Search for strong electric fields in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV using azimuthal anisotropy of prompt $D^0$ and $\bar{D}^0$ mesons

The CMS Collaboration

Abstract

The strong Coulomb field created in ultrarelativistic heavy ion collisions is expected to produce a rapidity-dependent difference ($\Delta v_2$) in the second Fourier coefficient of the azimuthal distribution (elliptic flow, $v_2$) between $D^0$ $(u\bar{c})$ 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 $\langle \Delta v_2 \rangle$. The rapidity-averaged value is found to be $\langle \Delta v_2 \rangle = 0.001 \pm 0.001 \text{ (stat)} \pm 0.003 \text{ (syst)}$ in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ 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.

Submitted to Physics Letters B
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]. Charmed D\(^0\) (\( \bar{u}c \)) and D\(^0\) (\( u\bar{c} \)) mesons (henceforth referred to as D\(^0\) mesons, except where explicitly stated otherwise) inherit the properties of heavy quarks that have a longer period for interacting with the medium, on average, than quarks forming light-flavor mesons [14, 15].

In ultrarelativistic heavy ion collisions, very strong and transient (\( \sim 10^{-1} \text{ fm/c} \)) magnetic and electric fields are expected to be induced by the collision spectators and participants [16]. Such electromagnetic (EM) fields are predicted to produce a difference in the \( v_n \) harmonics for positively and negatively charged particles [16]. In such a picture, the magnetic field is mainly responsible for splitting the rapidity \( (y) \)-odd directed flow \( (v_1) \) [16, 17]. 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 [16]. 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 [17, 18].

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 [19, 20]. In this analysis, the selection of D\(^0\) mesons uses multivariate methods [21] 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 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 [22]. 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 D\(^\bar{0}\) mesons, \( \Delta v_2 \), 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 $0.175 \times 0.175 \ (\Delta \eta \times \Delta \phi)$ 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. [23].

The analysis presented in this letter uses approximately $4.27 \times 10^9$ 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 [24]. Further selections are applied offline to reject events from background processes (beam-gas interactions and nonhadronic collisions), see Ref. [25] 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 [26] (tune CP5 [27]) are embedded into MB events from HYDJET 1.8 [28]. 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 $p_T > 1.0$ 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 $\pm 200$ MeV/$c^2$ window of the world-average $D^0$ meson mass of $(1864.83 \pm 0.05)$ MeV/$c^2$ [29]. 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 [21] is employed. For the BDT training, fake $D^0$ 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 and required to match $D^0$ mesons at the generator level. The variables related to $D^0$ mesons used to discriminate the signal from the background are: $\chi^2$ 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 uncer-
tainty in $p_T$, 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 [21] 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 $1 < |y| < 2$.

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 [22]. In this method, the $v_n$ coefficients of D^0 candidates (including backgrounds) are measured using

$$v_n\{\text{SP}\} = \frac{\langle Q_n^D Q_{nA}^* \rangle}{\sqrt{\langle Q_n^A Q_{nA}^* \rangle \langle Q_{nA} Q_{nB}^* \rangle}},$$

with the Q-vectors expressed as $Q_n \equiv \sum_{j=1}^{M} w_j e^{i n \phi_j}$, 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 $\phi_j$), of tracks with $p_T$ above a certain threshold (with $w_j$ taken as track $p_T$ in $\phi_j$ 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 [12,30]. 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 $Q_{nA}^D$ 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 $\langle Q_{nA}^D Q_{nA}^* \rangle$ is made considering all D^0 meson candidates in all selected events. To avoid autocorrelations, the terms $\langle Q_{nA}^D Q_{nA}^* \rangle$ 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 ($\Delta v_n$) 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 $\Delta v_n$ is measured as:

$$\Delta v_n\{\text{SP}\} = \frac{\langle Q_n^D Q_{nA}^* \rangle - \langle Q_n^{\bar{D}} Q_{nA}^* \rangle}{\sqrt{\langle Q_n^A Q_{nA}^* \rangle \langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nB} Q_{nC}^* \rangle}}.$$
component corresponding to the incorrect mass assignment for the assumed pion and kaon particles, \( SW(m_{\text{inv}}) \). The width of \( SW(m_{\text{inv}}) \) and the ratio between the yields of \( SW(m_{\text{inv}}) \) and \( S(m_{\text{inv}}) \) are fixed by the values extracted from MC simulations. In this case, the following expression can be used for extracting \( v_n^{\text{sig}} \):

