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Precision electroweak measurements with ATLAS

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The electroweak sector of the Standard Model can be tested via precision measurements of fundamental observables. The ATLAS Collaboration has recently measured the effective leptonic weak mixing angle using data collected during Run 1 of the LHC at a centre-of-mass energy of 8 TeV. The result is $\sin^2\theta^l_{\mathrm{eff}} = 0.23140 \pm 0.00036$, yielding a precision similar to that of the recently published Tevatron legacy result and to the most precise individual observable measurements from lepton colliders. The W-boson mass was first measured at the LHC in the ATLAS Collaboration using LHC Run 1 data at a centre-of-mass energy of 7 TeV. The obtained result is the most precise individual measurement of the W-boson mass $m_W = 80370 \pm 19$ MeV. Prospects for these electroweak measurements at the HL-LHC are also discussed.

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1. Weak mixing angle measurement

In the Standard Model (SM), the Z-boson couplings differ for left- and right-handed fermions, leading to an asymmetry in the angular distributions of positively and negatively charged leptons produced in Z boson decays. This asymmetry depends on the weak mixing angle, i.e the relative coupling strengths between the photon and the Z boson. The effective leptonic weak mixing angle has been measured precisely at the LEP and SLC electron-positron colliders, and more recently at the Tevatron and LHC hadron colliders. There is an observed 3.2 standard-deviation difference between the two most precise individual measurements, namely the combined LEP/SLD measurement of the b-quark forward-backward asymmetry, and the SLD left-right polarisation asymmetry measurement. This provides a further motivation to perform competitive measurements at the LHC. Recently, the ATLAS Collaboration made public a measurement of the effective leptonic weak mixing angle using $\sqrt{s} = 8$ TeV data collected in 2012 with the ATLAS detector [1], corresponding to an integrated luminosity of 20.2 fb^{-1} [2].

The measurement of $\sin^2\theta^l_{\text{eff}}$ in ATLAS is inferred from the A_4 angular coefficient, one of the eight coefficients, which together with the unpolarised cross section, describe entirely the production dynamics of the Z boson in perturbative quantum chromodynamics (QCD). The measurement of the angular coefficients relies on the reconstruction of the angular distributions of the leptons in the rest frame of the Z boson. A fit to reference angular distributions is then performed and angular coefficients are extracted in the full phase space. The measurement is performed in three orthogonal channels that are analysed independently, and then combined, after verifying their compatibility: two central electrons (eeCC), two central muons ($\mu\mu$CC), one central and one forward electron (eeCF). The data are binned in invariant mass m_{ll} and rapidity $|y_{ll}|$, and the angular coefficients are extracted taking into account the correlations and migrations between the measurement bins. Figure 1 (left) shows the acceptance multiplied by the selection efficiency for each of the analysis channels. The sensitivity of the eeCF channel is expected to be the highest since there is less dilution due to the ambiguity in the knowledge of the incoming valence quark direction derived from the longitudinal boost of the Z boson. The agreement between data and Monte Carlo (MC) for the angular distribution, $\cos\theta$, is shown for the eeCF category in the mass bin $80 < m_{ll} < 100$ GeV in Figure 1 (right).

The combined result is found to be: $\sin^2\theta^l_W = 0.23140 \pm 0.00021$ (stat.) ± 0.00024 (PDF) ± 0.00016 (syst.) where the first uncertainty corresponds to the data statistical uncertainty, the second to the PDF uncertainties in the MMHT14 PDF set [3], and the third to all other systematic uncertainties. To assess the impact of the choice of the PDF set on the final result of the measurement, several PDF sets were compared: CT10 [4], CT14 [5] and NNPDF31 [6]. The largest deviation was found to be due to CT10 and is equal to 28×10^{-5} and was not taken as an additional uncertainty. Figure 2 compares the ATLAS result to previous measurements and shows that it has a precision similar to that of the most precise LEP/SLC measurements and to that of the combined result from Tevatron. The result from using only the central channels shows a similar precision to the CMS 8 TeV result (which didn't include forward electrons). The ATLAS result agrees with the expectation from global electroweak (EW) fits $\sin^2\theta_W = 0.23150 \pm 0.00006$ [7].

