The Compact Muon Solenoid Experiment

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V+jets from CMS

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Abstract

The production of vector bosons ($V = W, Z$ or γ) in association with jets is a stringent test of perturbative QCD and is a background process in searches for new physics. Total and differential cross-section measurements of vector bosons produced in association with jets (and heavy flavour quarks) are presented. The data have been recorded with the CMS detector at the LHC and are compared to next-to leading order calculations and event simulations that devise matrix element calculations interfaced with parton showers.

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Abstract

The production of vector bosons ($V = W, Z, \text{ or } \gamma$) in association with jets is a stringent test of perturbative QCD and is a background process in searches for new physics. Total and differential cross-section measurements of vector bosons produced in association with jets (and heavy flavour quarks) are presented. The data have been recorded with the CMS detector at the LHC and are compared to next-to(-next-to)-leading-order calculations and event simulations that devise matrix element calculations interfaced with parton showers.

Keywords: CMS, physics, W+jets, Z+jets, vector boson, jets, electroweak, standard model

1. Introduction

Vector bosons ($V = W, Z, \text{ or } \gamma$) produced in association with jets (V+jets) provide important test of perturbative quantum chromodynamics (QCD) calculation. Precise measurements of these processes can improve the validation and tuning of the models used in Monte Carlo (MC) simulation. Such measurements also provide crucial inputs in the determination of parton distribution functions (PDFs). The V+jets process itself is a background process for both the Higgs boson production and for many searches of physics beyond the standard model (SM). Therefore, a thorough study of these processes is vital at the LHC. Measurements of V+jets from CMS detector [1] using proton-proton collision data collected at $\sqrt{s} = 8 \text{ TeV}$ and 13 TeV are reported. The collision data corresponds to integrated luminosities of $< 20 \text{ fb}^{-1}$ and 2.5 fb^{-1} respectively. The measured cross sections are unfolded to particle level in order to correct for detector effects. The measurements are compared to predictions from MC generators

and fixed-order calculations. In the case of fixed-order calculations where parton-level prediction is provided, a nonperturbative correction is applied before comparing to measurements.

2. Z+jets

Differential cross section measurements of associated production of Z bosons with jets using pp collision data of 2.5 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ are presented [2]. The differential cross sections are measured as a function of jet transverse momenta (p_T), jet absolute rapidity ($|y|$) and scalar sum of p_T of jets in an event (H_T) up to the inclusive jet multiplicities of 3. Jets have $p_T > 30 \text{ GeV}$ and $|y| < 2.4$. Z bosons are identified via their decays into $\mu^+\mu^-$ pairs. The measurements are compared to the prediction from MADGRAPH5_AMC@NLO [3] interfaced with PYTHIA 8 [4] which is an event generator devising next-to-leading-order (NLO) matrix element calculations up to 2 additional partons merged using FxFx scheme. The measurements are also compared to a next-to-next-to-leading-order (NNLO) calculation for $Z + 1\text{jet}$ [5]. The jet multiplicity distribution is shown in Figure 1. Figure 2 shows the highest- p_T jet p_T distribution. Good agreement with multileg NLO generator and NNLO calculation are observed.

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A more comprehensive analysis where kinematic distributions of jets are studied up to the inclusive jet multiplicities of 5 has been performed with $\sqrt{s} = 8$ TeV data corresponding to integrated luminosity of 19.6 fb^{-1} [6]. Additionally, the double differential cross section with respect to transverse momentum and rapidity of the highest p_T jet, where the rapidity region of the jets is extended to $|y| \leq 4.7$, is measured [7] as shown in Figure 3. Theoretical predictions used in comparison are MADGRAPH [8] interfaced with PYTHIA 6 [9] and SHERPA 2 [10].

Figure 1: Measured Z+jets cross section as a function of inclusive jet multiplicity, compared to the prediction of MadGraph5_AMC@NLO.

