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Results of vector boson production, both inclusive and in association with jets, at the LHC

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Recent measurements of W and Z bosons with the ATLAS and CMS detectors at the LHC are presented. These measurements were performed using about 5 fb^{-1} of 2011 and more than 20 fb^{-1} of 2012 data. The cross-sections were measured for inclusive W and Z processes as well as for the processes associated with one or several jets. The analyses themselves are briefly described, and the main results are presented and discussed.

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1. Motivation and Introduction

The production of W and Z bosons is theoretically well understood and their cross-sections are known at next-to-next-to-leading order (NNLO) perturbation theory [1]. The production processes give a direct access to parameters of the Standard Model (SM) and allow for a precision test of its predictions. The clear experimental signatures (background is on a few percent level for most of the measurements) make these objects also interesting for studies of the detector performance, such as calibration and efficiency measurements.

Before the LHC era, most precision measurements of the parton density functions (PDFs) at low Bjorken x were performed at the HERA experiments [2]. With the new measurements from ATLAS and CMS, PDFs can be measured in a different kinematic regime (low x and high Q^2). Therefore, a comparison of these LHC PDFs with previous measurements provides a test of the validity of the QCD evolution into a region of high Q^2 at low x. In addition, measurement of the $boson/boson + jet$ cross section as function of the transverse momenta help to test predictions of perturbative QCD.

ATLAS and CMS are general purpose experiments, which are located at two different collision points of the LHC [3]. Both detectors have a similar design: the ATLAS and CMS detectors comprise an inner tracking detector immersed in a magnetic field, a calorimeter, and a muon spectrometer. Table 1 shows the acceptance of various ATLAS and CMS sub-detector systems, which is also the basis for the fiducial phase-space definition used in most measurements (see Table 1). A detailed description of both detectors can be found in [4] and [5]. Vector boson production was studied using the datasets collected in the years 2010 to 2012 at two center-of-mass energies of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.

Precision measurements of W and Z boson production must be performed in the electron and muon decay modes ($Z \to ee(\mu\mu)$, $W \to e\nu(\mu\nu)$) due to the enormous background present in the quark or $\tau\tau$ decay channels. The combination of both measurements provides not only an important test of the compatibility of both measurements, but also significantly improves the systematic uncertainties due to different detector modelling effects.

This article is structured as follows: the results on the inclusive and differential single boson production are described in Section 2, while a selection of measurements of the production in association with jets is presented in Section 3.

Detector part	ATLAS	CMS
Inner detector	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 2.5$
Central calorimeter	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 3.0$
Calorimeter extension	$\lvert\eta\rvert < 4.9$	$\lvert\eta\rvert < 5.0$
Muon system	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$

Table 1: Basic parameters of detector geometry for ATLAS [4] and CMS [5] experiments in pseudo-rapidity η.

2. Inclusive and Differential Measurements

The differential production cross-sections in bins of boson rapidity (y) and lepton invariant

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mass (M_{ll}) are very sensitive distributions for constraining PDFs. The ATLAS measurement of the Drell-Yan process is based on an integrated luminosity of 4.9 fb^{-1} of the 2011 dataset, reaching an invariant mass up to 1.5 TeV [6]. The measured cross-sections have been compared to different PDF sets, shown in Fig. 1 (left). CMS has published a double-differential $Z \to ll$ measurement in bins of boson rapidity and invariant mass [7] using six mass bins and a fine rapidity binning, Fig. 1 (right). The data have the potential to constrain PDFs, in particular for anti-quarks at large Bjorken-x, in the context of a PDF fit involving the world data sensitive to the proton structure.

