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Vector boson production in association with jets at CMS

Metin Yalvac for the CMS Collaboration

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The production cross section of highly boosted vector bosons (V = W, Z or gamma) recoiling against jets is studied, with CMS data, differentially as function of the transverse momentum and angular correlations of the final state particles. The measurements are confronted with different state-of-the-art theory predictions that include next-to-leading order calculations and matrix-element plus parton shower event simulations.

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Vector boson production in association with jets at CMS *

Metin Yalvac[a,b,1,2], Kadir Ocalan[c,2]

[a] *Middle East Technical University, Ankara, TURKEY*
[b] *Yozgat Bozok University, Yozgat, TURKEY*
[c] *Necmettin Erbakan University, Konya, TURKEY*

Abstract

The production cross section of highly boosted vector bosons (V = W, Z or γ) recoiling against jets is studied, with CMS data, differentially as function of the transverse momentum and angular correlations of the final state particles. The measurements are confronted with different state-of-the-art theory predictions that include next-to-leading order calculations and matrix-element plus parton shower event simulations.

Keywords: Standard model physics, Vector boson+jets, Perturbative quantum chromodynamics

1. Introduction

Vector boson (W/Z/γ) plus jets (V+jets) production processes play an important role at hadron colliders by means of probing the fundamental structure of the strong and electroweak (EW) interactions. Vector boson productions have a clear experimental signatures and larger cross sectionsin proton-proton (pp) collisions at the CERN Large Hadron Collider (LHC). Measurements of V+jets processes including regions at high transverse momentum p_T and high jet multiplicities provide a valuable information for other Standard Model (SM) and beyond the SM processes in which V+jets productions constitute an important background. Besides, measurements of V+jets processes enable precision tests of perturbative quantum chromodynamics (pQCD) sector of the SM. Comparisons of the V+jets measurements with the predictions from Monte Carlo (MC) based event generators and higher-order theoretical calculations allow improving those predictions for accurate description of experimental data. Furthermore, precise measurements of such processes provide substantial inputs for constraining parton distributions functions (PDFs) in the proton. In this report, the latest results of the V+jets measurements are presented, based on 8 TeV (2012) and 13 TeV (2015, 2016) pp collision data, from the Compact Muon Solenoid (CMS) experiment [1] at the LHC.

2. W+jets at 13 TeV

The differential measurement of the W+jets production at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 2.2 fb^{-1} is presented [2]. The muon decay channel $W(\mu\nu)$+jets is used in this analysis. The differential cross sections are measured as functions of the exclusive and inclusive jet multiplicities up to 6 jets. The differential cross sections are measured as functions of the jet p_T, the jet rapidity $|y|$, and the scalar p_T sum of the jets H_T for the events with inclusive four jets. The differential cross sections are also measured for the angular correlation variables including the azimuthal correlation between the muon and the closest jet and for the $\Delta\varphi(\mu, j_i)$ variable, where the ith jet is ordered in p_T.

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Email addresses: myalvac@cern.ch (Metin Yalvac), kadir.ocalan@cern.ch (Kadir Ocalan)

[1] Speaker

[2] On Behalf of the CMS Collobration.

The measured W+jets differential cross sections are compared with multileg matrix element (ME) predictions at leading-order (LO) and next-to-LO (NLO). MADGRAPH5_aMC@NLO (MG5_aMC) generator using the FxFx merging scheme is interfaced with PYTHIA8 for parton showering and hadronisation. The measured differential cross sections are also compared with the fixed-order calculation based on the N-jettiness subtraction scheme (N_{jetti}) at next-to-NLO (NNLO) for W+1-jet production. The nonperturbative correction is included in the NNLO prediction.

The measured differential cross sections are unfolded to the particle level. The phase space is restricted to events with a muon with $p_T > 25$ GeV and $|\eta| < 2.4$. The events are further required to be in the transverse mass peak region of the W boson, defined by $m_T > 50$ GeV. Jets are required to have $p_T > 30$ GeV, $|y| < 2.4$ and a spatial separation from the muons by the requirement of ΔR> 0.4.