3. W+jets

The production of W bosons in association with jets has been studied in pp collision at $\sqrt{s} = 8$ TeV for jets with $p_T > 30 \text{ GeV}$ and $|\eta| < 2.4$ [11]. The data used corresponds to integrated luminosity of 19.6 fb^{-1} . The W bosons are identified by their subsequent decay into a muon and a neutrino yielding the final state with one high p_T isolated muon and significant missing transverse energy (E_T^{miss}). Muons are required to have $p_T > 25 \text{ GeV}$ and $|\eta| < 2.1$. The results of up to 7 jets on jet multiplicity distributions and up to inclusive 4 jets on

Figure 2: Cross sections differential in p_T of the leading jet for inclusive jet multiplicity of 1, compared to the predictions of MadGraph5_AMC@NLO and NNLO inclusive one-jet production (indicated as NNLO1j).

observables are presented. The measurements are compared to several predictions including multileg event generators and fixed-order parton-level calculations. The generators used are MadGraph [8] interfaced with PYTHIA 6 [9], which uses a leading-order (LO) matrix element calculation, MadGraph5_AMC@NLO [3] + PYTHIA 8 [4] and SHERPA 2 [10], which use NLO matrix element calculations. The differential cross sections are also compared with the NLO parton-level predictions of BlackHat+SHERPA [12] and with a NNLO calculation for the production of W + 1 jet [5, 13]. Good agreement is observed with MadGraph5_AMC@NLO and (NNLO and NLO) fixed order calculations. Figure 4 shows the inclusive jet multiplicity distribution. Figure 5 shows the H_T distribution for events with $N_{\text{jet}} \geq 1$. BlackHat+SHERPA underestimates the data at high H_T as expected since it is fixed-order prediction with maximum of 2 jets and contributions from higher jet multiplicities is missing. Figure 6 shows differential cross section as a function of the rapidity difference between the leading- p_T and subleading- p_T jets.

Figure 3: Double differential cross section versus leading jet transverse momentum for various rapidity bins in the di-muon channel. The black lines are MadGraph predictions normalized to the inclusive NNLO cross-section. The SHERPA 2 predictions is shown as blue band whose thickness indicates the statistical uncertainty.

4. W + 2b quark jets

Measurement of the W boson production cross section in association with two b jets in pp collisions at $\sqrt{s} = 8$ TeV is studied with data corresponding to integrated luminosity of 19.8 fb^{-1} [14]. The W bosons are reconstructed via their leptonic decays to muons and electrons channel. The resulting cross section for the combined lepton channels is $0.69 \pm 0.02(\text{stat}) \pm 0.11(\text{syst}) \pm 0.07(\text{theo}) \pm 0.02(\text{lumi})$ pb. The measurement is compared to theoretical predictions including MCFM [15, 16] (corrected for hadronization), MadGraph 5 [8]+PYTHIA 6 in the four- and five-flavour schemes (FS), and MadGraph 5+PYTHIA 8 in the four-flavour scheme. The resulting cross section predictions in the fiducial volume at the hadron level and including the estimated hadronization and DPS corrections when needed are compared in Figure 7 with the measured value. The predictions agree with the measured cross section within one standard deviation.

5. Z + b quark jets

The measurement of the production of a Z boson in association with at least one jet originating from a b quark in proton-proton collisions at $\sqrt{s} = 8$ TeV is presented [17]. Differential cross sections are measured on data for a total integrated luminosity of 19.8 fb^{-1} using Z boson decays into electrons or muons, and identified b quark jets. Cross sections are measured in combined

Figure 4: Measured W+jets cross section as a function of inclusive jet multiplicity, compared to the predictions of MadGraph, MadGraph5_AMC@NLO, SHERPA 2, and BLACKHAT+SHERPA..

