Jet and Multijet Results from CMS

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Abstract. QCD measurements with jets are presented, from proton-proton collisions at a centre-of-mass energy of 7 TeV at the CERN LHC. The data were collected with the CMS detector during the 2010 data-taking period, and correspond up to an integrated luminosity of 36 pb$^{-1}$. The measured inclusive-jet and dijet production cross sections are compared to perturbative QCD predictions at next-to-leading-order, and are found to be in good agreement. Observables sensitive to multijet production, such as the hadronic event shapes, the dijet azimuthal decorrelations, and the ratio of the 3-jet to 2-jet production cross section, are compared to the predictions of various QCD Monte-Carlo generators.

1. Introduction
In Quantum Chromodynamics (QCD), events with two or more high transverse-momentum jets arise in proton-proton collisions from parton-parton scattering, where the outgoing scattered partons manifest themselves as hadronic jets. The inclusive jet and dijet production cross sections are benchmarks of the standard model (SM), and confront the perturbative QCD predictions at the smallest distance scales ever probed. The cross-section measurements can be used to constrain the parton momentum distributions (PDF) in the proton, and are sensitive to the strong coupling constant. Significant deviations from the predictions of the inclusive jet and dijet cross sections at high transverse momentum or dijet invariant mass, could also be an indication of new phenomena beyond the SM. Other observables, such as the dijet azimuthal decorrelations, the hadronic event shapes, and the ratio of the 3-jet to 2-jet production cross section, are sensitive to multijet production and can be used to differentiate between the various QCD Monte-Carlo generators.

In this paper, various QCD measurements with jets are reported, using proton-proton collisions at a centre-of-mass energy of 7 TeV at the CERN Large Hadron Collider (LHC). The data were collected with the Compact Muon Solenoid (CMS) detector during the 2010 run, and correspond to an integrated luminosity of up to 36 pb$^{-1}$. The paper is organized as follows: the CMS detector is described briefly in Section 2, and the jet reconstruction approach is described in Section 3. The inclusive jet and dijet cross-section measurements are reported in Section 4, while the multijet-sensitive measurements are discussed in Section 5. Section 6 summarizes the results.

2. The CMS Detector
The CMS coordinate system has its origin at the centre of the detector, with the $z$-axis pointing along the direction of the counterclockwise beam. The azimuthal angle is denoted as $\phi$, the polar angle as $\theta$, and the pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. The central feature
of the CMS detector is a superconducting solenoid, of 6 m internal diameter, that produces an axial magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, a lead-tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadronic calorimeter. Outside the field volume, in the forward region (3 < |η| < 5), is an iron/quartz-fiber hadronic calorimeter. Muons are measured in gas detectors embedded in the steel return yoke outside the solenoid, in the pseudorapidity range |η| < 2.4. A detailed description of the CMS experiment can be found in Ref. [1].

3. Jet Reconstruction

Jets are reconstructed using the anti-$k_T$ clustering algorithm [2] with size parameters $R = 0.5$ and $R = 0.7$. The clustering is performed using four-momentum summation. The rapidity $y$ and the transverse momentum $p_T$ of a jet with energy $E$ and momentum $\vec{p} = (p_x, p_y, p_z)$ are defined as $y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)$ and $p_T = \sqrt{p_x^2 + p_y^2}$, respectively. The inputs to the jet clustering algorithm are the four-momentum vectors of the reconstructed particles. Each such particle is reconstructed with the particle-flow technique [3] which combines the information from several subdetectors. The resulting jets require an additional energy correction to take into account the non-linear and non-uniform response of the CMS calorimetric system to the neutral-hadron component of the jet (the momentum of charged hadrons and photons is measured accurately by the tracker and the ECAL, respectively). The jet-energy corrections are derived using simulated events, generated by PYTHIA6.4.22 (PYTHIA6) [4] and processed through the CMS detector simulation based on GEANT4 [5], and in situ measurements with dijet and photon+jet events [6]. An offset correction is also applied to take into account the extra energy clustered in jets due to additional proton-proton interactions within the same bunch crossing (pile-up). The jet-energy correction depends on the $\eta$ and $p_T$ of the jet, and is applied as a multiplicative factor to the jet four-momentum vector. The multiplicative factor is in general smaller than 1.2, and approximately uniform in $\eta$. For a jet $p_T = 100$ GeV the typical factor is 1.1, decreasing towards 1.0 with increasing $p_T$. The dijet invariant mass is calculated from the corrected four-momentum vectors of the two jets with the highest $p_T$ (leading jets): $M_{JJ} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$.

4. Cross-Section Measurements

The data samples used for this measurement were collected with single-jet high level triggers (HLT) [7] which required at least one jet in the event to satisfy the condition $p_T > 30, 50, 70, 100$ and 140 GeV, respectively, in uncorrected jet transverse momentum. The online jet reconstruction used only calorimetric information and the resulting HLT jets had typically much lower energy response than the offline particle-flow jets. For the construction of the inclusive-jet and dijet spectra, each bin is populated by events collected only with the fully efficient trigger with the highest threshold.

