

Measurement of dijet angular distributions and search for beyond the standard model physics in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract

A measurement is presented of dijet angular distributions in proton-proton collisions at $\sqrt{s} = 13$ TeV, using data collected with the CMS detector at the CERN LHC and corresponding to an integrated luminosity of 138 fb^{-1} . For the first time, the dijet angular distributions, corrected for detector effects, are compared with the predictions of perturbative quantum chromodynamics at next-to-next-to-leading order, including next-to-leading-order electroweak corrections. While data are generally found to be in agreement with predictions, a small difference in shape of the normalized distributions is seen for dijet masses ranging from 2.4 to 4.8 TeV and above 6 TeV. The distributions are used to search for proposed signatures of quark compositeness, extra spatial dimensions, quantum black holes, dark-matter mediators, axion-like particles, and anomalous gluon couplings. The most stringent limits to date are set for most of these scenarios. Quark contact interactions are excluded at 95% confidence level (CL) up to a scale of 17 (37) TeV for destructive (constructive) interference in a benchmark scenario, valid to next-to-leading order in quantum chromodynamics, and in which only left-handed quarks participate. The coupling of axion-like particles to the gluon, c_g/f_a , is constrained to be lower than 0.42 TeV^{-1} at 95% CL. The anomalous triple-gluon coupling, C_G/Λ^2 , in a standard model effective field theory is constrained to be lower than 0.0076 TeV^{-2} at 95% CL.

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1 Introduction

Pairs of highly energetic jets of particles (dijets) are produced through pointlike scattering of quarks and gluons (partons) in proton-proton (pp) collisions. Measurements of dijet production at the CERN LHC allow the testing of parton interactions predicted by quantum chromodynamics (QCD) at the highest energy scales with unprecedented precision [1–5]. As an attempt to address open questions not explained by the standard model (SM) of particle physics, many theories beyond the SM (BSM) have been proposed. Several of these models predict new interactions of quarks and gluons, making dijet production sensitive to signatures of BSM physics, including quark compositeness [6–8], extra dimensions [9, 10], quantum black holes (QBHs) [11–15], dark-matter (DM) mediators [16, 17], axion-like particles (ALPs) [18], and anomalous gluon couplings in an effective field theory (EFT) [19].

Example processes of dijet production through QCD and BSM interactions are depicted in Fig. 1. At leading order (LO), dijet production in pp collisions has significant contributions from t -channel scattering (an example diagram with strong coupling g_s is shown in Fig. 1, upper row, left). The BSM processes, however, can be dominated by s -channel production, as well as four-fermion contact interactions (CIs). Depending on the masses and couplings of BSM particles, they can manifest themselves as resonances in pair production, or nonresonant modification of the dijet cross section as a function of the invariant mass and scattering angle. Resonant production of BSM particles has been strongly constrained by searches in the dijet invariant mass spectrum by the ATLAS and CMS Collaborations [20, 21], and nonresonant enhancements of dijet production have been probed in measurements sensitive to the angular distribution of jets [22–24].

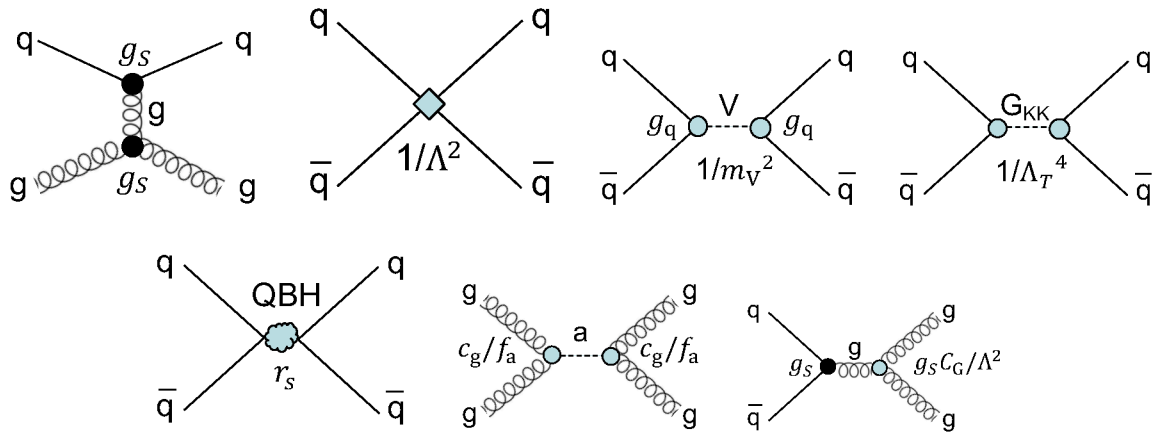


Figure 1: Example diagrams of dijet production processes in QCD and BSM physics. Upper row: t -channel quark-gluon scattering in QCD (left), quark-quark scattering via a BSM contact interaction (center left), quark pair production through an s -channel BSM resonance (center right), and quark pair production through gravitons in models with extra spatial dimensions (right). Lower row: quark pair production through a quantum black hole (left), gluon pair production through an axion-like particle (center), and gluon pair production with a dimension-6 effective field theory anomalous gluon coupling operator (right). A description of the symbols in the diagrams is given in Section 5.

In searches for nonresonant effects from BSM phenomena in dijet production, it is crucial to have a precise description of the SM expectation. Exploiting the huge phase space available for dijet cross sections, constraints can be imposed on the strong coupling constant and the parton distribution functions (PDFs), as performed with triple-differential measurements in

Refs. [3, 5]. Those measurements are reported as functions of the dijet mass (M_{jj}), the Lorentz boost of the dijet center-of-mass system with respect to the lab system $y_{\text{boost}} = |y_1 + y_2|/2$, and $|y_1 - y_2|$, where y_1 and y_2 are the rapidities of the two jets with highest transverse momenta p_T (referred to as the two leading jets in the following). A combined fit, also including parameters representing contributions from CIs, has been performed using double-differential inclusive jet measurements as a function of jet p_T and absolute rapidity $|y|$ in Ref. [22].

For the analysis presented in this Letter, to maximize the sensitivity to BSM effects, we focus on a much reduced phase space at large M_{jj} and low values of y_{boost} . It is advantageous to choose an observable that minimizes the sensitivity to PDFs and the strong coupling constant, which motivates the use of the normalized dijet angular distribution that is defined as $\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$. The QCD dijet production cross section is almost independent of χ_{dijet} , apart from a small deviation at low values of χ_{dijet} originating from subdominant contributions of s -channel QCD processes and higher-order corrections. In contrast, many signatures of BSM physics would manifest themselves as an excess of events at small values of χ_{dijet} . Hence, the normalized distribution provides sensitivity to the scattering dynamics with minimal PDF dependence, as the angular distributions of the dominant underlying QCD processes of $qg \rightarrow qg$, $q\bar{q}(q') \rightarrow q\bar{q}(q')$, and $gg \rightarrow gg$ are similar [25].

In this Letter, our previous measurement of dijet angular distributions [23] is extended to higher dijet masses, using a data sample collected in 2016–2018 by the CMS experiment at $\sqrt{s} = 13$ TeV, and corresponding to an integrated luminosity of 138 fb^{-1} [26–28]. The strategy of the analysis is two-fold. First, we search for evidence of BSM physics in the dijet angular distributions as measured by the detector (detector level), considering models with CIs, extra dimensions, QBHs, and DM mediators. New constraints are also placed on models with ALPs [18] and on anomalous gluon coupling in an EFT [29]. Second, we present a new measurement of the dijet angular distributions, unfolded for detector effects (particle level). For the first time, we compare a measurement directly to a next-to-next-to-LO (NNLO) perturbative QCD prediction including next-to-LO (NLO) electroweak (EW) corrections [30]. Tabulated results can be found in the HEPData record for this analysis [31].

2 The CMS detector

The CMS apparatus [32, 33] is a multipurpose, nearly hermetic detector, designed to trigger on [34–36] and identify electrons, muons, photons, and (charged and neutral) hadrons [37–39]. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are reconstructed using gas-ionization detectors interleaved with the layers of the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [32, 33]. Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of $4 \mu\text{s}$ [34]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to a few kHz before data storage [35, 36].

3 Event reconstruction and selection

Events are reconstructed using the particle-flow algorithm [40] 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 [41] with a distance parameter of $R = 0.4$, as implemented in the FASTJET package [42]. The jet energies are corrected for the nonlinear and nonuniform response of the calorimeters through corrections obtained from data and Monte Carlo (MC) simulations [43].

Events are selected online using a variety of different jet triggers based on the highest jet p_T or the scalar sum of the p_T of all jets in the event (H_T). The selection threshold varied over the course of the data-taking period, ranging in the HLT between 450 and 550 GeV, and 900 and 1050 GeV for p_T and H_T , respectively.

In the offline event selection, events with at least two reconstructed jets are selected. Spurious jets from noise are rejected by applying loose quality criteria [44] to jet properties. Anomalous events due to a variety of reconstruction failures, detector malfunctions, or noncollision backgrounds are rejected by event filters that are designed to identify more than 85–90% of the spurious events, with a mistagging rate less than 0.1% [45]. The primary vertex [39] is taken to be the reconstructed vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [46]. For each event, a reconstructed primary vertex is required that lies 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 two leading jets are used to measure the χ_{dijet} distributions in several regions of M_{jj} . The M_{jj} regions considered are listed in Table 1. The width of the M_{jj} regions is larger than the experimental resolution, and the highest M_{jj} region was defined to maximize the expected sensitivity to the BSM signals considered, while guaranteeing at least 50 expected events in that region. The phase space for this analysis is defined by events with $1 < \chi_{\text{dijet}} < 16$ and $|y_{\text{boost}}| < 1.11$. This selection restricts the rapidities $|y_1|$ and $|y_2|$ of the two highest p_T jets to be less than 2.5, i.e., within the acceptance of the tracking detector. The dijets with the highest (leading) and second-highest (sub-leading) jet p_T are required to have p_T values above 500 and 200 GeV, respectively. The trigger efficiency exceeds 99% over the entire analysis phase space. The observed number of events, N_{dijet} , after selection in each M_{jj} bin is listed in Table 1. The highest value of M_{jj} observed in the data is 8.3 TeV.

