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Measurement of the forward-backward asymmetry of electron and muon pair-production in *pp* collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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This talk presents measurements from the ATLAS experiment of the forward-backward asymmetry in the reaction $pp \rightarrow Z/\gamma^* \rightarrow l^+l^-$ (with l being electrons or muons) and the extraction of the effective weak mixing angle. The results are based on the full set of data collected in 2011 in pp collisions at the LHC at $\sqrt{s}$ = 7 TeV, corresponding to an integrated luminosity of 4.8 fb^{-1}. The measured asymmetry values are found to be in agreement with the corresponding Standard Model predictions. The combination of the muon and electron channels yields a value of the effective weak mixing angle of $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF})$. This result agrees with the current world average from the Particle Data Group fit. An estimate for the asymmetry parameter A_μ is also presented.

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1. Introduction

The vector and axial-vector couplings in the neutral current annihilation process $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$ lead to a forward-backward asymmetry A_{FB} in the polar angle distribution of the final state lepton ℓ^- with respect to the quark direction in the rest frame of the dilepton system. This talk presents measurements of A_{FB} in electron and muon pairs from Z/γ^* boson decays and the extraction of the weak mixing angle by the ATLAS experiment [1, 2]. The results are based on the full set of pp collision data collected in 2011 at the LHC at a centre-of-mass energy of $\sqrt{s}$ = 7 TeV, corresponding to an integrated luminosity of 4.8 fb^{-1}.

The differential cross section for the annihilation process can be written at leading order as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}(\cos\theta)} = \frac{4\pi\alpha^2}{3\hat{s}}\left[\frac{3}{8}A(1+\cos^2\theta)+B\cos\theta\right], \tag{1.1}$$

where $\sqrt{\hat{s}}$ is the centre-of-mass energy of the quark and anti-quark, and θ is the angle between the lepton and the quark in the rest frame of the dilepton system. The coefficients A and B are functions of $\sqrt{\hat{s}}$ and of the electroweak vector and axial-vector couplings. In the case that the dilepton system has non-vanishing transverse momentum, p_{T}, the four-momentum of the incoming (anti-)quark is not known, as it is no longer collinear with the incoming beams. The impact of this effect on the asymmetry measurement is minimized by choosing a particular rest frame of the dilepton system, the Collins–Soper (CS) frame [3], in which the angle between the lepton and the quark, θ^*_{CS}, is calculated. The sign of $\cos\theta^*_{\mathrm{CS}}$ is defined with respect to the direction of the quark, which is, however, ambiguous in pp collisions. It is therefore chosen by measuring the longitudinal boost of the final-state dilepton system in the laboratory frame, and assuming that this is in the same direction as that of the quark in the initial state. This assumption leads to a fraction of events with wrongly assigned quark direction, which causes a dilution of the observed asymmetry. The probability of correct quark direction assignment increases with the boost of the dilepton system, thus reducing the dilution for dileptons produced at large rapidities. With this assumption, $\cos\theta^*_{\mathrm{CS}}$ can be written as a function of the lepton momenta in the laboratory frame,

$$\cos\theta^*_{\mathrm{CS}} = \frac{p_{\mathrm{Z},\ell\ell}}{|p_{\mathrm{Z},\ell\ell}|}\frac{2(p_1^+p_2^- - p_1^-p_2^+)}{m_{\ell\ell}\sqrt{m_{\ell\ell}^2+p_{\mathrm{T},\ell\ell}^2}} \tag{1.2}$$

with

$$p_i^{\pm} = \frac{1}{\sqrt{2}}(E_i \pm p_{\mathrm{Z},i}),$$

where E is the energy and p_{Z} the longitudinal momentum of the lepton ($i=1$) and anti-lepton ($i=2$). The variables $p_{\mathrm{Z},\ell\ell}$, $m_{\ell\ell}$, and $p_{\mathrm{T},\ell\ell}$ denote the longitudinal momentum, invariant mass and transverse momentum of the dilepton system, respectively. The first factor in eq. 1.2 defines the sign of $\cos\theta^*_{\mathrm{CS}}$ according to the longitudinal direction of flight of the dilepton system, as discussed above. The events with $\cos\theta^*_{\mathrm{CS}} \geq 0$ are classified as forward (F), while those having $\cos\theta^*_{\mathrm{CS}} < 0$ are classified as backward (B). The asymmetry A_{FB} is then defined as

