Phys. Lett. B 850 (2024) 138518

Contents lists available at ScienceDirect

Physics Letters B

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

Letter

Study of azimuthal anisotropy of $\Upsilon(1S)$ mesons in pPb collisions at $\sqrt{s_{NN}} = 8.16\,\text{TeV}$

The CMS Collaboration *

CERN, Geneva, Switzerland

ARTICLE INFO

Editor: M. Doser

Keywords:
CMS
pPb
Heavy ion
v2
Upsilon
Flow

ABSTRACT

The azimuthal anisotropy of $\Upsilon(1S)$ mesons in high-multiplicity proton-lead collisions is studied using data collected by the CMS experiment at a nucleon-nucleon center-of-mass energy of 8.16 TeV. The $\Upsilon(1S)$ mesons are reconstructed using their dimuon decay channel. The anisotropy is characterized by the second Fourier harmonic coefficients, found using a two-particle correlation technique, in which the $\Upsilon(1S)$ mesons are correlated with charged hadrons. A large pseudorapidity gap is used to suppress short-range correlations. Nonflow contamination from the dijet background is removed using a low-multiplicity subtraction method, and the results are presented as a function of $\Upsilon(1S)$ transverse momentum. The azimuthal anisotropies are smaller than those found for charmonia in proton-lead collisions at the same collision energy, but are consistent with values found for $\Upsilon(1S)$ mesons in lead-lead interactions at a nucleon-nucleon center-of-mass energy of 5.02 TeV.

1. Introduction

Substantial azimuthal (ϕ) correlations are observed among particles emitted over a wide pseudorapidity (η) range in heavy ion collisions at the BNL RHIC [1–5] and the CERN LHC [6–11]. These correlations are understood to arise from a nearly ideal hydrodynamic behavior of the strongly interacting quark-gluon plasma (QGP) created in such collisions [12–14]. Similar long-range correlations are also observed in high particle multiplicity events in smaller colliding systems, such as proton-proton (pp) [15–18], proton-lead (pPb) [19–27], proton-gold [28], deuteron-gold [29], and ^{3}He–gold [30,31]. The origin of the observed correlations in light systems is still under active investigation [32–35].

Heavy-flavor quarks (charm and bottom) are produced in the early stages of heavy ion collisions via hard scattering processes. Therefore, they experience the entire evolution of the produced medium [36], making them useful probes to study the properties of the created matter. The effect of the QGP medium on the propagating heavy-flavor quarks can be studied using the anisotropic azimuthal distribution of the emitted particles, which is experimentally characterized by its Fourier components. The second order coefficient, elliptic flow (v_2), reflects the anisotropy of the initial collision geometry [37]. Positive v_2 values have been reported for charmed mesons like D^0 (open charm) [38–42] at RHIC and LHC, in gold-gold and lead-lead (PbPb) collisions, respectively, indicating the presence of collective flow for charm quarks. The situation for J/ψ mesons (hidden charm) is less clear. In this case, the LHC results also support the presence of collective flow [43,44], but similar non-zero values were not observed at RHIC [45].

Positive v_2 values have also been found in high-multiplicity pPb collisions for D^0 and J/ψ mesons by the CMS Collaboration [46,47]. Measurements by the ATLAS [48] and CMS Collaborations [34] show indication of positive v_2 signals for charm quarks in high-multiplicity pp collisions. Also, muons for heavy-flavor hadron decays in high-multiplicity pPb collisions have positive v_2 values, as reported by the ALICE Collaboration [49]. These results suggest the possibility of collective flow for charm quarks in pp and pPb collisions. Bottom quarks, on the other hand, show little, if any, sign of collective flow in either heavy or light collision systems. Both ALICE [50] and CMS [51] have found v_2 values for the bottom quark $\Upsilon(1S)$ meson in PbPb collisions which are consistent with zero. Also, a dissociation transport model calculation predicts zero v_2 for $\Upsilon(1S)$ in pPb collisions [52]. Measurements by CMS of D^0 mesons arising from b hadron decays [34] in pp and pPb collisions, and by ATLAS of the azimuthal anisotropy of muons from bottom hadron decays in pp collisions [48], have also failed to find significant evidence of bottom quark flow. In order to further clarify the situation for heavy-quark flow in large and small systems, a measurement of the v_2 value for $\Upsilon(1S)$ mesons in pPb collisions will allow a more direct comparison of the flow of hidden charm and hidden bottom mesons in pPb. These measurements are particularly important in light of the uncertainty still remaining regarding the origin of collective behavior in lighter systems.

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

https://doi.org/10.1016/j.physletb.2024.138518
Received 4 October 2023; Received in revised form 8 January 2024; Accepted 4 February 2024
Available online 9 February 2024
0370-2693/© 2024 The Author(s). Published by Elsevier B.V. Funded by SCOAP³. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

This Letter reports measurements of v_2 values for $\Upsilon(1S)$ mesons based on long-range, two-particle correlations in high-multiplicity pPb collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 8.16$ TeV. The v_2 coefficient for the $\Upsilon(1S)$ meson is determined over a wide transverse momentum (p_T) range. To correct for the residual contribution from nonflow effects, such as back-to-back jet-like correlations, the v_2 results are presented after subtracting correlations obtained from low-multiplicity pPb events. The results for this analysis are tabulated in the HEPData record [53].

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, as well as a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The hadron forward (HF) calorimeters, located at $3 < |\eta| < 5$, extend the η coverage provided by the barrel and endcap detectors. The HF calorimeters are azimuthally subdivided into 20° modular wedges and further segmented to form 0.175×0.175 radians ($\Delta\eta\times\Delta\phi$) towers. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid within the coverage of $|\eta| < 2.4$. Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of about 100 kHz within a fixed latency of about 4 μs [54]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing. The HLT reduces the event rate to about 1 kHz before data storage [55]. 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. [56].

3. Event selection

This analysis uses pPb collision data collected with the CMS detector in 2016, corresponding to an integrated luminosity of 186 nb^{-1} [57,58]. Events are selected by the Level-1 trigger requiring two muon candidates reconstructed in the muon detectors using the loosest possible selection criteria to maximize detection efficiency. Additional event selection criteria are applied to remove beam-gas interaction as discussed in [59]. Also, at least one HF tower on each side is required to have transverse energy $E_T > 3$ GeV in order to reject non-hadronic collisions. Pileup events, where multiple overlapping collisions occur in a single bunch crossing, are rejected by requiring that only one primary vertex be found within 15 cm from the nominal interaction point along the beam axis and within 0.2 cm of the beam axis in the transverse direction.

The azimuthal anisotropy results are reported for high-multiplicity events in the range $70 \le N_{trk}^{offline} < 300$, where $N_{trk}^{offline}$ is the number of reconstructed primary charged-particle tracks [60] with $|\eta| < 2.4$ and $p_T > 0.4$ GeV/c. This range corresponds to the 25% of minimum bias events with the highest particle multiplicities. Events with $N_{trk}^{offline} < 50$ (corresponding to the 40% of events with the lowest particle multiplicities) are also used to estimate the possible contribution of residual back-to-back jet-like correlations. Similar selection criteria and background corrections have been used in previous pp and pPb analyses [32,61,62].

To keep only high-quality muons, a set of offline selection criteria are applied to select "soft" muons [63,64]. A soft muon is required to have a matched reconstructed track in the inner tracking system. This track must have at least six silicon tracker (pixel+strip) hits, with at least one of these hits occurring in the silicon pixel tracker. In addition, the distance of the closest approach of a muon track to the primary vertex must be less than 0.3 cm and 20 cm in the transverse and longitudinal directions, respectively. Also, the pairs of oppositely charged muons are fitted with a common vertex constraint, and the χ^2 probability calculated by a Kalman vertex filter fit [65] is required to be greater than 1%. Lastly, the muons are selected in the kinematic range $p_T^{\mu} > 3.5$ GeV/c and $|\eta^{\mu}| < 2.4$ to ensure high efficiency for the $\Upsilon(1S)$ meson reconstruction. The $|\eta^{\mu}| < 2.4$ range corresponds to the center-of-mass pseudorapidity range of $-2.87 < \eta_{CM}^{\mu} < 1.93$.