Table 1: Observed number of events, N_{dijet} , after selection in each M_{jj} bin.

M_{jj} bin [TeV]	N_{dijet}
2.4–3.0	1 363 868
3.0–3.6	283 202
3.6–4.2	68 232
4.2–4.8	17 731
4.8–5.4	5 040
5.4–6.0	1 423
6.0–7.0	433
>7.0	50

The χ_{dijet} distributions obtained after event reconstruction and selection, called detector level in the following, are normalized to unity in each M_{jj} region. These distributions,

$$\frac{1}{N_{\text{dijet}}} \frac{dN_{\text{dijet}}}{d\chi_{\text{dijet}}}, \quad (1)$$

are then analyzed in two ways. First, signatures of BSM physics are searched for at the detector level. Second, the distributions are unfolded for detector effects to obtain the dijet angular distributions at what is referred to as the particle level,

$$\frac{1}{\sigma_{\text{dijet}}} \frac{d\sigma_{\text{dijet}}}{d\chi_{\text{dijet}}}, \quad (2)$$

where σ_{dijet} is the corrected total dijet cross section in the M_{jj} region.

Fluctuations in jet response arising from the jet p_{T} resolution of the detector can cause lower-energy jets to be misidentified as one of the two leading jets. Such fluctuations can also produce bin-to-bin migrations in the χ_{dijet} and M_{jj} regions. The response matrix, obtained by smearing particle-level jets with a detector response parameterization (discussed in Section 4), encodes the probabilities that an event in a given bin j at the particle level is reconstructed in a bin i at the detector level. The response matrix enables both forward folding of theoretical predictions to the detector level for BSM searches and backward unfolding of the raw data distributions to the particle level for the measurement.

4 The QCD predictions and uncertainties

We compute predictions of the normalized dijet angular distribution from perturbative QCD at NNLO using NNLOJET [30] in the FASTNLO framework [47]. The same jet clustering algorithm used at the detector level is applied to the outgoing partons in the NNLO prediction. Following recommendations outlined in Ref. [48], the dijet invariant mass of the two leading jets, M_{jj} , is chosen as the central reference value for both the factorization scale, μ_{F} , and renormalization scale, μ_{R} , in the perturbative calculation: $\mu_{\text{F}} = \mu_{\text{R}} = M_{\text{jj}}$. For comparison to our previous publication [23] using predictions at NLO, the average p_{T} of the two leading jets, $\langle p_{\text{T}} \rangle$, is used as an alternative: $\mu_{\text{F}} = \mu_{\text{R}} = \langle p_{\text{T}} \rangle$. Since $M_{\text{jj}} = 2\langle p_{\text{T}} \rangle \cosh(|y_1 - y_2|/2)$, the two scale choices, M_{jj} and $\langle p_{\text{T}} \rangle$, coincide up to a factor of two for $\chi_{\text{dijet}} = \exp(|y_1 - y_2|)$ approaching unity, but differ for larger values of χ_{dijet} .

The two scale choices exhibit different perturbative convergence behavior, which is usually associated with predictions at some order i that successively include the next higher-order prediction within the estimated uncertainty. In particular, K factors, $K_i = \sigma_{\text{N}^{i+1}\text{LO}}/\sigma_{\text{N}^i\text{LO}}$, are expected to lie around unity within scale variations and to be closer to unity with increasing i . In addition, scale variation uncertainty bands are expected to overlap and decrease in size with increasing i . This is fulfilled for our central scale choice of M_{jj} , but not for $\langle p_{\text{T}} \rangle$, where the scale dependence at NNLO can be as large as that at NLO. Therefore, the latter is employed only as an alternative to derive an additional estimate for the scale dependence of the normalized dijet angular distribution.

For all simulated samples, the PDFs are taken from the NNPDF3.1 set [49] at NNLO. For an alternative PDF, the CT14 sets [50] at NNLO and NLO were also studied.

Electroweak corrections for dijet production [51] have a nonnegligible effect on the normalized χ_{dijet} distributions, requiring corrections of 1% (5%) at low (high) M_{jj} .

We evaluated the impact of nonperturbative effects due to the hadronization and multiple parton interactions on the QCD predictions using PYTHIA 8.212 with the CUETP8M1 tune [52, 53] and HERWIG++ 2.7.1 [54] with tune EE5C [55]. Particle-level jets are computed from the four-vectors of generated stable particles (lifetime $c\tau > 1$ cm, including muons, excluding neutrinos). The effects are found to be negligible in both MC generators. Therefore, we are able to directly compare the data corrected to the particle level with the parton-level theoretical predictions.

The uncertainty related to the choices of the μ_F and μ_R scales are evaluated following the proposal in Refs. [56, 57] by varying the default choice of scales in the following 6 combinations: $(\mu_F/M_{jj}, \mu_R/M_{jj}) = (1/2, 1/2), (1/2, 1), (1, 1/2), (1, 2), (2, 1),$ and $(2, 2)$. The uncertainty in PDFs is determined using the 100 MC replicas provided in NNPDF3.1 [58]. The uncertainty in the strong coupling constant has a negligible impact on the normalized χ_{dijet} distribution. The NNLO calculation has a statistical uncertainty from the MC integration. A summary of the leading systematic uncertainties in the theoretical predictions is shown in Table 2. The two central scale choices display a considerably different perturbative convergence and residual scale uncertainty. For the BSM search, we account for the difference between the scale choices M_{jj} and $\langle p_T \rangle$ as an additional uncertainty, since they are not covered by the scale uncertainty from variations of the scale around the central choice $\mu_F = \mu_R = M_{jj}$.

Table 2: Summary of the leading theoretical uncertainties in the normalized χ_{dijet} distributions. The full analysis takes into account correlations between χ_{dijet} bins; however, this table shows the contributions in the lowest χ_{dijet} bin for two representative M_{jj} bins. This illustrates the magnitude of the contributions for these M_{jj} bins.

M_{jj} bin [TeV]	3.0–3.6	>7.0
$\mu_{R,F}$ variations (6 points)	+2.2% -1.3%	+2.7% -1.5%
$\mu_{R,F}$ choice (M_{jj} vs. $\langle p_T \rangle$)	2.5%	9.6%
PDF (NNPDF3.1 NNLO)	0.1%	5.5%
Theory NNLO statistical	0.5%	4.4%
Nonperturbative effects	<1%	<1%
Total theoretical	3.5%	12.2%

To map the above particle-level predictions to the detector level, we make use of MC event generators and a detailed simulation of the CMS detector using GEANT4 [59]. Samples of QCD multijet production are generated at LO with PYTHIA 8.212 [60] with the CP5 tune [61]. An alternative sample of QCD multijet production is generated at LO with MADGRAPH5_aMC@NLO v2.6.5 [62] with up to four additional jets in the matrix element computation. The sample is binned in the scalar sum of all jet transverse momenta H_T . The MADGRAPH5_aMC@NLO generator is interfaced with PYTHIA for the parton showering and hadronization. To avoid double-counting of jets from the matrix element calculations and the parton shower, jets are matched using the MLM scheme [63]. A second alternative sample of QCD multijet production is obtained using HERWIG 7.1.4 [54, 64] at LO.

To predict the background in the search for BSM physics, a detector-level prediction is computed starting from the prediction at NNLO in QCD with EW corrections. A response matrix is applied, mapping the particle-level M_{jj} and χ_{dijet} distributions onto the measured values. The response matrix is obtained from the PYTHIA MC event generator. Detector-level jets are determined from the particle-level jets by smearing their p_T , using a double-sided Crystal Ball

parameterization [65, 66] of the response. The parameterization takes into account the full jet energy resolution, including non-Gaussian tails, and is matched to data.

5 The BSM predictions and uncertainties

A common signature of quark compositeness [6–8] is the appearance of new interactions between quark constituents at some characteristic mass scale, Λ , that is much larger than the quark masses. At energies well below Λ , these interactions are approximated with a CI characterized by a four-fermion coupling (an example diagram is shown in Fig. 1, upper row), described by the effective Lagrangian [7, 8]:

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

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 integers with possible values of 0, +1, or −1. The various combinations of $(\eta_{LL}, \eta_{RR}, \eta_{RL})$ correspond to different CI models. The investigated CI scenarios with color-singlet couplings between quarks use the $(\eta_{LL}, \eta_{RR}, \eta_{RL})$ values shown in Table 3.

Table 3: The different combinations of $(\eta_{LL}, \eta_{RR}, \eta_{RL})$ used in the search for CIs between quarks and the corresponding mass scale name.

Λ	$(\eta_{LL}, \eta_{RR}, \eta_{RL})$
Λ_{LL}^\pm	$(\pm 1, 0, 0)$
Λ_{RR}^\pm	$(0, \pm 1, 0)$
Λ_{VV}^\pm	$(\pm 1, \pm 1, \pm 1)$
Λ_{AA}^\pm	$(\pm 1, \pm 1, \mp 1)$
$\Lambda_{(V-A)}^\pm$	$(0, 0, \pm 1)$

We note that the models with positive (negative) η_{LL} or η_{RR} lead to destructive (constructive) interference with the QCD terms and a lower (higher) dijet cross section. In all CI models discussed in this paper, NLO QCD corrections are employed to calculate the cross sections. In pp collisions, the Λ_{LL}^\pm and Λ_{RR}^\pm models result in identical tree-level cross sections and NLO corrections, and consequently lead to the same sensitivity. For Λ_{VV}^\pm , Λ_{AA}^\pm , and $\Lambda_{(V-A)}^\pm$ the CI predictions are identical at tree level, but exhibit different NLO corrections and yield different sensitivity. To calculate the CI terms and the interference between the CI and QCD terms at NLO in QCD, the CIJET 1.0 program [67] is employed. Scale and PDF uncertainties in the CI terms and QCD processes are treated as correlated.