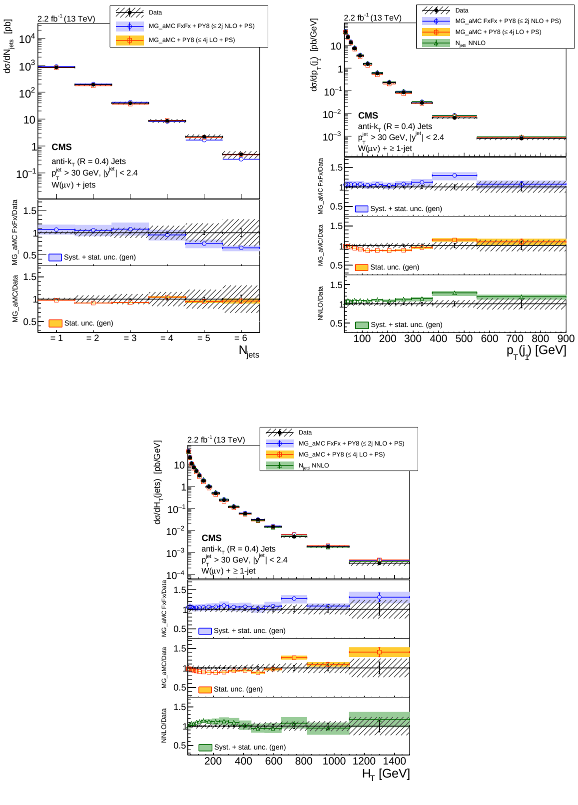

Figure 1: Measured W+jets differential cross section as functions of the exclusive jet multiplicity (top left) up to 6 jets and the leading jet pT (top right) and the scalar p_T sum of the jets H_T (bottom) for events with at least one jet [2].

Figure 1 shows that the first differential measurement of the cross sections for a W boson produced in association with jets in pp collisions at a center-of-mass energy of 13 TeV. MG5_aMC N(LO) predictions at LO and NLO agree well with data for the jet multiplicity within uncertainties. The leading jet p_T and the H_T data distributions are well described by the predictions including the NNLO calculation.

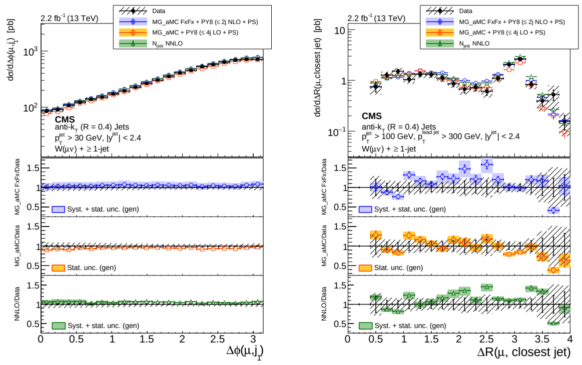

Figure 2: Measured W+jets differential cross section as functions of angular variables $\Delta\varphi(\mu, j_1)$ (left) and ΔR(μ, closest jet) (right) for events with at least one jet [2].

Figure 2 shows the differential cross sections as functions of angular variables. The azimuthal separation $\Delta\varphi(\mu, j_1)$ between the muon and the jet, is sensitive to the implementation of particle emissions and other nonperturbative effects modeled by parton showering algorithms in MC generators. The angular distance between the muon and closest jet ΔR(μ, closest jet) in events with one or more jets probes contribution of EW radiative processes to W+jets using the information on angular correlation between the muon emitted in the W boson decay and the direction of the closest jet. In the collinear region (small ΔR values), it is sensitive to the modeling of W boson radiative emission from initial or final state quarks. For the analysis of the ΔR distribution, jets in the event are required to have $p_T > 100$ GeV, with the leading jet $p_T > 300$ GeV. This selection results in a boosted event topology, where two jets recoil against each other and one of them can lose a significant amount of energy to the decay products through the real W boson emission. Both $\Delta\varphi(\mu, j_1)$ and ΔR(μ, closest jet) data distributions are described reasonably by the predictions within the uncertainties.

