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# Measurement of the azimuthal anisotropy of $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration\*

## Abstract

The second-order Fourier coefficients ( $v_2$ ) characterizing the azimuthal distributions of  $\Upsilon(1S)$  and  $\Upsilon(2S)$  mesons produced in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV are studied. The  $\Upsilon$  mesons are reconstructed in their dimuon decay channel, as measured by the CMS detector. The collected data set corresponds to an integrated luminosity of  $1.7 \text{ nb}^{-1}$ . The scalar product method is used to extract the  $v_2$  coefficients of the azimuthal distributions. Results are reported for the rapidity range  $|y| < 2.4$ , in the transverse momentum interval  $0 < p_T < 50 \text{ GeV}/c$ , and in three centrality ranges of 10–30%, 30–50% and 50–90%. In contrast to the  $J/\psi$  mesons, the measured  $v_2$  values for the  $\Upsilon$  mesons are found to be consistent with zero.

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## 1 Introduction

The primary motivation for studying high-energy heavy ion collisions is to better understand the hot and dense matter produced in these interactions [1]. Lattice quantum chromodynamics (LQCD) calculations indicate that at sufficiently high temperatures an environment is created for a crossover to occur from hadronic matter to a strongly interacting system of deconfined quarks and gluons [2]. This deconfined medium is called the “quark-gluon plasma” (QGP) [3]. One of the most prominent signatures of QGP formation is that the production of quarkonia, the bound states of a heavy quark and its antiquark, is suppressed with respect to expectations from scaling the yields in proton-proton collisions by the number of binary nucleon-nucleon (NN) collisions. This suppression arises because the quarkonia binding is weakened by color screening caused by the surrounding partons in the medium [4], and therefore the extent of the quarkonia suppression is expected to be sequentially ordered by the binding energies of the quarkonia states. In heavy ion collisions, the majority of heavy quarks are produced from hard scattering processes at an early stage and therefore can interact with the QGP throughout its entire evolution.

Because of the binding energy dependence of the screening, the bottomonium states ( $Y(1S)$ ,  $Y(2S)$ ,  $Y(3S)$ ,  $\chi_b$ , etc.) are particularly useful probes to understand the space-time evolution of the QGP. The sequential suppression of the yield of  $Y(nS)$  states was first observed by CMS [5, 6] at a NN center-of-mass energy  $\sqrt{s_{NN}} = 2.76$  TeV. More recently, results with improved statistical precision have been reported by both the ALICE Collaboration [7] and CMS Collaboration [8, 9] at  $\sqrt{s_{NN}} = 5.02$  TeV. The suppression of the  $Y(1S)$  meson has also been studied at  $\sqrt{s_{NN}} = 200$  GeV at RHIC [10]. The available experimental data, spanning from 0.20 to 5.02 TeV, have provided new insight into the thermal properties of the QGP [11].

The screening due to the QGP can also result in an azimuthal asymmetry in the observed yields of quarkonia. In non-central heavy ion collisions, the produced QGP has a lenticular shape in the transverse plane. Consequently, the average path length for quarkonia traveling through the medium depends on the direction taken with respect to this shape, with a larger suppression in the direction of the longer axis [12–15]. The anisotropic distribution of particles can be characterized by the magnitudes of the Fourier coefficients ( $v_n$ ) of the azimuthal correlation of particles, through the relation

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n \cos[n(\phi - \Psi_n)]. \quad (1)$$

Here  $\phi$  is the angle of the particles and  $\Psi_n$  is the angle characterizing the symmetry plane of the  $n$ th harmonic based on the charged particle density distribution [16]. By studying the azimuthal distribution of the quarkonia, it is possible to develop a more comprehensive understanding of the dynamics of their production.

Measurements of  $v_2$  values have been reported for  $J/\psi$  mesons by the ALICE Collaboration [17, 18] and the CMS Collaboration [19] at  $\sqrt{s_{NN}} = 5.02$  TeV and 2.76 TeV, respectively. Significant evidence for an azimuthal asymmetry in the particle yields is found for both experiments. However, the  $J/\psi$  asymmetry can also arise from the late-stage recombination of uncorrelated charm quark pairs inside the QGP, which acts in the opposite direction as color screening. The relative contribution of recombination to the inclusive cross section of bottomonium states is expected to be smaller than for charmonium states [20–23]. For this reason, the azimuthal anisotropy of bottomonia better reflects the screening that occurs during its passage through the QGP medium. The ALICE Collaboration has measured the  $v_2$  for  $Y(1S)$  mesons at forward rapidity ( $2.5 < y < 4$ ) using 5.02 TeV PbPb collisions [24].

