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Measurements of the azimuthal anisotropy of prompt and nonprompt charmonia in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

The CMS collaboration

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

Abstract: The second-order (v_2) and third-order (v_3) Fourier coefficients describing the azimuthal anisotropy of prompt and nonprompt (from b-hadron decays) J/ψ, as well as prompt $\psi(2\mathrm{S})$ mesons are measured in lead-lead collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The analysis uses a data set corresponding to an integrated luminosity of $1.61\,\mathrm{nb}^{-1}$ recorded with the CMS detector. The J/ψ and $\psi(2\mathrm{S})$ mesons are reconstructed using their dimuon decay channel. The v_2 and v_3 coefficients are extracted using the scalar product method and studied as functions of meson transverse momentum and collision centrality. The measured v_2 values for prompt J/ψ mesons are found to be larger than those for nonprompt J/ψ mesons. The prompt J/ψ v_2 values at high p_{T} are found to be underpredicted by a model incorporating only parton energy loss effects in a quark-gluon plasma medium. Prompt and nonprompt J/ψ meson v_3 and prompt $\psi(2\mathrm{S})$ v_2 and v_3 values are also reported for the first time, providing new information about heavy quark interactions in the hot and dense medium created in heavy ion collisions.

Keywords: Charm Physics, Collective Flow, Heavy Ion Experiments, Quarkonium

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1 Introduction

In high energy heavy ion collisions, a very strongly-interacting medium of deconfined quarks and gluons, known as the quark-gluon plasma (QGP), is created [1]. Quarkonia, bound states of a heavy quark and its antiquark, e.g., charmonia (J/ψ, ψ(2S)), and bottomonia (ϒ(1S, 2S, 3S)), are useful probes to study the properties of the QGP. Since heavy quarks are predominantly produced at the early stages of collisions by hard partonic scattering processes, they experience the whole space-time evolution of the medium. Models including static color screening [2, 3] and gluo-dissociation effects [4–6] inside a QGP medium predict a suppression of quarkonium yields in nucleus-nucleus (AA) collisions compared to proton-proton (pp) collisions [7]. On the other hand, quarkonia may also be created by recombination of quarks and antiquarks which were initially uncorrelated, thereby resulting in an enhancement of the measured yields [8].

Experimentally, the modification of particle yields in heavy ion collisions is quantified by the nuclear modification factor, defined as the ratio of yields in AA collisions to those in pp collisions scaled by the estimated number of binary nucleon-nucleon (NN) collisions. Results from the CERN SPS, BNL RHIC, and CERN LHC experiments show significant suppression of J/ψ mesons in AA collisions [9–19]. At the LHC, the ALICE Collaboration [17, 18] observed a weaker suppression of J/ψ mesons in the low transverse momentum (p_{T}) region below 3 GeV/c than was seen by experiments at the SPS and RHIC. This result has been interpreted as a sign of enhanced recombination processes at LHC energies because of the larger production cross section of charm quarks [17, 18, 20, 21]. These measurements have provided information to constrain theoretical models that incorporate different in-medium effects on charmonium states in order to describe thermal characteristics of the QGP.

Another effective way to probe the dynamics of the QGP is the study of the azimuthal (ϕ) distribution of particles produced in heavy ion collisions. Azimuthal anisotropies of the particles can be characterized by Fourier coefficients (v_n) of the ϕ distribution with respect to the event plane, which corresponds to the direction of maximal particle density [22]. The presence of non-zero Fourier coefficients is referred to as collective flow by analogy to hydrodynamic models. In particular, the second-order (v_2) and the third-order (v_3) components are predominantly sensitive to initial collision geometry and event-by-event fluctuations, respectively [23]. Because of the initial anisotropic shape of the QGP in the transverse plane, quarkonia produced by initial hard-scattering processes experience different path lengths while traveling through the medium. Larger energy loss, and therefore larger suppression, can occur for quarkonia moving in directions corresponding to larger average path lengths. On the other hand, quarkonia created via recombination can have an asymmetric ϕ distribution as a result of asymmetries in quark densities [24, 25].

In LHC experiments, sizable v_2 values have been observed for J/ψ mesons in lead-lead (PbPb) collisions at center-of-mass energies per nucleon pair $\sqrt{s_{_{\mathrm{NN}}}} = 2.76$ and 5.02 TeV [26–29], indicating collective flow behavior of charm quarks. However, these results have limitations that prevent drawing firm conclusions on the origin of the v_2 for J/ψ mesons, given the large measurement uncertainties and the lack of separation between prompt and nonprompt J/ψ mesons. Measurements of nonprompt J/ψ mesons, which originate from bottom hadron decays, provide useful information on the propagation of bottom quarks in the QGP.

The CMS Collaboration has shown that in PbPb collisions the suppression of prompt J/ψ (of p_{T} above 6.5 GeV/c) within jets depends upon the fragmentation [30]. Theoretical calculations suggest that jet quenching may drive the modulation of the ϕ distribution of J/ψ at high p_{T} [31]. These studies motivate the measurement of the azimuthal anisotropy for prompt J/ψ mesons at higher p_{T} to investigate the path length dependence of jet quenching [32, 33].

Azimuthal correlations for ψ(2S) mesons are also a subject of interest. Prompt ψ(2S) mesons have been found to be significantly more suppressed than prompt J/ψ mesons in PbPb collisions [19, 34]. Measurements of v_2 and v_3 values for prompt ψ(2S) mesons are expected to provide constraints on in-medium effects for charmonium states with different binding energies in heavy ion collisions [21, 35].

This paper reports measurements of v_n values for prompt and nonprompt J/ψ mesons, as well as prompt ψ(2S) meson, using PbPb data collected with the CMS detector at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02$ TeV in 2018. The prompt and nonprompt J/ψ v_3, and prompt ψ(2S) v_n values are measured for the first time. The charmonium states are identified via their dimuon decay channel. The data set corresponds to an integrated luminosity of 1.61 nb^{-1} [36, 37], allowing the extraction of v_n values as functions of meson transverse momentum and PbPb event centrality (i.e., the degree of overlap of the two Pb ions). The numerical values of the results for this analysis are tabulated in the HEPDATA record [38].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. The forward hadron (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end, and together they provide coverage in the range $3.0 < |\eta| < 5.2$. The HF calorimeters are composed of individual detector elements, or towers, having $\Delta\eta \times \Delta\phi = 0.175 \times 0.175$. Centrality is determined by the total transverse energy deposited in both of the HF calorimeters, and is defined as the fraction of the total hadronic inelastic nucleus-nucleus cross section, with 0% representing the largest overlap of the two colliding Pb nuclei [39].

Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution, for muons with p_T up to 100 GeV/c, of 1% in the barrel and 3% in the endcaps. The p_T resolution in the barrel is better than 7% for muons with p_T up to 1 TeV/c [40]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [41].

3 Event selection

Events of interest are selected using a two-tiered trigger system. The first level (Level-1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [42]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [43]. The trigger for this analysis was designed to have several stages. First, at least two muon candidates should be reconstructed at Level-1. At the HLT, the events are required to contain at least one Level-2 (L2) muon and another Level-3 (L3) muon, with requirements on their invariant mass being within 1–5 GeV/c^2. L2 muons are identified by matching the tracks to the hits in the outer muon spectrometer. For L3 muons, full tracks from the L2 muon tracks and the inner tracker information are used in the reconstruction, in addition requiring at least ten high-quality hits in the inner tracker [43].