4. Analysis

4.1. Two-particle correlation technique

The Υ signals are reconstructed using their dimuon decay channel. The invariant mass of the selected dimuons is studied in the range 8–14 GeV/c^2, which covers the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonance peaks, and which is sufficient to ensure the stability of the description of the background dimuon distribution in the high-mass region [66].

In calculating the invariant mass distribution and in determining the anisotropy of the detected particles, acceptance and efficiency corrections are applied event-by-event. Acceptance is defined as the probability for both decay muons originating from an Υ meson to have $p_T^{\mu} > 3.5$ GeV/c and $|\eta^{\mu}| < 2.4$. The efficiency correction is determined as a function of p_T using the PYTHIA 8.212 [67] Monte Carlo (MC) generator with tune CUETP8M1 [68] and its range is 0.74–0.98. The PYTHIA MC samples are embedded in pPb MC events generated by EPOS LHC [69] that simulate underlying background events. The MC events are reweighted such that the p_T spectra of $\Upsilon(1S)$ mesons match the ones in pPb data. The efficiency values are found to not significantly depend on multiplicity, as also found in previous bottomonium and charmonium studies for pPb collisions [70,71]. The efficiency, calculated using a full simulation of the CMS detector based on GEANT4 [72], gives the fraction of dimuons within the acceptance that are reconstructed, satisfy the trigger selection, and pass the analysis selection criteria described in Section 3. An additional correction to the dimuon efficiency is applied to take into account possible differences between data and MC simulation using the "tag-and-probe" method with muon pairs from J/ψ meson decays [63]. This technique calculates the single-muon efficiency in both data and simulation by requiring a tight selection on one muon (the "tag" muon), which is then paired with the other muon that has looser selection criteria (the "probe" muon). The ratio of the single-muon efficiency in data to that in simulation is applied as an event-by-event weight to the dimuon efficiency in simulation. The systematic uncertainty originating from the scale factor is calculated by varying its value by its uncertainty.

The v_n harmonics for the Υ particles are measured using the long-range ($|\Delta\eta| > 1$) two-particle correlation technique previously discussed in Refs. [6,7,19]. The Υ candidates (trigger particles) with transverse momentum p_T^{trig} in the ranges [0, 3], [3, 6], [6, 10], [10, 30] GeV/c are coupled with the charged tracks (associated particles) with transverse momentum $0.3 < p_T^{assoc} < 3$ GeV/c and pseudorapidity $|\eta^{assoc}| < 2.4$. The associated particle yields are corrected for the detector acceptance, reconstruction efficiency, and fractions of misidentified tracks [18].

The per-trigger-particle associated yield distribution is defined by

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

where $\Delta\eta$ and $\Delta\phi$ are differences in η and ϕ of the pair, N_{trig} and N_{pair} are the numbers of trigger particles and trigger-associated pairs, respectively, in the event. This analysis procedure is repeated for each $m_{\mu^+\mu^-}$ and p_T interval. The S($\Delta\eta$, $\Delta\phi$) distribution represents the per-trigger particle yield of trigger-associated pairs from the same event ($m_{\mu^+\mu^-}$, p_T) range. A mixed-event pair yield distribution, B($\Delta\eta$, $\Delta\phi$), is constructed by pairing the Υ candidates with charged-particle tracks from different events to account for the combinatorial background and

pair-acceptance effects. The normalization factor, B(0, 0), is the mixed-events yield for both particles of the pair going in the same direction, corresponding to the maximum pair-acceptance. The sample of mixed events is formed by randomly selecting ten events from the same multiplicity ($N_{\rm trk}^{\rm offline}$) and $p_{\rm T}$ ranges that fall within the same 2 cm wide longitudinal primary vertex range as the Υ candidate event. The specific multiplicity range limits for the mixed events are [70, 80], [80, 90], [90, 110], [110, 150], [150, 300] and [0, 35], [35, 50] for high- and low-multiplicity events, respectively. The ranges are combined for the final reported results. These multiplicity ranges are selected to have similar Υ candidate yields. We also report a result for the extended $p_{\rm T}$ range of 0–30 GeV/c, by combining the per-trigger-particle associated yield distribution from individual $p_{\rm T}$ intervals.

Both signal and background distributions are normalized by $N_{\rm trig}$ after summing up the pair density distributions and the total number of the trigger particles for all events. To quantify the correlation structure, the two-dimensional (2D) distributions are projected onto 1D distributions in $\Delta\phi$ by averaging over the $\Delta\eta$ range.

4.2. Elliptic flow extraction

The dimuon invariant mass spectrum for the Υ candidates is fitted using a signal function, Sig($m_{\mu^+\mu^-}$), and a background function, Bkg($m_{\mu^+\mu^-}$), to describe the Υ signals and background dimuons, respectively. To take into account the different momentum resolutions of the muons in the endcap and barrel sections, a sum of two Crystal Ball (CB) functions [73] is used to model each Υ state. The width parameters for the two CB functions are allowed to vary independently, while the mean and radiative-tail parameters are set to be equal. All parameters are kept to be the same among the three Υ states except for the mean and width parameters, which have values for the excited states, Υ(2S) and Υ(3S), that are equal to those for the Υ(1S) state multiplied by the PDG [74] mass ratios to the Υ(1S) state. The Bkg($m_{\mu^+\mu^-}$) is formed by taking the product of an exponential function, which models the combinatorial mass distribution in the high-mass region, and an error function, which models the saturation that occurs because of the muon $p_{\rm T}$ cutoff. The yield parameters for the Υ signals $N_{1\rm S}$, $N_{2\rm S}$, and $N_{3\rm S}$, and the background dimuons $N_{\rm Bkg}$ are left free in the fit. More details about the fitting procedure can be found in Ref. [51].

For the elliptic flow extraction, the azimuthal anisotropy harmonics are determined from a Fourier decomposition,

$$\frac{1}{N_{\rm trig}}\frac{{\rm d}N_{\rm pair}}{{\rm d}\Delta\phi} = \frac{N_{\rm assoc}}{2\pi}\left\{1+\sum_n 2V_n\cos(n\Delta\phi)\right\}, \quad (2)$$

where V_n are the Fourier coefficients and $N_{\rm assoc}$ represents the total number of pairs per trigger particle for a given ($p_{\rm T}^{\rm trig}, p_{\rm T}^{\rm assoc}$) range; V_n is assumed to be the product of single-particle anisotropies of Υ(1S) mesons and reference charged particles [62]. The Fourier coefficients are studied across the dimuons invariant mass range, by dividing it into 23 intervals. The number of intervals is chosen to ensure similar yield in each $m_{\mu^+\mu^-}$ interval. The number of intervals was varied and found to have little effect on the final results. The first three terms of the Fourier series $V_n^{\rm Sig+Bkg}$, with n = 1, 2, and 3, capture the most significant components and are determined for each $m_{\mu^+\mu^-}$ interval using a binned χ^2 fit. Fig. 1 shows a typical $\Delta\phi$ projection fit.

