PROCEEDINGS OF SCIENCE

Production of vector bosons in association with jets at the CMS experiment

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The study of the production of vector bosons in association with jets is of importance for the understanding of QCD, and for the modelling of backgrounds in searches for yet undiscovered particles in similar final states. These proceedings describe the most recent results obtained with the CMS detector for the studies of vector bosons produced in association with both light and heavy-flavor quark jets. Focus is put on the discrepancies in comparisons of data with theoretical predictions.

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1. Introduction

The study of the production of vector bosons in association with jets (V+jets) is of importance for a precise understanding of QCD. Furthermore, it is a background in many searches for yet undiscovered particles, e.g those predicted by supersymmetry and exotic models, and the studies can serve as a candle for these models. It is also relevant for studies of properties of the recently discovered 125 GeV boson in the same final state. In these proceedings the most recent V+jets measurements by the CMS collaboration are described. A complete overview can be found at [1].

2. Vector bosons + light jets

To study the Z+jets final state, Z candidates are reconstructed using electrons and muons with $p_T(l) > 20$ GeV, and an opposite-sign, same flavor pair is required to have an invariant mass $71 < m(ll) < 111$ GeV. Jets are obtained from constituents reconstructed with the particle-flow algorithm [2], combining the information from all sub-detectors of the CMS detector [3], and employing the anti-k$_T$ algorithm with a cone size of 0.5 [4]. Requiring the jets to have a transverse momentum $p_T(j) > 50$ GeV, the basic kinematics of the V and jets in the selected Z+jet events are well modelled: the data agrees in both shape and scale with the predicted p_T distributions after applying an overall NNLO scaling factor to the predictions of MadGraph interfaced with Pythia for the showering. For searches for yet undiscovered particles, observables related to the event

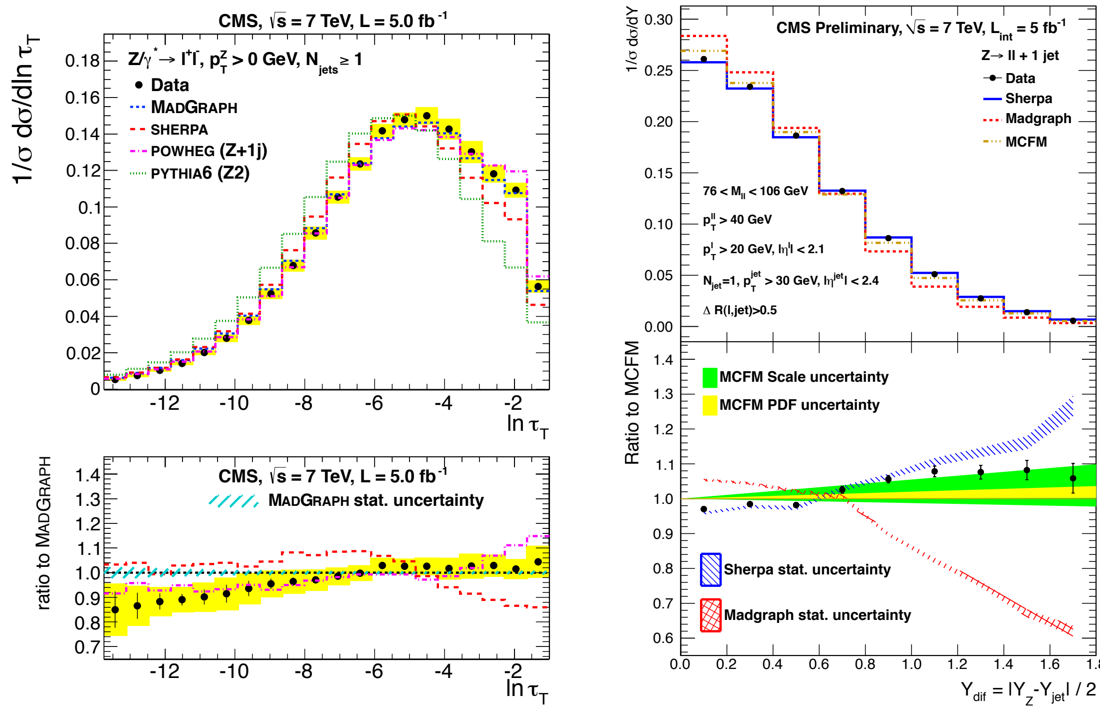

Figure 1: The measurements of the 'thrust' in the Z+jets final state (left) and the 'rapidity difference' in the Z/γ+1-jet final state (right) and the comparisons with predictions from different generators.