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To reject beam-related background processes, events are required to have at least one reconstructed primary vertex, and the clusters in the silicon pixel detector are required to be compatible with the vertex position. There must be at least two towers that contain energy deposits above 4 GeV in each of the HF detectors. The primary vertex, which is reconstructed from two or more tracks, is required to be located within 15 cm of the central point of the detector along the beam axis. In addition, the reconstructed muons are selected using a set of offline muon identification criteria [30]. To ensure the reconstruction efficiency of single muons is larger than 10%, muons within the following kinematic domains are selected:

$$\begin{aligned} &p_{\mathrm{T}}^{\mu} > 3.5\,\mathrm{GeV}/c && \text{for } |\eta^{\mu}| < 1.2, \\ &p_{\mathrm{T}}^{\mu} > (5.47 - 1.89|\eta^{\mu}|)\,\mathrm{GeV}/c && \text{for } 1.2 < |\eta^{\mu}| < 2.1, \text{ and} \\ &p_{\mathrm{T}}^{\mu} > 1.5\,\mathrm{GeV}/c && \text{for } 2.1 < |\eta^{\mu}| < 2.4. \end{aligned} \tag{3.1}$$

4 Acceptance and efficiency corrections

Correction factors are applied to all results to account for the detector acceptance, as well as for the trigger, reconstruction, and selection efficiencies for $\mu^+\mu^-$ pairs. The correction factors are derived from simulated prompt and nonprompt J/ψ and ψ(2S) meson samples which are then embedded in simulated PbPb collisions. Corrections are evaluated in the same bins of p_{T}, centrality, and rapidity (y) used in the v_n analyses. The meson samples are generated with PYTHIA 8.212 [44] using the CP5 underlying event tune [45], while the decay of bottom hadrons is simulated with EVTGEN 1.3.0 [46], which provides a better description of the kinematic distribution of nonprompt charmonia. These meson events are then embedded into simulated PbPb collision events generated using HYDJET 1.9 [47], and propagated through the CMS detector with the GEANT4 package [48]. The p_{T} distributions for simulated J/ψ and ψ(2S) mesons are compared to those in data with fine p_{T} intervals, and the ratios of data over the simulation are used to reweight the simulation to better describe the data as a function of p_{T}. This weighting procedure accounts for possible mismodeling of the J/ψ and ψ(2S) meson kinematics. Moreover, the reconstructed charmonia in data include feed-down contributions from heavier quarkonium state decays. These contributions are not explicitly considered in the simulation, but their effect on the kinematic distribution of the simulated charmonia is taken into account by the p_{T} reweighting procedure.

The acceptance in a given analysis bin is defined as the fraction of generated J/ψ and ψ(2S) mesons in that bin that decay into two muons passing the kinematic requirements defined in eq. (3.1), and reflects the geometrical coverage of the CMS detector. The value of the acceptance increases with dimuon p_{T} and varies from 0.05–0.76.

The efficiency in a given analysis bin is defined as the ratio of the number of reconstructed J/ψ and ψ(2S) mesons from which both muons pass the selections described in section 3 and the number of generated J/ψ mesons from which both muons pass the kinematic requirements defined in eq. (3.1). Individual components of the efficiency (trigger, track reconstruction, and muon identification) are measured using single muons from J/ψ meson decays in both collision data and simulated samples, using a "tag-and-probe" (T&P) technique [49, 50]. The ratio in the efficiency between the data and simulated samples is used as a correction factor for the efficiency extracted from the simulation. The reciprocals of the acceptance and efficiency corretion factors are used as event-by-event weights when the distributions of invariant mass and average v_n are computed.

5 Signal extraction

The signal candidates for J/ψ (ψ(2S)) mesons are extracted in the kinematic range of $6.5 < p_T < 50$ GeV/c, $|y| < 2.4$, and centrality 0–90% (0–60%). The results are reported as functions of p_T and $\langle N_{part} \rangle$, where $\langle N_{part} \rangle$ is the average number of participating nucleons in a given centrality interval [39]. The centrality range for p_T-dependent results is limited to 10–60% to ensure a large anisotropy of the QGP. The most central collisions (0–10%) are excluded due to the small eccentricity in the initial geometry of the medium, while the most peripheral collisions (60–90%) are excluded because of the poor resolution in extracting the v_n coefficients. In addition, the lower p_T region is extended down to 3 GeV/c (4 GeV/c) for J/ψ (ψ(2S)) in the forward rapidity region. Details of the kinematic selection and $\langle N_{part} \rangle$ values for each centrality interval can be found in tables 2 and 3 in Appendix A. The mass ranges of 2.6–3.5 and 3.3–4.1 GeV/c^2 are used to study the J/ψ and ψ(2S) mesons, respectively.

The separation of the prompt and nonprompt charmonium production components relies on the measurement of a secondary $\mu^+\mu^-$ vertex displaced from the primary collision vertex. The pseudo-proper decay length [51] is defined as $\ell_{J/\psi} = L_{xyz}\, m_{J/\psi}\, c/|p_{\mu\mu}|$, where L_{xyz} is the distance between the primary and dimuon vertices, $m_{J/\psi}$ is the world average value [52] of the J/ψ meson mass (assumed for all dimuon candidates), and $p_{\mu\mu}$ is the dimuon momentum. To extract prompt and nonprompt J/ψ meson yields, the invariant mass spectrum of $\mu^+\mu^-$ pairs and their $\ell_{J/\psi}$ distribution are fitted using a two-dimensional (2D) extended unbinned maximum likelihood fit. The parameters of different components of the 2D probability density function (pdf) are obtained through fits to the invariant mass and the $\ell_{J/\psi}$ distributions, which are further used in the final 2D fits. These fits are performed for each v_n interval in the measured kinematic region. The evaluation of v_n coefficients is detailed in section 6. Figure 1 shows the dimuon invariant mass and $\ell_{J/\psi}$ projection of the 2D fit in the ranges $3.0 < p_T < 4.5$ GeV/c and $0.0 < v_2 < 0.3$ for the 10–60% centrality interval.

