Two-particle azimuthal correlations in p interactions using pPb collisions at $\sqrt{sNN}$ =8.16TeV

Canelli, Maria Florencia ; Kilminster, Benjamin ; Caminada, Lea ; Botta, Cristina ; Brzhechko, Danyyl ; Del Burgo, Riccardo ; Heikkilä, Jaana K ; Huwiler, Marc ; Jofrehei, Arash ; Leontsinis, Stefanos ; Macchiolo, Anna ; Meiring, Peter ; Missiroli, Marino ; Mikuni, Vinicius Massami ; Molinatti, Umberto ; Neutelings, Izaak ; Reimers, Arne ; Robmann, Peter ; Sanchez Cruz, Sergio ; Schweiger, Korbinian ; Takahashi, Yuta ; CMS Collaboration ; et al

DOI: https://doi.org/10.1016/j.physletb.2023.137905

Physics Letters B 844 (2023) 137905

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Two-particle azimuthal correlations in γp interactions using pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

The CMS Collaboration *

CERN, Geneva, Switzerland

ARTICLE INFO

Article history:
Received 28 April 2022
Received in revised form 14 March 2023
Accepted 6 April 2023
Available online 20 July 2023
Editor: M. Doser

Keywords:
CMS
Photon-proton
Collectivity

ABSTRACT

The first measurements of the Fourier coefficients ($V_{n\Delta}$) of the azimuthal distributions of charged hadrons emitted from photon-proton (γp) interactions are presented. The data are extracted from 68.8 nb^{-1} of ultra-peripheral proton-lead (pPb) collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV using the CMS detector. The high energy lead ions produce a flux of photons that can interact with the oncoming proton. This γp system provides a set of unique initial conditions with multiplicity lower than in photon-lead collisions but comparable to recent electron-positron and electron-proton data. The $V_{n\Delta}$ coefficients are presented in ranges of event multiplicity and transverse momentum (p_{T}) and are compared to corresponding hadronic minimum bias pPb results. For a given multiplicity range, the mean p_{T} of charged particles is smaller in γp than in pPb collisions. For both the γp and pPb samples, $V_{1\Delta}$ is negative, $V_{2\Delta}$ is positive, and $V_{3\Delta}$ consistent with 0. For each multiplicity and p_{T} range, $V_{2\Delta}$ is larger for γp events. The γp data are consistent with model predictions that have no collective effects.

1. Introduction

A wide variety of measurements suggest the existence of collectivity in the collisions of small systems such as the proton-proton (pp) [1–5] and proton-nucleus (pA) [6–17] collisions. Such collectivity could indicate the formation of a hot, strongly interacting "quark gluon plasma" (QGP), characterized by nearly ideal hydrodynamic behavior [18–20], or could alternatively arise from gluon saturation in the initial state [21,22]. Properties of the QGP have been previously studied in a wide range of high-energy nucleus-nucleus (AA) collisions at the CERN LHC and BNL RHIC [23–33]. In these studies, collectivity is observed via the azimuthal correlations of particles that are far apart in rapidity. This phenomenon is known as the "ridge" [21], and has been unexpectedly observed in high-multiplicity pp and pPb collisions since the start of the LHC operation [1–17]. The two-particle azimuthal correlations can be characterized by their Fourier components ($V_{n\Delta}$) where n represents the order of the moment. If the two-particle correlations can be factorized into the product of the corresponding single particle azimuthal distributions, then the single-particle azimuthal anisotropy Fourier coefficients v_n can be extracted as $v_n = \sqrt{V_{n\Delta}}$ [34]. The second (v_2) and third (v_3) coefficients are known as elliptic and triangular flow, respectively, and are directly related to the initial collision geometry and its fluctuations, which influence the medium evolution and provide information about its fundamental transport properties [35–38].

In high-multiplicity events, v_2 and v_3 depend upon the hadron species [15,39–43] and scale with the number of valence quarks in the hadron [15]. Such results suggest a common origin of the collectivity seen in PbPb, as well as in high-multiplicity pp and pPb events, where a hydrodynamic description can be used to reasonably reproduce the measurements in each case [44–47]. Probing systems with even smaller interaction regions is therefore important to understand the reach of such a hydrodynamic description. The search for collectivity has been recently extended to electron-positron ($\mathrm{e}^+\mathrm{e}^-$), electron-proton (ep), photon-proton (γp), and photon-nucleus interactions [48–52]. So far, no long-range near-side ridge has been detected in these systems. In $\mathrm{e}^+\mathrm{e}^-$ collisions [48,49], strong exclusion limits have been set on the ridge yield, while in ep collisions (deep inelastic scattering and photoproduction) [50,51], the extracted Fourier coefficients are finite but do not conclusively imply collective behavior. In photon-nucleus collisions [52], finite v_2 and v_3 are measured after applying a template fit procedure to remove noncollective correlations, assuming they scale with multiplicity.

High-energy pPb ultra-peripheral collisions at the LHC, where the impact parameter is larger than the nucleus radius provide a new system to extend the search of long-range correlations to photon-proton collisions. At TeV energies, the lead (Pb) nuclei generate a very large quasi-real photon flux [53]. In the equivalent photon approximation [54–56], this flux can be considered

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

https://doi.org/10.1016/j.physletb.2023.137905

as γ beams of virtuality $Q^2 < 1/R^2$, where R is the effective radius of the charge distribution. For Pb nuclei at 2.56 TeV with radius $R \approx 7$ fm, the quasi-real photon beams have virtualities $Q^2 < 10^{-3}$ GeV^2, but very large longitudinal energy, up to $E_\gamma = \hbar c/\alpha R \approx 73$ GeV, where α is the reciprocal Lorentz relativistic factor.

This study complements recent results from small collision systems, such as e^+e^- and ep [48,49,51]. The CMS detector has been used to collect a large sample of γp interactions that occur in ultra-peripheral pPb collisions. The beam energies were 6.50 TeV for the protons and 2.56 TeV per nucleon for the Pb nuclei, resulting in a center-of-mass energy per nucleon pair ($\sqrt{s_{_{\mathrm{NN}}}}$) of 8.16 TeV. The resulting γp center-of-mass energy can fluctuate up to ~1.4 TeV. The γp results are compared to both hadronic minimum bias (MB) pPb collisions (previously studied in Ref. [57]) and predictions of the PYTHIA v8.2 [58] model interfaced with the Delphes v3.4.2 fast simulation package [59]. The minimum bias data are compared to predictions from the HIJING v2.1 generator [60] coupled to a full GEANT4 simulation of the detector [61].

2. Experimental apparatus and data sample

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 is the silicon tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections that cover the range $|\eta| < 3.0$. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixels and 15 148 silicon strip detector modules, and provides an impact parameter resolution of about 15 µm and a transverse momentum (p_T) resolution better than 1.5% at $p_T \approx 100$ GeV/c. Event selection for this analysis makes use of detectors in the forward region: hadron forward (HF) calorimeters that use quartz fibers embedded in a steel absorber covering the region $3.0 < |\eta| < 5.2$ and the two Zero Degree Calorimeters (ZDCs) which measure neutral particles with $|\eta| > 8.3$ [62]. Analysis in the midrapidity region is based upon objects produced by the CMS particle-flow (PF) algorithm [63], which reconstructs and identifies final-state particles with an optimized combination of information from the various elements of the CMS detector. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [64].

The analysis is performed using data recorded by CMS during the LHC pPb run in 2016 with an integrated luminosity of 68.8 nb^{-1}. The proton-going direction is towards the side of the detector with positive η. As a result of the energy difference between the colliding beams, the nucleon-nucleon (NN) center-of-mass for pPb collisions is not at rest with respect to the laboratory frame. Massless particles emitted at $\eta_{\mathrm{cm}} = 0$ in the NN center-of-mass frame will be detected at $\eta = +0.465$ in the laboratory frame. The event samples were collected by the CMS experiment with a two-level trigger system [57] consisting in the level-1 (L1), where events are selected by custom hardware processors and the high-level trigger (HLT), that uses fast versions of the offline software.

Samples of both γp-enhanced and MB events were collected requiring energy deposits in at least one of the HF calorimeters above a threshold of approximately 1 GeV at L1. The HLT system requires the presence of at least one charged particle (track) with $p_T > 0.4$ GeV/c in the pixel tracker. Track reconstruction was performed online as part of the HLT trigger with a reconstruction algorithm that is identical to the one used offline [65]. More details of the MB trigger can be found in Ref. [66]. For each event, the reconstructed vertex with the highest number of associated tracks was selected as the primary vertex. A zero bias trigger requiring only the presence of proton and lead bunches in the CMS detector was used to independently study the trigger efficiency ($\varepsilon_{\mathrm{trig}}$). The beam bunches were detected by induction counters placed 175 m from the interaction point on each side of the experiment. In addition, a sample of events with neither beam present was collected for noise studies.

3. Event selection

For both γp and MB samples, the reconstructed primary vertex was required to be within 15 cm of the nominal interaction point along the beam axis (z) and within 0.15 cm in the transverse plane. The strategy for track selection is described in Ref. [65]. The impact parameter significance of reconstructed tracks with respect to the primary vertex in the longitudinal and transverse directions was required to be <3 standard deviations. Finally, the relative uncertainty in the p_T of the track was required to be <10%. At least two reconstructed tracks with $|\eta| < 2.4$ and $p_T > 0.4$ GeV/c were required to be associated with the primary vertex. Beam-related background was suppressed by rejecting events for which <25% of all reconstructed tracks pass the standard track selection criteria as in Ref. [57].