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

(3)

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

\[
\alpha(m_{\text{inv}}) = [S(m_{\text{inv}}) + SW(m_{\text{inv}})]/[S(m_{\text{inv}}) + SW(m_{\text{inv}}) + B(m_{\text{inv}})]
\]

\[= \alpha^{\text{signal}}(m_{\text{inv}}) + \alpha^{\text{swap}}(m_{\text{inv}}).
\]

(4)

For extracting the difference \( \Delta v_n^{\text{sig}} \), the following expression is employed:

\[
\Delta v_n^{\text{sig+bkg}}(m_{\text{inv}}) = \Delta v_n^{\text{sig}}(\alpha^{\text{signal}}(m_{\text{inv}}) - \alpha^{\text{swap}}(m_{\text{inv}})) + \text{const}.
\]

(5)

The term \( v_n^{\text{bkg}}(m_{\text{inv}}) \) from Eq. (3) is modeled with a linear function, while the constant parameter \( \text{const} \) in Eq. (5) is added to account for possible fluctuations in the background \( v_n \) component. The relevance of this \( \text{const} \) parameter was investigated by redoing \( \Delta v_n \) 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. Figure 1 shows an example of a simultaneous fit for \( v_2 \) and \( \Delta v_2 \).

Figure 1: Simultaneous fit of the \( \pi K \) invariant mass (left) and \( v_2 (\Delta v_2) \) as function of invariant mass (right) for \( 3.0 < p_T < 3.5 \text{ GeV/c} \), centrality 20–70%, and \( -0.6 < y < 0.0 \).

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

\[
v_n^{\text{sig}} = f_{\text{prompt}}v_n^{\text{prompt}} + (1 - f_{\text{prompt}})v_n^{\text{non-prompt}}.
\]

(6)

The non-prompt D\( ^0 \) meson contamination is taken into account as a systematic uncertainty, after estimating the prompt D\( ^0 \) meson fraction and checking that the non-prompt D\( ^0 \) meson fraction...
is always smaller than 12%. The prompt and nonprompt $D^0$ meson fractions are obtained using the distance of closest approach (DCA) to the primary vertex variable, which is defined as the flight distance of the $D^0$ particle times the sine of the pointing angle in three dimensions. 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 $v_n^{\text{nonprompt}}$ 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 $\Delta v_n$ after comparing the default analysis configuration with the variations.

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 ($\pm$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 $D^0$ 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 $\Delta v_2$. 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–
Table 1: Summary of systematic uncertainties in absolute values for $v_2$, $v_3$, and $\Delta v_2$. 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                             | 0.002–0.011| 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  | 0.0004–0.007| 0.0003–0.005    |
| $D^0$ efficiency correction               | —          | 0.004–0.007| 0.0040–0.0045   |
| Nonprompt $D^0$ meson contamination       | 0.0002–0.0077| 0.004    |                 |
|                                          | $v_3$      |          |                 |
| 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 |
|                                          | $\Delta v_2$ |        |                 |
| 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|          |                 |

10%, 10–30%, and 30–50%. The results extend previously published data from CMS [22], by extending the high-$p_T$ coverage to $\sim 60.0$ GeV/$c$ and by providing finer $p_T$ bins. These high-precision data are compatible with previous measurements from Ref. [22], 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, a behavior similar to that observed for inclusive charged particles [31]. 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 [32], CUJET 3.0 [33], and SUBATECH [34] include collisional and radiative energy losses, while those from the models TAMU [35] and PHSD [15] 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, and PHSD. 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), none of the models provide a quantitative description over the full range. This puts more stringent constraints on the development of the collective flow for charm quarks in the QGP medium, giving 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
Figure 2: Prompt $D^0$ meson flow coefficients $v_2$ (upper) and $v_3$ (lower) at midrapidity ($|y| < 1.0$) 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 [32], CUJET 3.0 [33], SUBATECH [34], TAMU [35], and PHSD [15]).