The projected sensitivity for the measurement of the weak mixing angle was also studied [8], assuming 3000 fb^{-1} of data at $\sqrt{s} = 14$ TeV to be collected with an upgraded ATLAS detector

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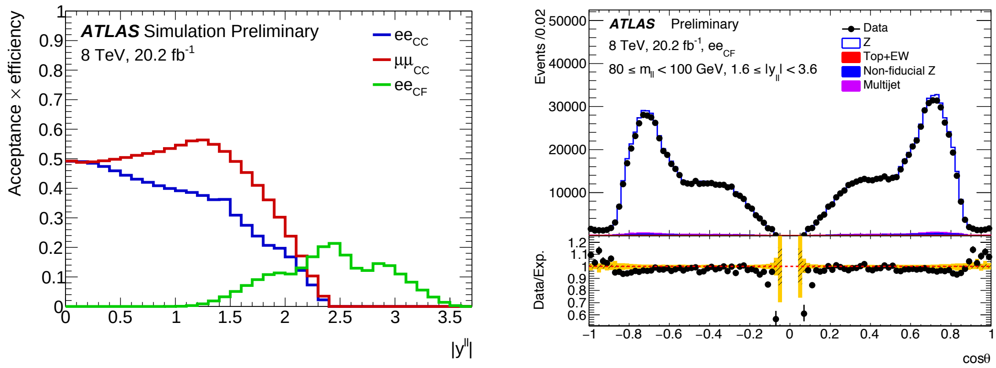

Figure 1: (a) Z-boson acceptance times selection efficiency as a function $|y_{ll}|$ for the eeCC, $\mu\mu$CC and eeCF analysis channels, and (b) distribution of $\cos\theta$ for the eeCF channel in the $80-100$ GeV mass bin, with the yellow band representing the statistical and experimental systematic uncertainties on the predictions [2].

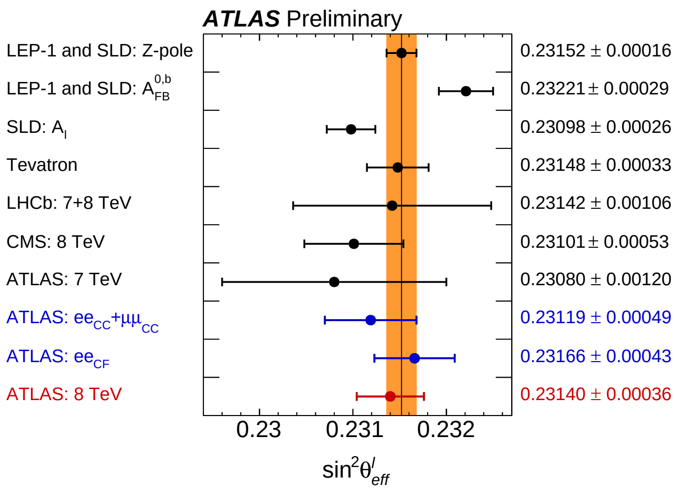

Figure 2: Comparison of the effective leptonic weak mixing angle measurement by ATLAS to the previous measurements at LEP/SLD, at the Tevatron, and at the LHC [2].

during the High Luminosity LHC (HL-LHC) phase. Z bosons decaying to electrons pairs are considered to study the forward-backward asymmetry as a function of the dilepton invariant mass and rapidity in three channels eeCC, eeCF and eeFF. A global fit is performed to extract $\sin^2\theta_W^l$ while constraining at the same time the PDF uncertainties (profiling procedure). The expected precision was found to be 18×10^{-5} with a dominant uncertainty due to PDFs ($\pm16\times10^{-5}$). An improvement is expected when using prospective PDFs. In particular, when using PDFs from a HL-LHC scenario the total precision reaches 15×10^{-5}. Furthermore with projected PDFs from a potential future high energy electron-proton collider (LHeC) the precision on the weak mixing angle reaches 8×10^{-5}.

