Published for SISSA by Springer

Received: October 15, 2022
Accepted: January 30, 2023
Published: July 17, 2023

Azimuthal anisotropy of dijet events in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

Abstract: The path-length dependent parton energy loss within the dense partonic medium created in lead-lead collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is studied by determining the azimuthal anisotropies for dijets with high transverse momentum. The data were collected by the CMS experiment in 2018 and correspond to an integrated luminosity of $1.69\,\mathrm{nb}^{-1}$. For events containing back-to-back jets, correlations in relative azimuthal angle and pseudorapidity (η) between jets and hadrons, and between two hadrons, are constructed. The anisotropies are expressed as the Fourier expansion coefficients v_n, $n = 2$–4 of these azimuthal distributions. The dijet v_n values are extracted from long-range ($1.5 < |\Delta\eta| < 2.5$) components of these correlations, which suppresses the background contributions from jet fragmentation processes. Positive dijet v_2 values are observed which increase from central to more peripheral events, while the v_3 and v_4 values are consistent with zero within experimental uncertainties.

Keywords: Hadron-Hadron Scattering, Heavy-Ion Collision, Jets, Particle Correlations and Fluctuations

ArXiv ePrint: 2210.08325

https://doi.org/10.1007/JHEP07(2023)139

JHEP07(2023)139

Contents

1 Introduction

Hydrodynamic flow in relativistic heavy ion collisions is produced as initial-state geometry asymmetries transform into final-state momentum asymmetries. These asymmetries are commonly characterized by the Fourier expansion coefficients v_2, v_3, v_4, etc., of the particle azimuthal distributions. The anisotropic flow for hadrons in heavy ion collisions has been extensively studied at the BNL RHIC [1–14] and at the CERN LHC [15–29]. However, relatively few similar measurements have been done for jets [30–32]. Since partons fragmenting into high transverse momentum (p_{T}) jets are produced in hard processes, instead of emerging from the thermalized medium, they are not expected to "flow" in a hydrodynamic sense. However, the jet yields can exhibit correlations with the symmetry planes in an event since the evolving parton showers experience various in-medium path lengths or medium densities as they pass through the quark-gluon plasma [33–37]. The magnitude of these correlations depends on the details of the path-length dependent energy loss [36]. In particular, the jets coplanar with the second-order symmetry plane, also known as the "event plane", are expected to suffer less energy loss, leading to a measurable v_2 signal. Indeed, azimuthal anisotropies of high p_{T} hadrons up to ∼100 GeV have been observed [24, 28], suggesting a path-length dependence of the parton energy loss. Performing dedicated jet azimuthal anisotropy measurements can greatly increase the accessible p_{T} range and give better estimates of the initial parton kinematics. The ATLAS and ALICE Collaborations have published inclusive jet v_2 results using data for lead-lead

(PbPb) collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{_{NN}}} = 2.76$ TeV [30, 31]. The ATLAS collaboration subsequently extended this measurement to higher v_n harmonics at $\sqrt{s_{_{NN}}} = 5.02$ TeV [32]. The higher v_n harmonics for jets arise from fluctuations of initial-state geometry or medium density. These studies find significant positive and centrality-dependent v_2 values for inclusive jets. The ATLAS study [32] also finds positive and mostly centrality-independent v_3 values for inclusive jets, while the v_4 coefficients are consistent with zero.

In this paper, we measure jet v_2, v_3, and v_4 coefficients in events containing back-to-back high-p_T jets, denoted as dijet v_n coefficients, via jet-hadron correlations. Data for lead-lead collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV with a total integrated luminosity of 1.69 nb^{-1} [38, 39] were collected by the CMS experiment in 2018. In contrast to previous jet v_n measurements that determine the inclusive jet v_n by the jet azimuthal correlation with the direction of maximum particle density [30–32], here the dijet v_n is determined from jet-hadron and hadron-hadron (hereafter referred to as "dihadron") correlations. The methodology developed for this work focuses on addressing the issue of nonflow contributions affecting the extracted harmonic coefficients. These nonflow correlations are a particular problem for high-energy jets for which, as a consequence of momentum conservation, there is a nearly back-to-back counterpart in azimuth. The "away-side" jet fragmentation products are known to significantly contribute to the flow-like correlations. For jet-hadron correlations, these contributions from jet fragmentation are addressed taking advantage of the properties of the dijet system, and for dihadron correlations they are mitigated with a hadron p_T cut. Then, a Fourier analysis is performed on large relative pseudorapidity $\Delta\eta$ ("long range") components of jet-hadron and dihadron correlations. To separate the jet and hadron v_n signals and extract the dijet v_n values, it is assumed that the measured jet-hadron and dihadron correlations factorize, i.e., they can be expressed as products of the jet and hadron v_n or the product of two hadron v_n values, respectively [22]. This work extends the suite of experimental methods and measurements that address details of the dependence of parton energy loss on in-medium path length and medium density fluctuations. Tabulated results are provided in the HEPData record for this analysis [40].

2 The CMS experiment

The central feature of the CMS apparatus 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, and a brass and scintillator hadron calorimeter, each composed of barrel and two endcap sections. The CMS silicon tracker measures charged-particle tracks within $|\eta| < 2.5$. It consists of 1856 silicon pixel and 15 148 silicon strip detector modules. Two hadron forward (HF) steel and quartz-fiber calorimeters complement the barrel and endcap detectors, extending the calorimeter from the range $|\eta| < 3.0$ provided by the barrel and endcap out to $|\eta| < 5.2$. The HF calorimeters are subdivided in azimuth (φ) into 20° modular wedges and further segmented to form 0.175×0.175 ($\Delta\eta\times\Delta\varphi$) "towers". Muons are measured in the range $|\eta| < 2.4$, with detection planes located outside of the solenoid core made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [41].

A particle-flow algorithm [42] using an optimized combination of information from various elements of the CMS detector is used to reconstruct leptons, photons, and charged and neutral hadrons. These are collectively referred to as particle-flow candidates. The sum of the transverse energies detected in the HF detectors ($3.0 < |\eta| < 5.2$) is used to define the event centrality [43] in terms of percentiles of the total inelastic hadronic cross section, with 0% corresponding to the largest overlap of the colliding nuclei.

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz [44]. The second level, known as the high-level trigger, 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 around 1 kHz before data storage [45].

3 Event selection

The events are selected using a high-level trigger that requires at least one calorimeter-based jet with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$. These jets are reconstructed using the anti-k_{T} jet clustering algorithm with a distance parameter of $R = 0.4$ [46]. The underlying event contribution is subtracted from the jets using an iterative method [47] before the jet p_{T} is compared to the threshold. A minimum bias triggered sample is also used in the analysis as a control sample. For the minimum bias trigger, we require that on each side of the interaction point there is at least one HF tower above the readout threshold in the range of ∼6–12 GeV [45].

To reduce contamination from beam-gas collisions, vertex and noise filters are applied following the example of previous analyses [48]. We require that there are at least three HF towers on each side of the detector with an energy deposit of at least 3 GeV per tower. The primary vertex is required to have at least two tracks and to be reconstructed within 15 cm of the nominal interaction point in the beam direction (z) and within 2 cm in the transverse direction. The shapes of the clusters in the pixel detector are required to be compatible with those expected in a PbPb collision at the vertex location. Finally, we require that there are no anomalous signal shapes or spatial distributions in the hadronic barrel and endcap calorimeter readout [49].

Simulated event samples are used in the analysis to correct for biases in the jet reconstruction resulting from the underlying flow modulation and to correct for jet resolution effects. These samples are produced by embedding hard jet events generated with the PYTHIA 8.226 event generator [50] with tune CP5 [51] in soft underlying events (i.e., particles created from the bulk medium) simulated with the HYDJET 1.9 event generator [52]. This is denoted as the PYTHIA+HYDJET sample. The CMS detector response is simulated using the GEANT4 toolkit [53].

Because of the large number of elementary nucleon-nucleon collisions in central PbPb events, these events are more likely to produce jets compared to peripheral events with fewer collisions. This is taken into account in the PYTHIA+HYDJET simulation by applying a multiplicity-based weight for each event such that the charged-particle multiplicity distribution in the analysis region $|\eta| < 2.4$ matches the measured distribution. An additional reweighting procedure is performed to match the position distribution of the primary vertices in the beam direction in simulation and data.

To identify high-p_T dijet events, the two jets with highest p_T in the range of $|\eta| < 2$ are located. The highest p_T jet is called the "leading jet" and is required to pass the p_T selection of $p_{T,1} > 120\,\text{GeV}$. The second-highest p_T jet is referred to as the "subleading jet" and is required to have $p_{T,2} > 50\,\text{GeV}$. The azimuthal angle φ between the leading and subleading jets is required to be $|\Delta\varphi_{1,2}| > 5\pi/6$, ensuring that the two jets are back-to-back. Finally, both jets are required to fall within a tighter range of $|\eta| < 1.3$ to ensure the most stable jet reconstruction performance and to allow for full tracker acceptance on both sides of the jets. The events containing such pairs of back-to-back jets are referred as "dijet events".

