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Measurement of prompt D^0 and \bar{D}^0 meson azimuthal anisotropy and search for strong electric fields in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration ^{*}

CERN, Switzerland



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ABSTRACT

The strong Coulomb field created in ultrarelativistic heavy ion collisions is expected to produce a rapidity-dependent difference (Δv_2) in the second Fourier coefficient of the azimuthal distribution (elliptic flow, v_2) between D^0 ($\bar{u}c$) and \bar{D}^0 ($u\bar{c}$) mesons. Motivated by the search for evidence of this field, the CMS detector at the LHC is used to perform the first measurement of Δv_2 . The rapidity-averaged value is found to be $\langle \Delta v_2 \rangle = 0.001 \pm 0.001$ (stat) ± 0.003 (syst) in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. In addition, the influence of the collision geometry is explored by measuring the D^0 and \bar{D}^0 mesons v_2 and triangular flow coefficient (v_3) as functions of rapidity, transverse momentum (p_T), and event centrality (a measure of the overlap of the two Pb nuclei). A clear centrality dependence of prompt D^0 meson v_2 values is observed, while the v_3 is largely independent of centrality. These trends are consistent with expectations of flow driven by the initial-state geometry.

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1. Introduction

The observation of a strongly-coupled quark-gluon plasma (QGP), a state of matter composed of deconfined quarks and gluons, was established by experiments investigating ultrarelativistic heavy ion collisions at the BNL RHIC [1–4] and CERN LHC [5,6]. The azimuthal particle correlations constitute an effective tool to probe the properties of the QGP [1–9]. These correlations are parameterized by a Fourier expansion [10–12], with the magnitude of the Fourier coefficients, v_n , providing information about the initial collision geometry and its fluctuations [12]. The second- (v_2) and third- (v_3) order Fourier coefficients are referred to as “elliptic” and “triangular” flow harmonics, respectively. Measuring these coefficients for particle species with different quark composition provides additional information about this hot and dense medium [13]. Because of their large mass, charm and bottom quarks are produced earlier in the collisions than the light quarks (up and down) [14,15]. In addition, the charm and bottom quarks have masses many times larger than the typical temperatures in the QGP [16]. These heavy quarks experience the full evolution of the medium until the hadronization phase. As a consequence, the v_n of charmed D^0 ($\bar{u}c$) and \bar{D}^0 ($u\bar{c}$) mesons (henceforth referred to as D^0 mesons, except where explicitly stated otherwise) are ex-

pected to receive important contributions from medium energy loss and coalescence effects [17,18].

In ultrarelativistic heavy ion collisions, very strong and transient ($\sim 10^{-1}$ fm/c) magnetic and electric fields are expected to be induced by the collision spectators and participants [19]. Such electromagnetic (EM) fields are predicted to produce a difference in the v_n harmonics for positively and negatively charged particles [19]. In such a picture, the magnetic field is mainly responsible for splitting the rapidity (y)-odd directed flow (v_1) [19,20]. The electric field is predicted to induce a charge-dependent splitting in the v_2 coefficient and in the average transverse momentum ($\langle p_T \rangle$) values of the emitted particles [19]. As charm quarks are expected to be created very early in the collision, they have a higher probability of interacting with this strong EM field than the light flavor quarks [20,21].

In this letter, measurements of the v_2 and v_3 coefficients as functions of D^0 meson rapidity, p_T , and lead-lead (PbPb) collision centrality are presented. The collision centrality bins are given in percentage ranges of the total inelastic hadronic cross section, with the 0–10% centrality bin corresponding to the 10% of collisions having the largest overlap of the two nuclei. The flow harmonics are measured using the scalar product method [22,23]. In this analysis, the selection of D^0 mesons uses multivariate methods [24] for selecting D^0 candidates and their antiparticles. The contamination from nonprompt D^0 candidates, arising from B meson decay, is considered as a systematic uncertainty. Using the data recorded in PbPb collisions during the 2018 LHC run period, corresponding to

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

0.58 nb^{-1} of integrated luminosity, the flow coefficients are measured within the rapidity range $|y| < 2$, which is twice as large as achieved in previous CMS measurements [25]. The extension of the measurements to this larger rapidity range, together with smaller statistical uncertainties provided by a larger data set, furnish important inputs for a better understanding of the three-dimensional evolution of the QGP formed in heavy ion collisions. Measurements of the v_2 difference between D^0 and \bar{D}^0 mesons, Δv_2 , as a function of rapidity are presented as a method to probe possible effects originating from the Coulomb fields.

2. Experimental apparatus and data sample

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there are four primary subdetectors including a silicon pixel and strip tracker detector, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Iron and quartz-fiber Cherenkov hadron forward (HF) calorimeters cover the pseudorapidity range $2.9 < |\eta| < 5.2$. The HF calorimeters are segmented to form 0.175×0.175 ($\Delta\eta \times \Delta\phi$) towers. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [26].

The analysis presented in this letter uses approximately 4.27×10^9 minimum bias (MB) PbPb collision events collected by the CMS experiment during the 2018 LHC run. The MB events are triggered by requiring signals in both forward and backward sides of the HF calorimeters [27]. Further selections are applied offline to reject events from background processes (beam-gas interactions and non-hadronic collisions), see Ref. [28] for details. Events are required to have at least one interaction vertex, reconstructed based on two tracks or more, and with a distance of less than 15 cm from the center of the nominal interaction point along the beam axis. The primary interaction vertex is defined as the one with the highest track multiplicity in the event. The shapes of the clusters in the pixel detector have to be compatible with those expected from particles produced at the primary vertex location. The PbPb collision events are also required to have at least two calorimeter towers in each HF detector with energy deposits of more than 4 GeV per tower. These criteria select $(99 \pm 2)\%$ of inelastic hadronic PbPb collisions. The possibility to have values higher than 100% reflects the possible presence of ultra-peripheral (nonhadronic) collisions in the selected event sample.

Events from Monte Carlo (MC) simulations are used to study both prompt and nonprompt D^0 meson processes. The events are generated using an embedding procedure, in which D^0 mesons generated by PYTHIA 8.212 [29] (tune CP5 [30]) are embedded into MB events from HYDJET 1.9 [31]. A full simulation of the CMS detector is performed using GEANT4 [32]. The prompt D^0 meson MC simulation is employed to define signal selections and measure efficiency corrections, while the nonprompt D^0 meson MC sample is used to estimate systematic uncertainties coming from nonprompt D^0 contamination.

3. Reconstruction and selection of D^0 mesons

Prompt D^0 mesons are reconstructed from the decay $D^0 \rightarrow \pi^+ + K^-$ and $\bar{D}^0 \rightarrow \pi^- + K^+$ with a branching fraction of $(3.94 \pm 0.04)\%$, using selected tracks with $p_T > 1.0 \text{ GeV}/c$ and within the acceptance of $|\eta| < 2.4$. Candidates are formed by combining pairs

of tracks from oppositely charged particles and requiring an invariant mass (m_{inv}) within a $\pm 200 \text{ MeV}/c^2$ window of the world-average D^0 meson mass of $(1864.83 \pm 0.05) \text{ MeV}/c^2$ [33]. For each pair of selected tracks, two possible candidates for D^0 and \bar{D}^0 mesons are considered by assuming one of the tracks has the pion mass, while the other track has the kaon mass, and vice versa. Kinematic vertex fits are performed to reconstruct the secondary vertices of D^0 candidate decays.