2. W-boson mass measurement

The loop-induced radiative corrections to the W-boson mass in the EW sector of the SM are dominated by the running of the electromagnetic coupling due to light-quark loops, and the contribution from top (and bottom) quarks and Higgs-boson loops in the W-boson propagator. Therefore, probing the relation between the W boson, top and Higgs boson masses provides a stringent test of the consistency of the SM. The global EW fit predicts m_W= 80358 $\pm$ 8 MeV [7] setting a natural goal of 8 MeV for the precision of the W-boson mass measurement. The W-boson mass was measured with highest precision in LEP and Tevatron experiments leading to a combined value of m_W= 80385 $\pm$ 15 MeV (dominated by the precision of CDF experiment of 19 MeV). The measurement of the W-boson mass is particularly challenging at the LHC as compared to the LEP and Tevatron experiments, due to the large number of interactions per bunch crossing (pileup) and to the significant contributions of second-generation quarks to W-boson production, where 25% of the inclusive W-boson production rate is induced by at least one s or c quark. Recently, the first measurement of m_W at the LHC collider was performed by the ATLAS Collaboration [9], using data recorded in 2011 at a centre-of-mass energy of 7 TeV corresponding to 4.6 fb^{-1} of integrated luminosity. The W-boson decays into an electron or muon and a neutrino are considered. A total of 5.89$\times$10^6 of W boson candidates are selected in the electron decay channel and 7.84$\times$10^6 in the muon decay channel. Since it is not possible to directly reconstruct the W-boson mass from its decay products, the measurement relies on mass-sensitive final state variables, the transverse momentum of the charged lepton p_{T}^{ℓ} and the W-boson transverse mass m_{T}. The variable m_{T} is defined as $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}p_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\phi)}$ where $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is the neutrino missing transverse momentum and ϕ is the opening azimuthal angle between the charged lepton and missing transverse momenta. The neutrino missing transverse momentum is defined as $\vec{p}_{\mathrm{T}}^{\mathrm{miss}} = -(\vec{u}_{\mathrm{T}} + \vec{p}_{\mathrm{T}}^{\ell})$, the hadronic recoil, $\vec{u}_{\mathrm{T}}$, being the vector sum of the transverse energy of all clusters reconstructed in the calorimeters excluding the lepton deposits. Predictions of these final-state distributions for different values of m_W are obtained by reweighting the W-boson invariant mass distribution in the simulated reference sample according to a Breit-Wigner distribution. These distributions, referred to as templates, are compared to the observed distributions and a χ^2 minimisation is performed to extract the best fit template and the corresponding measured W boson mass. The final W boson mass is obtained from the combination of the electron and muon decay channels and of the charges and lepton pseudorapidity categories. Fitting ranges of 32$< p_{\mathrm{T}}^{\ell} <$45 GeV and 66$< m_{\mathrm{T}} <$ 99 GeV, optimised to minimise the total expected measurement uncertainty, are used to derive the W boson mass.

2.1 Experimental precision

The measurement requires an accurate calibration of the detector response and a well defined physics modelling. The Z boson sample is used to validate the analysis and to provide significant experimental (lepton and recoil calibration) and theoretical constraints (using ancillary measurements). The procedures used in the W-boson mass analysis for lepton calibration rely mainly on the published results by ATLAS [10, 11], based on W and Z samples at centre-of-mass energies of 7 and 8 TeV. Lepton momentum and energy corrections are derived exploiting the precisely measured value of the Z-boson mass at LEP [12]. The lepton identification and reconstruction efficiency corrections are derived from W and Z boson events using the tag-and-probe method. The hadronic recoil has to be precisely calibrated, as it affects mostly the determination of the W-boson mass through its impact on the m_{T} distribution where it enters directly in the definition of m_{T}, and only slightly for p_{T}^{ℓ} through the selection cuts. The hadronic recoil is highly sensitive to the pileup as well as to the underlying event activity. The calibration of the recoil corrects first for the modelling of the overall event activity in simulation, separately in the W and Z boson samples, which causes a recoil resolution mismodelling. As a second step, it corrects for residual discrepancies in the recoil response and resolution derived using Z boson events in data, and transferred to the W boson sample. The uncertainties from the hadronic recoil calibration affect the W-boson mass by 2.6 MeV when fitting the p_{T}^{ℓ} distribution and by 13 MeV for m_{T}. Background contributions to the W boson event sample from Z boson, boson pair, $W \to \tau\nu$ and top-quark production are estimated using simulation. Contributions from multijet production are estimated with data-driven techniques. The estimation of the multijet background contribution follows similar procedures in the electron and muon decay channels, and relies on template fits to kinematic distributions in background-dominated regions.