4 Jet and track reconstruction

For this study, jets are reconstructed using the anti-k_T algorithm with a distance parameter $R = 0.4$, as implemented in the FastJet framework [54]. Only the calorimeter information is used as an input to the anti-k_T algorithm. The underlying event contribution is subtracted from the raw jet energy using an iterative "noise/pedestal" subtraction algorithm [47]. First, the mean energy $\langle E_T(\eta)\rangle$ and dispersion $\langle \sigma_T(\eta)\rangle$ for the calorimeter cells sharing the same η position is calculated. This determines the pedestal as a function of pseudorapidity $P(\eta) = \langle E_T(\eta)\rangle + \langle \sigma_T(\eta)\rangle$. Then, the pedestal values are subtracted from each calorimeter cell and jets for the next iteration step are clustered from the pedestal-subtracted calorimeter towers using the anti-k_T algorithm with $R = 0.3$. In the next iteration step, the pedestal functions are calculated again, but this time excluding all towers that are within $R = 0.5$ of any reconstructed jet with $p_T > 15\,\text{GeV}$. The updated pedestal functions give the final estimate of the underlying event background. This background estimate is subtracted from the $R = 0.4$ jets and the jet energy is further calibrated using jet energy corrections calculated as a function of p_T and η following the method described in ref. [55].

We have chosen to reconstruct jets using only calorimeter information because this minimizes a reconstruction bias caused by the hydrodynamic flow. This bias arises from the use of the φ-averaged event energy in the underlying event subtraction. However, flow modulations lead to higher underlying event occupancies in the direction of the event plane compared to the direction perpendicular to it. This artificially enhances the v_2-like signal in jet-hadron correlations, since jets coplanar with the event plane have increased probability to pass the analysis selections. The same is true for higher order event planes, but with smaller effects. As calorimeters generally require higher p_T particles to produce a signal as compared to the tracker, and hydrodynamic flow is more strongly experienced by lower p_T particles, using only calorimeter information to reconstruct jets reduces the size of this bias significantly. For example, in the PYTHIA+HYDJET simulation, for the 0–10%

JHEP07(2023)139

centrality bin, the size of this bias is $v_2^{\text{bias}} \approx 0.155$ when the jets are reconstructed from particle-flow candidates, with $v_2^{\text{bias}} \approx 0.079$ when only calorimeter information is used.

The track reconstruction used in PbPb collisions is described in ref. [56]. The charged-particle tracks used in this analysis are required to have at least 11 hits in the tracker layers and satisfy a stringent fit quality requirement, where the fit χ^2, divided by the product of the number of fit degrees of freedom and the number of tracker layers hit, is required to be less than 0.18. To decrease the likelihood of counting nonprimary charged particles originating from secondary decay products, it is required that the distance of closest approach of a charged-particle track to at least one primary vertex in the event divided by its uncertainty is less than 3. Furthermore, it is required that the relative p_{T} uncertainty for the tracks is less than 10%. Finally, in order to reduce the contribution of misreconstructed tracks with very high p_{T}, it is required that for tracks with $p_{\text{T}} > 20\,\text{GeV}$, there is an associated energy deposit in the calorimeters corresponding to at least half of the track momentum. Corrections for tracking efficiency, detector acceptance, and misreconstruction rate are obtained and applied following the procedures discussed in ref. [48].

5 Jet-hadron and dihadron angular correlations

Correlations between jets and charged particles are studied using two-dimensional distributions of the relative pseudorapidity $\Delta\eta$ and relative azimuth $\Delta\varphi$ of the charged particles with respect to the jet axis. These distributions are constructed by correlating each charged particle with leading and subleading jets, separately, and are normalized by the number of dijets. The analysis uses three charged particle p_{T} (p_{T}^{ch}) bins with bin borders 0.7, 1, 2 and 3 GeV, and three centrality intervals, 0–10, 10–30, and 30–50%. Since the majority of the measured charged particles are hadrons, the charged particles are often referred to as hadrons in this paper.

The raw correlations give the per-dijet normalized yield of leading jet-hadron or subleading jet-hadron pairs from the same event

$$S^{\text{raw}}(\Delta\eta, \Delta\varphi) = \frac{1}{N_{\text{dijet}}} \frac{\mathrm{d}^2 N^{\text{same}}}{\mathrm{d}\Delta\eta \mathrm{d}\Delta\varphi}, \tag{5.1}$$

where N_{dijet} is the number of dijets satisfying the selection criteria and N^{same} is the number of jet-hadron pairs. However, since the detector has limited acceptance in η, it is more likely to find jet-hadron pairs with small rather than large $\Delta\eta$ values. Thus, the raw correlation shapes have the charged-particle yield falling rapidly towards large $\Delta\eta$. Detector inefficiencies can also lead to nontrivial effects on the correlation distributions. A mixed-event method, where jets and hadrons from different events are paired, is used to correct for these effects [22, 57]. By construction, such mixed-event correlations have structures due to detector and acceptance effects, but contain no physics correlations. For the mixed events, we require the primary vertex positions along the beam axis to match within 0.5 cm and the centrality percentile to be within 0.5 percentage points of those for the original data events. The charged hadrons are selected from minimum bias events to minimize jet-induced bias and to adequately capture the long-range flow correlations of the underlying event. The mixed-event pair distribution is given by

$$ME(\Delta\eta,\Delta\varphi)=\frac{\mathrm{d}^2N^{\mathrm{mixed}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\varphi}. \tag{5.2}$$

The maximum of the mixed event distribution is found at $(0,0)$ since no pairs with $\Delta\eta = 0$ and $\Delta\varphi = 0$ are lost as a consequence of finite acceptance. Thus, the ratio $ME(0,0)/ME(\Delta\eta,\Delta\varphi)$ gives the normalized correction factor. Then, we construct the per-dijet associated charged-particle yield, corrected for acceptance effects, as

$$S(\Delta\eta,\Delta\varphi)=\frac{1}{N_{\mathrm{dijet}}}\frac{\mathrm{d}^2N}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\varphi}=\frac{ME(0,0)}{ME(\Delta\eta,\Delta\varphi)}S^{\mathrm{raw}}(\Delta\eta,\Delta\varphi). \tag{5.3}$$

In order to study the v_n components for the dijets, we need to separate the short-range correlations from the long-range correlations in the acceptance-corrected distribution. The short-range correlations from jet fragmentation manifest themselves as a Gaussian-like peak around $(\Delta\eta,\Delta\varphi) = (0,0)$ together with an elongated peak in $\Delta\eta$ around $\Delta\varphi = \pi$. These are removed from the distribution by imposing selections in $\Delta\eta$ and $\Delta\varphi$ as illustrated in figure 1. First, we project the $\Delta\varphi$ distributions corresponding to the range $1.5 < |\Delta\eta| < 2.5$ from both leading and subleading jet-hadron distributions. For these projections, the short-range correlation contribution to the near-side ($|\Delta\varphi| < \pi/2$) distributions is negligible, but the elongated jet peak is still present in the away-side ($|\Delta\varphi| > \pi/2$) distribution. However, in a statistical distribution, the leading and subleading jet peaks are separated by $\Delta\varphi = \pi$. It follows that for an unbiased long-range $\Delta\varphi$ distribution LR, we can write $\mathrm{LR}(\Delta\varphi_{\mathrm{leading}}) = \mathrm{LR}(\pi - \Delta\varphi_{\mathrm{subleading}})$. As the near sides of the long-range leading and subleading jet-hadron distributions have negligible bias coming from the jet peak, the long-range $\Delta\varphi$ distribution in the entire 2π range can be found by combining the near sides of these two distributions and shifting the subleading one by π.

Once the long-range jet-hadron correlation distributions are projected on $\Delta\varphi$, the Fourier coefficients are found by fitting the distribution with the function

$$f_{\mathrm{Fourier}}(\Delta\varphi)=A\left(1+\sum_{n=1}^{4}2V_{n\Delta}\cos(n\Delta\varphi)\right), \tag{5.4}$$

where A is an overall normalization factor and $V_{n\Delta}$ is the fitted Fourier component of order n. When we fit the jet-hadron distribution, the extracted $V_{n\Delta}$ components reflect both the dijet and the hadron v_n values.