Typical pPb collisions produce particles at both positive and negative rapidity [40,57,67]. However, γp events are expected to be very asymmetric in the laboratory frame since the photon energy is generally much smaller than the proton beam energy.

For the γp-enhanced selection, a rapidity gap is defined as a continuous region in which there is low detector activity, as done in Ref. [68]. The detector acceptance $|\eta| < 5.0$ is divided into 20 bins. Threshold values are assigned to each η bin, they delimit the energy from all PF candidates that can be considered significant and which contain at least 99.7% of detector activity caused by detector noise or by beam-gas events. These thresholds were obtained by studying the zero-bias events triggered on noncolliding bunches. For each event, a given η bin was considered to be empty if the energy registered from the PF candidates was below its assigned threshold value. For the 10 bins in the regions $|\eta| < 2.5$ the energy threshold was 6 GeV and no high-purity tracks with $p_T > 200$ MeV/c were allowed. For the four bins from $-5.0 < \eta < -3.0$ in the lead-going region the thresholds were 16.9, 15.3, 16.4, and 13.4 GeV, respectively. For the bin $-2.5 > \eta > -3.0$ only neutral hadrons were considered and the energy threshold was 13.4 GeV. The forward rapidity gap ($\Delta\eta^F$) variable was then defined as the difference from $\eta = -5.0$ to the lower edge of the first nonempty η bin.

The MB selection requires the coincidence of at least one tower with energy above 3.0 GeV in both HF calorimeters and at least two tracks with $|\eta| < 2.5$. In contrast, a γp-enhanced selection is designed to capture events with an intact Pb nucleus, particle production in the positive η region, and a large rapidity gap [69–71]. The first two requirements are met by requiring no neutrons in the ZDC on the Pb-going side and at least 10 GeV in the highest energy tower of the HF calorimeter on the p-going side. To ensure a large rapidity gap, we require $5.0 < \Delta\eta^F < 7.5$. This corresponds to not having a particle within the negative-η region. A total of 8.6×10^6 γp-enhanced and 1.0×10^9 MB candidate events were selected. In Ref. [68] the purity of the γp-enhanced sample with the ZDC selection is estimated to be about 95% and it is weakly dependent on particle multiplicity. The requirement of no neutron emission used in this analysis gives an additional suppression of pomeron-Pb events.

The reconstructed track multiplicity ($N_{\mathrm{trk}}^{\mathrm{offline}}$) is defined as the number of tracks from the primary vertex with $p_T > 0.4$ GeV/c, and $|\eta| < 2.4$. Fig. 1 shows the $N_{\mathrm{trk}}^{\mathrm{offline}}$ spectra for the γp-enhanced and

Table 1
Mean $N_{trk}^{offline}$ for the γp-enhanced and the MB data sets for five classes of $N_{trk}^{offline}$ (abreviated as N_{trk}^{off}). Statistical uncertainties are negligible.

Sample	$2 \le N_{trk}^{off} < 5$	$5 \le N_{trk}^{off} < 10$	$10 \le N_{trk}^{off} < 35$	$5 \le N_{trk}^{off} < 35$	$2 \le N_{trk}^{off} < 35$
γp-enhanced	2.6	5.8	11.3	6.0	2.9
γp-simulated	2.6	5.9	11.4	6.2	2.9
MB	3.0	6.9	21.5	18.5	16.6
MB-simulated	3.1	6.9	20.7	17.2	15.7

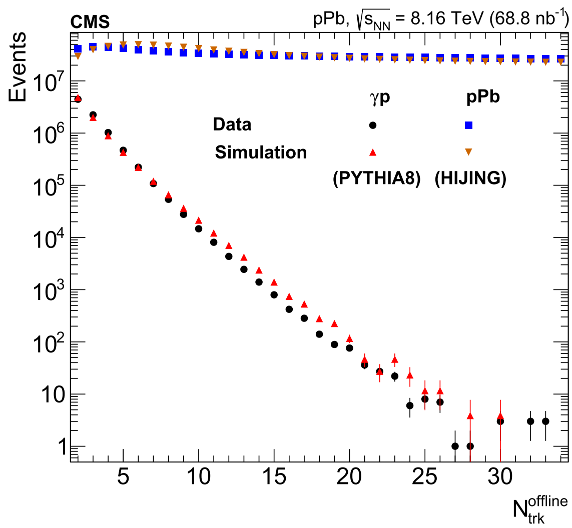

Fig. 1. The $N_{trk}^{offline}$ spectra for γp and MB samples. The simulated γp distribution has been normalized to the same event yield as the γp-enhanced data sample.

MB data samples along with simulations from the PYTHIA8 and HIJING event generators. For the γp-simulated sample, the events are restricted to those with no tracks in the $\eta < 0$ region and normalized to the γp-enhanced yield. In contrast to the MB sample, the γp-enhanced spectrum drops very rapidly with multiplicity up to a limiting value of 34. The $\langle N_{trk}^{offline}\rangle$ value corresponding to the $2 \le N_{trk}^{offline} < 35$ range for the γp-enhanced sample is $\approx$2.9 and about 16.6 for the MB sample. The $N_{trk}^{offline}$ distribution from the zero bias data control sample has $\langle N_{trk}^{offline}\rangle \approx 0.84$. The γp-simulated sample shows a shape and range that is consistent with the γp-enhanced data sample. Three $N_{trk}^{offline}$ bins are used to analyze the γp-enhanced events: $2 \le N_{trk}^{offline} < 5$, $5 \le N_{trk}^{offline} < 10$, $10 \le N_{trk}^{offline} < 35$. The first two deliver a comparable number of particle pairs and the third one aims to probe the higher $N_{trk}^{offline}$ domain by averaging the last part of the distribution. Table 1 indicates the $\langle N_{trk}^{offline}\rangle$ values for the data and simulated γp and MB samples. The mean p_T, $\langle p_T\rangle$, values of charged particles in the γp and MB data samples are 0.67 ± 0.01 and 0.74 ± 0.01 GeV/c respectively.

4. Analysis technique

To ensure a high tracking efficiency, only tracks with $0.3 < p_T < 3.0$ GeV/c are used in the analysis. The two-particle correlation analysis techniques described below are identical to those used in previous CMS measurements in pp, pPb, and PbPb collisions [3,6,26]. For each multiplicity class, the "trigger particles" are tracks whose p_T, labeled as p_T^{trig}, is within a particular given range. The number of trigger particles in the event is denoted by N_{trig}. Particle pairs are then formed by associating each trigger particle with the remaining tracks whose $p_T$is denoted as p_T^{assoc}. In this analysis p_T^{trig} and p_T^{assoc} have a common range. Two different $p_T$ranges are studied, i.e., [0.3, 3.0] and [1.0, 3.0] GeV/c. These are the same as those used in previous studies of the ridge [6] and observations of correlations between v_n coefficients [57] in pPb collisions.

The two-dimensional correlation function is defined as

$$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0)\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}, \quad (1)$$

where $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ of the pair and N^{pair} is the number of pairs. The same-event pair distribution, $S(\Delta\eta,\Delta\phi)$, represents the yield of particle pairs from the same event in a given ($\Delta\eta$, $\Delta\phi$) bin. Entries have been weighted by the product of inverse efficiencies evaluated for the kinematics of the two particles. The mixed-event pair distribution $B(\Delta\phi,\Delta\eta)$ is constructed by pairing the trigger particles in each event with the associated charged particles from 100 different randomly selected events in the same 0.5 cm wide vertex range and from the same track multiplicity class. It accounts for random combinatorial backgrounds and pair-acceptance effects. The same-event and mixed-event pair distributions are first calculated for each event, and then averaged over the events within the track multiplicity class. The mixed-event distribution is normalized by the sum of background events. The ratio $B(0,0)/B(\Delta\eta,\Delta\phi)$ is the pair-acceptance correction factor, where $B(0,0)$ represents the mixed-event associated yield for both particles of the pair going in the same direction and thus having maximum pair acceptance.

Fig. 2 (left) shows the two-particle correlation functions for γp-enhanced (upper row) and MB (lower row) events within the multiplicity range $2 \le N_{trk}^{offline} < 35$ as functions of $\Delta\eta$ and $\Delta\phi$. This $N_{trk}^{offline}$ range integrates all the yields all statistics for γp events, significantly suppressing fluctuations seen in smaller bins. For the γp distribution, the $\Delta\eta$ range is limited to $|\Delta\eta| < 2.5$ by the $\Delta\eta^F$ selection and the acceptance of the tracker. Both distributions show a large jet peak centered at $\Delta\eta = \Delta\phi = 0$, as well as a broader distribution from the recoiling jet centered at $\Delta\eta = 0$ and $\Delta\phi = \pi$. Neither distribution displays a "ridge"-like structure at $|\Delta\phi| \approx 0$ for $|\Delta\eta| > 2$. Fig. 2 (right) shows the projections of the two-dimensional correlation functions onto the $\Delta\phi$ axis for $|\Delta\eta| > 2$, away from the jet fragmentation peak. These distributions are fitted over the $\Delta\phi$ range $[0,\pi]$ to a Fourier decomposition series $\propto 1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)$, from where the measured $V_{n\Delta}$ are extracted. Only the first three terms are included in the fit, since additional terms have a negligible effect on its quality.

