W/Z + JETS AND W/Z + HEAVY FLAVOR PRODUCTION AT THE LHC

A.A. PARAMONOV
for the ATLAS and CMS collaborations
High Energy Physics Division, Argonne National Laboratory,Argonne, Illinois 60439, USA

The ATLAS and CMS experiments at the LHC conduct an extensive program to study production of events with a $W^{\pm}$ or Z^0 boson and particle jets. Dedicated studies focus on final states with the jets containing decays of heavy-flavor hadrons (b-tagged jets). The results are obtained using data from proton-proton collisions at $\sqrt{s} = 7$ TeV from the LHC at CERN. The set of measurements constitute a stringent test of the perturbative QCD calculations.

1 Introduction

Production of jets in association with a massive vector boson ($W^{\pm}$ or Z^0) is a well-understood process that provides tests of calculations based on quantum chromodynamics (QCD). These events are also substantial backgrounds to standard model (SM) measurements and searches for new physics. The studies of the associated production constitute a foundation for development of perturbative QCD (pQCD) calculations and Monte Carlo (MC) simulations. The ATLAS [1] and CMS [2] experiments at the LHC have reported their results using data from proton-proton collisions at $\sqrt{s} = 7$ TeV collisions in Refs. [3,4,5,6]. Previously, the associated production of a massive vector boson and jets was studied at the Tevatron using $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The measurements at the LHC offer wider reach in momenta of the jets than the previous studies.

Production of jets containing heavy-flavor hadrons in association with a massive boson is of special interest. The results of these studies are presented in Refs. [7,8,9,10,11]. Identification of jets with decays of heavy flavor hadrons, b-tagging, was performed via reconstruction of a secondary vertex within a jets. In Ref. [10] jets were not used but B-mesons were identified via secondary vertices from $B \rightarrow D + X$ decays. The associated production of heavy-flavor hadrons is less understood than of that of light particle jets. Therefore, the experimental input is of key importance for development of the MC simulations and pQCD calculations. Also, these measurements can provide constraints on the parton density functions (PDF's).

The measurements with a $W^{\pm}$ boson and a Z^0 boson are complementary. Both final states are sensitive to similar physics processes but they are different from the experimental point of view. The experimental signatures of the two bosons are different. Identification of a $W^{\pm}$ boson requires a well-identified lepton (an electron or a muon) and large imbalance of the vector sum of transverse momenta of all reconstructed objects in event (missing-p_{T}). Identification of a Z^0 requires two oppositely-charged leptons of the same flavor (two electrons or two muons).

All the experimental results have been corrected for all known instrumental effects and are often quoted is a specific range of jet and lepton kinematics, similar to the detector acceptance. That is done to avoid prediction-dependent extrapolation and to facilitate comparisons with theoretical predictions. Theoretical calculations at next-to-leading order (NLO) in pQCD are presented for final states with a vector boson and up to four jets.

2 Backgrounds and Systematic Uncertainties

Reconstruction of the di-lepton invariant mass allows significant reduction of backgrounds to events with a Z^0 boson. The majority of observed events are from the associated production of a Z^0 and jets. The irreducible backgrounds are the top quark pair production ($t\bar{t}$), dibosons, and Wt. These are estimated using MC simulations normalized with the measured luminosity and predicted cross sections. Background with one or two non-prompt ("fake") leptons are from events with a $W^{\pm}$ bosons and associated jets and multi-jet events, correspondingly. Rates of events with "fake" leptons are obtained using control regions in data. The requirement for a jet with decay of a heavy-flavor hadron enhances the fraction of events from the $t\bar{t}$ production.

Events with a $W^{\pm}$ boson and jets are produced at a higher rate than with a Z^0 boson. The major background with a non-prompt lepton is from the multi-jet production. The background is evaluated using orthogonal control regions in data. The contribution from multi-jet events is different for the electron and muon decay modes of $W^{\pm}$ bosons. Therefore, comparison of the measured cross section from the two decay modes can provide information of biases related to the evaluation of the backgrounds. The backgrounds with a prompt lepton are from $t\bar{t}$ production, dibosons, and events with a Z^0 boson and jet. The top pair production becomes the dominant background in final states with four or more jets (the jets are counted when $p_{\mathrm{T}} > 20$, 25, or 30 GeV). The top pair production is also substantial for events with a b-tagged jet. The top pair production is the dominant background that limits our ability to measure cross section for events with a $W^{\pm}$ and two b-jets. The top background is less prominent for measurements involving a Z^0 boson in the final state.

The major systematic uncertainties are from the jet energy scale (JES) calibration and efficiency of b-tagging. The uncertainty on the JES grows rapidly when the absolute value of jet rapidity is above two.

3 Results

The high cross section of the associated production of a massive boson and jets allows detailed studies of the kinematic distributions using differential and inclusive cross sections. Such studies have been performed by the CMS [3] and ATLAS [4,5,6] collaborations. Figs. 1 and 2 illustrate the cross sections measured as a function of inclusive jet multiplicity and transverse momentum of the leading jet. The studies have been conducted for a variety of kinematic observables such as invariant mass of multiple jets, angular and rapidity separation between jets, and so on. The measured ratios of cross sections allow cancellation of major systematic uncertainties.