To obtain the hadron v_n values, we also construct dihadron correlations from the same dijet events as the jet-hadron correlations. We select all charged hadrons in the analysis hadron p_{T} bins as trigger particles, and pair them with all other charged particles in the same p_{T} bin, referred to as the associated particles. We follow the same event mixing procedure to correct for the detector and acceptance effects as for the jet-hadron correlations. However, since dihadron correlations do not have jet information, the elongated jet peak cannot be removed from the away side of the correlation distribution. To mitigate the

JHEP07(2023)139

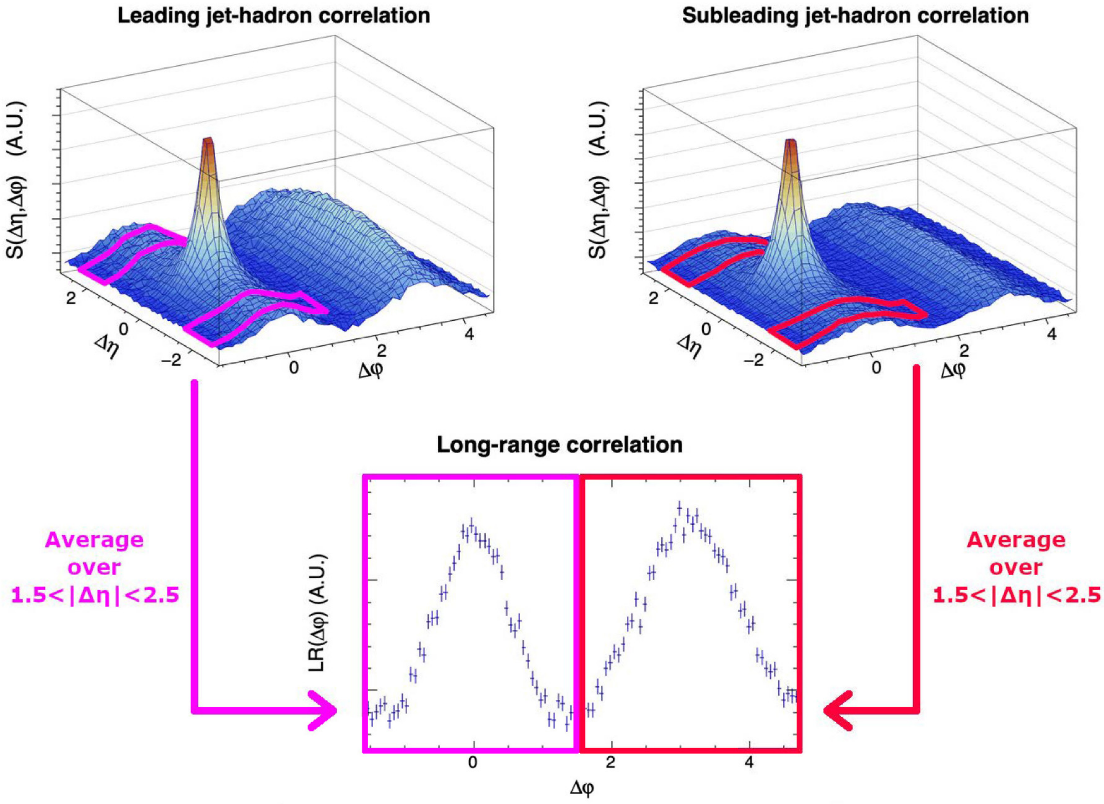

Figure 1. Illustration on how the long-range correlation distribution is constructed. The shape of the $\Delta\varphi$ projection corresponding to the range $1.5 < |\Delta\eta| < 2.5$ is determined from both leading and subleading jet-hadron correlation distributions for $|\Delta\varphi| < \pi/2$. The whole 2π range for the $\Delta\varphi$ distribution is obtained by combining these two components.

resulting background from high-p_{T} jet particles, we limit the hadron p_{T} selection with the highest $p_{\mathrm{T}}^{\mathrm{ch}}$ studied in the analysis to $2 < p_{\mathrm{T}}^{\mathrm{ch}} < 3\,\mathrm{GeV}$. One should notice that also for dihadron correlations, the dihadron $V_{n\Delta}$ values obtained from eq. (5.4) are a mixture of trigger hadron v_n and associated hadron v_n values.

It is argued in refs. [58, 59] that in the absence of nonflow correlations, the dihadron $V_{n\Delta}$ values factorize as

$$V_{n\Delta}^{\mathrm{dihadron}} = v_n^{\mathrm{trigger}} v_n^{\mathrm{associated}}, \tag{5.5}$$

where v_n^{trigger} is the v_n of the trigger hadron and $v_n^{\mathrm{associated}}$ is the v_n of the associated hadron. However, it is shown in ref. [27] that p_{T} dependent event plane angle fluctuations can break the factorization, even without nonflow contributions. The validity of the factorization assumption is tested in refs. [22, 60] and shown to work with good accuracy up to $p_{\mathrm{T}}^{\mathrm{associated}} \approx 4\,\mathrm{GeV}$. Above this p_{T} value, the factorization assumption starts to break down, primarily because of dijet fragmentation contributions. This is reflected in the upper hadron p_{T} limit in this analysis, as noted earlier. The jet-hadron correlation distributions are constructed in such a way that both the near- and the away-side dijet fragmentation contributions are explicitly removed. Thus, even though jets have very high p_{T} particles in them, the factorization is also expected to be a good approximation for the jet-hadron correlations.

Since the same momentum range for both trigger and associated hadrons is used for dihadron correlations, the hadron v_n can be extracted by taking the square root of the fitted dihadron $V_{n\Delta}$ values. By obtaining the hadron v_n in this way, we are able to calculate dijet v_n value using the factorization assumption:

$$v_n^{\text{dijet}} = \frac{V_{n\Delta}^{\text{jet-hadron}}}{v_n^{\text{hadron}}}. \tag{5.6}$$

Each hadron p_{T} bin gives us a data point for the dijet v_n in the corresponding centrality bin. Since the dijet v_n should not depend on the hadron p_{T} selection used to extract it, we merge all three analysis hadron p_{T} bins to get the dijet v_n value from one wide $0.7 < p_{\text{T}} < 3\,\text{GeV}$ bin. The validity of the factorization assumption in eq. (5.6) was tested using PYTHIA+HYDJET simulation where we introduced a certain dijet v_2 value at the generator level and were able to extract a consistent value following the analysis procedure.

The dijet v_n values still need to be corrected for the jet reconstruction bias. This is done by determining the dijet v_n values from PYTHIA+HYDJET simulations where jets are embedded isotropically in the azimuthally anisotropic HYDJET background. The dijet v_n values extracted from this simulation study are, therefore, solely a result of the jet reconstruction bias. To accurately estimate the absolute amount of energy that is added to or subtracted from the jets by the azimuthal anisotropies of the underlying event, both the hadron v_2 and the dihadron yields need to be matched simultaneously between data and simulation. This is obtained by tuning the simulation such that one of these quantities matches, and using a scaling factor for the extracted v_n^{bias} value to take the difference found for the other into account.

For the nominal strategy, we start by matching the dihadron yields. This is achieved to a good accuracy by the multiplicity-based weighting that is applied to the PYTHIA+HYDJET simulation, as explained in section 3. Then, we determine the hadron and dijet v_2 values from the simulation. An additional PYTHIA+HYDJET study showed that if the dihadron yield is kept constant and the hadron v_2 is varied by a certain percentage, the dijet v_2 value also changes by the same percentage. This means that the scaling factor for v_n^{bias} that accounts for the difference in the simulated and observed hadron v_2 can be directly obtained from the data-to-simulation hadron v_2 ratio. The jet reconstruction bias is then corrected by subtracting the scaled v_n^{bias} value obtained this way from the raw data dijet v_n value.

The second strategy used to evaluate systematic uncertainties matches the hadron v_2, and then applies a scaling factor to take into account the differences in dihadron yields. As a starting point for this strategy, we use a PYTHIA+HYDJET simulation, where instead of using the nominal multiplicity-based weighting to take into account the larger number of nucleon-nucleon collisions in central events, we use a centrality-based weighting scheme. In this scheme, we weight the centrality distribution determined from the HF calorimeters to match between data and simulation. Then, we check the underlying event energy density in

JHEP07(2023)139

random cones to see which centrality range in the simulation corresponds to similar energy densities in the data. The best match is found when the nominal centrality definition in the simulation is shifted 4 percentage points upwards. In this case, for example, the 0–10% centrality bin in data is matched with the 4–14% centrality bin in the PYTHIA+HYDJET simulation. After the centrality distributions are matched, we apply an event shape engineering method presented in ref. [61] to match the hadron v_2 between simulation and data. It is shown in ref. [61] that the elliptic flow and the magnitude of the second-order flow vector Q_2 normalized by the square root of event multiplicity are correlated. Thus, a selection based on this variable in the PYTHIA+HYDJET simulation event-by-event can be done to control the extracted hadron v_2 value. The Q_2-vector magnitude is defined as

$$Q_2 = \sqrt{Q_x^2 + Q_y^2}, \tag{5.7}$$

where

$$Q_x = \sum_i \cos(2\varphi_i), \; Q_y = \sum_i \sin(2\varphi_i). \tag{5.8}$$

Only particles from the HYDJET part of the simulation in $|\eta| < 0.75$ and $p_{\mathrm{T}} < 3\,\mathrm{GeV}$ are used. Using a Q_2-vector selection where hadron v_2 values in data and simulation match, the dijet v_n values are determined from the PYTHIA+HYDJET simulation. We have found in the previously described additional PYTHIA+HYDJET study that when hadron v_2 is kept the same, changing multiplicity does not affect the dijet v_2 linearly. Instead, we found a multiplicity-dependent function which allows us to calculate different scaling factors for each centrality bin. Thus, the dijet v_n^{bias} values obtained after applying the Q_2-vector selection need to be scaled by the ratio of dihadron yields in data and simulation times this centrality dependent scaling factor. As before, the obtained dijet v_n^{bias} values are subtracted from the raw data dijet v_n values to get the final corrected dijet v_n results.

