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Search for quark compositeness in dijet angular distributions from pp collisions at $\sqrt{s} = 7$ TeV

The CMS collaboration

Abstract: A search for quark compositeness using dijet angular distributions from pp collisions at $\sqrt{s} = 7$ TeV is presented. The search has been carried out using a data sample corresponding to an integrated luminosity of $2.2\,\mathrm{fb}^{-1}$, recorded by the CMS experiment at the LHC. Normalized dijet angular distributions have been measured for dijet invariant masses from 0.4 TeV to above 3 TeV and compared with a variety of contact interaction models, including those which take into account the effects of next-to-leading-order QCD corrections. The data are found to be in agreement with the predictions of perturbative QCD, and lower limits are obtained on the contact interaction scale, ranging from 7.5 up to 14.5 TeV at 95% confidence level.

Keywords: Hadron-Hadron Scattering

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In theories of physics beyond the standard model, it has been proposed that quarks are composite particles and are bound states of more fundamental entities [1, 2]. Models of quark compositeness may explain the number of quark generations, quark charges, and quark masses, which are not predicted in the standard model. A common signature of quark compositeness models is the appearance of new interactions between quark constituents at a characteristic scale Λ that is much larger than the quark masses. At energies well below Λ, these interactions can be approximated by a contact interaction (CI) characterized by a four-fermion coupling. In this Letter, flavor-diagonal color-singlet couplings between quarks are studied. These can be described by the effective Lagrangian [1, 3]

$$L_{\rm qq} = \frac{2\pi}{\Lambda^2}\left[\eta_{LL}(\overline{\rm q}_L\gamma^\mu {\rm q}_L)(\overline{\rm q}_L\gamma_\mu {\rm q}_L) + \eta_{RR}(\overline{\rm q}_R\gamma^\mu {\rm q}_R)(\overline{\rm q}_R\gamma_\mu {\rm q}_R) + 2\eta_{RL}(\overline{\rm q}_R\gamma^\mu {\rm q}_R)(\overline{\rm q}_L\gamma_\mu {\rm q}_L)\right],$$

where the subscripts L and R refer to the chiral projections of the quark fields and η_{LL}, η_{RR}, and η_{RL} can be 0, +1, or −1. The various combinations of η_{LL}, η_{RR}, and η_{RL} correspond to different CI models. The following CI scenarios are investigated:

$$\begin{aligned}
\Lambda &= \Lambda^{\pm}_{LL} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm1, 0, 0),\\
\Lambda &= \Lambda^{\pm}_{RR} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (0, \pm1, 0),\\
\Lambda &= \Lambda^{\pm}_{VV} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm1, \pm1, \pm1),\\
\Lambda &= \Lambda^{\pm}_{AA} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm1, \pm1, \mp1),\\
\Lambda &= \Lambda^{\pm}_{(V-A)} \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (0, 0, \pm1).
\end{aligned}$$

In pp collisions these models result in the same limits for $\Lambda^{\pm}_{LL}$ and $\Lambda^{\pm}_{RR}$, and at tree level for $\Lambda^{\pm}_{VV}$ and $\Lambda^{\pm}_{AA}$ as well as for $\Lambda^{+}_{(V-A)}$ and $\Lambda^{-}_{(V-A)}$.

High energy proton-proton collisions with large momentum transfers predominantly produce events containing two jets with high transverse momenta (dijets). Such events probe the scattering partons at the shortest distance scales and provide a fundamental test of quantum chromodynamics (QCD). The angular distribution of these two jets with respect to the beam direction is directly sensitive to the underlying dynamics of the parton-parton scattering and does not strongly depend on the parton distribution functions (PDFs). Distributions of the polar scattering angle θ^* in the parton-parton center-of-mass frame from QCD processes are peaked in the forward and backward directions, whereas contact interactions give rise to more isotropic distributions in θ^*.