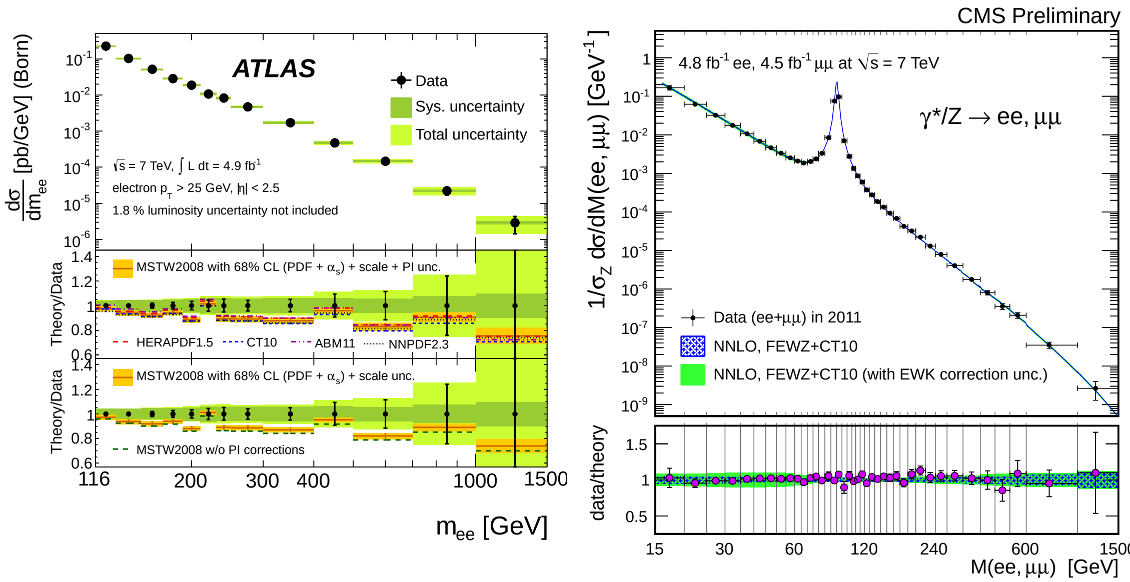

Figure 1: Measurement of invariant mass distribution, performed with ATLAS [6] (left) and CMS [7] (right) experiments.

The measurement of the transverse momentum (p_T) distribution of vector bosons, especially in the regime $p_T < 40$ GeV, allows to test so-called resummation techniques of perturbative QCD calculations. In addition, these measurements are crucial for a precision measurement of the W boson mass at hadron colliders. Hence, new experimental results provide a valuable input for tuning and understanding theoretical models.

The measurement of the vector boson p_T spectrum is more complicated than the vector boson rapidity distribution due to larger bin-to-bin migration effects, induced by the limited detector resolution. The ATLAS analysis is based on the 2010 data-set [8] (see Fig. 2 (left)). The CMS analyses were performed using 36 pb^{-1} at $\sqrt{s} = 7$ TeV [10] and 18.4 pb^{-1} at $\sqrt{s} = 8$ TeV [9] (see Fig. 2 (right)). Only a small amount of $\sqrt{s} = 8$ TeV data was used for analysis in order to stay at low PU run dedicated to precise boson physics. The differential cross section was measured up to 350 GeV and compared with predictions of several event generators. In general, a good agreement can be seen. Measurements with 2011 and 2012 data, which are currently in process, will extend the p_T range up to 900 GeV and increase the precision.

A measurement of angular correlations in Drell–Yan lepton pairs via the ϕ^* observable was performed with the ATLAS detector using 4.6 fb^{-1} of 2011 data [11] (see Fig. 3). ϕ^* is defined as $\tan(\phi_{acop}/2)\sin(\theta^*_\eta)$, where $\phi_{acop} = \pi - \Delta\phi$, $\Delta\phi$ being the azimuthal opening angle between the

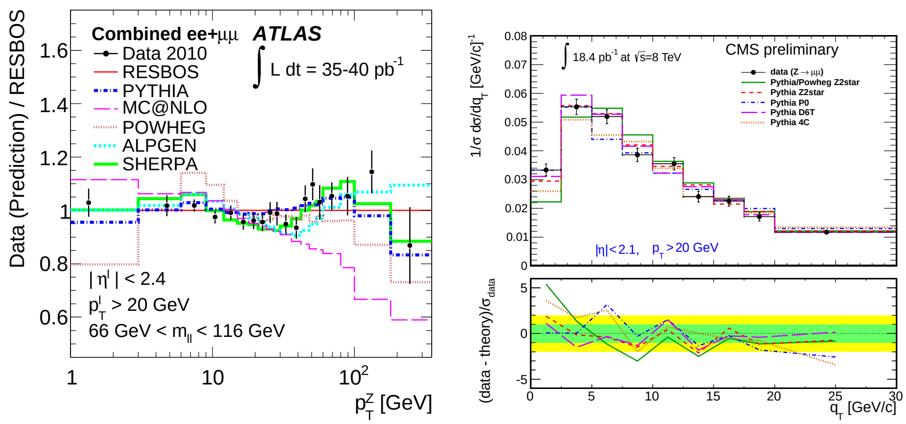

Figure 2: Z boson transverse momentum, measured with 2010 ATLAS data [8] (left) and 2012 CMS data [9] (right).