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kinematic topology, e.g. azimuthal correlations, are of interest. In particular, the 'thrust' of the Z+jet final state shows discrepancies when comparing with different generators, as is shown in Fig. 1 (left): MadGraph and Powheg model the data well, whereas Pythia (as expected) and also Sherpa are shifted to lower values than observed, showing a predicted spectrum which is more dijet-like [5].

Another measurement sensitive to the orientations between the V and the jet in the γ+jet final state is the triple differential cross section as a function of $p_{\mathrm{T}}(\gamma), |\eta(\gamma)|, |\eta(j)|$. Selecting jets with $p_{\mathrm{T}}(j) > 30$ GeV, and requiring reconstructed photons to have $p_{\mathrm{T}}(\gamma) > 40$ GeV, the differential cross section is measured as a function of $p_{\mathrm{T}}(\gamma)$, in eight bins of $|\eta(\gamma)|, |\eta(j)|$. After correcting for the measured photon purity, the comparison of data with Sherpa and JetPhox shows that Jetphox agrees well, whereas Sherpa overall underestimates the cross section [6].

To test the modelling of the V+jets kinematics, also variables related to rapidity are studied. Selecting exactly one jet with $p_{\mathrm{T}}(j) > 30$ GeV, the rapidity distributions of the Z/γ+1-jet events are well modelled for both the V (Y_V) and the jet (Y_j) in the final state. Other variables which are measured are: the rapidity sum ($|Y_V + Y_j|/2$), which is related to the boost of the V+j system, and the rapidity difference ($|Y_V - Y_j|/2$), which is related to the polar angle in the V+j centre-of-momentum. The comparison of these variables at the particle level show agreement with NLO generators (MCFM and Owens), whereas the comparison with generators which employ the Matrix Element + parton showering scheme shows significant discrepancies: as is shown in Fig. 1 (right), Sherpa reproduces the observed rapidity difference better than MadGraph. These differences are attributed to the different matching procedures [7].

Furthermore, the V+jets final state is used to study douple-parton scattering (DPS). Selecting one lepton, and requiring a transverse mass $M_{\mathrm{T}} > 50$ GeV, DPS has been studied with different sensitive observables in the W+2-jets final state. The modelling of DPS in MadGraph has been shown to describe the data correctly, and among the set of studies observables the angle between the V and the pair of jets (ΔS) has been found to be the most sensitive [8].

3. Vector boson + heavy-flavor jets

Studies of the production of vector bosons in association with heavy-flavor quark jets (V+HF) are of particular interest to the understanding of modelling of heavy flavor quarks. In order to select events from V+HF production, jets originating from heavy-flavor quarks are identified by exploiting their relatively long lifetimes. After the V+HF event selection, the remaining backgrounds need to be estimated, in particular those originating from the misidentification of light jets and the production of $t\bar{t}$.

In the Z+b-jets final state, backgrounds from light jets are reduced by criteria on the flight distance significance, and the non-b backgrounds are estimated from the distribution of the mass of the reconstructed secondary vertices. The background due to $t\bar{t}$ is reduced by a requirement on the significance of the transverse missing energy, and it is estimated using the distribution of the dilepton invariant mass. Furthermore, the background due to diboson production is estimated using the CMS measurements of diboson production [9]. The cross-section measurements of the Z+b-jets final state are performed as function of b-jet multiplicity: the cross section is measured both in association with exactly 1 b jet ('Z+1b-jet') and with at least 2 b jets ('Z+2b-jets'). The