After the D^0 candidate reconstruction, a selection using a boosted decision tree (BDT) algorithm from the TMVA package [24] is employed. For the BDT training, misidentified D^0 candidates in data events, where pion and kaon have the same charge, are used to mimic the combinatorial background. The signal candidates are taken from MC simulations of prompt D^0 mesons and are required to match D^0 particles at the generator level. The variables related to D^0 mesons used to discriminate the signal from the background are: χ^2 probability for the D^0 vertex fit, 3D distance between the secondary and primary vertices and its significance, the decay length significance projected in the xy -plane, and the angle in two and three dimensions between the momentum of the D^0 meson candidate and the line connecting the primary and the secondary vertices (pointing angle). Related to the decay products of the D^0 meson candidate, the variables used are: the uncertainty in p_T returned by the track fitting procedure, the significance of the z and the xy distances of closest approach to the primary vertex, and the number of hits in the tracker detector. These variables are chosen by analyzing their BDT ranking (variables more frequently used in the decision tree) and correlation matrix among all variables. Different BDT boost algorithms are tested, choosing the adaptive boost algorithm [24] as default. Overtraining checks are done for all analysis bins by comparing the BDT distributions from training and testing D^0 meson samples. In addition, a BDT cut optimization is performed in bins of centrality, p_T , and rapidity, doing a scan in different BDT scores and finding the one resulting in maximal D^0 mesons signal significance for each analysis bin. Compared to a cutoff-based procedure, this BDT selection almost doubles the signal significance for D^0 mesons in $1 < |y| < 2$, and increases the signal significance by 30% for D^0 mesons in $|y| < 1$, for events with collision centrality in the range 0–30%. For the remaining analysis bins a similar performance of BDT and cutoff-based methods is observed.

4. Analysis technique

The elliptic and triangular flow coefficients of D^0 mesons are extracted using the scalar product (SP) method, similarly to what was done in a previous CMS publication [25]. In this method, the v_n coefficients of D^0 candidates (including backgrounds) are measured using

$$v_n\{\text{SP}\} \equiv \frac{\langle Q_n^{D^0} Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}, \quad (1)$$

with the Q -vectors expressed as $Q_n \equiv \sum_{j=1}^M w_j e^{in\phi_j}$, where the sum is over the total number (M) of HF towers above a certain energy threshold (with the weights w_j taken as the energy deposited in the HF tower at azimuthal angle ϕ_j), of tracks with p_T above a certain threshold (with w_j taken as track p_T in ϕ_j angle), or of selected D^0 meson candidates (with w_j taken equal to 1).

The Q -vectors related to HF and the tracker are measured and corrected for detector irregularities by applying a flattening and a recentering procedure [12,34]. The Q_{nA} and Q_{nB} are defined using the event-plane measurements from the negative ($-5 < \eta < -3$, HF-) and the positive ($3 < \eta < 5$, HF+) sides of HF, and Q_{nC} is measured using the tracker information in the region of $|\eta| < 0.75$,

allowing to minimize the correlations among the three regions, with a gap of more than two units of rapidity. The $Q_n^{D^0}$ vector is defined for each D^0 meson candidate. The averages $\langle Q_{nA} Q_{nB}^* \rangle$, $\langle Q_{nA} Q_{nC}^* \rangle$, and $\langle Q_{nB} Q_{nC}^* \rangle$ are made considering all selected events, while the average $\langle Q_n^{D^0} Q_{nA}^* \rangle$ is made considering all D^0 meson candidates in all selected events. To avoid autocorrelations, the terms $\langle Q_n^{D^0} Q_{nA}^* \rangle$ and $\langle Q_{nA} Q_{nB}^* \rangle$ use $A = HF- (HF+)$ when the D^0 meson candidate is at positive (negative) pseudorapidity.

One goal of this analysis is to measure the difference (Δv_n) between D^0 and \bar{D}^0 meson flow coefficients, v_n , as a function of rapidity, to probe effects from EM fields. The difference Δv_n is measured as:

$$\Delta v_n\{SP\} \equiv \frac{\langle Q_n^{D^0} Q_{nA}^* \rangle - \langle Q_n^{\bar{D}^0} Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle}{\langle Q_{nB} Q_{nC}^* \rangle}}}. \quad (2)$$

The v_n and Δv_n of D^0 meson candidates are first measured as a function of their m_{inv} . The extraction of the D^0 mesons signal v_n (Δv_n), v_n^{sig} (Δv_n^{sig}), is performed via a simultaneous binned χ^2 fit of the m_{inv} distribution and of v_n (Δv_n). The m_{inv} distribution is fit with three components: a third-order polynomial to model the combinatorial background, $B(m_{inv})$; two Gaussians with the same mean but different widths to describe the m_{inv} in different kinematic regions for the D^0 mesons signal, $S(m_{inv})$; and one additional Gaussian distribution for the swap component corresponding to the incorrect mass assignment for the assumed pion and kaon particles, $SW(m_{inv})$. The width of $SW(m_{inv})$ and the ratio between the yields of $SW(m_{inv})$ and $S(m_{inv})$ are fixed by the values extracted from MC simulations. In this case, the following expression can be used for extracting v_n^{sig} :

$$v_n^{sig+bkg}(m_{inv}) = \alpha(m_{inv})v_n^{sig} + [1 - \alpha(m_{inv})]v_n^{bkg}(m_{inv}). \quad (3)$$

The $\alpha(m_{inv})$ parameter, which characterizes the signal fraction as a function of mass, is defined as follows:

$$\begin{aligned} \alpha(m_{inv}) &= [S(m_{inv}) + SW(m_{inv})] / [S(m_{inv}) + SW(m_{inv}) + B(m_{inv})] \\ &= \alpha^{signal}(m_{inv}) + \alpha^{swap}(m_{inv}). \end{aligned} \quad (4)$$

For extracting the difference Δv_n^{sig} , the following expression is employed:

$$\Delta v_n^{sig+bkg}(m_{inv}) = \Delta v_n^{sig}(\alpha^{signal}(m_{inv}) - \alpha^{swap}(m_{inv})) + const. \quad (5)$$

The term $v_n^{bkg}(m_{inv})$ from Eq. (3) is modeled with a linear function, while the constant parameter $const$ in Eq. (5) is added to account for possible fluctuations in the background v_n component. The relevance of this $const$ parameter was investigated by redoing Δv_n measurements in MC simulation (without azimuthal correlations or effects from EM fields), indicating that this parameter improves the fit quality and does not introduce artificial signals. A cross-check is performed by redoing the measurements using a linear function instead of a constant. No significant changes in the central values of Δv_2 and on their uncertainties are observed. Fig. 1 shows an example of a simultaneous fit for v_2 and Δv_2 .