In order to reduce the contribution to v_n coefficients from back-to-back jet correlations, one can correct v_n by subtracting correlations from very low-multiplicity events (v_n^{sub}), as done in Refs. [4,57,72]. In order to test whether a collective signal is present, the data are compared to PYTHIA8 predictions, which do not include collective effects.

5. Systematic uncertainties

The systematic uncertainties of the experimental procedure are evaluated by varying the analysis conditions and extracting new $V_{n\Delta}$ coefficients. The following effects were considered:

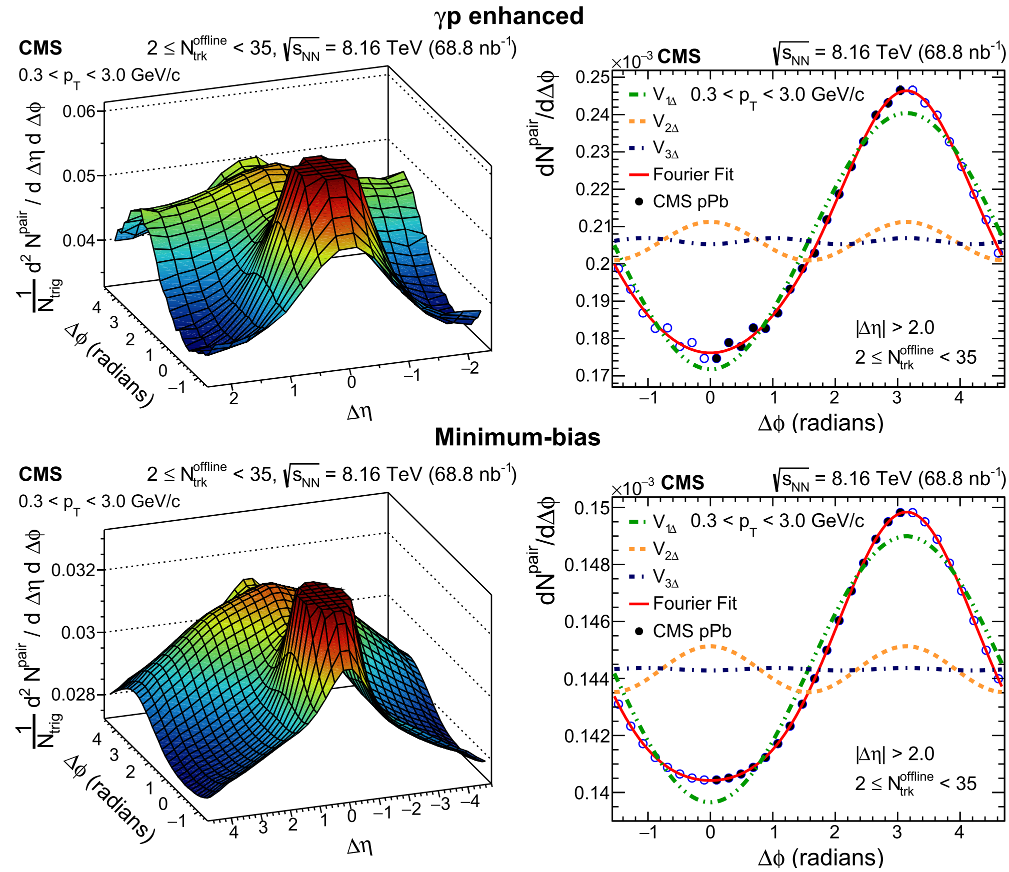

Fig. 2. Two-dimensional (left) and one-dimensional (right) correlation plots for γp-enhanced (upper) and MB (lower) events for $0.3 < p_T < 3.0\,\mathrm{GeV}/c$ and $2 \leq N_{trk}^{offline} < 35$. For the two-dimensional distributions, the jet peak centered at $\Delta\eta = \Delta\phi = 0$ is truncated to increase visibility. The rapidity gap requirement for the γp-enhanced sample limits the $|\Delta\eta|$ range to $|\Delta\eta| < 2.5$. The one-dimensional $\Delta\phi$ distributions are symmetrized by construction around $\Delta\phi = 0$ and π. The Fourier coefficients, $V_{n\Delta}$ in the right column are fit over the $\Delta\phi$ range $[0, \pi]$. Points outside this range are shown as open circles and are obtained by symmetrization of those in $[0, \pi]$. Statistical error bars are shown for both one-dimensional distributions.

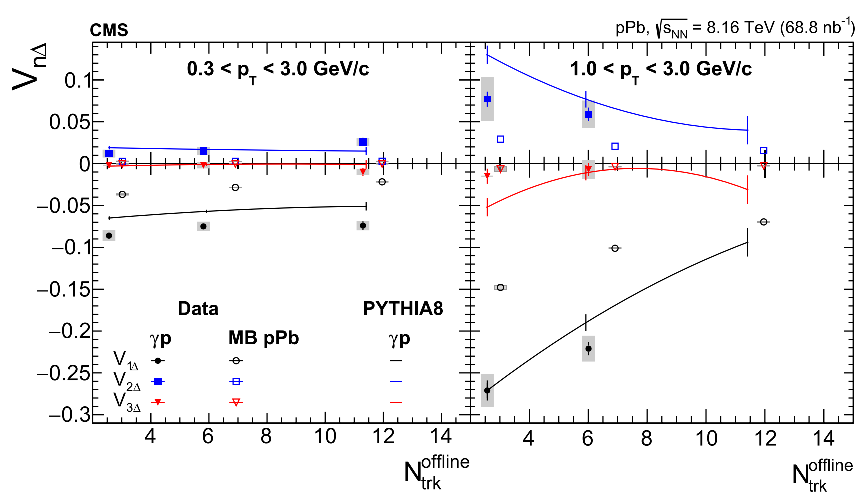

Fig. 3. Dependence of $V_{n\Delta}$ on $N_{trk}^{offline}$ for γp and MB events for two different $p_T$ranges. Systematic uncertainties are shown by the shaded bars in the two panels. The $2 \leq N_{trk}^{offline} < 5$, $5 \leq N_{trk}^{offline} < 10$, $10 \leq N_{trk}^{offline} < 35$ are used for the lower p_T range and $2 \leq N_{trk}^{offline} < 5$ and $5 \leq N_{trk}^{offline} < 35$ for the higher range. The points are placed at the mean value of the corresponding $N_{trk}^{offline}$ range. Lines indicate the prediction for γp events from PYTHIA8.

1. The systematic uncertainties associated with the choice of the $\Delta\eta^F$ range, which has a resolution of 0.5 units in η and ensures low detector activity on one half of the detector, were estimated by repeating the analysis with $\Delta\eta^F \in [4.5, 5.0)$, just below the range of the nominal analysis. This alternative selection affects the track multiplicity and decreases the purity of the γp-enhanced sample up to 8% [68]. The estimated size of this uncertainty has maximum values of 7% for $V_{1\Delta}$ and 27% for $V_{2\Delta}$ within the $N_{trk}^{offline}$ range considered in this analysis. For the MB data there is no rapidity gap requirement and so no systematic uncertainty is assigned for this effect.

Table 2
The $V_{n\Delta}$ coefficients for γp-enhanced events, as functions of $p_T$and $N_{trk}^{offline}$. Statistical and systematic uncertainties are added in quadrature.

$p_T$range		$2 \leq N_{trk}^{offline} < 5$	$5 \leq N_{trk}^{offline} < 10$	$10 \leq N_{trk}^{offline} < 35$
	$V_{1\Delta}$	-0.086 ± 0.006	-0.075 ± 0.005	-0.074 ± 0.007
$0.3 < p_T < 3.0$ GeV/c	$V_{2\Delta}$	0.012 ± 0.004	0.015 ± 0.004	0.026 ± 0.006
	$V_{3\Delta}$	-0.002 ± 0.001	-0.002 ± 0.004	-0.010 ± 0.006
		$2 \leq N_{trk}^{offline} < 5$	$5 \leq N_{trk}^{offline} < 35$	
	$V_{1\Delta}$	-0.271 ± 0.021	-0.221 ± 0.017	
$1.0 < p_T < 3.0$ GeV/c	$V_{2\Delta}$	0.077 ± 0.027	0.059 ± 0.017	
	$V_{3\Delta}$	-0.015 ± 0.009	-0.007 ± 0.013	

2. The effect of tracking inefficiency and misreconstructed track rate was studied by varying the track quality requirements. The selection thresholds on the significance of the transverse and longitudinal track impact parameter were varied from 2 to 5 standard deviations. In addition, the relative $p_T$uncertainty is varied from 0.05 to 0.10. This translates into a 3.5% uncertainty in $V_{1\Delta}$ for the $2 \leq N_{trk}^{offline} < 5$ category.
3. The sensitivity of the results to the primary vertex position along the beam axis (z_{vtx}) was quantified by comparing events with different z_{vtx} locations from −15 to +15 cm. The magnitude of this systematic effect goes up to 150% for $V_{3\Delta}$ with numerical estimations of ±0.003 for $5 \leq N_{trk}^{offline} < 10$ and $10 \leq N_{trk}^{offline} < 35$ respectively, in the $0.3 < p_T < 3.0$ GeV/c category, and up to ±0.013 for $1.0 < p_T < 3.0$ GeV/c.
4. The trigger efficiency depends upon $N_{trk}^{offline}$. It decreases substantially for $N_{trk}^{offline} < 10$, reaching 70% for $N_{trk}^{offline} = 2$. To study this effect, a parallel data sample with weighted events as $(1/\varepsilon_{trig})$ was produced. The full difference of the $V_{n\Delta}$ with and without the correction was taken as the uncertainty. This uncertainty is 2.3% for $V_{1\Delta}$ and 17% for $V_{2\Delta}$ for the sample with $2 \leq N_{trk}^{offline} < 5$.

