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QCD Jet Physics with the CMS Detector at the LHC

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We present QCD studies with jets collected by the CMS experiment at the Large Hadron Collider (LHC), including inclusive jet and dijet cross section measurements, the dijet polar and azimuthal angular distributions, and jet and event shapes. The data are compared to QCD predictions at NLO and NNLO and we show the sensitivity to physics processes beyond the Standard Model.

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QCD Jet Physics with the CMS Detector at the LHC

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Abstract

We present QCD studies with jets collected by the CMS experiment at the Large Hadron Collider (LHC), including inclusive jet and dijet cross section measurements, the dijet polar and azimuthal angular distributions, and jet and event shapes. The data are compared to QCD predictions at NLO and NNLO and we show the sensitivity to physics processes beyond the Standard Model.

Keywords: CMS, Physics, QCD, Jet

1. Jet Performance

Four types of jets are reconstructed at CMS [1], which differently combine individual contributions from sub detectors to form the inputs to the jet clustering algorithm: *Calorimeter jets* are reconstructed using energy deposits in the electromagnetic (ECAL) and hadronic (HCAL) calorimeter cells, combined into calorimeter towers. The *Jet-Plus-Tracks* (JPT) algorithm [2] exploits the excellent performance of the CMS tracking detectors to improve the p_T response and resolution of calorimeter jets. Starting from a calorimeter jet, the momenta of the tracks associated to the jet are added and the expected average energy deposition in the calorimeters is subtracted. The *Particle Flow* (PFlow or PF) algorithm [3, 4] combines the information from all CMS sub-detectors to identify and reconstruct all particles in the event, namely muons, electrons, photons, charged hadrons and neutral hadrons. *Track jets* are reconstructed from well measured tracks [5]. The clustering for all types is performed with the anti- k_T algorithm [6] with jet size parameter $R = 0.5$.

CMS has developed a factorized multi-step procedure for the jet energy calibration back to the particle jet level (JEC) [7]. Two complementary approaches are pursued to determine the jet energy correction factors: utilizing MC truth information (MC truth JEC), and using physics processes from pp collisions for in-situ jet calibration.

The relative correction removes variations in jet response versus jet η relative to a central control region ($|\eta| < 1.3$) chosen as a reference because of the uniformity of the detector. The dijet p_T balance has been used to measure the jet response as a function of pseudorapidity.

Figure 1 (left) shows the data/MC (PYTHIA 6 [8]) ratio for the relative response, as measured with the dijet balance method. The jets in data are additionally corrected using an residual corrections on top of the nominal MC truth correction. We assume an uncertainty of $\pm 2\% \times |\eta|$ which after the residual corrections is clearly a conservative estimate, as can be seen in Figure 1.

The absolute correction removes variations in jet response versus jet p_T . The p_T balance and the MPF (missing E_T projection fraction) methods in photon+jet events have been used to study the jet response in the central region as a function of jet p_T . First studies have shown that the MPF response agrees better with the true response than p_T balancing response does, because it is less sensitive to the presence of secondary jets in the event. Observed agreement between data and MC when the same MPF method is applied indicates that the simulation describes the detector response within 5% precision.

Figure 1: Left: Data/MC ratio for the relative response obtained from the dijet p_T balance method for calorimeter. The jets in MC are corrected for MC-truth JEC, whereas jets in data are corrected for MC-truth JEC plus the residual correction discussed in the text. The $\pm 2\% \times |\eta|$ uncertainty band is overlaid. Right: Comparison between the unfolded measured spectra and the theory predictions for particle-flow jets. For better visibility the spectra are multiplied by arbitrary factors (indicated in the legend).

Jet energy resolutions have been studied using the asymmetry method in dijet data events. The full dijet asymmetry analysis procedure is applied to the selected data sample and compared to the results from a PYTHIA 6 QCD dijet sample obtained with the same method. While still limited by the size of the available data sample, data and simulation are in reasonable agreement, typically at 10% level. As expected, the resolutions for jets employing tracking information are improved compared to the calorimeter jets. More details about CMS jet performance can be found in [9, 10].

2. Inclusive Jets

Using about 60 nb^{-1} of data collected from proton–proton collisions, the jet transverse momentum spectrum is measured in the p_T range of 18–700 GeV and for different rapidities $|y| < 3.0$. Three different jet reconstruction methods were compared as a function of p_T and for different bins in rapidity y . The unfolded, measured jet p_T spectra are shown in Figure 1 (right), which also includes the NLO predicted curve. The systematic uncertainties due to experimental effects are shown as yellow bands. The largest systematic uncertainties arise from a current imprecise knowledge of the absolute jet energy scale and the jet energy scale relative to the central region of the detector. The results from the three different jet reconstruction methods agree with the theoretical prediction and with each other to within 20% over most of the measured p_T and rapidity ranges, well within the uncertainties associated with particle-flow jet energy scale, which is the most accurate of the three measurements. More details can be found in [11].

3. Dijet Azimuthal Decorrelations

We have measured the differential dijet azimuthal distributions in several p_T^{max} regions with a data sample of 72 nb^{-1} . These are the first measurements of $\Delta\varphi_{dijet}$ distributions in proton-proton collisions at 7 TeV.

Figure 2 shows the ratios of the data dijet azimuthal distributions to the predictions of PYTHIA 6, HERWIG++ [12], and MADGRAPH [13] in p_T^{max} regions. The predictions from PYTHIA 6 and HERWIG++ are in reasonable agreement with the data. MADGRAPH predicts about 20% less azimuthal decorrelation, for $\Delta\varphi_{dijet}$ away from π , than what is observed in the data. The sensitivity of the dijet azimuthal distributions to the initial and final-state radiation was also studied. More details can be found in [14].