The signal component of the V_2 coefficient is found using a simultaneous binned χ^2 fit of the invariant mass and V_2 distribution, with

$$V_2^{\rm Sig+Bkg}(m_{\mu^+\mu^-}) = \alpha_1(m_{\mu^+\mu^-})V_2^{\Upsilon(1S)} + \alpha_2(m_{\mu^+\mu^-})V_2^{\Upsilon(2S)} + \alpha_3(m_{\mu^+\mu^-})V_2^{\Upsilon(3S)} + [1-\alpha_1(m_{\mu^+\mu^-}) - \alpha_2(m_{\mu^+\mu^-}) - \alpha_3(m_{\mu^+\mu^-})]v_2^{\rm Bkg}(m_{\mu^+\mu^-}), \quad (3)$$

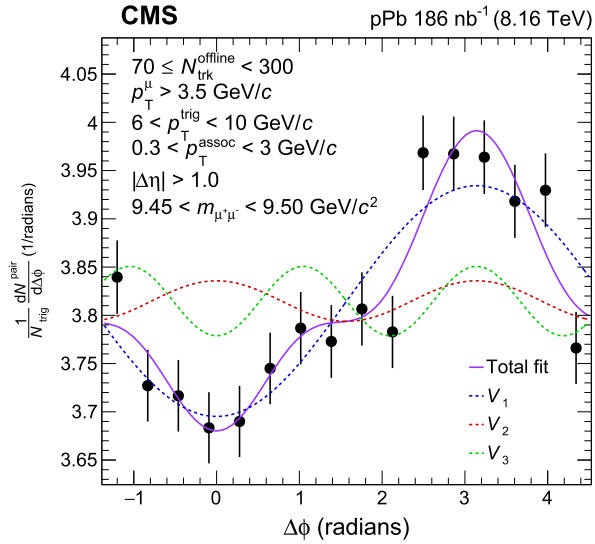

Fig. 1. The $\Delta\phi$ projection of the Υ(1S)-track correlation function for the long-range correlation region ($|\Delta\eta| > 1$) in high-multiplicity events ($70 \le N_{\rm trk}^{\rm offline} < 300$). The three dashed lines represent the first three Fourier coefficients V_1 (blue), V_2 (red), V_3 (green); the magenta solid line corresponds to the total fit.

where $V_2^{\Upsilon(iS)}$ ($i = 1,2,3$) is the V_2 value for the Υ(iS) mesons and is assumed to be independent of $m_{\mu^+\mu^-}$. The V_2 distribution of the background dimuons as a function of mass, $V_2^{\rm Bkg}(m_{\mu^+\mu^-})$, is described by a second order polynomial function. The $\alpha_i(m_{\mu^+\mu^-})$ factors are the signal fractions for the Υ(iS) states as a function of $m_{\mu^+\mu^-}$, as given by

$$\alpha_i(m_{\mu^+\mu^-}) = {\rm Sig}_{\Upsilon(iS)}(m_{\mu^+\mu^-})/[{\rm Sig}_{\Upsilon(1S)}(m_{\mu^+\mu^-}) + {\rm Sig}_{\Upsilon(2S)}(m_{\mu^+\mu^-}) + {\rm Sig}_{\Upsilon(3S)}(m_{\mu^+\mu^-}) + {\rm Bkg}(m_{\mu^+\mu^-})]. \quad (4)$$

Fig. 2 shows the fit to the mass spectrum and $V_2^{\rm Sig+Bkg}$ as a function of the invariant mass for dimuon pairs with $0 < p_{\rm T}^{\rm trig} < 3$ GeV/c (the lowest $p_{\rm T}$ range) and event multiplicities $70 \le N_{\rm trk}^{\rm offline} < 300$.

4.3. Dijet subtraction

The back-to-back nature of dijets can result in a significant V_2 signal even if there is a large $\Delta\eta$ gap between the Υ(1S) trigger particles and the associated charged hadrons. This nonflow contribution is subtracted using the low-multiplicity subtraction method developed in Refs. [18,62]. The $V_2^{\rm Sig}$ values for $N_{\rm trk}^{\rm offline} < 50$ are subtracted from the corresponding values in the higher multiplicity region, with

$$V_2^{\rm sub} = V_2^{\rm Sig}(70 \le N_{\rm trk}^{\rm offline} < 300) - V_2^{\rm Sig}(N_{\rm trk}^{\rm offline} < 50) \times \frac{N_{\rm assoc}(N_{\rm trk}^{\rm offline} < 50)}{N_{\rm assoc}(70 \le N_{\rm trk}^{\rm offline} < 300)} \times \frac{J_{\rm jet}(70 \le N_{\rm trk}^{\rm offline} < 300)}{J_{\rm jet}(N_{\rm trk}^{\rm offline} < 50)}, \quad (5)$$

where $J_{\rm jet}$ represents the near-side jet yield, which is defined as the integral in the short-range region ($|\Delta\eta| < 1$) of the 1D $\Delta\phi$ correlation functions. The associated ratio, $N_{\rm assoc}(N_{\rm trk}^{\rm offline} < 50)/N_{\rm assoc}(70 \le N_{\rm trk}^{\rm offline} < 300)$, is introduced to account for the enhanced jet yield due to the difference in the associated track yield regardless of the $\Delta\eta$ gap. The ratio, $J_{\rm jet}(70 \le N_{\rm trk}^{\rm offline} < 300)/J_{\rm jet}(N_{\rm trk}^{\rm offline} < 50)$, is introduced to

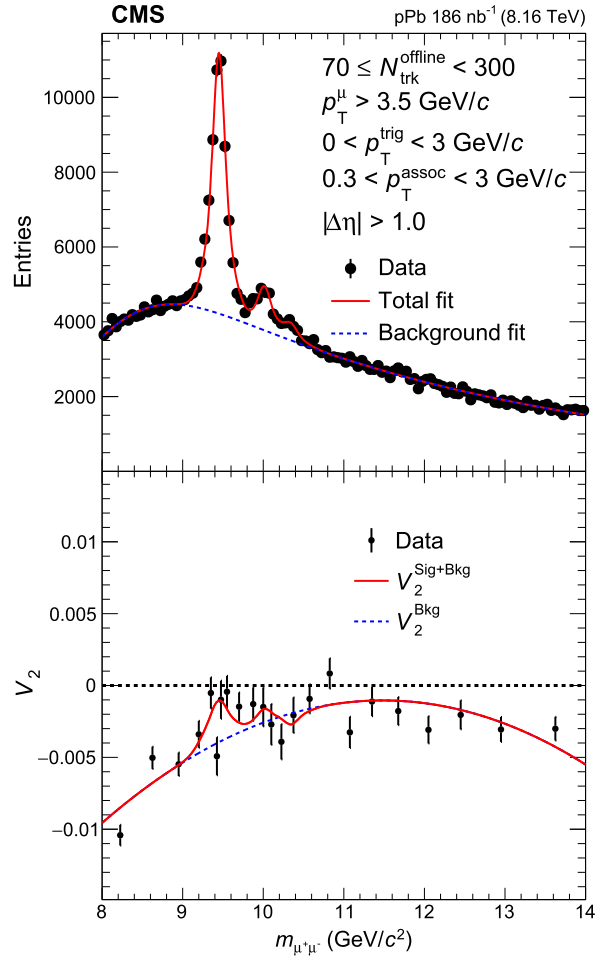

Fig. 2. Simultaneous fit of the $m_{\mu^+\mu^-}$ and V_2 distributions for high-multiplicity ($70 \le N_{trk}^{offline} < 300$) pPb events. The symbols indicate the event yields in the upper plot and V_2 values from the Fourier component fit in the lower plot. The red solid (blue dash) lines correspond to the total (background) simultaneous fit to both distributions.

account for the enhanced jet correlations resulting from the selection of higher-multiplicity events. For $p_T < 10$ GeV/c, where the $\Upsilon(1S)$ candidates tend to have values of η outside the acceptance for charged particles (of $|\eta| < 2.4$), the jet yield ratio cannot be directly estimated from the two-particle azimuthal correlations. In this case, based on previous analyses in the charm sector where no p_T dependence was observed [46,47], the jet yield ratio value is assumed to be the same as that for the high-p_T region. The $\Upsilon(1S)$ V_2 results, after subtracting the correlations obtained from low-multiplicity events, are denoted as V_2^{sub}.

To determine the $\Upsilon(1S)$ v_2 values, factorization is assumed, where the two-particle V_2 value is taken as the product of single particle v_2 values for the trigger $\Upsilon(1S)$ particle and the associated charged hadrons, with

$$v_2^{sub}(p_T^{trig}) = \frac{V_2^{sub}(p_T^{trig}, p_T^{assoc})}{\sqrt{V_2^{sub}(p_T^{assoc}, p_T^{assoc})}}. \quad (6)$$

The quantity $V_2^{sub}(p_T^{assoc}, p_T^{assoc})$ represents the Fourier coefficients extracted by correlating two reference charged particles.

