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Search for new physics with dijet angular distributions in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract: A search is presented for extra spatial dimensions, quantum black holes, and quark contact interactions in measurements of dijet angular distributions in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$. The data were collected with the CMS detector at the LHC and correspond to an integrated luminosity of $2.6\,\text{fb}^{-1}$. The distributions are found to be in agreement with predictions from perturbative quantum chromodynamics that include electroweak corrections. Limits for different contact interaction models are obtained. In a benchmark model, valid to next-to-leading order in QCD and in which only left-handed quarks participate, quark contact interactions are excluded up to a scale of 11.5 and 14.7 TeV for destructive or constructive interference, respectively. The production of quantum black holes is excluded for masses below 7.8 or 5.3 TeV, depending on the model. The lower limits for the scales of virtual graviton exchange in the Arkani-Hamed-Dimopoulos-Dvali model of extra spatial dimensions are in the range 7.9–11.2 TeV, and are the most stringent set of limits available.

Keywords: Beyond Standard Model, Hadron-Hadron scattering (experiments)

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Contents

1 Introduction

In the standard model (SM), pointlike parton-parton scattering in high energy proton-proton collisions can give rise to dijet events, containing at least two jets with large transverse momenta (p_{T}). Such events may be used to test the perturbative predictions of quantum chromodynamics (QCD) and to search for signatures of new physics (NP), such as quark substructure or compositeness [1–3], as well as for additional compactified large spatial dimensions [4, 5], and quantum black holes [6–8].

The angular distribution of dijets with respect to the beam direction is sensitive to the dynamics of the scattering process, yet is not strongly dependent on the parton distribution functions (PDFs), since the angular distributions of the dominant underlying processes, $\mathrm{qg} \to \mathrm{qg}$, $\mathrm{q\overline{q}(q')} \to \mathrm{q\overline{q}(q')}$, and $\mathrm{gq} \to \mathrm{gg}$, are similar [9]. The dijet angular distribution is typically expressed in terms of $\chi_{\text{dijet}} = \exp[|(y_1 - y_2)|]$, where y_1 and y_2 are the rapidities of the two jets with highest p_{T} (the leading jets). The choice of this variable is motivated by the fact that the χ_{dijet} distribution is uniform in Rutherford scattering, and permits signatures from NP that have more-isotropic scattering-angle distributions than QCD processes to be more easily identified and examined as they could produce an excess of events at low values of χ_{dijet}.

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 are approximated through contact interactions (CI) characterized by four-fermion couplings. The most stringent limits on quark CI come from searches studying dijet angular distributions at high dijet invariant masses (M_{jj}) [10–12], and inclusive jet p_{T} distributions [13]. A previous search performed by the CMS Collaboration at the CERN LHC at $\sqrt{s} = 8\,\text{TeV}$ using dijet angular distributions [11] provided lower limits on Λ ranging from 8.8 to 15.2 TeV, for a variety of CI models. The ATLAS Collaboration recently presented a similar analysis at $\sqrt{s} = 13\,\text{TeV}$ in ref. [14], which obtained lower limits on quark CI scales in the range 13.1–29.5 TeV, depending on the model.

The Arkani-Hamed-Dimopoulos-Dvali (ADD) model [4, 5] of compactified large extra dimensions (ED) provides a possible solution to the SM hierarchy problem. In proton-proton collisions at the LHC, the ADD model predicts signatures of virtual graviton exchange that result in a nonresonant enhancement of dijet production and an angular distribution that differs from the QCD expectation. Signatures from virtual graviton exchange have previously been sought at the LHC in dilepton [15–18], diphoton [19–21], and dijet [11, 22] final states, and the most stringent limits on the cutoff scale come from the dijet angular analysis of CMS at $\sqrt{s} = 8\,\text{TeV}$ [11] that range from 5.9 to 8.4 TeV, depending on the model of virtual graviton exchange.

In models with large ED, the fundamental Planck scale can be comparable to the electroweak scale, which can make black hole production possible at the LHC [23–27]. Semiclassical black holes that have masses much larger than the Planck scale and decay into multijets through Hawking radiation [28], have previously been sought in multijet final states [29–33]. Quantum black holes (QBH), produced with mass close to the reduced Planck scale, decay predominantly into dijets that can be studied using dijet angular distributions [6–8]. Recent searches for QBH in dijet final states at the LHC are reported in refs. [10, 12, 30, 31, 34–36]. Lower bounds on QBH masses published by the CMS Collaboration at $\sqrt{s} = 8\,\text{TeV}$ range from 5.0 to 6.3 TeV for different QBH models [35].

