Standard Model: Electroweak Physics with CMS and ATLAS at 13 TeV

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Abstract. This paper presents cross section measurements for inclusive W/Z boson production, and W/Z boson production in association with jets and diboson production, performed by the CMS [1] and ATLAS [2] collaborations using proton-proton (pp) collisions data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV at LHC. Differential and total production cross sections for various processes, are computed and compared to higher order predictions of the standard model (SM). Recent results on effective leptonic weak mixing angle are also presented.

1. Introduction
In the SM of particle physics, the production of diboson final states at the TeV scale provides a reference both for physics measurements and for the understanding of the detector response. The high centre-of-mass energy at the Large Hadron Collider (LHC) [3] allows for the production of events with high jet transverse momenta and high jet multiplicities associated with electroweak bosons. It is therefore very important to have precise diboson measurements as well as reliable and accurate theoretical predictions for these processes. The measurements presented in this paper, are based on the pp collision data collected by the CMS and ATLAS detectors at the LHC in 2012, 2015 and 2016.

2. Cross section measurements
The inclusive production cross sections of $W^\pm\rightarrow\ell^\pm\nu$ and $Z\rightarrow\ell^+\ell^-$ boson with a subsequent decay into charged leptons are measured at $\sqrt{s} = 13$ TeV [4, 5] using data collected by the CMS and ATLAS experiments, corresponding to a total an integrated luminosity of 43 pb$^{-1}$ and 81 pb$^{-1}$ respectively. The measured values agree with next-to-next-to-leading-order QCD cross-section calculations. Fig. 1 shows inclusive cross sections and ratios of cross sections for electron and muon decay channels.

For W+jets, the differential cross-section measurement is performed [6] in the $\mu\nu+jets$ final state, and is based on $\sqrt{s} = 13$ TeV pp collision data corresponding to an integrated luminosity of 2.2 fb$^{-1}$, recorded by the CMS detector at the LHC during run II in 2015. The measured differential cross sections as a function of leading jet transverse momentum ($p_T(j_1)$) are shown in Fig. 2. The measured cross sections are compared with predictions, which include multileg leading-order (LO) and next-to-LO (NLO) matrix element calculations interfaced with parton showers, as well as a next-to-next-to-LO (NNLO) calculation.
Figure 1. Ratios of the W and Z boson total inclusive cross sections in the electron and muon channels compared to the expected values of the SM and previous experimental checks of lepton universality, provided by the CMS (left [4]) and ATLAS (right [5]) collaborations. 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. The PDG average values and the result are shown with total uncertainties.

Figure 2. Differential cross-section measurement for the transverse momenta of the leading jet [6], compared to the predictions of NLO MADGRAPH5_aMC@NLO (denoted as MG5_aMC) FxFx, LO MG5_aMC and fixed-order NNLO. The black circular markers with the gray hatched band represent the unfolded data measurement and the total experimental uncertainty. The LO MG5_aMC prediction is given only with its statistical uncertainty. The bands around the NLO MG5_aMC FxFx and NNLO predictions represent their theoretical uncertainties including both statistical and systematic components. The lower panels show the ratios of the prediction to the unfolded data.
Measurements of the production cross section of a Z boson in association with jets in pp collisions at $\sqrt{s} = 13$ TeV are also presented, using data corresponding to an integrated luminosity of 3.16 fb$^{-1}$ [8] and 2.2 fb$^{-1}$ [7] collected by the ATLAS and CMS experiments respectively in 2015. The measured cross sections are compared with predictions from different Monte Carlo generators based on LO and NLO matrix elements for up to two additional partons interfaced with parton shower and fixed-order predictions at NNLO order. The measured cross section as a function of jet $p_T$ are shown in Figs. 3 and 4.

**Figure 3.** Measured cross section as a function of jet $p_T$ for exclusive Z+1 jet events [8]. The data is compared to the predictions from BlackHat+Sherpa, Sherpa 2.2, Alpgen+PYTHIA6 (denoted as Py6), MG5_AMC+Py8 CKKWL, and MG5_AMC+Py8 FxFx. The error bars correspond to the statistical uncertainty, and the hatched bands to the data statistical and systematic uncertainties (including luminosity) added in quadrature.

**Figure 4.** Measured cross section as a function of the transverse momentum of the first jet [7]. The measurement is compared with LO MG5_AMC+PYTHIA8 (denoted as PY8), NLO MG5_AMC+PY8, fixed-order NNLO, and Geneva (denoted as GE), which is a combination of NNLO calculation with next-to-next-to leading logarithmic (NNLL) resummation interfaced with PY8. The error bars represent the statistical uncertainty and the grey hatched bands represent the total uncertainty, including the systematic and statistical components.