5. Systematic uncertainties

The systematic uncertainties from acceptance and efficiency corrections are estimated by comparing the v_2^{sub} values with and without applying the corrections. To account for the differences between MC simulation and data for the single-muon efficiency, an additional correction factor from the tag-and-probe technique is used. The difference between the resulting v_2^{sub} and the nominal v_2^{sub} value is taken as the systematic uncertainty for this source.

Table 1
Absolute systematic uncertainties (10^{-2}) included in the measurement of v_2^{sub} evaluated in different $p_T^{\Upsilon(1S)}$ ranges (in Ge V / c).

Systematic source	$p_T^{\Upsilon(1S)}$ range in GeV/c.				
	[0-3]	[3-6]	[6-10]	[10-30]	[0-30]
Acceptance	0.04	0.05	0.10	0.26	0.07
Efficiency	0.01	0.01	0.02	0.05	0.05
Tag-and-probe technique	0.11	0.10	0.03	0.07	0.03
Signal function	0.06	0.03	0.02	0.21	0.10
Background function	0.03	0.01	0.13	0.59	0.12
V_2 background function	0.31	0.07	0.12	0.03	0.07
Parameter choice	0.06	0.01	0.04	0.07	0.01
Jet ratio	0.32	0.43	2.18	1.88	0.45
MC closure test	0.66	0.23	0.35	0.32	0.50
Total	0.81	0.51	2.22	2.03	0.70

To estimate the systematic uncertainty for the fit procedure, alternative functions are used instead of the nominal functions. A sum of Crystal Ball and Gaussian functions is used as an alternative function for the signal mass distribution. For the background template, a fourth-order polynomial is used to replace the product of the error function and the exponential function. The background function in the $V_2^{Sig+Bkg}$ shape is also changed, from a second-order to a third-order polynomial.

In the simultaneous fitting step described in Section 4.2, all parameters for the Sig($m_{\mu^+\mu^-}$) and Bkg($m_{\mu^+\mu^-}$), except the yields for the Υ states and the background dimuons, are fixed to achieve fit stability. The uncertainties associated with holding these fit parameters fixed are studied by releasing them, one by one, and redoing the fit. The differences between the nominal v_2^{sub} values and those where a parameter is allowed to vary are determined, and the root-mean-square average value is taken as the fit uncertainty.

The final v_2^{sub} value can be affected by the amount of low-multiplicity subtraction. The systematic uncertainty associated with this effect is estimated by varying the jet ratio in Eq. (5) by $\pm 3\sigma$ for $p_T < 10$ GeV/c, and by $\pm 1\sigma$ for $p_T > 10$ GeV/c; here, σ is the standard deviation of the jet ratio, as obtained by fitting the $\Delta\phi$ distribution for $\Delta\eta < 1$. In this analysis, jets are mostly produced in the same direction as the $\Upsilon(1S)$ particles. As the geometrical acceptance in the CMS detector for charged particles is $|\eta| < 2.4$, we lose part of the jet tracks (the ones at $|\eta^{trk}| > 2.4$) when the $\Upsilon(1S)$ is in the high-$|\eta|$ region around 2.4. This leads to a truncation of jets in the $\Delta\eta\Delta\phi$ 2D distribution. Because such truncations are mostly found at low-p_T, the jet yield ratio is calculated from the fit using only the high-p_T region. Hence, a larger variation is considered for the p_T ranges below 10 GeV/c.

The response of the CMS detector to the MC generated particles was simulated using the GEANT4 toolkit. To check the robustness of the full simulation, a closure test is performed by comparing generator- and reconstruction-level results in the MC simulation. The uncertainty associated with this closure test is in the range 0.002–0.007.

Individual systematic uncertainties are expected to be uncorrelated, and are therefore added in quadrature to obtain the final quoted values. Systematic uncertainties from HLT trigger biases and pileup effects are assumed to be the same for $\Upsilon(1S)$ particles and charged particles and, consequently, they cancel in applying Eq. (6).

The systematic uncertainties for each source are listed in Table 1. The total systematic uncertainty for the measured v_2^{sub} values, taken as the sum in quadrature of all sources considered, is in the range 0.005–0.022, depending on the $\Upsilon(1S)$ meson p_T. Because of the low yield of dimuons in the highest p_T interval, the uncertainties for the signal extraction in the mass fit (signal function and background function) are found to be the largest for this interval. The uncertainty is

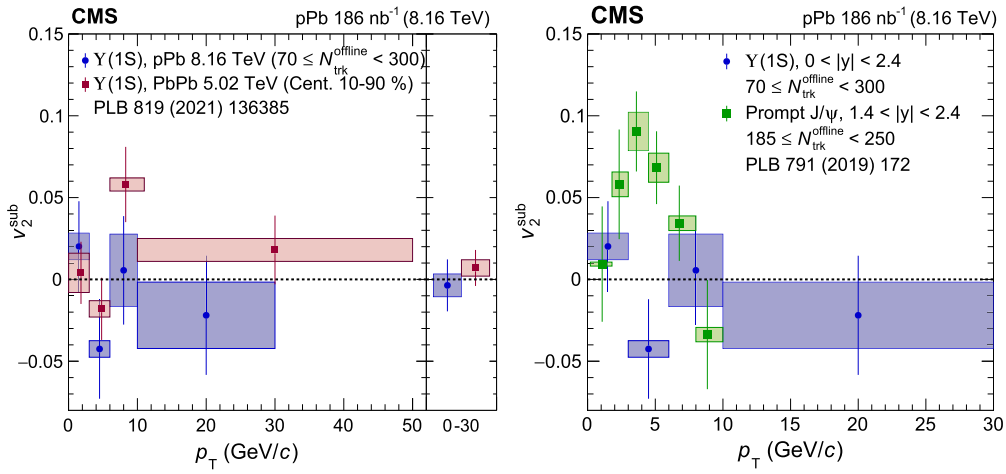

Fig. 3. The p_T dependent v_2^{sub} values of Υ(1S) mesons measured in the high-multiplicity region $70 \leq N_{trk}^{offline} < 300$, where a low-multiplicity region $N_{trk}^{offline} < 50$ is used to estimate and correct for the dijet contribution. (Left) The results are compared to the corresponding results from PbPb collisions at 5.02 Te V, measured within the 10–90% centrality range [51]. The integrated range is 0–50 Ge V / c for PbPb. (Right) The same distribution is also compared with the v_2^{sub} values for prompt J/ψ mesons within $1.4 < |y| < 2.4$ in pPb collisions at 8.16 Te V for $185 \leq N_{trk}^{offline} < 250$, where a low-multiplicity range with $N_{trk}^{offline} < 35$ was used to estimate and correct for the dijet contribution [47]. The vertical bars denote statistical uncertainties and the shaded boxes represent systematic uncertainties, while the widths of the boxes represent the p_T ranges.

dominated by the MC closure test, the background function, the jet ratio, and the V_2 background function.

6. Results

Fig. 3 shows the comparison of the current v_2^{sub} results for Υ(1S) mesons in pPb collisions with those for Υ(1S) in PbPb (left panel) [51] and J/ψ in pPb (right panel) [47], as a function of the Υ(1S) meson p_T. The symbols are plotted at the center of each p_T range. The average p_T for the highest range is found to be around 15 GeV/c. The observed v_2^{sub} values for Υ(1S) in pPb are consistent with zero over the measured p_T range, as also found for centrality-integrated PbPb data. This suggests that the azimuthal anisotropy of Υ(1S) mesons does not significantly depend on the size of the system despite the different level of suppression in pPb and PbPb collisions [71]. Future v_2 measurements for the excited states with larger data sets would be an interesting subject to further study the medium response of bottomonia in small collision systems. In Fig. 3 (right), we also compare our results with those of J/ψ mesons, which exhibit significant flow-related correlations for the range of $0 < p_T < 10$ GeV/c [47]. It should be noted that the $N_{trk}^{offline}$ ranges are different for the J/ψ and Υ(1S) measurements. Restricting the Υ(1S) study to an $N_{trk}^{offline}$ range similar to that for the J/ψ analysis does not significantly change the observed Υ(1S) distribution, although it does increase the statistical uncertainties. In contrast to the Υ(1S) results, positive v_2^{sub} values are reported for J/ψ mesons in the range $2 < p_T < 8$ GeV/c. To investigate the variation in v_2^{sub} for these two quarkonium species, a p-value comparison is employed. The p-value determined for each J/ψ v_2^{sub} value against the hypothesis of an equivalent v_2^{sub} value for Υ(1S) mesons in the p_T integrated range, taking into account the given uncertainties. Notably, in the range $2 < p_T < 8$ GeV/c, p-values less than 0.05, indicating dissimilar results, are observed for the two J/ψ p_T intervals within the range $3 < p_T < 6$ GeV/c, with p-values of 0.0035 and 0.0150, respectively. This indicates that bottom quarks experience less collective motion, if any, than charm quarks in pPb collisions.