Measurements of dijet angular distributions at the Sp$\overline{\text{p}}$S by the UA1 Collaboration [37], at the Fermilab Tevatron by the D0 [38, 39] and CDF [40] Collaborations, and at the LHC by the ATLAS [12, 14, 36, 41–43] and CMS [11, 44–46] Collaborations have previously been reported. In this paper, the earlier searches by CMS [11, 45, 46] at $\sqrt{s} = 7$ and 8 TeV are extended to higher M_{jj} using data that correspond to an integrated luminosity of 2.6 fb^{-1} at $\sqrt{s} = 13\,\text{TeV}$, following the same analysis strategy reported by the previous publications. The measurement of the dijet angular distributions, unfolded for detector effects, is presented and is then analyzed for the presence of contact interactions, large extra dimensions, and quantum black holes.

2 The CMS detector and event selection

The CMS apparatus is based on a superconducting solenoid of 6 m internal diameter, providing an axial field of 3.8 T. Within the solenoid and nearest to the interaction point are the silicon pixel and strip trackers. Surrounding the tracker volume are the lead tungstate crystal electromagnetic calorimeter and the brass and scintillator hadron calorimeter. The pixel and tracker cover a pseudorapidity region of $|\eta| < 2.5$ while the calorimeters cover $|\eta| < 3.0$. In addition, CMS has extensive forward calorimetry, which extends the coverage to $|\eta| < 5.0$. Finally, muons are measured in gas-ionization detectors embedded in the steel flux-return yoke of the solenoid, with a coverage of $|\eta| < 2.4$. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [47].

Events are reconstructed using the particle-flow algorithm [48, 49] to identify and reconstruct individual particles from each collision by combining information from all CMS subdetectors. Identified particles include charged hadrons, neutral hadrons, electrons, muons, and photons. The particles are clustered into jets using the anti-k_T algorithm [50] with a jet size parameter $R = 0.4$ as implemented in FastJet 3.0.1 [51]. The jet energies are corrected for the combined response function of the calorimeters using corrections derived from data and Monte Carlo (MC) simulations [52]. To compare data with next-to-leading order (NLO) and pythia 8.212 [53, 54] predictions, particle-level jets are reconstructed by applying the same jet clustering algorithm to the four-vectors of generated stable particles (lifetime $c\tau > 1\,\mathrm{cm}$) in the case of pythia8, and to the outgoing partons in the case of NLO predictions.

A two-tiered system, consisting of the level-1 (L1) and high-level (HLT) triggers, is used by CMS to record events of interest [55]. The selection criteria for this analysis are based upon the scalar sum of the transverse momenta of the jets reconstructed by the L1 and HLT systems. The selection threshold was varied over the course of the data taking and was between 100 and 175 GeV at L1 and between 650 and 800 GeV at HLT.

In the offline event selection, events with at least two reconstructed jets are selected. Spurious jets from noise or non-colliding backgrounds are rejected by applying loose quality criteria [56] to jet properties. For each event a reconstructed primary vertex [57] is required to lie 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. The primary vertex is defined as the vertex with the highest sum of squares of all associated physics-object transverse momenta. The physics objects are the objects returned by the anti-k_T algorithm applied to all charged tracks associated with the vertex, plus the corresponding associated missing transverse momentum.

The two leading jets are used to measure the dijet angular distributions in several regions of M_jj which are, in units of TeV, 1.9–2.4, 2.4–3.0, 3.0–3.6, 3.6–4.2, 4.2–4.8, and >4.8. The highest three M_jj ranges were chosen to maximize the expected sensitivity to the NP signals considered. The phase space for this analysis is defined by selecting events with $1 \leq \chi_\mathrm{dijet} < 16$ and $|y_\mathrm{boost}| < 1.11$, where $y_\mathrm{boost} = (1/2)(y_1 + y_2)$. This selection restricts the rapidities $|y_1|$ and $|y_2|$ of the two highest-p_T jets to be less than 2.5 and their p_T to be larger than 200 GeV. The trigger efficiency exceeds 99% over the entire phase space. The highest value of M_jj observed in the data is 6.8 TeV.

3 Unfolding and experimental uncertainties

Fluctuations in jet response from the jet p_T resolution of the detector can cause low-energy jets to be misidentified as leading jets. Such fluctuations can produce bin-to-bin migrations in both χ_dijet and M_jj. The measured distributions are corrected for these migrations and unfolded to the particle level using the D'Agostini iteration method [58] implemented in the RooUnfold package [59]. The unfolding corrections are determined using a twodimensional response matrix mapping the generator-level M_{jj} and χ_{dijet} distributions onto the measured values. This matrix is obtained using particle-level jets from the PYTHIA8 MC event generator that are smeared in p_{T} using a double-sided Crystal-Ball parameterization [60] of the response. This parameterization takes into account the full jet energy resolution including non-Gaussian tails. The unfolding corrections change the shape of the dijet angular distributions by less than 1% across χ_{dijet} in the lowest M_{jj} range, and by less than 5% across χ_{dijet} in the highest M_{jj} range.