The systematic uncertainties were added in quadrature. For the γp-enhanced sample with $N_{trk}^{offline} < 35$ the final uncertainties in $V_{n\Delta}$ are 8.4 and 31% for $n = 1$ and 2, respectively. For the minimum bias sample the uncertainties for $V_{2\Delta}$ are 11% for $2 \leq N_{trk}^{offline} < 5$ and smaller than 2.6% for the rest of the $N_{trk}^{offline}$ range. Since p_T^{trig} and p_T^{assoc} have the same range, the fractional uncertainties in v_n are half those of $V_{n\Delta}$.

6. Results

Fig. 3 and Table 2 show the measured $V_{n\Delta}$ coefficients as a function of $N_{trk}^{offline}$ for the two different p_T ranges for the γp and MB pPb samples. For the MB sample, the results are consistent with those in [57] before the subtraction procedure. Both the γp and MB distributions show a negative $V_{1\Delta}$, a positive $V_{2\Delta}$ of smaller magnitude than $V_{1\Delta}$, and a $V_{3\Delta}$ that is consistent with zero. For a given $N_{trk}^{offline}$ and $p_T$range, both $V_{1\Delta}$ and $V_{2\Delta}$ are larger in the γp samples than in the MB results. For both samples, the magnitude of $V_{1\Delta}$ tends to decrease with $N_{trk}^{offline}$, while $V_{2\Delta}$ has at most a weak $N_{trk}^{offline}$ dependence. Their magnitudes are both larger in the higher $p_T$range.

Fig. 3 also shows predictions from the PYTHIA8 generator for $V_{n\Delta}$ from γp collisions. The predictions of $V_{2\Delta}$ and $V_{3\Delta}$ from PYTHIA8 are reasonably consistent with the γp data and have a similar dependence upon p_T and $N_{trk}^{offline}$. The $V_{1\Delta}$ prediction is smaller in magnitude than the measured values for the low p_T range.

Fig. 4 shows v_2 as a function of $N_{trk}^{offline}$ and $p_T$for both γp and MB data sets. For $0.3 < p_T < 3.0$ GeV/c, the MB results are consistent with previously published CMS results [57]. Predictions from the PYTHIA8 and HIJING generators are also shown for γp and MB pPb interactions respectively, none of the models include collective effects. For both data and simulations, v_2 varies slowly with track multiplicity for the γp and pPb samples. At a given $N_{trk}^{offline}$, v_2 is larger in the higher $p_T$range. This is similar to trends observed in ep collisions [50,51]. The increase of v_2 with $p_T$is also present in the simulations although both generators slightly overshoot the data at higher p_T. For pPb collisions it has been shown that fluctuations in the proton shape can increase v_2 [73]. It is noticeable that at a given $p_T$and $N_{trk}^{offline}$, v_2 is higher for γp than for pPb interactions. Tabulated results are provided in the HEPData record for this analysis [74].

7. Summary

For the first time, the study of long-range particle correlations has been extended to photon-proton (γp) interactions. This study used proton-lead (pPb) collisions at $\sqrt{s_{_{NN}}} = 8.16$ TeV recorded with the CMS detector. The two-particle $V_{n\Delta}$ Fourier coefficients and corresponding single-particle v_2 azimuthal anisotropies are reported as functions of the multiplicity of charged hadrons ($N_{trk}^{offline}$) for two transverse momenta (p_T) ranges. For the γp sample, the largest observed multiplicity was $N_{trk}^{offline} \sim 35$. The mean $p_T$of charged particles is smaller in the γp sample than for pPb collisions within the same multiplicity range. No evidence for a long-range near-side ridge-like structure was found for either the γp or hadronic minimum bias pPb (MB) samples within this multiplicity range. In all $N_{trk}^{offline}$ and $p_T$ranges, $V_{1\Delta}$ is negative, $V_{2\Delta}$ is positive with a smaller magnitude than $V_{1\Delta}$, and $V_{3\Delta}$ is consistent with zero. The magnitudes of both $V_{1\Delta}$ and $V_{2\Delta}$ increase with p_T. This increase has also been seen in electron-proton collisions. At a given $p_T$and track multiplicity, v_2 is larger for γp-enhanced events than for MB pPb interactions. Predictions from the PYTHIA8 model describe well the γp data within uncertainties. This suggests the data are dominated by noncollective effects. Within the present experimental sensitivity, no significant collectivity signal is observed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Complete statement will be provided in proof.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the

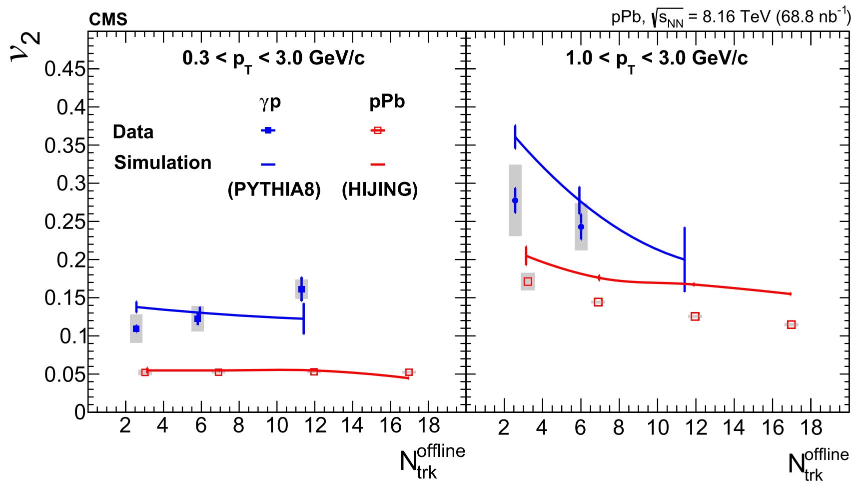

Fig. 4. Single-particle azimuthal anisotropy v_2 versus $N_{trk}^{offline}$ for γp-enhanced and pPb samples in two $p_T$regions. Systematic uncertainties are shown by the shaded bars in the two panels. Predictions from the PYTHIA8 and HIJING generators are shown for the γp and MB pPb samples respectively. For the γp events, same $N_{trk}^{offline}$ bin arrangement as in Fig. 3 is kept while for pPb the bins [2, 5), [5, 10), [10, 15) and [15, 20) are used.

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).

References

[1] CMS Collaboration, Observation of long-range, near-side angular correlations in proton-proton collisions at the LHC, J. High Energy Phys. 09 (2010) 091, https://doi.org/10.1007/JHEP09(2010)091, arXiv:1009.4122.

[2] ATLAS Collaboration, Observation of long-range elliptic azimuthal anisotropies in $\sqrt{s}$ = 13 and 2.76 TeV pp collisions with the ATLAS detector, Phys. Rev. Lett. 116 (2016) 172301, https://doi.org/10.1103/PhysRevLett.116.172301, arXiv:1509.04776.

[3] CMS Collaboration, Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. Lett. 116 (2015) 172302, https://doi.org/10.1103/PhysRevLett.116.172302, arXiv:1510.03068.

[4] CMS Collaboration, Evidence for collectivity in pp collisions at the LHC, Phys. Lett. B 765 (2017) 193, https://doi.org/10.1016/j.physletb.2016.12.009, arXiv:1606.06198.

[5] ATLAS Collaboration, Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. Lett. 124 (2020) 082301, https://doi.org/10.1103/PhysRevLett.124.082301, arXiv:1909.01650.

[6] CMS Collaboration, Observation of long-range near-side angular correlations in pPb collisions at the LHC, Phys. Lett. B 718 (2013) 795, https://doi.org/10.1016/j.physletb.2012.11.025, arXiv:1210.5482.

[7] C. Aidala, et al., PHENIX, Measurement of long-range angular correlations and azimuthal anisotropies in high-multiplicity p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C 95 (2017) 034910, https://doi.org/10.1103/PhysRevC.95.034910, arXiv:1609.02894.

[8] C. Aidala, et al., PHENIX, Creation of quark-gluon plasma droplets with three distinct geometries, Nat. Phys. 15 (2019) 214, https://doi.org/10.1038/s41567-018-0360-0, arXiv:1805.02973.

[9] ATLAS Collaboration, Observation of associated near-side and away-side long-range correlations in $\sqrt{s_{_{NN}}} = 5.02$ TeV proton-lead collisions with the ATLAS detector, Phys. Rev. Lett. 110 (2013) 182302, https://doi.org/10.1103/PhysRevLett.110.182302, arXiv:1212.5198.

[10] ATLAS Collaboration, Measurement with the ATLAS detector of multi-particle azimuthal correlations in p+Pb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Lett. B 725 (2013) 60, https://doi.org/10.1016/j.physletb.2013.06.057, arXiv:1303.2084.