After performing the fits for extracting the signal v_n , there is still a sizable fraction of nonprompt D^0 mesons embedded in v_n^{sig} . The extracted v_n can be written as

$$v_n^{sig} = f_{prompt} v_n^{prompt} + (1 - f_{prompt}) v_n^{nonprompt}. \quad (6)$$

The nonprompt D^0 meson contamination is taken into account as a systematic uncertainty, by checking that the nonprompt D^0 meson fraction is always smaller than 12% (i.e., comparable to the uncertainties in the reconstructed D^0 meson yield). This implies that the central values of v_n will not be considerably affected by this component, being compatible within statistical uncertainties. Such a low fraction arises from the use of prompt D^0 meson signals in the BDT training, together with variables that are highly correlated with the distance of closest approach (DCA) to the primary vertex, which is defined as the flight distance of the D^0 particle times the sine of the pointing angle in three dimensions. Additional DCA selection and dedicated training, involving prompt and nonprompt D^0 meson signals, do not bring considerable improvements in performance. The prompt and nonprompt D^0 meson fractions are obtained using the DCA variable. For prompt D^0 mesons, the nonzero DCA corresponds to the detector resolution, and is expected to be concentrated around zero. For nonprompt D^0 mesons, larger values of DCA result from the B meson decay. To extract the prompt and nonprompt D^0 meson fractions, a fit to the DCA distributions is performed in data considering DCA shapes from MC simulations for prompt and nonprompt D^0 meson components. The nonprompt D^0 meson v_n is estimated by considering two regions in the DCA: one with very low fraction (2.7–8.0%) of nonprompt D^0 particles (DCA < 0.012 cm), and one with a high fraction (62.0–88.0%) of nonprompt D^0 particles (DCA > 0.012 cm). Using this information together with Eq. (6), it is possible to estimate $v_n^{nonprompt}$ by solving a system of two equations from the two DCA regions. In the current analysis this procedure can only be done in wide p_T , centrality, and rapidity bins, because of the limited amount of data available in the region with DCA > 0.012 cm.

5. Systematic uncertainties

The sources of systematic uncertainties include the D^0 identification requirements (BDT selection); the probability distribution function (PDF) for modeling the background in the invariant mass fit; the impact of acceptance and efficiency of the D^0 meson yield; the variation of the PDF for modeling the background v_n ; and the remaining nonprompt D^0 contamination. With the exception of the last component, the uncertainties are quoted as absolute values of v_n and Δv_n after comparing the default analysis configuration with the variations. To diminish the influence of statistical fluctuations, after observing no special trends in the deviations from the default measurements, the systematic uncertainties are evaluated by averaging the deviations with a constant fit as a function of the analysis bins.

In order to take into account the systematic uncertainty associated with the BDT selection, the BDT cut is varied up and down by the maximal deviation between the BDT optimized selection based on MC simulations and data. The BDT cuts (and variations for systematic uncertainties) are defined in bins of collision centrality, p_T , and rapidity, ranging from 0.28 to 0.47 (± 0.02 –0.03). Regarding the effect of the background mass modeling, either an exponential function together with a second order polynomial, or just a second order polynomial, are considered instead of the default fit function using a third-order polynomial. To fit v_n as a function of mass, the default configuration using a linear function is replaced by either a constant or a second order polynomial. Although the D^0 meson selection efficiency essentially cancels in v_n measurements, a systematic uncertainty is assigned by comparing the results with and without applying corrections based on MC simulations in bins of p_T and rapidity. The D^0 meson selection efficiency times acceptance varies from 0.5 to 12.5% in the p_T range of 1.0–8.0 GeV/c, reaching a plateau of approximately 17.0% for $p_T > 15.0$ GeV/c.

The systematic uncertainties regarding contamination from nonprompt D^0 mesons are estimated by measuring nonprompt D^0

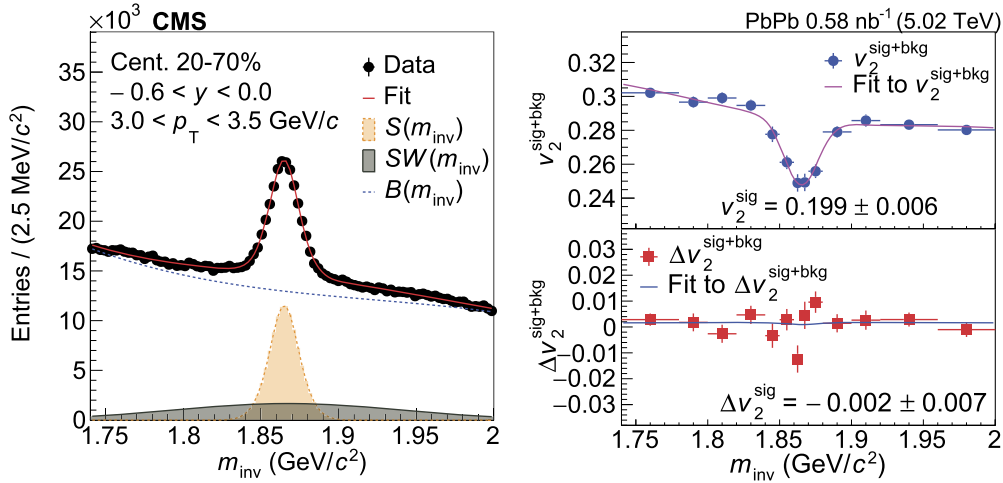


Fig. 1. Simultaneous fit of the πK invariant mass (left) and v_2 (Δv_2) as function of invariant mass (right) for $3.0 < p_T < 3.5$ GeV/c, centrality 20–70%, and $-0.6 < y < 0.0$.

Table 1

Summary of systematic uncertainties in absolute values for v_2 , v_3 , and Δv_2 . Ranges of the variation of uncertainties for all the bins are presented. The cells filled with “–” refer to the cases where the uncertainty cancels out.

Systematic sources	p_T bins	y bins	Centrality bins
	v_2		
BDT selection	0.002–0.014	0.0065	0.005
Bkg. mass PDF	0.0002–0.0017	0.0007–0.0015	0.0007–0.0011
Bkg. v_n PDF	0.01–0.05	0.004–0.007	0.003–0.005
D^0 efficiency correction	–	0.004–0.007	0.0040–0.0045
Nonprompt D^0 meson contamination	0.0002–0.0077	0.004	0.002–0.005
	v_3		
BDT selection	0.002–0.023	0.001–0.009	0.002–0.006
Bkg. mass PDF	0.0001–0.0040	0.0005–0.0008	0.0012–0.0040
Bkg. v_n PDF	0.01–0.05	0.003–0.004	0.0011
D^0 efficiency correction	–	0.002–0.004	0.003–0.005
Nonprompt D^0 meson contamination	0.0001–0.0090	0.0010–0.0015	0.0001–0.0008
	Δv_2		
BDT selection		0.001–0.009	
Bkg. mass PDF		0.00015–0.00030	
D^0 efficiency correction		0.001–0.004	
Nonprompt D^0 meson contamination		0.00002–0.00010	

meson v_n in wide bins of p_T , rapidity, and centrality. A relative systematic uncertainty is obtained by comparing v_n from mixed prompt and nonprompt D^0 mesons to the v_n derived from nonprompt D^0 mesons.

Table 1 summarizes the estimates of systematic uncertainties in absolute values for v_2 , v_3 , and Δv_2 . The ranges of variation of the uncertainties are presented for each binning.