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}}-\sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}}+\sigma_{\mathrm{B}}}, \tag{1.3}$$

where σ_F and σ_B are the cross sections for the respective forward and backward configurations. At leading order, the second term in eq. 1.1, $B\cos\theta$, describes the asymmetry A_{FB}.

Several Standard Model parameters can be extracted from the dependence of the A_{FB} values on the invariant dilepton mass. One of these is the electroweak mixing angle $\sin^2\theta_{\mathrm{W}}$, which is defined at tree level as $1-m_W^2/m_Z^2$. Depending on the renormalisation scheme, higher-order loop corrections may modify this relation. The effective weak mixing angle $\sin^2\theta_{\mathrm{W}}$ is related to the electroweak vector coupling $\bar{g}_V^f$. The relationship between the leptonic and quark $\sin^2\theta_{\mathrm{eff}}$ can be approximated as a flavour-dependent shift in the leptonic $\sin^2\theta_{\mathrm{eff}}$. The effect of the quark $\sin^2\theta_{\mathrm{eff}}$ on the measured A_{FB} is an order of magnitude smaller than the effect of the leptonic $\sin^2\theta_{\mathrm{eff}}$. The analysis therefore measures the leptonic $\sin^2\theta_{\mathrm{eff}}$, denoted by $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ in the following.

2. Analysis

The value of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ is extracted from measured A_{FB} distributions at detector level as a function of the invariant mass of the dilepton system by comparing it to MC predictions produced with varying values of the weak mixing angle. Corrections to take into account detector effects and dilution are applied.

The analysis uses several selections to optimise use of the ATLAS sub-detectors and maximise the sensitivity. Muons are measured in the muon spectrometer. Electrons are measured in two topologies, central-central (CC) and central-forward (CF). Central electrons are identified with tracking information from the ATLAS Inner Detector and the ATLAS electromagnetic LAr calorimeter and hadronic tile calorimeter. Signal and some background estimates ($Z\to\tau\tau$, diboson and top-quark pair-production) are taken from MC simulations. Multijet and W+jets backgrounds are estimated from data driven methods with various methods in various regions of the invariant dilepton mass $m_{\ell\ell}$. Figure 1 shows the observed cosine of the polar angle in the Collins–Soper frame ($\cos\theta_{\mathrm{CS}}^*$) at detector level for the CF electron channel. In this distribution the A_{FB} asymmetry is visible by eye.

Further unfolding to particle level and comparisons with MC signal simulations confirm the good description of the $\cos\theta_{\mathrm{CS}}^*$distribution. The unfolding is done in two steps, first detector effects are unfolded, and in a second step corrections for dilution and acceptance are applied using the same unfolding procedure.

For the extraction of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ the measured asymmetry $A_{\mathrm{FB}}^{\mathrm{means}}$ is obtained from the detector-level distribution after background subtraction. Several templates from a PYTHIA signal MC with varying $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ values are generated and fitted to the data in the mass range 70 to 250 GeV using a χ^2 fit. The results in the various lepton topologies are shown in Table 1. The most precise result is obtained in the CF electron channel where the direction of the incoming quark is constrained best, leading to the least amount of dilution. For the combined $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ the topologies are combined using quadratic error weighting. The final uncertainty is dominated by the PDF uncertainty, which was evaluated from the ATLAS-epWZ12 LO PDF which is a special variation of the ATLAS-epWZ PDF prepared for this analysis. The impact of the choice of PDF on the final result is very important, as demonstrated in Fig. 2. where $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ is estimated using various PDFs. The difference between $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ results due to choice of PDF is comparable to the size of the

