

Measurements of the production of a vector boson in association with jets in the ATLAS and CMS detectors

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Abstract. The production of a vector boson ($V = W, Z$) in association with jets is can be used for a precise test of perturbative QCD and is a dominant background process in many searches for physics beyond the Standard Model. The differential cross section measurements from CMS and ATLAS collaborations would be presented, and several theoretical predictions at leading order (LO) and next-to leading order (NLO) are compared to data, after the deconvolution of detector effects, with proton-proton collisions at a center of mass energy of 7, 8 and 13 TeV at LHC.

1 Introduction

The associated production of vector bosons and jets (V+jets) in proton-proton collisions at LHC is of prime interest in the physics program of the ATLAS and CMS experiments [1,2]. This type of processes is important for several physics aspects. First of all in perturbative QCD (pQCD) studies, where direct measurement of the quark content of the proton and parton density functions (PDF) can be made by measuring the production cross sections. Studying the differential cross sections is also essential to test the latest pQCD calculations at the highest precision available in the perturbative expansion, making these measurements an unique tool for the test the Monte Carlo event generators. In Standard Model physics, the W, Z plus jets production is an essential measurement in order to precisely estimate the background component of the Higgs boson and top pairs production. Furthermore, many Beyond the Standard Model searches (such as supersymmetry, new Higgs bosons, 4th generation of heavy quarks) have a similar topology with respect to the V+jets production, and thus the control on their backgrounds might be highly improved by means of these measurements.

2 Associated production of a W boson and jets

The associated production of a W boson and one or more jets has been measured in proton-proton collisions at the center of mass energy of 7 TeV both in ATLAS and CMS. The differential spectra are deconvolved for detector effects and compared to the theoretical predictions at LO and NLO precision.

2.1 W+jets at 7 TeV in ATLAS

The W+jets measurement in ATLAS [3] has been performed using an integrated luminosity of 4.6 fb^{-1} . Electrons and muons from the W boson decay must pass isolation criteria and are required to have a transverse momentum (p_T) of at least 25 GeV and pseudorapidity (η) less than 2.4. The reconstructed missing transverse energy is used to account for the presence of the neutrino, and the associated jets are clustered using the anti- K_T algorithm [4] with $R=0.4$. Jets must also have $p_T > 25 \text{ GeV}$ and rapidity (y) within the range of 4.4. The background coming from the production of top quark pairs is suppressed by requiring a b quark tag veto, and the multi-jet QCD background is estimated in data. Measured cross sections are unfolded to particle level using a Bayesian algorithm based on the Monte Carlo information. The differential cross sections are presented as a function of the leading jet

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momentum (Fig.1). Data are compared to the theoretical prediction of BlackHat+Sherpa (NLO) [5], ALPGEN (LO) [6], and Sherpa v.2 [7]. It can be seen that the LO calculations describe data in the hard part of the spectrum within the uncertainties, while a 10% overestimation is seen in the 200-400 GeV range. NLO calculations show good agreement in the comparison with unfolded data.

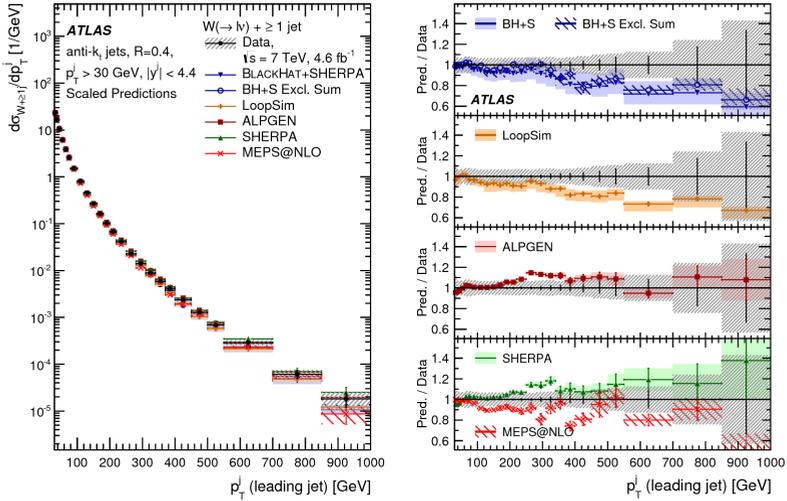


Figure 1. Differential W +jets cross sections as a function of the leading jet transverse momentum compared to the theoretical predictions of BlackHat+Sherpa at NLO, Sherpa (LO) and MadGraph+Pythia6 (LO) measured in ATLAS.