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 [36].

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 have stronger $v_n$ signals with smaller statistical and systematic uncertainties. These $p_T$- and rapidity-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, and can be understood in terms of collision geometry and viscosity effects, especially for smaller system sizes in peripheral events. The $v_3$ shows no centrality dependence, which is also consistent with expectations from collision geometry fluctuations [37].

Figure 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 $\Delta v_2$ 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 $\Delta v_2$ values are compatible with zero. The average over the full rapidity region is $\langle \Delta v_2 \rangle = 0.001 \pm 0.001$ (stat) $\pm 0.003$ (syst). In Ref. [16], the predicted $v_2$ splitting for inclusive charged
particles due to electric fields is $\sim0.001$ 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. The main reason is that light-flavor hadrons are predominantly produced at the freeze-out stage of the collision, while heavy-flavor hadrons are produced much earlier, soon after the collision takes place, when the EM field strength is several orders of magnitude stronger [17]. 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 expected in PbPb collisions, a first measurement of the $v_2$ flow coefficient difference ($\Delta v_2$) 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) $\pm 0.003$ (syst). This indicates that there is no evidence that charm hadron collective flow is affected by the strong Coulomb field created in ultrarelativistic heavy
Figure 4: Prompt $D^0$ meson $v_2$ and $v_3$ as functions of centrality, for $2.0 < p_T < 8.0 \text{ GeV}/c$ and for rapidity ranges $|y| < 1$ and $1 < |y| < 2$ (left). Prompt $D^0$ $v_2$ and $v_3$ as functions of rapidity, for $2.0 < p_T < 8.0 \text{ GeV}/c$ 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.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid 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 and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MESIAR and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MWST (Montenegro); NBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRI CI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTAR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).
Figure 5: Prompt $D^0$ meson $\Delta v_2$ 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.

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie doord Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science – EOS” – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG) under Germany’s Excellence Strategy – EXC 2121 “Quantum Universe” – 390833306; the Lendület (“Momentum”) Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFI 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 from 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 Thalis 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).

References

[1] BRAHMS Collaboration, “Quark-gluon plasma and color glass condensate at RHIC? the perspective from the BRAHMS experiment”, Nucl. Phys. A 757 (2005) 1, \texttt{doi:10.1016/j.nuclphysa.2005.02.130}, arXiv:nucl-ex/0410020.

[2] PHOBOS Collaboration, “The PHOBOS perspective on discoveries at RHIC”, Nucl. Phys. A 757 (2005) 28, \texttt{doi:10.1016/j.nuclphysa.2005.03.084}, arXiv:nucl-ex/0410022.

[3] STAR Collaboration, “Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration’s critical assessment of the evidence from RHIC collisions”, Nucl. Phys. A 757 (2005) 102, \texttt{doi:10.1016/j.nuclphysa.2005.03.085}, arXiv:nucl-ex/0501009.

[4] PHENIX Collaboration, “Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration”, Nucl. Phys. A 757 (2005) 184, \texttt{doi:10.1016/j.nuclphysa.2005.03.086}, arXiv:nucl-ex/0410003.

[5] B. Muller, J. Schukraft, and B. Wyslouch, “First results from PbPb collisions at the LHC”, Ann. Rev. Nucl. Part. Sci. 62 (2012) 361, \texttt{doi:10.1146/annurev-nucl-102711-094910}, arXiv:1202.3233.

[6] N. Armesto and E. Scomparin, “Heavy-ion collisions at the Large Hadron Collider: a review of the results from Run 1”, Eur. Phys. J. Plus 131 (2016) 52, \texttt{doi:10.1140/epjp/i2016-16052-4}, arXiv:1511.02151.