The dijet angular distributions are normalized to the integrated dijet cross sections in each M_{jj} range, denoted $(1/\sigma_{\mathrm{dijet}})(\mathrm{d}\sigma_{\mathrm{dijet}}/\mathrm{d}\chi_{\mathrm{dijet}})$, where σ_{dijet} is the cross section in the analysis phase space considered. The normalized angular distributions are relatively insensitive to many systematic effects. The main systematic uncertainties come from the jet energy scale, the jet energy resolution, and the unfolding correction. The effects of these uncertainties on the dijet angular distributions are described below.

The maximum jet energy scale uncertainty is less than 1% and has a dependence on η of less than 1% per unit of η [52, 61] in the phase space of the analysis. The resulting uncertainty in the χ_{dijet} distributions due to the jet energy calibration uncertainties is found to be 2.2% in the lowest M_{jj} range and 3.6% in the highest M_{jj} range, over all χ_{dijet} bins.

The jet energy resolution uncertainty is evaluated by changing the width of the Gaussian core of the Crystal-Ball parameterization of the response by up to ±10% [52, 61], depending upon the jet η, and comparing the resultant unfolded distributions before and after these changes. This uncertainty is found to be less than 1.1%. The systematic uncertainty from the modelling of the tails of the jet energy resolution is evaluated using a Gaussian function to parameterize the response, and assigning as an uncertainty half of the difference between the unfolded distributions determined from this Gaussian ansatz and the nominal correction, which covers the differences between the jet energy resolution tails in the data and simulation. The size of this uncertainty is less than 1%.

A source of uncertainty to the unfolding correction arises from the use of a parameterized model to simulate the jet p_{T} resolution of the detector. This uncertainty is estimated by comparing the smeared χ_{dijet} distributions to the ones from a detailed simulation of the CMS detector using GEANT4 [62], and is found to be less than 1% in all M_{jj} ranges. An additional systematic uncertainty is evaluated to account for mismodelling of the dijet kinematic distributions by applying the unfolding corrections determined with PYTHIA8 to smeared χ_{dijet} distributions from MADGRAPH5_aMC@NLO 2.2.2 [63], and comparing the results with the generated χ_{dijet} distributions. This uncertainty is found to be less than 1% for all M_{jj}.

The effect of additional interactions in the same or adjacent proton bunch crossings (pileup) relative to the interaction of interest is studied by comparing χ_{dijet} distributions in simulated samples where the distribution of pileup interactions is varied according to its uncertainty. The effect of this variation on the χ_{dijet} distributions is observed to be less than 1%.

A summary of the leading experimental systematic uncertainties is provided in table 1. Though in the subsequent analysis of the data the uncertainties are treated separately, for display in table 1 and in the figures the total experimental systematic uncertainty in the

Uncertainty	$1.9 < M_{\mathrm{jj}} < 2.4\,\mathrm{TeV}$	$M_{\mathrm{jj}} > 4.8\,\mathrm{TeV}$
Statistical	1.1%	26%
Jet energy scale	2.2%	3.6%
Jet energy resolution (core)	0.4%	1.1%
Jet energy resolution (tails)	0.6%	0.5%
Unfolding, modelling	0.1%	0.8%
Unfolding, detector simulation	0.3%	0.8%
Pileup	0.2%	0.2%
Total experimental	2.6%	26%
NLO QCD scale	$^{+7.9\%}_{-2.8\%}$	$^{+13\%}_{-4.9\%}$
PDF (CT14 eigenvectors)	0.15%	0.4%
Nonperturbative effects	<1%	<1%
Total theoretical	$^{+7.9\%}_{-2.8\%}$	$^{+13\%}_{-4.9\%}$

Table 1. Summary of main experimental and theoretical uncertainties in the normalized χ_{dijet} distributions. Although the change in the χ_{dijet} distribution from each uncertainty is taken into account in the statistical analysis, this table summarizes the uncertainty in just the smallest χ_{dijet} bin, for the smallest and largest bins in dijet mass. The uncertainty in the dijet bin with largest mass is dominated by the statistical experimental contribution, while the theoretical contribution is dominated by the uncertainty in the NLO QCD scale.

χ_{dijet} distributions is calculated as the quadratic sum of the contributions due to the uncertainties in the jet energy calibration, jet p_{T} resolution, unfolding correction, and pileup.