[11] ALICE Collaboration, Long-range angular correlations on the near and away side in p-Pb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Lett. B 719 (2013) 29, https://doi.org/10.1016/j.physletb.2013.01.012, arXiv:1212.2001.

[12] LHCb Collaboration, Measurements of long-range near-side angular correlations in $\sqrt{s_{_{NN}}} = 5$ TeV proton-lead collisions in the forward region, Phys. Lett. B 762 (2016) 473, https://doi.org/10.1016/j.physletb.2016.09.064, arXiv:1512.00439.

[13] ALICE Collaboration, Long-range angular correlations of π, K and p in pPb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Lett. B 726 (2013) 164, https://doi.org/10.1016/j.physletb.2013.08.024, arXiv:1307.3237.

[14] CMS Collaboration, Evidence for collective multiparticle correlations in p-Pb collisions, Phys. Rev. Lett. 115 (2015) 012301, https://doi.org/10.1103/PhysRevLett.115.012301, arXiv:1502.05382.

[15] CMS Collaboration, Long-range two-particle correlations of strange hadrons with charged particles in pPb and PbPb collisions at LHC energies, Phys. Lett. B 742 (2015) 200, https://doi.org/10.1016/j.physletb.2015.01.034, arXiv:1409.3392.

[16] ATLAS Collaboration, Measurement of multi-particle azimuthal correlations in pp, p+Pb and low multiplicity Pb+Pb collisions with the ATLAS detector, Eur. Phys. J. C 77 (2017) 428, https://doi.org/10.1140/epjc/s10052-017-4988-1, arXiv:1705.04176.

[17] ATLAS Collaboration, Measurement of long-range multiparticle azimuthal correlations with the subevent cumulant method in pp and p+Pb collisions with the ATLAS detector at the CERN large hadron collider, Phys. Rev. C 97 (2018) 024904, https://doi.org/10.1103/PhysRevC.97.024904, arXiv:1708.03559.

[18] J.-Y. Ollitrault, Anisotropy as a signature of transverse collective flow, Phys. Rev. D 46 (1992) 229, https://doi.org/10.1103/PhysRevD.46.229.

[19] U. Heinz, R. Snellings, Collective flow and viscosity in relativistic heavy-ion collisions, Annu. Rev. Nucl. Part. Sci. 63 (2013) 123, https://doi.org/10.1146/annurev-nucl-102212-170540, arXiv:1301.2826.

[20] C. Gale, S. Jeon, B. Schenke, Hydrodynamic modeling of heavy-ion collisions, Int. J. Mod. Phys. A 28 (2013) 1340011, https://doi.org/10.1142/S0217751X13400113, arXiv:1301.5893.

[21] K. Dusling, W. Li, B. Schenke, Novel collective phenomena in high-energy proton–proton and proton–nucleus collisions, Int. J. Mod. Phys. E 25 (2016) 1630002, https://doi.org/10.1142/S0218301316300022, arXiv:1509.07939.

[22] J.L. Nagle, J. Orjuela Koop, A quasiparticle transport explanation for collectivity in the smallest of collision systems (p + p and e^+e^-), Nucl. Phys. A 982 (2019) 455, https://doi.org/10.1016/j.nuclphysa.2018.09.005, arXiv:1807.04619.

[23] K.H. Ackermann, et al., STAR, Elliptic flow in au+au collisions at $\sqrt{s_{_{NN}}} = 130$ GeV, Phys. Rev. Lett. 86 (2001) 402, https://doi.org/10.1103/PhysRevLett.86.402, arXiv:nucl-ex/0009011.

[24] B. Alver, et al., PHOBOS, System size dependence of cluster properties from two-particle angular correlations in Cu+Cu and Au+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV, Phys. Rev. C 81 (2010) 024904, https://doi.org/10.1103/PhysRevC.81.024904, arXiv:0812.1172.

[25] CMS Collaboration, Long-range and short-range dihadron angular correlations in central PbPb collisions at a nucleon-nucleon center of mass energy of 2.76 TeV, J. High Energy Phys. 10 (2011) 076, https://doi.org/10.1007/JHEP07(2011)076, arXiv:1105.2438.

[26] 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) 10052, https://doi.org/10.1140/epjc/s10052-012-2012-3, arXiv:1201.3158.

[27] 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) 249–264, https://doi.org/10.1016/j.physletb.2012.01.060, arXiv:1109.2501.

[28] 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, https://doi.org/10.1103/PhysRevC.86.014907, arXiv:1203.3087.

[29] B.I. Abelev, et al., STAR, Long range rapidity correlations and jet production in high energy nuclear collisions, Phys. Rev. C 80 (2009) 064912, https://doi.org/10.1103/PhysRevC.80.064912, arXiv:0909.0191.

[30] B.I. Abelev, et al., STAR, Three-particle coincidence of the long range pseudorapidity correlation in high energy nucleus-nucleus collisions, Phys. Rev. Lett. 105 (2010) 022301, https://doi.org/10.1103/PhysRevLett.105.022301, arXiv:0912.3977.

[31] K. Adcox, et al., PHENIX, Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: experimental evaluation by the PHENIX collaboration, Nucl. Phys. A 757 (2005) 184, https://doi.org/10.1016/j.nuclphysa.2005.03.086, arXiv:nucl-ex/0410003.

[32] J. Adam, et al., STAR, Beam-energy dependence of identified two-particle angular correlations in $\sqrt{s_{_{NN}}} = 7.7 - 200$ GeV Au+Au collisions, Phys. Rev. C 101 (2020) 014916, https://doi.org/10.1103/PhysRevC.101.014916, arXiv:1906.09204.

[33] J. Adam, et al., STAR, Correlation measurements between flow harmonics in Au+Au collisions at RHIC, Phys. Lett. B 783 (2018) 459, https://doi.org/10.1016/j.physletb.2018.05.076, arXiv:1803.03876.

[34] S. Voloshin, Y. Zhang, Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions, Phys. Rev. C 70 (1996) 665, https://doi.org/10.1007/s002880050141, arXiv:hep-ph/9407282.

[35] B.H. Alver, C. Gombeaud, M. Luzum, J.-Y. Ollitrault, Triangular flow in hydrodynamics and transport theory, Phys. Rev. C 82 (2010) 034913, https://doi.org/10.1103/PhysRevC.82.034913, arXiv:1007.5469.

[36] C.G.B. Schenke, S. Jeon, Elliptic and triangular flow in event-by-event $D = 3 + 1$ viscous hydrodynamics, Phys. Rev. Lett. 106 (2011) 042301, https://doi.org/10.1103/PhysRevLett.106.042301, arXiv:1009.3244.

[37] C.S.Z. Qiu, U. Heinz, Hydrodynamic elliptic and triangular flow in Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, Phys. Lett. B 707 (2012) 151, https://doi.org/10.1016/j.physletb.2011.12.041, arXiv:1110.3033.

[38] B. Alver, G. Roland, Collision geometry fluctuations and triangular flow in heavy-ion collisions, Phys. Rev. C 81 (2010) 054905, https://doi.org/10.1103/PhysRevC.82.039903, arXiv:1003.0194, Phys. Rev. C 82 (2010) 039903 (Erratum).

[39] CMS Collaboration, Elliptic flow of charm and strange hadrons in high-multiplicity pPb collisions at $\sqrt{s_{_{NN}}} = 8.16$ TeV, Phys. Rev. Lett. 121 (2018) 082301, https://doi.org/10.1103/PhysRevLett.121.082301, arXiv:1804.09767.

[40] CMS Collaboration, Centrality and pseudorapidity dependence of the transverse energy density in pPb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Rev. C 100 (2019) 024902, https://doi.org/10.1103/PhysRevC.100.024902, arXiv:1810.05745.

[41] ALICE Collaboration, Multi-strange baryon production in pPb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Lett. B 758 (2016) 389, https://doi.org/10.1016/j.physletb.2016.05.027, arXiv:1512.07227.

[42] S.S. Adler, et al., PHENIX, Elliptic flow of identified hadrons in Au+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV, Phys. Rev. Lett. 91 (2003) 182301, https://doi.org/10.1103/PhysRevLett.91.182301, arXiv:nucl-ex/0305013.

[43] J. Adams, et al., STAR, Distributions of charged hadrons associated with high transverse momentum particles in pp and Au+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV, Phys. Rev. Lett. 95 (2005) 152301, https://doi.org/10.1103/PhysRevLett.95.152301, arXiv:nucl-ex/0501016.

[44] R.D. Weller, P. Romatschke, One fluid to rule them all: viscous hydrodynamic description of event-by-event central p+p, p+Pb and Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV, Phys. Lett. B 774 (2017) 351, https://doi.org/10.1016/j.physletb.2017.09.077, arXiv:1701.07145.

[45] P. Bozek, Collective flow in p-Pb and d-Pb collisions at TeV energies, Phys. Rev. C 85 (2012) 014911, https://doi.org/10.1103/PhysRevC.85.014911, arXiv:1112.0915.

[46] P. Bozek, W. Broniowski, Correlations from hydrodynamic flow in p-Pb collisions, Phys. Lett. B 718 (2013) 1557, https://doi.org/10.1016/j.physletb.2012.12.051, arXiv:1211.0845.