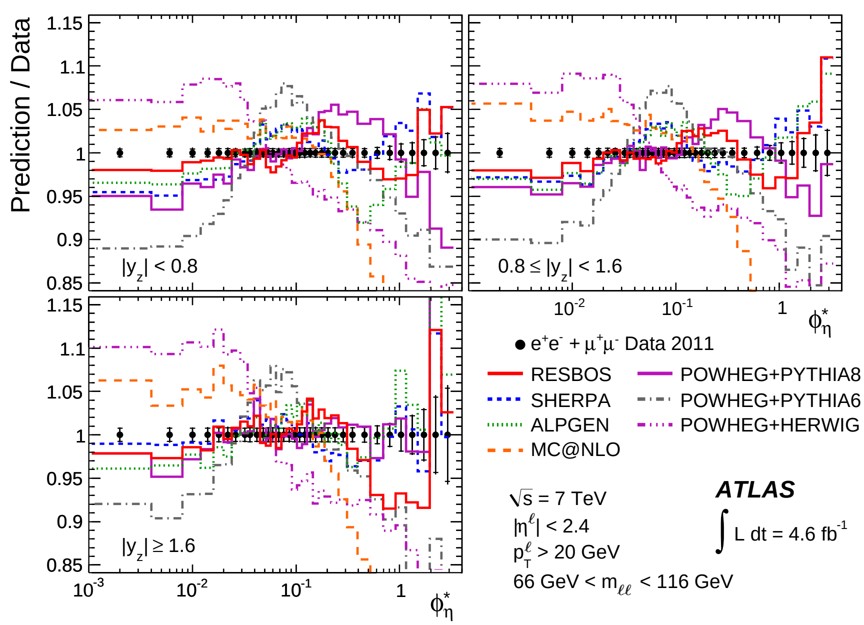

Figure 3: Comparison of ϕ^* measurement with 2011 ATLAS data and different theoretical predictions [11].

two leptons. The angle θ^*_η is defined by $\cos(\theta^*_\eta) = \tanh[(\eta^- - \eta^+)/2]$, where η^- and η^+ are the pseudo-rapidities of the negatively and positively charged leptons, respectively. Variable ϕ^* probes the same physics as the Z/γ^* boson transverse momentum, but has a better experimental resolution. The cross-section was measured single differentially in bins of ϕ^* and double differentially in bins of ϕ^* and Z boson rapidity. The disagreement between the data and predictions is quite significant compared to the precision of the measurement. This difference can be used as an excellent tool for further improvements of MC generators.

3. Vector Boson + jets

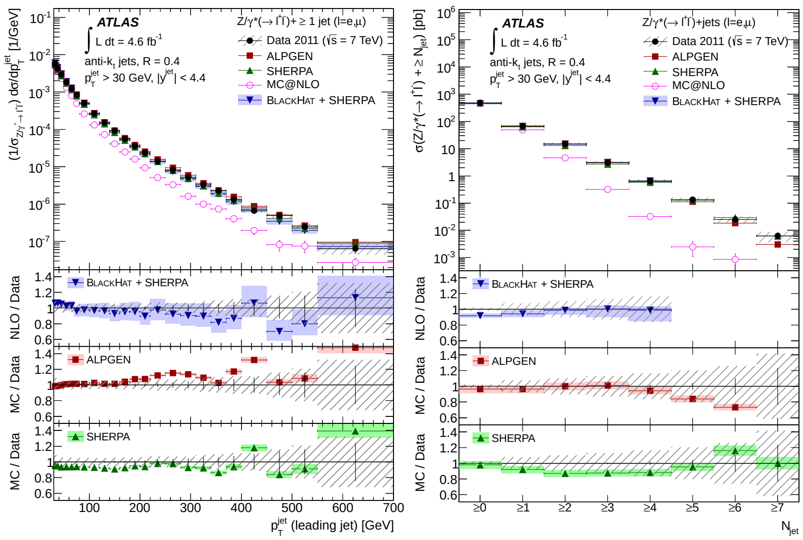

Figure 4: Measurement of jet transverse momentum (p_T^{jet}) and jet multiplicity (N_{jet}), performed with the ATLAS detector [14].