Another BSM physics scenario considered is a DM mediator particle that couples to DM particles and quarks. Depending on the couplings of such a mediator particle to DM and quarks, it can be observed as a narrow or wide resonance or even a nonresonant dijet signature. In a simplified model of interactions between DM and quarks [16, 17], a DM mediator with unknown mass, m_{med} , is assumed to be a spin-1 particle (vector V or axial-vector A) and to decay only to pairs of quarks or DM particles (an example diagram for a vector mediator with mass m_V is shown in Fig. 1, upper row). The DM mediator has a universal quark coupling, g_q , and a DM coupling, g_{DM} . The DM particles have mass, m_{DM} , which is set to 1 GeV in this analysis. Interactions of a DM vector and axial-vector mediator in this model are generated using MADDM version 2.0.6 [68, 69]. Scenarios with $g_q < 0.5$ that predict resonances with a width lower than

10% of the DM mediator mass have been excluded in dijet resonance searches [20, 21] across a large range of m_{med} . Therefore, scenarios with $g_q > 0.5$ are of particular interest in this search.

The Arkani-Hamed–Dimopoulos–Dvali (ADD) model [9, 10] of compactified large extra dimensions (EDs) provides a possible solution to the SM hierarchy problem. In pp collisions at the LHC, it predicts signatures of virtual graviton exchange that result in a nonresonant enhancement of dijet production (an example diagram is shown in Fig. 1, upper row), whose angular distribution differs from the predictions of QCD. For the ADD model, two parameterizations for virtual graviton exchange are considered: Giudice–Rattazzi–Wells (GRW) [70] and Han–Lykken–Zhang (HLZ) [71]. In the GRW convention, the sum over the Kaluza–Klein graviton excitations, G_{KK} , 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 string scale, M_S (by convention used as the cutoff); and the number of extra spatial dimensions, n_{ED} . The parameters M_S and n_{ED} are directly related to Λ_T [72]. We consider scenarios with 2–6 EDs. The case of $n_{\text{ED}} = 1$ is not considered, since it would require an ED roughly the size of the solar system; the gravitational potential at these distances would be noticeably modified, and this case is therefore excluded. The case of $n_{\text{ED}} = 2$ is special in the sense that the relation between M_S and Λ_T also depends on the parton-parton center-of-mass energy $\sqrt{\hat{s}}$. The ADD model predictions are calculated with PYTHIA.

In models with large EDs, the fundamental Planck scale is assumed to be closer to the EW scale, thereby implying the possibility of black hole production at the LHC [11–15]. Quantum black holes that are produced with a mass close to the Planck scale decay predominantly into dijets and can be studied using dijet angular distributions [73–76]. The QBH production is studied within the framework of the ADD model, with $n_{\text{ED}} = 6$ (ADD6), and the Randall–Sundrum model with $n_{\text{ED}} = 1$ (RS1) [77, 78] (an example diagram is shown in Fig. 1, lower row). In these models, the QBH production cross section is typically described by the classical geometrical cross section, $\sigma_{\text{QBH}} \approx \pi r_s^2$, where r_s is the Schwarzschild radius of the QBH. The Schwarzschild radius depends on the mass of the QBH, the Planck scale (M_P), and the number of spatial dimensions. Since QBHs are produced with a mass threshold close to the Planck scale, we set the minimum QBH mass, M_{QBH} , equal to M_P for simplicity. The QBH 3.0 generator [79] is used for the predictions.

Axion-like particles [80, 81] appear in extensions of the SM that could potentially solve the strong CP problem [82] and/or explain the nature of DM. Production of ALPs at the LHC can be described in a linear EFT, adding an ALP a with mass m_a to the SM with a new interaction at a characteristic high energy scale, f_a [83] (an example diagram is shown in Fig. 1, lower row). In the limit $m_a \ll f_a$, ALP couplings to SM bosons are purely derivative in the sense that the coupling term in the Lagrangian only contains the derivative of the ALP field. As a result, ALP interactions with SM bosons enhance cross sections at center-of-mass energies much larger than m_a . The coupling to gluons is $g_{\text{agg}} = 4c_g/f_a$, where c_g is the gluon operator coefficient. Within the range of validity of the EFT, enhancement of s -channel gluon pair production can be probed in dijet events [18]. Predictions are computed using MADGRAPH5_aMC@NLO 2.4.3 with the FEYNRULES ALP_linear_UFO implementation of an EFT for a light ALP [83]. The calculation is performed at LO with up to one extra jet in the matrix element calculations, using the MLM matching [63], and includes the interference with the SM production. We study modifications of the ALP coupling to gluons g_{agg} , while all other ALP couplings are set to 0 and the ALP mass to $m_a = 1 \text{ MeV}$.

More generally, dijet angular distributions can be used to constrain couplings in the SM EFT (SMEFT) [19, 29], assuming that BSM physics lies at an energy scale much larger than the

experimentally probed interaction energy. The SMEFT Lagrangian includes higher-dimension operators involving SM particles that are suppressed by powers of the BSM physics scale Λ . A dimension-6 triple-gluon operator is introduced with a coefficient C_G and is suppressed by $1/\Lambda^2$. The operator modifies processes with gluons in the initial or final state (an example diagram is shown in Fig. 1, lower row). Consistent with Ref. [29], predictions are computed using MADGRAPH5_aMC@NLO 2.4.3 with the FEYNRULES implementation TopEffTh of an EFT for top quarks [84] at LO with up to two extra jets in the matrix element calculation, using the MLM matching, and no interference with SM production. We study modifications of the triple-gluon coupling C_G/Λ^2 , while all other anomalous couplings are set to 0. The interference with the SM production of order C_G/Λ^2 was found to have no phenomenological relevance in dijet production up to NLO at the LHC energies [85]. The analysis reported here is mainly sensitive to contributions of order C_G^2/Λ^4 .

To take into account the NNLO QCD and NLO EW corrections to the SM dijet production when probing the BSM models, the cross section difference $\sigma_{\text{NNLO+EW corr}}^{\text{QCD}} - \sigma_{\text{LO}}^{\text{QCD}}$ is evaluated for each M_{jj} and χ_{dijet} bin and added to the BSM predictions that include LO SM QCD processes, namely ADD, QBH, DM, ALP, and SMEFT. With this procedure, an SM+BSM prediction is obtained where the QCD terms are corrected to NNLO including NLO EW corrections, while the BSM terms are calculated at LO. While the ADD and ALP BSM predictions (obtained by subtracting the predictions $\sigma_{\text{LO}}^{\text{BSM+QCD}} - \sigma_{\text{LO}}^{\text{QCD}}$) include the interference terms with the SM, the QBH, DM, and SMEFT BSM predictions do not include such interference terms.

Scale and PDF uncertainties in the CI predictions are taken into account. In the ADD and QBH models, the scale and PDF uncertainties have a negligible impact on the sensitivity, as the signals only appear in the highest mass bins, where the statistical uncertainties dominate. For the DM models, the effect on the acceptance due to the PDF uncertainty is found to be nonnegligible for $M_{\text{jj}} > m_{\text{med}}$ with DM mediators that have large mass and coupling. For example, for an axial-vector mediator with $m_{\text{med}} = 6$ TeV and $g_q = 1.0$, which corresponds to a resonance with $\Gamma/m_{\text{med}} = 50\%$, the uncertainty is 14% in the $6.0 < M_{\text{jj}} < 7.0$ TeV bin.

6 Experimental uncertainties

The normalized dijet angular distributions have reduced sensitivity to many experimental systematic effects compared to dijet mass M_{jj} or inclusive jet p_T cross section measurements. Systematic uncertainties arise from the jet energy scale (JES), the jet energy resolution (JER), triggering, and the detector simulation and modeling used to construct the response matrix. A summary of the size of leading experimental systematic uncertainties is provided in Table 4.

The overall JES uncertainty is less than 1%, and the variation of the JES as a function of pseudorapidity in the phase space of the analysis is less than 1% per unit η [43, 86]. The JES uncertainties related to each step in the derivation of the p_T - and η -dependent JES corrections are taken into account separately. The correlations of the JES uncertainty sources among the M_{jj} ranges and χ_{dijet} bins are included.

The JER uncertainty in this measurement is evaluated by changing the width of the Gaussian function of the Crystal Ball parameterization of the response by up to $\pm 5\%$ [43, 86], depending on the jet pseudorapidity, and comparing the resultant distributions before and after these changes. The systematic uncertainty from the modeling of the tails of the jet resolution is evaluated using a Gaussian function to parameterize the response, and assigning as an uncertainty half of the difference between the distributions determined from this Gaussian function and the nominal correction.

Table 4: Leading experimental uncertainties in the normalized χ_{dijet} distributions. The uncertainties in the lowest χ_{dijet} bin for two M_{jj} bins are shown as representative examples.

M_{jj} bin [TeV]	3.0–3.6	>7.0
Statistical	0.7%	25%
Jet energy scale	2.7%	6.8%
Jet energy resolution (core)	0.1%	2.0%
Jet energy resolution (tails)	0.5%	4.7%
ECAL L1 trigger	0.3%	2.8%
Response matrix modeling	0.6%	5.0%
Detector simulation	1.0%	4.6%
Pileup	<0.1%	<0.1%
Total experimental	3.0%	27%

A source of uncertainty in the detector simulation used for the response matrix 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 χ_{dijet} distributions obtained from this parametric model to those from a detailed simulation of the CMS detector using GEANT4 [59]. An additional systematic uncertainty is evaluated to account for the dependence of the response matrix on the physics model used to describe the dijet kinematics. This uncertainty is determined by applying the unfolding corrections (detailed in Section 8) determined with PYTHIA to smeared χ_{dijet} distributions from MADGRAPH5_aMC@NLO and HERWIG and comparing the results with the generated χ_{dijet} distributions.