2.2 Physics modelling

There is no single generator able to describe the various observed distributions. The simulated samples of inclusive vector-boson production are based on the Powheg MC generator [13, 14, 15] interfaced to Pythia 8 [16, 17], henceforth referred to as Powheg+Pythia 8. Ancillary measurements of Drell–Yan processes are used to validate (and tune) the model and to assess systematic uncertainties. The W and Z boson samples are reweighted to include the effects of higher-order QCD and EW corrections, as well as the results of fits to measured distributions which improve the agreement of the simulated lepton kinematic distributions with the data. The dominant source of EW corrections originates from QED final-state radiation (FSR) and is included in the simulated samples with PHOTOS [18]. The associated systematic uncertainties are negligible. The QED initial-state radiation (ISR) is included using the Pythia 8 parton shower (PS). Pure weak corrections due to virtual-loop and box diagrams, interferences between QED FSR and ISR and final-state emissions of lepton pairs are not included in the simulation and are considered as systematic uncertainties. The total EW uncertainties are similar in the electron and muon channels and amount to about 5 MeV for p_{T}^{ℓ} and 3 MeV for m_{T}. Fixed-order predictions at NNLO are used to model the differential cross section as a function of boson rapidity and the angular coefficients as a function of the transverse momentum and rapidity of the boson. For the rapidity, the model is validated by checking its agreement with the 7 TeV ATLAS W and Z differential cross section measurements [19]. These data show a weaker suppression of strangeness compared to the u-, d-quark sea densities in the PDF, which motivates the choice of the CT10nnlo PDF set for the baseline model. The other PDF sets which show a reasonable agreement with the data, MMHT14nnlo and CT14nnlo, are used to assess the uncertainties. The modelling of the A_i coefficients is validated by comparing with the 8 TeV measurement of the angular coefficients in Z-boson decays [20]. The accuracy of the Z data is propagated as an uncertainty in the W-boson mass. Good agreement between the measurements and the NNLO predictions is observed for the relevant angular coefficients, except for A_2, for which the full discrepancy is taken as an uncertainty. The W-boson transverse momentum at a given rapidity is modelled with the Pythia 8 PS generator. The QCD parameters of the PS model were determined by fits to the transverse momentum distribution of the Z boson measured at 7 TeV [21]. Alternative calculations, such as resummed predictions (DYRES [22], Resbos [23, 24]) and Powheg MiNLO+Pythia 8 [25, 26], were tried but found to predict a much harder

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W-boson transverse momentum for a given Z-boson transverse momentum. To validate the choice of Pythia 8 as a reference model for the W-boson mass measurement, the distribution of the parallel projection of the recoil along the lepton direction, a variable sensitive to p_{T}, is compared between data and the different predictions. These alternative calculations were strongly disfavoured by the data while PS predictions like Pythia 8, Herwig 7 and also Powheg+Pythia 8 show a good agreement. The uncertainty from the PDFs on the fixed-order predictions dominate the total uncertainty on the measurement and amounts to 8.0 MeV in the p_{T}^{ℓ} fit, and to 8.7 MeV in the m_{T} fit. These PDF variations are applied simultaneously to the boson rapidity, polarisation and transverse momentum. The PDF uncertainties are strongly anti-correlated between W^+ and W^- due to the fact that the total light-quark sea PDF is well constrained by deep inelastic scattering data [27], whereas the u-, d-, and s-quark decomposition of the sea is less precisely known.