Previous searches for quark compositeness at hadron colliders have been reported at the Sp$\overline{\rm p}$S by the UA1 [4] collaboration, at the Tevatron by the D0 [5, 6] and CDF [7] collaborations, and at the Large Hadron Collider (LHC) by the ATLAS [8, 9] and CMS [10, 11] collaborations. The limits on quark compositeness at the LHC [8–11] have been reported only for a color- and isospin-singlet CI model, $\Lambda^{\pm}_{LL/RR}$, where $\Lambda^{+}_{LL/RR}$ ($\Lambda^{-}_{LL/RR}$) corresponds to destructive (constructive) interference between the CI and QCD terms. In this Letter, our previous searches are extended to higher CI scales using a data sample corresponding to an integrated luminosity of 2.2 fb^{-1} at $\sqrt{s} = 7$ TeV, exploring for the first time at the LHC a wide range of CI models. Also, this is the first use of a recent CI prediction that includes next-to-leading-order (NLO) QCD corrections [12].

In this analysis, the normalized dijet angular distributions, defined as $(1/\sigma_{\text{dijet}})(\text{d}\sigma_{\text{dijet}}/\text{d}\chi_{\text{dijet}})$ where $\chi_{\text{dijet}} = \text{e}^{|y_1-y_2|}$, are studied for several ranges of the dijet invariant mass M_{jj}. Here, y_1 and y_2 are the rapidities of the two highest transverse momentum (p_{T}) jets, and they are related to the jet energy E and the projection of the jet momentum on the beam axis, p_{z}, by $y = \frac{1}{2}\ln[(E+p_{\text{z}})/(E-p_{\text{z}})]$. In the limit of massless scattering partons, χ_{dijet} is related to θ^* by $\chi_{\text{dijet}} = (1+|\cos\theta^*|)/(1-|\cos\theta^*|)$. The use of the variable χ_{dijet} is motivated by the fact that $\text{d}\sigma_{\text{dijet}}/\text{d}\chi_{\text{dijet}}$ is approximately uniform for QCD dijet processes, while CI models predict angular distributions that are strongly peaked at low values of χ_{dijet}.

The data for this analysis are collected with the Compact Muon Solenoid (CMS) detector at the LHC. The central feature of the CMS detector is a superconducting solenoid, 12.5 m long and with an internal diameter of 6 m, providing an axial field of 3.8 T. The field volume of the solenoid is instrumented with various particle detection systems. Charged particle trajectories are measured by a silicon pixel and strip tracker, covering $0 < \varphi < 2\pi$ in azimuth and $|\eta| < 2.5$, where pseudorapidity $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle relative to the counterclockwise proton beam direction with respect to the center of the detector. A lead-tungstate crystal electromagnetic calorimeter and a brass/scintillator hadronic calorimeter surround the tracking volume. A preshower detector made of silicon sensor planes and lead absorbers is installed in front of the electromagnetic calorimeter at $1.653 < |\eta| < 2.6$. Outside the solenoid, muons are measured in gas-ionization detectors embedded in the steel return yoke. A more detailed description of the CMS detector can be found elsewhere [13].

The CMS detector records events with a two-tiered trigger system consisting of a hardware-based Level-1 (L1) and a software-based High Level Trigger (HLT). In this study, single-jet triggers that reconstruct jets from calorimeter energy deposits at L1 and HLT are used to select events based on different jet-p_{T} thresholds. Seven combinations of (L1, HLT) p_{T} thresholds (in GeV) are used to select events: (36, 60), (68, 80), (92, 110), (92, 150), (92, 190), (92, 240), and (92, 300). All except the highest-threshold jet trigger were prescaled during the 2011 run. The efficiency of each single-jet trigger is measured as a function of M_{jj} using events selected by a lower-threshold trigger.

Jets are reconstructed offline using the anti-k_T clustering algorithm with a distance parameter $R = 0.5$ [14]. The four-vectors of particles reconstructed by the CMS particle-flow algorithm are used as input to the jet-clustering algorithm. The particle-flow algorithm [15, 16] combines information from all CMS subdetectors to provide a complete list of long-lived particles in the event. Reconstructed and identified particles include muons, electrons (with associated bremsstrahlung photons), photons (including conversions in the tracker volume), and charged and neutral hadrons. The jet energy scale is calibrated using measurements of energy balance in dijet and photon+jet events [17]. Extra energy clustered into jets from additional proton-proton interactions within the same bunch crossing (pileup) is taken into account on an event-by-event basis by a correction to the jet four-vectors. The average number of pileup interactions for the data sample used in this analysis has been estimated to be 5.

