Physics

Physics Research Publications

Purdue University *Year* 2010

Search for Quark Compositeness with the Dijet Centrality Ratio in pp Collisions at root s=7 TeV

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Search for Quark Compositeness with the Dijet Centrality Ratio in pp Collisions at $\sqrt{s} = 7$ TeV

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A search for quark compositeness in the form of quark contact interactions, based on hadronic jet pairs (dijets) produced in proton-proton collisions at $\sqrt{s} = 7$ TeV, is described. The data sample of the study corresponds to an integrated luminosity of 2.9 pb^{-1} collected with the CMS detector at the LHC. The dijet centrality ratio, which quantifies the angular distribution of the dijets, is measured as a function of the invariant mass of the dijet system and is found to agree with the predictions of the standard model. A statistical analysis of the data provides a lower limit on the energy scale of quark contact interactions. The sensitivity of the analysis is such that the expected limit is 2.9 TeV; because the observed value of the centrality ratio at high invariant mass is below the expectation, the observed limit is 4.0 TeV at the 95% confidence level.

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In the standard model (SM), most high energy proton-proton collisions are described by the scattering of partons (quarks or gluons) in the framework of quantum chromodynamics (QCD). The outgoing partons manifest themselves as two or more jets of hadrons, with the pseudorapidity η of the jets depending on the parton scattering angle. In QCD, the jet production rate peaks at large $|\eta|$ because the scattering is dominated by t-channel processes. Several new physics scenarios, including models of quark compositeness, produce a more isotropic angular distribution leading to enhanced jet production at smaller values of $|\eta|$ [1–6]. Other models of new physics predict the opposite: a decrease in jet production at small $|\eta|$ compared with the SM [7].

The dijet system consists of the two jets with the highest transverse momenta p_T in an event (the leading jets) with invariant mass m_{jj}. The dijet centrality ratio R_η is defined as the number of events with the two leading jets in the region $|\eta| < 0.7$ (*inner* events) divided by the number of events with the two jets in the region $0.7 < |\eta| < 1.3$ (*outer* events). Because many systematic effects cancel in this ratio, R_η provides an accurate test of QCD and is sensitive to new physics.

In this Letter we report a measurement of R_η in proton-proton collisions at $\sqrt{s} = 7$ TeV. The analysis is based on a data sample corresponding to an integrated luminosity of $2.9 \pm 0.3\ \mathrm{pb}^{-1}$ collected with the Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider.

The dijet centrality ratio is measured as a function of m_{jj} and is compared with predictions from perturbative QCD calculations performed at next-to-leading order (NLO) accuracy with the NLOJET++ program [8,9] in the FASTNLO framework [10]. We also compare the measured R_η with a QCD prediction obtained from the PYTHIA 6.420 event generator [11] with the D6T set of parameters [12]. We use CTEQ6.6 parton distribution functions (PDFs) [13] for the NLO calculation and CTEQ6LL [14] for the PYTHIA6 prediction. The effect of the CMS detector simulation [15] on the predictions for R_η is negligible.

We use R_η to search for evidence that quarks are composite particles. Quark compositeness at an energy scale Λ would appear at lower energies as a contact interaction, yielding an η distribution different from that predicted by QCD. We consider a model of contact interactions between left-handed quarks in the process $qq \to qq$ described by the effective Lagrangian $L_{qq} = (\pm 2\pi/\Lambda^2)(\bar{q}_L \gamma^\mu q_L) \times (\bar{q}_L \gamma_\mu q_L)$ [1]. We choose the positive sign of L_{qq} because it yields a more conservative exclusion limit on Λ (by about 5%) than the negative sign. In QCD, R_η is nearly independent of m_{jj}, with a value near 0.5. The presence of quark contact interactions described by L_{qq} would cause R_η to increase rapidly above a value of m_{jj} that depends on Λ. Previous searches for quark compositeness described by the interaction L_{qq} exclude $\Lambda < 3.4$ TeV at the 95% confidence level (C.L.) [16–21].