During the 2016 and 2017 data-taking periods, a gradual shift in the timing of the inputs of the ECAL L1 trigger in the $|\eta| > 2.0$ region caused a trigger inefficiency, denoted as “prefiring” [34]. Correction factors were computed from data and applied, with an effect of order $<1\%$ in $2.0 < |\eta| < 2.5$. The uncertainty related to the correction for this effect is also taken into account.

The effect on the χ_{dijet} distributions from additional interactions in the same or adjacent proton bunch crossings relative to the interaction of interest (pileup) is studied by varying the pileup distribution in simulated samples, taking into account luminosity-related dependencies.

The statistical analysis of the data treats uncertainties separately; however, in tables and figures a quadratic sum of all contributions is presented. While statistical uncertainties in the data and the theoretical prediction are treated as uncorrelated among all M_{jj} and χ_{dijet} bins, all systematic effects are treated as fully correlated among M_{jj} and χ_{dijet} bins. The only exceptions are the systematic uncertainties related to response matrix modeling, detector simulation, and JER tails, whose correlations among M_{jj} bins are less well known; thus they are considered with additional independent nuisance parameters per M_{jj} bin to account for potential uncorrelated components.

7 Search for BSM physics

To search for signatures of BSM physics, the detector-level distributions are compared to QCD and BSM predictions, using a response matrix to obtain predictions at the detector level. The log-likelihoods L_{QCD} and $L_{\text{QCD+BSM}}$ for the QCD-only and QCD+BSM hypotheses, respectively, are defined as products of Poissonian likelihood functions for each bin in the χ_{dijet} and M_{jj} re-

gions (before normalization). The predictions for each M_{jj} range are normalized to the number of observed events in that range. The asymptotic approximation [87, 88] of the CL_s criterion [89, 90] is used to set exclusion limits on various BSM model parameters, using the CMS statistical analysis tool, COMBINE [91]. The limits obtained using this approximation were tested against the CL_s limits obtained using ensembles of pseudo-experiments for several of the models examined, and the differences were found to be negligible. Nuisance parameters are profiled with respect to the QCD-only and QCD+BSM models by maximizing the corresponding likelihood functions. The p -values for the two hypotheses, $P_{\text{QCD+BSM}}(q > q_{\text{obs}})$ and $P_{\text{QCD}}(q < q_{\text{obs}})$, are based on the log-likelihood ratio $q = -2 \ln(L_{\text{QCD+BSM}}/L_{\text{QCD}})$. Limits on the QCD+BSM models are set based on the quantity $CL_s = P_{\text{QCD+BSM}}(q > q_{\text{obs}})/(1 - P_{\text{QCD}}(q < q_{\text{obs}}))$, which is required to be less than 0.05 for a 95% confidence level (CL) exclusion. Expected limits are obtained by using a QCD-only Asimov dataset solving the above requirement.

In Figs. 2–3, the χ_{dijet} distributions at the detector level are compared with representative examples of BSM predictions, which account for detector effects by applying the response matrix. The signal distributions are only shown for a subset of M_{jj} ranges, since those bins dominate the sensitivity to the BSM signals that were considered. While signatures of CI, ADD, and QBH mainly predict an excess at low χ_{dijet} in the highest M_{jj} bins, DM, ALP, and SMEFT predictions modify the χ_{dijet} distributions at lower M_{jj} , as well.

In the M_{jj} bins below 4.8 TeV, the measured distributions show a small difference in shape compared to the QCD-only prediction by an amount similar to the experimental and theoretical uncertainties. For M_{jj} in the range 4.8 to 7 TeV, generally good agreement is found between the measurement and the QCD-only prediction. In the highest M_{jj} bin and the lowest χ_{dijet} bin, another small difference compared to the QCD prediction is seen. The agreement of the data with QCD predictions is quantified by calculating $P_{\text{QCD}}(q < q_{\text{obs}})$, considering a CI signal in the likelihood ratio. When taking into account all M_{jj} bins, a significance of 0.3 standard deviations is found. Considering individual mass bins alone, the largest deviations are found in the 3–3.6 TeV and 7–13 TeV M_{jj} bins, with a local significance of 2.0 and 2.4 standard deviations, respectively. However, none of the signals considered would be localized in a single mass bin; thus we find no evidence for a BSM signal.

The measured χ_{dijet} distributions are used to determine exclusion limits on the BSM models. In the limit calculations, not all M_{jj} ranges are included in the likelihoods. The only ones used are those that improve the expected limits by more than 1%. In all cases, the 2.4–3.0 TeV M_{jj} bin (where no signal is expected) is included as a control region to constrain the experimental and theoretical systematic uncertainties. We use the mass bins with $M_{jj} > 3.6$ TeV, 4.2 TeV, and 4.8 TeV in searching for signals with the CI, ADD, and QBH models, respectively. For the DM mediators, we use mass bins that cover $M_{jj} < 1.2m_{\text{med}}$. For the ALP and SMEFT models, we only use the M_{jj} bins below the BSM physics scale, f_a and Λ , respectively. The observed and expected exclusion limits on different models obtained in this analysis at 95% CL are listed in Table 5.

For ADD and QBH models, the observed limits are worse than the expected limits, due to a slight excess of events in the lowest χ_{dijet} bin for the highest M_{jj} bin. The limit on CI $\Lambda_{\text{LL/RR}}^+$ is significantly lower than $\Lambda_{\text{LL/RR}}^-$, due to the destructive interference between the CI and QCD terms. The limit on Λ_{VV}^+ has two disjoint regions of observed exclusion. The lower limit on Λ_{VV}^+ is driven by pure CI terms and is followed by a gap in exclusion, when the CI and destructive interference terms balance each other. At large values of Λ_{VV}^+ , the destructive interference dominates and leads to the additional exclusion region. The most stringent lower limits to date are set on the scale of CIs, graviton exchange, and QBHs.

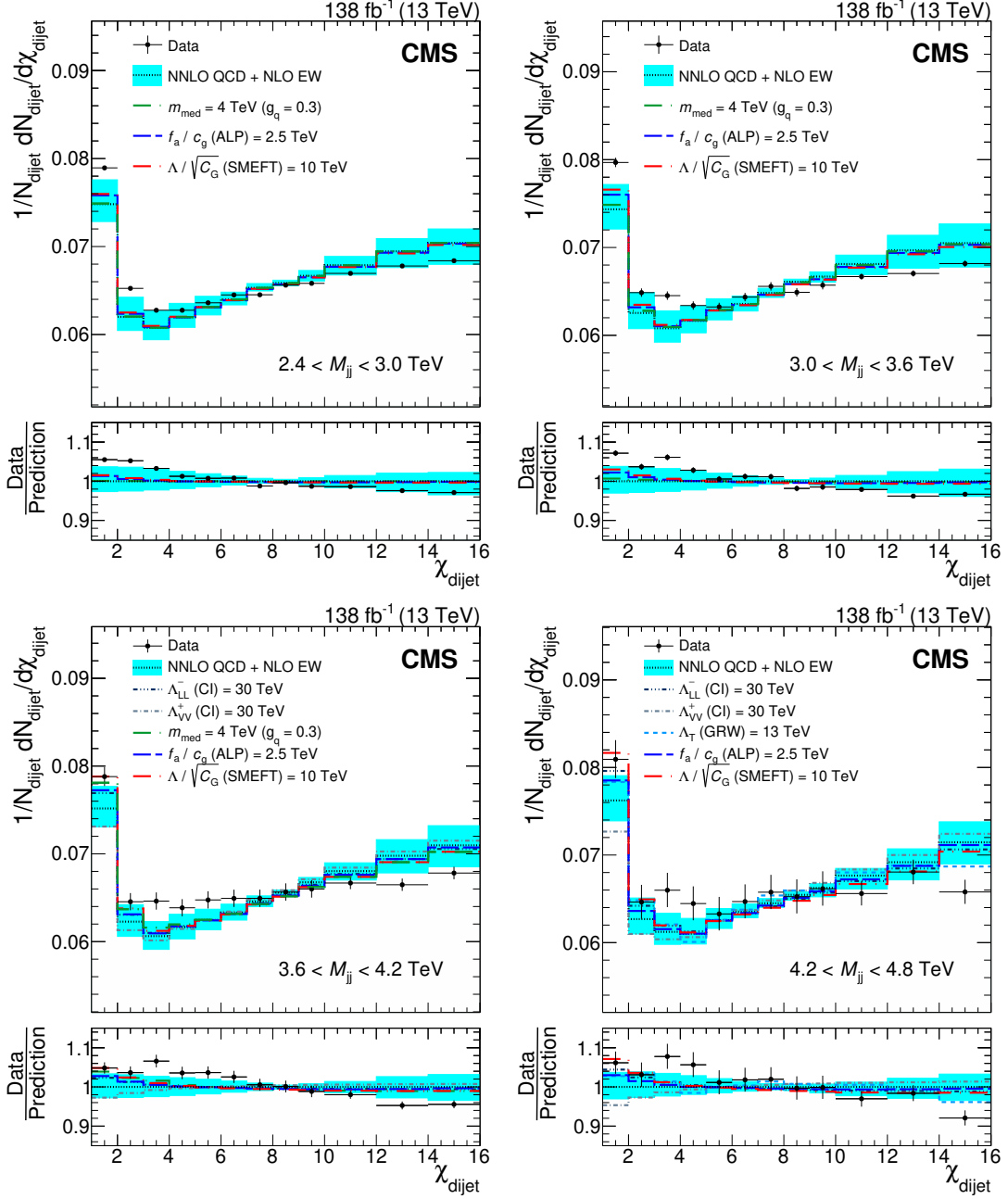


Figure 2: Normalized χ_{dijet} distributions for the $M_{j\bar{j}}$ bins up to 4.8 TeV. The data distributions at the detector level (points) are compared to NNLO predictions, corrected for the detector response (black dotted lines). The vertical bars on the points represent statistical and experimental systematic uncertainties combined in quadrature. The horizontal bars show the bin widths. Theoretical uncertainties are indicated with the blue bands. The prediction from various BSM scenarios, with parameter values given in the legend, are shown by the different dot-dashed lines. The lower plots display the ratio of the data to the NNLO QCD + NLO EW predictions.