7. Summary

The azimuthal anisotropy of Υ(1S) mesons, as quantified using the elliptic flow coefficients v_2^{sub}, is measured as a function of transverse momentum for the first time in high-multiplicity proton-lead (pPb) collision events at the center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 8.16$ TeV. The measurement is corrected for dijet background using a low-multiplicity subtraction method. The v_2^{sub} values are observed to be consistent with zero. These results are also consistent with those found previously in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Comparing v_2^{sub} of Υ(1S) and those of J/ψ mesons, the results suggest that any collectivity of bottomonia is smaller than that of charmonia in pPb collisions. The direct comparison of Υ(1S) flow results for pPb and PbPb reinforces the conclusion that there is no evidence for collective flow of bottom quarks in systems of any size.

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

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

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid and other centres 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: SC (Armenia), 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); SRNSF (Georgia); 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 programme and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); 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 and Fundamental Research Funds for the Central Universities (China); The Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); 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; ICSC – National Research Centre for High Performance Computing, Big Data and Quantum Computing, funded by the EU NexGeneration program (Italy); 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] 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.

[2] K. Adcox, et al., PHENIX, Flow measurements via two-particle azimuthal correlations in Au+Au collisions at $\sqrt{s_{_{NN}}} = 130$ GeV, Phys. Rev. Lett. 89 (2002) 212301, https://doi.org/10.1103/PhysRevLett.89.212301, arXiv:nucl-ex/0204005.

[3] B.B. Back, et al., PHOBOS, Energy dependence of elliptic flow over a large pseudorapidity range in Au+Au collisions at the BNL relativistic heavy ion collider, Phys. Rev. Lett. 94 (2005) 122303, https://doi.org/10.1103/PhysRevLett.94.122303, arXiv:nucl-ex/0406021.

[4] 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.

[5] B. Alver, et al., PHOBOS, High transverse momentum triggered correlations over a large pseudorapidity acceptance in Au+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV, Phys. Rev. Lett. 104 (2010) 062301, https://doi.org/10.1103/PhysRevLett.104.062301, arXiv:0903.2811.

[6] CMS Collaboration, Long-range and short-range dihadron angular correlations in central PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, J. High Energy Phys. 07 (2011) 076, https://doi.org/10.1007/JHEP07(2011)076, arXiv:1105.2438.

[7] CMS Collaboration, Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb at $\sqrt{s_{_{NN}}} = 2.76$ TeV, Eur. Phys. J. C 72 (2012) 2012, https://doi.org/10.1140/epjc/s10052-012-2012-3, arXiv:1201.3158.

[8] ALICE Collaboration, Elliptic flow of charged particles in Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, Phys. Rev. Lett. 105 (2010) 252302, https://doi.org/10.1103/PhysRevLett.105.252302, arXiv:1011.3914.

[9] 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.

[10] CMS Collaboration, Measurement of the elliptic anisotropy of charged particles produced in PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, Phys. Rev. C 87 (2013) 014902, https://doi.org/10.1103/PhysRevC.87.014902, arXiv:1204.1409.

[11] CMS Collaboration, Studies of azimuthal dihadron correlations in ultra-central PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, J. High Energy Phys. 02 (2014) 088, https://doi.org/10.1007/JHEP02(2014)088, arXiv:1312.1845.

[12] 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.

[13] R.S.U. Heinz, 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.

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

[15] 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.

[16] 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.

[17] CMS Collaboration, Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. Lett. 116 (2016) 172302, https://doi.org/10.1103/PhysRevLett.116.172302, arXiv:1510.03068.

[18] 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.

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

[20] ALICE Collaboration, Long-range angular correlations on the near and away side in pPb 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.

[21] 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.

[22] LHCb Collaboration, Measurements of long-range near-side angular correlations in $\sqrt{s_{_{NN}}} = 5.02$ 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.

[23] ALICE Collaboration, Long-range angular correlations of π, K and p in p-Pb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Lett. B 762 (2013) 164, https://doi.org/10.1016/j.physletb.2013.08.024, arXiv:1307.3237.

[24] 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.

[25] CMS Collaboration, Evidence for collective multi-particle correlations in pPb collisions, Phys. Rev. Lett. 115 (2015) 012301, https://doi.org/10.1103/PhysRevLett.115.012301, arXiv:1502.05382.

[26] 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.

[27] ATLAS Collaboration, Measurement of multi-particle azimuthal correlations with the subevent cumulant method in pp and p+Pb collisions with the ATLAS detector at the LHC, Phys. Rev. C 97 (2018) 024904, https://doi.org/10.1103/PhysRevC.97.024904, arXiv:1708.03559.

[28] 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.

[29] L. Adamczyk, et al., STAR, Long-range pseudorapidity dihadron correlations in d+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV, Phys. Lett. B 747 (2015) 265, https://doi.org/10.1016/j.physletb.2015.05.075, arXiv:1502.07652.

[30] A. Adare, et al., PHENIX, Measurements of elliptic and triangular flow in high-multiplicity He+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV, Phys. Rev. Lett. 115 (2015) 142301, https://doi.org/10.1103/PhysRevLett.115.142301, arXiv:1507.06273.

[31] 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.

[32] CMS Collaboration, Multiparticle correlation studies in pPb collisions at $\sqrt{s_{_{NN}}} =$ 8.16 TeV, Phys. Rev. C 101 (2020) 014912, https://doi.org/10.1103/PhysRevC.101.014912, arXiv:1904.11519.

[33] Y.M. Sinyukov, V.M. Shapoval, Correlation femtoscopy of small systems, Phys. Rev. D 87 (2013) 094024, https://doi.org/10.1103/PhysRevD.87.094024, arXiv:1209.1747.

[34] CMS Collaboration, Studies of charm and beauty hadron long-range correlations in pp and pPb collisions at LHC energies, Phys. Lett. B 813 (2021) 136036, https://doi.org/10.1016/j.physletb.2020.136036, arXiv:2009.07065.

[35] C. Shen, Studying QGP with flow: a theory overview, Nucl. Phys. A 1005 (2021) 121788, https://doi.org/10.1016/j.nuclphysa.2020.121788, arXiv:2001.11858.

[36] P. Braun-Munzinger, Quarkonium production in ultra-relativistic nuclear collisions: suppression versus enhancement, J. Phys. G 34 (2007) S471, https://doi.org/10.1088/0954-3899/34/8/S36, arXiv:nucl-th/0701093.

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

[38] L. Adamczyk, et al., STAR, Measurement of D^0 azimuthal anisotropy at midrapidity in Au+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV, Phys. Rev. Lett. 117 (2018) 212301, https://doi.org/10.1103/PhysRevLett.118.212301, arXiv:1701.06060.

[39] A. Adare, et al., PHENIX, Energy loss and flow of heavy quarks in Au+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV, Phys. Rev. Lett. 98 (2007) 172301, https://doi.org/10.1103/PhysRevLett.98.172301, arXiv:nucl-ex/0611018.

[40] ALICE Collaboration, Azimuthal anisotropy of D-meson production in Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, Phys. Rev. C 90 (2014) 034904, https://doi.org/10.1103/PhysRevC.90.034904, arXiv:1405.2001.

[41] ALICE Collaboration, D-meson azimuthal anisotropy in midcentral Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Rev. Lett. 120 (2018) 102301, https://doi.org/10.1103/PhysRevLett.120.102301, arXiv:1707.01005.

