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Jet production in association with vector bosons at LHC with the CMS detector

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We present measurements with the CMS detector of the associated production of vector bosons (W and Z) and hadronic jets in proton proton collision at $\sqrt{s} = 7$ TeV at the LHC. We focus in particular on two measurements: the production rate of jets in association with either a W or a Z boson, decaying to final states with electrons and muons, as measured on data collected in 2010 for an integrated luminosity of 36 pb^{-1}; and the measurement of angular correlations and event shapes in events with a Z boson and at least one hadronic jets, on data collected in 2011 for an integrated luminosity of 5 fb^{-1}. Data are compared to the predictions of perturbative QCD, in particular to Monte Carlo models that combine consistently leading order multi-leg matrix elements and parton shower.

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1. Introduction

The study of jet production in association with vector bosons is important for three main reasons: it provides a strigent test of perturbative QCD; an understanding of signatures with leptons, jets and possibly missing transverse energy is very important for searches; finally the production of a Z boson and hadronic jets is particularly useful for detector calibration. In recent years there have been huge progresses in the accuracy of the simulation of final states with many jets. Calculation now exists at next-to-leading order for W and Z with several accompaining jets [1, 2, 3]. There are also several event generators capable of making a consistent matching of leading order (LO) multi-leg matrix elements and parton shower, like AlpGen [4], Madgraph [5] or Sherpa [6]. NLO matrix elements have been succesfully combined with parton showers in the MC@NLO [7] and POWHEG [8] methods. Finally, first results on matching of multi-leg NLO matrix elements and parton shower are becoming available [9]. It is therefore quite interesting to compare the predictions of different models with data, to understand the limits of applicability of each of them. In this paper we report on recent CMS measurements on W/Z and hadronic jets at the Large Hadron Collider and we discuss the agreement of Monte Carlo simulation with data. We comment in particular the results on the rate of jets produced in association with a vector boson published in [10] and on recent measurement of angular correlation and event shapes in Z+jets events [11].

2. Analysis Strategy and Event selection

The CMS detector is described in detail elesewhere [12]. We will just describe a few key items that are relevant for the selection of W and Z bosons decaying to final states with electron and muons. The online and offline event selection is entirely based on the identification of the leptons from the boson decay, and does not rely in any way on the hadronic part of the event. The online selection requires at least one high transverse momentum electron or muon. The offline lepton identification criteria involve a transverse momentum (p_T) cut of 20 GeV on the lepton candidates, and lepton pseudorapidity (η) within tracker acceptance, i.e. $|\eta| < 2.5$. Rather loose quality criteria are also applied to reject fake electrons and muons and isolation requirements to suppress QCD background from decays in flight. Events with a Z boson are selected by requiring two oppesitely charged electrons or muons with invariant mass between 60 and 120 GeV. For W events a cut on the transverse mass of 20 GeV is applied to reject background; however the contamination from $t\bar{t}$ is relatively large, especially for more than two jets, because of W boson from t decays. For this reason the signal is extracted in each jet multiplicity bin via a combined fit of the transverse mass and a b-tagging variable. Jets are reconstructed with the anti-kt [13] algorithm, with a radius parameter of 0.5. The minimum p_T is 30 GeV for the analysis of jet multiplicity and 50 GeV for the analysis of event shapes and angular correlations in Z+jets. The quality of the data/simulation agreement at selection level is exemplified by Fig. 1 where the jet multiplicity distribution for jets with p_T >50 GeV is shown for events with a Z boson decaying to a pair of muons.

3. Jet rates in association with a W or a Z boson

Jet production rates in association with a W or a Z boson were measured in [10] for jets