The double-differential inclusive jet cross section [8], as a function of the jet $p_T$ and rapidity, is defined as:

$$\frac{d^2\sigma}{dp_T dy} = \frac{C_{\text{uns}}}{\epsilon \mathcal{L} \Delta p_T \Delta |y|} N_{\text{jets}},$$

where $N_{\text{jets}}$ is the number of jets, $\Delta p_T$ and $\Delta |y|$ are the widths of the $p_T$ and rapidity bins, respectively, $\epsilon$ is the event selection efficiency, $\mathcal{L}$ is the integrated luminosity and $C_{\text{uns}}$ is a correction factor for the detector smearing effects. The latter ranges from 10% in the central rapidity bins, to 50% in the outermost bin.

The double-differential dijet cross section [9] is measured as a function of the dijet invariant mass $M_{JJ}$ and $|y|_{\text{max}} = \max(|y_1|, |y_2|)$, and is expressed similar to eqn.1:
\[
\frac{d^2\sigma}{dM_{JJ}dy_{\text{max}}} = \frac{C_{\text{uns}}}{\epsilon L} \frac{N_{\text{evt}}}{\Delta M_{JJ}\Delta|y|_{\text{max}}},
\]

where \(N_{\text{evt}}\) is the number of dijet events. The unsmeared correction \(C_{\text{uns}}\) for the dijet cross section is smaller than 10% in the entire phase space of the measurement. In order to capture most of the gluon radiation and improve the dijet mass resolution, the measurement is performed using the larger jet size of \(R = 0.7\), as opposed to the other measurements presented in this paper, which use the default \(R = 0.5\) CMS size.

Figure 1 shows the inclusive-jet and dijet production cross sections, compared to the theory predictions. The latter consists of a perturbative QCD (pQCD) calculation at next-to-leading-order (NLO) and a non-perturbative correction to account for the multiple-parton interactions (MPI) and the hadronization effects. For the pQCD calculation, the PDF4LHC prescription [10] was used. The non-perturbative correction was calculated from various Monte-Carlo generators and ranges from 30% at low jet \(p_T\) (dijet mass) to a few percent at higher values. A more detailed comparison to the theory is shown in Fig. 2.

The experimental systematic uncertainty is dominated by the jet-energy scale uncertainty, which varies between 3-5% and results in a 20-50% cross-section uncertainty. The luminosity uncertainty is estimated to be 4% and propagates directly to the cross section. The theoretical uncertainty is dominated by the non-perturbative correction and the PDF uncertainty at low and high jet \(p_T\) (dijet mass) respectively.

The inclusive-jet cross section spans a \(p_T\) range from 18 GeV to 1.1 TeV and up to \(|y| = 3\) in jet rapidity. The dijet cross section spans an \(M_{JJ}\) range from 156 GeV to 3.5 TeV. Both cross-section measurements are found to be in good agreement with the theory predictions, in the entire phase space.

5. Multijet Measurements

The understanding of the QCD multijet production is critical for searches of physics beyond the SM, in hadronic final states. A typical example is Supersymmetry, where QCD is a dominant background. Observables which are sensitive to the QCD multijet production can be used to tune the various Monte-Carlo generators. In addition, they can be used to measure the strong coupling constant \(\alpha_S\).

The dijet azimuthal decorrelation is a simple observable that probes indirectly the multijet production. The normalized dijet cross section \(\frac{1}{\sigma_{\text{dijet}}} \frac{dN}{d\Delta\phi}\) as a function of the azimuthal separation \(\Delta\phi\) between the two leading jets, is measured in bins of the leading jet \(p_T\) and provides an indirect handle on the multijet production: the \(\Delta\phi\) values close to \(\pi\) denote the back-to-back dijet production, while values close to \(\pi/2\) denote the 3-jet or 4-jet region. This observable is free of many experimental uncertainties (e.g. jet-energy scale, luminosity), and the measurement was performed in CMS using the first 2.9 pb\(^{-1}\) of data [11].

Figure 3 shows the dijet azimuthal decorrelation compared to the pQCD predictions at leading-order (LO) and NLO. It also shows the measurement compared to the prediction from various Monte-Carlo generators. The LO prediction, as expected, fails to describe the dijet azimuthal decorrelation, while the NLO prediction improves the agreement in the range \(\Delta\phi \sim 2\pi/3-\pi\), which corresponds roughly to the 2-jet and 3-jet production. The Monte-Carlo generators are able to describe the measurement reasonably well in the entire range.