[7] ALICE Collaboration, “Elliptic flow of charged particles in PbPb collisions at 2.76 TeV”, Phys. Rev. Lett. 105 (2010) 252302, \texttt{doi:10.1103/PhysRevLett.105.252302}, arXiv:1011.3914.

[8] ATLAS Collaboration, “Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector”, Phys. Lett. B 707 (2012) 330, \texttt{doi:10.1016/j.physletb.2011.12.056}, arXiv:1108.6018.

[9] 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, \texttt{doi:10.1103/PhysRevC.87.014902}, arXiv:1204.1409.

[10] J.-Y. Ollitrault, “Determination of the reaction plane in ultrarelativistic nuclear collisions”, Phys. Rev. D 48 (1993) 1132, \texttt{doi:10.1103/PhysRevD.48.1132}, arXiv:nucl-ex/9303247.

[11] S. Voloshin and Y. Zhang, “Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions”, Z. Phys. C 70 (1994) 665, \texttt{doi:10.1007/s001710050514}, arXiv:nucl-ex/9407282.
[12] A. M. Poskanzer and S. A. Voloshin, “Methods for analyzing anisotropic flow in relativistic nuclear collisions”, Phys. Rev. C 58 (1998) 1671, doi:10.1103/PhysRevC.58.1671, arXiv:nucl-ex/9805001.

[13] D. Molnar and S. A. Voloshin, “Elliptic flow at large transverse momenta from quark coalescence”, Phys. Rev. Lett. 91 (2003) 092301, doi:10.1103/PhysRevLett.91.092301, arXiv:nucl-th/0302014.

[14] P. Braun-Munzinger, “Quarkonium production in ultra-relativistic nuclear collisions: Suppression versus enhancement”, J. Phys. G 34 (2007) 471, doi:10.1088/0954-3899/34/8/S36, arXiv:nucl-th/0701093.

[15] F.-M. Liu and S.-X. Liu, “Quark-gluon plasma formation time and direct photons from heavy ion collisions”, Phys. Rev. C 89 (2014) 034906, doi:10.1103/PhysRevC.89.034906, arXiv:1212.6587.

[16] U. Gursoy et al., “Charge-dependent flow induced by magnetic and electric fields in heavy ion collisions”, Phys. Rev. C 98 (2018) 055201, doi:10.1103/PhysRevC.98.055201, arXiv:1806.05288.

[17] S. K. Das et al., “Directed flow of charm quarks as a witness of the initial strong magnetic field in ultra-relativistic heavy ion collisions”, Phys. Lett. B 768 (2017) 260, doi:10.1016/j.physletb.2017.02.046, arXiv:1608.02231.

[18] S. Chatterjee and P. Bozek, “Large directed flow of open charm mesons probes the three dimensional distribution of matter in heavy ion collisions”, Phys. Rev. Lett. 120 (2018) 192301, doi:10.1103/PhysRevLett.120.192301, arXiv:1712.01189.

[19] STAR Collaboration, “Elliptic flow from two and four particle correlations in AuAu collisions at √s_{NN} = 130 GeV”, Phys. Rev. C 66 (2002) 034904, doi:10.1103/PhysRevC.66.034904, arXiv:nucl-ex/0206001.

[20] M. Luzum and J.-Y. Ollitrault, “Eliminating experimental bias in anisotropic-flow measurements of high-energy nuclear collisions”, Phys. Rev. C 87 (2013) 044907, doi:10.1103/PhysRevC.87.044907, arXiv:1209.2323.

[21] H. Voss, A. Höcker, J. Stelzer, and E. Tegenfeldt, “TMVA, the toolkit for multivariate data analysis with ROOT”, in XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT), p. 40. 2007. arXiv:physics/0703039, [PoS(ACAT)040]. doi:10.22323/1.050.0040.

[22] CMS Collaboration, “Measurement of prompt D^0 meson azimuthal anisotropy in PbPb collisions at √s_{NN} = 5.02 TeV”, Phys. Rev. Lett. 120 (2018) 202301, doi:10.1103/PhysRevLett.120.202301, arXiv:1708.03497.