3. Z+jets at 13 TeV

The measurement of the differential cross sections is presented for Z(ll)+jets production as functions of numerous observables in the combined dielectron and dimuon channels at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 2.2 fb^{-1} of data recorded in 2015[3]. Event selections used within the Z boson mass window of 71 to 111 GeV and lepton p_T > 20 GeV where lepton $|\eta| < 2.4$ with jet $p_T > 30$ GeV and jet $|y| < 2.4$.

The measured Z+jets differential cross sections are compared with different predictions. The predictions by the MG5_aMC are interfaced with PYTHIA8 and includes MEs computed at LO up to four additional partons using the k_T-MLM merging scheme and MEs computed for at NLO up to two additional partons using FxFx merging scheme. The PYTHIA8 tune CUETP8M1 is used for both MG5_aMC predictions. The prediction by GENEVA1.0-RC2 MC program (GE) employs an NNLO calculation for DrellYan (DY) production which is combined with higher-order resummation. Logarithms of the 0-jettiness resolution variable, τ, also known as beam thrust, are resummed at Next-to-next-to-leading-logarithm $NNLL'$ (denoted by $NNLL'_\tau$). The PYTHIA8 tune CUETP8M1 is used in this prediction as well. The last prediction obtained by performing the calculation at NNLO calculation for Z+1-jet using the N-jettiness subtraction scheme (N_{jetti}). Nonperturbative corrections are applied in the N_{jetti} NNLO prediction.

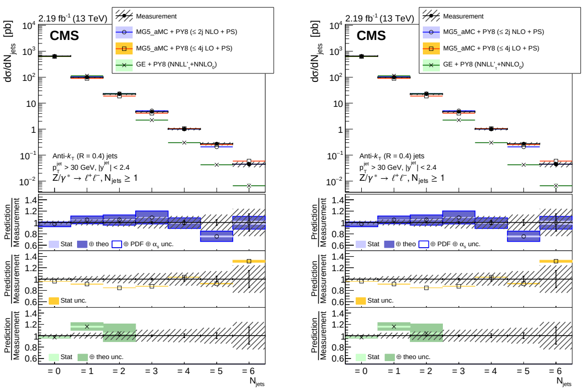

Figure 3: The measured Z+jets differential cross sections as functions of the jet multiplicity (left) and p_T of the leading jet (right), compared with various predictions [3].

Reasonable agreement is achieved between the measured and the predicted differential cross sections as a function of the jet multiplicity as shown in Figure 3. The GENEVA prediction describes the measured cross section up to a jet multiplicity of 2, but fails to describe the data for higher jet multiplicities. The measured leading jet p_T is not well reproduced at LO by the MG5_aMC prediction, where the data is underestimated especially in the low p_T region. The comparison with MG5_aMC at NLO and N_{jetti} NNLO predictions show that adding (N)NLO terms provides improved agreement with the data. The GENEVA prediction overall shows good agreement with the data within the uncertainties.

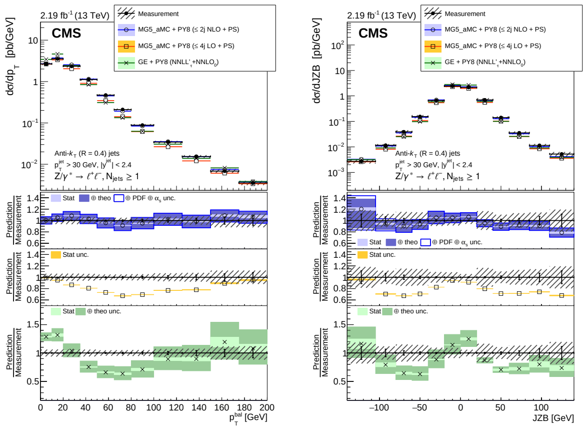

Figure 4: Measured Z+jets cross section as functions of the p_T balance (left) and Jet-Z balance (JZB) (right) between the Z boson and the accompanying jets compared with various predictions [3].

