced in $p\bar{p}$ collisions at a center-of-momentum energy of 1.96 TeV*", Phys. Rev. D93 (2016) 112016, arXiv: 1605.02719 [hep-ex].