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Search for quark compositeness in dijet angular distributions from pp collisions at sqrt(s) = 7 TeV

Author(s):
CMS Collaboration; Chatrchyan, Serguei; Bäni, Lukas; Bortignon, Pierluigi; Buchmann, Marco A.; Casal, Bruno; Chanon, Nicolas; Chen, Zhiling; Deisher, Amanda; Dissertori, Günther; Dittmar, Michael; Dünser, Marc; Eugster, Jürg; Freudenreich, Klaus; Grab, Christoph; Lecomte, Pierre; Lustermann, Werner; Martinez Ruiz del Arbol, Pablo; Mohr, Niklas; Moortgat, Filip; Nägeli, Christoph; Nef, Pascal; Nessi-Tedaldi, Francesca; Pape, Luc; Pauss, Felicitas; Peruzzi, Marco; Ronga, Frédéric J.; Rossini, Marco; Sala, Leonardo; Sanchez, Ann-Karin; Sawley, Marie-Christine; Starodumov, Andrey; Stieger, Benjamin; Takahashi, Maiko; Tauscher, Ludwig; Thea, Alessandro; Theofilatos, Konstantinos; Treille, Daniel; Urscheler, Christina; Wallny, Rainer; Weber, Hannsjörg A.; Wehrli, Lukas; Weng, J.; et al.

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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 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
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 \(\Lambda\) that is much larger than the quark masses. At energies well below \(\Lambda\), 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 \([1, 3]\)

\[
L_{qq} = \frac{2\pi}{\Lambda^2} [\eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)],
\]

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

- \(\Lambda = \Lambda_{LL}^\pm\) for \((\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm 1, 0, 0)\),
- \(\Lambda = \Lambda_{RR}^\pm\) for \((\eta_{LL}, \eta_{RR}, \eta_{RL}) = (0, \pm 1, 0)\),
- \(\Lambda = \Lambda_{VV}^\pm\) for \((\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm 1, \pm 1, \pm 1)\),
- \(\Lambda = \Lambda_{AA}^\pm\) for \((\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm 1, \pm 1, \mp 1)\),
- \(\Lambda = \Lambda_{(V-A)}^\pm\) for \((\eta_{LL}, \eta_{RR}, \eta_{RL}) = (0, 0, \pm 1)\).

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

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 \(\theta^*\) 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 \(\theta^*\).

Previous searches for quark compositeness at hadron colliders have been reported at the SpS 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, \(\Lambda_{LL/RR}^\pm\), where \(\Lambda_{LL/RR}^\pm\) 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 \(2.2\,\text{fb}^{-1}\) at \(\sqrt{s} = 7\,\text{TeV}\), 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
\[
\frac{(1/\sigma_{dijet})(d\sigma_{dijet}/d\chi_{dijet})}{\chi_{dijet} = e|y_1 - y_2|},
\]
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
\[
y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right).
\]
In the limit of massless scattering partons, \(\chi_{dijet}\) is related to \(\theta^*\) by
\[
\chi_{dijet} = \frac{(1 + |\cos \theta^*|)}{(1 - |\cos \theta^*|)}.
\]
The use of the variable \(\chi_{dijet}\) is motivated by the fact that \(d\sigma_{dijet}/d\chi_{dijet}\) is approximately uniform for QCD dijet processes, while CI models predict angular distributions that are strongly peaked at low values of \(\chi_{dijet}\).