6. Results

Results for prompt D^0 meson v_2 and v_3 anisotropic flow coefficients, obtained with 2018 PbPb data, as functions of p_T and for $|y| < 1$, are shown in Fig. 2 for three centrality ranges: 0–10%, 10–30%, and 30–50%. The results extend previously published data from CMS [25], by extending the high- p_T coverage to ~ 60.0 GeV/c and by providing finer p_T bins. These high-precision data are compatible with previous measurements from Ref. [25], and a clear trend of rise and fall from low to high p_T is observed for both v_2 and v_3 across the full centrality range. This behavior is similar to that observed for inclusive charged particles [35] for $|\eta| < 1.0$, also shown in Fig. 2. For noncentral collisions (i.e., centrality 10–50%), values of prompt D^0 meson v_2 are positive up to $p_T \sim 30.0$ –40.0 GeV/c, whereas the v_3 values become consistent with zero at $p_T \sim 10.0$ GeV/c.

Calculations from theoretical models at midrapidity ($|y| < 1$) are also presented. These models use different assumptions of the QGP properties, for example in the thermal evolution of the collision system and in the initial-state conditions before the formation of the QGP. In addition, different mechanisms are considered regarding the interaction of heavy quarks with the medium and for the hadronization process. Results from the models LBT [36], CUJET 3.0 [37], and SUBATECH [38] include collisional and radiative energy losses, while those from the models TAMU [39], PHSD [15], and TAMU SMCs [40] include only collisional energy loss. Initial-state fluctuations are included in the calculations by LBT, SUBATECH, and PHSD, and calculations for the v_3 coefficient are only available from these three models. Coalescence mechanisms are also included in LBT, SUBATECH, TAMU, PHSD, and TAMU SMCs. While most models seem to capture the qualitative trend of the data (except for the v_2 description provided by TAMU in the 10–50% centrality range), most of the models do not provide a quantitative description over the full range, except for TAMU SMCs. The TAMU SMCs version improves the TAMU model by implementing event-by-event space-momentum correlations (SMCs) between charm quarks and the high-flow partons in the QGP medium [40]. Since it does not include initial-state fluctuations, TAMU SMCs does not provide v_2 calculations for centrality values between 0–10%. This puts more stringent constraints on the development of the collective flow for charm quarks in the QGP medium, giving

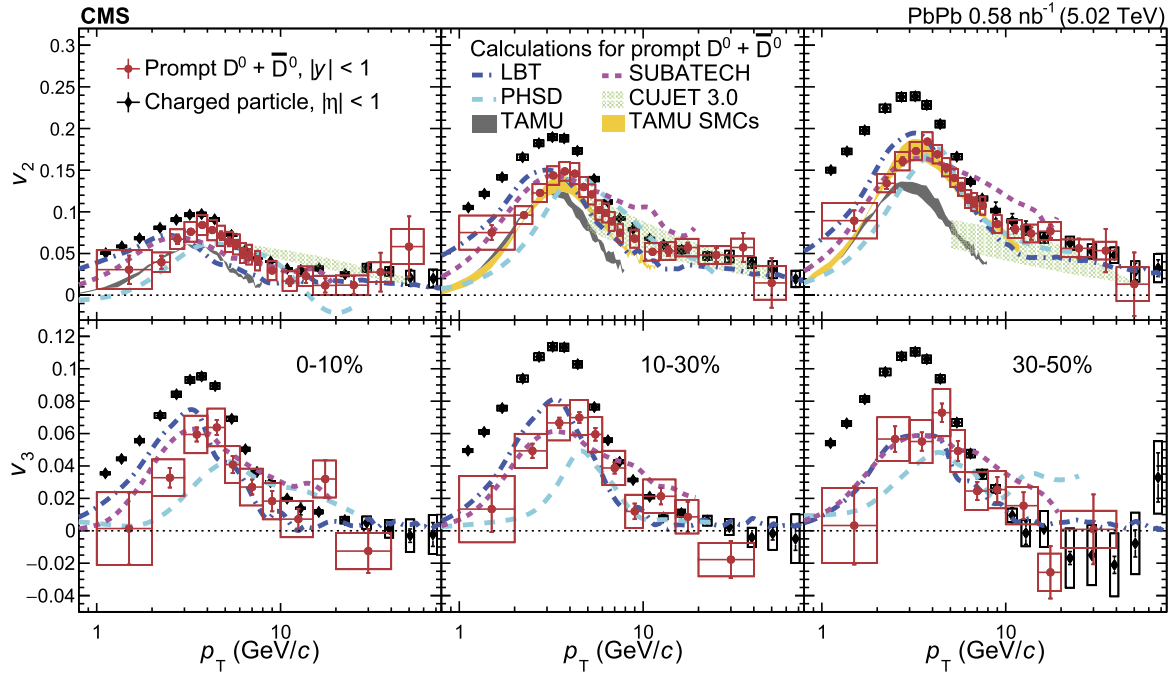


Fig. 2. Prompt D^0 meson and charged particle flow coefficients v_2 (upper) and v_3 (lower) at midrapidity ($|y| < 1.0$ for prompt D^0 mesons and $|\eta| < 1.0$ for charged particles) for the centrality classes 0–10% (left), 10–30% (middle), and 30–50% (right). The vertical bars and open boxes represent the statistical and systematic uncertainties, respectively. The horizontal bars represent the width of each p_T bin. Theoretical calculations for v_n coefficients of prompt D^0 mesons are also plotted for comparison: LBT [36], CUJET 3.0 [37], SUBATECH [38], TAMU [39], PHSD [15]. The TAMU SMCs model [40] is available only in the 10–50% centrality bins.

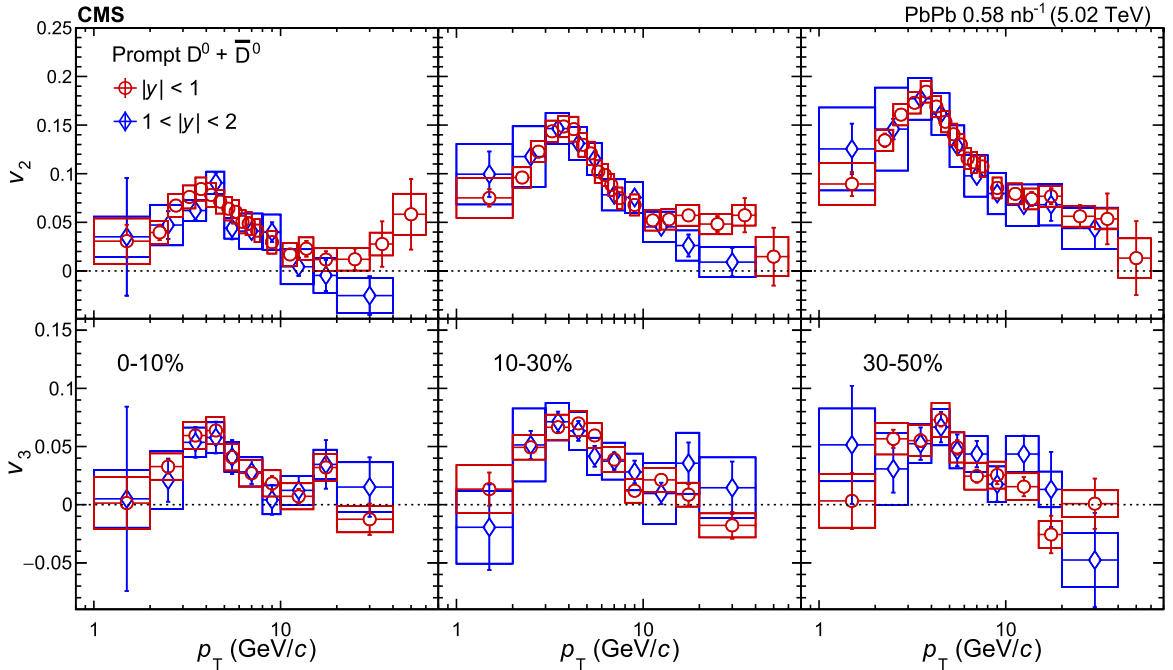


Fig. 3. Prompt D^0 meson flow coefficients v_2 (upper) and v_3 (lower) at midrapidity ($|y| < 1$, red open circles) and forward rapidity ($1 < |y| < 2$, blue open diamonds) for the centrality classes 0–10% (left), 10–30% (middle), and 30–50% (right). The vertical bars and open boxes represent the statistical and systematic uncertainties, respectively. The horizontal bars represent the width of each p_T bin.

further inputs for understanding heavy-quark interactions with the medium (for example, energy loss and coalescence mechanisms).