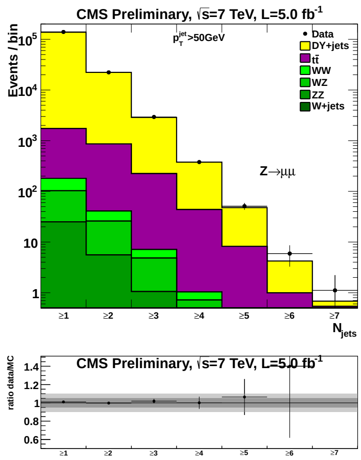
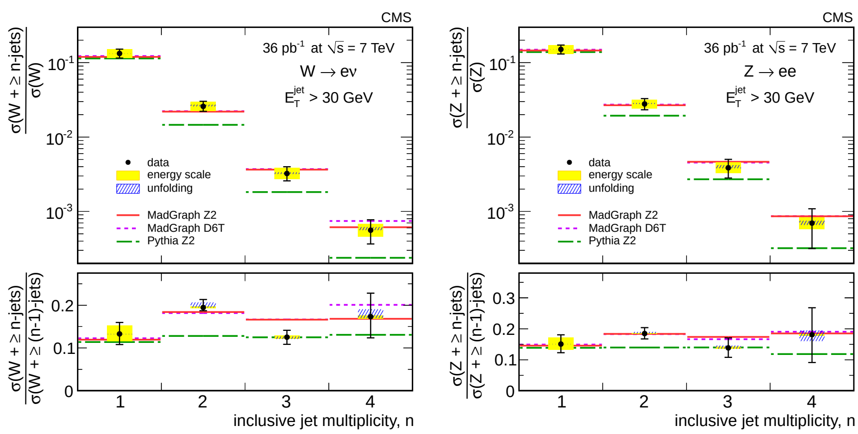


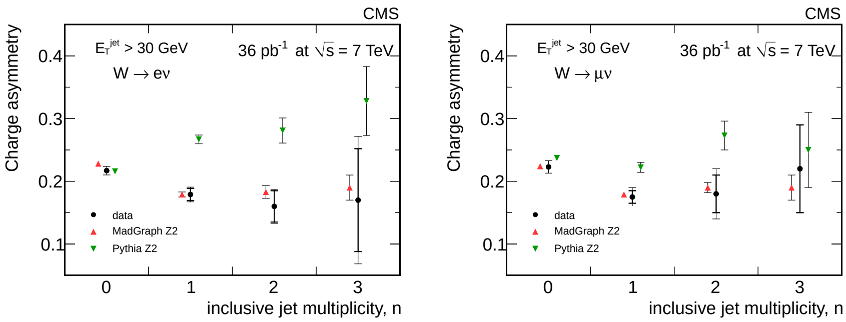
Figure 1: Jet multiplicity distribution for jets with p_T >50 GeV, after event selection in events with $Z \rightarrow \mu^+\mu^-$.

reconstructed as described above, and with a minimum transverse momentum of 30 GeV. The jet multiplicity distributions, normalized to the inclusive cross section, are shown in Fig. 2 for $W \rightarrow e\nu_e$ (a) and $Z \rightarrow e^+e^-$ (b) . Also the ratio of the cross section for n jets divided by the cross section for $(n-1)$ jets is shown in each plot. These ratios are all independent on the luminosity, and they allow to avoid the corresponding large systematic uncertainty. The distributions shown are corrected for detector effects with an unfolding technique, however no attempt is made at correcting the acceptance cuts imposed by the kinematic cuts on the leptons and by the invariant mass requirement. The dominating systematic uncertainty is arising from the jet energy scale. Data points are compared with the predictions of Pythia 6.424 [14] and of Madgraph 5.1.1 (with Pythia 6.424 for parton shower and hadronization). The prediction of Madgraph combines in a consistent manner LO matrix elements for up to 4 partons in addition to the vector boson and it



(a) (b)

Figure 2: Rate of events with anti-kT jets with transverse momentum greater than 50 GeV for $W \rightarrow e\nu_e$ (a) and $Z \rightarrow e^+e^-$ (b).



(a) (b)

