Search for New Physics with the Dijet Centrality Ratio

The CMS Collaboration

Abstract

We describe a search for new physics in hadronic jet pair ("dijet") production, using the first 120 nb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 7$ TeV recorded by the CMS detector at CERN. The study is based on the dijet centrality ratio, which is the ratio of the number of events where the two leading jets have pseudorapidity $|\eta| < 0.7$ to the number where both leading jets have $0.7 < |\eta| < 1.3$. The dijet centrality ratio is a measure of the angular distribution of the dijets and is sensitive to deviations from the standard model. We measure the centrality ratio as a function of the invariant mass of the dijet system and find good agreement with the predictions of QCD, allowing us to set limits on the presence of new physics.
1 Introduction

The 7 TeV center of mass energy of proton-proton collisions at the LHC opens up a new regime for exploration. Among the first possible signs of new physics phenomena could be a departure of the multiple hadronic jet production characteristics from those predicted by the standard model (SM). The angular distribution of jet pairs produced in the context of various new physics scenarios can help distinguish these mechanisms from the SM.

In the SM, events with at least two energetic jets (dijets) can arise in proton-proton collisions from parton-parton scattering. The outgoing scattered partons manifest themselves as hadronic jets. In SM production of dijet events, the pseudorapidity, \( \eta \), of the observed jets depends on the angular distribution of the scattered partons predicted by quantum chromodynamics (QCD). New physics beyond the SM typically produces more isotropic angular distributions than those predicted by QCD, resulting in more dijets at lower absolute values of pseudorapidity. This is because QCD processes are dominated by t-channel scattering, which produces the highest rates in the forward regions at larger pseudorapidity, while the production of new heavy particles (on- or off-shell) requires that both incoming partons carry a large fraction of their respective proton momentum, resulting in small pseudorapidity for the outgoing partons.

We present here a search for new physics phenomena leading to a departure from the QCD predictions, using the first data from the LHC at 7 TeV, corresponding to an integrated luminosity of \( 120 \pm 13 \text{ nb}^{-1} \), collected with the Compact Muon Solenoid Detector (CMS).

For this analysis we define the dijet centrality ratio, \( N(\vert \eta \vert < 0.7)/N(0.7 < \vert \eta \vert < 1.3) \), which is the number of events with both jets in the region \( \vert \eta \vert < 0.7 \) divided by the number of events with both jets in the region \( 0.7 < \vert \eta \vert < 1.3 \). Since many sources of systematic uncertainty cancel in this ratio, the dijet ratio provides a precise test of QCD and is sensitive to new physics.

This analysis is closely related to the CMS search for dijet resonances in the dijet mass spectrum, which uses same data sample [1]. Though the centrality ratio analysis is less sensitive in the case of resonances, it is more sensitive to the presence of contact interactions.

The analysis of dijet angular distributions [2] also provides sensitivity to quark contact interactions. The angular distribution analysis uses more complete angular information and has higher \( \vert \eta \vert \) coverage than this dijet centrality ratio analysis. It requires coarse mass bins to integrate large statistics in order to measure a few dijet angular distributions. The dijet centrality ratio uses less angular information and jets well contained in the barrel calorimeter to produce a single number per mass bin. This allows for fine binning in the dijet mass, which makes it also sensitive to narrow dijet resonances.

The measured dijet centrality ratio is compared to QCD predictions from PYTHIA [3] and calculations at next-to-leading order (NLO) performed with the NLOJet++ program [4, 5]. The measured ratio is also used to search for two models of new physics which are motivated by the possibility that quarks are composite particles. The first model considered here is a contact interaction [6] among left-handed quarks at an energy scale \( \Lambda \) in the process \( qq \rightarrow qq \). This is modeled with the effective Lagrangian \( L_{qq} = (\pm 2\pi/\Lambda^2)(\overline{q}_L\gamma^\mu q_L)(\overline{q}_L\gamma^\mu q_L) \) with “+” chosen for the sign of the interference. The second model is a dijet resonance coming from an excited quark [7] \( (q^*) \) in the process \( qg \rightarrow q^* \rightarrow qg \), where the compositeness scale is chosen to be equal to the \( q^* \) mass.