[23] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[24] CMS Collaboration, “The CMS trigger system”, JINST 12 (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[25] CMS Collaboration, “Charged-particle nuclear modification factors in PbPb and pPb collisions at √s_{NN} = 5.02 TeV”, JHEP 04 (2017) 039, doi:10.1007/JHEP04(2017)039, arXiv:1611.01664.
[26] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* 191 (2015) 159–168, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012

[27] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA 8 tunes from underlying-event measurements”, *Eur. Phys. J. C* 80 (2020) 415, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179

[28] I. P. Lokhtin and A. M. Snigirev, “A model of jet quenching in ultrarelativistic heavy ion collisions and high-$p_T$ hadron spectra at RHIC”, *Eur. Phys. J. C* 45 (2006) 211, doi:10.1140/epjc/s2005-02426-3, arXiv:hep-ph/0506189

[29] Particle Data Group, M. Tanabashi et al., “Review of particle physics”, *Phys. Rev. D* 98 (2018) 030001, doi:10.1103/PhysRevD.98.030001

[30] NA49 Collaboration, “Directed and elliptic flow of charged pions and protons in PbPb collisions at 40-A-GeV and 158-A-GeV”, *Phys. Rev. C* 68 (2003) 034903, doi:10.1103/PhysRevC.68.034903, arXiv:nucl-ex/0303001

[31] CMS Collaboration, “Azimuthal anisotropy of charged particles with transverse momentum up to 100 GeV/c in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, *Phys. Lett. B* 776 (2018) 195, doi:10.1016/j.physletb.2017.11.041, arXiv:1702.00630

[32] S. Cao, T. Luo, G.-Y. Qin, and X.-N. Wang, “Linearized Boltzmann transport model for jet propagation in the quark-gluon plasma: Heavy quark evolution”, *Phys. Rev. C* 94 (2016) 014909, doi:10.1103/PhysRevC.94.014909, arXiv:1605.06447

[33] J. Xu, J. Liao, and M. Gyulassy, “Bridging soft-hard transport properties of quark-gluon plasmas with CUJET3.0”, *JHEP* 02 (2016) 169, doi:10.1007/JHEP02(2016)169, arXiv:1508.00552

[34] M. Nahrgang et al., “Elliptic and triangular flow of heavy flavor in heavy-ion collisions”, *Phys. Rev. C* 91 (2015) 014904, doi:10.1103/PhysRevC.91.014904, arXiv:1410.5396

[35] M. He, R. J. Fries, and R. Rapp, “Heavy flavor at the Large Hadron Collider in a strong coupling approach”, *Phys. Lett. B* 735 (2014) 445, doi:10.1016/j.physletb.2014.05.050, arXiv:1401.3817

[36] CMS Collaboration, “Pseudorapidity and transverse momentum dependence of flow harmonics in pPb and PbPb collisions”, *Phys. Rev. C* 98 (2018) 044902, doi:10.1103/PhysRevC.98.044902, arXiv:1710.07864

[37] CMS Collaboration, “Measurement of higher-order harmonic azimuthal anisotropy in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Phys. Rev. C* 89 (2014) 044906, doi:10.1103/PhysRevC.89.044906, arXiv:1310.8651
A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan1, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambroggi, 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

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, A. Litomin, V. Makarenko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
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

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, E.S. Bols, S.S. Chhibra, J. D’Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, 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. Pétre, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

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

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
G. Bruno, F.J.J. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, J. Prisciandaro, A. Saggio, A. Taliercio, M. Teklishyn, P. Vischia, S. Wuyckens, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Universidade do Estado do Rio de Janeiro, 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. Szajder, M. Thié, E.J. Tonelli Manganote4, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
C.A. Bernardesa, L. Calligarisa, T.R. Fernandez Perez Tomela, E.M. Gregoresb, D.S. Lemosa, P.G. Mercadanteb, S.F. Novaesa, Sandra S. Padulaa