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 \(\theta\) 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 \(p_T\) 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 flavor-
tagged 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 \(\pm 24\) 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 \(\chi_{\text{dijet}} < 16\) and \(|y_{\text{boost}}| < 1.11\), where \(y_{\text{boost}} = \frac{1}{2}(y_1 + y_2)\). 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 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 \(\chi_{\text{dijet}}\) distributions. Unfolding correction factors are evaluated from two independent MC samples, \textsc{pythia} 6.422 [22] with tune D6T [23] and \textsc{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, \textsc{herwig}++ tune 2.3, \textsc{pythia}6 tunes D6T and Z2 (the Z2 tune is identical to the Z1 tune [23] except that Z2 uses the CTEQ6L PDF [25]), and \textsc{pythia}8 [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 \(\chi_{\text{dijet}}\) distributions to the ones from a detailed simulation of the CMS detector using \textsc{geant}4 [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 \(\eta\) 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 \(\eta\) [17]. The uncertainty on the jet \(p_T\) resolution is less than 10% [17]. The resulting uncertainty on the \(\chi_{\text{dijet}}\) 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 \(\chi_{\text{dijet}}\) bins, while the maximum uncertainty due to the...
<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>$0.4 &lt; M_{jj} &lt; 0.6\text{ TeV}$ (%)</th>
<th>$M_{jj} &gt; 3\text{ TeV}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Jet energy resolution tails</td>
<td>0.5</td>
<td>4.6</td>
</tr>
<tr>
<td>Unfolding, MC modeling</td>
<td>0.2</td>
<td>4.9</td>
</tr>
<tr>
<td>Unfolding, detector simulation</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>Total experimental systematic uncertainty</td>
<td>1.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>2.5</td>
<td>31.6</td>
</tr>
<tr>
<td>$\mu_f$ and $\mu_r$ scales</td>
<td>5.6</td>
<td>14.9</td>
</tr>
<tr>
<td>PDF (CTEQ6.6)</td>
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<td>0.7</td>
</tr>
<tr>
<td>Non-perturbative corrections</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Total theoretical systematic uncertainty</td>
<td>5.9</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Table 1. Summary of the leading experimental and theoretical uncertainties on the $\chi_{\text{dijet}}$ distributions. The maximum uncertainties over all $\chi_{\text{dijet}}$ 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.

The 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 $\chi_{\text{dijet}}$ 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 $\chi_{\text{dijet}}$ distributions from each sample. No significant effect was observed. The total systematic uncertainty on the $\chi_{\text{dijet}}$ 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 ($\mu_f$) and renormalization ($\mu_r$) scales are set to $\langle p_T \rangle$, 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 $\mu_f$ and $\mu_r$ scales. The uncertainty is evaluated following the proposal in ref. [32] by
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 \(\chi_{\text{dijet}}\) 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 \(\chi_{\text{dijet}}\) 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 \(\Lambda_{LL/RR} = 7\) 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 \(\pm 0.2\) TeV changes the expected limit by less than 0.5%.

The predictions for the various QCD+CI models at the scale of \(\Lambda = 7\) TeV are shown in figure 2 for the highest \(M_{jj}\) range. At low \(\chi_{\text{dijet}}\), 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 \(\Lambda\) follows a modified frequentist approach [3, 33-35]. The log-likelihood-ratio \(q = -2\ln(L_{\text{QCD+CI}}/L_{\text{QCD}})\) is used to discriminate between the QCD-only hypothesis and the QCD+CI hypothesis. The \(L_{\text{QCD+CI}}\) and \(L_{\text{QCD}}\) are written as a product of Poissonian likelihood functions for each bin in \(\chi_{\text{dijet}}\) 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 $|y_{\text{boost}}| < 1.11$ 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 $\chi_{\text{dijet}}$ 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 $\Lambda_{\text{LL/RR}} = 7$ 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 $\mu_r$ and $\mu_f$ 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 $\chi_{\text{dijet}}$ 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 $M_{jj} > 3$ 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 $\chi_{dijet}$ bin width. The shaded band represents the NLO QCD prediction and includes the systematic uncertainties due to $\mu_r$ and $\mu_f$ 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 $\text{CL}_{\text{ex}} = P_{\text{QCD}+\text{CI}}(q \geq q_{\text{obs}})/(1 - P_{\text{QCD}}(q \leq q_{\text{obs}})) < 0.05$.

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 $M_{jj} > 3.0$ TeV, the measured dijet angular distribution at low $\chi_{dijet}$ 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
Table 2. Observed and expected lower limits at 95% confidence level for the contact interaction scale $\Lambda$ for several quark CI models.

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

Figure 3. Observed (solid lines) and expected (dashed lines) 95% C.L. limits for the contact interaction scale $\Lambda$ for the different CI models. The dark (light) gray bands indicate the $\pm1\sigma$ ($\pm2\sigma$) 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 $\Lambda$ 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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Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev$^1$, P. Iaydjiev$^1$, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadijska, A. Karadzhinova, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

Universidad de Los Andes, Bogota, Colombia
A. Cabrera, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, R. Plestina$^5$, D. Polic, I. Puljak$^1$

University of Split, Split, Croatia
Z. Antunovic, M. Dzelalija, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

University of Cyprus, Nicosia, Cyprus
A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran$^6$, A. Ellithi Kamel$^7$, S. Khalil$^8$, M.A. Mahmoud$^9$, A. Radi$^{8,10}$