[42] CMS Collaboration, Measurement of prompt D^0 meson azimuthal anisotropy in Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Rev. Lett. 120 (2018) 202301, https://doi.org/10.1103/PhysRevLett.120.202301, arXiv:1708.03497.

[43] CMS Collaboration, Suppression and azimuthal anisotropy of prompt and nonprompt J/ψ production in PbPb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, Eur. Phys. J. C 77 (2017) 252, https://doi.org/10.1140/epjc/s10052-017-4781-1, arXiv:1610.00613.

[44] ALICE Collaboration, J/ψ elliptic and triangular flow in Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, J. High Energy Phys. 10 (2020) 141, https://doi.org/10.1007/JHEP10(2020)141, arXiv:2005.14518.

[45] L. Adamczyk, et al., STAR, Measurement of J/ψ azimuthal anisotropy in Au+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV, Phys. Rev. Lett. 111 (2013) 052301, https://doi.org/10.1103/PhysRevLett.111.052301, arXiv:1212.3304.

[46] CMS Collaboration, Elliptic flow of charm and strange hadrons in high-multiplicity p+Pb 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.

[47] CMS Collaboration, Observation of prompt J/ψ meson elliptic flow in high-multiplicity pPb collisions at $\sqrt{s_{_{NN}}} = 8.16$ TeV, Phys. Lett. B 791 (2019) 172, https://doi.org/10.1016/j.physletb.2019.02.018, arXiv:1810.01473.

[48] 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.

[49] ALICE Collaboration, Measurement of azimuthal anisotropy at forward and backward rapidity with muons in high-multiplicity pPb collisions at $\sqrt{s_{_{NN}}} = 8.16$ TeV, Phys. Lett. B 846 (2023) 137782, https://doi.org/10.1016/j.physletb.2023.137782, arXiv:2210.08980.

[50] ALICE Collaboration, Measurement of $\Upsilon(1S)$ elliptic flow at forward rapidity in Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Rev. Lett. 123 (2019) 192301, https://doi.org/10.1103/PhysRevLett.123.192301, arXiv:1907.03169.

[51] CMS Collaboration, Measurement of the azimuthal anisotropy of $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons in PbPb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Lett. B 819 (2021) 136385, https://doi.org/10.1016/j.physletb.2021.136385, arXiv:2006.07707.

[52] J. Kim, J. Seo, B. Byungsik, J. Hong, E.-J. Kim, Y. Kim, M. Kweon, S.H. Lee, S. Lim, J. Park, Model study on $\Upsilon(n\mathrm{S})$ modification in small collision systems, Phys. Rev. C 107 (2023) 054905, https://doi.org/10.1103/PhysRevC.107.054905, arXiv:2209.12303.

[53] HEPData record for this analysis, https://doi.org/10.17182/hepdata.131311, 2023.

[54] CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 15 (2020) P10017, https://doi.org/10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[55] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, https://doi.org/10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[56] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.

[57] CMS Collaboration, CMS luminosity measurement using 2016 proton-nucleus collisions at nucleon-nucleon center-of-mass energy of 8.16 TeV, CMS Physics Analysis Summary CMS-PAS-LUM-17-002, CERN, 2018, https://cds.cern.ch/record/2676164/files/LUM-18-002-pas.pdf.

[58] CMS Collaboration, Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS, Eur. Phys. J. C 81 (2021) 800, https://doi.org/10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.

[59] 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) 45, https://doi.org/10.1007/JHEP01(2018)045, arXiv:1710.09355.

[60] 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.

[61] 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.

[62] 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.

[63] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s_{_{NN}}} = 7$ TeV, J. Instrum. 7 (2012) P10002, https://doi.org/10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[64] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 13 (2018) P06015, https://doi.org/10.1088/1748-0221/13/06/P0615, arXiv:1804.04528.

[65] R.E. Kalman, A new approach to linear filtering and prediction problems, J. Basic Eng. D 82 (1960) 35, https://doi.org/10.1115/1.3662552.

[66] CMS Collaboration, Indications of suppression of excited Υ states in Pb-Pb collisions at $\sqrt{s_{_{NN}}} = 2.76$ TeV, Phys. Rev. Lett. 107 (2011) 052302, https://doi.org/10.1103/PhysRevLett.107.052302, arXiv:1105.4894.

[67] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[68] S.C.P. Skands, J. Rojo, Tuning PYTHIA 8.1: the Monash 2013 tune, Eur. Phys. J. C 74 (2014) 3024, https://doi.org/10.1140/epjc/s10052-014-3024-y, arXiv:1404.5630.

[69] T. Pierog, I. Karpenko, J.M. Katzy, E. Yatsenko, K. Werner, EPOS LHC: test of collective hadronization with data measured at the CERN large hadron collider, Phys. Rev. C 92 (2015) 034906, https://doi.org/10.1103/PhysRevC.92.034906, arXiv:1306.0121.

[70] CMS Collaboration, Measurement of prompt and nonprompt J/ψ production in pp and pPb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Eur. Phys. J. C 77 (2017) 269, https://doi.org/10.1140/epjc/s10052-017-4828-3, arXiv:1702.01462.

[71] CMS Collaboration, Nuclear modification of Υ states in pPb collisions at $\sqrt{s_{_{NN}}} = 5.02$ TeV, Phys. Lett. B 835 (2022) 137397, https://doi.org/10.1016/j.physletb.2022.137397, arXiv:2202.11807.

[72] 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.

[73] T. Skwarnicki, A study of the radiative CASCADE transitions between the Upsilon-Prime and Upsilon resonances, Ph.D. thesis, INP, Cracow, 1986, http://www-library.desy.de/preparch/desy/int_rep/f31-86-02.pdf.

[74] Particle Data Group, P.A. Zyla, et al., Review of particle physics, PTEP 2020 (2020) 083C01, https://doi.org/10.1093/ptep/ptaa104.

The CMS Collaboration

A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, P.S. Hussain, M. Jeitler,[1], N. Krammer, L. Lechner, D. Liko, I. Mikulec,

P. Paulitsch, F.M. Pitters, J. Schieck [1], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz [1]

Institut für Hochenergiephysik, Vienna, Austria

M.R. Darwish [2], T. Janssen, T. Kello [3], H. Rejeb Sfar, P. Van Mechelen

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

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

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato [4], E.M. Da Costa, G.G. Da Silveira [5], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, J. Martins [6], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo [7], A. Vilela Pereira

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

C.A. Bernardes [5], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

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

A. Aleksandrov, G. Antchev, 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, E. Shumka

University of Sofia, Sofia, Bulgaria

S. Thakur

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

T. Cheng, T. Javaid [8], M. Mittal, L. Yuan

Beihang University, Beijing, China

M. Ahmad, G. Bauer [9], Z. Hu, S. Lezki, K. Yi [9,10]

Department of Physics, Tsinghua University, Beijing, China

G.M. Chen [8], H.S. Chen [8], M. Chen [8], F. Iemmi, C.H. Jiang, A. Kapoor, H. Liao, Z.-A. Liu [11], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

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

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

M. Lu, Z. You

Sun Yat-Sen University, Guangzhou, China

N. Lu

University of Science and Technology of China, Hefei, China

X. Gao [3], D. Leggat, H. Okawa, Y. Zhang

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

Z. Lin, C. Lu, M. Xiao

Zhejiang University, Hangzhou, Zhejiang, China

C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

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, B.K. Chitroda, D. Ferencek, S. Mishra, M. Roguljic, A. Starodumov [12], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr., A. Kveton

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

S. Elgammal [13], A. Ellithi Kamel [14]

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

M. Abdullah Al-Mashad, M.A. Mahmoud

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

S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow, 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, P. Gras, G. Hamel de Monchenault, P. Jarry, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro [15], P. Simkina, M. Titov

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

C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, B. Diab, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

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

J.-L. Agram [16], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

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

S. Beauceron, B. Blancon, G. Boudoul, A. Carle, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen [17], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, L. Torterotot, M. Vander Donckt, P. Verdier, S. Viret