The differential cross sections for the balance in transverse momentum between the reconstructed jet and the Z boson are given in terms of p_T balance p_T^{bal} and the jet-Z boson balance (JZB) as shown in Figure 4 for events with at least one inclusive jet. The measurement of p_T^{bal} and JZB are sensitive to modeling of soft gluon radiation. The MG5_aMC prediction at NLO better describes the imbalance between the Z and the p_T of the jets which is either due to hadronic activity beyond the jet acceptance or due to lack of modeling for gluon radiation.

4. γ+jets at 13 TeV

Measurements of inclusive isolated photon and photon+jets productions using a data sample at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 2.2 fb^{-1} recorded in 2015 are presented

[4]. Measurements of differential production cross sections for such processes are important to probe directly the dynamics of hard scattering process and are sensitive for constraining gluon PDF in proton. Prompt photons at hadron colliders are produced via quark-gluon Compton scattering qg→qγ, quark-antiquark annihilation q$\bar{q}$→gγ, and parton fragmentation q$\bar{q}$(gg)→ $\gamma + X$ processes. In this study, the differential cross sections for the inclusive isolated photon production are measured as functions of the photon p_T and rapidity y. Furthermore, the differential cross sections for the photon+jets production are measured as functions of the photon p_T, the photon y, and the jet y for the jet with highest p_T.

The measured double differential cross sections for the inclusive γ production and the triple differential cross sections for the γ+jets production are compared with the QCD NLO prediction by the JETPHOX generator using NNPDF3.0 NLO PDF set.

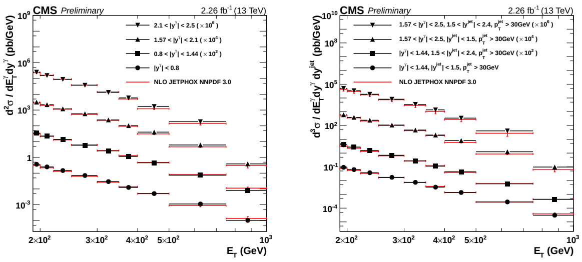

Figure 5: The measured double differential cross sections for isolated photon production (left) and the measured triple differential cross sections for photon+jets production (right) as a function of the photon E_T in different photon rapidity bins [4]. The measurements are compared with JETPHOX predictions at NLO accuracy.

Reasonable agreement is achieved between JETPHOX NLO predictions and γ(+jets) data for both the inclusive isolated photon production and the photon+jets production processes as shown in Figure 5. Results also show a good theory-to-data comparisons within the uncertainties in different rapidity bins. Effects of different PDF sets are also considered for both the isolated γ and γ+jets production and no sizeable difference found in theory-to-data comparisons for different PDF sets. Figure 6 shows the comparisons of the different PDF sets for both isolated γ and γ+jets processes.

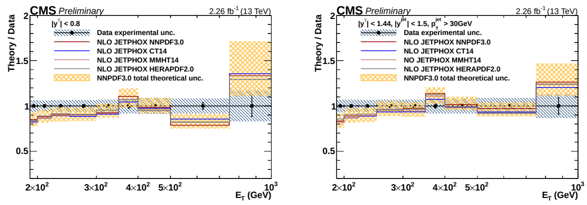

Figure 6: Theory-to-data cross section ratios using different PDF sets for inclusive isolated photons (left) and photon+jets (right) productions [4].