The measured cross sections are compared to the NLO calculations from BlackHat-Sherpa and MC simulations from Pythia, Sherpa and Alpgen matched to Herwig. The NLO pQCD predictions are found in good agreement with data. Leading-order (LO) matrix element calculations for final states with a vector boson and up to five partons are matched to parton showering in Sherpa and Alpgen+Herwig. These two generators are also in good agreement with data.

Production of a charm hadron in a jet and a $W^{\pm}$ boson is reported in Ref. [11]. The study has sensitivity to the strange quark PDF. Ratios of cross sections were measured to be $\sigma(W^{+}\bar{c}+X)/\sigma(W^{-}c+X) = 0.92\pm0.19(\text{stat.})\pm0.04(\text{syst.})$ and $\sigma(Wc+X)/\sigma(W+jet+X) = 0.143 \pm 0.015(\text{stat.})\pm0.024(\text{syst.})$. The ratios are measured in the kinematic region $p_{\mathrm{T}}^{\text{jet}} > 20$ GeV, $|\eta^{\text{jet}}| < 2.1$ for $W \to \mu\nu$ decays. The measured results are in agreement with theoretical predictions at NLO based on available parton distribution functions.

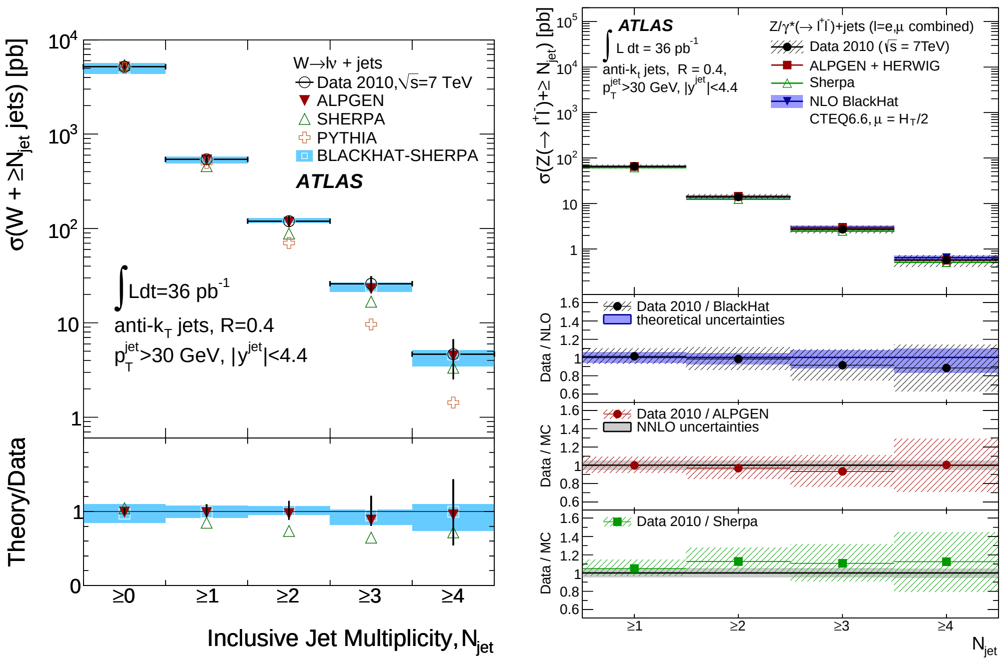

Figure 1: Measured cross sections as a function of jet multiplicity for events with a $W^{\pm}$ boson [6] (left) and with a Z^0 boson [5] (right). The solid bands correspond to the systematic uncertainties on the predicted cross sections.