4 Theoretical prediction and uncertainties

We compare the measured normalized dijet angular distributions with the predictions of perturbative QCD at NLO, which are made with NLOJET++ 4.1.3 [64] in the FASTNLO 2.1 framework [65]. With the inclusion of the electroweak (EW) corrections for dijet production [66], the predictions of the normalized χ_{dijet} distributions are corrected up to 1% and up to 5% at small and large M_{jj}, respectively. The factorization (μ_{f}) and renormalization (μ_{r}) scales are set to the average p_{T} of the two jets, $\langle p_{\mathrm{T}} \rangle$, and the PDFs are taken from the CT14 set [67]. The use of a more flexible statistical combination of multiple PDF sets as in PDF4LHC15_100 [67–72] exhibited only small differences as compared to the use of the CT14 PDF set alone, and had negligible impact on the CI limits described in the next section.

We evaluated the impact on the QCD predictions of nonperturbative effects related to hadronization and multiple parton interactions using PYTHIA 8 with the CUETP8M1 tune [73, 74] and HERWIG++ 2.7.1 [75] with tune EE5C. The effects are found to be negligible in both MC event generators. We can therefore compare the data corrected to particle-level with the parton-level theory predictions.

The choices of the μ_f and μ_r scales dominate the uncertainties in the QCD prediction. These uncertainties are evaluated following the proposal in refs. [76, 77] by changing the default choice of scales in the following 6 combinations: $(\mu_\mathrm{f}/\langle p_\mathrm{T}\rangle, \mu_\mathrm{r}/\langle p_\mathrm{T}\rangle) = (1/2, 1/2)$, $(1/2, 1)$, $(1, 1/2)$, $(2, 2)$, $(2, 1)$, and $(1, 2)$. These changes modify the predictions of the normalized χ_dijet distributions by up to 8% and up to 13% at small and large values of M_jj, respectively. The uncertainty due to the choice of PDFs is determined from the 28 eigenvectors of CT14 using the procedure described in ref. [78], and is found to be less than 0.15% at low M_jj and less than 0.4% at high M_jj. The uncertainty of the strong coupling constant has a negligible impact on the normalised χ_dijet distribution. A summary of the leading systematic uncertainties in the theoretical predictions is also given in table 1.

New physics signatures from CIs with flavor-diagonal color-singlet couplings between quarks are studied. These are described by the effective Lagrangian [2, 3]:

$$\mathcal{L}_\mathrm{qq} = \frac{2\pi}{\Lambda^2}\left[\eta_\mathrm{LL}(\overline{\mathrm{q}}_\mathrm{L}\gamma^\mu \mathrm{q}_\mathrm{L})(\overline{\mathrm{q}}_\mathrm{L}\gamma_\mu \mathrm{q}_\mathrm{L}) + \eta_\mathrm{RR}(\overline{\mathrm{q}}_\mathrm{R}\gamma^\mu \mathrm{q}_\mathrm{R})(\overline{\mathrm{q}}_\mathrm{R}\gamma_\mu \mathrm{q}_\mathrm{R}) + 2\eta_\mathrm{RL}(\overline{\mathrm{q}}_\mathrm{R}\gamma^\mu \mathrm{q}_\mathrm{R})(\overline{\mathrm{q}}_\mathrm{L}\gamma_\mu \mathrm{q}_\mathrm{L})\right],$$

where the subscripts L and R refer to the left and right chiral projections of the quark fields, respectively, and η_LL, η_RR, and η_RL are given the values of 0, +1, or −1. The various combinations of $(\eta_\mathrm{LL}, \eta_\mathrm{RR}, \eta_\mathrm{RL})$ correspond to different CI models. The following CI possibilities with color-singlet couplings among quarks are investigated:

Λ	$(\eta_\mathrm{LL}, \eta_\mathrm{RR}, \eta_\mathrm{RL})$
$\Lambda_\mathrm{LL}^\pm$	$(\pm1, 0, 0)$
$\Lambda_\mathrm{RR}^\pm$	$(0, \pm1, 0)$
$\Lambda_\mathrm{VV}^\pm$	$(\pm1, \pm1, \pm1)$
$\Lambda_\mathrm{AA}^\pm$	$(\pm1, \pm1, \mp1)$
$\Lambda_\mathrm{(V-A)}^\pm$	$(0, 0, \pm1)$

The models with positive (negative) η_LL or η_RR lead to destructive (constructive) interference with the QCD terms, and a lower (higher) cross section, respectively. In all CI models discussed in this paper, NLO QCD corrections are employed to calculate the cross sections. In proton-proton collisions the $\Lambda_\mathrm{LL}^\pm$ and $\Lambda_\mathrm{RR}^\pm$ models result in identical tree level cross sections and NLO corrections, and consequently lead to the same sensitivity. For $\Lambda_\mathrm{VV}^\pm$ and $\Lambda_\mathrm{AA}^\pm$, as well as for $\Lambda_\mathrm{(V-A)}^\pm$, the CI predictions are identical at tree level, but exhibit different NLO corrections and yield different sensitivity. For calculating the CI terms, as well as the interference between the CI terms and QCD terms at leading order (LO) and NLO in QCD, the CIJET 1.0 program [79] is employed.