	$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
CC electron	$0.2302 \pm 0.0009(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm 0.0010(\mathrm{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm 0.0010(\mathrm{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\mathrm{stat.}) \pm 0.0008(\mathrm{syst.}) \pm 0.0009(\mathrm{PDF}) = 0.2307 \pm 0.0015$
El. combined	$0.2308 \pm 0.0006(\mathrm{stat.}) \pm 0.0007(\mathrm{syst.}) \pm 0.0010(\mathrm{PDF}) = 0.2308 \pm 0.0013$
Combined	$0.2308 \pm 0.0005(\mathrm{stat.}) \pm 0.0006(\mathrm{syst.}) \pm 0.0009(\mathrm{PDF}) = 0.2308 \pm 0.0012$

Table 1: The $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ measurement results in each of the three studied channels: electron central-central, electron central-forward and muon. Results of the statistical combination of both electron channels and all three channels are shown as well.

total uncertainty on the measurement. For future precision extractions of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ progress in determination of PDFs is therefore crucial.

3. Results

Using the procedure described above ALTAS measures an effective weak mixing angle of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.2308 \pm 0.0005(\mathrm{stat.}) \pm 0.0006(\mathrm{syst.}) \pm 0.0009(\mathrm{PDF})$.

This value is compared to results from other experiments in Fig. 3. The most precise measurement of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ comes from the combination of results from the LEP and SLD experiments [6]. Those studies yield an average leptonic $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23153 \pm 0.00016$. The two most precise single measurements are extracted from the forward-backward asymmetry in b-quark final states, $A_{\mathrm{FB}}^{0,b}$, at LEP ($\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23221 \pm 0.00029$) and from the leptonic left-right polarization asymmetry, A_{LR}, at SLD ($\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23098 \pm 0.00026$).

An estimate for the asymmetry parameter A_μ is also obtained. The value of A_{FB} at the peak of the Z/γ^* resonance ($m_{\ell\ell} = m_Z$), $A_{\mathrm{FB}}^{0,\ell}$, can be written as a function of the asymmetry parameters A_ℓ and A_q, $A_{\mathrm{FB}}^{0,\ell} = \frac{3}{4}A_q A_\ell$, with ℓ (q) denoting the leptons (quarks) in the final (initial) state. The parameters A_ℓ and A_q are directly related to the electroweak vector and axial-vector couplings. The most precise measurements of the electron and muon asymmetry parameters were performed by SLD [6], yielding $A_e = 0.15138 \pm 0.00216$ and $A_\mu = 0.142 \pm 0.015$. The precision of the A_μ measurement is dominated by the statistical uncertainty, thus making it an interesting parameter to measure with the large number of $Z \to \mu\mu$ events produced at the LHC. The determination of A_μ in the LEP/SLD results is entirely based on asymmetry measurements in electron and muon final states without any assumptions on the involved A_f. In contrast, the determination of A_μ presented here uses the Standard Model prediction of A_q.

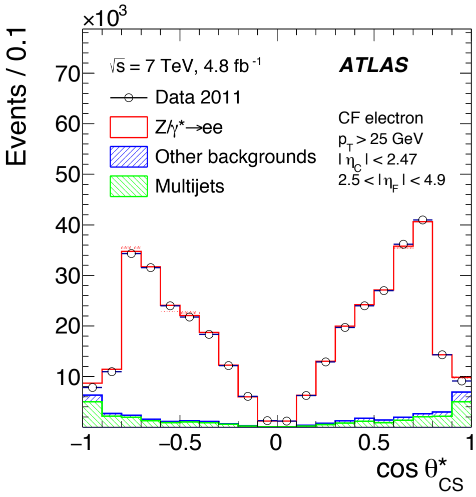

Figure 1: Distributions of the cosine of the polar angle in the Collins–Soper frame ($\cos\theta^{*}_{\mathrm{CS}}$) at detector level for the CF electron channel. Data are shown by open circles and the total expectation is shown as a line with a band representing the total uncertainty (statistical and systematic added in quadrature). The data-driven estimate for the multi-jet background and the simulation-based estimates for all other backgrounds are shown by the shaded areas.