6 Systematic uncertainties

The following sources of systematic uncertainty are considered in this analysis:

- *Acceptance correction.* Since jet correlations are small-angle correlations, and long-range correlations only depend on $\Delta\varphi$, the $\Delta\eta$ distribution at $|\eta| > 1.5$ should be uniform. To evaluate possible deviations from the uniformity that might arise from an imperfect acceptance correction, the analysis is repeated, extracting the long-range correlation distribution only from the negative ($-2.5 < \Delta\eta < -1.5$) or positive ($1.5 < \Delta\eta < 2.5$) sides of $\Delta\eta$. The larger difference from the nominal result is assigned as a systematic uncertainty.

- *Long-range extraction.* Uncertainties resulting from the long-range correlation distribution are determined by projecting the $\Delta\varphi$ distributions from two parts of the extraction region, $1.5 < |\Delta\eta| < 2.0$ and $2.0 < |\Delta\eta| < 2.5$. The larger difference from the nominal result is assigned as a systematic uncertainty.

JHEP07(2023)139

- *Jet angular resolution.* The uncertainty in the jet angular resolution is estimated by determining the resolution in the PYTHIA+HYDJET simulation by comparing the η and φ values for jet axes before and after detector effects are considered. The nominal η and φ values for jet axes in data are then varied by Gaussian distributions with widths based on the resolutions found in the simulation. The difference in results with and without the additional Gaussian dispersion is taken as the uncertainty.

- *Dijet bias in dihadron correlations.* It is possible that the dijet selection changes the hadron v_n with respect to minimum bias events. To check for this effect, we repeat the dihadron correlation measurement using a minimum bias data sample, and use the difference from the nominal results as an uncertainty.

- *Jet energy scale.* The related uncertainties are estimated by varying the jet energy corrections within their uncertainties and seeing how these changes affect the final correlations. The jet energy correction procedure is detailed in ref. [55].

- *Jet energy resolution.* This uncertainty is estimated by comparing the nominal results with the ones obtained by adding a Gaussian spread to the nominal jet energies, as a function of jet p_{T}, such that the jet energy resolution estimated from the simulation is worsened by 20%. The value of 20% is determined by comparing dijet momentum balance $x_j = p_{\mathrm{T}}^{\mathrm{subleading}}/p_{\mathrm{T}}^{\mathrm{leading}}$ distributions in peripheral 50–70% and 70–90% bins between data and PYTHIA+HYDJET simulation. The jet energy resolution in the simulation is worsened by different amounts, and comparing the shapes of the resulting x_j distributions to data, it is seen that the maximal difference between jet energy resolutions in data and simulation is 20%.

- *Tracking efficiency.* The tracking-related uncertainties are estimated by repeating the analysis without any tracking corrections.

- *Jet reconstruction bias correction.* There are several sources of uncertainty related to the jet reconstruction bias correction. First, there is uncertainty on the dijet v_n values determined from the PYTHIA+HYDJET simulation. The dijet v_n values from the simulation in each centrality bin are extracted by performing a constant fit to the results from different hadron p_{T} bins up to $p_{\mathrm{T}}^{\mathrm{ch}} = 4\,\mathrm{GeV}$. The uncertainty of this fit is included in the uncertainty of the jet reconstruction bias correction.

  Second, we compare the dijet v_n results obtained using two different matching strategies between simulation and data to determine the correction. Both of these are described in detail in the end of section 5.

  Third, the quark/gluon jet fraction in the PYTHIA+HYDJET simulation can be different from data, affecting the jet reconstruction bias correction. The potential difference is estimated to be less than 25% using a template fit to the multiplicity distribution of particle-flow candidates within the jet cone in the data. Then, the uncertainty is estimated by varying the quark/gluon jet fraction in simulation by this amount.

v_n	Source	0–10%	10–30%	30–50%
v_2	Acceptance correction	0.002	$<$0.001	0.001
	Long-range extraction	0.003	0.003	0.002
	Jet angle resolution	$<$0.001	$<$0.001	0.001
	Jet reconstruction bias	0.008	0.003	0.006
	Dijet bias for dihadron	0.002	0.001	0.001
	Tracking	$<$0.001	0.001	$<$0.001
	Jet energy scale	0.002	0.001	0.002
	Jet energy resolution	0.004	0.003	0.002
	Total for v_2	0.010	0.005	0.007
v_3	Acceptance correction	$<$0.001	0.001	0.002
	Long-range extraction	0.002	0.001	0.006
	Jet angle resolution	0.001	0.001	0.001
	Jet reconstruction bias	0.005	0.016	0.016
	Dijet bias for dihadron	$<$0.001	0.001	0.001
	Tracking	$<$0.001	$<$0.001	0.001
	Jet energy scale	0.001	0.001	0.004
	Jet energy resolution	0.003	0.001	0.001
	Total for v_3	0.006	0.017	0.017
v_4	Acceptance correction	0.003	0.002	0.005
	Long-range extraction	0.003	0.003	0.001
	Jet angle resolution	0.001	$<$0.001	$<$0.001
	Jet reconstruction bias	0.018	0.016	0.026
	Dijet bias for dihadron	$<$0.001	$<$0.001	$<$0.001
	Tracking	$<$0.001	$<$0.001	0.002
	Jet energy scale	0.003	0.001	0.003
	Jet energy resolution	0.002	0.003	0.002
	Total for v_4	0.019	0.017	0.026

Table 1. The breakdown of different sources of systematic uncertainty for dijet v_n, separately for the three centrality bins considered in the analysis.

The total systematic uncertainties are obtained by adding all the individual components together in quadrature. The relative contributions from different sources are listed in table 1 for the different dijet v_n harmonics. It can be seen from this table that the dominant source of uncertainty in most of the analysis bins arises from jet reconstruction. The jet reconstruction bias uncertainty is generally larger for higher v_n harmonics. While the simulated sample size is the same, the higher v_n coefficients have smaller signal sizes. Thus, they cannot be determined as accurately as the v_2 values for the correction.

7 Results

The extracted dijet v_2, v_3, and v_4 values in different hadron p_T bins are presented in figure 2. All results shown in this figure are corrected for the jet reconstruction bias effects. Some dependence of the dijet v_n values on the reference particle p_T is observed, which is

JHEP07(2023)139

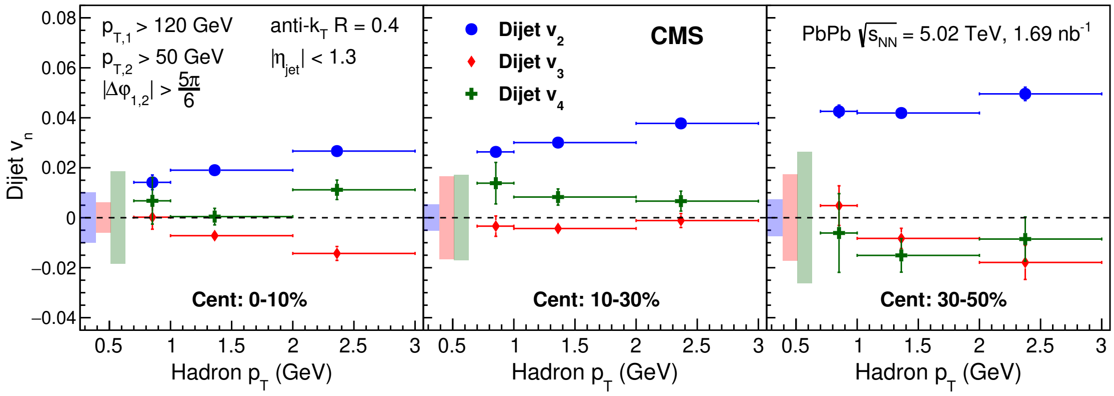

Figure 2. The dijet v_n data points factorized using different associated hadron p_T bins for 0–10% (left), 10–30% (middle), and 30–50% (right) centrality bins. The data points are corrected for the jet reconstruction bias effects. The vertical bars represent statistical uncertainties, while the p_T-independent systematic uncertainties are plotted as shaded areas on the left side of the panels.

consistent with the expectation of possible factorization breaking by residual back-to-back correlations.

The centrality dependence of the dijet v_n averaged over the reference particle p_T range of 0.7–3 GeV is presented in figure 3. The dijet v_2 measurements show positive values, indicating more jets observed coplanar with the event plane compared to the perpendicular direction. Since jets coplanar with event plane traverse less medium, these jets suffer less energy loss on average compared to those in the perpendicular direction. Thus, they are more likely to pass the analysis cuts, leading to the observed v_2 signal. The dijet v_2 magnitude is found to increase toward more peripheral collisions up to 30–50%, which is expected based on the increasing eccentricity of the collision overlap region. The current measurements are compared with previous CMS results on high-p_T hadron v_2 from ref. [28]. Since that earlier work used finer centrality bins, the high-p_T hadron v_2 values plotted in figure 3 are compiled by first combining the centrality bins to match the ones used in this analysis, weighting each centrality bin by the number of events. Then, all hadron v_2 points above 20 GeV are fitted with a constant to define a value corresponding to contributions from the jet fragmentation. We observe that the measured dijet v_2 values are consistent with the high-p_T hadron v_2 values within the uncertainties, and similar values are also observed by the ATLAS collaboration in ref. [32].