Events with at least two reconstructed jets are selected from an inclusive non flavortagged jet sample, and the two highest-p_T jets are used to measure the dijet angular distributions for different ranges in M_{jj}. Events with spurious jets from noise and non-collision backgrounds are rejected by applying loose quality criteria to the jet properties [18] and requiring a reconstructed primary vertex within ±24 cm of the detector center along the beam line and within 2 cm of the detector center in the plane transverse to the beam [19]. The rapidities $|y_1|$ and $|y_2|$ of the two highest-p_T jets are restricted to be less than 2.5 by selecting only events with $\chi_{\rm dijet} < 16$ and $|y_{\rm boost}| < 1.11$, where $y_{\rm boost} = \frac{1}{2}(y_1 + y_2)$. The lower limits of the M_{jj} ranges for the dijet angular distributions were chosen such that the trigger efficiencies exceed 99%, and are given by the values 0.4, 0.6, 0.8, 1.0, 1.2, 1.5, 1.9, 2.4, and 3.0 TeV. The data for the first five M_{jj} ranges are recorded using prescaled triggers and correspond to integrated luminosities of 0.77, 5.9, 32, 108, and 371 pb^{-1}, while the data for the mass ranges with $M_{jj} > 1.5$ TeV correspond to the full integrated luminosity of 2.2 fb^{-1}. The uncertainty on the integrated luminosities has been estimated to be 4.5% [20, 21]. The highest value of M_{jj} observed in this data sample is 3.9 TeV.

The dijet angular distributions are corrected for migration effects due to the finite jet energy and position resolutions. The four-momenta, rapidities, and azimuthal angles of generated jets from Monte Carlo (MC) event simulations are varied within their measured resolutions [17], and correction factors for each M_{jj} region are obtained from the ratio of the generated to the smeared $\chi_{\rm dijet}$ distributions. Unfolding correction factors are evaluated from two independent MC samples, PYTHIA 6.422 [22] with tune D6T [23] and HERWIG++ 2.4.2 [24] with tune 2.3, and the average of these corrections is applied to the data. The size of the correction factors varies from less than 1.3% in the lowest M_{jj} range to less than 10% in the highest M_{jj} range. The associated systematic uncertainties are taken as the maximum differences between the unfolding corrections obtained from four independent MC samples, HERWIG++ tune 2.3, PYTHIA6 tunes D6T and Z2 (the Z2 tune is identical to the Z1 tune [23] except that Z2 uses the CTEQ6L PDF [25]), and PYTHIA8 [26] tune 4C [27], and the nominal correction factors. These uncertainties range from less than 0.2% at low M_{jj} to less than 4.9% at high M_{jj}. A systematic uncertainty from using a parameterized model to simulate the finite jet p_T and position resolutions to determine the unfolding correction factors is estimated by comparing the smeared $\chi_{\rm dijet}$ distributions to the ones from a detailed simulation of the CMS detector using GEANT4 [28]. This uncertainty is found to be less than 1.3% (2.0%) in the lowest (highest) M_{jj} range and is added in quadrature to the unfolding uncertainties.

The dijet angular distributions are normalized to the integrated dijet cross sections in each M_{jj} range and are relatively insensitive to many systematic effects. For example, they show little dependence on the overall jet-energy scale and are independent of the luminosity uncertainty. However, they are sensitive to the rapidity dependence of the jet energy calibration and to the jet p_T resolution. For the phase space in p_T and η of the jets in this analysis, the jet energy scale uncertainties vary between 2% and 3% and have a dependence on pseudorapidity of less than 1% per unit of η [17]. The uncertainty on the jet p_T resolution is less than 10% [17]. The resulting uncertainty on the $\chi_{\rm dijet}$ distributions due to the jet energy calibration uncertainties is found to be less than 1.0% at low M_{jj} and less than 0.3% at high M_{jj} over all $\chi_{\rm dijet}$ bins, while the maximum uncertainty due to the

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Source of Uncertainty	$0.4 < M_{jj} < 0.6$ TeV (%)	$M_{jj} > 3$ TeV (%)
Jet energy scale	1.0	0.3
Jet energy resolution	0.2	0.6
Jet energy resolution tails	0.5	4.6
Unfolding, MC modeling	0.2	4.9
Unfolding, detector simulation	1.3	2.0
Total experimental systematic uncertainty	1.7	7.0
Statistical uncertainty	2.5	31.6
μ_r and μ_f scales	5.6	14.9
PDF (CTEQ6.6)	0.5	0.7
Non-perturbative corrections	1.7	1.1
Total theoretical systematic uncertainty	5.9	15.0