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

I. Lomidze, T. Toriashvili [18], Z. Tsamalaidze [12]

Georgian Technical University, Tbilisi, Georgia

V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, M. Teroerde

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

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

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

C. Dziwok, G. Flügge, W. Haj Ahmad [19], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

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

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, F. Blekman [20], K. Borras [21], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo [20], A. Geiser, A. Giraldi, G. Greau, A. Grohsjean, V. Guglielmi, M. Guthoff, A. Jafari [22], N.Z. Jomhari, B. Kaech, M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka [23], W. Lohmann [24], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, M. Mormile, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham [25,21], V. Scheurer, S. Schnake [21], P. Schütze, C. Schwanenberger [20], M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon [†], M. Van De Klundert, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Walter, Q. Wang, Y. Wen, K. Wichmann, L. Wiens [21], C. Wissing, S. Wuchterl, Y. Yang, A. Zimermmane Castro Santos

Deutsches Elektronen-Synchrotron, Hamburg, Germany

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

University of Hamburg, Hamburg, Germany

S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann [26], M. Horzela, U. Husemann, M. Klute, R. Koppenhöfer, A. Lintuluoto, S. Maier, S. Mitra, Th. Müller, M. Neukum, M. Oh, G. Quast, K. Rabbertz, J. Rauser, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch, X. Zuo

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

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

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

M. Csanád, K. Farkas, M.M.A. Gadallah [27], S. Lökös [28], P. Major, K. Mandal, G. Pásztor, A.J. Rádl [29], O. Surányi, G.I. Veres

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

M. Bartók [30], G. Bencze, C. Hajdu, D. Horvath [31,32], F. Sikler, V. Veszpremi

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [30], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, B. Ujvari [33]

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo [29], F. Nemes [29], T. Novak

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

J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra [34], R. Gupta, A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, P. Kumari, M. Meena, K. Sandeep, T. Sheokand, J.B. Singh [35], A. Singla, A.K. Virdi

Panjab University, Chandigarh, India

A. Ahmed, A. Bhardwaj, B.C. Choudhary, A. Kumar, M. Naimuddin, K. Ranjan, S. Saumya

University of Delhi, Delhi, India

S. Baradia, S. Barman [36], S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber [37], M. Maity [36], P. Palit, G. Saha, B. Sahu, S. Sarkar

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, J.R. Komaragiri [38], D. Kumar [38], A. Muhammad, L. Panwar [38], R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar, P.C. Tiwari [38], S. Verma

Indian Institute of Technology Madras, Madras, India

K. Naskar [39]

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, A. Thachayath

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati [40], A.K. Das, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu [41], A. Nayak [41], P. Saha, S.K. Swain, D. Vats [41]

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

A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

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

H. Bakhshiansohi [42,43], E. Khazaie [43], M. Zeinali [44]

Isfahan University of Technology, Isfahan, Iran

S. Chenarani [45], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], R. Aly [a,b,46], C. Aruta [a,b], A. Colaleo [a], D. Creanza [a,c], N. De Filippis [a,c], M. De Palma [a,b], A. Di Florio [a,b], W. Elmetenawee [a,b], F. Errico [a,b], L. Fiore [a], G. Iaselli [a,c], M. Ince [a,b], G. Maggi [a,c], M. Maggi [a], I. Margjeka [a,b], V. Mastrapasqua [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pellecchia [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a], D. Ramos [a], A. Ranieri [a], G. Selvaggi [a,b], L. Silvestris [a], F.M. Simone [a,b], Ü. Sözbilir [a], A. Stamerra [a], R. Venditti [a], P. Verwilligen [a]

[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], L. Brigliadori [a], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], M. Cuffiani [a,b], G.M. Dallavalle [a], T. Diotalevi [a,b], F. Fabbri [a], A. Fanfani [a,b], P. Giacomelli [a], L. Giommi [a,b], C. Grandi [a], L. Guiducci [a,b], S. Lo Meo [a,47], L. Lunerti [a,b], S. Marcellini [a], G. Masetti [a], F.L. Navarria [a,b], A. Perrotta [a], F. Primavera [a,b], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b]

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

S. Costa [a,b,48], A. Di Mattia [a], R. Potenza [a,b], A. Tricomi [a,b,48], C. Tuve [a,b]

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

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

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

L. Benussi, S. Bianco, S. Meola [49], D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

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

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

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

S. Buontempo [a], F. Carnevali [a,b], N. Cavallo [a,c], A. De Iorio [a,b], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a,b,50], P. Paolucci [a,26], 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,51], M. Bellato [a], D. Bisello [a,b], P. Bortignon [a], A. Bragagnolo [a,b], T. Dorigo [a], F. Gasparini [a,b], U. Gasparini [a,b], G. Grosso [a], L. Layer [a,52], E. Lusiani [a], M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], G. Strong [a], M. Tosi [a,b], S. Ventura [a], 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

S. Abu Zeid [a,53], C. Aimè [a,b], A. Braghieri [a], S. Calzaferri [a,b], D. Fiorina [a,b], P. Montagna [a,b], V. Re [a], C. Riccardi [a,b], P. Salvini [a], I. Vai [a], P. Vitulo [a,b]

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

P. Asenov [a,54], G.M. Bilei [a], D. Ciangottini [a,b], L. Fanò [a,b], M. Magherini [a,b], G. Mantovani [a,b], V. Mariani [a,b], M. Menichelli [a], F. Moscatelli [a,54], A. Piccinelli [a,b], M. Presilla [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

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

[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

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

[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], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], M. Grippo [a,b], B. Kiani [a,b], F. Legger [a], C. Mariotti [a], S. Maselli [a], A. Mecca [a,b], E. Migliore [a,b], E. Monteil [a,b], M. Monteno [a], R. Mulargia [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], M. Ruspa [a,c], K. Shchelina [a], F. Siviero [a,b], V. Sola [a], A. Solano [a,b], D. Soldi [a,b], A. Staiano [a], M. Tornago [a,b], D. Trocino [a], G. Umoret [a,b], A. Vagnerini [a,b]

[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], G. Sorrentino [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. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, M.S. Ryu, 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

E. Asilar, T.J. Kim, J. Park

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

J. Goh

Kyung Hee University, Department of Physics, Seoul, Korea

H.S. Kim, Y. Kim, S. Lee

Sejong University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

S. Ha, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Korea

M. Choi, M.R. Kim, H. Lee, Y. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Korea

T. Beyrouthy, Y. Maghrbi

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

K. Dreimanis, G. Pikurs, A. Potrebko, M. Seidel, V. Veckalns[55]

Riga Technical University, Riga, Latvia

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

Vilnius University, Vilnius, Lithuania

N. Bin Norjoharuddeen, S.Y. Hoh[56], I. Yusuff[56], Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, I. Heredia-De La Cruz[57], 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

C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bubanja, J. Mijuskovic[58], N. Raicevic

University of Montenegro, Podgorica, Montenegro

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

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

V. Avati, L. Grzanka, M. Malawski

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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, M. Pisano, J. Seixas, J. Varela

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

P. Adzic[59], 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, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, C. Perez Dengra,

A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas, J. Sastre, L. Urda Gómez, J. Vazquez Escobar, C. Willmott

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

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

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

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, A. García Alonso, G. Gomez, C. Lasaosa García, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

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

M.K. Jayananda, B. Kailasapathy[60], 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

D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, B. Bilin, A. Bocci, E. Brondolin, C. Caillol, T. Camporesi, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, F. Fallavollita[61], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, N. Kratochwil, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[62], A.G. Stahl Leiton, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk[63], K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada[64], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[64], L. Noehte[64], T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

T.K. Aarrestad, K. Androsov[63], M. Backhaus, P. Berger, A. Calandri, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen,

T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, A. Mascellani [63], F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, J. Steggemann [63], D. Valsecchi [26], R. Wallny

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

C. Amsler [65], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

Universität Zürich, Zurich, Switzerland

C. Adloff [66], C.M. Kuo, W. Lin, P.K. Rout, S.S. Yu

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

C. Asawatangtrakuldee, N. Srimanobhas

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu [67], E. Eskut, Y. Guler [68], E. Gurpinar Guler [68], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir [69], A. Polatoz, A.E. Simsek, B. Tali [70], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