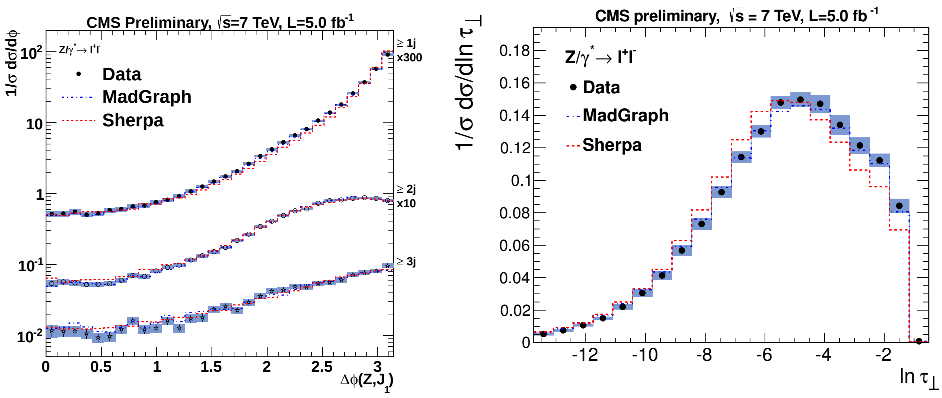
Figure 3: Charge asymmetry as a function of jet multiplicity for $\mathrm{W} \to \mathrm{e}\nu_{\mathrm{e}}$ (a) and $\mathrm{W} \to \mu\nu_{\mu}$ (b).

appears to be in better agreement with the data than Pythia. This is expected, given that Pythia only implements a parton shower model to describe intial state radiation, which is valid in the soft and collinear emission limit, and hence is expected to underestimate the rate of events with several hard jets. Similar results hold for $\mathrm{W} \to \mu\nu_{\mu}$ and $\mathrm{Z} \to \mu^{+}\mu^{-}$, as shown in [10].

The charge asymmetry in W + jets is shown in Fig. 3 as a function of the number of jets. This observable is defined as $[\sigma(W^{+}) - \sigma(W^{-})]/[\sigma(W^{+}) + \sigma(W^{-})]$, where $\sigma(W^{+})$ and $\sigma(W^{-})$ are the cross sections for W^{+} and W^{-} respectively. Once again the predictions from Madgraph show better agreement with the data.

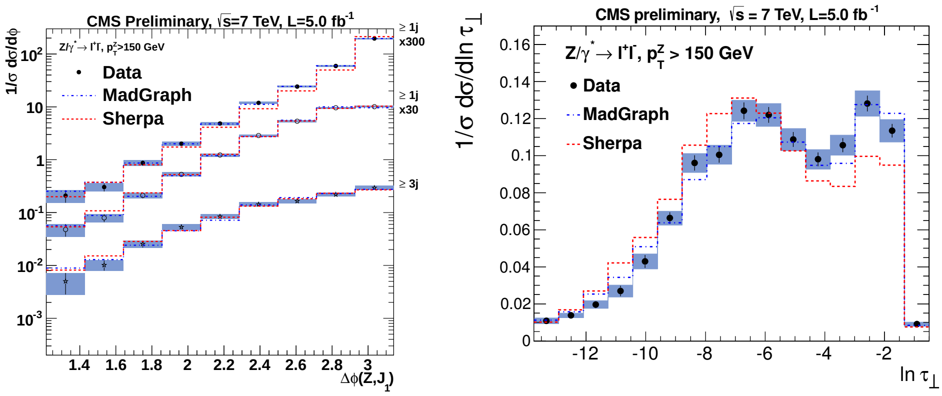
4. Angular correlations and event shapes in Z+jets

The Z boson signature is characterized by two high transverse momentum leptons. For this reason it is much less affected by backgrounds than W boson signature, and it allows for more detailed studies. CMS has characterized the hadronic recoil in Z+jet events from different point of view: the angular correlations between the Z boson and the jet direction (for jets with transverse momentum of 50 GeV), as well as the correlations between jet directions have been studied; moreover, the central transverse thrust $\tau_{\perp}$ has been studied, which is defined as $\tau_{\perp} = 1 - \max_{\vec{n_T}} \frac{\Sigma_i |\vec{p}_{T,i} \cdot \vec{n_T}|}{\Sigma_i p_{T,i}}$, where $\vec{p}_{T,i}$ are the jet transverse momenta and $\vec{n_T}$ is the direction that maximises the ratio term. For a “pencil-like” events with the Z boson recoiling against a single jet $\tau \to 0$, while for a very spherical event with many jets $\tau \to 0.36$. Both angular correlations and central transverse thrust were measured both inclusively and requiring certain conditions on the Z boson transverse momentum and/or the number of jets in the event, such that different regions of the phase space, also relevant for searches, were explored. Fig. 4 (a) shows the azimutal angle between the Z boson the leading jet ($\Delta\phi(\mathrm{Z}, \mathrm{J}_1)$) for events with at least 1, at least 2 and at least 3 jets. Fig. 4 (b) shows the central transverse thrust for events with at least one jet. Data are compared with the predictions of Madgraph 5.1.1 (with Pythia 6.424 for parton shower and hadronization) and Sherpa 1.3.1. The agreement is generally good for both generators in $\Delta\phi(\mathrm{Z}, \mathrm{J}_1)$, with a slight preference on Madgraph. This is confirmed by the transverse thrust distribution where Sherpa appears to be slightly shifted to the left with respect to the data points (i.e. there are fewer “spherical” multi-jet events) which is consistent with the fact that this version of the program is known to slightly underestimate the global jet multiplicity for large number of jets.