This paper reports on the measurement of  $v_2$  coefficients using the scalar product method [25, 26] for  $\Upsilon(1S)$  and  $\Upsilon(2S)$  mesons at midrapidity ( $|y| < 2.4$ ) in PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The data set was collected with the CMS detector in 2018 and corresponds to an integrated luminosity of  $1.7 \text{ nb}^{-1}$ . The  $\Upsilon$  mesons are reconstructed through their dimuon decay channel. The  $v_2$  values for  $\Upsilon(1S)$  mesons are measured in four transverse momentum ( $p_T$ ) intervals (0–3, 3–6, 6–10, and 10–50 GeV/ $c$ ) for different centrality classes. Centrality is defined as the fraction of the total inelastic nucleus-nucleus cross section with 0% representing the largest overlap of the two colliding Pb nuclei. For this analysis, events are classified in three centrality intervals (10–30%, 30–50%, and 50–90%), with 10–30% corresponding to the most central events. More central (0–10%) and more peripheral (90–100%) collisions are excluded because of small eccentricity in the initial geometry and low event selection efficiency, respectively. Because of their lower production cross section compared to that of  $\Upsilon(1S)$  mesons, the  $\Upsilon(2S)$  mesons are measured in one interval that spans  $|y| < 2.4$ ,  $0 < p_T < 50$  GeV/ $c$ , and centrality 10–90%.

## 2 The CMS Detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, as well as a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The Hadronic Forward (HF) calorimeters, located at  $3 < |\eta| < 5$ , extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel and endcap detectors. The collision centrality is estimated experimentally using the sum of the transverse energy deposited in the HF calorimeters. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid within the pseudorapidity coverage of  $|\eta| < 2.4$ . 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. [27].

## 3 Event Selection

Events were selected based on several trigger stages. First, at least two muon candidates reconstructed in the fast hardware-based trigger system are required. In the high level trigger, Level-2 (L2) muons are identified by requiring fitted tracks in the outer muon spectrometer. At Level-3 (L3), muons are reconstructed using full tracks from the L2 muon tracks and the inner tracker information, with a minimum of ten high-quality hits in the inner tracker [28]. Finally, events are required to contain at least one L2 muon and another L3 muon, with their invariant mass being greater than  $7 \text{ GeV}/c^2$ . To reject beam-related background processes (beam scraping events and beam-gas collisions), events are required to pass the following conditions: (a) that at least one reconstructed primary vertex exists, (b) that the width of silicon pixel detector clusters is compatible with the vertex position [29], and (c) that at least two towers in each of the two HF detectors located on opposite sides of CMS detect energy above 4 GeV. The primary vertex, which is reconstructed based on two tracks or more, is required to be located within 15 cm from the central point of the detector along the beam axis.

For high-quality muon identification, a set of offline selection criteria is applied. This selection requires that the reconstructed muon is matched to a track reconstructed in the inner tracking detector, which has at least six silicon tracker hits, with at least one of these hits occurring in the inner silicon pixel detector array. In addition, the distance of closest approach of a muon

track from the nearest primary vertex must be less than 0.3 and 20 cm in the transverse and the longitudinal directions, respectively. To assure high efficiency, the individual muons were required to have  $p_T^\mu > 3.5 \text{ GeV}/c$ , with  $|\eta^\mu| < 2.4$ . Pairs of oppositely charged muons are fitted with a common vertex constraint and used in this analysis if the confidence level of the fit is greater than 1%.

## 4 Analysis

The  $Y$  meson signals and combinatorial backgrounds for selected dimuon pairs are separated using fits to the invariant mass ( $m_{\text{inv}}$ ) distribution. The range of the studied mass spectrum is 8–14  $\text{GeV}/c^2$ , which covers both  $Y(1S)$  and  $Y(2S)$  resonance peaks, as well as the  $Y(3S)$  mesons.