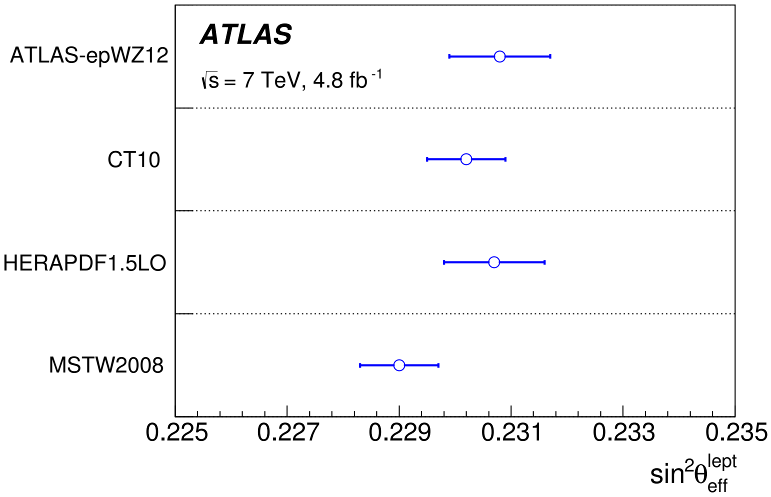

Figure 2: Comparison of the extracted $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ values when using different PDFs in the templates. Only PDF systematic errors are shown. Errors on *MSTW* and *CT10* are calculated using the *CT10* error set, while those on *ATLAS-epWZ12* and *HERA1.5LO* are calculated using the *ATLAS-epWZ12* error set.

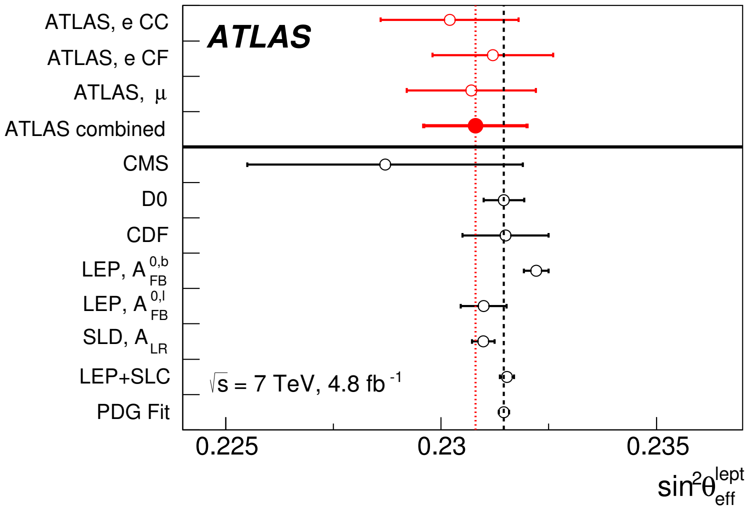

Figure 3: Comparison of the results of this analysis with other published results for $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$. This includes the most precise measurements from LEP and SLC, and the leptonic $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ measurements from the hadron collider experiments CMS [9], D0 [8], and CDF [7]. Also shown are the values of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ from the LEP+SLC global combination [6] (which includes all $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ measurements performed at the two colliders) and from the PDG global fit [10]. The vertical dotted line shows the central value of the ATLAS combined measurement reported here, while the vertical dashed line represents that of the current PDG global fit [10].

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