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

G. Karapinar [71], K. Ocalan [72], M. Yalvac [73]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya [74], O. Kaya [75], S. Tekten [76]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak [67], Y. Komurcu, S. Sen [77]

Istanbul Technical University, Istanbul, Turkey

O. Aydilek, S. Cerci [70], B. Hacisahinoglu, I. Hos [78], B. Isildak [79], B. Kaynak, S. Ozkorucuklu, C. Simsek, D. Sunar Cerci [70]

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

D. Anthony, E. Bhal, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou [80], K. Walkingshaw Pass, R. White

University of Bristol, Bristol, United Kingdom

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

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, C.E. Brown, O. Buchmuller, V. Cacchio, V. Cepaitis, G.S. Chahal [83], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, D.G. Monk, J. Nash [84], M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee [26], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Imperial College, London, United Kingdom

K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, TX, USA

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

Catholic University of America, Washington, DC, USA

S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio [85], C. West

The University of Alabama, Tuscaloosa, AL, USA

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

Boston University, Boston, MA, USA

G. Benelli, B. Burkle, X. Coubez [21], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan [86], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, M. Narain, N. Pervan, S. Sagir [87], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

Brown University, Providence, RI, USA

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

University of California, Davis, Davis, CA, USA

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

University of California, Los Angeles, CA, USA

R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, W. Si, S. Wimpenny

University of California, Riverside, Riverside, CA, USA

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

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

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

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

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

California Institute of Technology, Pasadena, CA, USA

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

Carnegie Mellon University, Pittsburgh, PA, USA

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

University of Colorado Boulder, Boulder, CO, USA

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

Cornell University, Ithaca, NY, USA

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, K.F. Di Petrillo, J. Dickinson, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[88], F. Ravera, A. Reinsvold Hall[89], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

Fermi National Accelerator Laboratory, Batavia, IL, USA

P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R.D. Field, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, E. Kuznetsova[90], K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu

University of Florida, Gainesville, FL, USA

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

Florida State University, Tallahassee, FL, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy [53], M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva

Florida Institute of Technology, Melbourne, FL, USA

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

University of Illinois Chicago, Chicago, USA

M. Alhusseini, K. Dilsiz [91], L. Emediato, R.P. Gandrajula, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili [92], J. Nachtman, O. Neogi, H. Ogul [93], Y. Onel, A. Penzo, C. Snyder, E. Tiras [94]

The University of Iowa, Iowa City, IA, USA

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

Johns Hopkins University, Baltimore, MD, USA

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

The University of Kansas, Lawrence, KS, USA

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

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, A. Bethani, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, L. Wang, K. Wong

University of Maryland, College Park, MD, USA

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

Massachusetts Institute of Technology, Cambridge, MA, USA

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

University of Minnesota, Minneapolis, MN, USA

L.M. Cremaldi

University of Mississippi, Oxford, MS, USA

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

University of Nebraska-Lincoln, Lincoln, NE, USA

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

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

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

Northeastern University, Boston, MA, USA

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

Northwestern University, Evanston, IL, USA

R. Band, R. Bucci, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[,12], R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

University of Notre Dame, Notre Dame, IN, USA

B. Bylsma, M. Carrigan, L.S. Durkin, B. Francis, C. Hill, M. Joyce, A. Lesauvage, M. Nunez Ornelas, K. Wei, B.L. Winer, B.R. Yates

The Ohio State University, Columbus, OH, USA

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

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, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic[,15], J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar

Purdue University Northwest, Hammond, IN, USA

D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Rotter, W. Shi, S. Yang, E. Yigitbasi, L. Zhang[95], Y. Zhang

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, G.P. Van Onsem

University of Rochester, Rochester, NY, USA

K. Goulianos

The Rockefeller University, New York, NY, USA

B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban[24], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Routray, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

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

H. Acharya, A.G. Delannoy, S. Fiorendi, T. Holmes, E. Nibigira, S. Spanier

University of Tennessee, Knoxville, TN, USA

O. Bouhali[96], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[97], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

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

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

Texas Tech University, Lubbock, TX, USA

E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

Vanderbilt University, Nashville, TN, USA

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

University of Virginia, Charlottesville, VA, USA

P.E. Karchin, N. Poudyal

Wayne State University, Detroit, MI, USA

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

University of Wisconsin – Madison, Madison, WI, USA

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, I. Azhgirey, A. Babaev, I. Bayshev, A. Belyaev, V. Blinov [98], E. Boos, V. Borshch, D. Budkouski, V. Chekhovsky, R. Chistov [,98], A. Dermenev, T. Dimova [,98], I. Dremin, D. Elumakhov, V. Epshteyn, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, Y. Ivanov, V. Kachanov, A. Kaminskiy, L. Kardapoltsev [,98], V. Karjavine, A. Karneyeu, L. Khein, V. Kim [,98], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, O. Kodolova [,99], D. Konstantinov, V. Korenkov, V. Korotkikh, A. Kozyrev [,98], N. Krasnikov, A. Lanev, P. Levchenko, A. Litomin, N. Lychkovskaya, V. Makarenko, A. Malakhov, P. Mandrik, V. Matveev [,98], V. Murzin, A. Nikitenko [,100], S. Obraztsov, A. Oskin, I. Ovtin [,98], V. Palichik, P. Parygin, V. Perelygin, V. Petrov, S. Petrushanko, S. Polikarpov [,98], V. Popov, E. Popova, O. Radchenko [,98], R. Ryutin, M. Savina, V. Savrin, D. Selivanova, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen [,98], S. Slabospitskii, V. Smirnov, A. Snigirev, A. Sobol, D. Sosnov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, I. Tlisova, M. Toms, A. Toropin, S. Troshin, L. Uvarov, A. Uzunian, I. Vardanyan, E. Vlasov, A. Volkov, A. Vorobyev, N. Voytishin, B.S. Yuldashev [101], 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 TU Wien, Vienna, Austria.
[2] Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
[3] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[4] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[5] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[6] Also at UFMS, Nova Andradina, Brazil.
[7] Also at The University of the State of Amazonas, Manaus, Brazil.
[8] Also at University of Chinese Academy of Sciences, Beijing, China.
[9] Also at Nanjing Normal University, Nanjing, China.
[10] Now at The University of Iowa, Iowa City, Iowa, USA.
[11] Also at University of Chinese Academy of Sciences, Beijing, China.
[12] Also at an institute or an international laboratory covered by a cooperation agreement with CERN.
[13] Now at British University in Egypt, Cairo, Egypt.
[14] Now at Cairo University, Cairo, Egypt.
[15] Also at Purdue University, West Lafayette, Indiana, USA.
[16] Also at Université de Haute Alsace, Mulhouse, France.
[17] Also at Department of Physics, Tsinghua University, Beijing, China.
[18] Also at Tbilisi State University, Tbilisi, Georgia.
[19] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[20] Also at University of Hamburg, Hamburg, Germany.
[21] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[22] Also at Isfahan University of Technology, Isfahan, Iran.
[23] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[24] Also at Brandenburg University of Technology, Cottbus, Germany.
[25] Also at Forschungszentrum Jülich, Juelich, Germany.
[26] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[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 Wigner Research Centre for Physics, Budapest, Hungary.
[30] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[31] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[32] Now at Universitatea Babes-Bolyai – Facultatea de Fizica, Cluj-Napoca, Romania.
[33] Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.
[34] Also at Punjab Agricultural University, Ludhiana, India.
[35] Also at UPES – University of Petroleum and Energy Studies, Dehradun, India.
[36] Also at University of Visva-Bharati, Santiniketan, India.
[37] Also at University of Hyderabad, Hyderabad, India.
[38] Also at Indian Institute of Science (IISc), Bangalore, India.
[39] Also at Indian Institute of Technology (IIT), Mumbai, India.
[40] Also at IIT Bhubaneswar, Bhubaneswar, India.

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