Acceptance and efficiency correction factors are used as event-by-event weights when the invariant mass distribution and the average  $v_2$  values are computed. Acceptance is defined as the probability for both the decay muons originated from an  $Y$  meson to be within  $p_T^\mu > 3.5 \text{ GeV}/c$ ,  $|\eta^\mu| < 2.4$ . It is determined as a function of  $p_T$  using PYTHIA 8.212 [30] Monte Carlo (MC) generator with tune CP5 [31], where  $Y$  mesons from  $^3S_1$ ,  $^3P_J$ ,  $^3D_J$  bottomonium states form via the color-singlet [32, 33] and color-octet [34] mechanisms. The MC events are then reweighted to match the  $p_T$  spectra to the PbPb data. The efficiencies for reconstruction, muon identification, and trigger selection are calculated by a full simulation of the CMS detector using GEANT4 [35]. Each  $Y$  event is embedded in a HYDJET 1.9 [36] PbPb event to reproduce the hydrodynamic background environment. The average acceptance and efficiency factors are 53.7% (56.7%) and 56.9% (60.0%) for  $Y(1S)$  ( $Y(2S)$ ), respectively. A systematic uncertainty is assigned based on the difference found between the MC results and experimental data. The MC and experimental data are compared using the tag-and-probe method with single muons obtained from  $J/\psi$  meson decays [37, 38]. The efficiency ratio of data over simulation is applied as a weight for the derivation of the final dimuon efficiency.

The  $v_2$  values of  $Y$  candidates are determined using the scalar product (SP) method, in a similar way as the one employed to determine the elliptic flow of prompt  $D^0$  mesons in PbPb collisions [39]. Using this method, the particle asymmetries associated with different subevents are characterized by  $Q$ -vectors that are determined for different  $\eta$  ranges using either tracker or HF calorimeter data [25]. The  $Q$ -vectors are given by  $Q_2 = \sum_{k=1}^M \omega_k e^{2i\phi_k}$ , where the sum is over the multiplicity of particles for the tracker or the number of towers for the HF calorimeters,  $\phi$  is the azimuthal angle of the particle or the tower, and  $\omega$  is the weight given by the  $p_T$  of a particle in the tracker or the transverse energy deposited in a tower. A three subevent method [25, 39] is used, employing the tracker, with  $|\eta| < 0.75$ , and the two HF calorimeters that cover the ranges  $3 < \eta < 5$  (HF+) and  $-5 < \eta < -3$  (HF-). The  $Q$ -vector of an  $Y$  candidate is defined as  $Q_{2,Y} = e^{i2\phi}$  where  $\phi$  is the azimuthal angle of the candidate. The  $v_2$  coefficient is then given by

$$v_2 \{ \text{SP} \} \equiv \frac{\langle Q_{2,Y} Q_{2A}^* \rangle}{\sqrt{\frac{\langle Q_{2A} Q_{2B}^* \rangle \langle Q_{2A} Q_{2C}^* \rangle}{\langle Q_{2B} Q_{2C}^* \rangle}}}. \quad (2)$$

Here,  $Q_{2A}$  and  $Q_{2B}$  correspond to subevents based on the HF detectors, and  $Q_{2C}$  is based on the tracker. The subscripts  $A$  and  $B$  refer to either HF+ or HF-, depending on the rapidity of the  $Y$  candidate. In order to avoid autocorrelations and to reduce nonflow effects, the  $\eta$  gap between  $Y$  candidates and the subevent detector is required to be at least 3 units. For this reason, HF+ is selected for  $A$  ( $B$ ) when the  $Y$  candidate is produced at negative (positive) rapidity.

The  $\langle \rangle$  brackets denote averages over all  $Y$  candidate events, taking the real part of the  $Q$ -vector products. The denominator in Eq. (2) is a resolution correction that depends on the particle multiplicity in the HF detector referenced by the  $A$  subscript [25]. The lower panel of Fig. 1 shows an example of the resulting  $v_2$  distribution as a function of the  $Y$  candidate invariant mass. The separation of signal and background is done in two steps. First, the yields of  $Y$