A detailed description of the CMS detector can be found elsewhere [22]. The CMS coordinate system is right-handed with the origin at the center of the detector, the x axis directed toward the center of the LHC ring, and the y axis directed upward; ϕ is the azimuthal angle, θ the polar angle, and $\eta \equiv -\ln(\tan[\theta/2])$ the pseudorapidity. The central feature of the CMS apparatus is a superconducting solenoid that surrounds the silicon pixel and strip tracker as well as the barrel and end cap calorimeters

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(covering the region $|\eta| < 3$): a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadronic calorimeter (HCAL). The ECAL barrel extends to $|\eta| = 1.479$ and the HCAL barrel to $|\eta| = 1.305$. The HCAL and ECAL cells are grouped into towers projecting radially outward from the origin. In the region $|\eta| < 1.74$ these calorimeter towers have width $\Delta\eta = \Delta\phi = 0.087$. ECAL and HCAL cell energies above noise suppression thresholds are summed within each projective tower to define the calorimeter tower energy.

We reconstruct jets by applying the anti-k_T clustering algorithm [23] to the calorimeter towers with the distance parameter $R = 0.7$. The energy E and momentum $\vec{p}$ of a jet are defined as the scalar and vector sums, respectively, of the calorimeter cell energies associated with the jet. We apply p_T- and η-dependent scales to E and $\vec{p}$ to correct for the nonlinearity and nonuniformity of the calorimeter response. The jet energy corrections and resolutions are determined and validated using simulated, test beam, and collision data [24].

A set of independent single-jet triggers with varying thresholds on uncorrected jet p_T is employed in the online trigger system. We use data from three of these triggers, with thresholds of 15, 30, and 50 GeV, in the m_{jj} ranges where the triggers have efficiency greater than 99.5% for both inner and outer events. By studying the relative efficiency of parallel triggers in the collision data, we determine that these three triggers meet this efficiency requirement for m_{jj} greater than 156, 244, and 354 GeV, respectively, where these values are three of the predefined bin edges for m_{jj}. The requirement of $m_{jj} > 156$ GeV results in a minimum jet p_T of 25 GeV.

To remove potential instrumental and noncollision backgrounds we impose the following requirements: events must have a primary vertex reconstructed with $|z| < 24$ cm [25]; jets must have at least 1% of their total energy detected in the ECAL, no more than 98% of their energy detected in a single HCAL photodetector, and no more than 90% of their energy in a single calorimeter cell (ECAL or HCAL). These jet identification criteria remove less than 0.1% of the selected events at all values of m_{jj}.

In Fig. 1 we show the observed numbers of inner and outer dijet events and R_η in bins of m_{jj}; the bin widths roughly correspond to the m_{jj} resolution. The event counts, which are corrected for the trigger reduction factors (prescales), fall steeply with increasing m_{jj}. We compare R_η with NLO and PYTHIA6 predictions for m_{jj} values up to 1120 GeV. The error bars represent the combination of statistical and experimental systematic uncertainties (described in detail later). The horizontal lines near the end of the error bars denote the statistical uncertainty on this ratio of Poisson-distributed variables computed with Clopper-Pearson intervals [26].

We apply an m_{jj}-dependent correction to the NLO prediction to account for nonperturbative effects of hadronization and multiple parton interactions. This correction, which is approximately 10% at low m_{jj} and 2% for m_{jj} greater than 400 GeV, is obtained from PYTHIA6. The predictions of PYTHIA6 and HERWIG++ [27] for this correction agree to within a few percent.