Sums of two Crystal Ball (CB) functions [53], with different widths but common mean and tail parameters, are used to extract the signal yield values from the invariant mass distribution. Two separate sums of CB functions are used to describe the prompt and nonprompt contributions to the J/ψ signal. The tail parameters, as well as relative contributions of the two CB functions and the ratio of their widths, are fixed to the values obtained from simulation. The background component for the invariant mass distribution is described by a sum of Chebyshev polynomial functions up to order N, where N is determined by performing the log-likelihood ratio (LLR) test [54]. This procedure is done for each analysis bin, while the tail and width ratio parameters are kept fixed. The polynomial order is chosen as the minimum so that increasing it does not significantly improve

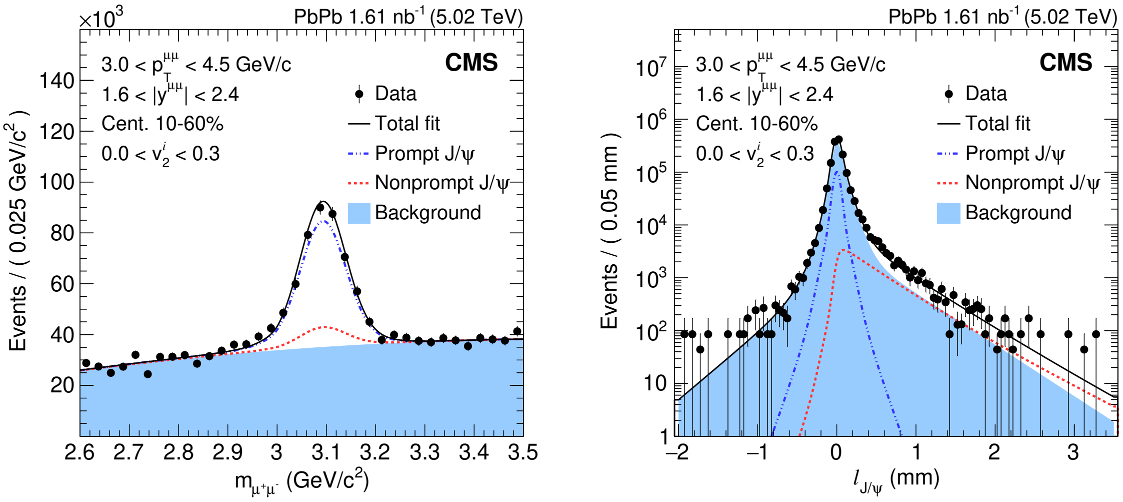

Figure 1. Invariant mass (left) and $\ell_{J/\psi}$ (right) distributions for the bin of $3.0 < p_T < 4.5$ GeV/c and $0.0 < v_2 < 0.3$ in centrality 10–60%. The solid lines represent the total fit, while the dashed and dash–dotted lines represent the prompt and nonprompt components, respectively. The background contributions are shown by the filled blue histograms.

the quality of the fit. In most analysis bins, the first-order Chebyshev polynomial function is used as the background function.

Prompt and nonprompt signals and background components of $\ell_{J/\psi}$ distributions are parameterized using collision data and simulated samples. The *sPlot* technique [55] is used to obtain $\ell_{J/\psi}$ distributions of J/ψ signal and background from data, which have different invariant mass distributions. The correlation between the mass and $\ell_{J/\psi}$ is found to be very small, such that its impact on the final results is negligible. This justifies the use of the dimuon mass distribution to separate signal and background distributions of $\ell_{J/\psi}$ using the *sPlot* [30] technique. The $\ell_{J/\psi}$ resolution is obtained by fitting the negative tail of the J/ψ signal $\ell_{J/\psi}$ distribution in data using a sum of two Gaussian functions. Note that $\ell_{J/\psi}$ can have negative values as a result of the finite detector resolution. The shape of the $\ell_{J/\psi}$ distributions of prompt J/ψ signals is described by the $\ell_{J/\psi}$ resolution. The $\ell_{J/\psi}$ distribution of nonprompt J/ψ signals is parameterized by the sum of three exponential functions convoluted with the resolution function. The parameters of the three exponential functions are determined by a fit of the $\ell_{J/\psi}$ distribution of simulated nonprompt J/ψ mesons at the generator level. The background $\ell_{J/\psi}$ distribution in data is fit to a sum of exponential functions. To extract the yields of prompt and nonprompt J/ψ mesons, a fit to the $m_{\mu^+\mu^-}$ and $\ell_{J/\psi}$ distributions is performed, where the free parameters include the J/ψ meson yield, nonprompt J/ψ meson fraction, and background yield. A more detailed description of the fitting procedure can be found in ref. [19].

For ψ(2S) mesons, the nonprompt component is reduced by placing tight constraints on the $\ell_{J/\psi}$ distribution. The constraint, studied in simulated samples, rejects the nonprompt ψ(2S) contamination while maintaining a prompt ψ(2S) purity of at least 90%. The remaining contribution of nonprompt ψ(2S) mesons ranges from 5 to 10% and is assigned as a systematic uncertainty for the nonprompt ψ(2S) contamination.

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6 Extraction of v_n

The v_n ($n = 2$ and 3) values of J/ψ and ψ(2S) candidates are determined using the scalar product (SP) method [56]. The Q-vectors are defined in the complex plane $Q_n = \sum_{k=1}^{M} \omega_k e^{in\phi_k}$, obtained using the tracker or calorimeters. Here, M is the multiplicity of particles in the tracker or the number of towers for HF; ϕ is the azimuthal angle of the particle or the tower; ω_k is the weighting factor, that is the p_T of a particle for the tracker or the transverse energy deposited in an HF tower. In this analysis, Q-vectors from three subevents are calculated using the tracker at the mid-pseudorapidity ($|\eta| < 0.75$) and similarly the two HF calorimeters covering the forward ($3 < \eta < 5$, HF+) and backward ($-5 < \eta < -3$, HF−) regions. Two different procedures are applied in extracting v_2 of J/ψ and ψ(2S). The procedure for extracting ψ(2S) v_2 has been established in previous publications [56], while a new method is applied to the extraction of J/ψ v_2 with the advantage of avoiding making assumptions of background candidate v_2. The v_n coefficient for J/ψ or ψ(2S) mesons is obtained as follows:

$$v_n\{\mathrm{SP}\} \equiv \frac{\left\langle Q_n^{\mathrm{J}/\psi,\psi(2\mathrm{S})} Q_{nA}^{*} \right\rangle}{\sqrt{\frac{\langle Q_{nA} Q_{nB}^{*}\rangle \langle Q_{nA} Q_{nC}^{*}\rangle}{\langle Q_{nB} Q_{nC}^{*}\rangle}}}. \tag{6.1}$$

The Q-vector of the J/ψ or ψ(2S) candidate is defined as $Q_n^{\mathrm{J}/\psi} = e^{in\phi}$, where ϕ is the azimuthal angle of the candidate. The subscripts A and B refer to either HF+ or HF−, depending on the rapidity of the J/ψ or ψ(2S) candidate. Flattening and recentering procedures are applied to the Q-vectors relative to HF and the tracker for removing detector acceptance effects. To avoid short-range non-collective correlations, the η gap between the J/ψ or ψ(2S) candidate and the detector used for the subevent determination is required to be at least three units of rapidity [56–58]. For this purpose, HF+ is selected for A (B) when J/ψ and ψ(2S) candidates are produced at negative (positive) rapidity. The subscript C denotes the subevents taken from the tracker. The denominator in eq. (6.1) is the correction factor to remove the finite resolution effect of the detectors and finite final-state multiplicity.