Results for the rapidity dependence of heavy-flavor collective flow are presented for the first time for prompt D^0 meson v_2 and v_3 as functions of p_T , both at midrapidity ($|y| < 1$) and in the forward ($1 < |y| < 2$) region, as shown in Fig. 3. No clear rapidity dependence is observed for both v_2 and v_3 as functions of p_T . This

observation is similar to that for inclusive charged-hadron measurements [41].

In Fig. 4 (left), results for prompt D^0 mesons v_2 and v_3 , averaged over $2.0 < p_T < 8.0$ GeV/c, for $|y| < 1$ and $1 < |y| < 2$, are presented as a function of collision centrality. This p_T range is chosen in order to cover the widest possible p_T range, while maximizing the D^0 meson signal yield significance. These p_T - and rapidity-

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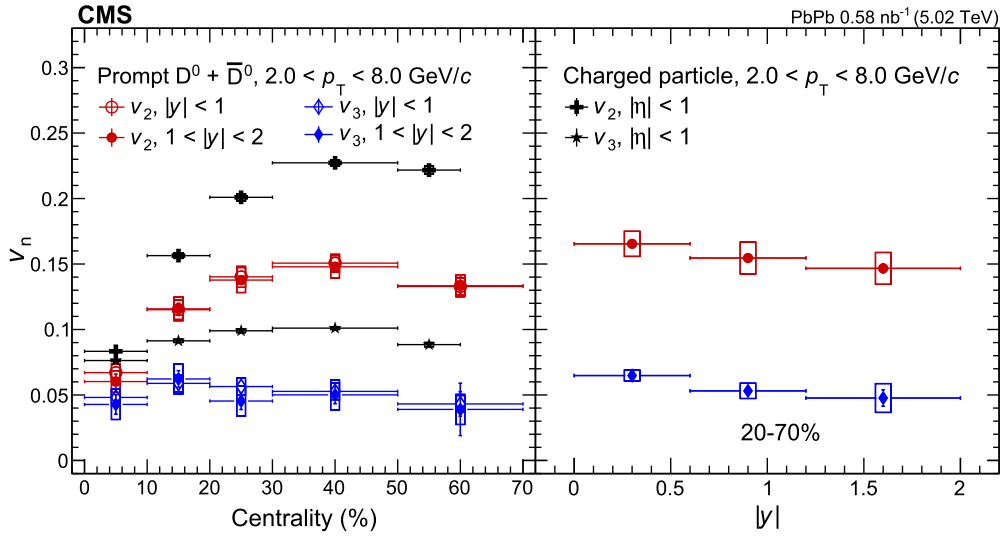


Fig. 4. Prompt D^0 meson v_2 and v_3 as functions of centrality, for $2.0 < p_T < 8.0$ GeV/c and for rapidity ranges $|y| < 1$ and $1 < |y| < 2$. The results are compared with charged particle v_2 and v_3 in the same p_T range and with $|\eta| < 1$ (left). Prompt D^0 v_2 and v_3 as functions of rapidity, for $2.0 < p_T < 8.0$ GeV/c and for centrality 20–70% (right). The vertical bars represent statistical uncertainties and open boxes represent systematic uncertainties. The horizontal bars represent the width of each bin.

integrated results include an additional centrality bin (50–70%), which has an insufficient number of events for the full differential analysis. For both mid- and forward-rapidity regions, the v_2 results show a clear increase from the most central to mid-central events, and then a declining trend toward the most peripheral events. This trend is similar to that observed for inclusive charged particles (also shown in Fig. 4), and can be understood in terms of collision geometry and viscosity effects. In particular, a faster increase of v_2 is observed from central to peripheral collisions for charged particles compared to prompt D^0 mesons. This feature was also observed when comparing v_2 of low- p_T J/ψ with charged pions [42], where it is claimed that this could be understood in terms of two phenomena: one, associated with transport models predicting an increasing fraction of regenerated J/ψ at low- p_T , when going from peripheral to central collisions; the other, not related to regeneration, is associated with a possible partial or later thermalization of charm quarks compared to light quarks [42]. The v_3 shows no centrality dependence, which is also consistent with expectations from collision geometry fluctuations [43].

Fig. 4 (right) presents results for the rapidity dependence of prompt D^0 meson v_2 and v_3 , for centrality 20–70%, averaged over $2.0 < p_T < 8.0$ GeV/c. A weak rapidity dependence of v_2 and v_3 is observed in the data.

Finally, to search for effects of strong EM fields, the difference Δv_2 between the v_2 values of D^0 and \bar{D}^0 mesons is measured. These results are presented in Fig. 5, as a function of rapidity, averaged over $2.0 < p_T < 8.0$ GeV/c and for centrality 20–70%. For all rapidity bins, the Δv_2 values are compatible with zero. The average over the full rapidity region is $\langle \Delta v_2 \rangle = 0.001 \pm 0.001$ (stat) ± 0.003 (syst). In Ref. [19], the predicted v_2 splitting for inclusive charged particles due to electric fields is ~ 0.001 at the LHC energies. While quantitative predictions for v_2 splitting of D^0 mesons are not yet available, they are expected to be much larger than those for inclusive charged particles. In the case of Δv_1 , the ALICE collaboration reported results about three orders of magnitude larger than measurements for charged hadrons [44], although the uncertainties prevent a clear conclusion. The main reason is that heavy-flavor quarks are usually produced much earlier than light-flavor quarks, the former being predominantly produced soon after the collision takes place, when the EM field strength is several or-

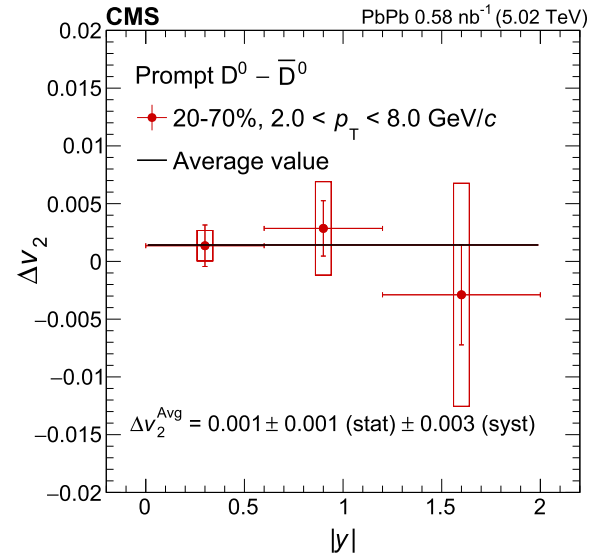


Fig. 5. Prompt D^0 meson Δv_2 as a function of rapidity, for $2.0 < p_T < 8.0$ GeV/c and centrality 20–70%. The vertical bars represent statistical uncertainties and open boxes represent systematic uncertainties. The horizontal bars represent the width of each bin.

ders of magnitude stronger [20]. The results presented here pose constraints on possible EM effects on charm quarks.