For the ADD model, two parameterizations for virtual graviton exchange are considered, Giudice-Rattazzi-Wells (GRW) [80] and Han-Lykken-Zhang (HLZ) [81]. In the GRW convention, the sum over the Kaluza-Klein graviton excitations in the effective field theory is regulated by a single cutoff parameter Λ_T. In the HLZ convention, the effective theory is described in terms of two parameters, the cutoff scale M_S and the number of extra spatial dimensions n_ED. The parameters M_S and n_ED are directly related to Λ_T [82]. We consider models with 2–6 EDs. The case of $n_\mathrm{ED} = 1$ is not considered since it would require an ED of the size of the order of the solar system; the gravitational potential at these distances would be noticeably modified and this case is therefore excluded by observation. The case of $n_{\rm ED} = 2$ is special in the sense that the relation between $M_{\rm S}$ and $\Lambda_{\rm T}$ also depends on the parton-parton center-of-mass energy $\sqrt{\hat{s}}$. The ADD predictions are calculated with PYTHIA8.

Quantum black hole production is studied within the framework of the ADD model with $n_{\rm ED} = 6$, and the Randall-Sundrum model with $n_{\rm ED} = 1$ (RS1) [83, 84]. In these models, the QBH production cross section is typically described by the classical geometrical cross section $\sigma_{\rm QBH} \approx \pi r_{\rm s}^2$, where $r_{\rm s}$ is the Schwarzschild radius of the black hole. The Schwarzschild radius depends on the mass of the QBH, the Planck scale ($M_{\rm P}$), and the number of spatial dimensions. Since QBHs are produced with mass threshold close to the Planck scale, we set the minimum quantum black hole mass $M_{\rm QBH}$ equal to $M_{\rm P}$ for simplicity. The QBH 3.0 generator [85] is used for the predictions.

To take into account the NLO QCD and EW corrections to SM dijet production when probing the ADD and QBH models, the cross section difference $\sigma^{\rm QCD}_{\rm NLO+EW\ corr} - \sigma^{\rm QCD}_{\rm LO}$ is evaluated for each $M_{\rm jj}$ and $\chi_{\rm dijet}$ bin and added to the ADD and QBH predictions. This procedure provides an SM+ADD or SM+QBH prediction wherein the QCD terms are corrected to NLO with EW corrections while the ADD or QBH terms are calculated at LO. In all the predictions, changes from theoretical uncertainties associated with scales and PDFs are applied only to the QCD prediction, thereby treating the effective NP terms as fixed benchmark terms.

5 Results

The normalized $\chi_{\rm dijet}$ distributions for all mass bins are compared to NLO predictions with EW corrections in figure 1. No significant deviation from the theory is observed. The distributions are also compared to predictions for QCD+CI with $\Lambda^+_{\rm LL} = 11$ TeV, QCD+ADD with $\Lambda_{\rm T}$ (GRW) $= 10$ TeV, and QCD+QBH with $M_{\rm QBH}$ ($n_{\rm ED} = 6$ ADD) $= 7.5$ TeV. The QCD+ADD $\Lambda_{\rm T}$ (GRW) $= 10$ TeV prediction corresponds to QCD+ADD $M_{\rm S}$ (HLZ) $= 10.1$, 11.9, 10.0, 9.9 and 8.4 TeV for $n_{\rm ED} = 2$, 3, 4, 5 and 6, respectively. The signal distributions are shown only for the highest three ranges of $M_{\rm jj}$, since those bins dominate the sensitivity to the NP signals considered. An expanded version of the normalized $\chi_{\rm dijet}$ distributions in the highest three ranges of $M_{\rm jj}$ is shown in figure 2. The measured $\chi_{\rm dijet}$ distributions are used to determine exclusion limits on the NP models.

