Overview of precision measurements (angular coefficients, charge asymmetry, $\sin^2\theta^l_{\text{eff}}$, $m_W$, etc) at the LHC

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The review summarizes the selected results of electroweak precision measurements from the CMS and ATLAS experiments at the LHC
Precision electroweak (EWK) measurements are an important part of the CERN research program. These are one of the most stringent test of self-consistency of the Standard Model (SM), probing the electroweak symmetry breaking (EWSB) mechanism, and tuning the Monte Carlo generators. Also, precision measurements give constraints on New Physics and allow to keep under control background processes that mimic potential new phenomena.

The Large Hadron Collider (LHC) provides the highest particle interaction energy ever achieved before and produces unprecedented volumes of data during its two multi-year runs. In 2009–2012 the LHC was running with proton beams colliding at \(\sqrt{s} = 7\) and 8 TeV (RUN1). During Run 2 (RUN2), the LHC has operated from 2015 until the end of 2018 with \(\sqrt{s} = 13\) TeV and its peak instantaneous luminosity at \(2.1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}\). For this time the integrated luminosity recorded by the CMS experiment \(L_{\text{int}}\) has reached approximately 30 \(fb^{-1}\) for RUN1 and 160 \(fb^{-1}\) for RUN2. In this paper we present a review of the selected electroweak physics results from the Compact Muon Solenoid (CMS) and A Toroidal LHC ApparatuS (ATLAS) experiments at the LHC \([1, 2]\).

One of the most important direction in electroweak physics is the study of the mediators of weak interactions. The measurements of electroweak vector–boson production an the branching ratios of Z/W-bosons decays at hadron colliders provide a benchmark for the understanding of quantum chromodynamic (QCD) and electroweak (EW) processes. They also could indicate a new physics effects. The ATLAS and CMS experiments carried out the wide range of measurements of full cross sections of the gauge bosons Z and W, their masses and decay channels probabilities. Results of these measurements are fully compatible between each other and agree with SM predictions (Fig. 1).

One of the rules of the standard model is that bosons such as the Z and W bosons will decay equally into muons and electrons. But if the standard model is incomplete, the data could show a preference for one type of lepton over the other. The lepton universality has been confirmed by CMS in \(Z(W) \mu^+ \mu^- (\mu \nu)\) and \(e^+ e^- (e \nu)\) decays at 13 TeV (Fig. 2(a)) and by both the ATLAS and CMS experiments in \(W \rightarrow \tau \nu / W \rightarrow \mu \nu / W \rightarrow e \nu\) decays (Fig. 2(b)). The good agreement between experiments and with SM predictions are also observed.

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**Figure 1:** (a) – \(\sqrt{s}\) dependence of full production cross sections for \(W^+, W^-, W\) and \(Z\); (b) – values of gauge bosons cross sections measured in different decay channels with ratio to theoretical predictions \([3]\).

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**Figure 2:** (a) – Comparison of observed cross sections for \(W^+, W^-, W\) and \(Z\) decays at 13 TeV. (b) – Values of gauge bosons cross sections measured in different decay channels with ratio to theoretical predictions.
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The Standard Model has parameters that are not predicted by the theory. The high-precision measurements of these parameters is therefore of great importance for testing the overall consistency of the SM as well as allow to apply new constrains on physics beyond the SM. The mass of W-boson \(m_W\) is one of the free parameters of the Standard model. The \(m_W\) was measured in SPS, Tevatron and LEP experiments at different energies [7–15]. At the LHC such of measurements were done by ATLAS collaboration at \(\sqrt{s} = 7\) TeV [16]. The W-boson mass value obtained in the experiment is \(m_W = 80370 \pm 19\) MeV which is in good agreement with global electroweak fit value \(m_W = 80356 \pm 8\) MeV.

The measurements of the effective weak angle \(\theta_{eff}^l\) were also performed at \(\sqrt{s} = 7\) and 8 TeV by the CMS [17], ATLAS [18, 19], and LHCb [20] experiments. The follows values are provided: \(\sin^2\theta_{eff}^l = 0.23140 \pm 0.00021\) (stat) \(\pm 0.00016\) (syst) \(\pm 0.00024\) (PDF) by ATLAS and \(\sin^2\theta_{eff}^l = 0.23101 \pm 0.00036\) (stat) \(\pm 0.00018\) (syst) \(\pm 0.00031\) (PDF) by CMS. Both results are consist with global electroweak fit value \(\sin^2\theta_{eff}^l = 0.23150 \pm 0.00006\) within uncertainties.

Figures 3(a) and 3(b) summarize the ATLAS and CMS measurements of \(m_W\) and \(\sin^2\theta_{eff}^l\) to previous measurements from different accelerators experiments. The results obtained in the LHC experiments are compatible to each other as well as to results from another experiments. CMS and ATLAS have significantly improved the measurement accuracy of these important parameters.