[47] P. Bozek, W. Broniowski, Collective dynamics in high-energy proton-nucleus collisions, Phys. Rev. C 88 (2013) 014903, https://doi.org/10.1103/PhysRevC.88.014903, arXiv:1304.3044.

[48] A. Badea, A. Baty, P. Chang, G.M. Innocenti, M. Maggi, C. Mcginn, M. Peters, T.-A. Sheng, J. Thaler, Y.-J. Lee, Measurements of two-particle correlations in e^+e^- collisions at 91 GeV with ALEPH archived data, Phys. Rev. Lett. 123 (2019) 212002, https://doi.org/10.1103/PhysRevLett.123.212002, arXiv:1906.00489.

[49] Y.C. Chen, et al., Belle, Measurement of two-particle correlations of hadrons in e^+e^- collisions at Belle, Phys. Rev. Lett. 128 (2022) 142005, https://doi.org/10.1103/PhysRevLett.128.142005, arXiv:2201.01694.

[50] I. Abt, et al., ZEUS, Two-particle azimuthal correlations as a probe of collective behaviour in deep inelastic ep scattering at HERA, J. High Energy Phys. 04 (2020) 070, https://doi.org/10.1007/JHEP04(2020)070, arXiv:1912.07431.

[51] I. Abt, et al., ZEUS, Azimuthal correlations in photoproduction and deep inelastic *ep* scattering at HERA, J. High Energy Phys. 12 (2021) 102, https://doi.org/10.1007/JHEP12(2021)102, arXiv:2106.12377.

[52] ATLAS Collaboration, Two-particle azimuthal correlations in photonuclear ultraperipheral Pb+Pb collisions at 5.02 TeV with ATLAS, Phys. Rev. C 104 (2021) 014903, https://doi.org/10.1103/PhysRevC.104.014903, arXiv:2101.10771.

[53] A.J. Baltz, The physics of ultraperipheral collisions at the LHC, Phys. Rep. 458 (2008) 1, https://doi.org/10.1016/j.physrep.2007.12.001, arXiv:0706.3356.

[54] C.F. von Weizsäcker, Radiation emitted in collisions of very fast electrons, Z. Phys. 88 (1934) 612, https://doi.org/10.1007/BF01333110.

[55] E.J. Williams, Nature of the high-energy particles of penetrating radiation and status of ionization and radiation formulae, Phys. Rev. 45 (1934) 729, https://doi.org/10.1103/PhysRev.45.729.

[56] E. Fermi, On the theory of collisions between atoms and electrically charged particles, Nuovo Cimento 2 (1925) 143, https://doi.org/10.1007/BF02961914, arXiv:hep-th/0205086.

[57] CMS Collaboration, Observation of correlated azimuthal anisotropy Fourier harmonics in pp and p+Pb collisions at the LHC, Phys. Rev. Lett. 120 (2018) 092301, https://doi.org/10.1103/PhysRevLett.120.092301, arXiv:1709.09189.

[58] I. Helenius, C.O. Rasmussen, Hard diffraction in photoproduction with PYTHIA 8, Eur. Phys. J. C 79 (2019) 413, https://doi.org/10.1140/epjc/s10052-019-6914-1, arXiv:1901.05261.
[59] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, M. Selvaggi, DELPHES 3, DELPHES 3, a modular framework for fast simulation of a generic collider experiment, J. High Energy Phys. 02 (2014) 057, https://doi.org/10.1007/JHEP02(2014)057, arXiv:1307.6346.
[60] X.-N. Wang, M. Gyulassy, HIJING: a Monte Carlo model for multiple jet production in pp, pA and AA collisions, Phys. Rev. D 44 (1991) 3501, https://doi.org/10.1103/PhysRevD.44.3501.
[61] S. Agostinelli, et al., GEANT4, GEANT4—a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.
[62] O. Surányi, et al., Performance of the CMS zero degree calorimeters in pPb collisions at the LHC, J. Instrum. 16 (2021) P05008, https://doi.org/10.1088/1748-0221/16/05/P05008, arXiv:2102.06640.
[63] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. 12 (2017) P10003, https://doi.org/10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
[64] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.
[65] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. 9 (2014) P10009, https://doi.org/10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.
[66] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, https://doi.org/10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
[67] CMS Collaboration, Pseudorapidity distributions of charged hadrons in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV, J. High Energy Phys. 01 (2018) 045, https://doi.org/10.1007/JHEP01(2018)045, arXiv:1710.09355.
[68] CMS Collaboration, First measurement of the forward rapidity gap distribution in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV, arXiv:2301.07630, 2023.
[69] ATLAS Collaboration, Rapidity gap cross sections measured with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C 72 (2012) 1926, https://doi.org/10.1140/epjc/s10052-012-1926-0, arXiv:1201.2808.
[70] CMS Collaboration, Measurement of diffraction dissociation cross sections in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. D 92 (2015) 012003, https://doi.org/10.1103/PhysRevD.92.012003, arXiv:1503.08689.
[71] J.D. Bjorken, Rapidity gaps and jets as a new physics signature in very high-energy hadron hadron collisions, Phys. Rev. D 47 (1993) 101, https://doi.org/10.1103/PhysRevD.47.101.
[72] CMS Collaboration, Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions, Phys. Lett. B 724 (2013) 213, https://doi.org/10.1016/j.physletb.2013.06.028, arXiv:1305.0609.
[73] H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Imprints of fluctuating proton shapes on flow in proton-lead collisions at the LHC, Phys. Lett. B 772 (2017) 681, https://doi.org/10.1016/j.physletb.2017.07.038, arXiv:1705.03177.
[74] HEPData record for this analysis, https://doi.org/10.17182/hepdata.89877, 2022.

The CMS Collaboration

A. Tumasyan [1]

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth [2], M. Jeitler [2], N. Krammer, L. Lechner, D. Liko, I. Mikulec, F.M. Pitters, N. Rad, J. Schieck [2], R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz [2], M. Zarucki

Institut für Hochenergiephysik, Vienna, Austria

M.R. Darwish [3], E.A. De Wolf, T. Janssen, T. Kello [4], A. Lelek, M. Pieters, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, A. Morton, D. Müller, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov [5], G. Mestdach, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Ghent University, Ghent, Belgium

A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, P. Vischia, S. Wertz, S. Wuyckens

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

G.A. Alves, C. Hensel, A. Moraes

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, E. Belchior Batista Das Chagas, H. Brandao Malbouisson, W. Carvalho, J. Chinellato [6], E. Coelho, E.M. Da Costa, G.G. Da Silveira [7], D. De Jesus Damiao, S. Fonseca De Souza, J. Martins [8], D. Matos Figueiredo, M. Medina Jaime [9], C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

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

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

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

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

University of Sofia, Sofia, Bulgaria

T. Cheng, W. Fang [4], Q. Guo, M. Mittal, H. Wang, L. Yuan

Beihang University, Beijing, China

M. Ahmad, G. Bauer, Z. Hu, Y. Wang, K. Yi [10,11]

Department of Physics, Tsinghua University, Beijing, China

E. Chapon, G.M. Chen [12], H.S. Chen [12], M. Chen, T. Javaid [12], A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu [13], R. Sharma, A. Spiezia, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, S. Zhang [12], J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

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

Z. You

Sun Yat-Sen University, Guangzhou, China

X. Gao [4]

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

M. Xiao

Zhejiang University, Hangzhou, Zhejiang, China

C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

Universidad de Antioquia, Medellin, Colombia

D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac, T. Sculac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov [14], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

University of Cyprus, Nicosia, Cyprus

M. Finger [14], M. Finger Jr. [14], A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

S. Abu Zeid [15], Y. Assran [16,17], E. Salama [17,15]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

A. Lotfy, M.A. Mahmoud

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, J. Pata, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, T. Tuuva

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro [18], M. Titov, G.B. Yu

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, R. Granier de Cassagnac, A. Hakimi, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

J.-L. Agram [19], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine [19], D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, K. Shchablo, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

G. Adamov, Z. Tsamalaidze [14]

Georgian Technical University, Tbilisi, Georgia

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M.P. Rauch, J. Schulz, M. Teroerde

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

C. Dziwok, G. Flügge, W. Haj Ahmad [20], O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl [21], T. Ziemons

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras [22], V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, A. De Wit, M.M. Defranchis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, E. Gallo [23], A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari [24], N.Z. Jomhari, A. Kasem [22], M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann [25], T. Madlener, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otarid, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, C. Schwanenberger, A. Singh, R.E. Sosa Ricardo, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev, R. Zlebcik

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, V. Kutzner, J. Lange, T. Lange, A. Malara, C.E.N. Niemeyer, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, B. Vormwald, I. Zoi

University of Hamburg, Hamburg, Germany

J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann [21], C. Heidecker, U. Husemann, I. Katkov [14], P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, Th. Müller, M. Musich, M. Neukum, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, R.F. Von Cube, M. Wassmer, M. Weber, R. Wolf, S. Wozniewski, S. Wunsch

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, G. Paspalaki, A. Stakia

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

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas

University of Ioánnina, Ioánnina, Greece

M. Bartók [26], M. Csanád, M.M.A. Gadallah [27], S. Lökös [28], P. Major, K. Mandal, A. Mehta, G. Pásztor, O. Surányi, G.I. Veres

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath [29], F. Sikler, V. Veszpremi, G. Vesztergombi [†,30]