2.1 W +jets at 7 TeV in CMS

The W +jets cross section in CMS [8] has been measured using an integrated luminosity of 5 fb^{-1} . Electrons and muons from the W boson decay must be isolated and are required to have $p_T > 25 \text{ GeV}$ and $|\eta| < 2.1$. Associated jets are clustered using the anti- K_T algorithm with $R=0.5$. Jets must also have $p_T > 25 \text{ GeV}$ and have $|\eta| < 2.4$. A cut on the missing transverse mass (M_T) of the neutrino and the muon is applied, requiring $M_T > 50 \text{ GeV}$. The background coming from the production of top quark pairs is taken into account requiring a b quark tag veto, and the multi-jet QCD background is estimated again with a data-driven technique. Measured cross sections are unfolded to particle level using the SVD algorithm based on the Monte Carlo simulation. The differential cross sections are presented as a function of the leading jet momentum and as a function of the scalar sum of all the jets in the event, namely H_T (Fig.2). Data are compared to the theoretical expectations of MadGraph5 [9]+Pythia6 [10] (LO), BlackHat+Sherpa (NLO) and Sherpa (LO). It can be seen that the NLO predictions of BlackHat+Sherpa are not describing properly the spectra of the H_T distribution. It is shown that the LO MadGraph+Pythia6 prediction is over-estimating data in the full range of p_T of the leading jet and H_T .

3 Associated production of a Z boson and jets

The associated production of a Z boson and at least one jet measurement in proton-proton collisions at the center of mass energy of 8 TeV in CMS is presented. The differential cross sections are unfolded for detector effects and compared to the theoretical predictions at the LO and NLO precision.

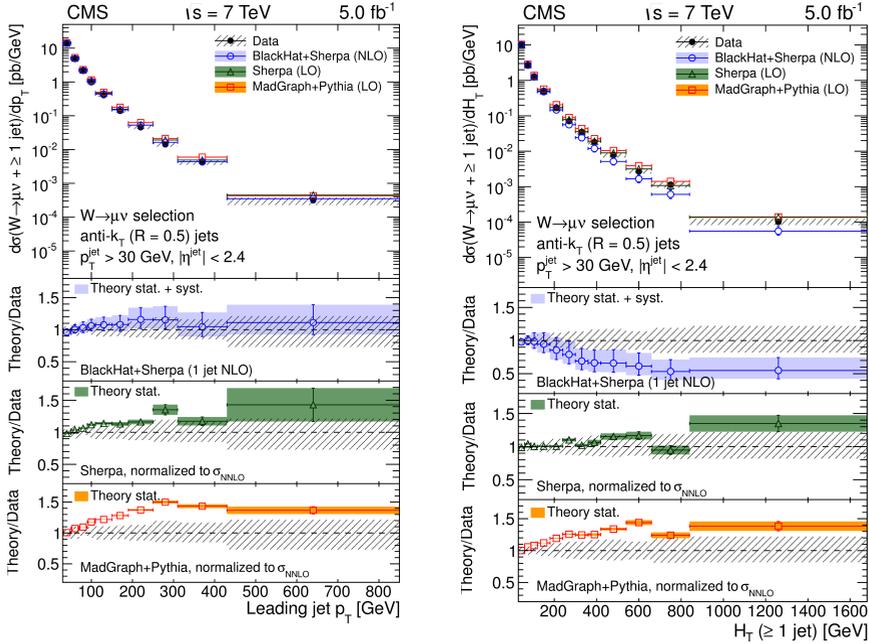


Figure 2. Differential W +jets cross sections as a function of the leading jet transverse momentum (left) and H_T (right) compared to the theoretical predictions of BlackHat+Sherpa at NLO, Sherpa (LO) and MadGraph+Pythia6 (LO) measured in CMS.