Table 1. Summary of the leading experimental and theoretical uncertainties on the χ_{dijet} distributions. The maximum uncertainties over all χ_{dijet} bins for the lowest and highest M_{jj} ranges are given. The dominant experimental contribution is the statistical uncertainty while the dominant contribution to the NLO perturbative QCD uncertainty is the factorization and renormalization scale uncertainty.

jet p_{T} resolution uncertainty varies from 0.2% at low M_{jj} to 0.6% at high M_{jj}. In addition, uncertainties on the tails of the jet p_{T} resolutions [17] result in systematic uncertainties on the χ_{dijet} distributions ranging from less than 0.5% at low M_{jj} to less than 4.6% at high M_{jj}. The effect of pileup was investigated by dividing the data into low and high pileup samples based upon the vertex multiplicity, and comparing the χ_{dijet} distributions from each sample. No significant effect was observed. The total systematic uncertainty on the χ_{dijet} distributions, calculated as the quadratic sum of the contributions due to the uncertainties in the jet energy calibration, the jet p_{T} resolution, and the unfolding correction, is less than 1.7% for the lowest M_{jj} range and less than 7% for the highest M_{jj} range. A summary of the leading systematic uncertainties is provided in table 1.

Predictions at NLO in perturbative QCD are made for the dijet angular distributions with NLOJET++ 2.0.1 [29] in the FASTNLO framework version 1.4 [30]. The factorization (μ_f) and renormalization (μ_r) scales are set to $\langle p_{\mathrm{T}} \rangle$, the mean p_{T} of the two jets, and the PDFs are taken from the CTEQ6.6 set [31]. Correction factors are applied to the predictions to account for non-perturbative effects due to hadronization and multiple parton interactions. These correction factors are used to correct the parton QCD calculations to the particle level, and they are determined by the average of the corrections estimated using PYTHIA6 tune D6T and HERWIG++ tune 2.3. This uncertainty is found to encompass alternative choices of MC tunes, PYTHIA6 tune Z2 or PYTHIA8 tune 4C, and is estimated to be less than 1.7% (1.1%) at low (high) M_{jj}.

The dominant source of uncertainty on the QCD predictions is due to the choices of the μ_f and μ_r scales. The uncertainty is evaluated following the proposal in ref. [32] by

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varying the default choice of scales in the following 6 combinations: $(\mu_f/\langle p_T\rangle, \mu_r/\langle p_T\rangle) = (1/2, 1/2)$, $(1/2, 1)$, $(1, 1/2)$, $(2, 2)$, $(2, 1)$ and $(1, 2)$. These scale variations modify the predictions of the normalized χ_{dijet} distributions by less than 5.6% (15%) at low (high) M_{jj}. The uncertainty due to the choice of PDFs is determined from the 22 uncertainty eigenvectors of CTEQ6.6 using the procedure described in ref. [31], and is found to be less than 0.5% at low M_{jj} and less than 0.7% at high M_{jj}. The leading systematic uncertainties on the theoretical predictions are listed in table 1.

The measured differential dijet angular distributions, corrected for instrumental effects and normalized to their respective integrals, are compared to QCD predictions in figure 1 for different M_{jj} ranges. Overall the theoretical predictions provide a good description of the data for all M_{jj} ranges.

The measured dijet angular distributions are used to set limits on a variety of CI models. Only color-singlet models, which predict the largest deviations of the dijet angular distributions from the standard model, are considered. In fact, for the general case of a CI model containing both color-singlet and color-octet contributions, there are certain regions in the theory parameter space where the CI predictions for the dijet angular distributions become indistinguishable from the QCD predictions, because of interference between these contributions [12].

