Production of $W$ and $Z$ bosons in proton - proton collisions at Large Hadron Collider has been extensively studied by the ATLAS and CMS Collaborations during the Run 1 period. Data collected at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV were analysed. Both collaborations produced nearly 60 publications dealing with $W/Z$ physics in total. A wide range of topics is covered.

A representative selection of the aforementioned results is presented. Expectations for the Run 2 period are summarised.


1 Introduction

Investigation of production and properties of the $W$ and $Z$ bosons constitutes a significant part of the research program at hadron colliders. Wide range of possible measurements allows one to investigate a broad range of aspects. It is possible to perform basic and precision tests of quantum chromodynamics (QCD), to constrain parton distribution functions (PDFs), to test parton emission calculations and resummation models, to do stronger and more stringent tests of QCD, or to extract Standard Model parameters. Some measurements of $W$ and $Z$ boson properties are sensitive to physics beyond the Standard Model.

During the Run 1 period at LHC [1], the ATLAS [2] and CMS [3] Collaborations produced nearly 60 publications dealing with $W/Z$ physics in total. A wide range of topics is covered: production cross section of inclusive $W$ and $Z$ bosons decaying into $e$, $\mu$, $\tau$ and $b$ channels, differential Drell-Yan cross sections, differential cross sections of $W$ and $Z$ as a function of boson transverse momentum, rapidity and $\Phi_\eta$ observable, production of $W$ and $Z$ in association with light jets, ratio of the $W + \text{jets}$ to $Z + \text{jets}$ cross sections, production of $W$ and $Z$ in association with $c$ and $b$ quark, forward-backward asymmetry of Drell-Yan lepton pairs, lepton charge asymmetry in inclusive $W$ production, weak mixing angle with the Drell-Yan process, angular distributions in the decay of $W$ and $Z$, and electroweak production of dijets in association with a $Z$ boson.

To provide as apposite and as transparent as possible representation of $W/Z$ physics results achieved by both collaborations during the Run 1 period, main results of selected publications on the following topics will be briefly depicted in the next: inclusive production cross section of $W$ and $Z$ decaying leptonically, differential Drell-Yan cross section, differential cross section of $Z$ as a function of boson transverse momentum, rapidity and $\Phi_\eta$ observable, production of $Z$ in association with light jets, ratio of the $W + \text{jets}$ to $Z + \text{jets}$ cross sections and production of a $Z$ boson in association with a $b$ quark.

2 Selected results from Run 1

The CMS Collaboration performed measurements of inclusive $W$ and $Z$ boson production cross sections in the lepton channel [4] using 18 pb$^{-1}$ of 8 TeV data. This data sample with low pileup was collected in May 2012. Assuming lepton universality, the results from electron and muon channels are combined by calculating an average cross section value weighted by their statistical and systematic uncertainties.

Results are compared with the theoretical prediction calculated at NNLO with the program Fully Exclusive $W$ and $Z$ Production (FEWZ [5]) using MSTW2008 set of PDFs [6]. Comparison of measured and predicted fiducial cross sections of
$W$ versus $Z$ and of $W^+$ versus $W^-$ is shown in Figure 1 for several PDF sets. The measurement is consistent with theoretical predictions. It has a discriminating power between PDF sets.

Drell-Yan differential cross section as a function of dilepton mass was measured at 7 TeV by the ATLAS Collaboration and at 7 and 8 TeV by the CMS Collaboration.

The ATLAS Collaboration measured high mass Drell-Yan fiducial differential cross section using 4.9 fb$^{-1}$ of 7 TeV data [7]. Measurement was performed only in the electron channel. The measured cross section was compared to the theoretical prediction calculated using FEWZ3.1 with 5 NNLO PDFs. Measurement is consistent with the theory prediction, although the data are systematically above the theory. Measurement does not enable to distinguish between PDFs.

Low mass Drell-Yan distribution was measured by the ATLAS Collaboration using 35 pb$^{-1}$ collected in 2010 and 1.6 fb$^{-1}$ collected in 2011 [8]. The measurement was performed in the electron and muon channel in the range of dilepton masses between 26 and 66 GeV and these measurements are combined. The analysis is extended to the range between 12 and 66 GeV in the muon channel using only data from the year 2010. The measured fiducial differential cross section is compared to NLO prediction (FEWZ), NLO + Leading Logarithm resummed Parton Shower (POWHEG [9]) and NNLO (FEWZ). Only NNLO prediction is able to reproduce the data. The necessity of using NNLO prediction was confirmed by QCD analysis of data.