3.1 Z+jets differential and double differential cross sections at 8 TeV in CMS

The Z+jets differential cross section measurement in CMS [11] has been performed using an integrated luminosity of 5 fb^{-1} . Electron and muon pairs from the Z boson decay must be isolated and must have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.4$. The dilepton pairs are selected if their invariant mass lies within the mass range of $[71; 111] \text{ GeV}$. Jets are clustered using the anti- K_T algorithm with $R=0.5$ and must pass a $p_T > 25 \text{ GeV}$ threshold, and have $|\eta| < 2.4$. Measured cross sections are unfolded to particle level using the Bayesian unfolding algorithm exploiting the simulation information. The differential cross sections are presented as a function of the jet multiplicity (Fig.3). Data are compared to the theoretical expectations of MadGraph5+Pythia6 (LO) and Sherpa v.2 (NLO up to the second jet). Good agreement is seen in the unfolded cross sections. The double differential cross sections has also been measured as a function of the leading jet momentum and several ranges of rapidity, up to $|\eta| < 4.7$ [6].

3.2 Z+jets differential cross sections at 13 TeV in ATLAS

The Z+jets differential cross sections, measured at a center of mass energy of 13 TeV , have been studied with the ATLAS detector [12] with an integrated luminosity of 85 pb^{-1} . Dielectron (dimuon) pairs coming from the Z boson decay must be isolated and must have $p_T > 25 \text{ GeV}$ and $|\eta| < 2.47(2.4)$. The dilepton invariant mass is taken within the mass range of $[66; 116] \text{ GeV}$. Jets are clustered using anti- K_T algorithm with $R=0.4$ and must also have a transverse momentum of at least 30 GeV and $|\eta| < 2.5$. Measured cross sections are corrected to particle level using a correction factor calculated with the Sherpa event generator. The differential cross sections are presented as a function of the jet multiplicity (Fig.4). Data are compared to the theoretical predictions of MadGraph_aMC@NLO+Pythia8 [13] (up to four partons at LO) and Sherpa v.2 (NLO up to the second jet). A good agreement is seen in the measured cross sections.

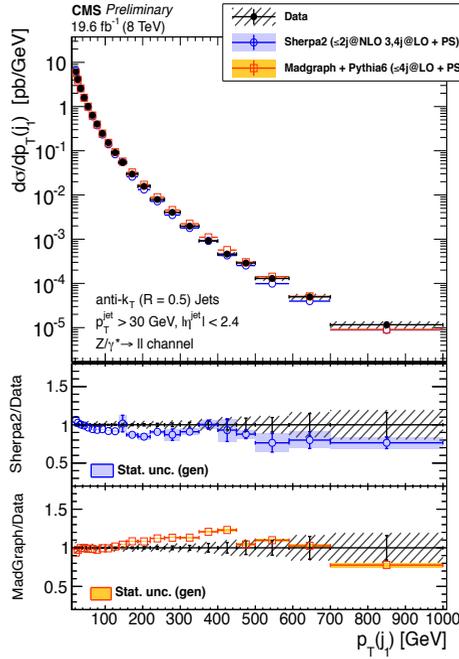


Figure 3. Differential Z+jets cross sections as a function of the leading jet transverse momentum compared to the theoretical predictions of Sherpa v2 (NLO up to the second jet) and MadGraph+Pythia6 (LO) measured in CMS.

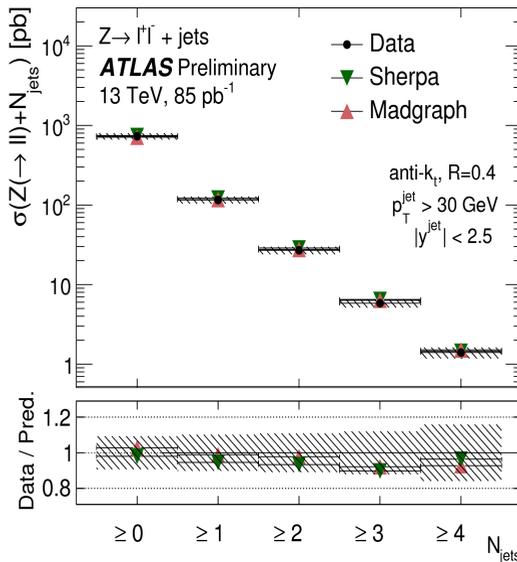


Figure 4. The 13 TeV differential Z+jets cross sections as a function of the jet multiplicity compared to the theoretical predictions of Sherpa v2 (NLO up to the second jet) and MadGraph_aMC@NLO+Pythia8 (LO) measured with the ATLAS detector.