The dijet v_3 and v_4 results in the middle and right panels of figure 3 are found to be compatible with zero within experimental uncertainties in each centrality bin. Recent theory calculations for high-p_T hadrons [36] and $R = 0.2$ inclusive jets [37] predict jet v_3 values that are positive and less than 0.005 in magnitude. At this level, the precision of the current measurement is not sufficient to probe the impact of the fluctuations in the initial-state geometry and medium density on the dijet azimuthal distributions. The results for the dijet v_3 values are consistent with the CMS high-p_T hadron measurements in ref. [28], which are also compatible with zero. In contrast, the recent ATLAS results show positive inclusive jet v_3 for $R = 0.2$ jets above 71 GeV [32]. However, the ATLAS analysis is made with different selection criteria (lower jet p_T and smaller distance parameter) and

JHEP07(2023)139

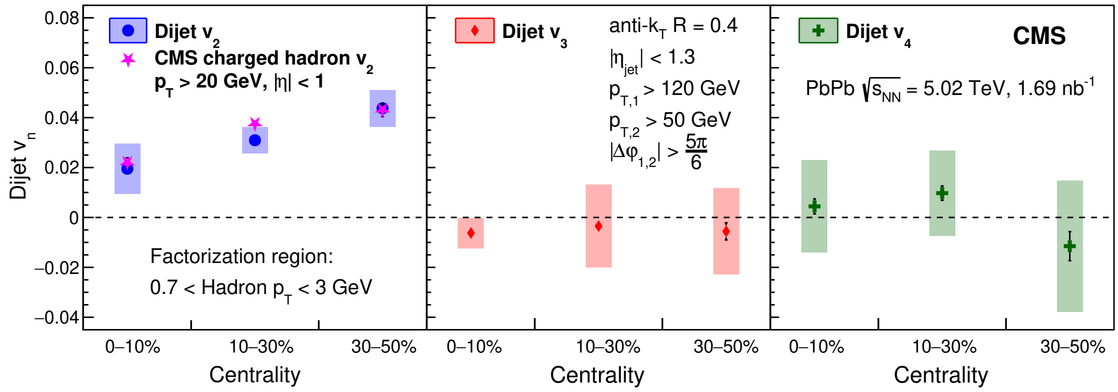

Figure 3. Dijet v_2 (left), v_3 (middle), and v_4 (right) results presented as functions of centrality. The dijet v_2 results are compared to CMS high-p_{T} hadron v_2 results from ref. [28]. The shaded areas represent systematic uncertainties and the vertical bars are the statistical uncertainties.

the ATLAS inclusive jet and CMS dijet populations are different, so the two results should not be directly compared.

8 Summary

The Fourier coefficients v_2, v_3, and v_4 are determined for jets from events containing back-to-back jets ("dijet v_n") in lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$. The jet-hadron correlation technique used for this measurement has been developed to unambiguously separate jet fragmentation-related contributions from the long-range correlations due to the in-medium path length and medium density dependencies of parton energy loss.

The dijet v_2 values are found to be positive, meaning that more jets are observed coplanar with the event plane than perpendicular to this plane. The dijet v_2 values increase with increasing eccentricity of the initial collision region, from about 2.0% in the 0–10% centrality bin to about 4.4% in the 30–50% centrality bin. These results are qualitatively consistent with expectations from a path-length dependence of in-medium energy loss. For all measured centrality bins, the dijet v_3 and v_4 values are consistent with zero within experimental uncertainties. However, the current results do not have the precision needed to probe the effects of the initial-state geometry and medium density fluctuations on the dijet azimuthal distributions. The measured dijet v_n values provide valuable input to a more precise and quantitative description of the partonic energy loss in the quark-gluon plasma.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy — EXC 2121 "Quantum Universe" — 390833306, and under project number 400140256 — GRK2497; the Hungarian Academy of Sciences, the New National Excellence Program — ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

JHEP07(2023)139

References

[1] PHOBOS collaboration, *Centrality and pseudorapidity dependence of elliptic flow for charged hadrons in Au+Au collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. C* **72** (2005) 051901 [nucl-ex/0407012] [INSPIRE].

[2] PHOBOS collaboration, *System size, energy, pseudorapidity, and centrality dependence of elliptic flow*, *Phys. Rev. Lett.* **98** (2007) 242302 [nucl-ex/0610037] [INSPIRE].

[3] PHOBOS collaboration, *Non-flow correlations and elliptic flow fluctuations in gold-gold collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. C* **81** (2010) 034915 [arXiv:1002.0534] [INSPIRE].

[4] PHENIX collaboration, *Elliptic flow of identified hadrons in Au+Au collisions at s(NN)**(1/2) = 200-GeV*, *Phys. Rev. Lett.* **91** (2003) 182301 [nucl-ex/0305013] [INSPIRE].

[5] PHENIX collaboration, *Scaling properties of azimuthal anisotropy in Au+Au and Cu+Cu collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. Lett.* **98** (2007) 162301 [nucl-ex/0608033] [INSPIRE].

[6] PHENIX collaboration, *Energy loss and flow of heavy quarks in Au+Au collisions at* $\sqrt{s_{NN}} = 200$*-GeV*, *Phys. Rev. Lett.* **98** (2007) 172301 [nucl-ex/0611018] [INSPIRE].

[7] PHENIX collaboration, *Measurements of directed, elliptic, and triangular flow in Cu+Au collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. C* **94** (2016) 054910 [arXiv:1509.07784] [INSPIRE].

[8] PHENIX collaboration, *Pseudorapidity Dependence of Particle Production and Elliptic Flow in Asymmetric Nuclear Collisions of p+Al, p+Au, d+Au, and* ^{3}*He+Au at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. Lett.* **121** (2018) 222301 [arXiv:1807.11928] [INSPIRE].

[9] STAR collaboration, *Elliptic flow in Au + Au collisions at* $\sqrt{s_{NN}} = 130$ *GeV*, *Phys. Rev. Lett.* **86** (2001) 402 [nucl-ex/0009011] [INSPIRE].

[10] STAR collaboration, *Elliptic flow from two and four particle correlations in Au+Au collisions at* $\sqrt{s_{NN}} = 130$*-GeV*, *Phys. Rev. C* **66** (2002) 034904 [nucl-ex/0206001] [INSPIRE].

[11] STAR collaboration, *Particle type dependence of azimuthal anisotropy and nuclear modification of particle production in Au + Au collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. Lett.* **92** (2004) 052302 [nucl-ex/0306007] [INSPIRE].

[12] STAR collaboration, *Azimuthal anisotropy in Au+Au collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. C* **72** (2005) 014904 [nucl-ex/0409033] [INSPIRE].

[13] STAR collaboration, *Elliptic flow of electrons from heavy-flavor hadron decays in Au + Au collisions at* $\sqrt{s_{\rm NN}} = 200$*, 62.4, and 39 GeV*, *Phys. Rev. C* **95** (2017) 034907 [arXiv:1405.6348] [INSPIRE].

[14] STAR collaboration, *Measurement of* D^0 *azimuthal anisotropy at midrapidity in Au+Au collisions at* $\sqrt{s_{NN}} = 200$ *GeV*, *Phys. Rev. Lett.* **118** (2017) 212301 [arXiv:1701.06060] [INSPIRE].

[15] ALICE collaboration, *Elliptic flow of charged particles in Pb-Pb collisions at* 2.76 *TeV*, *Phys. Rev. Lett.* **105** (2010) 252302 [arXiv:1011.3914] [INSPIRE].

JHEP07(2023)139

[16] ALICE collaboration, *Higher harmonic anisotropic flow measurements of charged particles in Pb-Pb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, *Phys. Rev. Lett.* **107** (2011) 032301 [arXiv:1105.3865] [INSPIRE].

[17] ALICE collaboration, *Elliptic flow of identified hadrons in Pb-Pb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, *JHEP* **06** (2015) 190 [arXiv:1405.4632] [INSPIRE].

[18] ALICE collaboration, *Anisotropic flow of charged particles in Pb-Pb collisions at* $\sqrt{s_{\rm NN}} = 5.02$ *TeV*, *Phys. Rev. Lett.* **116** (2016) 132302 [arXiv:1602.01119] [INSPIRE].

[19] ATLAS collaboration, *Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead-lead collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV with the ATLAS detector*, *Phys. Lett. B* **707** (2012) 330 [arXiv:1108.6018] [INSPIRE].

[20] ATLAS collaboration, *Measurement of the azimuthal anisotropy for charged particle production in* $\sqrt{s_{NN}} = 2.76$ *TeV lead-lead collisions with the ATLAS detector*, *Phys. Rev. C* **86** (2012) 014907 [arXiv:1203.3087] [INSPIRE].