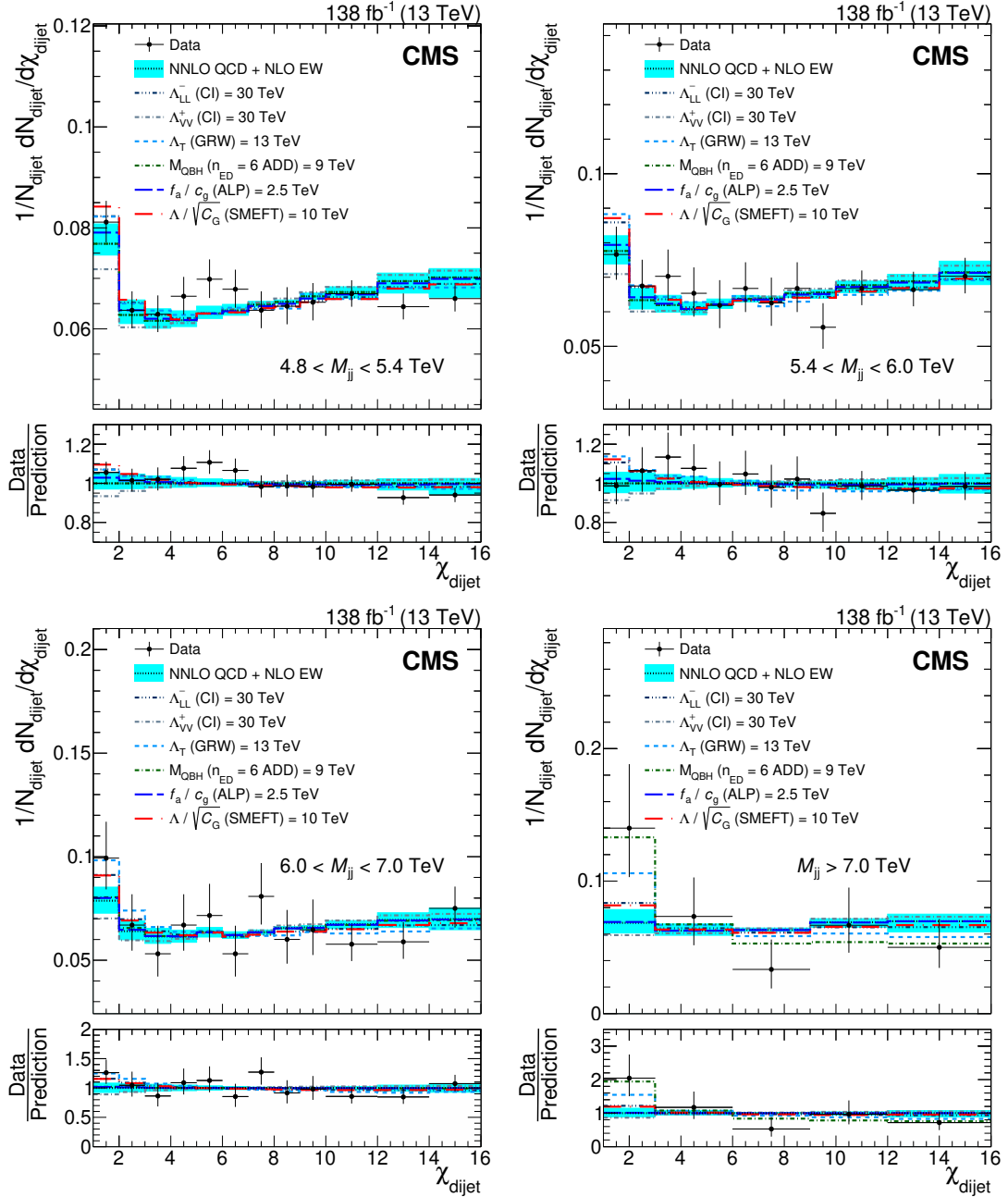


Figure 3: Normalized χ_{dijet} distributions for the M_{jj} bins above 4.8 TeV. Notations as in Fig. 2.

Table 5: Observed and expected exclusion limits at 95% CL for various BSM models. The ± 1 standard deviation values for the expected limits are quoted, as shown in the last column.

Model	Observed limit	Expected limit
CI $\Lambda_{LL/RR}^+$ (NLO)	17 TeV	18_{-2}^{+20} TeV
CI $\Lambda_{LL/RR}^-$ (NLO)	37 TeV	34_{-5}^{+8} TeV
CI Λ_{VV}^+ (NLO)	<19 and 27–31 TeV	41_{-22}^{+17} TeV
CI Λ_{VV}^- (NLO)	50 TeV	45_{-7}^{+11} TeV
CI Λ_{AA}^+ (NLO)	19 TeV	39_{-21}^{+16} TeV
CI Λ_{AA}^- (NLO)	49 TeV	44_{-7}^{+11} TeV
CI $\Lambda_{(V-A)}^+$ (NLO)	14.9 TeV	$14.0_{-1.4}^{+1.8}$ TeV
CI $\Lambda_{(V-A)}^-$ (NLO)	15.7 TeV	$14.6_{-1.6}^{+2.2}$ TeV
ADD Λ_T (GRW)	13.4 TeV	14.2 ± 1.0 TeV
ADD M_S (HLZ) $n_{ED} = 2$	15.0 TeV	16.0 ± 1.1 TeV
ADD M_S (HLZ) $n_{ED} = 3$	15.9 TeV	16.9 ± 1.2 TeV
ADD M_S (HLZ) $n_{ED} = 4$	13.4 TeV	14.2 ± 1.0 TeV
ADD M_S (HLZ) $n_{ED} = 5$	12.1 TeV	12.8 ± 0.9 TeV
ADD M_S (HLZ) $n_{ED} = 6$	11.3 TeV	11.9 ± 0.8 TeV
QBH M_{QBH} (ADD, $n_{ED} = 6$)	8.5 TeV	9.1 ± 0.3 TeV
QBH M_{QBH} (RS1)	6.3 TeV	6.8 ± 0.4 TeV
DM mediator m_{med}	6.2 TeV	6.2 ± 0.8 TeV
ALP c_g/f_a	0.42 TeV^{-1}	$0.38 \pm 0.03 \text{ TeV}^{-1}$
SMEFT C_G/Λ^2	0.0076 TeV^{-2}	$0.0081 \pm 0.0012 \text{ TeV}^{-2}$

For a vector or axial-vector DM mediator with $g_{DM} = 1.0$ and $m_{DM} = 1 \text{ GeV}$, we compute limits as functions of the mediator mass, which are shown in Fig. 4. Unlike our previous search from dijet angular distributions [23] using only data with $0.5m_{med} < M_{jj} < 1.2m_{med}$, we consider all mass bins satisfying $M_{jj} < 1.2m_{Med}$ to better constrain the background uncertainties. Compared to previous searches for dijet resonances [20, 21], this search sets the most stringent limits on DM mediator masses near 4.5 TeV, where the mediator width is 10% of its mass or larger.

In Fig. 5 (left), we present limits on the ALP gluon coupling, c_g , as a function of the characteristic energy scale, f_a . The limit on the ratio f_a/c_g for energy scales f_a beyond the reach of this measurement can be inferred from any point on the limit curve, which is linear above 7 TeV (our highest M_{jj} bin). While an earlier reinterpretation using simplified assumptions reported an exclusion bound at $c_g/f_a = 0.33 \text{ TeV}^{-1}$ [18], our limit is slightly weaker at $c_g/f_a = 0.42 \text{ TeV}^{-1}$. An important difference between the previous limit and our result is that we consider 2- and 3-jet production in MADGRAPH5_aMC@NLO for signal and interference, while the previous result only considered $2 \rightarrow 2$ processes for the signal, interference, and background.

In Fig. 5 (right), the 95% CL upper limits on the anomalous triple-gluon coupling, C_G , in SMEFT is shown as a function of the BSM physics energy scale, Λ . While a previous result using simplified assumptions on the experimental analysis reported a 95% CL upper limit on C_G/Λ^2 of 0.032 TeV^{-2} [29], our 95% CL upper limit of $C_G/\Lambda^2 = 0.0076 \text{ TeV}^{-2}$ is stronger. It is also more stringent than the upper limit obtained from multijet production of 0.036 TeV^{-2} [92], as well as from top quark production [93]. It should be noted that top quark production is uniquely sensitive to linear contributions of C_G/Λ^2 , while dijet production is dominated by quadratic contributions of order C_G^2/Λ^4 .

