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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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(-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, or γ) produced in association with jets (V+jets) provide an 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. These measurements also provide crucial inputs in the determination of the 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 $\sqrt{s} = 8$ TeV and 13 TeV are reported. The collision data corresponds to integrated luminosities of < 20 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.

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 $\sqrt{s} = 13$ 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 $p_T > 30$ 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 + 1jet [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].

The production of W bosons in association with jets has been studied in pp collision at $\sqrt{s} = 8$ TeV for jets with $p_T > 30$ GeV and $|y| < 2.4$ [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 $p_T > 25$ GeV and $|y| < 2.1$. The results of up to 7 jets on jet multiplicity distributions and up to inclusive 4 jets on observables are presented. The measurements are compared to several predictions including multi-leg 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 $N_{jet} \geq 1$. 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. Fugure 6 shows differential cross section as a function of the rapidity difference between the leading-$p_T$ and subleading-$p_T$ jets.

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 $p_T > 30$ GeV and $|y| < 2.4$ [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 $p_T > 25$ GeV and $|y| < 2.1$. The results of up to 7 jets on jet multiplicity distributions and up to inclusive 4 jets on observables are presented. The measurements are compared to several predictions including multi-leg 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 $N_{jet} \geq 1$. 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. Fugure 6 shows differential cross section as a function of the rapidity difference between the leading-$p_T$ and subleading-$p_T$ jets.
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 an 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 $0.69 \pm 0.02$ (stat) $\pm 0.11$ (syst) pb. The measurement is compared to theoretical predictions including MC@NLO [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 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 $3.55 \pm 0.12$ (stat.) $\pm 0.7$ (syst.) pb and $0.331 \pm 0.011$ (stat.) $\pm 0.035$ (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 $(9.3 \pm 0.4$ (stat.) $\pm 0.7$ (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/γ* + jets and photon (γ) + jets is presented. The measure-
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 $p_T$ of the vector bosons ($V=Z$ or $\gamma$) for inclusive jet multiplicities of 1 and 2. The analysis also presents the ratio $p_T^2/\sigma_T$, $\log(p_T^2/H_T^2)$, and the inclusive 1-jet over inclusive 2-jet $p_T^2$ cross section ratio. For $\gamma +$ jets, the $\gamma$ 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 $p_T$ 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 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 NNLO inclusive one-jet production (indicated as NNLO1j).

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 $W+\text{b}\bar{\text{b}}$ 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(b) 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 func-
tion of $p_T^\gamma$ for an inclusive $\gamma$+jets, $N_{\text{jet}} \geq 1$ selection for central rapidi-
ties $|y| < 1.4$, compared with predictions from MadGraph+PYTHIA
6 and BlackHat. The bottom plots give the ratio of the various theo-
etical 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, bet-
er agreement is observed with higher order (NLO or
NNLO) predictions than LO predictions.

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