The cross section of oppositely charged W-boson pairs is measured [9] by the ATLAS collaboration, using data corresponding to an integrated luminosity of 3.16 fb$^{-1}$ at $\sqrt{s} = 13$ TeV. The measured fiducial cross section is in agreement with the prediction in the fiducial phase space with two different acceptance calculations as shown in Fig. 5.
Measurements of ZZ production in the four lepton (4ℓ) channel, pp → Z/γ∗Z/γ∗ → 4ℓ in pp collisions at √s = 13 TeV are also presented. The datasets correspond to 36.1 fb−1 and 35.9 fb−1, collected by the ATLAS and CMS experiments in 2015 and 2016 respectively, are analysed. The integrated cross section is also extrapolated to a total phase space and to all SM decays of Z bosons with mass between 66 GeV and 116 GeV. The CMS experiment reports a measurement of the total cross-section σ (pp → ZZ) = 17.2 ± 0.5(stat) ± 0.7(syst) ± 0.4(theo) ± 0.4(lumi) pb [10]. A similar result, σ = 17.3 ± 0.9 ± 0.6 (stat.) ± 0.5 (syst.) ± 0.6 (lumi.) pb, is reported by the ATLAS experiment [11]. The measurements are found to be in good agreement with the SM. The total production cross-section measurements are summarized in Fig. 6.

Finally the production of WZ boson pairs is recently examined for centre-of-mass energy of 13 TeV by the ATLAS and CMS collaborations. The measurements are performed in the leptonic decay modes WZ → ℓνℓ′ℓ′, (where ℓℓ′=e,μ). The measured inclusive cross section by the ATLAS experiment is σ (pp → WZ) = 51.8 ± 0.8 (sys.) ± 0.9 (mod) ± 1.2 (lumi.) pb [12]. The measured cross section reported by the CMS is σ (pp → WZ) = 39.9 ± 3.2 (stat.) ± 2.9 (syst) ± 0.4 (theo) ± 1.3 (lumi.) pb [13]. Fig. 7 shows the measured cross sections for the various centre-of-mass energies.

3. Measurement of the W-boson mass
A measurement of the mass of the W boson (mW) is reported by the ATLAS experiment, using a data sample recorded at a centre-of-mass energy of 7 TeV, corresponding to an integrated luminosity of 4.6 fb−1. The value of mW is obtained from template fits to the reconstructed distributions of the charged lepton transverse momentum and of the W boson transverse mass in the electron and muon decay channels. The individual measurements of mW are consistent
Figure 7. Measured and predicted inclusive cross sections as function of the centre-of-mass energy provided by the ATLAS (left [12]) and CMS (right [13]) collaboration.

and their combination yields a value of $80.370 \pm 7 \text{(stat.)} \pm 11 \text{(exp.syst.)} \pm 14 \text{(mod.syst.)}$ MeV [14]. Fig.8 shows an overview of the $m_W$ measurement.

Figure 8. Determinations of $m_W$ from the $P_T^\ell$ and $m_T$ distributions, and for the combination of the $P_T^\ell$ and $m_T$ distributions, in the muon and electron decay channels and for $W^+$ and $W^-$ events. The horizontal lines and bands show the statistical and total uncertainties of the individual $m_W$ determinations. The combined result for $m_W$ and its statistical and total uncertainties are also shown (vertical line and bands) [14].

4. Effective leptonic weak mixing angle measurements

A measurement of the effective leptonic weak mixing angle ($\sin^2 \theta_{eff}$) is presented by both experiment at $\sqrt{s} = 8$ TeV. The ATLAS collaboration analysed a dataset corresponding to an integrated luminosity of 20.1 fb$^{-1}$. The combination of 6 million electron and 7.5 million muon pairs from Z-boson decays in the central region, complemented by 1.5 million electron pairs with one electron in the forward region of the detector, leads to optimal sensitivity to the weak mixing angle. The measured vale of $\sin^2 \theta_{eff}$ is $0.23140 \pm 0.00021 \text{(stat.)} \pm 0.00024 \text{(PDF)} \pm 0.00016 \text{(syst.)}$ [16]. Similar results are reported by the CMS experiment, by analysing datasets corresponding to integrated luminosities of 18.8 and 19.6 fb$^{-1}$ in the dimuon and dielectron channels, respectively. The combined result from the dielectron and dimuon channels provided by CMS, is $\sin^2 \theta_{eff} = 0.23101 \pm 0.00036 \text{(stat.)} \pm 0.00018 \text{(syst.)} \pm 0.00016 \text{(theo)} \pm 0.00031 \text{(PDF)}$ [15]. Figs. 9 and 10 are showing detailed results from both experiments.
Figure 9. The extracted values of $\sin^2 \theta_{e\ell}^{\text{eff}}$ in the muon and electron channels, and their combination. The horizontal bars include statistical, experimental, and PDF uncertainties. The PDF uncertainties are obtained both without (top) and with (bottom) using the Bayesian $\chi^2$ weighting [15].

Figure 10. Comparison of the measurements of the effective leptonic weak mixing angle, $\sin^2 \theta_{e\ell}^{\text{eff}}$, is represented together with its uncertainty as a vertical band. The ATLAS combined result for all channels is shown, together with the results for the eeCF channel alone and for the combined eeCC and $\mu\mu$CC channels [16].

5. Summary
Measurements of W and Z boson production cross sections performed by the ATLAS and CMS collaborations at a centre-of-mass energy of 13 TeV have been presented. The results from both experiments are compatible and all of the presented results are in good agreement with the SM predictions within uncertainties. The measurement of $m_W$ is compatible and similar in precision to the currently leading measurements performed by the CDF and D0 collaborations [17, 18]. A comparison of the extracted $\sin^2 \theta_{e\ell}^{\text{eff}}$ with previous results from LEP, SLC, Tevatron, and LHC, also indicates consistency with the mean of the most precise LEP and SLD results, as well as with the other measurements.

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