7. Summary

Measurements of the elliptic (v_2) and triangular (v_3) flow coefficients of prompt D^0 mesons are presented as functions of transverse momentum (p_T), rapidity, and collision centrality, in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results improve previously published CMS data by extending the p_T and rapidity coverage and by providing more differential information in p_T , rapidity, and centrality. A clear centrality dependence of prompt D^0 meson v_2 is observed, while v_3 is largely centrality independent. These trends are consistent with the expectation that v_2 and v_3 are driven by initial-state geometry. A weak rapidity dependence of prompt D^0

meson v_2 and v_3 is observed. When comparing various theoretical calculations to the data at midrapidity, no model is able to describe the data over the full centrality and p_T ranges.

Motivated by the search for evidence of the strong electric field excited in PbPb collisions, a first measurement of the v_2 flow coefficient difference (Δv_2) between D^0 and \bar{D}^0 mesons as a function of rapidity is presented. The rapidity-averaged v_2 difference is measured to be $\langle \Delta v_2 \rangle = 0.001 \pm 0.001$ (stat) ± 0.003 (syst). This indicates that there is no evidence that charm hadron collective flow is affected by the strong Coulomb field created in ultrarelativistic heavy ion collisions. Future comparisons of theoretical models with these results may provide constraints on the electric conductivity of the quark-gluon plasma.

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.

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FIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced by European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, project no. 02.a03.21.0005 (Russia); the Tomsk Polytechnic University Competitiveness Enhancement Program; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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The CMS Collaboration

A.M. Sirunyan[†], A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambrogio, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, R. Frühwirth¹, M. Jeitler¹, N. Krammer, L. Lechner, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck¹, R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz¹, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, A. Litomin, V. Makarenko, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello², A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, I. Khvastunov³, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Ghent University, Ghent, Belgium

G. Bruno, F.J.J. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaître, J. Prisciandaro, A. Saggio, A. Talierno, M. Teklishyn, P. Vischia, S. Wuyckens, J. Zobec

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

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

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁵, D. De Jesus Damiao, S. Fonseca De Souza, H. Malbouisson, J. Martins⁶, D. Matos Figueiredo, M. Medina Jaime⁷, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, E.J. Tonelli Manganote⁴, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, G. Antchev, I. Atanasov, 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

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

University of Sofia, Sofia, Bulgaria

W. Fang², X. Gao², Q. Guo, H. Wang, L. Yuan

Beihang University, Beijing, China

M. Ahmad, Z. Hu, Y. Wang

Department of Physics, Tsinghua University, Beijing, China

E. Chapon, G.M. Chen⁸, H.S. Chen⁸, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, A. Spiezia, J. Tao, J. Wang, E. Yazgan, H. Zhang, S. Zhang⁸, J. Zhao

Institute of High Energy Physics, Beijing, China

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

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

Z. You

Sun Yat-Sen University, Guangzhou, China

M. Xiao

Zhejiang University, Hangzhou, China

C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, A. Sarkar, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

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

Universidad de Antioquia, Medellin, Colombia

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

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, D. Majumder, B. Mesic, M. Roguljic, A. Starodumov⁹, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger¹⁰, M. Finger Jr.¹⁰, A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A.A. Abdelalim^{11,12}, S. Abu Zeid¹³, S. Khalil¹²

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro¹⁴, M. Titov, G.B. Yu

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

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

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

J.-L. Agram¹⁵, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine¹⁵, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

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

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

A. Khvedelidze¹⁰

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze¹⁰

Tbilisi State University, Tbilisi, Georgia

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

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

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

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

C. Dziwok, G. Flügge, W. Haj Ahmad¹⁶, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁷, T. Ziemons

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

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, K. Beernaert, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras¹⁸, V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranichis, L. Didukh, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, L.I. Estevez Banos, E. Gallo¹⁹, A. Geiser, A. Giralaldi, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari²⁰, N.Z. Jomhari, H. Jung, A. Kasem¹⁸, M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann²¹, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otariid, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, R.E. Sosa Ricardo, H. Tholen, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev, R. Zlebcik

Deutsches Elektronen-Synchrotron, Hamburg, Germany

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

University of Hamburg, Hamburg, Germany

M. Akbiyik, M. Baselga, S. Baur, J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann¹⁷, C. Heidecker, U. Husemann, M.A. Iqbal, I. Katkov²², S. Kudella, S. Maier, M. Metzler, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoie, D. Schäfer, M. Schnepf, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf, S. Wozniewski

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

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

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Giannelos, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitaras, N. Manthos, I. Papadopoulos, J. Stroligas, F.A. Triantis, D. Tsitsonis

University of Ioánnina, Ioánnina, Greece

M. Bartók²³, R. Chudasama, M. Csanad, M.M.A. Gadallah²⁴, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

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

G. Bencze, C. Hajdu, D. Horvath²⁵, F. Sikler, V. Veszpremi, G. Vesztergombi[†]

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²³, J. Molnar, Z. Szillasi, D. Teyssier

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo, S. Lökös²⁶, F. Nemes, T. Novak

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

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

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati²⁷, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak²⁸, D.K. Sahoo²⁷, N. Sur, S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra²⁹, R. Gupta, A. Kaur, A. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

M. Bharti³⁰, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber³¹, M. Maity³², K. Mondal, S. Nandan, P. Palit, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh³⁰, S. Thakur³⁰

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

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

Indian Institute of Technology Madras, Madras, India

D. Dutta, V. Jha, D.K. Mishra, K. Naskar³³, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, U. Sarkar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy, N. Sahoo

Tata Institute of Fundamental Research-B, Mumbai, India

S. Dube, B. Kansal, A. Kapoor, K. Kotheekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

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

H. Bakhshiansohi³⁴

Department of Physics, Isfahan University of Technology, Isfahan, Iran

S. Chenarani³⁵, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, R. Aly^{a,b,36}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, A. Di Pilato^{a,b}, W. Elmetenawee^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, I. Margjeka^{a,b}, J.A. Merlin^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^a, F.M. Simone^{a,b}, R. Venditti^a, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, C. Ciocca^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, T. Diotallevi^{a,b}, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi^{a,b}, P. Giacomelli^a, L. Giommi^{a,b}, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,37}, S. Marcellini^a, G. Masetti^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b,38}, S. Costa^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,38}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, A. Cassese^a, R. Ceccarelli^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, F. Fiori^a, E. Focardi^{a,b}, G. Latino^{a,b}, P. Lenzi^{a,b}, M. Lizzo^{a,b}, M. Meschini^a, S. Paoletti^a, R. Seidita^{a,b}, G. Sguazzoni^a, L. Viliani^a