[21] ATLAS collaboration, *Measurement of the distributions of event-by-event flow harmonics in lead-lead collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV with the ATLAS detector at the LHC*, *JHEP* **11** (2013) 183 [arXiv:1305.2942] [INSPIRE].

[22] CMS collaboration, *Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, *Eur. Phys. J. C* **72** (2012) 2012 [arXiv:1201.3158] [INSPIRE].

[23] CMS collaboration, *Measurement of the elliptic anisotropy of charged particles produced in PbPb collisions at* $\sqrt{s}_{NN} = 2.76$ *TeV*, *Phys. Rev. C* **87** (2013) 014902 [arXiv:1204.1409] [INSPIRE].

[24] CMS collaboration, *Azimuthal anisotropy of charged particles at high transverse momenta in PbPb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, *Phys. Rev. Lett.* **109** (2012) 022301 [arXiv:1204.1850] [INSPIRE].

[25] CMS collaboration, *Measurement of higher-order harmonic azimuthal anisotropy in PbPb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, *Phys. Rev. C* **89** (2014) 044906 [arXiv:1310.8651] [INSPIRE].

[26] CMS collaboration, *Studies of azimuthal dihadron correlations in ultra-central PbPb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, *JHEP* **02** (2014) 088 [arXiv:1312.1845] [INSPIRE].

[27] CMS collaboration, *Evidence for transverse momentum and pseudorapidity dependent event plane fluctuations in PbPb and pPb collisions*, *Phys. Rev. C* **92** (2015) 034911 [arXiv:1503.01692] [INSPIRE].

[28] CMS collaboration, *Azimuthal anisotropy of charged particles with transverse momentum up to 100 GeV/ c in PbPb collisions at* $\sqrt{s}_{NN} = 5.02$ *TeV*, *Phys. Lett. B* **776** (2018) 195 [arXiv:1702.00630] [INSPIRE].

[29] CMS collaboration, *Principal-component analysis of two-particle azimuthal correlations in PbPb and pPb collisions at CMS*, *Phys. Rev. C* **96** (2017) 064902 [arXiv:1708.07113] [INSPIRE].

[30] ATLAS collaboration, *Measurement of the azimuthal angle dependence of inclusive jet yields in Pb+Pb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV with the ATLAS detector*, *Phys. Rev. Lett.* **111** (2013) 152301 [arXiv:1306.6469] [INSPIRE].

[31] ALICE collaboration, *Azimuthal anisotropy of charged jet production in* $\sqrt{s_{\rm NN}} = 2.76$ *TeV Pb-Pb collisions*, *Phys. Lett. B* **753** (2016) 511 [arXiv:1509.07334] [INSPIRE].

[32] ATLAS collaboration, *Measurements of azimuthal anisotropies of jet production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector*, Phys. Rev. C **105** (2022) 064903 [arXiv:2111.06606] [INSPIRE].

[33] X.-N. Wang, *Jet quenching and azimuthal anisotropy of large p(T) spectra in noncentral high-energy heavy ion collisions*, Phys. Rev. C **63** (2001) 054902 [nucl-th/0009019] [INSPIRE].

[34] M. Gyulassy, I. Vitev and X.N. Wang, *High p_T azimuthal asymmetry in noncentral A+A at RHIC*, Phys. Rev. Lett. **86** (2001) 2537 [nucl-th/0012092] [INSPIRE].

[35] E.V. Shuryak, *The Azimuthal asymmetry at large p(t) seem to be too large for a 'jet quenching'*, Phys. Rev. C **66** (2002) 027902 [nucl-th/0112042] [INSPIRE].

[36] B. Betz et al., *Cumulants and nonlinear response of high p_T harmonic flow at $\sqrt{s_{NN}} = 5.02$ TeV*, Phys. Rev. C **95** (2017) 044901 [arXiv:1609.05171] [INSPIRE].

[37] Y. He et al., *Event-by-event jet anisotropy and hard-soft tomography of the quark-gluon plasma*, Phys. Rev. C **106** (2022) 044904 [arXiv:2201.08408] [INSPIRE].

[38] CMS collaboration, *CMS luminosity measurement using nucleus-nucleus collisions at $\sqrt{s_{NN}} = 5.02$ TeV in 2018*, CMS-PAS-LUM-18-001, CERN, Geneva (2022).

[39] CMS collaboration, *Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS*, Eur. Phys. J. C **81** (2021) 800 [arXiv:2104.01927] [INSPIRE].

[40] CMS collaboration, *Azimuthal anisotropy of dijet events in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV*, https://www.hepdata.net/record/ins2165916 [DOI:10.17182/HEPDATA.130961].

[41] CMS collaboration, *The CMS Experiment at the CERN LHC*, 2008 JINST **3** S08004 [INSPIRE].

[42] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, 2017 JINST **12** P10003 [arXiv:1706.04965] [INSPIRE].

[43] CMS collaboration, *Jet Momentum Dependence of Jet Quenching in PbPb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, Phys. Lett. B **712** (2012) 176 [arXiv:1202.5022] [INSPIRE].

[44] CMS collaboration, *Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV*, 2020 JINST **15** P10017 [arXiv:2006.10165] [INSPIRE].

[45] CMS collaboration, *The CMS trigger system*, 2017 JINST **12** P01020 [arXiv:1609.02366] [INSPIRE].

[46] M. Cacciari, G.P. Salam and G. Soyez, *The anti-k_t jet clustering algorithm*, JHEP **04** (2008) 063 [arXiv:0802.1189] [INSPIRE].

[47] O. Kodolova, I. Vardanyan, A. Nikitenko and A. Oulianov, *The performance of the jet identification and reconstruction in heavy ions collisions with CMS detector*, Eur. Phys. J. C **50** (2007) 117 [INSPIRE].

[48] CMS collaboration, *Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, JHEP **04** (2017) 039 [arXiv:1611.01664] [INSPIRE].

[49] CMS collaboration, *Identification and Filtering of Uncharacteristic Noise in the CMS Hadron Calorimeter*, 2010 JINST **5** T03014 [arXiv:0911.4881] [INSPIRE].

[50] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015) 159 [arXiv:1410.3012] [INSPIRE].

[51] CMS collaboration, *Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements*, Eur. Phys. J. C **80** (2020) 4 [arXiv:1903.12179] [INSPIRE].

JHEP07(2023)139

[52] I.P. Lokhtin et al., *Heavy ion event generator HYDJET++ (HYDrodynamics plus JETs)*, *Comput. Phys. Commun.* **180** (2009) 779 [arXiv:0809.2708] [INSPIRE].

[53] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [INSPIRE].

[54] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J. C* **72** (2012) 1896 [arXiv:1111.6097] [INSPIRE].

[55] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in pp collisions at* 8 *TeV*, 2017 *JINST* **12** P02014 [arXiv:1607.03663] [INSPIRE].

[56] CMS collaboration, *Description and performance of track and primary-vertex reconstruction with the CMS tracker*, 2014 *JINST* **9** P10009 [arXiv:1405.6569] [INSPIRE].

[57] CMS collaboration, *In-medium modification of dijets in PbPb collisions at* $\sqrt{s_{\mathrm{NN}}} = 5.02$ *TeV*, *JHEP* **05** (2021) 116 [arXiv:2101.04720] [INSPIRE].

[58] M. Luzum, *Collective flow and long-range correlations in relativistic heavy ion collisions*, *Phys. Lett. B* **696** (2011) 499 [arXiv:1011.5773] [INSPIRE].

[59] B.H. Alver, C. Gombeaud, M. Luzum and J.-Y. Ollitrault, *Triangular flow in hydrodynamics and transport theory*, *Phys. Rev. C* **82** (2010) 034913 [arXiv:1007.5469] [INSPIRE].

[60] ALICE collaboration, *Harmonic decomposition of two-particle angular correlations in Pb-Pb collisions at* $\sqrt{s_{NN}} = 2.76$ *TeV*, *Phys. Lett. B* **708** (2012) 249 [arXiv:1109.2501] [INSPIRE].

[61] J. Schukraft, A. Timmins and S.A. Voloshin, *Ultra-relativistic nuclear collisions: event shape engineering*, *Phys. Lett. B* **719** (2013) 394 [arXiv:1208.4563] [INSPIRE].