2.3 Results

The final combination of all categories gives consistent result with a χ^2/dof of 29/27, which indicates the accuracy of the experimental and theoretical modelling. The obtained result is: $m_W = 80370 \pm 7$ (stat.) ± 11 (exp. syst.) ± 14 (mod. syst.) MeV, where the first uncertainty is statistical, the second corresponds to the experimental systematic uncertainty, and the third to the physics modelling systematic uncertainty. The final measurement uncertainty is dominated by modelling uncertainties, mainly the strong interaction uncertainties. Lepton calibration uncertainties are the dominant sources of experimental systematic uncertainty for the extraction of m_W from the p_{T}^{ℓ} distribution. The uncertainty in the recoil calibration dominates the experimental systematic uncertainty for the m_{T} distribution. In the final result, the muon decay channel has a weight of 57% and the p_{T}^{ℓ} dominates the measurement with a weight of 86%. Finally the charges contribute similarly with a weight of 52% for W^+ and of 48% for W^-. The result is compatible with the current world average and provides a world leading precision measurement together with the CDF Collaboration. The different m_W results are compared in Figure 3, together with the SM prediction.

2.4 Prospects for the W-boson mass measurement

In order to improve the precision of the W-boson mass measurement at the LHC, special low pileup data were collected by ATLAS in 2017 and 2018 at centre-of-mass energies of 5 and 13 TeV with an integrated luminosity of respectively $\sim$ 250 and 340 pb^{-1}. This data set provides a clean environment with an improved resolution of the recoil leading to a better resolution in the W-boson transverse mass distribution and to a possible measurement of the W-boson transverse momentum. Since the imperfect knowledge of the W-boson transverse momentum contributes highly to the W-boson mass uncertainty, it is important to reach a percent level precision in 5 GeV bins. The prospects for this measurement have been studied [28]. The prospects for the W-boson mass measurement for low pileup data at the HL-LHC and HE-LHC have also been studied [29]. In one week of running to collect 200 pb^{-1}, i.e about 2×10^6 W-boson candidates at $\sqrt{s} = 14$ TeV and about 3×10^6 at $\sqrt{s} = 27$ TeV, a statistical sensitivity on the W-boson mass of less than 10 MeV can be reached. If five to ten weeks of data are collected, a statistical uncertainty of 3 MeV can be reached. A reduction of the order of 30% in the PDF uncertainties can be reached with the extended tracker in the upgraded ATLAS detector. A reduction in PDF uncertainty of about a

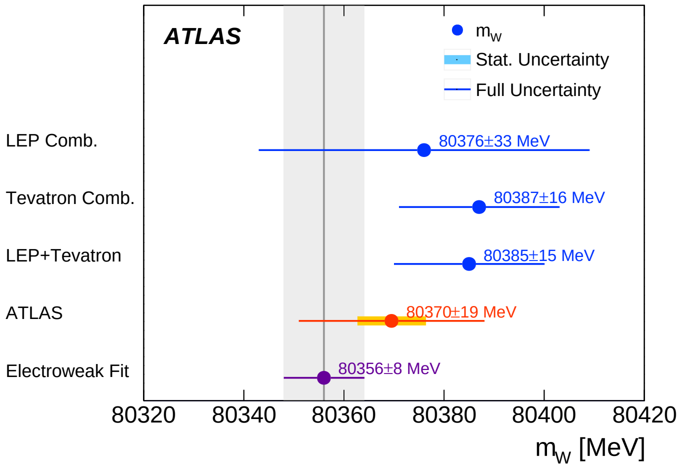

Figure 3: The W-boson mass measured in ATLAS is compared to the combined measurements in LEP and Tevatron experiments, and to the SM prediction from an EW fit [9].

factor of two is obtained with the HL-LHC PDF sets. A 2 MeV PDF uncertainty is reached with LHeC PDF sets, a further factor of ~ 4 improvement. A total (stat+PDF) uncertainty of about 11 MeV is obtained with 200 pb^{-1} of data with the current PDF sets.

3. Conclusions

The ATLAS Collaboration has performed very precise measurements of the effective leptonic weak mixing angle and of the W-boson mass using data collected during Run 1 of the LHC. Prospects of these electroweak measurements at the HL-LHC have been also studied. It is expected to reach a higher level of precision on these fundamental observables in the coming years at the LHC.

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