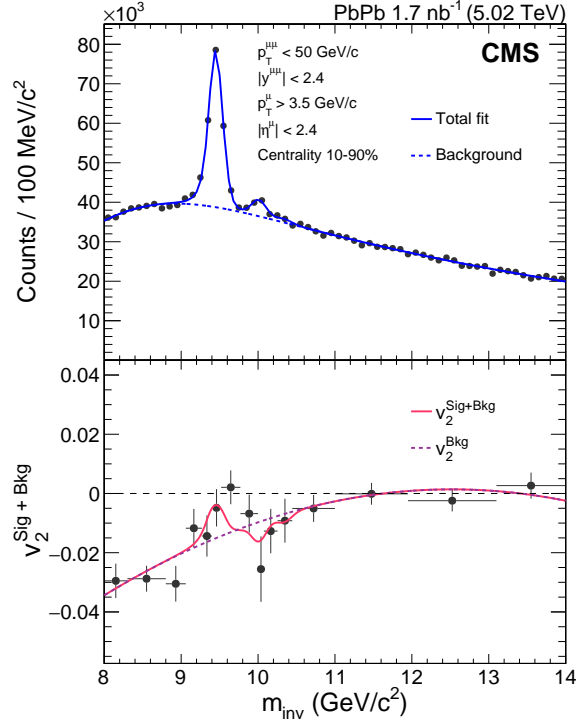


Figure 1: Simultaneous fit of the dimuon invariant mass spectrum and the  $v_2^{\text{Sig+Bkg}}$  distribution, as defined in Eq. (3), for  $p_T < 50 \text{ GeV}/c$  and with centrality 10–90%. The solid (signal + background) and dashed (background only) blue lines show the result of the mass fit, and the solid and dashed red lines show the corresponding results for the binned  $\chi^2$  fit to the  $v_2$  distribution.

signals are extracted from the invariant mass distribution without using the  $v_2$  information. The purpose of this step is to find the best parameters for the probability distribution describing the  $Y$  mass peaks. Unbinned log-likelihood fits to the mass distribution are used to obtain the best fit to the data. The analysis is done using a single rapidity range with  $|y| < 2.4$  and, thus, uses  $Y$  candidates obtained in both the barrel and endcap regions of CMS. For this reason, the signal mass distribution (Sig) for each  $Y$  meson is formed by the sum of two Crystal Ball (CB) functions [40], to account for the different mass resolutions of the two regions. For both CB functions, the mass and the radiative tail parameters are constrained to be equal since these are not sensitive to the detector resolution. The  $Y(1S)$  mass is taken as a free parameter of the fit, allowing for a possible scaling error in the momentum calibration for the reconstructed tracks. The mean ( $m_0$ ) and width ( $\sigma$ ) parameters for the excited states ( $Y(2S)$  and  $Y(3S)$ ) are found by scaling the  $Y(1S)$  values by the ratio of published masses [41]. Other parameters for the excited states are constrained to be identical to those of the  $Y(1S)$  mesons. The normalization parameters  $N_{\text{sig},1S}$ ,  $N_{\text{sig},2S}$  and  $N_{\text{sig},3S}$  are free parameters of the fit. More details about the parameters for the invariant mass fit can be found in Ref. [9].

The background mass spectrum (Bkg) is modeled by a function obtained by multiplying a real-valued error function and an exponential function. The error function is used to reproduce a kinematic enhancement found at low mass, resulting from the single muon  $p_T$  threshold. The

exponential component is motivated by the exponentially falling structure of the combinatorial background in the high mass region. There are four parameters characterizing the shape of background, the  $\mu$  and  $\sigma$  parameters of the error function, the decay length of the exponential function, and an overall normalization parameter.

In the second step, the invariant mass and  $v_2$  distributions are fitted simultaneously using binned  $\chi^2$  fits. The signal function parameters are fixed to the values obtained from the previous step, although the normalizations  $N_{\text{sig},1S}$ ,  $N_{\text{sig},2S}$ , and  $N_{\text{sig},3S}$  and the background function parameters are left free. The  $v_2$  dependence on  $m_{\text{inv}}$  is taken as

$$v_2^{\text{Sig+Bkg}}(m_{\text{inv}}) = \alpha_1(m_{\text{inv}})v_2^{Y(1S)} + \alpha_2(m_{\text{inv}})v_2^{Y(2S)} + \alpha_3(m_{\text{inv}})v_2^{Y(3S)} + [1 - \alpha_1(m_{\text{inv}}) - \alpha_2(m_{\text{inv}}) - \alpha_3(m_{\text{inv}})]v_2^{\text{Bkg}}(m_{\text{inv}}), \quad (3)$$

where,  $v_2^{Y(iS)}$  ( $i = 1, 2, 3$ ) is the  $v_2$  value for the  $Y(iS)$  mesons and is assumed to be independent of  $m_{\text{inv}}$ . The  $\alpha_i(m_{\text{inv}})$  coefficients are the fractions that the  $Y(iS)$  states occupy as a function of invariant mass, as determined from the fit. They are defined as

$$\alpha_i(m_{\text{inv}}) = \text{Sig}_{Y(iS)}(m_{\text{inv}}) / [\text{Sig}_{Y(1S)}(m_{\text{inv}}) + \text{Sig}_{Y(2S)}(m_{\text{inv}}) + \text{Sig}_{Y(3S)}(m_{\text{inv}}) + \text{Bkg}(m_{\text{inv}})]. \quad (4)$$