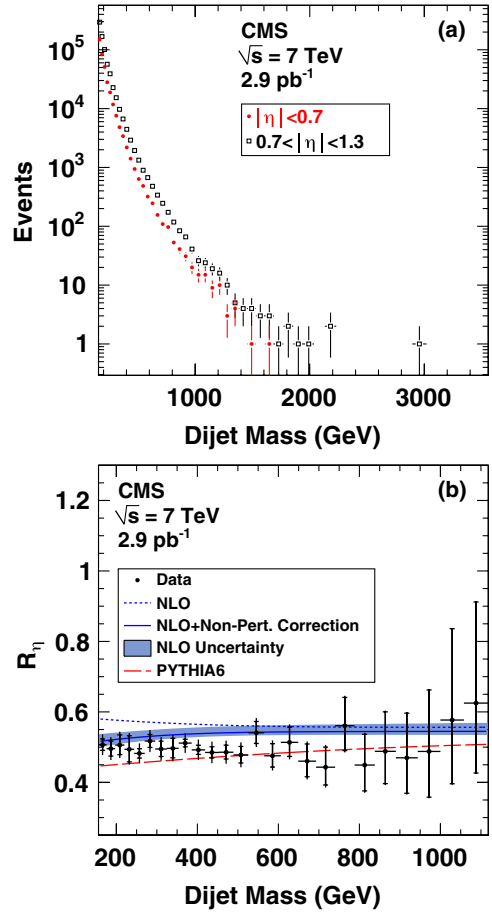

FIG. 1 (color online). (a) Event counts corrected for trigger prescales for inner (solid circles) and outer (open boxes) dijets and (b) the observed R_η as functions of m_{jj}. We compare R_η with predictions for QCD from PYTHIA6 (dashed line), NLO calculations (dotted line), and NLO plus nonperturbative corrections (solid line) and its uncertainty (band).

The NLO prediction is shown as a band that accounts for uncertainties related to the choices of the renormalization scale μ_R, the factorization scale μ_F, and the PDFs used in the calculation. The scale uncertainties, which are approximately 3%–4% depending on m_{jj}, are evaluated by varying the scales from the default choice of $\mu_R = \mu_F = p_T$ to $p_T/2$, p_T, and $2p_T$ in the following six combinations: $(\mu_R, \mu_F) = (p_T/2, p_T/2)$, $(2p_T, 2p_T)$, $(p_T, p_T/2)$, $(p_T, 2p_T)$, $(p_T/2, p_T)$, and $(2p_T, p_T)$. The PDF uncertainties are estimated with repeated evaluations of the NLO-predicted R_η for the PDFs in the CTEQ6.6, MSTW2008 [28], and NNPDF2.0 [29] sets and are found to be less than 1%. The band also includes the uncertainty arising from the correction for nonperturbative effects, which we conservatively take to be 20% of the correction factor.

The measured R_η is nearly flat with a value of about 0.5 as predicted by both the corrected NLO calculation and PYTHIA6. The observed average ratio is about 7% lower than that of the corrected NLO prediction, and about 7% higher than that of the PYTHIA6 prediction. The data are in better agreement with the corrected NLO prediction at low m_{jj}, where the significant nonperturbative corrections improve the agreement, and with the PYTHIA6 prediction at intermediate and high m_{jj}.

To test for the presence of quark compositeness with R_η, we employ a log-likelihood-ratio statistic that compares the likelihood of the null (QCD only) hypothesis $\mathcal{L}_{\rm QCD}$ with that of the alternative hypothesis that quark contact interactions are present in addition to QCD $\mathcal{L}_{\rm alt}$:

$$\mathcal{R}_{\rm LL} = \ln\mathcal{L}_{\rm alt} - \ln\mathcal{L}_{\rm QCD}. \quad (1)$$

The total likelihood is the product of the individual bin likelihoods, which for m_{jj} bin i is

$$\mathcal{L}_i = \mathcal{P}(n_{{\rm tot},i}|\mu_{{\rm tot},i})\mathcal{B}(n_{{\rm in},i}|n_{{\rm tot},i}, \rho_i), \quad (2)$$

where the first factor is the Poisson probability to observe $n_{{\rm tot},i}$ events when expecting $\mu_{{\rm tot},i}$ and the second is the binomial probability to observe $n_{{\rm in},i}$ inner events given $n_{{\rm tot},i}$ and a predicted probability to be inner of ρ_i [where $\rho = R_\eta/(1 + R_\eta)$]. Since the first factor in Eq. (2) contains no information on R_η, we remove it from the statistical inference by conditioning the probabilities by the observed values of $n_{{\rm tot},i}$ [30,31]. We compare the value of $\mathcal{R}_{\rm LL}$ in the data with distributions of the expected values for both hypotheses, obtained from ensembles of pseudoexperiments, to either claim the discovery of quark compositeness or to set exclusion bounds on the compositeness scale Λ with the frequentist-inspired CL_s method [32]. In this method, $\mathcal{R}_{\rm LL}$ values for which $\mathrm{CL}_s = \mathrm{CL}_{s+b}/\mathrm{CL}_b < 0.05$ are excluded at the 95% C.L., where CL_{s+b} and CL_b are the probabilities for $\mathcal{R}_{\rm LL}$ to have a lower value than that observed, given the alternative and null hypotheses, respectively. This protects against an exclusion claim when the data have little sensitivity to the new physics.