4 Differential W+jets and Z+jets cross-section ratio in ATLAS

The differential cross section ratio between W+jets and Z+jets is an important tool to test the pQCD predictions, exploiting the advantage of many important systematics cancelation in the ratio, thus increasing the precision in the final results. Furthermore, the precise modeling of the jet recoil against the vector boson is an important measurement for many searches for physics beyond the Standard Model. Events are collected using 4.6 fb^{-1} of the 7 TeV data taking of the ATLAS detector [14]. Isolated leptons are selected from the boson decay if they have $p_T > 25 \text{ GeV}$ and $|\eta| < 2.47$. Associated jets are clustered using the anti- k_T algorithm with $R=0.4$. Jets must have $p_T > 25 \text{ GeV}$ and $|y| < 4.4$. Additional requirements on the missing transverse energy and mass are imposed for the W boson reconstruction, and the dilepton pairs are selected in the range of the Z boson mass according to the Z+jets selection. Data are unfolded to particle level by means of the Bayesian unfolding procedure. Unfolded data are then compared to the LO predictions of ALPGEN, Sherpa and the NLO prediction of BlackHat+Sherpa. Differential cross section ratios are presented as a function of the leading jet transverse momentum (Fig. 5), showing general good agreement all over the spectrum, but with some tensions that can be seen comparing data to the Sherpa prediction around 300 GeV, where the generator overestimates data.

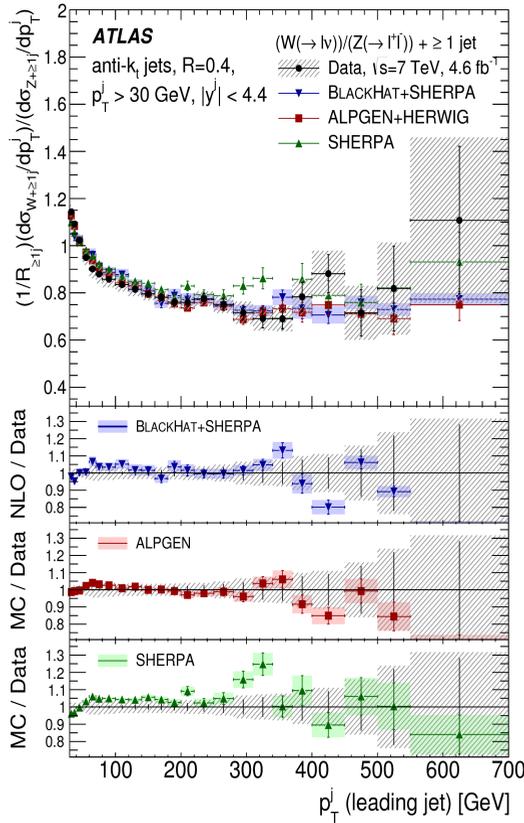


Figure 5. Differential W+jets/Z+jets cross sections ratio as a function of the leading jet transverse momentum compared to the theoretical predictions of Sherpa (LO), ALPGEN (LO) and BlackHat+Sherpa (NLO) measured with the ATLAS detector.

5 Associated production of a Z boson and b jets in CMS

The associated production of a Z boson and jets originated from the hadronization of a b quark is a unique subprocess of the V+jets events. The Z+b final state is a dominant background for the Higgs production in the HZ mode and it appears in the final state of many beyond the Standard Model processes. The Z+b final state is also essential to understand the b quark production mechanism in high energy proton collisions, allowing to test the so called 4-flavour scheme (4FS), with massive b quarks in the final state, and the 5-flavour scheme (5FS), with massless b quarks in the initial state. The Z+b differential cross sections have been measured by CMS with 20 fb^{-1} in 8 TeV collisions [15]. The b-jets are identified with a b-tagging technique that exploits the characteristics of the secondary vertex reconstruction, and must pass a threshold in p_T of 30 GeV and pseudorapidity less than 2.4. The Z boson decay products are selected using the same Z+jets criteria. The dominant top-induced background is evaluated in data, and the true fraction of bottom, charm and light flavours is extracted by fitting the secondary vertex mass distribution. Data are unfolded using the SVD algorithm and the results are compared to the theoretical calculations in the 4- and 5-flavour schemes in pQCD made with MadGraph+Pythia6, and the 5-flavour scheme prediction of Powheg [16] (NLO for the leading jet). Differential cross sections are presented as a function of the leading b-jet p_T and as a function of the invariant mass of the bb system (Fig. 6). An overall normalization discrepancy of about 20% is seen in the 4-flavour scheme for the b-jet spectrum, while the NLO prediction of Powheg correctly describes the data. The 5-flavour scheme appears to overestimate data in the soft Z momentum region. Good agreement is seen in the bb invariant mass distribution comparing data with all the predictions.