A modified frequentist approach [86, 87] is used to set exclusion limits on the scale Λ. The log-likelihoods $L_{\rm QCD}$ and $L_{\rm QCD+NP}$ are defined for the respective QCD-only and QCD+NP hypotheses as a product of Poissonian likelihood functions for each bin in $\chi_{\rm dijet}$ for the highest three ranges of $M_{\rm jj}$. The predictions for each $M_{\rm jj}$ range are normalized to the number of observed events in that range. The p-values for the two hypotheses, $P_{\rm QCD+NP}(q \geq q_{\rm obs})$ and $P_{\rm QCD}(q \leq q_{\rm obs})$, are based on the log-likelihood ratio $q = -2\ln(L_{\rm QCD+NP}/L_{\rm QCD})$. They are evaluated by generating distributions of q using ensembles of pseudo-experiments, where systematic uncertainties are represented as Gaussian-constraint nuisance parameters and are treated according to the frequentist paradigm [88]. Limits on the QCD+NP models are set based on the quantity

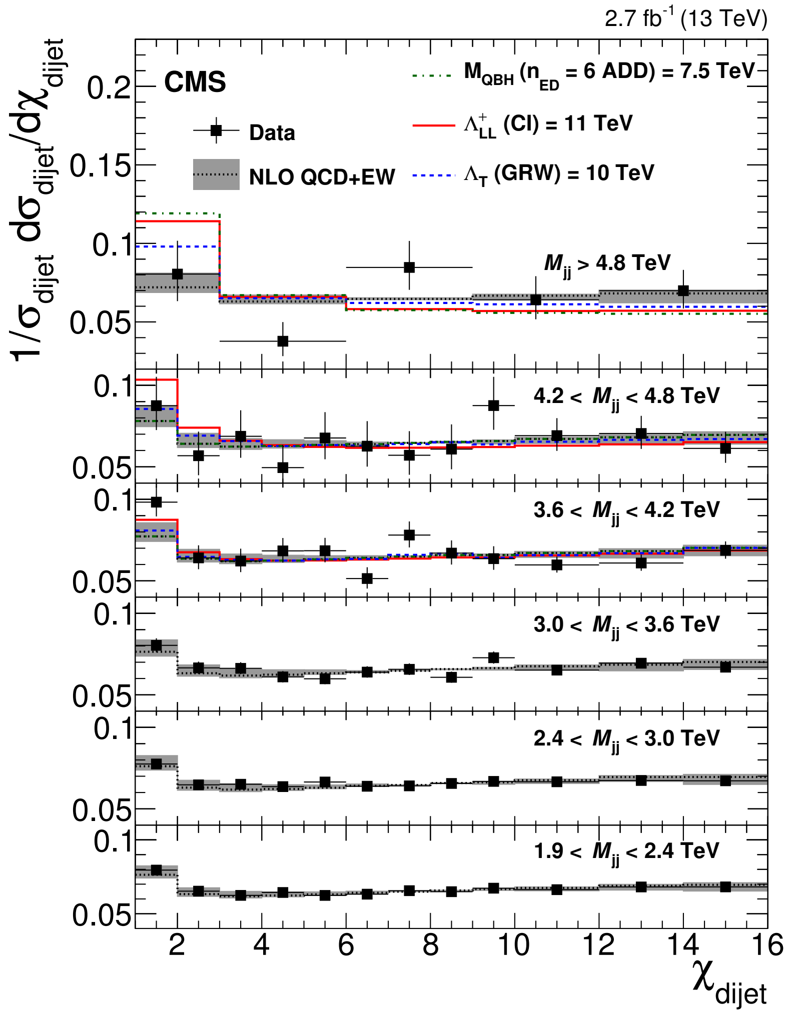

Figure 1. Normalized χ_{dijet} distributions for 2.6 fb^{-1} of integrated luminosity at $\sqrt{s} = 13\,\text{TeV}$. The corrected distributions in data are compared to NLO predictions (black dotted line). The vertical bar on each data point represents statistical and systematic experimental uncertainties combined in quadrature. The horizontal bar indicates the bin width. Theoretical uncertainties are indicated by the gray bands. Also shown are the predictions for QCD+QBH with $n_{\text{ED}} = 6$ and $M_{\text{QBH}} = 7.5\,\text{TeV}$ (green dashed-dotted line), QCD+CI with $\Lambda^{+}_{\text{LL}} = 11\,\text{TeV}$ (red solid line), and QCD+ADD with $\Lambda_{\text{T}}\,(\text{GRW}) = 10\,\text{TeV}$ (blue dashed line).

$\text{CL}_{\text{s}} = P_{\text{QCD+NP}}(q \geq q_{\text{obs}})/(1 - P_{\text{QCD}}(q \leq q_{\text{obs}}))$, which is required to be less than 0.05 for an exclusion at 95% confidence level (CL). The observed and expected exclusion limits on different CI, ADD, and QBH models obtained in this analysis at 95% CL are listed in table 2. The observed limits are smaller than the expected limits owing to a slight excess of events in the lowest χ_{dijet} bin in the 3.6–4.2 TeV mass bin. The limits on M_{S} for the different numbers of extra dimensions, n_{ED}, directly follow from the limit for Λ_{T}. The limits for the CI scale $\Lambda^{+}_{\text{LL/RR}}$ are also determined for the case in which the data are not corrected for detector effects, and are found to agree with the quoted ones within 3%.