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, I. Atanasov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov
Beihang University, Beijing, China
W. Fang\textsuperscript{2}, X. Gao\textsuperscript{2}, Q. Guo, H. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China
E. Chapon, G.M. Chen\textsuperscript{8}, H.S. Chen\textsuperscript{8}, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, A. Spiezia, J. Tao, J. Wang, E. Yazgan, H. Zhang, S. Zhang\textsuperscript{5}, J. Zhao

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

Sun Yat-Sen University, Guangzhou, China
Z. You

Zhejiang University, Hangzhou, China
M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, A. Sarkar, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, D. Majumder, B. Mesic, M. Roguljic, A. Starodumov\textsuperscript{9}, T. Susa

University of Cyprus, Nicosia, Cyprus
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

Charles University, Prague, Czech Republic
M. Finger\textsuperscript{10}, M. Finger Jr.\textsuperscript{10}, A. Kveton, J. Tomsa

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim\textsuperscript{11,12}, S. Abu Zeid\textsuperscript{13}, S. Khalil\textsuperscript{12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken
Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellari, J. Karancsi, J. Molnar, Z. Szillasi, D. Teysier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. Csorgo, S. Lókös, F. Nemes, T. Novák

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak, D.K. Sahoo, N. Sur, S.K. Swain

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

University of Delhi, Delhi, 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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
M. Bharti, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber, M. Maity, K. Mondal, S. Nandan, P. Palit, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh, S. Thakur

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
D. Dutta, V. Jha, D.K. Mishra, K. Naskar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, U. Sarkar

Tata Institute of Fundamental Research-B, 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

Indian Institute of Science Education and Research (IISER), Pune, India
S. Dube, B. Kansal, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Department of Physics, Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani, S.M. Etesami, M. Khakzad, M. Mohammadnejad Najafabadi, M. Naseri

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
M. Abbrescia, R. Aly, C. Calabria, A. Colaleo, D. Creanza, N. De Filippis,
M.T. Grippo, F. Ligabue, E. Manca, G. Mandorli, A. Messineo, F. Palla, A. Rizzi, G. Rolandi, S. Roy Chowdhury, A. Scribano, N. Shafiei, P. Spagnolo, R. Tenchini, G. Tonelli, N. Turini, A. Venturi, P.G. Verdini

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

**INFN Sezione di Torino**, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy
N. Amapane, R. Arcidiacono, S. Argiro, M. Arneodo, N. Bartosik, R. Bellan, A. Bellora, C. Biino, A. Cappati, N. Cartiglia, S. Cometti, M. Costa, R. Covarelli, N. Demaria, B. Kiani, F. Legger, C. Mariotti, S. Maselli, E. Migliore, V. Monaco, E. Monteil, M. Monteno, M.M. Obertino, G. Ortona, L. Pacher, N. Pastrone, M. Pelliccioni, G.L. Pinna Angioni, M. Ruspa, R. Salvatico, F. Siviero, V. Sola, A. Solano, D. Soldi, A. Staiano, D. Trocino

**INFN Sezione di Trieste**, Università di Trieste, Trieste, Italy
S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, A. Da Rold, G. Della Ricca, F. Vazzoler

**Kyungpook National University**, Daegu, Korea
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

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

**Hanyang University, Seoul, Korea**
B. Francois, T.J. Kim, J. Park

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

**Kyung Hee University, Department of Physics, Seoul, Republic of Korea**
J. Goh, A. Gurtu

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

**Seoul National University, Seoul, Korea**
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, 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

**University of Seoul, Seoul, Korea**
D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, I.J. Watson

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

**Sungkyunkwan University, Suwon, Korea**
Y. Choi, C. Hwang, Y. Jeong, H. Lee, J. Lee, Y. Lee, I. Yu
College of Engineering and Technology, American University of the Middle East (AUM), Kuwait
Y. Maghrbi

Riga Technical University, Riga, Latvia
V. Veckalns

Vilnius University, Vilnius, Lithuania
A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropesa Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