(a) (b)

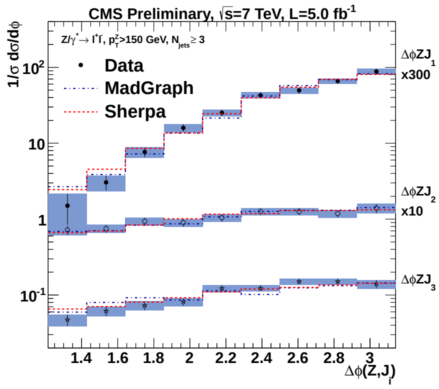
Figure 4: (a) Azimuthal angle between the Z boson and the leading jet and (b) transverse thrust distribution for Z+jets events.



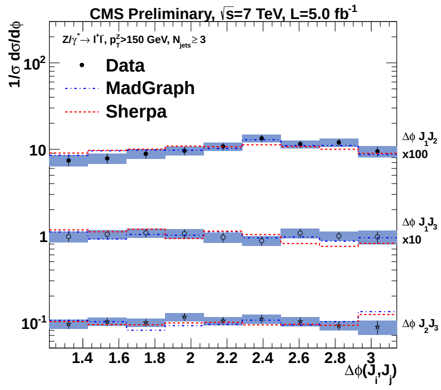
(a) (b)

Figure 5: (a) Azimuthal angle between the Z boson and the leading jet and (b) transverse thrust distribution for Z+jets events with Z transverse momentum greater than 150 GeV.

Fig. 5 shows the same observables shown in Fig. 4, but with a transverse momentum cut on the Z boson of 150 GeV. These cuts aim at reproducing a phase space configuration that is relevant for searches, e.g. SuSy searches, where a high transverse momentum invisible Z can be a sizeable background. The angular correlation distribution becomes more peaked because the Z boson transverse momentum cut selects events with a Z boson recoiling against sizeable hadronic activity. Also the thrust distribution gets globally shifted to the left with respect to the one shown in Fig. 4, because Z boson transverse momentum cut tends to select "Z+1 jet-like" events. The comparison with Monte Carlo predictions shows the same features observed in Fig. 4, with the transverse thrust distribution predicted by Sherpa slightly shifted to the left of the data points. An even more extreme region of the phase space was studied, where in addition to the Z boson transverse momentum cut of 150 GeV, a minimum of 3 jets was required. Results with this selection are shown in Fig. 6 for the azimuthal angle between the Z boson and each of the 3 leading jets (a) and for the azimuthal angle between each jet pair (b). Both the Monte Carlo models



(a)



(b)

Figure 6: (a) Azimuthal angle between the Z boson and the three leading jet and (b) azimuthal angle between each pair of the three leading jets for Z+jets events with Z transverse momentum greater than 150 GeV and at least three jets.

we studied show good agreement with the data. It is also interesting to notice that the angular correlations betwen jets become rather flat, meaning that in this extreme region of the phase space the directions of the jets are essentially randomized.

5. Conclusion

Results from CMS on W/Z+jets at 7 TeV have been presented. In particular we concentrated on jet rates in association with a W/Z boson and azimuthal correlations and event shapes in Z+jets. The observables studied probe perturbative QCD in an unprecedented energy regime, and show good agreement with the predictions of matched calculations that use consistently leading order multi-leg matrix elements and parton showers.

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