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo ^{a,b}, F. Ferro ^a, R. Mulargia ^{a,b}, E. Robutti ^a, S. Tosi ^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia ^a, A. Beschi ^{a,b}, F. Brivio ^{a,b}, F. Cetorelli ^{a,b}, V. Ciriolo ^{a,b,17}, F. De Guio ^{a,b}, M.E. Dinardo ^{a,b}, P. Dini ^a, S. Gennai ^a, A. Ghezzi ^{a,b}, P. Govoni ^{a,b}, L. Guzzi ^{a,b}, M. Malberti ^a, S. Malvezzi ^a, D. Menasce ^a, F. Monti ^{a,b}, L. Moroni ^a, M. Paganoni ^{a,b}, D. Pedrini ^a, S. Ragazzi ^{a,b}, T. Tabarelli de Fatis ^{a,b}, D. Valsecchi ^{a,b,17}, D. Zuolo ^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo ^a, N. Cavallo ^{a,c}, A. De Iorio ^{a,b}, F. Fabozzi ^{a,c}, F. Fienga ^a, G. Galati ^a, A.O.M. Iorio ^{a,b}, L. Layer ^{a,b}, L. Lista ^{a,b}, S. Meola ^{a,d,17}, P. Paolucci ^{a,17}, B. Rossi ^a, C. Sciacca ^{a,b}, E. Voevodina ^{a,b}

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi ^a, N. Bacchetta ^a, D. Bisello ^{a,b}, A. Boletti ^{a,b}, A. Bragagnolo ^{a,b}, R. Carlin ^{a,b}, P. Checchia ^a, P. De Castro Manzano ^a, T. Dorigo ^a, U. Dosselli ^a, F. Gasparini ^{a,b}, U. Gasparini ^{a,b}, S.Y. Hoh ^{a,b}, M. Margoni ^{a,b}, A.T. Meneguzzo ^{a,b}, M. Presilla ^b, P. Ronchese ^{a,b}, R. Rossin ^{a,b}, F. Simonetto ^{a,b}, G. Strong, A. Tiko ^a, M. Tosi ^{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

A. Braghieri ^a, S. Calzaferri ^{a,b}, D. Fiorina ^{a,b}, P. Montagna ^{a,b}, S.P. Ratti ^{a,b}, V. Re ^a, M. Ressegotti ^{a,b}, C. Riccardi ^{a,b}, P. Salvini ^a, I. Vai ^a, P. Vitulo ^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

M. Biasini ^{a,b}, G.M. Bilei ^a, D. Ciangottini ^{a,b}, L. Fanò ^{a,b}, P. Lariccia ^{a,b}, G. Mantovani ^{a,b}, V. Mariani ^{a,b}, M. Menichelli ^a, A. Rossi ^{a,b}, A. Santocchia ^{a,b}, D. Spiga ^a, T. Tedeschi ^{a,b}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov ^a, P. Azzurri ^a, G. Bagliesi ^a, V. Bertacchi ^{a,c}, L. Bianchini ^a, T. Boccali ^a, R. Castaldi ^a, M.A. Ciocci ^{a,b}, R. Dell'Orso ^a, M.R. Di Domenico ^{a,b}, S. Donato ^a, L. Giannini ^{a,c}, A. Giassi ^a, M.T. Grippo ^a, F. Ligabue ^{a,c}, E. Manca ^{a,c}, G. Mandorli ^{a,c}, A. Messineo ^{a,b}, F. Palla ^a, A. Rizzi ^{a,b}, G. Rolandi ^{a,c}, S. Roy Chowdhury ^{a,c}, A. Scribano ^a, N. Shafiei ^{a,b}, P. Spagnolo ^a, R. Tenchini ^a, G. Tonelli ^{a,b}, N. Turini ^a, 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

F. Cavallari ^a, M. Cipriani ^{a,b}, D. Del Re ^{a,b}, E. Di Marco ^a, M. Diemoz ^a, E. Longo ^{a,b}, P. Meridiani ^a, G. Organtini ^{a,b}, F. Pandolfi ^a, R. Paramatti ^{a,b}, C. Quaranta ^{a,b}, S. Rahatlou ^{a,b}, C. Rovelli ^a, F. Santanastasio ^{a,b}, L. Soffi ^{a,b}, R. Tramontano ^{a,b}

^a INFN Sezione di Roma, Rome, Italy

^b Sapienza Università di Roma, Rome, 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, A. Cappati^{a,b}, N. Cartiglia^a, S. Cometti^a, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, F. Legger^a, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, G. Ortona^a, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, M. Ruspa^{a,c}, R. Salvatico^{a,b}, F. Siviero^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a, D. Trocino^{a,b}

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, A. Da Rold^{a,b}, G. Della Ricca^{a,b}, F. Vazzoler^{a,b}

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

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

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon

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

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

Hanyang University, Seoul, Republic of Korea

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

Korea University, Seoul, Republic of Korea

J. Goh, A. Gurtu

Kyung Hee University, Department of Physics, Seoul, Republic of Korea

H.S. Kim, Y. Kim

Sejong University, Seoul, Republic of Korea

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

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

H.D. Yoo

Yonsei University, Department of Physics, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

Y. Maghrbi

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

V. Veckalns³⁹

Riga Technical University, Riga, Latvia

A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

Vilnius University, Vilnius, Lithuania

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

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

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

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz⁴⁰, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

J. Mijuskovic³, N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

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

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

V. Avati, L. Grzanka, M. Malawski

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

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

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk⁴¹, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

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

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

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

A. Baginyan, A. Golunov, I. Golutvin, I. Gorbunov, V. Karjavine, I. Kashunin, A. Lanev, A. Malakhov, V. Matveev^{42,43}, V.V. Mitsyn, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, O. Teryaev, V. Trofimov, N. Voytishin, B.S. Yuldashev⁴⁴, A. Zarubin, V. Zhiltsov

Joint Institute for Nuclear Research, Dubna, Russia

G. Gavrillov, V. Golovtsov, Y. Ivanov, V. Kim⁴⁵, E. Kuznetsova⁴⁶, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrillov, N. Lychkovskaya, A. Nikitenko⁴⁷, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Steppenov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

O. Bychkova, R. Chistov⁴⁸, M. Danilov⁴⁸, A. Oskin, P. Parygin, S. Polikarpov⁴⁸

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, A. Demiyarov, A. Ershov, A. Gribushin, O. Kodolova, V. Korotkikh, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

V. Blinov⁴⁹, T. Dimova⁴⁹, L. Kardapoltsev⁴⁹, I. Ovtin⁴⁹, Y. Skovpen⁴⁹

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, A. Iuzhakov, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

Tomsk State University, Tomsk, Russia

P. Adzic⁵⁰, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

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

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

Universidad Autónoma de Madrid, Madrid, Spain

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

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

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Russo⁵¹, L. Scodellaro, I. Vila, J.M. Vizan Garcia

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

M.K. Jayananda, B. Kailasapathy⁵², D.U.J. Sonnadara, D.D.C. Wickramaratna

University of Colombo, Colombo, Sri Lanka

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

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

T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, G. Cerminara, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emrskova, F. Fallavollita⁵³, D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Orfanelli, L. Orsini, F. Pantaleo¹⁷, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabaday, A. Racz, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas⁵⁴, J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsiros, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada⁵⁵, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V. Stampf, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