We use the NLO prediction corrected for nonperturbative effects to describe the shape of R_η for the null hypothesis. To minimize the effect of potential discrepancies between the NLO prediction and actual QCD dijet production, we include an overall offset of R_η in the null hypothesis. This offset is determined with the data in the m_{jj} range between 490 and 790 GeV. (The lower bound is chosen to avoid the region where nonperturbative corrections are significant, and the upper bound is chosen to avoid the signal region for compositeness.) As noted above, the data lie below the NLO prediction, yielding an offset of $\Delta R_\eta = -0.050 \pm 0.021(\text{stat.}) \pm 0.039(\text{syst.})$. Using ensembles of simulated data, we determine that the probability (p value) for observing $|\Delta R_\eta| > 0.050$, given the NLO prediction, is 0.29.

PYTHIA6 is used to describe R_η for the alternative hypothesis. We apply an m_{jj}-dependent correction that accounts for NLO contributions to the QCD part of this prediction. We do not apply this correction, which is derived for t-channel QCD processes, to the contact interaction part of the prediction because it is not physically motivated and yields less conservative exclusion limits on Λ. Since the contact interaction model is not valid for m_{jj} near the compositeness scale, we exclude data above a Λ-dependent m_{jj} threshold for the testing of each Λ value hypothesis.

In Table I we report the systematic uncertainties related to the measurement of R_η and the NLO QCD model. The dominant source of uncertainty on the measurement is the 1% uncertainty in the relative jet energy scale (JES) between the inner and outer η regions, which results in a 5%–13% uncertainty on R_η depending on m_{jj}. This relative uncertainty has a much larger impact than a 10% uncertainty on the JES common to both regions. The simulation of jet energy reconstruction is verified by examination of transverse momentum conservation for selected events and for events where the dijet system consists of an inner and an outer jet.

For the QCD model, the sources of uncertainty include the choice of scale and PDFs in the NLO calculation and the nonperturbative corrections described above. In addition, we take the statistical uncertainty on the offset described above and the difference between the PYTHIA6 and

TABLE I. Systematic uncertainties on R_η related to the measurement of R_η (detector uncertainties) and to the QCD model (model uncertainties). For each source of uncertainty, we show the range of values over the entire m_{jj} range and at a representative point in the signal region.

Source	Full range	$m_{jj} = 1.6$ TeV
Detector uncertainty		
Relative JES	0.02–0.05	0.032
Absolute JES	0.00–0.03	0.003
Jet energy resolution	0.003	0.003
Other	0.01	0.010
Total detector	0.02–0.05	0.034
Model uncertainty		
PYTHIA6–NLO	0.00–0.05	0.032
Offset	0.021	0.021
Scale	$^{+(0.01-0.05)}_{-(0.01-0.02)}$	$^{+0.029}_{-0.011}$
PDF	$^{+(0.002-0.004)}_{-(0.002-0.007)}$	$^{+0.002}_{-0.003}$
MC statistics	0.005	0.005
Nonpert. corr.	0.002–0.014	0.002
Total model	$^{+(0.02-0.07)}_{-(0.01-0.05)}$	$^{+0.044}_{-0.034}$
Total	$^{+(0.03-0.09)}_{-(0.03-0.08)}$	$^{+0.055}_{-0.048}$