5. V+HF-jets

5.1. W+c-jet at 13 TeV

Inclusive and differential cross section measurements of the associated production of a W boson and a charm quark-jet (W+c) based on a data sample at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}, recorded in 2016 are presented [5]. The total and the differential cross sections are measured, where the latter is measured as a function of the absolute pseudorapidity η of the muon. Results are compared with theoretical predictions using different PDF sets and can be are used to probe the strange quark content of the proton.

In this measurement W bosons are identified by their decays into a muon and a neutrino. The charm quarks are tagged through the full reconstruction of D*(2010)$^\pm$ mesons in their decays D*(2010)$^\pm$→D$^0\pi^\pm{}_{slow}$→K$^\mp\pi^\pm\pi^\pm{}_{slow}$. The measurements are performed for the muon $p_T > 26$ GeV in the acceptance of $|\eta(\mu)| < 2.4$ and for the c-jet $p_T > 5$ GeV. The measurements are compared with MCFM6.8 QCD NLO predictions using various PDF sets as summarized in Figure 7.

5.2. Z+c-jet at 8 TeV

Measurements of the associated production of a Z boson and a charm quark jet (Z+c), and comparisons to the associated production with a bottom quark jet (Z+b) are presented based on 8 TeV data corresponding to an integrated luminosity of 19.7 fb^{-1} are presented [6]. The Z+c production cross section and the cross section ratio are also measured as a function of the p_T of the Z boson and of the heavy flavour jet. HF-quark jets are identified using three signatures: semileptonic decay mode and hadronic decays of charm hadrons D$^\pm$→K$^\mp\pi^\pm\pi^\pm$ and D*(2010)$^\pm$→D^0($\overline{\text{D}}^0$)$\pi^\pm$ (where D^0($\overline{\text{D}}^0$)→K$^\mp\pi^\pm$).

The measurements of the $Z(ll) + 1c$ associated production are performed in fiducial phase space of the

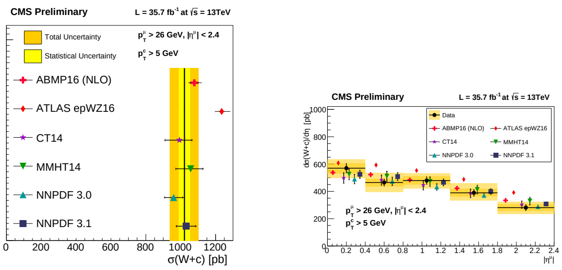

Figure 7: Total cross section (left) and differential cross section (right) measurement for the W+c-jets production. The measured cross sections are compared with the MCFM6.8 NLO predictions using different PDF sets [5].

isolated leptons with $p_T(l) > 20$ GeV, $|\eta(l)| < 2.1$, dilepton invariant mass window $71 < m_{ll} < 111$ GeV and at least one c or b jet with $p_T(j) > 25$ GeV and $|\eta(j)| < 2.5$. The differential cross section measurments of the Z+c and the Z+c/Z+b ratio are compared with the predictions by MG5_aMC at LO and NLO and by MCFM with different PDF sets. Figure 8 shows the differential cross section of the Z+c (left) and Z+c/Z+b ratio (right) as a function of Z boson p_T. The MG5_aMC (N)LO+PYTHIA 6(8) predictions describe well the measurement. MCFM fixed order calculation at NLO (using different PDF sets) predicts smaller cross section both inclusively and differentially. Figure 8 also shows that all predictions reproduce the data in Z+c/Z+b cross section ratio better.

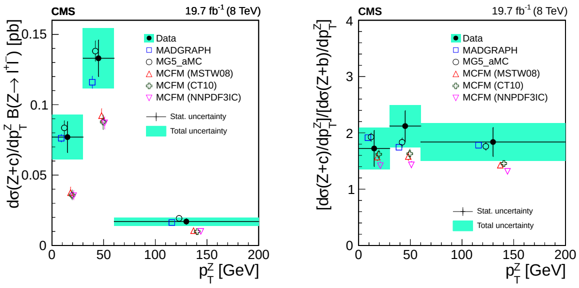

Figure 8: Differential cross section for the Z+c (left) and differential cross section for the ratio Z+c/Z+b (right) as a function of Z boson p_T [6].The measured distributions are compared with the predictions from MG5_aMC at (N)LO and from MCFM NLO fixed-order calculation [6].