Figure 2: Left: $\Delta\phi_{dijet}$ distributions in different leading jet p_T^{max} regions. The curves represent predictions from PYTHIA 6, HERWIG++, and MADGRAPH. Detector resolution effects on jet p_T and position have been included in the MC predictions at the generated particle level. The data points include statistical (inner ticks) and systematic uncertainties. Right: The ratio R_{32} at hadron level from data (solid circles) compared with PYTHIA 6 (dashed line) and MADGRAPH (solid line). The shaded area indicates the size of the systematic error.

4. Measurement of the 3-jet to 2-jet Cross Section Ratio

The ratio of the inclusive three-jet to two-jet cross sections with $p_T > 50$ GeV and $|\eta| < 2.5$ has been measured as a function of total jet p_T in the range $0.2 \text{ TeV} < H_T < 1 \text{ TeV}$ using an integrated luminosity of 76 nb^{-1} . The variable H_T was defined as the scalar transverse momentum sum of all jets with $p_T > 50$ GeV. The ratio plateaus at value of about 0.8 in agreement with predictions of PYTHIA and MADGRAPH MC calculations, as can be seen in Figure 2 (Right). More details can be found in [15].

5. Hadronic Event Shapes

We have performed a first study of two event-shapes variables, the central transverse thrust and the central thrust minor. The term *central* (C) indicates that the input to the calculation of these quantities are jets in the central region of the detector ($|\eta| < 1.3$).

The central transverse thrust is defined as [16]:

$$T_{\perp,C} \equiv \max_{\vec{n}_T} \frac{\sum_{i \in C} |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_{i \in C} p_{\perp,i}}. \quad (1)$$

where $p_{\perp,i}$ are the transverse momenta of all selected jets with respect to the beam axis. The transverse axis, for which the maximum is obtained, is the thrust axis $\vec{n}_{T,C}$.

The central thrust minor is a measure of the momentum out of the plane defined by $\vec{n}_{T,C}$ and the beam axis. It is defined as:

$$T_{m,C} \equiv \frac{\sum_{i \in C} |\vec{p}_{\perp,i} \times \vec{n}_{T,C}|}{\sum_{i \in C} p_{\perp,i}}. \quad (2)$$

The variable that is typically used in perturbative calculations is $\tau_{\perp,C} \equiv 1 - T_{\perp,C}$, referred to as central transverse thrust in the following.

We used a data sample of proton-proton collision data that corresponds to an integrated luminosity of 78 nb^{-1} . Event shapes were shown to be robust against the choice of jet reconstruction object, as well as to uncertainties in the jet energy scale and experimental resolution. We compared the data with predictions from the PYTHIA 6, PYTHIA 8, HERWIG++, MADGRAPH and ALPGEN Monte Carlo generators, after full detector simulation. The event shape distributions from PYTHIA 6 and HERWIG++ show satisfactory agreement with the data, while discrepancies are found between

Figure 3: Left: The central transverse thrust distribution for calorimeter jets in events with leading jet $p_T > 60 \text{ GeV}/c$. The bars represent the statistical error on the data, and the yellow bands represent the sum of statistical and systematic errors. Right: transverse jet shape δR^2 as function of JPT corrected jet transverse momentum p_T for a dijet sample. Also shown are predictions based on the PYTHIA 6.401 tune D6T (filled histogram) and HERWIG++(2.2.0, solid line) event generators.

the data and predictions from ALPGEN [17], MADGRAPH and PYTHIA 8 [18], as can be seen in Figure 3 (left). Tuning of the event generators to better model the data is currently under investigation, with the input provided by this measurement. More details can be found in [19].

6. Jet Transverse Structure and Momentum Distribution

The charged particle multiplicity within jets, the transverse jet shape δR^2 for charged particles and the integrated jet shapes have been measured using a first data set corresponding to an integrated luminosity of 10 to 78 nb^{-1} . In general the data is observed to follow the trends expected from QCD as a function of the jet transverse momentum. The measured data are described within the uncertainty of the measurement by the current leading order QCD Monte Carlos PYTHIA 6 and HERWIG++ up to the highest transverse momenta observed up to now. At low p_T the measured jets are a few percent broader than predicted by HERWIG++ and narrower than predicted by PYTHIA 6 for the tunes shown here, as can be seen in Figure 3 (right). The data of the integrated jet shape are sensitive to the underlying event but not yet precise enough to differentiate between more recent theoretical prescriptions. More details can be found in [20].

7. Conclusions

We have presented first studies of jet energy calibration and jet resolutions in early pp collisions recorded by CMS at $\sqrt{s} = 7 \text{ TeV}$. Three different techniques are used to reconstruct jets in CMS: calorimeter jets, Jet-Plus-Track jets and Particle-Flow jets. Significantly better performance for jet types employing tracking information have been observed compared to the objects using calorimeter-only information. Current physics analyses in CMS use 10% (5%) jet calibration uncertainties for calorimeter jets (Jet-Plus-Track and Particle Flow jets), with an additional 2% uncertainty per unit rapidity. Observations from the current limited statistics datasets support these numbers as conservative estimates. First QCD results were presented including inclusive jet and dijet cross section measurements, the dijet polar and azimuthal angular distributions, and jet and event shapes. Mostly a good agreement with theory predictions was found.

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