The background  $v_2$  value,  $v_2^{\text{Bkg}}(m_{\text{inv}})$ , is modeled as a second-order polynomial function of the invariant mass. Figure 1 shows an example of a simultaneous fit to the mass (upper panel) and  $v_2$  distributions (lower panel).

## 5 Systematic Uncertainties

The systematic uncertainties in this analysis come from various sources, including the modeling of signal and background probability functions, as well as acceptance and efficiency corrections (muon identification and trigger). The uncertainties for the various sources are studied as functions of  $p_T$  and centrality. However, within the limits of the evaluation, no clear  $p_T$  or centrality trend is found. For the uncertainty associated with the signal, an alternative function is formed by adding one CB and one Gaussian function having equal mass parameters. The differences in the  $v_2$  values from the nominal one are taken as the uncertainties. The difference is typically less than 0.0025 for the  $Y(1S)$  mesons and is equal to 0.014 for the  $Y(2S)$  mesons. The uncertainties resulting from holding the final fit parameters constant are studied by releasing each parameter, one by one, and redoing the fit with the additional free parameter. The largest deviation of the resulting  $v_2$  values from the nominal result is taken as the uncertainty. The difference is found typically in the range 0.0006 to 0.005 for the  $Y(1S)$  mesons and is 0.0093 for the  $Y(2S)$  mesons. To determine the uncertainty related to the background modeling, the functions for both the invariant mass distribution and  $v_2^{\text{Bkg}}(m_{\text{inv}})$  are varied. For the mass distribution, a fourth-order polynomial is used as an alternative functional behavior. For the  $v_2^{\text{Bkg}}(m_{\text{inv}})$  function, two alternative functions are introduced instead of the nominal second-order polynomial, one as the third-order polynomial and the other as an exponential function. The uncertainty associated with the choice of the  $v_2^{\text{Bkg}}(m_{\text{inv}})$  function is assigned as the maximum difference found for the two alternative functions used to model the background. The uncertainty values in the choice of the background modeling functions for the mass and  $v_2$  distributions are typically in the range 0.001–0.009 for the  $Y(1S)$  mesons, and are found to be 0.012 and 0.030, respectively for the  $Y(2S)$  mesons.

The uncertainty resulting from the acceptance and efficiency corrections is evaluated by comparing the results with and without weighting the simulated  $p_T$  spectra. By virtue of the cylin-

drical symmetry of the detector, the effect of these corrections is minor. An additional systematic uncertainty for the efficiency is assigned based on the tag-and-probe method. The difference of the  $v_2$  values with and without applying the tag-and-probe correction is assigned as the uncertainty and is found to be in the range 0.002–0.012. Finally, uncertainties resulting from the hadronic event selection are considered. The collision event filter is varied, thus allowing for a migration of  $\Upsilon(1S)$  and  $\Upsilon(2S)$  mesons across centrality boundaries. The effect on the measured  $v_2$  value is taken as a systematic uncertainty. For  $\Upsilon(1S)$  the differences are typically below 0.0008 and for  $\Upsilon(2S)$  the uncertainty is 0.0067. Individual systematic uncertainties are expected to be uncorrelated and are therefore added in quadrature for the final assigned values. The absolute systematic uncertainty in the  $v_2$  values for the  $\Upsilon(1S)$  meson range in most intervals from 0.002 to 0.015, which is smaller than the statistical uncertainty. The largest uncertainty corresponds to the most peripheral and lowest  $p_T$  interval measured, which is dominated by the uncertainty related to the  $v_2^{\text{Bkg}}(m_{\text{inv}})$  modeling and hadronic event selection. The uncertainty for the  $\Upsilon(2S)$   $v_2$  value, which is obtained for the integrated interval only, is 0.037.

