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Overview of precision measurements (angular coefficients, charge asymmetry, $sin^2\theta^l_{eff}$, 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

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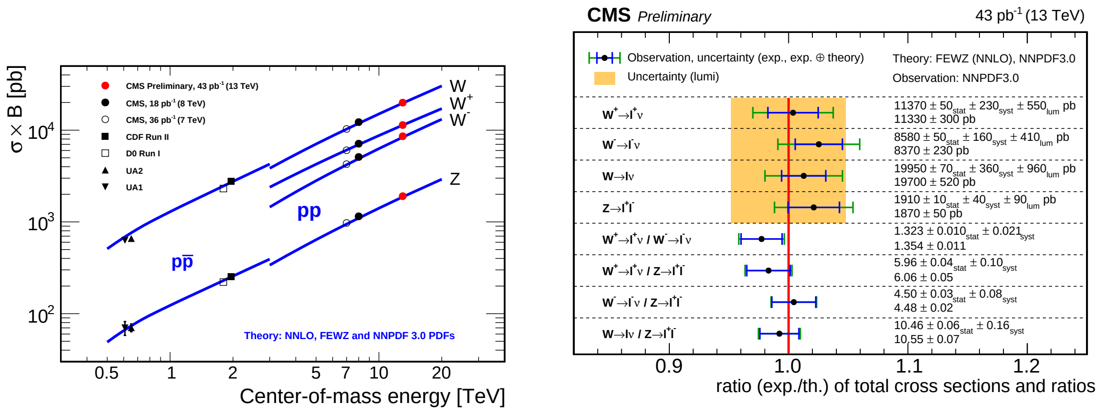
Precision electroweak (EWK) measurements are an important part of the CERN research program. These are one of the most stringent test of self-consistency of the Standard Model (SM), probing the electroweak symmetry breaking (EWSB) mechanism, and tuning the Monte Carlo generators. Also, precision measurements 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 $2.1 \times 10^{34} cm^{-2} s^{-1}$. For this time the integrated luminosity recorded by the CMS experiment L_{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].

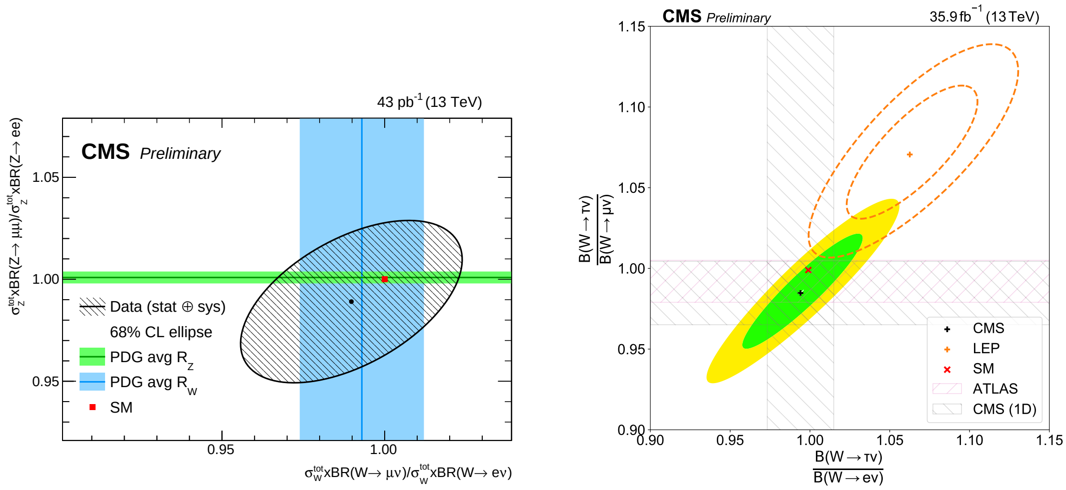
One of the most important direction in electroweak physics is the study of the mediators of weak interactions. The measurements of electroweak vector–boson production an the branching ratios of Z/W-bosons decays at hadron colliders provide a benchmark for the understanding of quantum chromodynamic (QCD) 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).



(a) (b)

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].

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 $W \to \tau\nu/W \to \mu\nu/W \to e\nu$ decays (Fig. 2(b)). The good agreement between experiments and with SM predictions are also observed.



(a) (b)

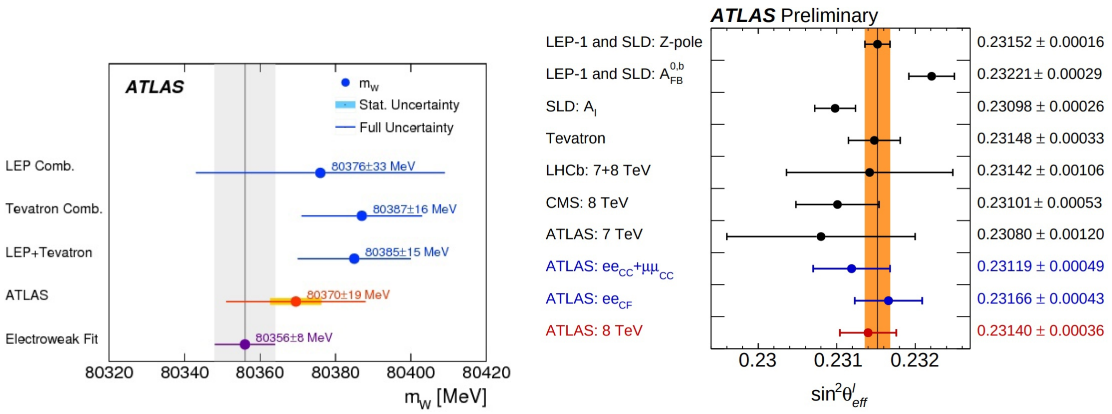
Figure 2: (a) – Ratios of the W and Z boson total inclusive cross sections in the electron and muon channels compared to previous experimental checks of lepton universality and the Standard model expectation. The contour obtained from the data (full circle) represent the 68% CL (full line) area accounting for the full set of statistical and systematic uncertainties [3]. (b) – Two-dimensional distributions of the ratios $R_{\tau/e}$ versus $R_{\tau/\mu}$ compared to similar LEP [4] and ATLAS [5] results and to the SM expectation. The green and yellow bands (dashed lines for the LEP results) correspond to the 68% and 95% CL for the resulting two-dimensional Gaussian distribution. The one-dimensional (1D) 68% CL bands are also overlaid for a better visual comparison with the corresponding ATLAS $R_{\tau/\mu}$ result [5, 6].