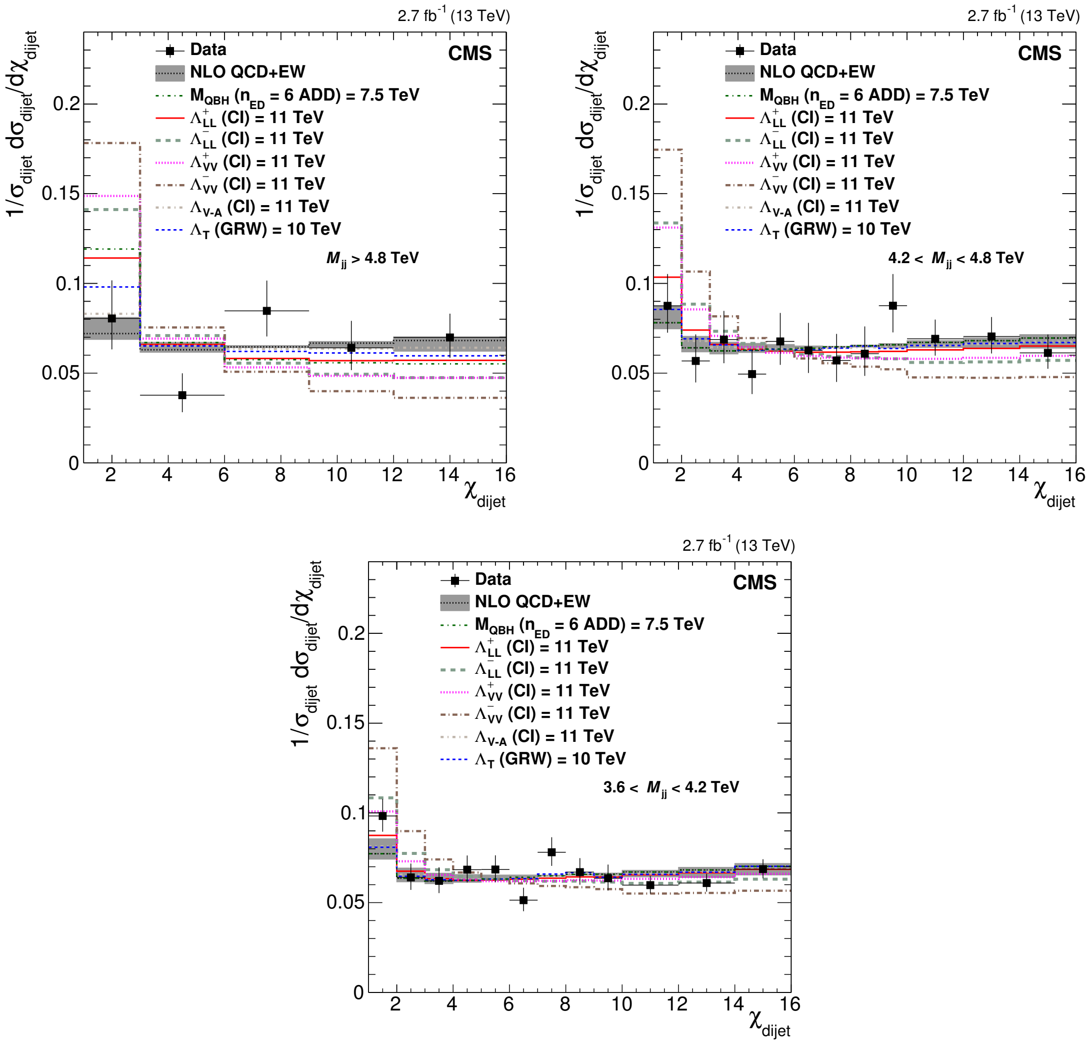

Figure 2. Normalized χ_{dijet} distributions for 2.6 fb^{-1} of integrated luminosity in the highest three mass bins. The corrected distributions in data are compared to NLO predictions with non-perturbative corrections (black dotted line). The vertical bar on each data point represents statistical and systematic experimental uncertainties combined in quadrature. The horizontal bar indicates the bin width. Theoretical uncertainties are indicated by the gray band. Also shown are the predictions for various QBH, CI, and ADD models.

The agreement of the data with QCD predictions is quantified by calculating $P_{\text{QCD}}(q \leq q_{\text{obs}})$ as described above. The largest excess is found in the 3.6–4.2 TeV mass bin with a significance of 1.8 standard deviations.