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, P.S. Hussain, M. Jeitler[2], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck[2], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish[3], T. Janssen, T. Kello[4], H. Rejeb Sfar, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols, J. D'Hondt, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux, G. De Lentdecker, L. Favart, D. Hohov, J. Jaramillo, K. Lee, M. Mahdavikhorrami, I. Makarenko, A. Malara, S. Paredes, L. Pétré, N. Postiau, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium

D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Rendón, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, N. Van Den Bossche, B. Vermassen, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

A. Benecke, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, A. Taliercio, T.T. Tran, P. Vischia, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, E. Coelho, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, J. Martins[7], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[8], A. Vilela Pereira

JHEP07(2023)139

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

S. Thakur

Beihang University, Beijing, China

T. Cheng, T. Javaid[9], M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China

M. Ahmad, G. Bauer[10], Z. Hu, S. Lezki, K. Yi[10,11]

Institute of High Energy Physics, Beijing, China

G.M. Chen[9], H.S. Chen[9], M. Chen[9], F. Iemmi, C.H. Jiang, A. Kapoor, H. Kou, H. Liao, Z.-A. Liu[12], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin, C. Li, Q. Li, X. Lyu, Y. Mao, S.J. Qian, X. Sun, D. Wang, J. Xiao, H. Yang

Sun Yat-Sen University, Guangzhou, China

M. Lu, Z. You

University of Science and Technology of China, Hefei, China

N. Lu

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

X. Gao[4], D. Leggat, H. Okawa, Y. Zhang

Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin, C. Lu, M. Xiao

JHEP07(2023)139

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, B.K. Chitroda, D. Ferencek, S. Mishra, M. Roguljic, A. Starodumov[13], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

Charles University, Prague, Czech Republic
M. Finger[13], M. Finger Jr.[13], A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
H. Abdalla[14], Y. Assran[15,16]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M. Abdullah Al-Mashad, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, P. Jarry, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[17], P. Simkina, M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, B. Diab, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[18], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
S. Beauceron, B. Blancon, G. Boudoul, A. Carle, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen[19], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, L. Torterotot, M. Vander Donckt, P. Verdier, S. Viret

Georgian Technical University, Tbilisi, Georgia
I. Bagaturia[20], I. Lomidze, Z. Tsamalaidze[13]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, M. Erdmann, P. Fackeldey, D. Fasanella, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, M.y. Lee, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, S. Mondal, S. Mukherjee, D. Noll, A. Novak, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, H. Reithler, A. Schmidt, S.C. Schuler, A. Sharma, A. Stein, L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[21], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

JHEP07(2023)139

Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, F. Blekman[22], K. Borras[23], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[22], A. Geiser, A. Giraldi, G. Greau, A. Grohsjean, V. Guglielmi, M. Guthoff, A. Jafari[24], N.Z. Jomhari, B. Kaech, M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[25], W. Lohmann[26], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, M. Mormile, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham[27,23], V. Scheurer, S. Schnake[23], P. Schütze, C. Schwanenberger[22], M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon[†], M. Van De Klundert, F. Vazzoler, A. Velyka, A. Ventura Barroso, R. Walsh, D. Walter, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[23], C. Wissing, S. Wuchterl, Y. Yang, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany

A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, M. Bonanomi, P. Connor, K. De Leo, M. Eich, K. El Morabit, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, M. Hajheidari, J. Haller, A. Hinzmann, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, A. Mehta, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, M. Rieger, O. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann[28], M. Horzela, U. Husemann, M. Klute, R. Koppenhöfer, A. Lintuluoto, S. Maier, S. Mitra, Th. Müller, M. Neukum, M. Oh, G. Quast, K. Rabbertz, J. Rauser, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

JHEP07(2023)139

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, M.M.A. Gadallah[29], S. Lökös[30], P. Major, K. Mandal, G. Pásztor, A.J. Rádl[31], O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[32], G. Bencze, C. Hajdu, D. Horvath[33,34], F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[32], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, B. Ujvari[35]

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[31], F. Nemes[31], T. Novak

Panjab University, Chandigarh, India
J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[36], R. Gupta, A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, P. Kumari, M. Meena, K. Sandeep, T. Sheokand, J.B. Singh[37], A. Singla, A. K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B.C. Choudhary, A. Kumar, M. Naimuddin, K. Ranjan, S. Saumya

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[38], S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[39], M. Maity[38], P. Palit, G. Saha, B. Sahu, S. Sarkar

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, J.R. Komaragiri[40], D. Kumar[40], A. Muhammad, L. Panwar[40], R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar, P.C. Tiwari[40], S. Verma

Bhabha Atomic Research Centre, Mumbai, India
K. Naskar[41]

JHEP07(2023)139

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[42], A.K. Das, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[43], A. Nayak[43], P. Saha, S.K. Swain, D. Vats[43]

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[44,45], E. Khazaie[45], M. Zeinali[46]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[47], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,48], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], W. Elmetenawee[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], M. Ince[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], D. Ramos[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], A. Stamerra[a], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], L. Brigliadori[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,49], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,50], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,50], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
G. Barbagli[a], G. Bardelli[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Meola[51], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy

M. Bozzo[a,b], P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy

A. Benaglia[a], G. Boldrini[a], F. Brivio[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B.S. Pinolini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Università G. Marconi[d], Roma, Italy

S. Buontempo[a], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,52], P. Paolucci[a,28], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy

P. Azzi[a], N. Bacchetta[a,53], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso[a], L. Layer[a,54], E. Lusiani[a], M. Passaseo[a], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], M. Sgaravatto[a], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy

S. Abu Zeid[a,55], C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy

P. Asenov[a,56], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,56], A. Piccinelli[a,b], M. Presilla[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy

P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a,b], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], V. D'Amante[a,d], R. Dell'Orso[a], M.R. Di Domenico[a,d], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], G. Mandorli[a,c], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a,b], F. Palla[a], S. Parolia[a,b], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c],

S. Roy Chowdhury[a], T. Sarkar[a], A. Scribano[a], N. Shafiei[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Barria[a], M. Campana[a,b], F. Cavallari[a], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], R. Tramontano[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], E. Migliore[a,b], E. Monteil[a,b], M. Monteno[a], R. Mulargia[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], K. Shchelina[a], F. Siviero[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], M. Tornago[a,b], D. Trocino[a], G. Umoret[a,b], A. Vagnerini[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], G. Sorrentino[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, M.S. Ryu, S. Sekmen, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
E. Asilar, T.J. Kim, J. Park

Korea University, Seoul, Korea
S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh

Sejong University, Seoul, Korea
H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

JHEP07(2023)139

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, Y. Kang, D. Kim, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, J.A. Merlin, I.C. Park, Y. Roh, D. Song, I.J. Watson, S. Yang

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, Y. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia
K. Dreimanis, G. Pikurs, M. Seidel, V. Veckalns

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Carvalho Antunes De Oliveira, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, S.Y. Hoh[57], I. Yusuff[57], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, I. Heredia-De La Cruz[58], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, J. Mijuskovic[59], N. Raicevic

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, M. Gul, H.R. Hoorani, W.A. Khan, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

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

M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, J. Varela

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

P. Adzic[60], M. Dordevic, P. Milenovic, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas, J. Sastre, L. Urda Gómez, J. Vazquez Escobar, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, A. García Alonso, G. Gomez, C. Lasaosa García,

C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[61], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, B. Bilin, A. Bocci, E. Brondolin, C. Caillol, T. Camporesi, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, F. Fallavollita[62], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, N. Kratochwil, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[63], A.G. Stahl Leiton, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk[64], K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[65], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[65], L. Noehte[65], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov[64], M. Backhaus, P. Berger, A. Calandri, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, A. Mascellani[64], F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, J. Steggemann[64], D. Valsecchi[28], R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[66], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei,

B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

National Central University, Chung-Li, Taiwan
C. Adloff[67], C.M. Kuo, W. Lin, P.K. Rout, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, H. Cheng, W.-S. Hou, R. Khurana, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[68], E. Eskut, Y. Guler[69], E. Gurpinar Guler[69], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[70], A. Polatoz, A.E. Simsek, B. Tali[71], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
G. Karapinar[72], K. Ocalan[73], M. Yalvac[74]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[75], O. Kaya[76], S. Tekten[77]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[68], Y. Komurcu, S. Sen[68]

Istanbul University, Istanbul, Turkey
O. Aydilek, S. Cerci[71], B. Hacisahinoglu, I. Hos[78], B. Isildak[79], B. Kaynak, S. Ozkorucuklu, C. Simsek, D. Sunar Cerci[71]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, E. Bhal, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko,

JHEP07(2023)139

B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[80], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[81], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[82], Sh. Jain, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, C.E. Brown, O. Buchmuller, V. Cacchio, V. Cepaitis, G.S. Chahal[83], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, D.G. Monk, J. Nash[84], M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[28], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio[85], C. West

Boston University, Boston, Massachusetts, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, C. Erice, E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan

Brown University, Providence, Rhode Island, USA
G. Benelli, B. Burkle, X. Coubez[23], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[86], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, M. Narain, N. Pervan, S. Sagir[87], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, California, USA
J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, D. Pellett, B. Regnery, Y. Yao, F. Zhang

JHEP07(2023)139

University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, W. Si, S. Wimpenny

University of California, San Diego, La Jolla, California, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
N. Amin, C. Campagnari, M. Citron, G. Collura, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, A.J. Li, P. Masterson, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, P. Siddireddy, D. Stuart, S. Wang

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, I. Dutta, A. Latorre, J.M. Lawhorn, J. Mao, H.B. Newman, T. Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, S. Murthy, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, F. Marini, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

Cornell University, Ithaca, New York, USA
J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, D. Gadkari, S. Hogan, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, K.F. Di Petrillo, J. Dickinson, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, S. Grünendahl,

D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[88], F. Ravera, A. Reinsvold Hall[89], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

University of Florida, Gainesville, Florida, USA

P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R.D. Field, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, E. Kuznetsova, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu