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

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro
J. Mijuskovic, N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

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

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluji, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk, K. Doroba, A. Kalinowski, M. Konecki, J. Krolakowski, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
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
Joint Institute for Nuclear Research, Dubna, Russia
A. Baginyan, A. Golunov, I. Golutvin, I. Gorbunov, V. Karjavine, I. Kashunin, A. Lanev, A. Malakhov, V. Matveev42,43, V.V. Mityun, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, O. Teryaev, V. Trofimov, N. Voityushin, B.S. Yuldashev,44, A. Zarubin, V. Zhiltsov

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim45, E. Kuznetsova46, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, 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 Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko47, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
O. Bychkova, R. Chistov48, M. Danilov48, A. Oskin, P. Parygin, S. Polikarpov48

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, O. Kodolova, V. Korotkikh, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov49, T. Dimova49, L. Kardapoltsev49, I. Ovtin49, Y. Skovpen49

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, 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

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov

Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic50, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

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

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

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

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Caldero, A. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernandez Manteca, A. García Alonso, G. Gomez, C. Martínez Rivero, P. Martínez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Priels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Russo

University of Colombo, Colombo, Sri Lanka
MK Jayananda, B. Kailasapathy, D.U.J. Sonnadara, DDC Wickramarathna

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland
T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baiillon, 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. Emriskova, F. Fallavollita, 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. Mejiers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Orfaneli, L. Orsini, F. Pantaleo, L. Pape, E. Perez, M. Peruzzi, A. Petrelli, G. Petracciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwik, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas, J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kottlinski, U. Langenegger, T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegä, C. Dörfer, 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. Reitnspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönberger, L. Shchutska, V. Stampf, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
C. Amsler, C. Bott, 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

National Central University, Chung-Li, Taiwan
C. Adloff⁵⁷, C.M. Kuo, W. Lin, A. Roy, T. Sarkar⁵², S.S. Yu

National Taiwan University (NTU), Taipei, 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

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

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

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak⁶⁶, G. Karapinar⁶⁷, K. Ocalan⁶⁸, M. Yalvac⁶⁹

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

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak⁶⁰, Y. Komurcu, S. Sen⁷⁴

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

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

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
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

Rutherford Appleton Laboratory, Didcot, 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

Imperial College, London, 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. Shitlipsky, M. Stoye, A. Tapper, K. Uchida, T. Virdee¹⁷, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli, S.C. Zenz
Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

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

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

The University of Alabama, Tuscaloosa, USA
A. Buccilli, O. Charaf, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

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

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

University of California, Davis, Davis, 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, Los Angeles, 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, Riverside, Riverside, USA
K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, 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, Santa Barbara - Department of Physics, Santa Barbara, 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

California Institute of Technology, Pasadena, 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

Carnegie Mellon University, Pittsburgh, USA
J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

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

**University of Maryland, College Park, 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

**Massachusetts Institute of Technology, Cambridge, 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. Mckinn, 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

**University of Minnesota, Minneapolis, 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 Mississippi, Oxford, USA**
J.G. Acosta, S. Oliveros

**University of Nebraska-Lincoln, Lincoln, 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

**State University of New York at Buffalo, Buffalo, USA**
G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen, S. Rappoccio, B. Roozbahani

**Northeastern University, Boston, 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

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

**University of Notre Dame, Notre Dame, 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. Musienko12, R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala

**The Ohio State University, Columbus, USA**
J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, W. Ji, A. Lefeld, B.L. Winer, B.R. Yates

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

Purdue University, West Lafayette, 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 Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, 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

University of Rochester, Rochester, 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

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA
H. Acharya, A.G. Delannoy, S. Spanier

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

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

Vanderbilt University, Nashville, 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

University of Virginia, Charlottesville, 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

Wayne State University, Detroit, USA
P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

University of Wisconsin - Madison, Madison, WI, 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

†: 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 Şişman University, Sırnak, 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 Bingöl University, Bingöl, 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, Korea