6 Summary

Normalized dijet angular distributions have been measured at $\sqrt{s} = 13$ TeV with the CMS detector over a wide range of dijet invariant masses. The distributions are found to be in agreement with predictions of perturbative QCD and are used to set lower limits on the

Model	Observed lower limit (TeV)	Expected lower limit (TeV)
$\Lambda^{+}_{\mathrm{LL/RR}}$ (NLO)	11.5	12.1±1.2
$\Lambda^{-}_{\mathrm{LL/RR}}$ (NLO)	14.7	17.3±3.4
$\Lambda^{+}_{\mathrm{VV}}$ (NLO)	13.3	13.9±1.2
$\Lambda^{-}_{\mathrm{VV}}$ (NLO)	18.6	22.2±5.4
$\Lambda^{+}_{\mathrm{AA}}$ (NLO)	13.3	13.9±1.2
$\Lambda^{-}_{\mathrm{AA}}$ (NLO)	18.6	22.1±5.1
$\Lambda^{+}_{(\mathrm{V-A})}$ (NLO)	8.4	9.5±1.6
$\Lambda^{-}_{(\mathrm{V-A})}$ (NLO)	8.4	9.5±1.7
ADD Λ_{T} (GRW)	9.4	9.8±1.2
ADD M_{S} (HLZ) $n_{\mathrm{ED}} = 2$	10.1	10.6±1.3
ADD M_{S} (HLZ) $n_{\mathrm{ED}} = 3$	11.2	11.7±1.4
ADD M_{S} (HLZ) $n_{\mathrm{ED}} = 4$	9.4	9.8±1.2
ADD M_{S} (HLZ) $n_{\mathrm{ED}} = 5$	8.5	8.9±1.1
ADD M_{S} (HLZ) $n_{\mathrm{ED}} = 6$	7.9	8.2±1.0
$n_{\mathrm{ED}} = 6$ ADD QBH M_{QBH}	7.8	7.7±0.3
$n_{\mathrm{ED}} = 1$ RS QBH M_{QBH}	5.3	5.3±0.4

Table 2. Observed and expected exclusion limits at 95% CL for various CI, ADD, and QBH models.

contact-interaction scale for a variety of quark-compositeness models that include next-to-leading order QCD corrections, models with large extra dimensions, and models of quantum black-hole production. The 95% confidence level lower limits for the contact interaction scale Λ are in the range 8.4–18.6 TeV. Also excluded are quantum black holes with masses up to 7.8 TeV in the ADD model for $n_{\mathrm{ED}} = 6$, and up to 5.3 TeV in the Randall-Sundrum model for $n_{\mathrm{ED}} = 1$. The lower limits for the scales of ADD models, Λ_{T} (GRW) and M_{S} (HLZ), are in the range 7.9–11.2 TeV, and are the most stringent set of limits available.

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25: Also at University of Visva-Bharati, Santiniketan, India
26: Also at Indian Institute of Science Education and Research, Bhopal, India
27: Also at Institute of Physics, Bhubaneswar, India
28: Also at University of Ruhuna, Matara, Sri Lanka
29: Also at Isfahan University of Technology, Isfahan, Iran
30: Also at Yazd University, Yazd, Iran
31: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
32: Also at Università degli Studi di Siena, Siena, Italy
33: Also at Purdue University, West Lafayette, U.S.A.
34: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
35: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
36: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
37: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
38: Also at Institute for Nuclear Research, Moscow, Russia
39: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
41: Also at University of Florida, Gainesville, U.S.A.
42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
43: Also at California Institute of Technology, Pasadena, U.S.A.
44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
46: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
47: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
48: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
49: Also at National and Kapodistrian University of Athens, Athens, Greece
50: Also at Riga Technical University, Riga, Latvia
51: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
52: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
53: Also at Adiyaman University, Adiyaman, Turkey

54: Also at Istanbul Aydin University, Istanbul, Turkey
55: Also at Mersin University, Mersin, Turkey
56: Also at Cag University, Mersin, Turkey
57: Also at Piri Reis University, Istanbul, Turkey
58: Also at Gaziosmanpasa University, Tokat, Turkey
59: Also at Ozyegin University, Istanbul, Turkey
60: Also at Izmir Institute of Technology, Izmir, Turkey
61: Also at Marmara University, Istanbul, Turkey
62: Also at Kafkas University, Kars, Turkey
63: Also at Istanbul Bilgi University, Istanbul, Turkey
64: Also at Yildiz Technical University, Istanbul, Turkey
65: Also at Hacettepe University, Ankara, Turkey
66: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
67: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
68: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
69: Also at Utah Valley University, Orem, U.S.A.
70: Also at Argonne National Laboratory, Argonne, U.S.A.
71: Also at Erzincan University, Erzincan, Turkey
72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
73: Also at Texas A&M University at Qatar, Doha, Qatar
74: Also at Kyungpook National University, Daegu, Korea

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