Wigner Research Centre for Physics, Budapest, Hungary

S. Czellar, J. Karancsi [26], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo [31], F. Nemes [31], T. Novak

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra [32], R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi

Panjab University, Chandigarh, India

A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

University of Delhi, Delhi, India

M. Bharti [33], R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber [34], M. Maity [35], S. Nandan, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh [33], S. Thakur [33]

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Indian Institute of Technology Madras, Madras, India

D. Dutta, V. Jha, V. Kumar, D.K. Mishra, K. Naskar [36], P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, G.B. Mohanty, U. Sarkar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati [37], D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu [38], A. Nayak [38], N. Sur, S.K. Swain

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Dube, B. Kansal, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

H. Bakhshiansohi [39], M. Zeinali [40]

Isfahan University of Technology, Isfahan, Iran

S. Chenarani [41], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], R. Aly [a,c,42], 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], A. Di Pilato [a,b], W. Elmetenawee [a,b], L. Fiore [a], A. Gelmi [a,b], M. Gul [a], G. Iaselli [a,c], M. Ince [a,b], S. Lezki [a,b], G. Maggi [a,c], M. Maggi [a], I. Margjeka [a,b], V. Mastrapasqua [a,b], J.A. Merlin [a], S. My [a,b], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], A. Ranieri [a], G. Selvaggi [a,b], L. Silvestris [a], F.M. Simone [a,b], R. Venditti [a], P. Verwilligen [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana [a,b], D. Bonacorsi [a,b], L. Borgonovi [a], S. Braibant-Giacomelli [a,b], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], C. Ciocca [a], M. Cuffiani [a,b], G.M. Dallavalle [a], T. Diotalevi [a,b], F. Fabbri [a], A. Fanfani [a,b], E. Fontanesi [a,b], P. Giacomelli [a], L. Giommi [a,b], C. Grandi [a], L. Guiducci [a,b], F. Iemmi [a,b], S. Lo Meo [a,43], 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], N. Tosi [a]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b,44], S. Costa [a,b,44], A. Di Mattia [a], R. Potenza [a,b], A. Tricomi [a,b,44], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], A. Cassese [a], R. Ceccarelli [a,b], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], F. Fiori [a], 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]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo [a,b], F. Ferro [a], R. Mulargia [a,b], E. Robutti [a], S. Tosi [a,b]

[a] *INFN Sezione di Genova, Genova, Italy*

[b] Università di Genova, Genova, Italy

A. Benaglia [a], A. Beschi [a,b], F. Brivio [a,b], F. Cetorelli [a,b], V. Ciriolo [a,b,21], 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. Malberti [a], S. Malvezzi [a], A. Massironi [a], D. Menasce [a], F. Monti [a,b], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b], D. Valsecchi [a,b,21], D. Zuolo [a,b]

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

S. Buontempo [a], N. Cavallo [a,c], A. De Iorio [a,b], F. Fabozzi [a,c], F. Fienga [a], A.O.M. Iorio [a,b], L. Lista [a,b], S. Meola [a,d,21], P. Paolucci [a,21], B. Rossi [a], C. Sciacca [a,b]

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

P. Azzi [a], N. Bacchetta [a], D. Bisello [a,b], P. Bortignon [a], A. Bragagnolo [a,b], R. Carlin [a,b], P. Checchia [a], P. De Castro Manzano [a], T. Dorigo [a], F. Gasparini [a,b], U. Gasparini [a,b], S.Y. Hoh [a,b], L. Layer [a,45], M. Margoni [a,b], A.T. Meneguzzo [a,b], M. Presilla [a,b], P. Ronchese [a,b], R. Rossin [a,b], 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]

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

C. Aime' [a,b], A. Braghieri [a], S. Calzaferri [a,b], D. Fiorina [a,b], P. Montagna [a,b], S.P. Ratti [a,b], V. Re [a], M. Ressegotti [a,b], C. Riccardi [a,b], P. Salvini [a], I. Vai [a], P. Vitulo [a,b]

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

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

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

K. Androsov [a], P. Azzurri [a], G. Bagliesi [a], V. Bertacchi [a,c], L. Bianchini [a], T. Boccali [a], E. Bossini [a], R. Castaldi [a], M.A. Ciocci [a,b], R. Dell'Orso [a], M.R. Di Domenico [a,d], S. Donato [a], L. Giannini [a,c], A. Giassi [a], M.T. Grippo [a], F. Ligabue [a,c], E. Manca [a,c], G. Mandorli [a,c], A. Messineo [a,b], F. Palla [a], G. Ramirez-Sanchez [a,c], A. Rizzi [a,b], G. Rolandi [a,c], S. Roy Chowdhury [a,c], 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]

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

F. Cavallari [a], M. Cipriani [a,b], 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,b], R. Tramontano [a,b]

[a] INFN Sezione di Roma, Roma, Italy
[b] Sapienza Università di Roma, Roma, 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], J. Berenguer Antequera [a,b], C. Biino [a], A. Cappati [a,b], N. Cartiglia [a], S. Cometti [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], B. Kiani [a,b], F. Legger [a], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b],

V. Monaco [a,b], E. Monteil [a,b], M. Monteno [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], G.L. Pinna Angioni [a,b], M. Ruspa [a,c], R. Salvatico [a,b], 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,b]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale, Novara, Italy*

S. Belforte [a], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], A. Da Rold [a,b], G. Della Ricca [a,b], F. Vazzoler [a,b]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, B.C. Radburn-Smith, S. Sekmen, Y.C. Yang

Kyungpook National University, Daegu, Korea

H. Kim, D.H. Moon

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

B. Francois, T.J. Kim, J. Park

Hanyang University, Seoul, Korea

S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Korea University, Seoul, Korea

J. Goh, A. Gurtu

Kyung Hee University, Department of Physics, Seoul, Korea

H.S. Kim, Y. Kim

Sejong University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, K. Lee, S. Lee, K. Nam, B.H. Oh, M. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

Seoul National University, Seoul, Korea

D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

University of Seoul, Seoul, Korea

H.D. Yoo

Yonsei University, Department of Physics, Seoul, Korea

Y. Choi, C. Hwang, Y. Jeong, H. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Korea

Y. Maghrbi

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

V. Veckalns

Riga Technical University, Riga, Latvia

A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, A. Vaitkevicius

Vilnius University, Vilnius, Lithuania

W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [46], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

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

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramírez García, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

J. Mijuskovic [5], N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

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

V. Avati, L. Grzanka, M. Malawski

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

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

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

P. Adzic [47], M. Dordevic, P. Milenovic, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, 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, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, L. Urda Gómez, C. Willmott

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

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, S. Sanchez Cruz, A. Trapote

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

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

M.K. Jayananda, B. Kailasapathy [48], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka

T.K. Aarrestad, D. Abbaneo, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, E. Brondolin, T. Camporesi, M. Capeans Garrido, G. Cerminara, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, A. David, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita [49], D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Guilbaud, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, S. Mallios, M. Mannelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, T. Quast, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas [50], S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, M. Verzetti, K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada [51], W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, M. Missiroli, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, G. Perrin, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, J. Steggemann [52], R. Wallny, D.H. Zhu

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

C. Amsler [53], C. Botta, D. Brzhechko, M.F. Canelli, R. Del Burgo, J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, K. Schweiger, Y. Takahashi

Universität Zürich, Zurich, Switzerland

C. Adloff [54], C.M. Kuo, W. Lin, A. Roy, T. Sarkar [35], S.S. Yu

National Central University, Chung-Li, Taiwan

L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

F. Boran, S. Damarseckin [55], Z.S. Demiroglu, F. Dolek, C. Dozen [56], I. Dumanoglu [57], E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler [58], I. Hos [59], C. Isik, E.E. Kangal [60], O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir [61], A. Polatoz, A.E. Simsek, B. Tali [62], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

B. Isildak [63], G. Karapinar [64], K. Ocalan [65], M. Yalvac [66]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya [67], O. Kaya [68], Ö. Özçelik, S. Tekten [69], E.A. Yetkin [70]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak [57], Y. Komurcu, S. Sen [71]

Istanbul Technical University, Istanbul, Turkey

F. Aydogmus Sen, S. Cerci [62], B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci [62]

Istanbul University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

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

E. Bhal, S. Bologna, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou [72], J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [73], C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal [74], D. Colling, P. Dauncey, G. Davies, M. Della Negra, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash [75], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee [21], N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

S. Abdullin, A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith, J. Wilson

Baylor University, Waco, TX, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

Catholic University of America, Washington, DC, USA

A. Buccilli, O. Charaf, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, AL, USA

A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, D. Gastler, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, S. Yuan, D. Zou

Boston University, Boston, MA, USA

G. Benelli, B. Burkle, X. Coubez [22], D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan [76], K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, J. Luo, M. Narain, S. Sagir [77], R. Syarif, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

Brown University, Providence, RI, USA

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko [†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Y. Yao, F. Zhang

University of California, Davis, Davis, CA, USA

M. Bachtis, R. Cousins, A. Dasgupta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Los Angeles, CA, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, W. Si, S. Wimpenny, Y. Zhang

University of California, Riverside, Riverside, CA, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, J. Duarte, R. Gerosa, D. Gilbert, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, A. Vartak, F. Würthwein, A. Yagil