6. EW Z+2-jets at 13 TeV

Measurement of the EW production of two jets in association with a Z boson using datasets at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 35.9 fb^{-1} recorded in 2016 is presented[7]. The pure EW production of the Z(ll)+2-jets final state (where l corresponds to both electron and moun) is characterized by the production of a Z boson in association with two high-p_T jets with large separation in η and low hadronic activity in-between. A multivariate analysis (MVA) method is used to separate EW Z+2-jets signal events from the large DY+jets strong processes. Several discriminating variables are used in this method to achieve the best separation.

The MVA output is built by training a boosted decision tree (BDT) to achieve separation in the dielectron and dimuon channels separately. The fit for the BDT output distribution of the signal and the background compositions in the dimuon channel is shown in Figure 9. Using events in the signal-enriched region with BDT>0.92, the gap veto efficiency, which is defined as fraction of events which do not have reconstructed kinematics above a given threshold of the third jet, is also shown in Figure 9. Measurements are compared with DY+jets signal events generated with the PYTHIA8 or the HERWIG++ parton shower models. Data disfavor background only predictions and are in reasonable agreement with the presence of the signal for both parton shower predictions. This is the first cross section measurement for this process at 13 TeV which tests the gauge structure of the EW sector and is sensitive to anomalous trilinear gauge couplings (aTGC) searches. This measurement shows no evidence for the aTGC but suggests a limit on aTGC.

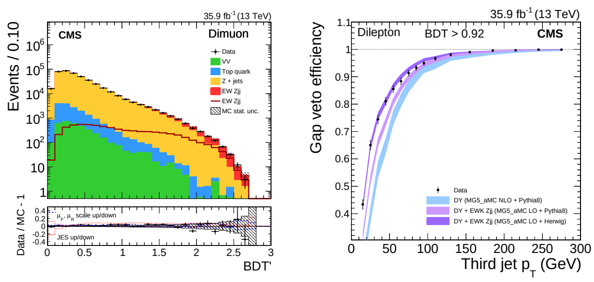

Figure 9: The signal and background distributions including the fit in the BDT output (left) in the dimuon decay channel and the gap veto efficiency in the combined lepton channel as a function of the third jet p_T (right) distinguishing among parton shower models [7].

7. Summary

The CMS Collaboration has provided a broad range of V+jets measurements by exploiting 8/13 TeV pp collision data at the LHC. The CMS V+jets measurements deepen our understanding of QCD and EW processes and their theoretical modeling. Particularly, these measurements enable precise tests of pQCD predictions and nonperturbative effects and provide valuable inputs to the modeling of the proton PDFs (such as s, c, and b quark PDFS by V+HF-jets, gluon PDF from γ+jets measurements) and to the background modeling for Higgs and new physics studies. High precision has been achieved in the CMS measurements of inclusive and differential cross sections and ratios of cross sections using new experimental methods and larger datasets. The measurements are compared with a large number of different predictions and with predictions using several dedicated PDF sets. The measured cross sections are compared with several predictions by the ME calculations, parton shower models, and (N)NLO fixed-order theoretical calculations. The measurements are generally in good agreement with the predictions for the variables that are probed where better descriptions of the data are provided by the ME calculations at NLO and the fixed-order NNLO calculations. Higher precision is achieved in differential cross section measurements. To this end, there is still need to improve modeling and precisions for the remained discrepancies and to constrain experimental uncertainties using larger datasets with the ongoing and near future CMS V+jets measurements.

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