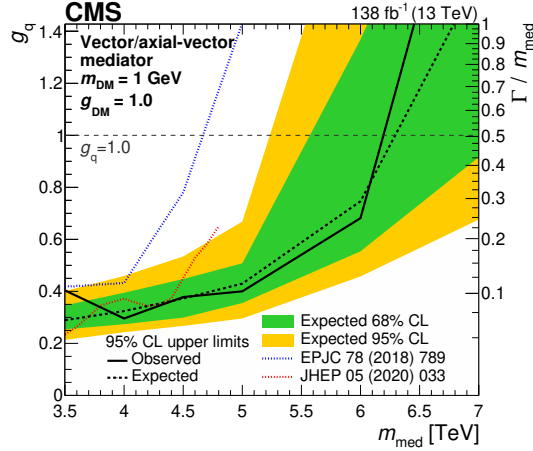


Figure 4: The 95% CL upper limits on the universal quark coupling g_q as functions of a vector or axial-vector mediator mass, with $g_{DM} = 1.0$ and $m_{DM} = 1$ GeV. The observed (solid line) and expected (dashed line) limits and their 68% and 95% confidence intervals (shaded bands) are shown. A dashed horizontal line shows the coupling strength for a benchmark DM mediator with $g_q = 1$. Results are compared to the previous searches using dijet angular [23] (blue dotted line) and dijet mass [21] (red dotted line) distributions. The vertical scale on the right axis gives the corresponding values of Γ/m_{med} .

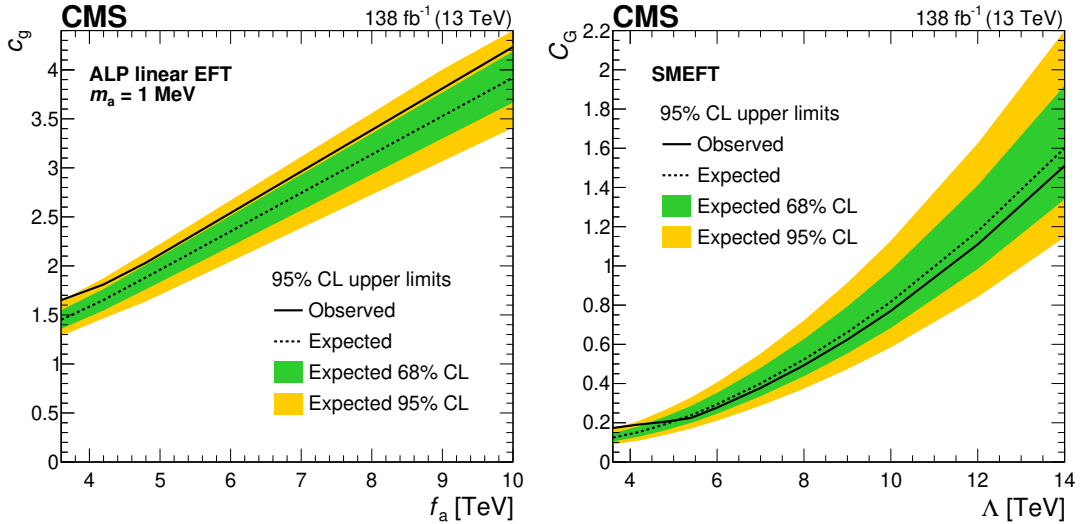


Figure 5: The 95% CL upper limits on the ALP gluon coupling (left) in linear EFT, c_g , as functions of the characteristic energy scale, f_a , assuming $m_a = 1$ MeV. Only χ_{dijet} distributions with $M_{jj} < f_a$ are used to obtain the limits on c_g . The 95% CL upper limits on the anomalous triple-gluon coupling (right), C_G , in SMEFT as functions of the BSM physics energy scale, Λ . Only χ_{dijet} distributions with $M_{jj} < \Lambda$ are used to obtain the limits on C_G . The observed limits (solid lines), expected limits (dashed lines), and their 68% and 95% confidence intervals (shaded bands) are shown.

8 Unfolding for the detector effects

In the unfolding procedure used in this analysis, a measured distribution at the detector level is corrected for detector effects, yielding a particle-level distribution. In a maximum likelihood template fit, the detector response matrix is inverted to obtain the measured distribution at the particle level. The approach is similar to the one outlined in Ref. [94], though a maximum likelihood fit instead of a least-squares fit is used. The signal strength modifiers μ_j are the ratios of the number of events predicted by the fit to data to the expected number of events at the particle level in simulation. The total number of expected events y_i in bin i at the detector level is given by

$$y_i = \sum_{j=1}^M R_{ij} \mu_j x_j + b_i. \quad (3)$$

Here, R_{ij} is the response matrix corresponding to the number of events in a bin i at the detector level, given the number of events in bin j at the particle level, M is the total number of bins in the particle-level distribution, and b_i corresponds to the total number of expected background events in the i -th bin at the detector level. In our measurement, the background is negligible. If the response matrix can be inverted, the expected number of true events $x_j \mu_j$ at the particle level is given by:

$$x_j \mu_j = \sum_{i=1}^N R_{ji}^{-1} (y_i - b_i), \quad (4)$$

where N is the total number of bins in the detector-level distribution. This solution is obtained by minimizing the negative log-likelihood function:

$$-2 \ln \mathcal{L}(\vec{\mu}) = -2 \sum_i^N \ln P(n_i, y_i), \quad (5)$$

where n_i is the total number of data events in the i -th detector-level bin, $P(n_i, y_i)$ is the Poisson probability distribution, and no regularization term is added. Terms accounting for systematic uncertainties have been added as nuisance parameters to the negative log-likelihood function and profiled. The dijet angular distributions at the particle level are measured in bins with $M_{jj} > 3.0$ TeV, accounting for migrations from the 2.4–3.0 TeV bin at the detector level into the higher-mass M_{jj} bins at the particle level. The unfolding changes the shape of the χ_{dijet} distributions by $<1\%$ and $<10\%$ for all values of χ_{dijet} in the lowest and highest M_{jj} ranges, respectively.

The resulting particle-level dijet angular distributions are shown in Figs. 6–7. The correlations between bins introduced by the unfolding are provided in Fig. 8. For $M_{jj} = 4.8$ –7.0 TeV, generally good agreement is found between the measurement and the NNLO predictions with both choices of the central scale. In the M_{jj} bins below 4.8 TeV, the two NNLO NNPDF3.1 predictions disagree by an amount larger than the uncertainty in the prediction with the central scale $\mu_F = \mu_R = M_{jj}$. We observe a small tension between the data and the NNLO predictions when considering only the six variations of scales around their central value, but not when using the alternative scale choice of $\langle p_T \rangle$. An alternative prediction using the CT14 PDF set at NNLO shows negligible differences with respect to the default prediction using NNPDF3.1, demonstrating the insensitivity of the observable to the choice of PDF. For reference, we also show the NLO prediction with the CT14 PDFs and $\langle p_T \rangle$ scale used in the previous publication [22], which also agrees well with the default prediction.