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 parameter 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 θ^l_{eff} 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: $sin^2\theta^l_{eff} = 0.23140 \pm 0.00021(stat) \pm 0.00016(syst) \pm 0.00024(PDF)$ by ATLAS and $sin^2\theta^l_{eff} = 0.23101 \pm 0.00036(stat) \pm 0.00018(syst) \pm 0.00031(PDF)$ by CMS. Both results are consist with global electroweak fit value $sin^2\theta^l_{eff} = 0.23150 \pm 0.00006$ within uncertainties.

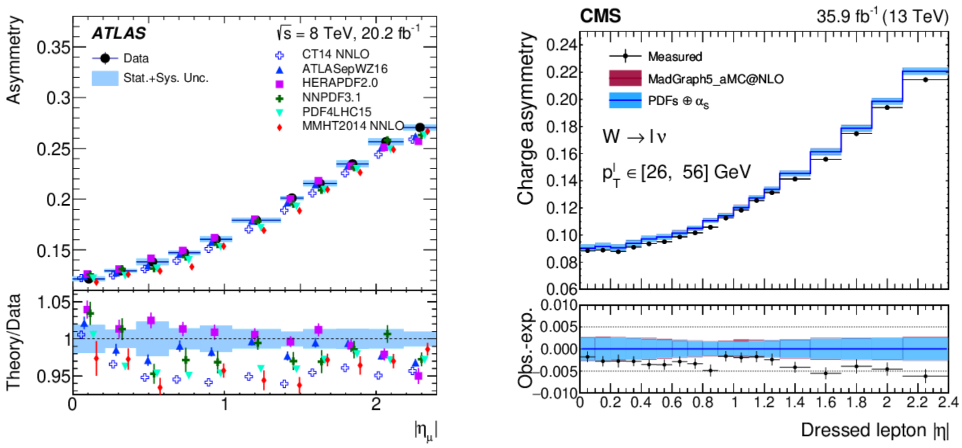
Figures 3(a) and 3(b) summarize the ATLAS and CMS measurements of m_W and $sin^2\theta^l_{eff}$ to previous measurements from different accelerators experiments. The results obtained in the LHC experiments are compatible to each other as well as to results from another experiments. CMS and ATLAS have 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).



(a) (b)

Figure 3: Comparison of the LHC measurements of: (a)– W-boson mass m_W, (b)– sine of Wienberg effective weak mixing angle $sin^2\theta^l_{eff}$ with previous measurements and global electroweak fit values [19].



(a) (b)

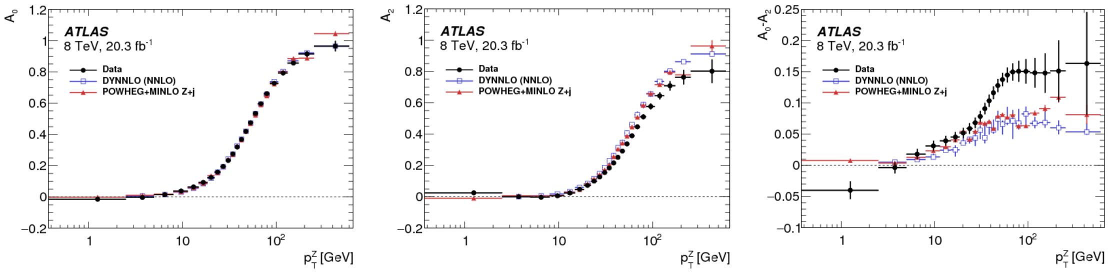
Figure 4: Absolute differential W-boson charge asymmetry as a function of $|\eta|$ measured by ATLAS (a) [21] and CMS (b) [22]. The lower panel in each plot shows the ratio (difference for (b)) of observation and expectation for the asymmetry and the relative uncertainty.

This phenomena is called W-boson charge asymmetry and could be defined as $\mathcal{A} = \sigma^+_\eta - \sigma^-_\eta / \sigma^+_\eta + \sigma^-_\eta$, where $\sigma^{+(-)}_\eta = \frac{d\sigma^{+(-)}}{d\eta}$ – pseudorapidity differential cross section of $W^{+(-)}$-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 $sin^2\theta^l_{eff}$ 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 ($q\bar{q} \rightarrow \gamma^\star/Z^0 \rightarrow l^+l^-$) [23] products also can be used for studying the parton distribution functions. The double differential cross section of this process could be written as follows for all orders of the perturbative QCD theory:

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

where θ^* and ϕ^* 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.



(a) (b) (c)

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 $Z \to ee + Z \to \mu\mu$ 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 $Z \to \mu\mu$ channel [27]. The results are fully compatible with ATLAS ones.

In conclusion, it can be noted that at present all the results of EW meaurements 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.

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