To extract the prompt and nonprompt J/ψ meson v_n values, the J/ψ candidates are classified into fine v_n intervals of their flow vector SPs (i.e., eq. (6.1) but not averaged over all J/ψ candidates). Then, a simultaneous invariant mass and $\ell_{\mathrm{J}/\psi}$ fit, as described in section 5, is performed in each v_n interval to extract the corresponding inclusive J/ψ meson yield and the nonprompt J/ψ meson fraction, and to obtain the SP distribution of both prompt and nonprompt J/ψ signal. The prompt J/ψ meson v_n values can be obtained by:

$$v_n^{\mathrm{prompt}} = \frac{\sum (1 - f_i) v_n^i Y^i}{\sum (1 - f_i) Y^i}, \tag{6.2}$$

while the nonprompt J/ψ meson v_n values can be obtained by:

$$v_n^{\mathrm{nonprompt}} = \frac{\sum f_i v_n^i Y^i}{\sum f_i Y^i}. \tag{6.3}$$

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Here v_n^i is the center of the i-th SP bin, while f_i and Y^i are the nonprompt J/ψ meson fraction and inclusive J/ψ meson yield in the same bin, respectively.

A different method is used to extract the prompt ψ(2S) meson flow harmonics. The average Q-vectors of all prompt ψ(2S) meson candidates are divided into bins of invariant mass, as shown in the lower panel of figure 2. For every invariant mass bin, the prompt ψ(2S) meson v_n coefficient is calculated using eq. (6.1). The ψ(2S) candidate invariant mass spectrum and v_n distribution as a function of invariant mass are fit simultaneously using binned χ^2 fits. The invariant mass spectrum is fit with the sum of two CB functions and a Chebyshev polynomial function, as described in section 5. The v_n distribution is fit to the following formula:

$$v_n^{\text{Sig+Bkg}}(m_{\text{inv}}) = \alpha(m_{\text{inv}}) v_n^{\psi(2S)} + [1 - \alpha(m_{\text{inv}})] v_n^{\text{Bkg}}(m_{\text{inv}}), \tag{6.4}$$

where $v_n^{\psi(2S)}$ is the prompt ψ(2S) meson v_n, which is independent of m_{inv} by definition; $v_n^{\text{Bkg}}(m_{\text{inv}})$ is the background v_n modeled as a first-order polynomial function of invariant mass; and $\alpha(m_{\text{inv}})$ is the ψ(2S) signal fraction as a function of invariant mass:

$$\alpha(m_{\text{inv}}) = \frac{\text{Sig}_{\psi(2S)}(m_{\text{inv}})}{[\text{Sig}_{\psi(2S)}(m_{\text{inv}}) + \text{Bkg}(m_{\text{inv}})]}. \tag{6.5}$$

An example of a simultaneous fit to the mass distribution (upper panel) and v_n profile (lower panel) for ψ(2S) mesons is shown in figure 2 for a representative analysis bin.

7 Systematic uncertainties

Systematic uncertainties in this analysis originate from various sources including the modeling of signal and background pdfs, and acceptance and efficiency corrections (trigger, track reconstruction, and muon identification). For uncertainties from the signal pdf, two factors are considered. The first factor is the choice of the signal pdf, and the second is the values of fixed parameters in the invariant mass fit. To evaluate uncertainty on the choice of two CB fit functions, an alternative pdf is formed by adding one CB function and one Gaussian function. The deviation of v_n to the nominal one is quoted as the uncertainty. Uncertainties from the fixed signal shape parameters are studied by releasing each parameter one at a time. The root-mean-square (RMS) of differences between the nominal and altered v_n results is assigned as the uncertainty. For the uncertainty in the background pdf, an exponential of a Chebyshev polynomial is considered as an alternative pdf for the invariant mass distribution. The variation in the v_n results is quoted as the systematic uncertainty.

The uncertainty due to the acceptance correction is evaluated by comparing results with and without p_{T} reweighting of the signal shape in simulated samples. The variation of efficiencies due to the T&P correction is considered. The change of results by varying the T&P correction within its uncertainty is quoted as an uncertainty in the final v_n results. In addition, the uncertainty due to hadronic event selection is considered. The collision event filter is varied, thus allowing for a migration of J/ψ and ψ(2S) mesons across centrality boundaries. The effect on measured v_n values is taken as a systematic uncertainty. Then,

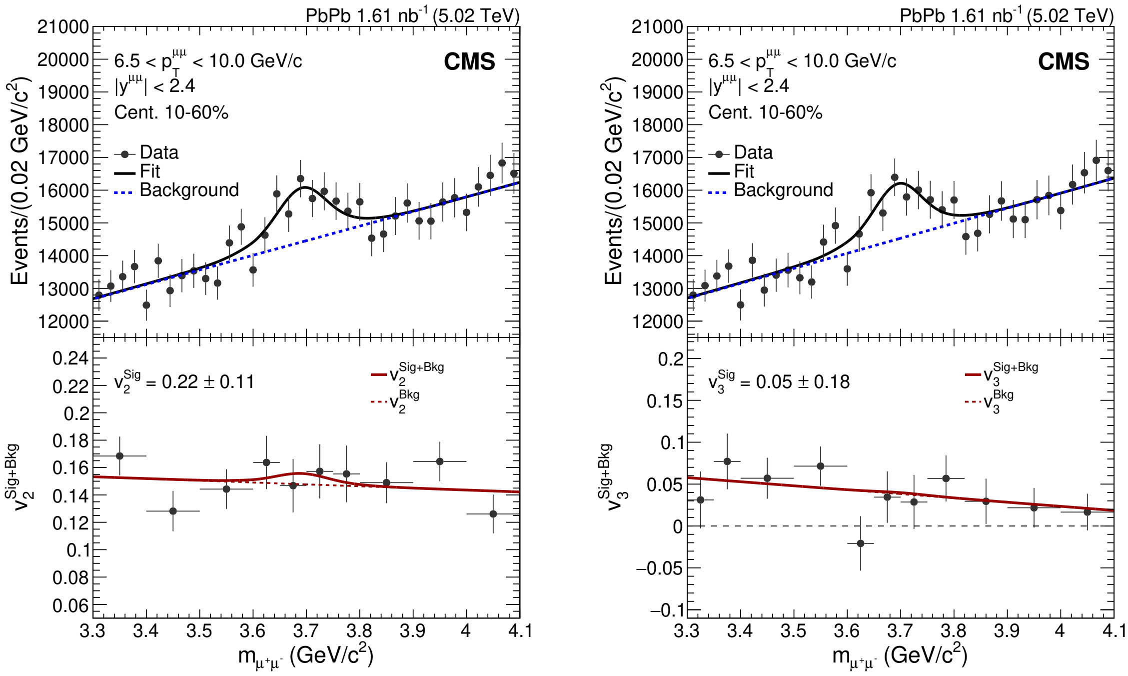

Figure 2. Simultaneous fits of the dimuon invariant mass spectrum and the $v_2^{\mathrm{Sig+Bkg}}$ (left) and $v_3^{\mathrm{Sig+Bkg}}$ (right) distributions for ψ(2S) mesons, as defined by eq. (6.4), for $6.5 < p_{\mathrm{T}} < 10$ GeV/c and centrality 10–60%. In the upper panel, the solid black (signal + background) and dashed blue (background only) lines show the result of the mass fit. In the lower panel, the vertical lines of the v_n^{Sig} points represent the statistical uncertainty. The solid (v_n signal + background) and the dashed (v_n background) lines indicate the corresponding fit to the v_n distributions.

the differences of resulting v_n values from the nominal ones are considered as the systematic uncertainty for the event selection.