Florida State University, Tallahassee, Florida, USA

T. Adams, A. Askew, R. Habibullah, V. Hagopian, T. Kolberg, G. Martinez, H. Prosper, O. Viazlo, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy[55], M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, Illinois, USA

M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C.E. Gerber, D.J. Hofman, D. S. Lemos, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, X. Wang, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini, K. Dilsiz[90], L. Emediato, R.P. Gandrajula, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[91], J. Nachtman, O. Neogi, H. Ogul[92], Y. Onel, A. Penzo, C. Snyder, E. Tiras[93]

Johns Hopkins University, Baltimore, Maryland, USA

O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, S. Sekhar, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, Kansas, USA

A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bean, Z. Flowers, T. Isidori, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, Kansas, USA

B. Allmond, S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam, D. Roy

JHEP07(2023)139

Lawrence Livermore National Laboratory, Livermore, California, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, USA
E. Adams, A. Baden, O. Baron, A. Belloni, A. Bethani, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
D. Abercrombie, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, P. Harris, M. Hu, D. Kovalskyi, J. Krupa, Y.-J. Lee, K. Long, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
R.M. Chatterjee, B. Crossman, A. Evans, J. Hiltbrand, B.M. Joshi, C. Kapsiak, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, Mississippi, USA
L.M. Cremaldi

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, M. Bryson, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, C. Joo, R. Kamalieddin, I. Kravchenko, I. Reed, J.E. Siado, G.R. Snow[†], W. Tabb, A. Wightman, F. Yan, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, New York, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, M. Morris, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Krishna, J. Li, J. Lidrych, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, K.A. Hahn, Y. Liu, N. Odell, M.H. Schmitt, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA
R. Band, R. Bucci, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman,

C. Moore, Y. Musienko[13], R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA
B. Bylsma, M. Carrigan, L.S. Durkin, B. Francis, C. Hill, M. Joyce, A. Lesauvage, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
F.M. Addesa, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic, J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar

Rice University, Houston, Texas, USA
D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Rotter, W. Shi, S. Yang, E. Yigitbasi, L. Zhang[94], Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus, G.P. Van Onsem

The Rockefeller University, New York, New York, USA
K. Goulianos

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban[26], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Routray, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, A.G. Delannoy, S. Fiorendi, T. Holmes, E. Nibigira, S. Spanier

JHEP07(2023)139

Texas A&M University, College Station, Texas, USA
O. Bouhali[95], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[96], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, V. Hegde, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, A. Whitbeck

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, B. Cox, G. Cummings, J. Hakala, R. Hirosky, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara, B. Tannenwald

Wayne State University, Detroit, Michigan, USA
P.E. Karchin, N. Poudyal

University of Wisconsin - Madison, Madison, Wisconsin, USA
S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov[97], E. Boos, V. Borshch, D. Budkouski, V. Chekhovsky, R. Chistov[97], A. Demiyanov, A. Dermenev, T. Dimova[97], I. Dremin, V. Epshteyn, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, Y. Ivanov, V. Kachanov, L. Kardapoltsev[97], V. Karjavine, A. Karneyeu, L. Khein, V. Kim[97], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, O. Kodolova[98], D. Konstantinov, V. Korenkov, V. Korotkikh, A. Kozyrev[97], N. Krasnikov, A. Lanev, P. Levchenko, A. Litomin, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[97], V. Murzin, A. Nikitenko[99], S. Obraztsov, A. Oskin, I. Ovtin[97], V. Palichik, P. Parygin, V. Perelygin, S. Petrushanko, S. Polikarpov[97], V. Popov, E. Popova, O. Radchenko[97], M. Savina, V. Savrin, D. Selivanova, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[97], S. Slabospitskii, V. Smirnov, A. Snigirev, D. Sosnov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, I. Tlisova, M. Toms, A. Toropin, L. Uvarov, A. Uzunian, I. Vardanyan, E. Vlasov, A. Vorobyev, N. Voytishin, B.S. Yuldashev[100], A. Zarubin, I. Zhizhin, A. Zhokin

JHEP07(2023)139

† Deceased
[1] Also at Yerevan State University, Yerevan, Armenia
[2] Also at TU Wien, Vienna, Austria
[3] Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
[4] Also at Université Libre de Bruxelles, Bruxelles, Belgium
[5] Also at Universidade Estadual de Campinas, Campinas, Brazil
[6] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[7] Also at UFMS, Nova Andradina, Brazil
[8] Also at The University of the State of Amazonas, Manaus, Brazil
[9] Also at University of Chinese Academy of Sciences, Beijing, China
[10] Also at Nanjing Normal University Department of Physics, Nanjing, China
[11] Now at The University of Iowa, Iowa City, Iowa, USA
[12] Also at University of Chinese Academy of Sciences, Beijing, China
[13] Also at an institute or an international laboratory covered by a cooperation agreement with CERN
[14] Also at Cairo University, Cairo, Egypt
[15] Also at Suez University, Suez, Egypt
[16] Now at British University in Egypt, Cairo, Egypt
[17] Also at Purdue University, West Lafayette, Indiana, USA
[18] Also at Université de Haute Alsace, Mulhouse, France
[19] Also at Department of Physics, Tsinghua University, Beijing, China
[20] Also at Ilia State University, Tbilisi, Georgia
[21] Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[22] Also at University of Hamburg, Hamburg, Germany
[23] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[24] Also at Isfahan University of Technology, Isfahan, Iran
[25] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[26] Also at Brandenburg University of Technology, Cottbus, Germany
[27] Also at Forschungszentrum Jülich, Juelich, Germany
[28] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[29] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[30] Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
[31] Also at Wigner Research Centre for Physics, Budapest, Hungary
[32] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
[33] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[34] Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[35] Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
[36] Also at Punjab Agricultural University, Ludhiana, India
[37] Also at UPES — University of Petroleum and Energy Studies, Dehradun, India
[38] Also at University of Visva-Bharati, Santiniketan, India
[39] Also at University of Hyderabad, Hyderabad, India
[40] Also at Indian Institute of Science (IISc), Bangalore, India
[41] Also at Indian Institute of Technology (IIT), Mumbai, India
[42] Also at IIT Bhubaneswar, Bhubaneswar, India
[43] Also at Institute of Physics, Bhubaneswar, India
[44] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[45] Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran
[46] Also at Sharif University of Technology, Tehran, Iran
[47] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[48] Also at Helwan University, Cairo, Egypt
[49] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[50] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[51] Also at Università degli Studi Guglielmo Marconi, Roma, Italy

JHEP07(2023)139

[52] *Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy*
[53] *Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[54] *Also at Università di Napoli 'Federico II', Napoli, Italy*
[55] *Also at Ain Shams University, Cairo, Egypt*
[56] *Also at Consiglio Nazionale delle Ricerche — Istituto Officina dei Materiali, Perugia, Italy*
[57] *Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
[58] *Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
[59] *Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[60] *Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia*
[61] *Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
[62] *Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy*
[63] *Also at National and Kapodistrian University of Athens, Athens, Greece*
[64] *Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
[65] *Also at Universität Zürich, Zurich, Switzerland*
[66] *Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
[67] *Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
[68] *Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
[69] *Also at Konya Technical University, Konya, Turkey*
[70] *Also at Izmir Bakircay University, Izmir, Turkey*
[71] *Also at Adiyaman University, Adiyaman, Turkey*
[72] *Also at Istanbul Gedik University, Istanbul, Turkey*
[73] *Also at Necmettin Erbakan University, Konya, Turkey*
[74] *Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey*
[75] *Also at Marmara University, Istanbul, Turkey*
[76] *Also at Milli Savunma University, Istanbul, Turkey*
[77] *Also at Kafkas University, Kars, Turkey*
[78] *Also at Istanbul University — Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
[79] *Also at Ozyegin University, Istanbul, Turkey*
[80] *Also at Vrije Universiteit Brussel, Brussel, Belgium*
[81] *Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
[82] *Also at University of Bristol, Bristol, United Kingdom*
[83] *Also at IPPP Durham University, Durham, United Kingdom*
[84] *Also at Monash University, Faculty of Science, Clayton, Australia*
[85] *Also at Università di Torino, Torino, Italy*
[86] *Also at Bethel University, St. Paul, Minnesota, USA*
[87] *Also at Karamanoğlu Mehmetbey University, Karaman, Turkey*
[88] *Also at California Institute of Technology, Pasadena, California, USA*
[89] *Also at United States Naval Academy, Annapolis, Maryland, USA*
[90] *Also at Bingol University, Bingol, Turkey*
[91] *Also at Georgian Technical University, Tbilisi, Georgia*
[92] *Also at Sinop University, Sinop, Turkey*
[93] *Also at Erciyes University, Kayseri, Turkey*
[94] *Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) — Fudan University, Shanghai, China*
[95] *Also at Texas A&M University at Qatar, Doha, Qatar*
[96] *Also at Kyungpook National University, Daegu, Korea*
[97] *Also at another institute or international laboratory covered by a cooperation agreement with CERN*
[98] *Also at Yerevan Physics Institute, Yerevan, Armenia*
[99] *Also at Imperial College, London, United Kingdom*
[100] *Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*

JHEP07(2023)139