In this analysis we present limits for a CI model that includes the exact NLO QCD corrections to dijet production induced by contact interactions [12], as well as limits extracted from various CI models implemented in PYTHIA8 [26]. In the latter case, the contributions of CI and QCD are calculated to leading order (LO). To take into account the NLO QCD corrections which are missing in the PYTHIA8 model, the cross-section difference $\sigma^{\text{QCD}}_{\text{NLO}} - \sigma^{\text{QCD}}_{\text{LO}}$ is added to the LO QCD+CI prediction in each M_{jj} and χ_{dijet} bin. With this procedure, we obtain a QCD+CI prediction where the QCD terms are corrected to NLO while the CI terms are calculated at LO. Non-perturbative corrections due to hadronization and multiple parton interactions are applied to the predictions. In figure 1, the predictions are shown for QCD+CI from ref. [12] at the CI scale $\Lambda^+_{LL/RR} = 7\,\text{TeV}$ for the two highest M_{jj} ranges. The highest M_{jj} range is the most sensitive to the CI signal, though omitting the second-highest M_{jj} range would decrease the expected limit on the CI scale by about 1% for $\Lambda^+_{LL/RR}$ and 13% for $\Lambda^-_{LL/RR}$. Varying the boundary between the two highest M_{jj} ranges by $\pm 0.2\,\text{TeV}$ changes the expected limit by less then 0.5%. The predictions for the various QCD+CI models at the scale of $\Lambda = 7\,\text{TeV}$ are shown in figure 2 for the highest M_{jj} range. At low χ_{dijet}, the CI predictions with exact NLO QCD corrections show smaller enhancement relative to QCD than the corresponding LO CI predictions, as described in detail in ref. [12].

The statistical method used to set limits on Λ follows a modified frequentist approach [3, 33–35]. The log-likelihood-ratio $q = -2\ln(\frac{L_{\text{QCD+CI}}}{L_{\text{QCD}}})$ is used to discriminate between the QCD-only hypothesis and the QCD+CI hypothesis. The $L_{\text{QCD+CI}}$ and L_{QCD} are written as a product of Poissonian likelihood functions for each bin in χ_{dijet} and for the two highest ranges of M_{jj}, where the predictions for each M_{jj} range are normalized to the number of observed events in that range. The p-values, $P_{\text{QCD+CI}}(q \geq q_{\text{obs}})$ and $P_{\text{QCD}}(q \leq q_{\text{obs}})$, are obtained from ensembles of pseudo-experiments for the two hypotheses. Systematic un-