Different components of the $\ell_{\mathrm{J}/\psi}$ pdf are varied to estimate the uncertainty in the nonprompt J/ψ meson fraction. The total (signal+background) distribution is used instead of individual distributions for the $\ell_{\mathrm{J}/\psi}$ uncertainty distribution. The $\ell_{\mathrm{J}/\psi}$ resolution obtained from prompt J/ψ meson simulation is used instead of that evaluated from data. The parameters used in the function to describe the bottom hadron decay length shape of the nonprompt J/ψ meson simulations are released in the final fit to data. Four exponential decay functions are also considered instead of three. The maximum deviation between each pair of two variations is taken as an uncertainty for bottom hadron decay length distribution of the nonprompt J/ψ. One additional exponential function on each side of the $\ell_{\mathrm{J}/\psi}$ distribution of the background is used for the systematic uncertainty estimation. The RMS of these four sources is taken as the systematic uncertainty for the nonprompt J/ψ fraction.

For the $v_2^{\mathrm{Bkg}}(m_{\mathrm{inv}})$ modeling of ψ(2S) mesons, a second-order polynomial is used as an alternative function. The deviation of v_n results from nominal ones is assigned as the systematic uncertainty. Uncertainties due to the nonprompt component in the ψ(2S) meson v_n are derived from the deviation of v_n by using a looser $\ell_{\mathrm{J}/\psi}$ requirement that has twice the residual efficiency for nonprompt ψ(2S) mesons compared to the nominal case. The total

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Uncertainty source	Prompt J/ψ		Nonprompt J/ψ		Prompt ψ(2S)	
	v_2	v_3	v_2	v_3	v_2	v_3
Total systematic	1.3–5.2	2.2–5.3	1.9–8.1	3.3–9.1	32.0–63.0	30.0–82.0
Signal parameters	0.4–3.0	0.1–3.0	0.9–5.0	0.1–3.0	3.0–10.0	10.0–30.0
Event selection	0.1–5.0	0.2–3.0	0.9–6.0	0.3–2.0	10.0–30.0	5.0–20.0
Nonprompt J/ψ fraction	0.3–4.0	0.8–4.0	0.4–6.0	2.0–9.0	—	—
Nonprompt ψ(2S) contam.	—	—	—	—	20.0–50.0	10.0–40.0
Background v_n	—	—	—	—	1.0–20.0	0.7–50.0

Table 1. Summary of the absolute total systematic uncertainty and its dominant contributions, in units of 10^{-3}.

uncertainty, calculated for each bin of p_T or $\langle N_{part}\rangle$, is determined by taking the quadratic sum of each individual source of uncertainty. In table 1, the total systematic uncertainty is summarized along with its dominant sources. The ranges provided are illustrative and represent the absolute values of the minimum and maximum uncertainties averaged over all p_T and $\langle N_{part}\rangle$ bins.

8 Results

The v_2 and v_3 coefficients measured for prompt and nonprompt J/ψ mesons in PbPb collisions are shown in figure 3, as functions of p_T and $\langle N_{part}\rangle$. There is at most a weak p_T dependence observed for the prompt and nonprompt J/ψ mesons within their respective uncertainties. Results in figure 3 also show sizable v_2 values for prompt J/ψ mesons even at high p_T, which are consistent with the v_2 of charged hadrons in the high p_T region [32, 33].

The measured v_2 values for nonprompt J/ψ mesons are smaller than those for prompt J/ψ mesons in the studied region. Such a difference could not have been observed at $\sqrt{s_{NN}} = 2.76$ TeV [28] because of the limited amount of data. These results are compatible with measurements from the ALICE and ATLAS Collaborations [27, 29], and extend to a higher p_T region. A similar finding has been observed for prompt and nonprompt D^0 [59]. These observations can be contrasted to those found for bottomonium measurements, in which the v_2 values for ϒ mesons are found to be consistent with zero [56, 60].

In figure 3 (right), the v_2 values for prompt and nonprompt J/ψ mesons are found to be smallest in the most central PbPb collision events (0–10%), which corresponds to $\langle N_{part}\rangle > 356$, and the v_2 values increase toward mid-central collision events. This is expected from the eccentricity in the initial collision geometry of these collisions. The lower panel of the same figure shows measured v_3 values for prompt and nonprompt J/ψ components. No significant nonzero v_3 values are found in studied kinematic intervals.

In figure 4, prompt J/ψ meson v_2 values are compared to a theoretical prediction [31], where high-p_T prompt J/ψ are produced from the jet fragmentation. The medium response of jets in PbPb collisions is simulated using the linear Boltzmann transport framework and the v_2 values are calculated as a consequence of path length dependent energy loss of jets

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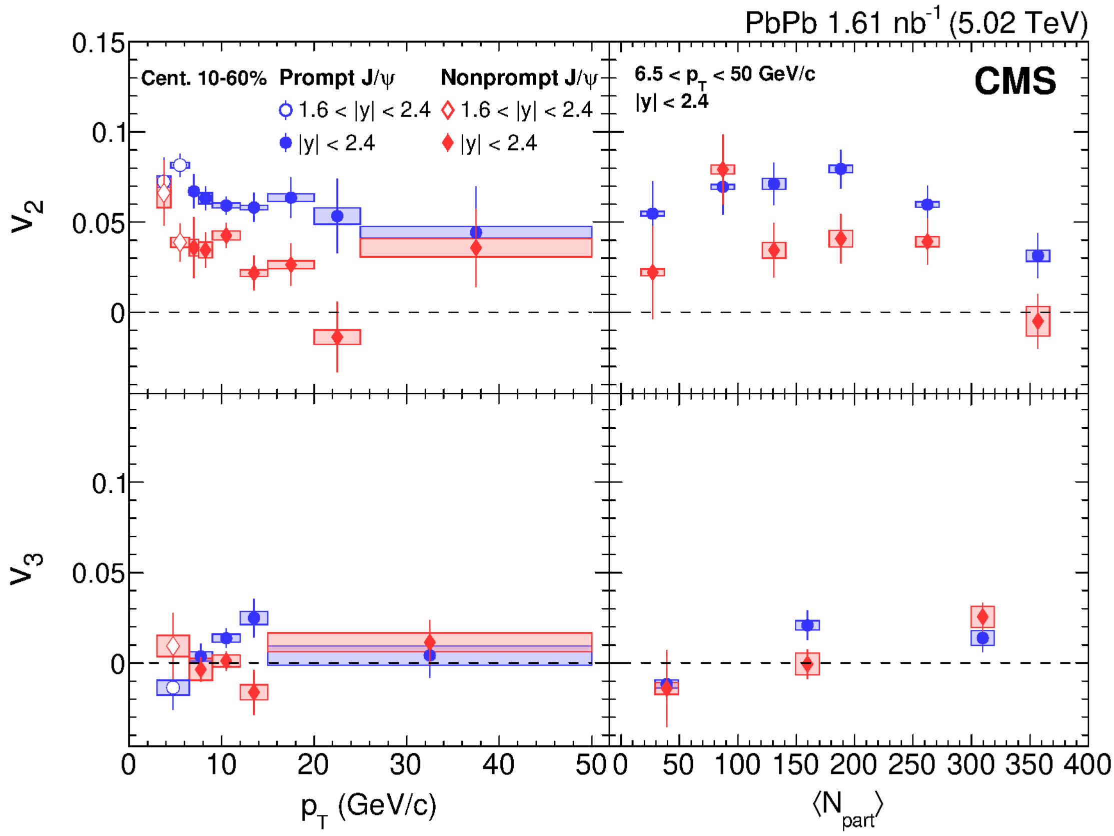