The CMS Collaboration measured the Drell-Yan distribution in electron, muon and combined channels using 7 TeV data collected in the year 2011 [10]. The range of dilepton mass is between 15 and 2000 GeV. Double differential cross section as a function of dilepton mass and rapidity was measured only in muon channel in the restricted mass range between 20 and 1500 GeV. The measured differential cross section normalised to the $Z$ cross section is compared with the NNLO pQCD prediction.
combined with LO and NLO EW prediction calculated using FEWZ. Both levels of EW predictions agree with the data. The double differential cross section is compared with NNLO pQCD prediction using various sets of PDFs (Figure 2). This is the first double differential Drell-Yan cross section measurement performed at a hadron collider and will provide precise inputs to update PDFs.

Figure 2: Double Drell-Yan differential cross section as a function of dilepton mass and rapidity in two dilepton mass windows. Taken from Ref. [10].

The CMS Collaboration also measured Drell-Yan differential and double differential cross section using 19.7 fb$^{-1}$ of 8 TeV data [11]. The range of dilepton mass is the same as in the 7 TeV measurement. Results agree with the NNLO theoretical prediction calculated by the FEWZ program.

Both collaborations measured differential cross section of Z boson as a function of Z transverse momentum and rapidity. The ATLAS Collaboration also investigated the observable $\Phi^*_\eta$ - an alternative probe of the Z transverse momentum, less sensitive to the lepton energy and momentum uncertainties*.

The ATLAS Collaboration measured normalised differential cross sections of Z using 4.7 fb$^{-1}$ of 7 TeV data [12]. Cross section was measured as a function of Z transverse momentum in three rapidity bins: $|y_Z| < 1$, $1 < |y_Z| < 2$ and $2 < |y_Z| < 2.4$. The range of Z boson transverse momentum is $< 0, 800 >$ GeV.

Comparison of theoretical predictions to the measured normalised differential cross-section is shown in Figure 3. As expected (two upper plots), fixed order NNLO predictions using DYNNLO1.3 [13, 14] and FEWZ can describe the data only at

* $\Phi^*_\eta = \tan(\frac{\pi - \Delta \Phi}{2}) \sin(\theta^*_\eta)$, where $\cos(\theta^*_\eta) = \tanh((\eta^- - \eta^+)/2)$ and $\Delta \Phi$ is the azimuthal opening angle between the two leptons [29].
large transverse momenta of $Z$ where radiation of high $p_T$ gluons dominates. Low $p_T$ region is dominated by soft gluon emission modeled by soft gluon resummation included in RESBOS [15], [16] (two lower plots).

Figure 3: Top left: comparison of measured $P_T^Z$ distribution with fixed order NNLO calculations of FEWZ and DYNNLO. Bottom left: comparison of measured $P_T^Z$ distribution to the soft gluon resummation calculation using RESBOS. Right: ratios of theoretical predictions to data. Taken from Ref. [12].

Measured normalised fiducial differential cross sections as a function of transverse momentum and $\Phi^*_\eta$ observable were used for tuning event generators PYTHIA8 [17] in standalone mode and in a configuration interfaced to POWHEG. Tuned were the parameters affecting transverse momentum - ordered, interleaved parton shower in PYTHIA8. The best prediction is provided by PYTHIA8, which is also able to describe the different rapidity bins with the single tune.

The CMS Collaboration measured absolute fiducial double differential cross section of the $Z$ boson as a function of $Z$ transverse momentum and rapidity using 19.7 fb$^{-1}$ of 8 TeV data [18]. The measurement is done in dimuon channel only. The transverse momentum of $Z$ is in the range $[0, 300]$ GeV, the differential cross section is measured in six rapidity bins.
The measured absolute fiducial $Z$ boson differential cross section as a function of $Z$ transverse momentum is compared with the NNLO prediction of FEWZ (Figure 4) in two selected rapidity bins (left two plots) and integrated over all rapidity bins (right plot). Predictions agree with data within uncertainties, which are dominated by scale uncertainties. Starting from 20 GeV, the shape is predicted correctly. For the lowest transverse momentum bin, the ratio prediction/data is different from the remaining bins - as expected for a fixed order prediction.

Production properties of $W$ and $Z$ boson created in association with jets were measured at 7 TeV and 8 TeV by the CMS Collaboration. The ATLAS Collaboration published only measurements at 7 TeV.