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
A. Hektor, M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland
V. Azzolini, P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
INFN Sezione di Torino $^a$, Università di Torino $^b$, Università del Piemonte Orientale (Novara) $^c$, Torino, Italy
N. Amapane$^{a,b}$, R. Arcidiacono$^{a,c}$, S. Argiro$^{a,b}$, M. Arneodo$^{a,c}$, C. Biino$^a$, C. Bottai$^{a,b}$, N. Cartiglia$^a$, R. Castello$^{a,b}$, M. Costa$^{a,b}$, G. Dellacasa$^a$, N. Demaria$^a$, A. Graziano$^{a,b}$, C. Mariotti$^{a,1}$, S. Maselli$^a$, E. Migliore$^{a,b}$, V. Monaco$^{a,b}$, M. Musich$^a$, M.M. Obertino$^{a,c}$, N. Pastrone$^a$, M. Pelliccioni$^a$, A. Potenza$^{a,b}$, A. Romero$^{a,b}$, M. Ruspa$^{a,c}$, R. Sacchi$^{a,b}$, A. Solano$^{a,b}$, A. Staiano$^a$, A. Vilela Pereira$^a$

INFN Sezione di Trieste $^a$, Università di Trieste $^b$, Trieste, Italy
S. Belforte$^a$, F. Cossutti$^a$, G. Della Ricca$^{a,b}$, B. Gobbo$^a$, M. Marone$^{a,b}$, D. Montanino$^{a,b,1}$, A. Penzo$^a$

Kangwon National University, Chunchon, Korea
S.G. Heo, S.K. Nam

Kyungpook National University, Daegu, Korea

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, Zero J. Kim, S. Song

Konkuk University, Seoul, Korea
H.Y. Jo

Korea University, Seoul, Korea

University of Seoul, Seoul, Korea
M. Choi, S. Kang, H. Kim, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Vilnius University, Vilnius, Lithuania
M.J. Bilinskas, I. Grigelionis, M. Janulis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos
University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

Joint Institute for Nuclear Research, Dubna, Russia

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia

Institute for Nuclear Research, Moscow, Russia

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov¹, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin¹, L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva¹, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia
State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin\textsuperscript{1}, V. Kachanov, D. Konstantinov, A. Korabiev, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic\textsuperscript{28}, M. Djordjevic, M. Ekmedzic, D. Krpic\textsuperscript{28}, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

CERN, European Organization for Nuclear Research, Geneva, Switzerland

Paul Scherrer Institut, Villigen, Switzerland

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

Universität Zürich, Zurich, Switzerland
E. Aguilo, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, M. Verzetti

National Central University, Chung-Li, Taiwan

National Taiwan University (NTU), Taipei, Taiwan

Cukurova University, Adana, Turkey

Middle East Technical University, Physics Department, Ankara, Turkey

Bogazici University, Istanbul, Turkey
M. Deliomeroglu, E. Gülmez, B. Isildak, M. Kaya, O. Kaya, S. Ozkorumculu, N. Sonmez
National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

Brunel University, Uxbridge, United Kingdom

Baylor University, Waco, U.S.A.
K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, U.S.A.
C. Henderson

Boston University, Boston, U.S.A.

Brown University, Providence, U.S.A.

University of California, Davis, U.S.A.
University of California, Los Angeles, Los Angeles, U.S.A.

University of California, Riverside, Riverside, U.S.A.

University of California, San Diego, La Jolla, U.S.A.

University of California, Santa Barbara, Santa Barbara, U.S.A.

California Institute of Technology, Pasadena, U.S.A.

Carnegie Mellon University, Pittsburgh, U.S.A.

University of Colorado at Boulder, Boulder, U.S.A.

Cornell University, Ithaca, U.S.A.

Fairfield University, Fairfield, U.S.A.
A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, U.S.A.
University of Florida, Gainesville, U.S.A.

Florida International University, Miami, U.S.A.
V. Gaultney, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, U.S.A.

Florida Institute of Technology, Melbourne, U.S.A.
M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, U.S.A.

The University of Iowa, Iowa City, U.S.A.

Johns Hopkins University, Baltimore, U.S.A.


University of Florida, Gainesville, U.S.A.

Florida International University, Miami, U.S.A.
V. Gaultney, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, U.S.A.