Figure 3. The v_2 (upper) and v_3 (lower) values, as functions of p_T (left) and $\langle N_{part} \rangle$ (right) for prompt and nonprompt J/ψ mesons. The results for $3 < p_T < 6.5$ and $6.5 < p_T < 50$ GeV/c are studied in the rapidity range of $1.6 < |y| < 2.4$ and $|y| < 2.4$, respectively (left). The kinematic range for the right panel is $6.5 < p_T < 50$ GeV/c and $|y| < 2.4$. The data points are positioned in the middle of each p_T bin. The vertical bars denote the statistical uncertainties and the rectangular bands show the systematic uncertainties.

in the QGP. Note that the model is calculated with the centrality interval 10–30%, whereas the data is for the centrality interval 10–60%. A finite v_2 value is predicted by the model calculation, suggesting that path length dependent energy loss of jets in this p_T range needs to be taken into account to describe the prompt J/ψ meson v_2. However, the magnitude of v_2 values in the data is found to be underpredicted by the model. As no strong centrality dependence in mid-central collision events is observed in data, this difference between the observed v_2 and theory calculation can not be explained by the different centrality intervals, indicating that additional contributions are needed to describe the prompt J/ψ meson v_2 at high p_T.

Figure 5 shows the first v_n measurements of the azimuthal anisotropy for prompt ψ(2S) mesons in heavy ion collisions together with the results for prompt J/ψ mesons. The v_2 values are found to be slightly larger for the prompt ψ(2S) than for the prompt J/ψ mesons, especially at higher p_T and in peripheral PbPb collisions, but the statistical significance of this difference is too low to draw any conclusion, with p-values of at best 10%. The v_3 values are found to be consistent with zero in the measured bins.

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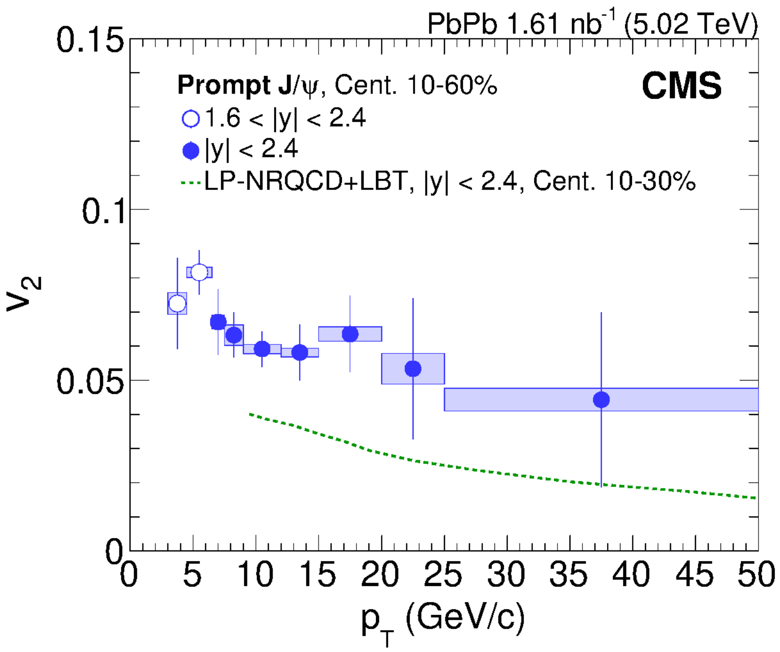

Figure 4. The v_2 values of prompt J/ψ mesons (blue circles) as a function of p_T in the 10–60% centrality range compared with a model calculation in ref. [31] (green dashed line). The results for $3 < p_T < 6.5$ and $6.5 < p_T < 50$ GeV/c are studied in the rapidity range of $1.6 < |y| < 2.4$ and $|y| < 2.4$, respectively. The vertical bars denote the statistical uncertainties and the rectangular bands show the systematic uncertainties.

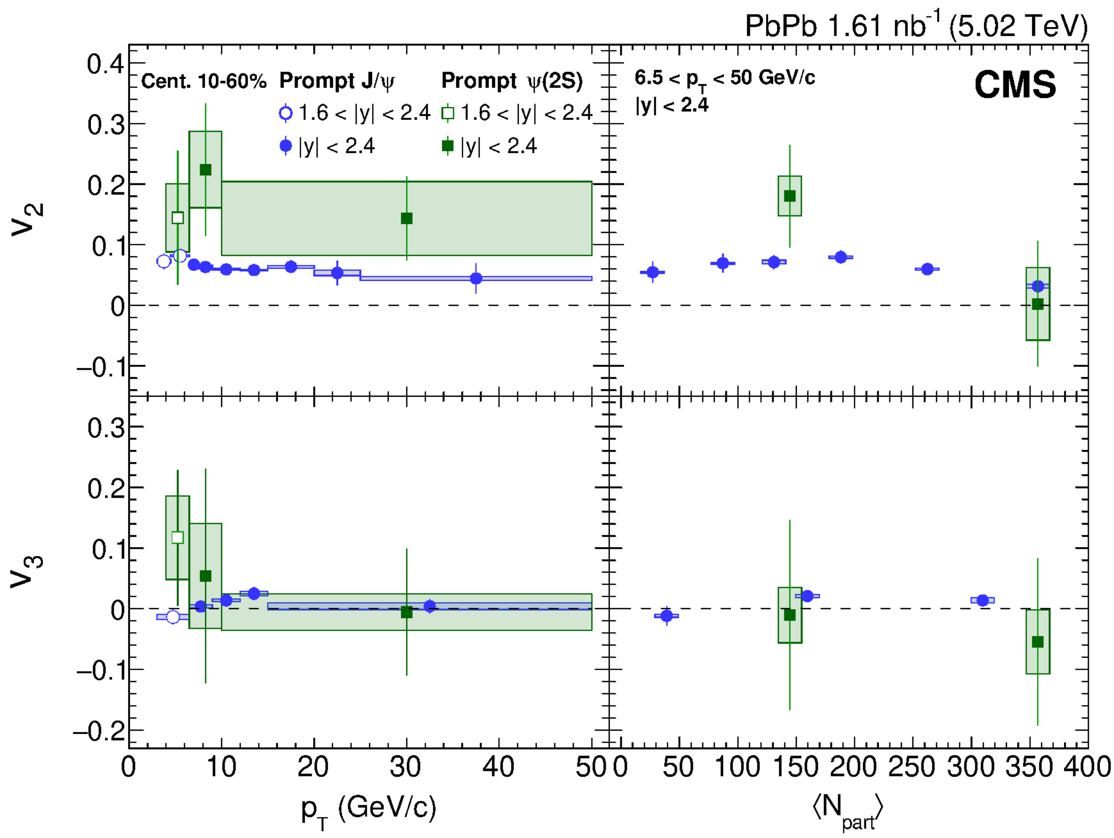

Figure 5. The v_2 (upper) and v_3 (lower) values, as functions of p_T (left) and $\langle N_{part} \rangle$ (right) for prompt J/ψ (blue circles) and prompt ψ(2S) (green squares) mesons. The results for $p_T < 6.5$ and $p_T > 6.5$ GeV/c are studied in the rapidity range of $1.6 < |y| < 2.4$ and $|y| < 2.4$, respectively (left). The kinematic range for the right panel is $6.5 < p_T < 50$ GeV/c and $|y| < 2.4$. The data points are positioned in the middle of each p_T bin. The vertical bars denote the statistical uncertainties and the rectangular bands show the systematic uncertainties.