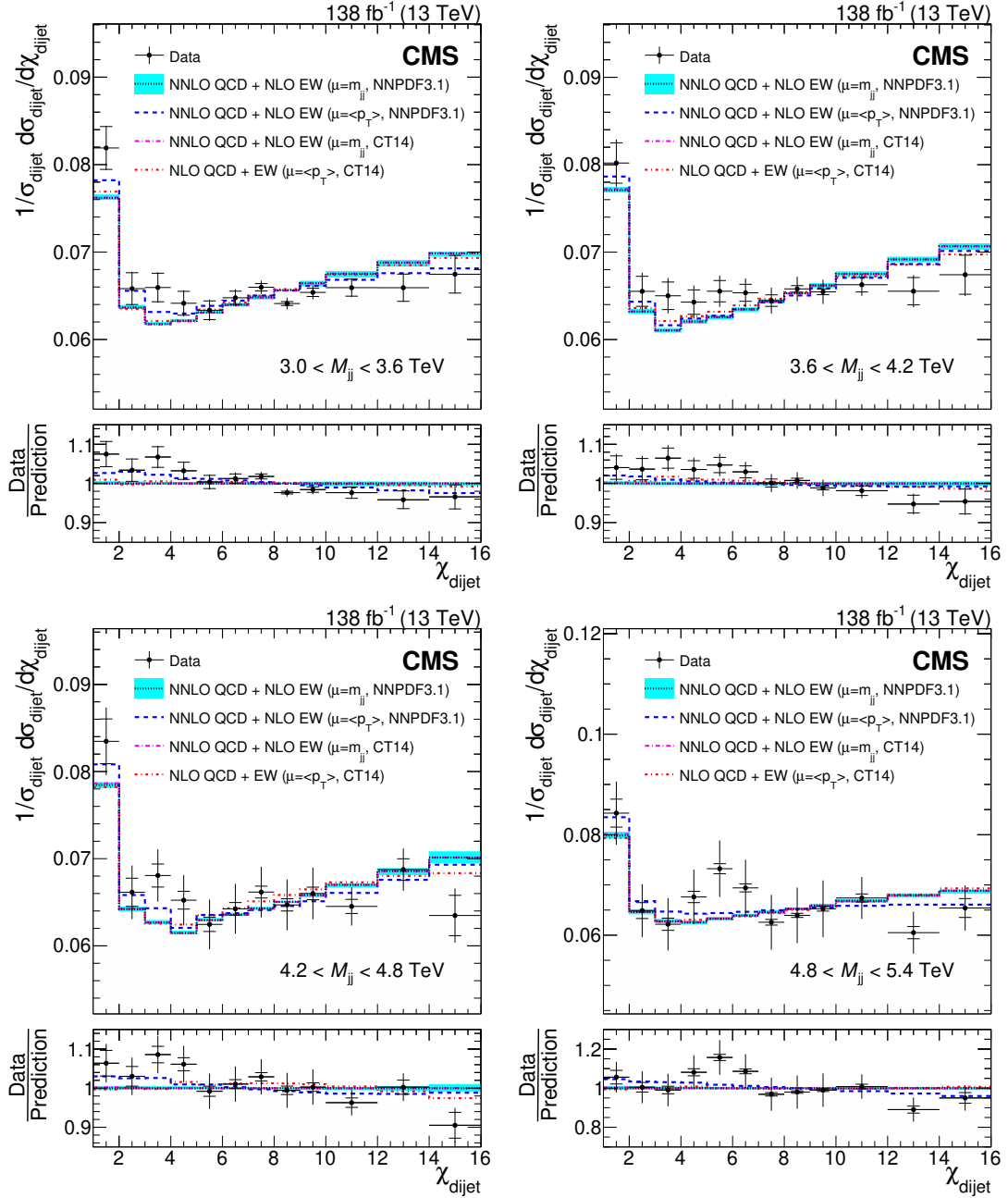


Figure 6: Normalized χ_{dijet} distributions from data (points) corrected for detector effects for four different ranges of M_{jj} . The inner vertical bars on the points correspond to the systematic uncertainties in the data, and the outer ones to the total uncertainties. The horizontal bars give the bin widths. Theoretical NNLO QCD + NLO EW predictions are shown for central scale choices $\mu_F = \mu_R = M_{\text{jj}}$ (black dotted line) and $\mu_F = \mu_R = \langle p_T \rangle$ (blue dashed line), both using the NNPDF3.1 PDF set. Prediction using the alternative CT14 PDF set (purple long-dashed-dotted line), and the NLO predictions from a previous CMS publication [22] (red short-dashed-dotted lines) are also plotted. Theoretical uncertainties with the central scale $\mu_F = \mu_R = M_{\text{jj}}$ and using NNPDF3.1 are indicated with the gray bands. The lower plots display the ratio of the data to the NNLO QCD + NLO EW predictions.

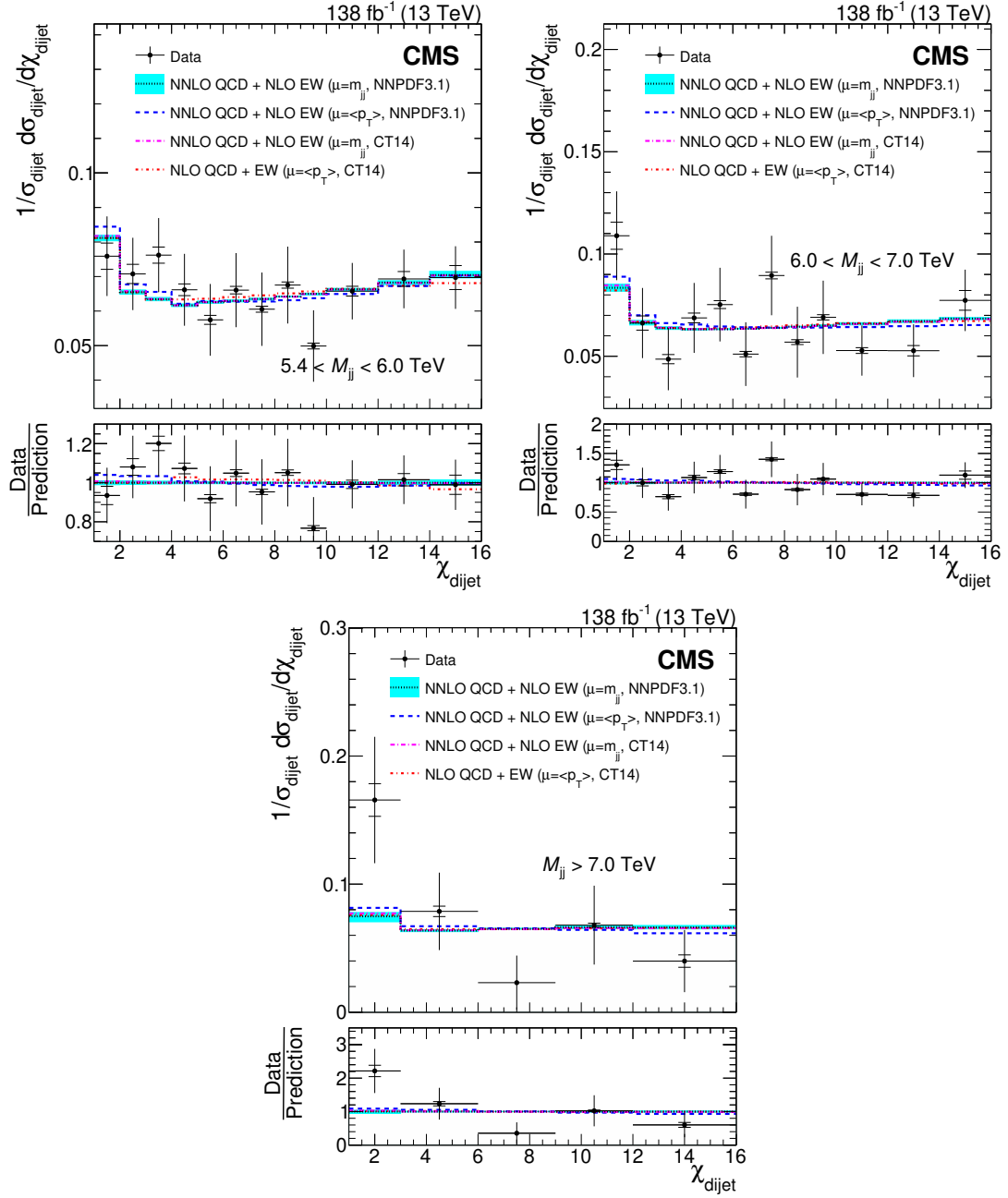


Figure 7: Normalized χ_{dijet} distributions corrected for detector effects for three different ranges of M_{jj} . Notations as in Fig. 6.

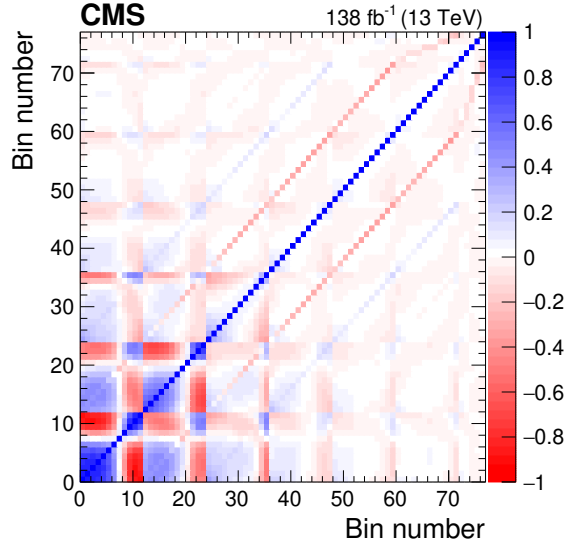


Figure 8: The correlation matrix of the maximum likelihood estimators of the signal strength modifiers. The matrix is obtained after the fit to data. The bin numbers correspond to 11 times the index (starting at 0) of the M_{jj} bin (3.0, 3.6, 4.2, 4.8, 5.4, 6.0, 7.0) GeV plus the index (starting at 0) of the χ_{dijet} bin (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14).

9 Summary

Normalized dijet angular distributions have been measured with the CMS detector over a wide range of dijet invariant masses, using proton-proton collisions at the LHC, corresponding to an integrated luminosity of 138 fb^{-1} . For the first time, the dijet angular distributions corrected for detector effects have been compared with predictions of perturbative quantum chromodynamics at next-to-next-to-leading order. Predictions assuming two different choices for the factorization and renormalization scales, $\mu_F = \mu_R = M_{jj}$ or $\langle p_T \rangle$, are found to differ by more than the six variations of scales commonly used to quantify the uncertainty in the predictions. While data are generally found to be in agreement with the standard model predictions, a small difference in the shape of the normalized distributions is seen for dijet masses below 4.8 TeV and above 6.0 TeV.

The distributions are used to set lower limits on beyond the standard model theories, including quark contact interaction models with next-to-leading-order quantum chromodynamic corrections, extra dimension models, quantum black hole production, dark-matter mediators, axion-like particles, and standard model effective field theory. The most stringent lower limits to date are set on the scale of graviton exchange. In the Giudice–Rattazzi–Wells convention, virtual graviton exchange is excluded up to a scale of 13.4 TeV at 95% confidence level (CL). The production of quantum black holes is excluded for masses below 8.5 and 6.3 TeV at 95% CL, depending on the scenario.

Limits for different contact interaction models are obtained. In the benchmark scenario, valid to next-to-leading order in quantum chromodynamics and in which only left-handed quarks participate, quark contact interactions are excluded to a scale of 17 (37) TeV at 95% CL for destructive (constructive) interference. Mediators in a simplified model of interactions between quarks and dark matter with masses between 4 and 6.2 TeV are excluded at 95% CL for vector and axial-vector mediators. The ratio of the gluon operator coefficient c_g to the characteristic high-energy scale f_a , c_g/f_a , is determined to have a 95% CL upper limit of 0.42 TeV^{-1} . The

anomalous triple-gluon coupling, C_G/Λ^2 , in a standard model effective field theory is constrained to be lower than 0.0076 TeV^{-2} at 95% CL.