Using 19.6 fb$^{-1}$ of 8 TeV data [19], the CMS Collaboration performed measurement of differential cross-section of $Z$ boson in association with jets as a function of the jet multiplicity, of the transverse momentum and of absolute pseudorapidity of the $n^{th}$ jet and of the scalar sum of the jet transverse momenta. Results of electron and muon channels were combined. Differential cross sections of the 1st and 2nd leading jets are compared to MADGRAPH [20] interfaced with PYHTIA6 [21] (LO) and to SHERPA [22] (NLO). For the leading jet, MADGRAPH describes data very well instead of the region 150-450 GeV where an excess of events in data over prediction is observed. Similar excess was observed by the CMS Collaboration at 7 TeV. SHERPA predicts slightly harder distributions than the measurement.

The ratio of the production cross section for $W$ and $Z$ bosons in association with jets has been measured by the ATLAS Collaboration using 4.6 fb$^{-1}$ of 7 TeV data [23].
Measurements of such ratios provide more precise test of pQCD with respect to the \( W/Z + \text{jets} \) measurements because of the cancellation of some experimental uncertainties like luminosity and jet energy scale and effects from non-perturbative processes (hadronization and multiparton interactions).

![Graph showing ratio of \( W + \text{jets} \) to \( Z + \text{jets} \) production cross sections as a function of the transverse momentum of the leading jet. Left: events with just 1 jet. Right: events with number of jets \( \geq 1 \). Taken from Ref. [23](#)](image)

Measurements are compared to NLO pQCD calculations using BLACKHAT + SHERPA [24] and to predictions of ALPGEN [25] and SHERPA LO event generators with parton showers. All signal samples created by event generators were normalised to NNLO in pQCD using FEWZ. Ratio of \( W + \text{jets} \) to \( Z + \text{jets} \) cross sections was investigated as a function of the exclusive jet multiplicity. Theoretical predictions describe data well, with a few exceptions. SHERPA overestimates data in the region of high jet multiplicity. Ratio of \( W + \text{jets} \) to \( Z + \text{jets} \) production cross sections as a function of the transverse momentum of the leading jet for events with just 1 jet (left plot) and for events with 1 and more jets (right plot) is shown in Figure 5. The drop in the ratio in the low \( p_T \) region is due to the \( W \) and \( Z \) bosons mass difference, which affects the scale of parton radiation, as well as due to the different vector boson polarization affecting kinematics of their decay products. ALPGEN provides the best description of data.
Measurements of production of massive vector bosons in association with the $c$ and $b$ quarks were performed by both collaborations.

The ATLAS Collaboration measured differential production cross sections for a $Z$ boson decaying into an electron or muon pair in association with $b$ jets using 4.6 fb$^{-1}$ of 7 TeV data \[26\].

![Cross sections for $Z + \geq 1$ b-jet and $Z + \geq 2$ b-jets](image_url)

Figure 6: Left: cross sections for $Z + \geq 1$ b-jet. Right: cross sections for $Z + \geq 2$ b-jets. Taken from Ref. \[26\].

Cross sections for $Z + \geq 1$ b-jet (left plot) and for $Z + \geq 2$ b-jets (right plot) are shown in Figure 6. The best description of data is provided by the NLO prediction of parton-level integrator MCFM \[27\]. The underestimation of the $Z + \geq 2$ b-jet cross section by the aMCatNLO \[28\] using the five flavour number scheme is probably due to the fact that it uses only LO prediction for $\geq 2$ b-jet b-jet process.

The differential cross section as a function of a b-jet transverse momentum and rapidity is best described by the aMCatNLO prediction using the five flavour number scheme. The same is true for the case of the differential cross section as a function of $Z$ transverse momentum and rapidity.
Summary

During the Run 1 period, the ATLAS and CMS Collaborations produced nearly 60 publications dealing with $W/Z$ physics in total. Typical precision of published values of integrated $W$ and $Z$ cross sections is at the level of a few percent, both for 7 TeV and 8 TeV data. Predictions of Standard Model were tested in most cases at NLO accuracy or higher. Analysis of data taken in the years 2010 and 2011 is nearly completed. Analysis of 8 TeV data from the year 2012 is still ongoing.

During the Run 2 period, center of mass energy will increase by a factor of 1.6. A new kinematic regime will be encountered. According the current expectations, about 100 fb$^{-1}$ of data will be collected during the whole Run 2 period, what represents four times the amount collected during Run 1. About 10 fb$^{-1}$ is expected during the first year of data taking. This constitutes 14 millions of $W^-$, 20 millions of $W^+$ and 4 millions of $Z$. These data will be used for basic tests of the Standard Model in the new kinematic region.

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