Florida Institute of Technology, Melbourne, U.S.A.
M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, U.S.A.

The University of Iowa, Iowa City, U.S.A.

Johns Hopkins University, Baltimore, U.S.A.
The University of Kansas, Lawrence, U.S.A.

Kansas State University, Manhattan, U.S.A.
A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, U.S.A.
J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, U.S.A.

Massachusetts Institute of Technology, Cambridge, U.S.A.

University of Minnesota, Minneapolis, U.S.A.

University of Mississippi, University, U.S.A.
L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, U.S.A.

State University of New York at Buffalo, Buffalo, U.S.A.

Northeastern University, Boston, U.S.A.

Northwestern University, Evanston, U.S.A.
University of Notre Dame, Notre Dame, U.S.A.

The Ohio State University, Columbus, U.S.A.
B. Bylsma, L.S. Durkin, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, C. Vuosalo, G. Williams

Princeton University, Princeton, U.S.A.

University of Puerto Rico, Mayaguez, U.S.A.

Purdue University, West Lafayette, U.S.A.

Purdue University Calumet, Hammond, U.S.A.
S. Guragain, N. Parashar

Rice University, Houston, U.S.A.

University of Rochester, Rochester, U.S.A.
B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, G. Petrillo, W. Sakumoto, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, U.S.A.
A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

Rutgers, the State University of New Jersey, Piscataway, U.S.A.

University of Tennessee, Knoxville, U.S.A.
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York
Texas A&M University, College Station, U.S.A.

Texas Tech University, Lubbock, U.S.A.
N. Akchurin, C. Bardak, J. Damgov, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans

Vanderbilt University, Nashville, U.S.A.

University of Virginia, Charlottesville, U.S.A.

Wayne State University, Detroit, U.S.A.
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamange Don, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

University of Wisconsin, Madison, U.S.A.

†: Deceased
1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
3: Also at Universidade Federal do ABC, Santo Andre, Brazil
4: Also at California Institute of Technology, Pasadena, U.S.A.
5: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
6: Also at Suez Canal University, Suez, Egypt
7: Also at Cairo University, Cairo, Egypt
8: Also at British University, Cairo, Egypt
9: Also at Fayoum University, El-Fayoum, Egypt
10: Now at Ain Shams University, Cairo, Egypt
11: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
12: Also at Université de Haute-Alsace, Mulhouse, France
13: Also at Moscow State University, Moscow, Russia
14: Also at Brandenburg University of Technology, Cottbus, Germany
15: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
16: Also at Eötvös Loránd University, Budapest, Hungary
17: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
18: Now at King Abdulaziz University, Jeddah, Saudi Arabia
19: Also at University of Visva-Bharati, Santiniketan, India
20: Also at Sharif University of Technology, Tehran, Iran
Also at Isfahan University of Technology, Isfahan, Iran
22: Also at Shiraz University, Shiraz, Iran
23: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
24: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
25: Also at Università della Basilicata, Potenza, Italy
26: Also at Laboratori Nazionali di Legnaro dell’ INFN, Legnaro, Italy
27: Also at Università degli studi di Siena, Siena, Italy
28: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
29: Also at University of California, Los Angeles, Los Angeles, U.S.A.
30: Also at University of Florida, Gainesville, U.S.A.
31: Also at Scuola Normale e Sezione dell’ INFN, Pisa, Italy
32: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
33: Also at University of Athens, Athens, Greece
34: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
35: Also at The University of Kansas, Lawrence, U.S.A.
36: Also at Paul Scherrer Institut, Villigen, Switzerland
37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
38: Also at Gaziosmanpasa University, Tokat, Turkey
39: Also at Adiyaman University, Adiyaman, Turkey
40: Also at The University of Iowa, Iowa City, U.S.A.
41: Also at Mersin University, Mersin, Turkey
42: Also at Kafkas University, Kars, Turkey
43: Also at Suleyman Demirel University, Isparta, Turkey
44: Also at Ege University, Izmir, Turkey
45: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
46: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
47: Also at Utah Valley University, Orem, U.S.A.
48: Also at Institute for Nuclear Research, Moscow, Russia
49: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
50: Also at Los Alamos National Laboratory, Los Alamos, U.S.A.
51: Also at Argonne National Laboratory, Argonne, U.S.A.
52: Also at Erzincan University, Erzincan, Turkey
53: Also at Kyungpook National University, Daegu, Korea