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

C. Amsler⁵⁶, C. Botta, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, J.K. Heikkilä, M. Huwiler, B. Kilminster, S. Leontsinis, A. Macchiolo, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, K. Schweiger, Y. Takahashi, S. Wertz

Universität Zürich, Zurich, Switzerland

C. Adloff⁵⁷, C.M. Kuo, W. Lin, A. Roy, T. Sarkar³², S.S. Yu

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

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

A. Bat, F. Boran, S. Damarseckin⁵⁸, Z.S. Demiroglu, F. Dolek, C. Dozen⁵⁹, I. Dumanoglu⁶⁰, E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler⁶¹, I. Hos⁶², C. Isik, E.E. Kangal⁶³, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir⁶⁴, A. Polatoz, A.E. Simsek, B. Tali⁶⁵, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Isildak⁶⁶, G. Karapinar⁶⁷, K. Ocalan⁶⁸, M. Yalvac⁶⁹

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁷⁰, O. Kaya⁷¹, Ö. Özçelik, S. Tekten⁷², E.A. Yetkin⁷³

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak⁶⁰, Y. Komurcu, S. Sen⁷⁴

Istanbul Technical University, Istanbul, Turkey

F. Aydogmus Sen, S. Cerci⁶⁵, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci⁶⁵

Istanbul University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

E. Bhal, S. Bologna, J.J. Brooke, D. Burns⁷⁵, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁷⁶, C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal⁷⁷, D. Colling, P. Dauncey, G. Davies, M. Della Negra, P. Everaerts, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, A. Morton, J. Nash⁷⁸, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee¹⁷, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli, S.C. Zenz

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Baylor University, Waco, USA

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

Catholic University of America, Washington, DC, USA

A. Buccilli, O. Charaf, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

A. Albert, D. Arcaro, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, D. Sperka, D. Spitzbart, I. Suarez, D. Zou

Boston University, Boston, USA

G. Benelli, B. Burkley, X. Coubez¹⁸, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan⁷⁹, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir⁸⁰, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganeli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

University of California, Riverside, Riverside, USA

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

University of California, San Diego, La Jolla, USA

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

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

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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka,

S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena⁸¹, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, M. Wang, H.A. Weber, A. Woodard

Fermi National Accelerator Laboratory, Batavia, USA

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

University of Florida, Gainesville, USA

Y.R. Joshi

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy¹³, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

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

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

M. Alhousseini, B. Bilki⁶¹, K. Dilsiz⁸², S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁸³, A. Moeller, J. Nachtman, H. Ogul⁸⁴, Y. Onel, F. Ozok⁸⁵, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi⁸⁶

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

F. Rebasoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

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

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

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

University of Nebraska-Lincoln, Lincoln, USA

G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko⁴², R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala

University of Notre Dame, Notre Dame, USA

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

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, N. Trevisani, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

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

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

University of Rochester, Rochester, USA

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban²¹, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

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

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

University of Tennessee, Knoxville, USA

O. Bouhali⁸⁷, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁸⁸, H. Kim, S. Luo, S. Malhotra, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

L. Ang, M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

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

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at Université Libre de Bruxelles, Bruxelles, Belgium.

³ Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

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 Universidade Federal de Pelotas, Pelotas, Brazil.

⁸ Also at University of Chinese Academy of Sciences, Beijing, China.

⁹ Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia.

¹⁰ Also at Joint Institute for Nuclear Research, Dubna, Russia.

¹¹ Also at Helwan University, Cairo, Egypt.

¹² Now at Zewail City of Science and Technology, Zewail, Egypt.

¹³ Also at Ain Shams University, Cairo, Egypt.

¹⁴ Also at Purdue University, West Lafayette, USA.

- ¹⁵ Also at Université de Haute Alsace, Mulhouse, France.
- ¹⁶ Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
- ¹⁷ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- ¹⁸ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- ¹⁹ Also at University of Hamburg, Hamburg, Germany.
- ²⁰ Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran.
- ²¹ Also at Brandenburg University of Technology, Cottbus, Germany.
- ²² Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
- ²³ Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary.
- ²⁴ Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
- ²⁵ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ²⁶ Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary.
- ²⁷ Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India.
- ²⁸ Also at Institute of Physics, Bhubaneswar, India.
- ²⁹ Also at G.H.G. Khalsa College, Punjab, India.
- ³⁰ Also at Shoolini University, Solan, India.
- ³¹ Also at University of Hyderabad, Hyderabad, India.
- ³² Also at University of Visva-Bharati, Santiniketan, India.
- ³³ Also at Indian Institute of Technology (IIT), Mumbai, India.
- ³⁴ Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
- ³⁵ Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
- ³⁶ Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy.
- ³⁷ Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
- ³⁸ Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
- ³⁹ Also at Riga Technical University, Riga, Latvia, Riga, Latvia.
- ⁴⁰ Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ⁴¹ Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ⁴² Also at Institute for Nuclear Research, Moscow, Russia.
- ⁴³ Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ⁴⁴ Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
- ⁴⁵ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ⁴⁶ Also at University of Florida, Gainesville, USA.
- ⁴⁷ Also at Imperial College, London, United Kingdom.
- ⁴⁸ Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ⁴⁹ Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ⁵⁰ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ⁵¹ Also at Università degli Studi di Siena, Siena, Italy.
- ⁵² Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- ⁵³ Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy, Pavia, Italy.
- ⁵⁴ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ⁵⁵ Also at Universität Zürich, Zurich, Switzerland.
- ⁵⁶ Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria.
- ⁵⁷ Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- ⁵⁸ Also at Şırnak University, Şırnak, Turkey.
- ⁵⁹ Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China.
- ⁶⁰ Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.
- ⁶¹ Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey.
- ⁶² Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey.
- ⁶³ Also at Mersin University, Mersin, Turkey.
- ⁶⁴ Also at Piri Reis University, Istanbul, Turkey.
- ⁶⁵ Also at Adiyaman University, Adiyaman, Turkey.
- ⁶⁶ Also at Ozyegin University, Istanbul, Turkey.
- ⁶⁷ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁶⁸ Also at Necmettin Erbakan University, Konya, Turkey.
- ⁶⁹ Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- ⁷⁰ Also at Marmara University, Istanbul, Turkey.
- ⁷¹ Also at Milli Savunma University, Istanbul, Turkey.
- ⁷² Also at Kafkas University, Kars, Turkey.
- ⁷³ Also at Istanbul Bilgi University, Istanbul, Turkey.
- ⁷⁴ Also at Hacettepe University, Ankara, Turkey.
- ⁷⁵ Also at Vrije Universiteit Brussel, Brussel, Belgium.
- ⁷⁶ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁷⁷ Also at IPPP Durham University, Durham, United Kingdom.
- ⁷⁸ Also at Monash University, Faculty of Science, Clayton, Australia.
- ⁷⁹ Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.
- ⁸⁰ Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ⁸¹ Also at California Institute of Technology, Pasadena, USA.
- ⁸² Also at Bingol University, Bingol, Turkey.
- ⁸³ Also at Georgian Technical University, Tbilisi, Georgia.
- ⁸⁴ Also at Sinop University, Sinop, Turkey.
- ⁸⁵ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

⁸⁶ Also at Nanjing Normal University Department of Physics, Nanjing, China.

⁸⁷ Also at Texas A&M University at Qatar, Doha, Qatar.

⁸⁸ Also at Kyungpook National University, Daegu, Korea, Daegu, Republic of Korea.