lepton channels as a function of observables characterizing the b jet and Z boson kinematics, and ratios of differential cross sections for the associated production with at least a b jet and with any jet are presented. The measured fiducial cross sections for events with at least one b jet, noted as Z(1b), and with at least two b jets noted as Z(2b) are $3.55 \pm 0.12(\text{stat.}) \pm 0.21(\text{syst.})$ pb and $0.331 \pm 0.011(\text{stat.}) \pm 0.035(\text{syst.})$ pb respectively. The ratio of the cross sections in the fiducial phase space for the production of at least two and at least one b jet is $(9.3 \pm 0.4(\text{stat.}) \pm 0.7(\text{syst.})) \times 10^{-2}$. Results are compared to theoretical predictions including MadGraph 5+PYTHIA 6 in the four- and five-flavour schemes and NLO POWHEG [18] in the five-flavour scheme. An overall good agreement is observed between unfolded data and the 5FS-based theoretical calculations for the Z(1b) final state in most of the ranges of the measured observables. Figure 8 shows the differential Z(1b) cross section as a function of the leading b jet p_T .

6. Photon (γ) + jets

The differential cross sections for the process $Z/\gamma^* + \text{jets}$ and photon (γ) + jets is presented. The measure-

Figure 5: Cross sections differential in H_T for inclusive jet multiplicity of 1, compared to the predictions of MADGRAPH, MADGRAPH5_aMC@NLO, SHERPA 2, BLACKHAT+SHERPA, and NNLO1j.

ments are based on data at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 19.7 fb^{-1} [19]. The differential cross sections and their ratios are presented as functions of p_T^V of the vector bosons ($V = Z$ or γ) for inclusive jet multiplicities of 1 and 2. The analysis also presents the ratio p_T^Z/H_T , $\log_{10}(p_T^Z/p_T^{j1})$, and the inclusive 1-jet over inclusive 2-jet p_T^V cross section ratio. For $\gamma + \text{jets}$, the γ has $p_T > 20$ GeV and $|\eta| < 1.4$. Jets have $p_T > 30$ GeV and $|\eta| < 2.4$. The measurements are compared to theoretical predictions including MADGRAPH+PYTHIA 6 and BLACKHAT. Figure 9 shows the measured p_T^γ spectrum for $N_{\text{jets}} \geq 1$ compared to theoretical predictions. There are deviations for low p_T values, and NLO BLACKHAT does better than LO MADGRAPH in describing the data.

7. Conclusion

CMS has an active physics program to measure vector boson production in association with jets including heavy flavour jets providing precision tests for perturbative QCD calculation. The data delivered by LHC at 8 TeV allows possibility to probe extreme kinematics

Figure 6: Cross sections differential in $\Delta y(j_1, j_2)$ for inclusive jet multiplicities of 2, compared to the predictions of MADGRAPH, MADGRAPH5_aMC@NLO, SHERPA 2, and BLACKHAT+SHERPA.

Figure 7: Comparison between the measured $W+b\bar{b}$ cross section and various QCD predictions. The blue error bars on the predictions represent the uncertainty in the given sample associated with PDF choice and the black bars represent the total uncertainty. In the case of the MADGRAPH+PYTHIA 6 (5F) sample, the effects of double parton interaction (DPS) are already included in the generated sample so the extra DPS factor was not needed and the blue and black error bars overlap perfectly.

Figure 8: Differential Z(1b) cross section as a function of the leading- p_T b jet p_T compared with the MADGRAPH 5FS, MADGRAPH 4FS and POWHEG theoretical predictions (shaded bands).

Figure 9: Differential cross section for photon production as a function of p_T^γ for an inclusive γ +jets, $N_{\text{jets}} \geq 1$ selection for central rapidities $|\eta| < 1.4$, compared with predictions from MADGRAPH+PYTHIA 6 and BLACKHAT. The bottom plots give the ratio of the various theoretical predictions to the data.

that were not previously accessible. The early results of Z+jets at 13 TeV is also presented. Measured V+jets differential cross sections in various observables have been compared to several predictions. In general, better agreement is observed with higher order (NLO or NNLO) predictions than LO predictions.

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