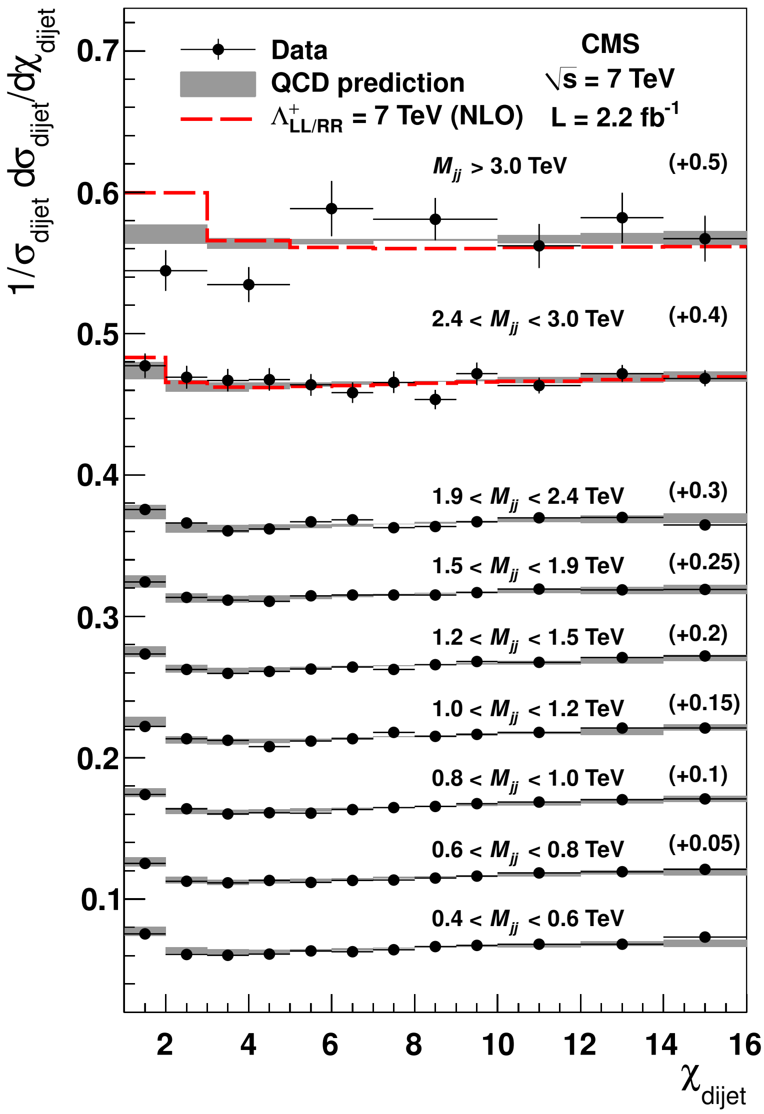

Figure 1. Normalized dijet angular distributions for $|y_{\rm boost}| < 1.11$ in several M_{jj} ranges. For clarity, the distributions are shifted vertically by the additive amounts shown in parentheses in the figure. The vertical error bars represent the statistical and systematic uncertainties added in quadrature. The horizontal bars correspond to the $\chi_{\rm dijet}$ bin width. The results are compared with the predictions of NLO QCD with CTEQ6.6 PDF (shaded band) and with predictions for QCD+CI from [12] at the CI scale $\Lambda^+_{LL/RR} = 7\,\text{TeV}$ (dashed histogram). Non-perturbative corrections due to hadronization and multiple parton interactions are applied to the predictions. The shaded band indicates the total uncertainty on the NLO QCD predictions due to μ_r and μ_f scale variations, PDFs, as well as the uncertainties from the non-perturbative corrections, which have all been added in quadrature.

certainties are represented by nuisance parameters which affect the $\chi_{\rm dijet}$ distribution. The nuisance parameters are varied within their Gaussian uncertainties when generating the distributions of q. The QCD+CI model is considered to be excluded at the 95% confidence

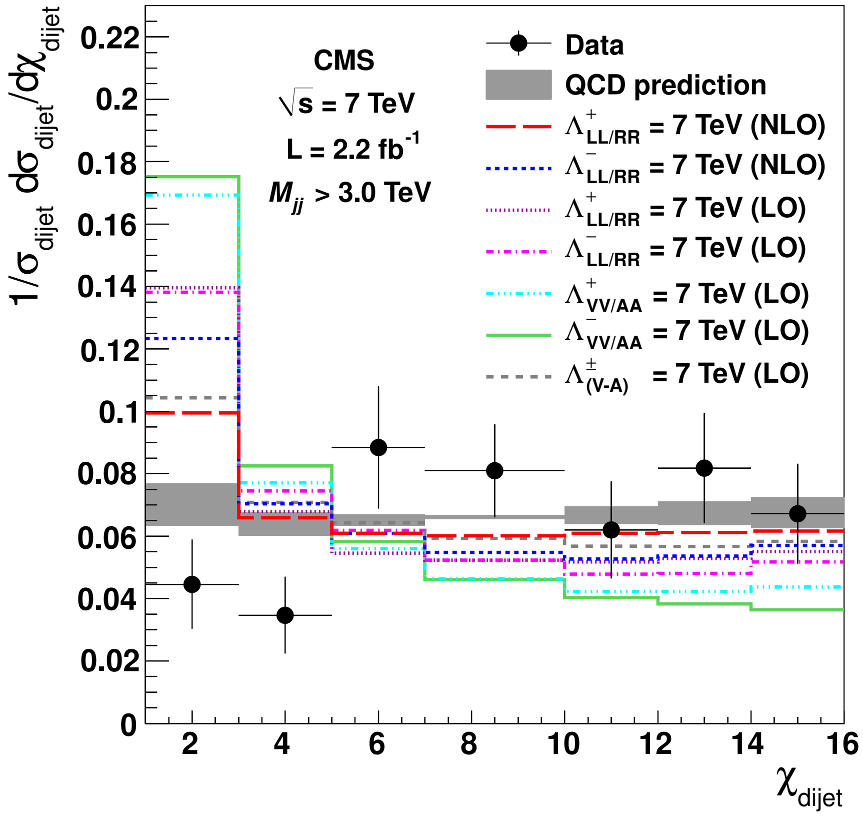

Figure 2. The normalized dijet angular distribution in the highest dijet mass range $M_{jj} > 3\,\text{TeV}$ compared to various contact interaction models (dashed and dotted histograms). Non-perturbative corrections due to hadronization and multiple parton interactions are applied to the predictions. The vertical error bars represent the statistical and systematic uncertainties added in quadrature. The horizontal bars correspond to the χ_{dijet} bin width. The shaded band represents the NLO QCD prediction and includes the systematic uncertainties due to μ_r and μ_f scale variations and PDF uncertainties, as well as the uncertainties from the non-perturbative corrections added in quadrature.