## 6 Results

The  $p_T$  integrated results are shown in Fig. 2 (left panel) for three centrality intervals. The  $\Upsilon(1S)$   $v_2$  values are consistent with zero within the statistical uncertainties. The rightmost points in this figure are the average  $v_2$  values in the 10–90% centrality interval. They are determined to be  $0.007 \pm 0.011$  (stat)  $\pm 0.005$  (syst) for  $\Upsilon(1S)$  mesons and  $-0.063 \pm 0.085$  (stat)  $\pm 0.037$  (syst) for  $\Upsilon(2S)$  mesons.

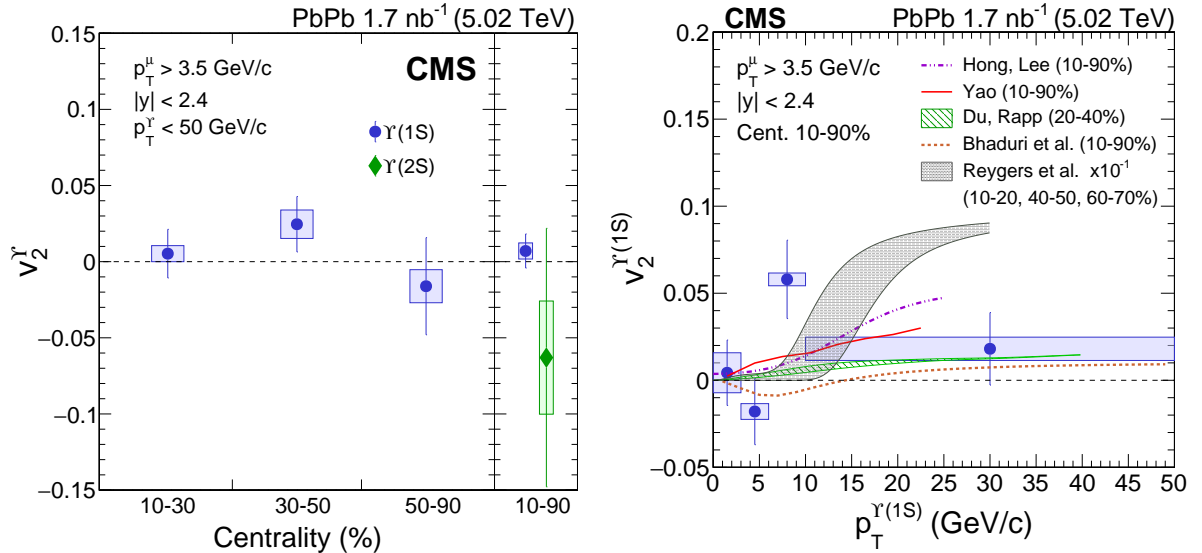


Figure 2: (left panel)  $p_T$  integrated  $v_2$  values for  $\Upsilon(1S)$  mesons measured in four centrality classes and for the  $\Upsilon(2S)$  meson in the 10–90% centrality range. (right panel)  $v_2$  of  $\Upsilon(1S)$  mesons as a function of  $p_T$  in the 10–90% centrality range compared with model calculations from Du and Rapp [22], Yao [42, 43], Hong and Lee [44, 45], Bhaduri et al. [46], and Reygers et al. [47]. All results are for the rapidity range  $|y| < 2.4$ . The vertical bars denote statistical uncertainties, and the rectangular boxes show the total systematic uncertainties.

In Fig. 2 (right panel), the  $p_T$  dependence of  $\Upsilon(1S)$  meson  $v_2$  values is measured for the 10–90% centrality interval. The  $v_2$  values are consistent with zero in the measured  $p_T$  range, except for the  $6 < p_T < 10$  GeV/c interval that shows a  $2.6 \sigma$  deviation from zero. The result is also compared with theoretical predictions from five different approaches. The green shaded area (Du,