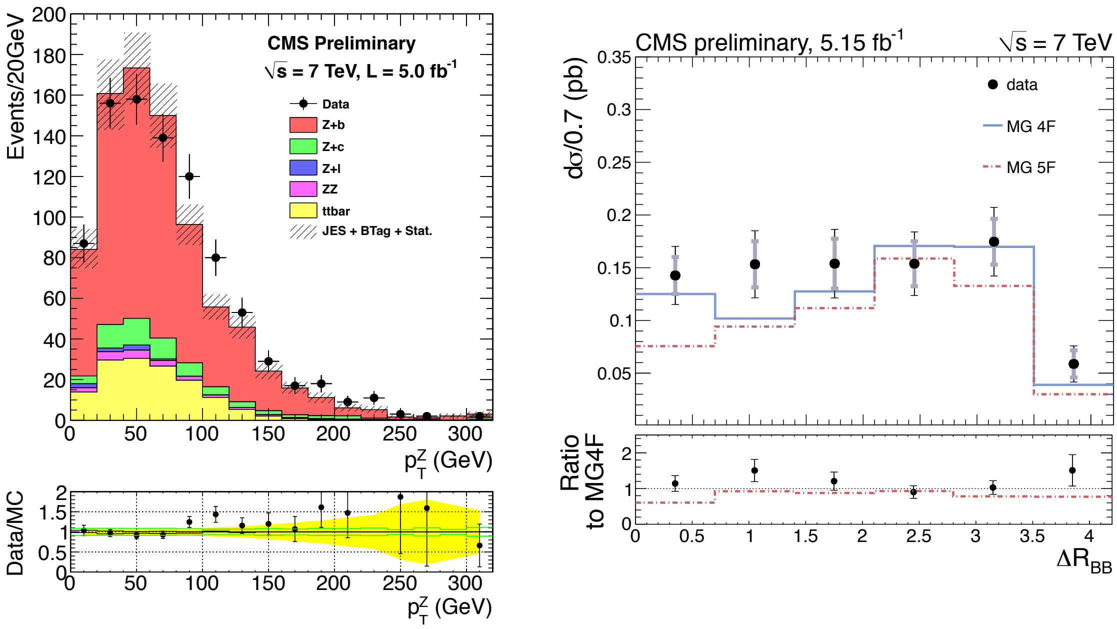

Figure 2: The distribution of the $p_{\mathrm{T}}(Z)$ in the Z+2b-jets final state (left) and the $\Delta R(b,b)$ observable in the Z+2b-hadrons final state (right).

cross-section measurements show agreement with MadGraph in both the four-flavor (4F) and five-flavor (5F) scheme. However, the modelling of the transverse momentum of the Z boson, $p_{\mathrm{T}}(Z)$, shows tensions comparing the distribution at the reconstruction level to the prediction of MadGraph in the 5-flavor scheme, as can be seen in Fig. 2 (left). This tension is observed in both the Z+b-jets final state [10] and the Z+2b-jets final state [11], and qualititavely confirms the predictions by aMC@NLO [12] of a harder expected spectrum. For a full understanding of this tension, comparisons with different generators with larger statistics are required.

Using an alternative b-tagging algorithm, which reconstructs vertices instead of jets, the region at small values of $\Delta R(b,b)$ in the Z+2b-hadrons final state is probed. This region is of interest as the collinear region is sensitive to contributions from gluon splitting. As is shown in Fig. 2 (right), MadGraph 5F underestimates the collinear region, whereas MadGraph 4F provides a better description [13].

The production of V+HF is also studied in final states with a W boson. After requiring two b-tagged jets, one lepton, and a transverse mass $M_T > 45$, the W+2b-jets final state is dominated by $t\bar{t}$ background. In order to control this background, the signal region is required to have two b-tagged jets, whereas the region used to control the background from $t\bar{t}$ is required to have two extra jets. Within the uncertainties, which are dominated by uncertainties due to b-tagging and jet energy scale uncertainties, the cross sections are found in agreement with the predictions from MadGraph, scaling the prediction by a NNLO correction factor. Kinematics of the final state are found to be well described by MadGraph 5F + Pythia6 [14].

Finally, the study of the final state of a W in association with one c quark (W+c) is of interest as it allows to access the strange-quark content of the proton. The measurement [15] exploits the