The hadronic event-shape variables probe directly the QCD multijet production. In particular, two event-shape variables have been studied: the central transverse thrust \(T_{\text{tr},C}\) and the central thrust minor \(T_{m,C}\). The two variables probe different QCD radiative processes and are mostly sensitive to the modeling of two- and three-jet topologies. The term \textit{central} (C) indicates that the input to the calculation of these quantities are jets in the central region of
Figure 1. Left: differential inclusive-jet production cross section, as a function of jet $p_T$ in various rapidity bins. Right: differential dijet production cross section, as a function of the dijet invariant mass, in various rapidity bins. The cross sections are scaled by the factors shown in the figures. The points represent the measured cross sections, corrected for detector effects, while the curves represent the pQCD predictions at next-to-leading-order, corrected for non-perturbative effects.

the detector ($|\eta| < 1.3$), where sub-leading contributions in the calculation of the event-shape variables are less significant, and systematic uncertainties on the jet reconstruction are smaller. The central transverse thrust is defined as:

$$\tau_{\perp,C} \equiv 1 - \max_{\vec{p}_T} \frac{\sum_{i} |\vec{p}_{\perp,i} \cdot \hat{n}_T|}{\sum_{i} \vec{p}_{\perp,i}} ,$$

where $p_{\perp,i}$ is the transverse momentum of selected jet $i$. The axis $\hat{n}_T$ which maximizes the sum, and thus minimizes $\tau_{\perp,C}$, is called the transverse thrust axis $\hat{n}_{T,C}$. The central transverse thrust is a measure of the radiation along the transverse thrust axis. The central thrust minor is a measure of the radiation out of the plane defined by $\hat{n}_{T,C}$ and the beam axis. It is defined as:

$$T_{m,C} \equiv \frac{\sum_{i} |\vec{p}_{\perp,i} \times \hat{n}_{T,C}|}{\sum_{i} \vec{p}_{\perp,i}} .$$

Two-jet events that are well balanced have low values of these two variables, while isotropic multijet events have high values. The measurement is free of many experimental uncertainties, and has been performed using 3.2 pb$^{-1}$ of data [12].

Figure 4 shows the distributions of the logarithms of the central transverse thrust and the central thrust minor variables, for events where the leading-jet $p_T > 200$ GeV. The measurements are compared to the predictions of various Monte-Carlo generators. For the given generator tunes considered here, PYTHIA6 and HERWIG++ [13] describe well the measurement in both the 2-jet and 3-jet region. The other generators, namely (PYTHIA8 [14], ALPGEN [15], MADGRAPH [16]) are less successful in describing the data.

Another direct probe of the multijet production, is the ratio of the 3-jet over 2-jet production cross section. The measurement has been performed using the entire 2010 CMS dataset [17],
and expressed as a function of $H_T$. The latter is the scalar sum of the jet transverse momenta: $H_T = \sum_j p_{T,j}$. Many experimental systematic uncertainties are cancelled in the ratio, leading to a robust measurement, covering the $H_T$ range from 200 GeV to 2.5 TeV. The 3-jet over 2-jet ratio, is in general sensitive to the strong coupling constant $\alpha_S$, but the format examined here (as a function of $H_T$) is more suitable for studies of the soft jet production. Thus, the measurement is compared to the predictions from Monte-Carlo generators, after correcting for detector smearing effects. Figure 5 shows the measured 3-jet to 2-jet cross-section ratio, compared to different models. The MADGRAPH generator, interfaced with PYTHIA6 for the MPI and hadronization, gives the best description of the data.
Figure 3. Normalized $\Delta \phi_{dijet}$ distributions in several $p_{T,max}$ regions, scaled by the multiplicative factors given in the figure for easier presentation. Left: the curves represent predictions from various Monte-Carlo generators. Right: the curves represent predictions from LO (dotted line) and NLO pQCD (solid line). Non-perturbative corrections have been applied to the predictions. The error bars on the data points include statistical and systematic uncertainties.
Figure 4. Distributions of the logarithm of the central transverse thrust (left) and central thrust minor (right) for events with a leading jet $p_T > 200$ GeV, from data and from five MC simulations. The error bars on the data points represent the statistical uncertainty on the data, and the shaded bands represent the sum of statistical and systematic errors.

Figure 5. The measured 3-jet over 2-jet cross-section ratio (filled circles) as a function of $H_T$, and the predictions of Monte-Carlo generators (curves). Error bars represent statistical uncertainties. The shaded area indicates the size of the combined systematic uncertainty.
6. Summary

CMS has performed various QCD studies with jets, using proton-proton collisions at \(\sqrt{s} = 7\) TeV, from the 2010 LHC run, corresponding to integrated luminosity up to 36 pb\(^{-1}\). The inclusive-jet and dijet production cross sections have been measured in a previously unexplored kinematic region, reaching jet-\(p_T\) values beyond 1 TeV and dijet invariant masses up to 3.5 TeV. Both measurements are in good agreement with the pQCD predictions at NLO. The dijet azimuthal decorrelations and the hadronic event-shape variables have been also measured, using approximately 3 pb\(^{-1}\) of data and compared to Monte-Carlo generator predictions. Both measurements are well reproduced by the PYTHIA6 and HERWIG++ generators. Finally, the 3-jet over 2-jet production ratio as a function of \(H_T\) is best reproduced by MADGRAPH, interfaced with PYTHIA6.

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