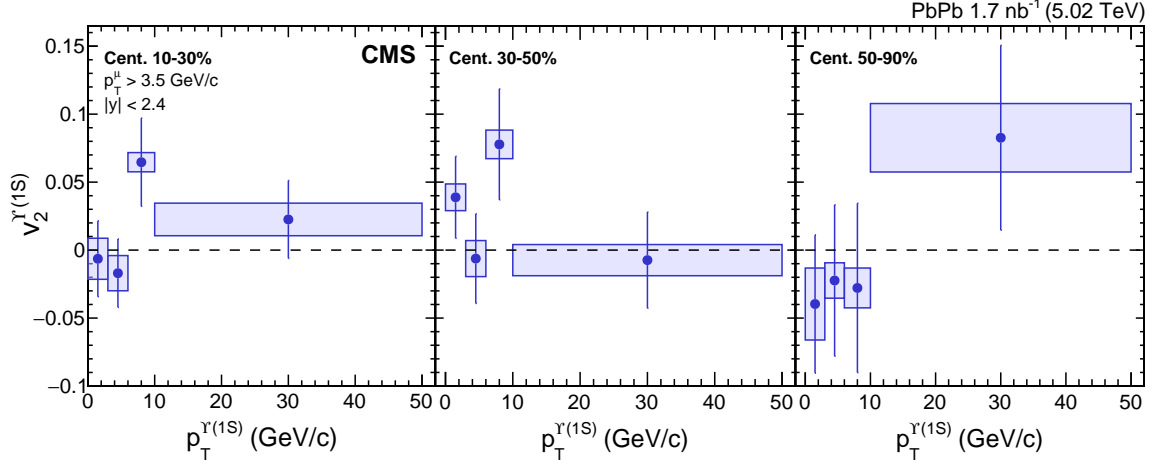


Figure 3: The  $v_2$  coefficients for  $Y(1S)$  mesons as a function of  $p_T$  in three centrality classes: 10–30% (left panel), 30–50% (middle panel) and 50–90% (right panel). The rapidity range is  $|y| < 2.4$ . The vertical lines indicate the statistical uncertainties and the rectangular boxes show the total systematic uncertainties.

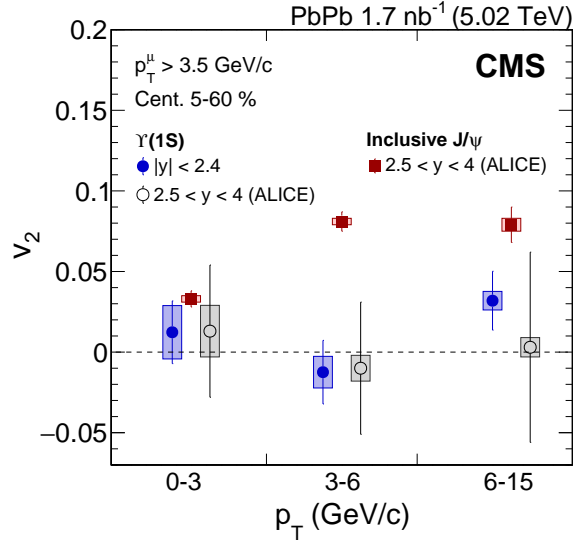


Figure 4: The  $v_2$  for  $Y(1S)$  mesons as a function of  $p_T$  in the rapidity range  $|y| < 2.4$  compared with the ALICE results for  $Y(1S)$  (open circles) and  $J/\psi$  (full squares) mesons measured in  $2.5 < y < 4$  [24]. All results are obtained in the range  $0 < p_T < 15$  GeV/c and centrality interval 5–60%. The vertical bars denote statistical uncertainties, and the rectangular boxes show the total systematic uncertainties.

Rapp [22]) is a calculation using the kinetic rate equation framework for the time evolution of bottom quarks. In this model, the in-medium effect is applied with a lattice QCD based equation of state. Note that it is calculated for the centrality interval 20–40%. The red line (Yao et al. [42, 43]) is computed from a real-time simulation of heavy quarks using coupled Boltzmann transport equations. The dissociation and recombination rates are calculated from potential non-relativistic QCD for this model. The dashed violet curve (Hong, Lee [44, 45]) is another kinetic model prediction in which the heavy quark collisional terms are obtained from Bethe-Salpeter amplitude and hard thermal loop resummation. A diffusion constant  $D(2\pi T) = 6$ , where  $T$  is the temperature of the medium, was used. With this parameter, the nuclear modification factor, which is the ratio of the quarkonium yield in a nucleus-nucleus collision to the corresponding yield in a proton-proton (pp) collision scaled by the number of binary collisions, is consistent with the CMS result in Ref. [9]. The dashed brown line (Bhaduri et al. [46]) shows the result of 3+1d quasiparticle anisotropic hydrodynamics framework. The initial conditions for temperature and shear viscosity to entropy density ratio are tuned to the identified hadron spectra and flow harmonics in 5.02 TeV PbPb data [48]. The gray shaded area (Reygers et al. [47]) is another hydrodynamics calculation based on the blast-wave fits using the data of lighter particles, which was scaled down by a factor of 1/10. The  $v_2$  values are computed in three centrality intervals (10–20%, 40–50%, 60–70%) and the gray envelope is constructed to minimally cover all results. Despite their slightly different  $p_T$  dependence, all models in the figure derive small  $v_2$  values for  $p_T < 10$  GeV/ $c$ , which is consistent with the experimental result. For the highest  $p_T$  range, however, the kinetic model (Hong, Lee) and the blast-wave model begin to deviate from the observed behavior. In particular, the blast-wave model predicts a  $v_2$  value much larger than found. In this model, the elliptic flow of  $Y(1S)$  is expected to sharply rise from  $p_T = 9$  GeV/ $c$ , following the mass ordering of  $v_2(p_T)$  by lighter particles used for the fit [47].