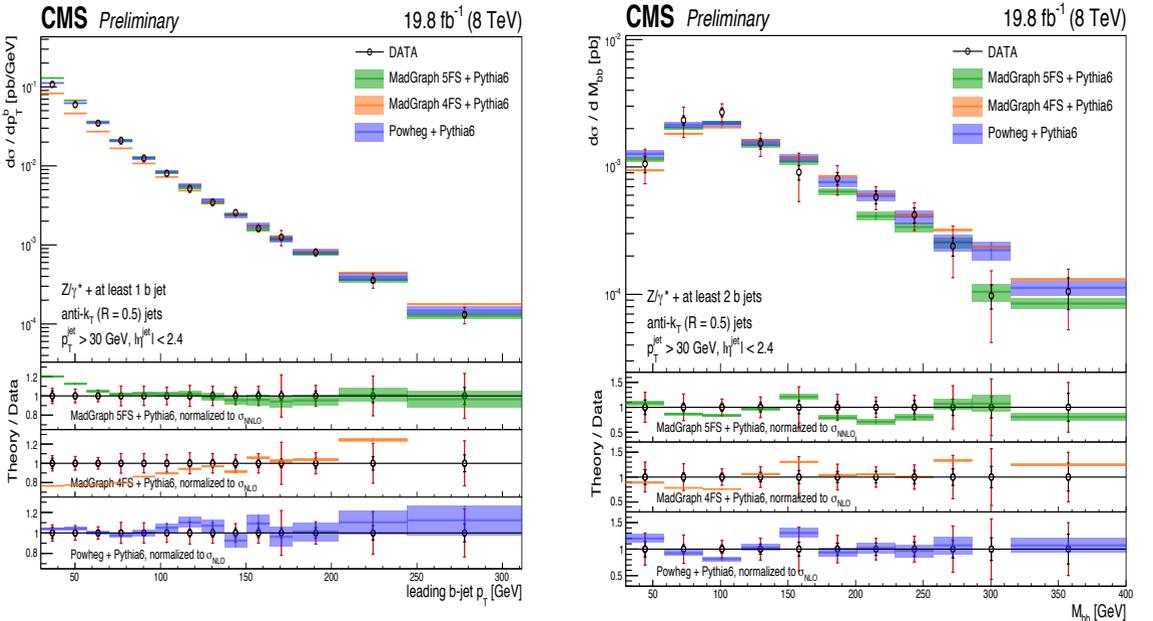


Figure 6. Differential Z+b cross sections as a function of the leading b-jet transverse momentum (left) and as a function of the bb invariant mass compared to the theoretical predictions of MadGraph 4FS and 5FS (LO) and Powheg (NLO for the leading jet) with the CMS detector.

6 Conclusions

Differential cross sections for the associated production of a W or Z boson and jets have been measured in the ATLAS and CMS experiments at a center of mass energy of 7, 8 and 13 TeV in proton-proton collisions at LHC. The W boson plus jets has been measured in ATLAS and CMS at 7 TeV and compared to several LO and NLO predictions; the Z+jets has been measured by CMS at 8 TeV, showing also the double-differential cross sections as a function of the momentum and rapidity of the leading jet, and in ATLAS at 13 TeV. The ratio between W and Z bosons plus with at least one associated jet has been measured as a function of the leading jet momentum and compared to the NLO calculations. The Z+b differential cross sections has been measured by CMS as a function of the most energetic b-jet momentum and as a function of the invariant mass of the leading and sub-leading b jet. The results have been compared to the LO predictions in the 4FS and 5FS and the NLO predictions for the first jet. All the differential cross sections measured in data presented have been unfolded to particle level in order to be compared to the theoretical predictions in perturbative QCD, allowing a test of the theoretical interpretation with collision data.

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