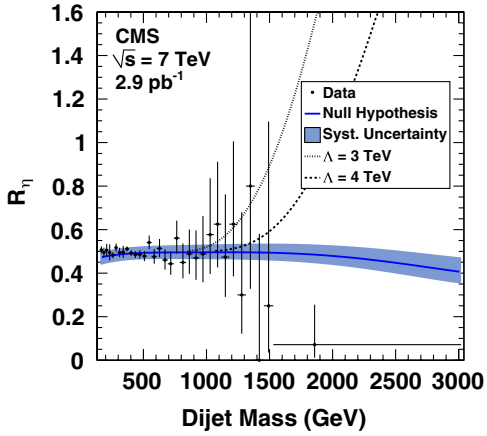

FIG. 2 (color online). The observed dijet centrality ratio as a function of m_{jj} compared with the null (QCD) hypothesis (solid line), including the total systematic uncertainty (band), and to hypotheses of quark contact interactions with $\Lambda = 3$ TeV (dotted line) and 4 TeV (dashed line).

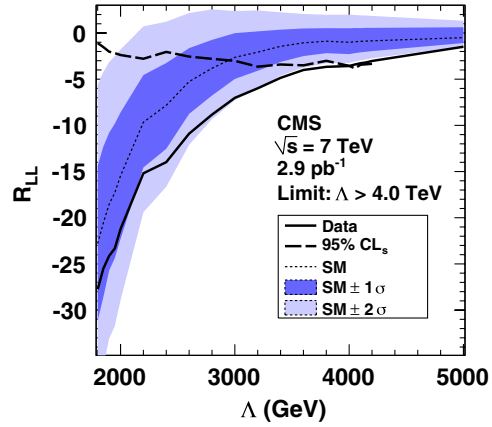

FIG. 3 (color online). Summary of the limit for the contact interaction scale Λ. We show $\mathcal{R}_{\rm LL}$ versus Λ for the data (solid line), the 95% CL_s (dashed line), and the SM expectation (dotted line) with 1σ (dark) and 2σ (light) bands.

NLO predictions as systematic uncertainties related to our choice of model. For the compositeness hypothesis, R_η increases steeply with m_{jj}, and the 10% uncertainty on the absolute JES dominates the uncertainty on the Λ scale being probed.

Figure 2 shows our data in comparison with the null hypothesis. Alternative hypotheses with contact interaction scales of $\Lambda = 3$ and 4 TeV are also shown. In this figure, the data from the 15 sparsely populated m_{jj} bins in the range 1530–3020 GeV are combined into a single bin for presentation purposes. The band indicates the total systematic uncertainty, which is included in the ensembles of pseudoexperiments with the method of Ref. [33]; i.e., the uncertainties enter the ensembles as nuisance parameters that affect the expected numbers of inner and outer events.

To quantify the agreement of the data with the SM expectation, we determine the offset of the data with respect to the NLO model for the full m_{jj} range, finding $-0.037 \pm 0.007(\mathrm{stat.}) \pm 0.039(\mathrm{syst.})$ with a p value of 0.34. Given this consistency of the data with the QCD hypothesis, we determine 95% C.L. limits on the contact interaction scale Λ.

We summarize the determination of the limit in Fig. 3. We show $\mathcal{R}_{\rm LL}$ versus Λ for the data and for the SM expectation (with 1σ and 2σ bands) along with the highest value of $\mathcal{R}_{\rm LL}$ excluded at the 95% C.L. with the CL_s method. High $\mathcal{R}_{\rm LL}$ values indicate new physics. The expected exclusion region comprises those values of Λ for which the SM-expected $\mathcal{R}_{\rm LL}$ (conditioned by the observed numbers of events $n_{\mathrm{tot},i}$) is less than the 95% CL_s contour, and is seen to be $\Lambda < 2.9$ TeV. The observed exclusion region comprises values for which the measured $\mathcal{R}_{\rm LL}$ is less than the 95% CL_s contour, and is seen to be $\Lambda <$ 4.0 TeV. The observed limit is higher than expected because for $m_{jj} > 1.4$ TeV the measured R_η is lower than its expectation under the SM.

In summary, we present a measurement of the dijet centrality ratio in 7 TeV proton-proton collisions. The dijet centrality ratio is found to exhibit little dependence on the dijet invariant mass and to agree with the expectation of the standard model. We exclude quark compositeness described by a contact interaction between left-handed quark fields at energy scales of $\Lambda < 4.0$ TeV at the 95% C.L. This is the most stringent limit to date.

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