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9 Summary

The second-order (v_2) and third-order (v_3) Fourier coefficients of azimuthal distributions for prompt and nonprompt J/ψ, and prompt ψ(2S) mesons are measured in PbPb collisions as functions of transverse momentum (p_T) and event centrality. The v_2 values for prompt and nonprompt J/ψ mesons both indicate a decreasing trend from mid-central towards central collision events. Within present experimental uncertainties, these v_2 values show no clear p_T dependence between 3 and 50 GeV/c. The prompt J/ψ meson v_2 values are found to be larger than those of nonprompt J/ψ mesons throughout the studied kinematic region, suggesting different in-medium effects for charm and bottom quarks. The prompt J/ψ meson v_2 values are larger than those from a model calculation which considered the prompt J/ψ production above 10 GeV/c from jet fragmentation. This discrepancy indicates additional effects are required to describe the observed sizable v_2 at high p_T for prompt J/ψ mesons. The v_3 values for prompt and nonprompt J/ψ mesons are reported for the first time, and found to be consistent with zero in the measured p_T and centrality intervals. The v_2 and v_3 values are also measured for prompt ψ(2S) mesons and are compatible with, although slightly larger than, those of prompt J/ψ mesons. These J/ψ and ψ(2S) meson measurements provide new information about heavy quark interactions in the hot and dense medium created in heavy ion collisions.

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A Kinematic regions

The kinematic ranges for J/ψ and ψ(2S) mesons used in this study are summarized in table 2. The centrality and $\langle N_{part} \rangle$ values used are calculated using a Glauber model simulation [39] and are summarized in table 3.

	J/ψ	ψ(2S)
$\|y\| < 2.4$	$6.5 < p_T < 50$ GeV/c	$6.5 < p_T < 50$ GeV/c
$1.6 < \|y\| < 2.4$	$3 < p_T < 6.5$ GeV/c	$4 < p_T < 6.5$ GeV/c

Table 2. A Summary of the kinematic regions for J/ψ and ψ(2S) in the centrality interval 10–60%.

Centrality class	$\langle N_{part} \rangle$
0–10%	356.9 ± 0.9
10–20%	262.3 ± 1.3
20–30%	188.2 ± 1.4
30–40%	131.0 ± 1.4
40–50%	87.1 ± 1.3
50–90%	27.1 ± 0.6
0–20%	309.6 ± 1.0
20–40%	159.6 ± 1.4
40–90%	39.1 ± 0.7
10–60%	144.6 ± 1.2

Table 3. The centrality classes and $\langle N_{part} \rangle$ values for PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV used in this study.

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, P.S. Hussain, M. Jeitler[1], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck[1], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[1]

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

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

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

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

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Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[5], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

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

University of Sofia, Sofia, Bulgaria
A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

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

Beihang University, Beijing, China
T. Cheng, T. Javaid[8], M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, G. Bauer[9], Z. Hu, S. Lezki, K. Yi[9,10]

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

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin, C. Li, Q. Li, X. Lyu, Y. Mao, S.J. Qian, X. Sun, D. Wang, J. Xiao, H. Yang

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

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) — Fudan University, Shanghai, China
X. Gao[3], D. Leggat, H. Okawa, Y. Zhang

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao

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

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

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, B.K. Chitroda, D. Ferencek, S. Mishra, M. Roguljic, A. Starodumov[12], T. Susa

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

Charles University, Prague, Czech Republic
M. Finger[12], M. Finger Jr.[12], A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[13,14], E. Salama[15,16]

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

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

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

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

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

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

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

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

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

Georgian Technical University, Tbilisi, Georgia
I. Bagaturia[20], I. Lomidze, Z. Tsamalaidze[12]

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

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

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

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

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

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

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, D. Karasavvas, P. Kontaxakis, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,13], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], W. Elmetenawee[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], M. Ince[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], D. Ramos[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], A. Stamerra[a], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], L. Brigliadori[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,48], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,49], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,49], C. Tuve[a,b]

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

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INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Meola[28], D. Piccolo

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

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

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

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

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

S. Buontempo[a], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,50], P. Paolucci[a,28], B. Rossi[a], C. Sciacca[a,b]

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

P. Azzi[a], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], G. Grosso[a], L. Layer[a,51], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

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

S. Abu Zeid[a,16], C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

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

P. Asenov[a,52], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,52], A. Piccinelli[a,b], M. Presilla[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

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

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

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

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy

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

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

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

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

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

Kyungpook National University, Daegu, Korea

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

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

G. Bak, P. Gwak, H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

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

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh

Sejong University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

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

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

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

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

Riga Technical University, Riga, Latvia
K. Dreimanis, G. Pikurs, M. Seidel, V. Veckalns[53]

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, S.Y. Hoh[54], I. Yusuff[54], Z. Zolkapli

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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, I. Heredia-De La Cruz[55], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

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

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

University of Montenegro, Podgorica, Montenegro
I. Bubanja, J. Mijuskovic[56], N. Raicevic

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

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

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, J. Varela

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
P. Adzic[57], M. Dordevic, P. Milenovic, J. Milosevic

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

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, A. García Alonso, G. Gomez, C. Lasaosa García,

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

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[58], D.U.J. Sonnadara, D.D.C. Wickramarathna

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, B. Bilin, A. Bocci, E. Brondolin, C. Caillol, T. Camporesi, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, F. Fallavollita[59], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, N. Kratochwil, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[60], A.G. Stahl Leiton, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk[61], K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[62], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[62], L. Noehte[62], T. Rohe

ETH Zurich — Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov[61], M. Backhaus, P. Berger, A. Calandri, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, A. Mascellani[61], F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, J. Steggemann[61], D. Valsecchi[28], R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[63], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei,

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

National Central University, Chung-Li, Taiwan
C. Adloff[64], C.M. Kuo, W. Lin, P.K. Rout, S.S. Yu

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

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

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[65], E. Eskut, Y. Guler[66], E. Gurpinar Guler[66], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[67], A. Polatoz, A.E. Simsek, B. Tali[68], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
G. Karapinar[69], K. Ocalan[70], M. Yalvac[71]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[72], O. Kaya[73], S. Tekten[74]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[65], Y. Komurcu, S. Sen[65]