A similar dijet centrality ratio was measured at the Tevatron [8, 9] and used to set a limit on quark contact interaction scale of \( \Lambda > 2.8 \text{ TeV} \) at 95% C.L.
2 Dijet Mass and Centrality Ratio Measurement

The CMS calorimeter system comprises an inner electromagnetic calorimeter (ECAL) and an outer hadronic calorimeter (HCAL), both of which have a projective tower geometry and lie within the volume of the superconducting solenoid. The ECAL is based on lead tungstate crystals, with an $\eta - \phi$ segmentation of $0.019 \times 0.019$, and an energy resolution of $2.8\% / \sqrt{E} \oplus 12\% / E \oplus 0.3\%$, with $E$ in GeV. The HCAL is a multilayered brass/scintillator detector, with $0.087 \times 0.087$ segmentation, and a resolution of roughly $100\% / \sqrt{E}$ with $E$ in GeV. The CMS detector is described in detail elsewhere [10].

Jets are reconstructed in this analysis with the anti-$k_T$ [11] algorithm with cone size $R=0.7$, applied to electromagnetic and hadronic calorimeter towers. The jet energy and momentum are corrected for the nonlinear response of the calorimeter relative to generated jet energies. The performance of the CMS detector with respect to jet reconstruction is described in detail elsewhere [12]. The data sample used in this analysis is identical to that of the search for new physics in the dijet mass distribution. In the related note [1], the reconstruction, selection, and excellent data quality are described in detail.

We select events where the two highest-$p_T$ jets lie in the pseudorapidity range $|\eta| < 1.3$. Selected events are classified either as inner if the two leading jets lie in the range $|\eta| < 0.7$ or as outer if both jets lie in the range $0.7 < |\eta| < 1.3$. To compute the dijet centrality ratio we only use inner and outer events, which are roughly 50% of the whole sample.

We use collision events that pass one of three jet triggers with thresholds of 15, 30, and 50 GeV (before jet energy corrections). These triggers are fully efficient for dijet masses exceeding 150, 230, and 330 GeV, respectively. We use data from the lowest energy trigger for the first four dijet mass bins ($154 < \text{dijet mass} < 244$ GeV), the second-lowest energy trigger for the next four dijet mass bins ($244 < \text{dijet mass} < 354$ GeV), and the third trigger for the remaining data ($\text{dijet mass} > 354$ GeV).

In the SM the dijet centrality ratio is nearly flat as a function of dijet mass, with a value of $0.5 - 0.6$. The presence of new physics may dramatically affect the dijet centrality ratio. The ratio rises rapidly in the presence of contact interactions, with the departure from the SM prediction occurring at a dijet mass that depends on the scale $\Lambda$ of the interaction. Resonances such as excited quarks canra the ratio to peak near the mass of the resonance. In the next section we show the predicted dijet centrality ratio as a function of dijet mass for NLO QCD, QCD predictions from PYTHIA, and several new physics scenarios (along with the data) in Figs. 1 and 2.

3 Observed Dijet Centrality Ratio

The observed dijet mass spectra for inner and outer events from a data sample corresponding to an integrated luminosity of $120 \text{nb}^{-1}$ appear in Fig. 1. In the left hand plot, we show the number of inner and outer dijets versus dijet mass; the numbers are scaled by the appropriate trigger reduction factors (prescales) to obtain the expected steeply falling spectra. In the right hand plot of Fig. 1, we compare the measured dijet centrality ratio $^1$ as a function of dijet mass with the QCD predictions from NLO calculations and PYTHIA for events with dijet mass less than 838 GeV. The data for all dijet masses can be seen in Fig. 2.

$^1$The uncertainties in this ratio of Poisson-distributed numbers are calculated using Clopper-Pearson [13] intervals.
We apply a mass-dependent correction to the NLO prediction to account for non-perturbative effects that are absent from the NLO calculation. These corrections, which are approximately 10% at dijet mass below 400 GeV and negligible at higher dijet masses, are derived from studies of multiple parton interactions and hadronization with PYTHIA in manner similar to that described in [14]. We also correct the PYTHIA prediction with an NLO/LO k-factor, which accounts for a 5-10% effect depending on dijet mass.

The NLO prediction is shown as a band to account for uncertainties related to the choices of the renormalization scale, factorization scale, and parton distribution function (PDF) used in the calculation. The scale uncertainties are approximately 3 - 4% on the centrality ratio depending on dijet mass, while the PDF uncertainties have a negligible effect. The band also includes a 2% uncertainty arising from the correction for non-perturbative effects.