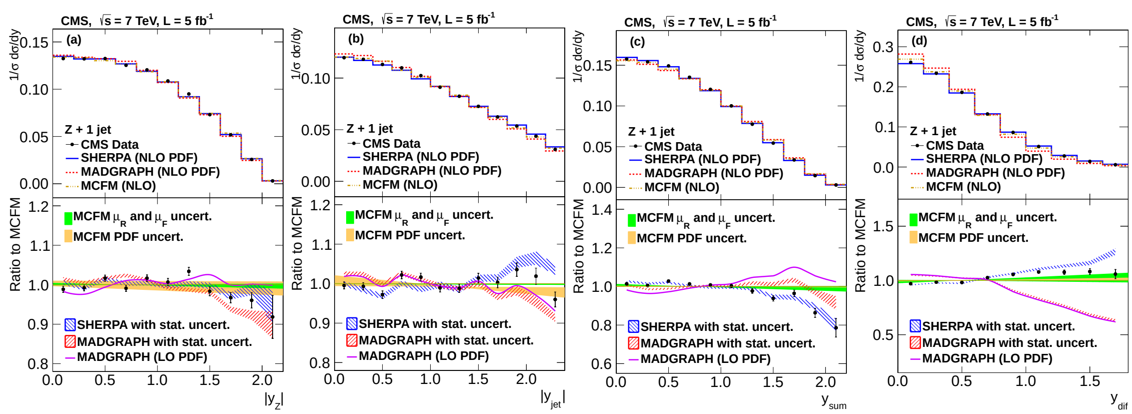

Figure 5: Z + jet measurements in rapidity bins, performed with the CMS detector [13].

The understanding of the vector-boson production in association with jets (V+jets) at the LHC not only provides an important test of perturbative QCD, but is also important as a main source of backgrounds to many searches for physics beyond the Standard Model. Several measurements have already been published by ATLAS and CMS [12–17], and only a few results will be described here in more detail.

The measurement of jet transverse momentum (p_T^{jet}) and jet multiplicity(N_{jet}) [14] was performed with the full 2011 dataset by the ATLAS experiment (see Fig. 4). The data have been unfolded to the particle level and compared with predictions from the SHERPA generator (v1.4.1 with the MEnloPS approach), from MC@NLO interfaced with HERWIG, from the ALPGEN generator, interfaced with HERWIG, and with fixed-order calculations from BlackHat+SHERPA. The

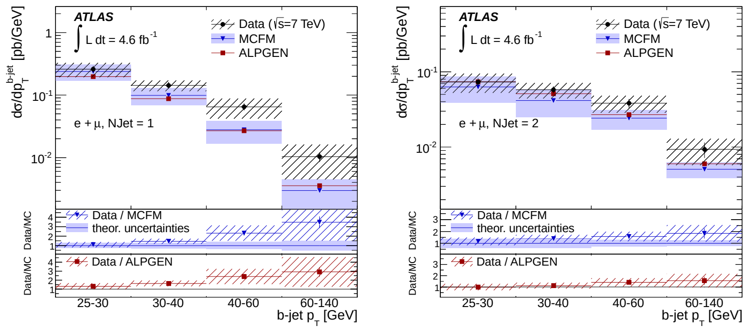

Figure 6: The measurement of differential $W+$ b-jets cross-sections as a function of p_T^{jet} in the 1-jet (left) and 2-jet (right) fiducial regions, performed with the ATLAS detector using 2011 data-set [16].

predictions of the matrix element plus parton shower generators and the fixed-order calculations are mostly consistent with the measured values over a large kinematic range. MC@NLO fails to describe both distributions.

The measurement of Z+jets events in bins of boson rapidity (Y_Z), which is necessary for the characterization of the Higgs boson properties was performed with the full 2011 dataset by the CMS experiment [13]. The basic quantities Y_Z, Y_{jet} are in general agreement with predictions from Madgraph, SHERPA, and MCFM. The derived quantities $Y_{sum} = |Y_Z + Y_{jet}|/2$ and $Y_{dif} = |Y_Z - Y_{jet}|/2$ show some disagreement with two hybrid MCs. SHERPA is significantly better than Madgraph at describing the shape of the Y_{sum} and Y_{dif}.

The measurement of W boson production associated with b jets provides not only a further test of perturbative QCD, but also a possibility for the probing of associated Monte Carlo techniques such as the identification of b-quarks. The corresponding measurements are based on the 2011 data and were performed by the ATLAS [16] and CMS [17] experiments.

ATLAS measurement of p_T^{jet} spectrum, obtained by combining the muon and electron channel results, presented in Fig. 6. The measurements were performed with a single b-tagged jet requirement in the $W+$1-jet and $W+$2-jet samples and were compared to the MCFM predictions corrected for hadronization and double-parton interaction effects and to the Alpgen predictions interfaced to Herwig and Jimmy and scaled by the NNLO inclusive W normalization factor. In the 1-jet fiducial region, the measured cross-section is larger than the NLO predictions, but compatible within the theoretical and experimental uncertainties. The same measurement in the 2-jet fiducial region is found to be in agreement with the theoretical predictions.

4. Conclusion

The results of the inclusive and differential cross-section measurements of W and Z boson at the LHC have achieved high precision and are already now often dominated by theoretical uncertainties. The comparison of data and NNLO QCD calculation shows a very good agreement for many observables and hence demonstrates the good understanding of QCD in a new energy domain. The interpretation of the these measurements will lead to new constraints on proton PDFs, which will in turn be the basis for high precision electroweak measurements at the LHC, such as the determination of the W boson mass.

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