Istanbul University, Istanbul, Turkey
O. Aydilek, S. Cerci[68], B. Hacisahinoglu, I. Hos[75], B. Isildak[76], B. Kaynak, S. Ozkorucuklu, C. Simsek, D. Sunar Cerci[68]

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

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

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

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B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[77], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[79], Sh. Jain, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, C.E. Brown, O. Buchmuller, V. Cacchio, V. Cepaitis, G.S. Chahal[80], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, D.G. Monk, J. Nash[81], M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[28], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

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

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

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

The University of Alabama, Tuscaloosa, Alabama, U.S.A.
S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio[82], C. West

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

Brown University, Providence, Rhode Island, U.S.A.
G. Benelli, B. Burkle, X. Coubez[23], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[83], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, M. Narain, N. Pervan, S. Sagir[84], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

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

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

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

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

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

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

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

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

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

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

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J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[85], F. Ravera, A. Reinsvold Hall[86], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

University of Florida, Gainesville, Florida, U.S.A.
P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R.D. Field, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, E. Kuznetsova[87], K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu

Florida State University, Tallahassee, Florida, U.S.A.
T. Adams, A. Askew, R. Habibullah, V. Hagopian, T. Kolberg, G. Martinez, H. Prosper, O. Viazlo, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, U.S.A.
M.M. Baarmand, S. Butalla, T. Elkafrawy[16], M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, Illinois, U.S.A.
M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C.E. Gerber, D.J. Hofman, D. S. Lemos, A.H. Merrit, C. Mills, S. Nanda, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, X. Wang, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, U.S.A.
M. Alhusseini, K. Dilsiz[88], L. Emediato, R.P. Gandrajula, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[89], J. Nachtman, O. Neogi, H. Ogul[90], Y. Onel, A. Penzo, C. Snyder, E. Tiras[91]

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

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

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Kansas State University, Manhattan, Kansas, U.S.A.
B. Allmond, S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam, D. Roy

Lawrence Livermore National Laboratory, Livermore, California, U.S.A.
F. Rebassoo, D. Wright

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

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

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

University of Mississippi, Oxford, Mississippi, U.S.A.
L.M. Cremaldi

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

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

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

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

University of Notre Dame, Notre Dame, Indiana, U.S.A.
R. Band, R. Bucci, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton,

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J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[12], R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

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

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

University of Puerto Rico, Mayaguez, Puerto Rico, U.S.A.
S. Malik, S. Norberg

Purdue University, West Lafayette, Indiana, U.S.A.
A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic[17], J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, Indiana, U.S.A.
J. Dolen, N. Parashar

Rice University, Houston, Texas, U.S.A.
D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Rotter, W. Shi, S. Yang, E. Yigitbasi, L. Zhang[92], Y. Zhang

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

The Rockefeller University, New York, New York, U.S.A.
K. Goulianos

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

University of Tennessee, Knoxville, Tennessee, U.S.A.

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

Texas A&M University, College Station, Texas, U.S.A.

O. Bouhali[93], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[94], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, U.S.A.

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

Vanderbilt University, Nashville, Tennessee, U.S.A.

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

University of Virginia, Charlottesville, Virginia, U.S.A.

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

Wayne State University, Detroit, Michigan, U.S.A.

P.E. Karchin, N. Poudyal

University of Wisconsin — Madison, Madison, Wisconsin, U.S.A.

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

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

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov[95], E. Boos, V. Borshch, D. Budkouski, V. Chekhovsky, R. Chistov[95], A. Demiyanov, A. Dermenev, T. Dimova[95], I. Dremin, V. Epshteyn, A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, V. Ivanchenko, Y. Ivanov, V. Kachanov, L. Kardapoltsev[95], V. Karjavine, A. Karneyeu, L. Khein, V. Kim[95], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, O. Kodolova, D. Konstantinov, V. Korenkov, V. Korotkikh, A. Kozyrev[95], N. Krasnikov, A. Lanev, P. Levchenko, A. Litomin, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[95,96], V. Murzin, A. Nikitenko[97], S. Obraztsov, A. Oskin, I. Ovtin[95], V. Palichik, P. Parygin, V. Perelygin, S. Petrushanko, S. Polikarpov[95], V. Popov, E. Popova, O. Radchenko[95], M. Savina, V. Savrin, D. Selivanova, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[95], S. Slabospitskii, V. Smirnov, A. Snigirev, D. Sosnov, V. Sulimov,

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E. Tcherniaev, A. Terkulov, O. Teryaev, I. Tlisova, M. Toms, A. Toropin, L. Uvarov, A. Uzunian, I. Vardanyan, E. Vlasov, A. Vorobyev, N. Voytishin, B.S. Yuldashev[98], A. Zarubin, I. Zhizhin, A. Zhokin

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

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[47] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[48] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[49] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[50] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[51] Also at Università di Napoli 'Federico II', Napoli, Italy
[52] Also at Consiglio Nazionale delle Ricerche — Istituto Officina dei Materiali, Perugia, Italy
[53] Also at Riga Technical University, Riga, Latvia
[54] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[55] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[56] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[57] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
[58] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[59] Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
[60] Also at National and Kapodistrian University of Athens, Athens, Greece
[61] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[62] Also at Universität Zürich, Zurich, Switzerland
[63] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[64] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[65] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[66] Also at Konya Technical University, Konya, Turkey
[67] Also at Izmir Bakircay University, Izmir, Turkey
[68] Also at Adiyaman University, Adiyaman, Turkey
[69] Also at Istanbul Gedik University, Istanbul, Turkey
[70] Also at Necmettin Erbakan University, Konya, Turkey
[71] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[72] Also at Marmara University, Istanbul, Turkey
[73] Also at Milli Savunma University, Istanbul, Turkey
[74] Also at Kafkas University, Kars, Turkey
[75] Also at Istanbul University — Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[76] Also at Ozyegin University, Istanbul, Turkey
[77] Also at Vrije Universiteit Brussel, Brussel, Belgium
[78] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[79] Also at University of Bristol, Bristol, United Kingdom
[80] Also at IPPP Durham University, Durham, United Kingdom
[81] Also at Monash University, Faculty of Science, Clayton, Australia
[82] Also at Università di Torino, Torino, Italy
[83] Also at Bethel University, St. Paul, Minnesota, U.S.A.
[84] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[85] Also at California Institute of Technology, Pasadena, California, U.S.A.
[86] Also at United States Naval Academy, Annapolis, Maryland, U.S.A.
[87] Also at University of Florida, Gainesville, Florida, U.S.A.
[88] Also at Bingol University, Bingol, Turkey
[89] Also at Georgian Technical University, Tbilisi, Georgia
[90] Also at Sinop University, Sinop, Turkey
[91] Also at Erciyes University, Kayseri, Turkey
[92] Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) — Fudan University, Shanghai, China
[93] Also at Texas A&M University at Qatar, Doha, Qatar
[94] Also at Kyungpook National University, Daegu, Korea

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[95] *Also at another institute or international laboratory covered by a cooperation agreement with CERN*
[96] *Now at another institute or international laboratory covered by a cooperation agreement with CERN*
[97] *Also at Imperial College, London, United Kingdom*
[98] *Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*

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