The dijet centrality ratio in the data is nearly flat as predicted by QCD. The data are more consistent with the prediction from NLO (corrected for non-perturbative effects) than with the prediction from PYTHIA, irrespective of whether PYTHIA is corrected by the NLO/LO k-factor.

Figure 1: Dijet mass spectra (left) for inner (red) and outer (black) jets and dijet centrality ratio for events with dijet mass less than 838 GeV (right) in 120 nb$^{-1}$ of integrated luminosity. On the right panel, the ratio is compared to predictions for QCD from PYTHIA and from NLO calculations. The ratio for all events can be seen in Fig. 2.

4 Search for New Physics

Figure 2 shows a comparison of the measured dijet centrality ratio with the predictions of NLO QCD and various new physics models. To quantitatively test for the presence of new physics in the dijet centrality ratio, we use a log-likelihood-ratio statistic ($R_{LL}$) that compares the null hypothesis (SM only) to the hypothesis that new physics effects are present in addition to the SM. We compare the value of $R_{LL}$ in the data to distributions of the expected values for both hypotheses, obtained in ensembles of pseudoexperiments, to either claim the discovery of new physics or set exclusion bounds with the frequentist-inspired CL$_{s}$ method [15].

We use the NLO prediction plus non-perturbative corrections as the null hypothesis.
mize the effect, on the hypothesis testing, of potential discrepancies between the NLO prediction and the actual physics underlying dijet production, we use the data below dijet masses of 270 GeV to measure an overall offset of the QCD dijet centrality ratio relative to the NLO prediction; the shape of the NLO prediction is fixed. The result of the fit for the offset $(-0.013 \pm 0.012)$ is consistent with zero. We examine the measured ratio above dijet masses of 270 GeV to search for evidence of new physics, as discussed below, assuming this overall shift measured from the low dijet mass region.

![Dijet centrality ratio](image)

Figure 2: Dijet centrality ratio in 120 nb$^{-1}$ of integrated luminosity. The ratio is compared to predictions for NLO QCD plus non-perturbative corrections (see text), contact interactions with $\Lambda = 500, 1000, \text{and} 1500 \text{ GeV}$, and excited quark resonances with masses of 500 and 1200 GeV.

Systematic uncertainties are included in the ensembles of pseudoexperiments with the method of Cousins and Highland [16]; i.e., the uncertainties enter the ensembles as nuisance parameters that affect the number of inner and outer events expected.

The fact that this analysis is based on a ratio leads to the cancellation of many systematic effects. In Table 1, we report the systematic uncertainty related to the dijet centrality ratio measurement and the model for the QCD and contact interaction hypotheses.

The source of uncertainty with the greatest effect on the measurement of the ratio is the 1% imprecision in the relative jet energy scales for the inner and outer pseudorapidity regions, which results in a 5% uncertainty on the ratio. This relative uncertainty has a much larger effect on the ratio than a 10% shift in the energy scale for both regions, which has an effect on the ratio of less than 1%. Imperfectly modeled jet energy resolution and other detector effects have a small effect on the dijet centrality ratio.

While the 10% uncertainty on the absolute jet energy scale has little effect on the measurement of the dijet ratio, it does have a 10% effect on the measurement of the dijet mass. For QCD, the dijet ratio is slowly varying in dijet mass, so the 10% uncertainty on dijet mass is negligible for this model; however, the slope of the ratio is steep as a function of dijet mass for the new physics models, and the 10% uncertainty on dijet mass directly results in a 10% uncertainty on
Table 1: Systematic uncertainties related to the experimental measurement of the dijet uncertainty ratio (detector uncertainties) and to the models used in the setting limits for NLO QCD and contact interactions (model uncertainties).