level (C.L.) based on the quantity $\text{CL}_\text{s} = P_{\text{QCD+CI}}(q \geq q_{\text{obs}})/(1 - P_{\text{QCD}}(q \leq q_{\text{obs}})) < 0.05$. The observed and expected limits at 95% C.L. for the CI models considered are listed in table 2 and displayed in figure 3. All the observed limits agree within uncertainties with the expected limits, which are evaluated at the median of the test statistics distribution of the QCD-only model. The observed limits are slightly higher than the expected limits because, for the range $M_{jj} > 3.0\,\text{TeV}$, the measured dijet angular distribution at low χ_{dijet} is lower than, although statistically compatible with, the QCD prediction. The limits for the CI scale $\Lambda^{+}_{LL/RR}$ are also extracted using an alternative procedure in which the data are not corrected for detector effects and instead the MC predictions are convoluted with the detector resolutions. The limits obtained are found to agree with the quoted ones within 1.5%.

In summary, normalized dijet angular distributions have been measured with the CMS detector over a wide range of dijet invariant masses. The distributions are found to be

CI model	Observed limit (TeV)	Expected limit (TeV)
NLO $\Lambda^+_{LL/RR}$	7.5	$7.0^{+0.4}_{-0.6}$
NLO $\Lambda^-_{LL/RR}$	10.5	$9.7^{+1.0}_{-1.7}$
LO $\Lambda^+_{LL/RR}$	8.4	$7.9^{+0.5}_{-0.7}$
LO $\Lambda^-_{LL/RR}$	11.7	$10.9^{+1.7}_{-2.4}$
LO $\Lambda^+_{VV/AA}$	10.4	$9.5^{+0.5}_{-1.0}$
LO $\Lambda^-_{VV/AA}$	14.5	$13.7^{+2.9}_{-2.6}$
LO $\Lambda^\pm_{(V-A)}$	8.0	$7.8^{+1.0}_{-1.1}$

Table 2. Observed and expected lower limits at 95% confidence level for the contact interaction scale Λ for several quark CI models.

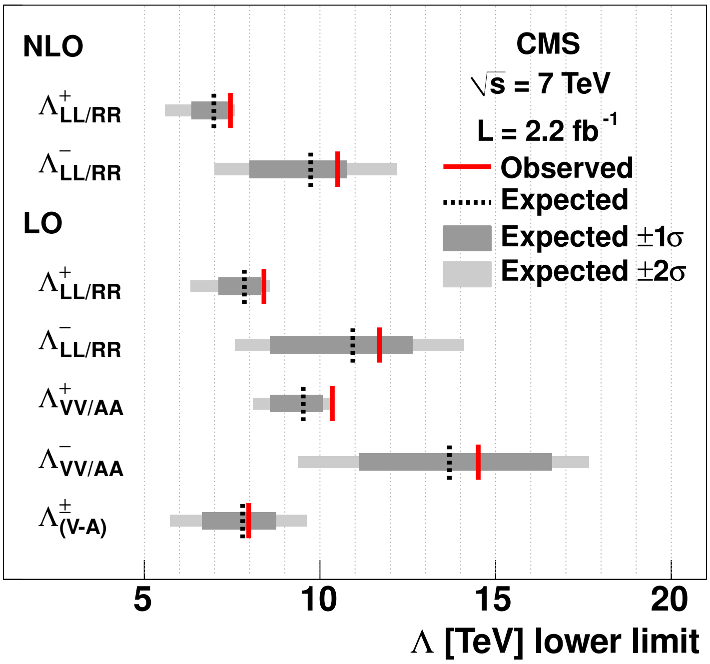

Figure 3. Observed (solid lines) and expected (dashed lines) 95% C.L. limits for the contact interaction scale Λ for the different CI models. The dark (light) gray bands indicate the $\pm 1\sigma$ ($\pm 2\sigma$) uncertainties on the expected limits.

in agreement with predictions of QCD and are used to set lower limits on the contact interaction scale for a variety of quark compositeness models, including models with NLO QCD corrections. The 95% confidence level lower limits for the contact interaction scale Λ are in the range $7.5 - 14.5$ TeV. These results represent the most comprehensive set of limits on the contact interaction scale to date.

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