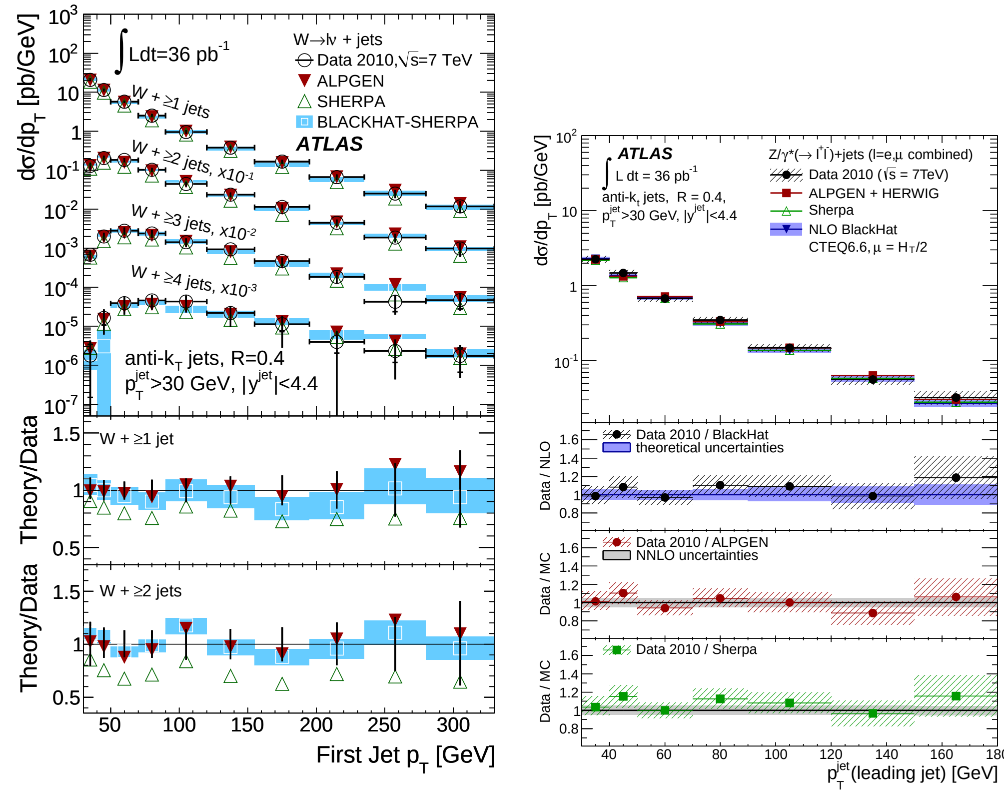

Figure 2: Measured cross sections as a function of p_{T} of the leading jet for events with a $W^{\pm}$ boson [6] (left) and with a Z^0 boson [5] (right). The solid bands correspond to the systematic uncertainties on the predicted cross sections.

Studies of the associated production of jets with decays of B mesons (b-jets) are described in Refs. [7,8,9]. These final state are backgrounds to the associated Higgs production; $pp \to HW$ and $pp \to HZ$, where $h \to b\bar{b}$. The results for production of a b-jet and a $W^{\pm}$ boson are presented in Fig. 3. The measured cross section slightly exceeds the predicted value for final states with a single b-jet and another jet. Ref. [7] presents cross sections for one and two b-jets with $p_T^{\rm jet} > 25$ GeV and $\eta^{\rm jet} < 2.1$. The measured cross sections are $\sigma(Z^0 + 2\,b\text{−jets} + X) = 0.37 \pm 0.02(\text{stat.}) \pm 0.07(\text{syst.}) \pm 0.02(\text{theory})$ pb and $\sigma(Z^0 + b\text{−jet} + X) = 3.78 \pm 0.05(\text{stat.}) \pm 0.31(\text{syst.}) \pm 0.11(\text{theory})$ pb. The cross section for two b-jets is in agreement with LO pQCD predictions.

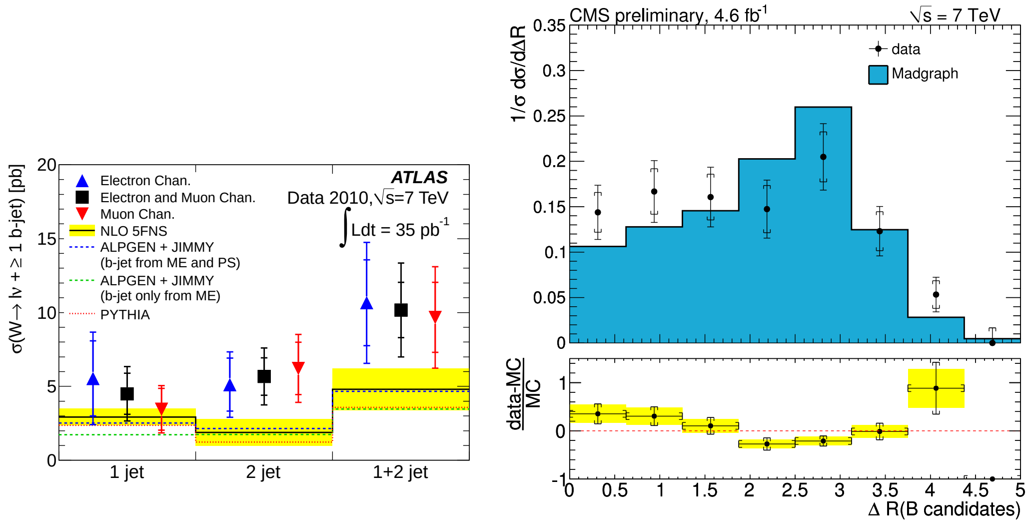

Figure 3: Exclusive cross sections for events with a b-jet and a $W^{\pm}$ (left) from ATLAS [8]. Distribution in angular separation, ΔR, between B meson candidates in events with a Z^0 (right) from CMS [10].

The study of the angular correlations between two B hadrons produced in association with a Z^0 boson is presented in Ref. [10]. Identification of B-hadron candidates utilizes displaced secondary vertices without involving jets. That allows to analyze production of B hadrons at small angular separation. The normalized production cross section as function of the angular separation is compared with QCD predictions at tree-level in Fig 3. The measurement is performed in the kinematic region defined for B hadrons with $p_{\rm T} > 15$ GeV and $|\eta| < 2$. This study gives further insight into the properties of heavy quark pair-production in association with a neutral vector bosons.

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