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>NLO QCD (Units of Ratio)</th>
<th>Contact Interactions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute JES</td>
<td>0.002 - 0.004</td>
<td>0.3 - 0.8</td>
</tr>
<tr>
<td>Relative JES</td>
<td>0.02 - 0.03</td>
<td>3.9 - 5.3</td>
</tr>
<tr>
<td>Other</td>
<td>0.01</td>
<td>2.0</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>0.003</td>
<td>0.6</td>
</tr>
<tr>
<td>Total Detector Resolution</td>
<td>0.02 - 0.03</td>
<td>4.5 - 5.8</td>
</tr>
<tr>
<td>Model Uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scale</td>
<td>+(0.014 - 0.023)</td>
<td>+(2.7 - 4.4)</td>
</tr>
<tr>
<td>Offset</td>
<td>-(0.005 - 0.008)</td>
<td>-(0.9 - 1.6)</td>
</tr>
<tr>
<td>Fit</td>
<td>0.005</td>
<td>1.0</td>
</tr>
<tr>
<td>PDF</td>
<td>0.002</td>
<td>0.3</td>
</tr>
<tr>
<td>Total Model</td>
<td>+(0.024 - 0.030)</td>
<td>+(4.8 - 5.9)</td>
</tr>
<tr>
<td></td>
<td>-(0.021 - 0.022)</td>
<td>-(4.0 - 4.3)</td>
</tr>
<tr>
<td>Total</td>
<td>+(0.034 - 0.042)</td>
<td>+(6.8 - 8.3)</td>
</tr>
<tr>
<td></td>
<td>-(0.031 - 0.037)</td>
<td>-(6.1 - 7.2)</td>
</tr>
</tbody>
</table>

The scale of the new physics being probed. For comparison with other sources of uncertainty we convert this 10% uncertainty on dijet mass into an uncertainty on the dijet ratio of 5 - 30%, depending on dijet mass.

The sources of uncertainty with the greatest effect on the NLO QCD model are the renormalization and factorization scales and the offset described above, with uncertainties of 3 - 4.5% and 4%, respectively, depending on dijet mass.

We find that the data are consistent with the SM expectation, and so we use the data to determine 95% C.L. limits on the contact interaction scale. To quantify the agreement with the NLO QCD expectation, we define a consistency statistic

$$ C = \sum_{\text{bins}} \frac{(R_{\text{obs}} - R_{\text{QCD}})^2}{\sigma_{\text{syst}}^2 + \sigma_{\text{stat}}^2}, $$

where $R_{\text{obs}}$ is the observed dijet centrality ratio, $R_{\text{QCD}}$ is the NLO QCD expectation, $\sigma_{\text{syst}}$ is the systematic uncertainty, and $\sigma_{\text{stat}}$ is the statistical uncertainty per bin. (We neglect bin-to-bin correlations among the systematic uncertainties, but we find that the effects of systematic uncertainties on this statistic are small.) The $p$-value of the observed data with respect to the expected distribution of the C statistic is 0.8, indicating good agreement with the QCD prediction.

In Fig. 3 we show the interpolation of the limit. We show $R_{LL}$ for the data, the 95% CLs points, and the SM expectation (with 1 and 2 $\sigma$ bands) versus contact interaction scale $\Lambda$. The limit is the point where the data line crosses the 95% CLs line; the expected limit is the point where the SM expectation crosses the 95% CLs line. We exclude a contact interaction with scale $\Lambda < 1.2$ TeV at 95% C.L. Given the observed number of events (inner+outer) in each dijet mass bin, we expect to exclude a contact interaction with scale $\Lambda < 1.2$ TeV and $1.4 < \Lambda < 1.5$ TeV. With the present data sample we cannot exclude the possibility of an excited quark with a mass of 0.5 TeV.
TeV at 95% C.L.

![Figure 3: Limit summary plot for contact interaction scale $\Lambda$. We show $R_{LL}$ for the data (solid black), the 95% CL$_s$ line (solid blue), and the SM expectation (dashed black) with 1 and 2 $\sigma$ bands (green/yellow) versus $\Lambda$.](image)

In the absence of contact interactions, we expect to surpass the Tevatron 95% C.L. limit of 2.8 TeV with approximately 4 pb$^{-1}$ of integrated luminosity; a figure illustrating the sensitivity can be found elsewhere [17].

## 5 Conclusion

We present here the first results from the CMS experiment in measuring the dijet centrality ratio $N(|\eta| < 0.7)/N(0.7 < |\eta| < 1.3)$ in 7 TeV collisions at the LHC, using a data sample corresponding to $120 \pm 13$ nb$^{-1}$ of integrated luminosity. The dijet centrality ratio observed in data is flat as predicted by QCD. The data are more consistent with the corrected NLO prediction than with the PYTHIA prediction. We exclude a contact interaction with scale $\Lambda < 1.9$ TeV at 95% C.L. With approximately 4 pb$^{-1}$ of integrated luminosity, we expect to exclude a contact interaction with scale $\Lambda < 3$ TeV at 95% C.L.

## References