Due to quark composition of proton (two positive-charged u-quarks and one negative-charged d-quark) difference in cross section of \(W^+\) and \(W^-\) production appears that can be seen at figure 1(b).
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Figure 3: Comparison of the LHC measurements of: (a) W-boson mass $m_W$, (b) sine of Weinberg effective weak mixing angle $\sin^2 \theta_{eff}$ with previous measurements and global electroweak fit values [19].

This phenomena is called W-boson charge asymmetry and could be defined as $A = \sigma_{+\eta} - \sigma_{-\eta}/\sigma_{+\eta} + \sigma_{-\eta}$, where $\sigma_{\pm\eta} = d\sigma_{\pm\eta}/d\eta$ — pseudorapidity differential cross section of $W^{\pm\eta}$-boson production. This variable provide an important constraints on the ratio of u- and d-quark distributions in the extended region of the Bjorken $x$ scaling variable and could be used for extraction of $\sin^2 \theta_{eff}$ value. The W boson charge asymmetry was measured as a function of the lepton pseudorapidity by ATLAS at $\sqrt{s} = 8$ TeV [21] and by CMS at $\sqrt{s} = 13$ TeV [22] (Fig. 4. The measured asymmetry is in a good agreement with calculations at NLO and NNLO.

The spatial characteristics of Z-boson decay ($q\bar{q} \rightarrow \gamma^*/Z^0 \rightarrow l^+l^-$) [23] products also can be used for studying the parton distribution functions. The double differential cross section of this

Figure 4: Absolute differential W-boson charge asymmetry as a function of $|\eta|$ measured by ATLAS (a) [21] and CMS (b) [22]. The lower panel in each plot shows the ratio (difference for (b)) of observation and expectation for the asymmetry and the relative uncertainty.
process could be written as follows for all orders of the perturbative QCD theory:

\[
\frac{d^2\sigma}{d\theta^* d\phi^*} = (1 + \cos^2\theta^*) + A_0 \frac{1}{2} (1 - 3 \cos^2\theta^*) + A_1 \sin(2\theta^*) \cos\phi^* + A_2 \frac{1}{2} \sin^2\theta^* \cos(2\phi^*) + A_3 \sin\theta^* \cos\phi^* + A_4 \cos\theta^* + A_5 \sin^2\theta^* \sin(2\phi^*) + A_6 \sin(2\theta^*) \sin\phi^* + A_7 \sin\phi^* \sin\theta^*
\]

where \(\theta^*\) and \(\phi^*\) are polar and azimuth angles in Collins–Soper frame [24]. \(A_i\) – angular polarisation coefficients which are functions of Z-bozon kinematic variables and provide information about Z-boson polarization properties. Full set of the coefficients \(A_0 - A_7\) as well as the difference \(A_0 - A_2\) meaningful the magnitude of rotation invariance violation (Lam–Tung relation) [25] was measured at the LHC at \(\sqrt{s} = 8\) TeV.

![Figure 5: Distributions of the angular coefficients](image)

**Figure 5:** Distributions of the angular coefficients \(A_0\) (a), \(A_2\) (b) and \(A_0 - A_2\) (c) as a function of \(p_T^Z\). The results from the rapidity-integrated measurements are compared to the NLO and NNLO calculations [26].

Coefficients \(A_0\), \(A_2\), and their difference \(A_0 - A_2\) in dependence on Z-bozon transverse momentum \(p_T^Z\) measured by ATLAS in combined \(Z \rightarrow ee + Z \rightarrow \mu\mu\) channel are demonstrated at figures 5. The distributions for full set of coefficients could be found in paper [26]. \(A_0\) and \(A_2\) grow up with \(p_T^Z\) increasing as it is expected and are well described by Monte Carlo simulations. However, the magnitude of Lam–Tung violation appears a twice more then it is predicted and indicates an incorrect description of the higher orders effects at high \(p_T^Z\). The first five coefficients \(A_0 - A_5\) were also measured by CMS in \(Z \rightarrow \mu\mu\) channel [27]. The results are fully compatible with ATLAS ones.

In conclusion, it can be noted that at present all the results of EW measurements in experiments at the LHC are in line with the predictions of the Standard Model. A further increase in the statistics of experimental data will improve the measurement accuracy and provide the observation of rare processes expected within the framework of the SM.

This work was supported by the Russian Foundation for Basic Research, project no. 20-32-90212.

**References**


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[5] ATLAS collaboration, Test of the universality of $\tau$ and $\mu$ lepton couplings in $W$-boson decays with the ATLAS detector. Test of the universality of $\tau$ and $\mu$ lepton couplings in $W$-boson decays from $t\bar{t}$ events with the ATLAS detector, Nature Phys. 17 (2020) 813 [2007.14040].


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