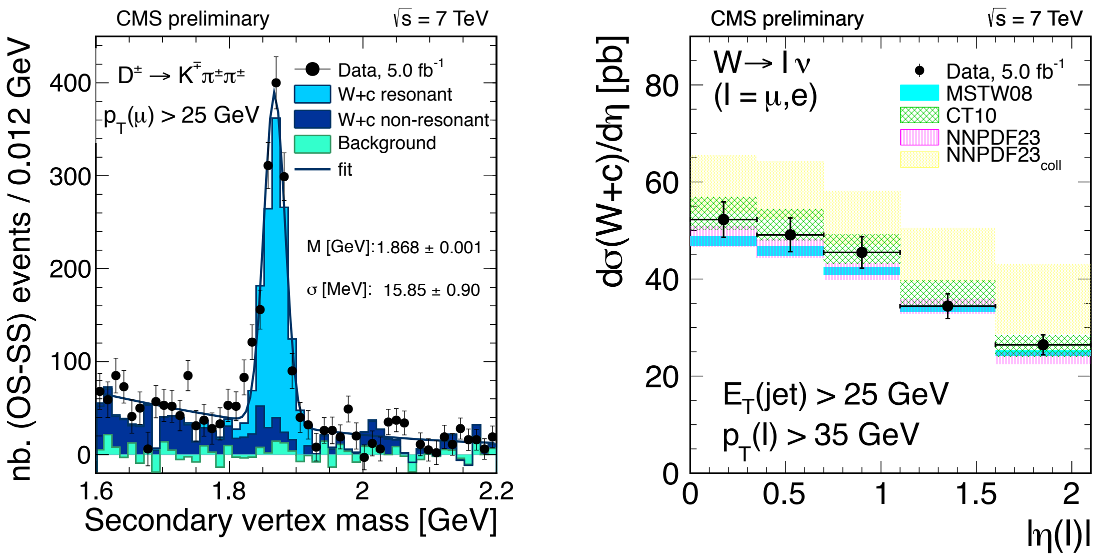

Figure 3: Left: the reconstructed secondary vertex mass of the $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ decay in the W+c final state, after correcting the predicted branching ratio and subtracting the backgrounds. Right: the differential W+c cross section measurement as a function of $|\eta(l)|$ compared with the predictions from different PDFs.

opposite-sign nature of the production mechanism: using exclusive charged D-meson decays, signal from W+c production can be reconstructed. Three hadronization modes are studied: $c^{\pm} \to D^{\pm}$, $c^{\pm} \to D^{*\pm} \to D^{0}\pi^{\pm}$, $c^{\pm} \to l^{\pm}$, allowing to reconstruct the charge of the D meson. The branching ratios of these decays are estimated *in situ*, and the same-sign events are used to model the background contribution from gluon splitting in the opposite-sign signal sample. An example of the reconstructed invariant mass is shown in Fig. 3 (left), and shows good agreement between data and simulation. Also the cross sections of both the W+c final state and the ratio W^{+}+c^{-}/W^{-}+c^{+} are in agreement with predictions. Their differential cross sections, as a function of the lepton pseudorapidity, are used to constrain PDFs, as is shown in Fig. 3 (right).

4. Conclusions

In the V+jets final state, basic kinematics are modelled well. However, discrepancies are observed in the modelling of event topologies. In the V+HF final states, the cross sections are overall in agreement with the predictions, but the kinematics of the final state particles show tensions when comparing data with predictions. Studying in more detail the tensions is of importance for the understanding of QCD, in searches for not yet discovered particles, as well as for studies of the recently discovered 125 GeV boson.

References

[1] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP#Vector_Boson_Jets_Production.

[2] CMS Collaboration, CMS-PAS-PFT-09-001 and CMS-PAS-PFT-10-001.

[3] CMS Collaboration, JINST **3** (2008) S08004.

[4] M. Cacciari, G. Salam, and G. Soyez, JHEP **04** (2008) 063 (http://arxiv.org/abs/0802.1189).

[5] CMS Collaboration, Phys.Lett.B **722** (2013) 238-261 (http://arxiv.org/abs/1301.1646).

[6] CMS Collaboration, CMS-PAS-QCD-11-005.

[7] CMS Collaboration, CMS-PAS-SMP-12-004.

[8] CMS Collaboration, CMS-PAS-FSQ-12-028 and Paolo Bartalini, this conference.

[9] Daniele Trocino, this conference.

[10] CMS Collaboration, JHEP **06** (2012) 126 (http://arxiv.org/abs/1204.1643).

[11] CMS Collaboration, CMS-PAS-SMP-13-004.

[12] R.Frederix et al, JHEP **09** (2011) 061 (http://arxiv.org/abs/1106.6019v2).

[13] CMS Collaboration, CMS-PAS-EWK-11-015.

[14] CMS Collaboration, CMS-PAS-SMP-12-026.

[15] CMS Collaboration, CMS-PAS-SMP-12-002.