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Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

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












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






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

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








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












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





















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




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














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





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





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























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












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






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




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

















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






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








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


















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







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


















M. Felcini , M. Grunewald 

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy





M. Abbrescia^{a,b} , M. Barbieri^{a,b}, M. Buonsante^{a,b} , A. Colaleo^{a,b} , D. Creanza^{a,c} , N. De Filippis^{a,c} , M. De Palma^{a,b} , W. Elmetenawee^{a,b,44} , N. Ferrara^{a,c} , L. Fiore^a , L. Generoso^{a,b}, L. Longo^a , M. Louka^{a,b} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^a , V. Mastrapasqua^{a,b} , S. My^{a,b} , F. Nenna^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} , F.M. Procacci^{a,b} , G. Pugliese^{a,c} , R. Radogna^{a,b} , D. Ramos^a 

A. Ranieri^a , L. Silvestris^a , F.M. Simone^{a,c} , Ü. Sözbilir^a , A. Stamerra^{a,b} ,
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














INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , P. Capiluppi^{a,b} , F.R. Cavallo^a ,
M. Cruciani^{a,b}, G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} ,
R. Farinelli^a , D. Fasanella^a , L. Ferragina^{a,b} , P. Giacomelli^a , C. Grandi^a ,
L. Guiducci^{a,b} , S. Lo Meo^{a,45} , M. Lorusso^{a,b} , L. Lunerti^a , S. Marcellini^a ,
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



INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

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

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

J. Altork^{a,b} , P. Assiouras^a , G. Barbagli^a , G. Bardelli^a , M. Bartolini^{a,b} ,
A. Calandri^{a,b} , B. Camaiani^{a,b} , A. Cassese^a , R. Ceccarelli^a , V. Ciulli^{a,b} ,
C. Civinini^a , R. D'Alessandro^{a,b} , L. Damenti^{a,b}, E. Focardi^{a,b} , T. Kello^a ,
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


















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L. Benussi , S. Colafranceschi⁴⁷ , S. Meola⁴⁸ , D. Piccolo 





INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy

M. Alves Gallo Pereira^a , F. Ferro^a , E. Robutti^a , S. Tosi^{a,b} 





















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A. Benaglia^a , F. Brivio^a , V. Camagni^{a,b} , F. Cetorelli^{a,b} , F. De Guio^{a,b} ,
M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , R. Gerosa^{a,b} , A. Ghezzi^{a,b} , P. Govoni^{a,b} ,
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









INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Scuola Superiore Meridionale (SSM)^d, Napoli, Italy

S. Buontempo^a , F. Confortini^{a,b} , C. Di Fraia^{a,b} , F. Fabozzi^{a,c} , L. Favilla^{a,d} ,
A.O.M. Iorio^{a,b} , L. Lista^{a,b,49} , P. Paolucci^{a,27} , B. Rossi^a 

INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università degli Studi di Cagliari^c, Cagliari, Italy









P. Azzi^a , N. Bacchetta^{a,50} , M. Biasotto^{a,51} , D. Bisello^{a,b} , L. Borella^a, P. Bortignon^{a,c} ,
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A.T. Meneguzzo^{a,b} , M. Missiroli^a , J. Pazzini^{a,b} , F. Primavera^{a,b} , P. Ronchese^{a,b} ,
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





































C. Aimè^a , A. Braghieri^a , M. Brunoldi^{a,b} , S. Calzaferri^{a,b} , P. Montagna^{a,b} ,
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INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy



























S. Ajmal^{a,b} , M.E. Ascioti^{a,b}, G.M. Bilei^{†a} , C. Carrivale^{a,b}, D. Ciangottini^{a,b} 

L. Della Penna^{a,b}, L. Fanò^{a,b} , V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,53} ,
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








































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



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






Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea






























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





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













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





























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










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














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
















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

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


Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine

A. Boyaryntsev , O. Dadazhanova, B. Grynyov 






















National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk 


































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J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , D. Dharmender, H. Flacher , J. Goldstein , H.F. Heath , M.-L. Holmberg , A. Karakoulaki, L. Kreczko , S. Paramesvaran , L. Robertshaw , M.S. Sanjrani³⁹, J. Segal, V.J. Smith 




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




Imperial College, London, United Kingdom

I. Andreou , R. Bainbridge , P. Bloch , O. Buchmuller, C.A. Carrillo Montoya , D. Colling , I. Das , P. Dauncey , G. Davies , M. Della Negra , S. Fayer, G. Fedi , G. Hall , H.R. Hoorani , A. Howard, G. Iles , C.R. Knight , P. Krueper , J. Langford , K.H. Law , L. Lyons , A.-M. Magnan , B. Maier , S. Mallios , A. Mastronikolis , M. Mieskolainen , J. Nash⁷⁸ , M. Pesaresi , P.B. Pradeep , B.C. Radburn-Smith , A. Richards, A. Rose , T.B. Runting , L. Russell , K. Savva , R. Schmitz , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , T. Virdee²⁷ , N. Wardle , D. Winterbottom , J. Xiao


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






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







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J.M. Hogan 









Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , S. Raj , B. Sahu , A.E. Simsek , B. Singhal , S.S. Yu 









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B. Bam , A. Buchot Perraguin , S. Campbell, R. Chudasama , S.I. Cooper , C. Crovella , G. Fidalgo , S.V. Gleyzer , C. Isik , R. Kaur , A. Khukhunaishvili , K. Matchev , E. Pearson, P. Rumerio⁷⁹ , E. Usai , R. Yi









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S. Cholak , G. De Castro, Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , J. Fulcher , J. Garcia De Castro , F. Golf , S. Jeon , J. O’Cain, I. Reed , J. Rohlf , K. Salyer , D. Sperka , I. Suarez , A. Tsatsos , E. Wurtz, A.G. Zecchinelli







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


K. Adamidis, H. Ancelin, M. Bachtis , D. Campos, R. Cousins , S. Crossley , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , Y.f. Lo , E. Manca , A. Nunez Del Prado , D. Saltzberg , V. Valuev

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













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
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A. Albert , S. Bhattacharya , A. Bornheim , O. Cerri, Z. Hao , R. Kansal , L. Mori, H.B. Newman , G. Reales Gutiérrez, T. Sievert, P. Simmerling , M. Spiropulu , C. Sun , J.R. Vlimant , R.A. Wynne , S. Xie , R.Y. Zhu 





















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J. Alison , S. An , M. Cremonesi, V. Dutta , E.Y. Ertorer , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, M. Kanemura, A. Khanal, C. Liu , M. Marchegiani , P. Meiring , S. Murthy , P. Palit , K. Park , M. Paulini , A. Roberts , A. Sanchez , Y. Zhou 






























































University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , J. Fraticelli , A. Hart , M. Herrmann, S. Kwan , J. Pearkes , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 



















Cornell University, Ithaca, New York, USA

J. Alexander , X. Chen , J. Dickinson , A. Duquette, J. Fan , X. Fan , J. Grassi , P. Kotamnives , K. Krzyzanska , J. Monroy , G. Niendorf , M. Oshiro , J.R. Patterson , A. Ryd , J. Thom , H.A. Weber , B. Weiss , P. Wittich , Y. Wu , R. Zou , L. Zygala 












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



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C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , M. Dittrich, R.D. Field, C. Huh , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , V. Sulimov , Y. Takahashi , J. Wang 

























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T. Adams , A. Al Kadhim , A. Askew , S. Bower , R. Goff, R. Hashmi , A. Hassani , T. Kolberg , G. Martinez , M. Mazza , H. Prosper , P.R. Prova, R. Yohay 










Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani , S. Das , S. Demarest, L. Hasa , M. Hohlmann , M. Lavinsky, E. Yanes










University of Illinois Chicago, Chicago, Illinois, USA

M.R. Adams , N. Barnett, A. Baty , C. Bennett , N. Brandman-hughes, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , H. Gupta , M. Hawksworth , A. Hingrajiya, D.J. Hofman , Z. Huang , J.h. Lee , C. Mills , S. Nanda , G. Nigmatkulov , B. Ozek , V. Pant, T. Phan, D. Pilipovic , R. Pradhan , E. Prifti, P. Roy, T. Roy , D. Shekar, N. Singh, F. Strug, A. Thielen, M.B. Tonjes , N. Varelas , M.A. Wadud , A. Wang , J. Yoo 
























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
Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , J. Davis , A.V. Gritsan , Z. Huang , L. Kang , S. Kyriacou , P. Maksimovic , N. Pinto , M. Roguljic , S. Sekhar , M.V. Srivastav , M. Swartz 
















The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , R. Bhattacharya , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , S. Popescu⁸⁸ , C. Rogan , C. Royon , S. Rudrabhatla , S. Sanders , C. Smith , G. Wilson 



































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A. Ahmad, B. Allmond , N. Islam, A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , G.G. Reddy , D. Roy , G. Sorrentino 











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A. Baden , A. Belloni , J. Bistany-riebman, S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim, S. Lascio , J. Lee, P. Major , A.C. Mignerey , C. Palmer , C. Papageorgakis , M.M. Paranjpe, E. Popova⁸⁹ , A. Shevelev , L. Zhang 














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A. Alpana , B. Crossman , W.J. Jackson, C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi , R. Rusack , O. Sancar , R. Saradhy , N. Strobbe 





















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K. Bloom , D.R. Claes , S.V. Dixit , G. Haza , J. Hossain , C. Joo , I. Kravchenko , K.H.M. Kwok , Y. Mehra, J. Morris , A. Rohilla , J.E. Siado , A. Vagnerini , A. Wightman 










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























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A. Aarif , G. Alverson , E. Barberis , S. Bein , J. Bonilla , B. Bylsma, M. Campana , R. Clark, J. Dervan , Y. Haddad , Y. Han , I. Israr , A. Krishna , M. Lu , N. Manganeli , R. Mccarthy , D.M. Morse , T. Orimoto , L. Skinnari , C.S. Thoreson , E. Tsai , D. Wood 








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S. Dittmer , K.A. Hahn , S. King, M. Mcginnis , Y. Miao , D.G. Monk , M.H. Schmitt , A. Taliercio , M. Velasco , J. Wang 
















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
















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














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S. Chandra , A. Gu , L. Gutay, M. Huwiler , M. Jones , A.W. Jung , I.G. Karslioglu , D. Kondratyev , J. Li , M. Liu , M. Macedo , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , N.R. Saha , J.F. Schulte , F. Wang , A.L. Wesolek, A. Wildridge , W. Xie , Y. Yao , Y. Zhong 












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





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






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





























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




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