University of California, San Diego, La Jolla, CA, USA

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, B. Marsh, H. Mei, A. Ovcharova, H. Qu, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

University of California, Santa Barbara - Department of Physics, Santa Barbara, CA, USA

A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, J. Ngadiuba, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, CA, USA

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, I. Vorobiev

Carnegie Mellon University, Pittsburgh, PA, USA

J.P. Cumalat, W.T. Ford, E. MacDonald, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, CO, USA

J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, A. Datta, A. Frankenthal, K. Mcdermott, J. Monroy, J.R. Patterson, D. Quach, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Cornell University, Ithaca, NY, USA

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, D. Lincoln, R. Lipton, T. Liu, J. Lykken, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena [78], O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, A. Woodard

Fermi National Accelerator Laboratory, Batavia, IL, USA

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Sturdy, J. Wang, X. Zuo

University of Florida, Gainesville, FL, USA

T. Adams, A. Askew, D. Diaz, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida State University, Tallahassee, FL, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy [15], M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, FL, USA

M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu, Z. Ye

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

M. Alhusseini, K. Dilsiz [79], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili [80], A. Moeller, J. Nachtman, H. Ogul [81], Y. Onel, F. Ozok [82], A. Penzo, C. Snyder, E. Tiras [83], J. Wetzel

The University of Iowa, Iowa City, IA, USA

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

Johns Hopkins University, Baltimore, MD, USA

C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

The University of Kansas, Lawrence, KS, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, A. Mohammadi

Kansas State University, Manhattan, KS, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, CA, USA

E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

University of Maryland, College Park, MD, USA

D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, G. Gomez-Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, Z. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, MA, USA

R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Minnesota, Minneapolis, MN, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, MS, USA

K. Bloom, M. Bryson, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, C. Joo, I. Kravchenko, J.E. Siado, G.R. Snow[†], W. Tabb, F. Yan

University of Nebraska-Lincoln, Lincoln, NE, USA

G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio

State University of New York at Buffalo, Buffalo, NY, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, J. Li, 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

Northeastern University, Boston, MA, USA

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

Northwestern University, Evanston, IL, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko[14], R. Ruchti, P. Siddireddy, M. Wayne, A. Wightman, M. Wolf, L. Zygala

University of Notre Dame, Notre Dame, IN, USA

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

The Ohio State University, Columbus, OH, USA

F.M. Addesa, B. Bonham, P. Das, G. Dezoort, P. Elmer, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

Princeton University, Princeton, NJ, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, PR, USA

A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, S. Karmarkar, M. Liu, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic, N. Trevisani, F. Wang, A. Wildridge, R. Xiao, W. Xie

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar

Purdue University Northwest, Hammond, IN, USA

A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts [†], J. Rorie, W. Shi, A.G. Stahl Leiton

Rice University, Houston, TX, 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

University of Rochester, Rochester, NY, USA

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban [25], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

Rutgers, The State University of New Jersey, Piscataway, NJ, USA

H. Acharya, A.G. Delannoy, S. Spanier

University of Tennessee, Knoxville, TN, USA

O. Bouhali [84], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [85], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, TX, USA

N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Texas Tech University, Lubbock, TX, USA

E. Appelt, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, TN, USA

M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, E. Wolfe

University of Virginia, Charlottesville, VA, USA

P.E. Karchin, N. Poudyal, P. Thapa

Wayne State University, Detroit, MI, USA

K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-Reichert, W. Vetens

University of Wisconsin - Madison, Madison, WI, USA

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov [86], E. Boos, V. Borchsh, P. Bunin, O. Bychkova, M. Chadeeva [86], V. Chekhovsky, A. Dermenev, T. Dimova [86], I. Dremin, V. Epshteyn [87], A. Ershov, M. Gavrilenko, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev,

I. Golutvin, I. Gorbunov, A. Iuzhakov, V. Ivanchenko, Y. Ivanov, V. Kachanov, A. Kalinin, A. Kamenev, L. Kardapoltsev [86], V. Karjavine, A. Karneyeu, L. Khein, V. Kim [86], M. Kirakosyan, M. Kirsanov, O. Kodolova [88], D. Konstantinov, V. Korotkikh, N. Krasnikov, E. Kuznetsova [89], A. Lanev, A. Litomin, O. Lukina, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev [86], V. Murzin, A. Nikitenko [90], S. Obraztsov, V. Okhotnikov, V. Oreshkin, I. Ovtin [86], V. Palichik, A. Pashenkov, V. Perelygin, S. Petrushanko, D. Philippov, G. Pivovarov, V. Popov, E. Popova [91], V. Rusinov, G. Safronov, M. Savina, V. Savrin, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen [86], I. Smirnov, V. Smirnov, A. Snigirev, D. Sosnov, A. Spiridonov, A. Stepennov, J. Suarez Gonzalez, L. Sukhikh, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, D. Tlisov [†], M. Toms [92], A. Toropin, L. Uvarov, A. Uzunian, I. Vardanyan, E. Vlasov [93], S. Volkov, A. Vorobyev, N. Voytishin, A. Zarubin, I. Zhizhin, A. Zhokin

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

[†] 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 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[6] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[7] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[8] Also at UFMS, Nova Andradina, Brazil.
[9] Also at Universidade Federal de Pelotas, Pelotas, Brazil.
[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 University of Chinese Academy of Sciences, Beijing, China.
[14] Also at an institute or an international laboratory covered by a cooperation agreement with CERN.
[15] Also at Ain Shams University, Cairo, Egypt.
[16] Also at Suez University, Suez, Egypt.
[17] Now at British University in Egypt, Cairo, Egypt.
[18] Also at Purdue University, West Lafayette, Indiana, USA.
[19] Also at Université de Haute Alsace, Mulhouse, France.
[20] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[21] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[22] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[23] Also at University of Hamburg, Hamburg, Germany.
[24] Also at Isfahan University of Technology, Isfahan, Iran.
[25] Also at Brandenburg University of Technology, Cottbus, Germany.
[26] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[27] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[28] Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary.
[29] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[30] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[31] Also at Wigner Research Centre for Physics, Budapest, Hungary.
[32] Also at G.H.G. Khalsa College, Punjab, India.
[33] Also at Shoolini University, Solan, India.
[34] Also at University of Hyderabad, Hyderabad, India.
[35] Also at University of Visva-Bharati, Santiniketan, India.
[36] Also at Indian Institute of Technology (IIT), Mumbai, India.
[37] Also at IIT Bhubaneswar, Bhubaneswar, India.
[38] Also at Institute of Physics, Bhubaneswar, India.
[39] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[40] Also at Sharif University of Technology, Tehran, Iran.
[41] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[42] Also at Helwan University, Cairo, Egypt.
[43] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[44] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[45] Also at Università di Napoli 'Federico II', Napoli, Italy.
[46] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

[47] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[48] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[49] Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
[50] Also at National and Kapodistrian University of Athens, Athens, Greece.
[51] Also at Universität Zürich, Zurich, Switzerland.
[52] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[53] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[54] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[55] Also at Şırnak University, Sirnak, Turkey.
[56] Also at Department of Physics, Tsinghua University, Beijing, China.
[57] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[58] Also at Beykent University, Istanbul, Turkey.
[59] Also at Istanbul Aydin University, Application and Research Center for Advanced Studies, Istanbul, Turkey.
[60] Also at Mersin University, Mersin, Turkey.
[61] Also at Izmir Bakircay University, Izmir, Turkey.
[62] Also at Adiyaman University, Adiyaman, Turkey.
[63] Also at Ozyegin University, Istanbul, Turkey.
[64] Also at Izmir Institute of Technology, Izmir, Turkey.
[65] Also at Necmettin Erbakan University, Konya, Turkey.
[66] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[67] Also at Marmara University, Istanbul, Turkey.
[68] Also at Milli Savunma University, Istanbul, Turkey.
[69] Also at Kafkas University, Kars, Turkey.
[70] Also at Istanbul Bilgi University, Istanbul, Turkey.
[71] Also at Hacettepe University, Ankara, Turkey.
[72] Also at Vrije Universiteit Brussel, Brussel, Belgium.
[73] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[74] Also at IPPP Durham University, Durham, United Kingdom.
[75] Also at Monash University, Faculty of Science, Clayton, Australia.
[76] Also at Bethel University, St. Paul, Minnesota, USA.
[77] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[78] Also at California Institute of Technology, Pasadena, California, USA.
[79] Also at Bingol University, Bingol, Turkey.
[80] Also at Georgian Technical University, Tbilisi, Georgia.
[81] Also at Sinop University, Sinop, Turkey.
[82] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[83] Also at Erciyes University, Kayseri, Turkey.
[84] Also at Texas A&M University at Qatar, Doha, Qatar.
[85] Also at Kyungpook National University, Daegu, Korea.
[86] Also at another institute or international laboratory covered by a cooperation agreement with CERN.
[87] Now at Istanbul University, Istanbul, Turkey.
[88] Also at Yerevan Physics Institute, Yerevan, Armenia.
[89] Now at University of Florida, Gainesville, Florida, USA.
[90] Also at Imperial College, London, United Kingdom.
[91] Now at University of Rochester, Rochester, New York, USA.
[92] Now at Baylor University, Waco, Texas, USA.
[93] Now at INFN Sezione di Torino, Università di Torino, Torino, Italy; Università del Piemonte Orientale, Novara, Italy.