The  $p_T$  differential results for  $Y(1S)$  mesons in each centrality interval are shown in Fig. 3 and the  $v_2$  values are found to be consistent with zero within uncertainties. A similar result has been obtained by the ALICE Collaboration [24], where the measurement was done in a complementary rapidity region ( $2.5 < y < 4$ ), as shown in Fig. 4. The CMS data points in this figure were analyzed using the same  $p_T$  range as the ALICE result to allow for a comparison where only the rapidity ranges of the two measurements differ. The ALICE Collaboration also measured inclusive  $J/\psi$   $v_2$  values (also shown in Fig. 4) with the same kinematic conditions as their  $Y(1S)$  results and there find a significant and finite  $v_2$  value. Together, the CMS and ALICE results indicate that the geometry of the medium has little influence on the  $Y(1S)$  yields [22, 49] and that recombination is not a dominant process in the production of this meson. The results also indicate that the path-length dependence of  $Y(1S)$  suppression is small.

The current results support the assumption of a high melting temperature of the  $Y(1S)$  meson. Consequently, the dissociation can only take place in the earliest stages of the collision. This makes the  $Y(1S)$  meson less sensitive to the path length than other quarkonia states.

## 7 Summary

The  $v_2$  coefficients for  $Y(1S)$  and  $Y(2S)$  mesons are measured in PbPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV. Results are reported for the rapidity range  $|y| < 2.4$ , in the transverse momentum interval  $0 < p_T < 50$  GeV/ $c$ , and in three centrality classes of 10–30%, 30–50%, and 50–90% for the  $Y(1S)$  meson, while the centrality interval 10–90% is used for the  $Y(2S)$  meson. The  $v_2$  values are observed to be compatible with zero for the  $Y(1S)$  meson in the measured kinematic and centrality intervals. The observation contrasts with the positive

$v_2$  values reported for  $J/\psi$  mesons, suggesting different medium effects for charmonia and bottomonia. This confirms, with higher statistical precision and with an extended  $p_T$  range, the result from the ALICE experiment measured in a complementary rapidity region. The measured values of  $v_2$  for  $p_T < 10$  GeV/ $c$  are consistent with the theoretical predictions based on the kinetic model, the hydrodynamics framework, and the blast-wave model. For the high  $p_T$  region, the  $Y(1S)$  result provides an important constraint for models. The  $v_2$  value found for  $Y(2S)$  mesons, which is being reported for the first time, is also consistent with zero. As there are expected to be differences in the various processes through which the QGP affects  $Y(1S)$  and  $Y(2S)$  mesons, these measurements provide new inputs for the study of bottomonia production in heavy ion collisions.

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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 and “Nauka” Project FSWW-2020-0008 (Russia); 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 Thalys and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan<sup>†</sup>, A. Tumasyan

### Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth<sup>1</sup>, M. Jeitler<sup>1</sup>, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck<sup>1</sup>, R. Schöfbeck, M. Spanring, W. Waltenberger, C.-E. Wulz<sup>1</sup>, M. Zarucki

### Institute for Nuclear Problems, Minsk, Belarus

V. Drugakov, V. Mossolov, J. Suarez Gonzalez

### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello<sup>2</sup>, 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. Clerboux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, L. Moureaux, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom

### Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, I. Khvastunov<sup>3</sup>, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

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

G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, J. Prisciandaro, A. Saggio, P. Vischia, 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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>4</sup>, E. Coelho, E.M. Da Costa, G.G. Da Silveira<sup>5</sup>, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, J. Martins<sup>6</sup>, D. Matos Figueiredo, M. Medina Jaime<sup>7</sup>, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote<sup>4</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

### Universidade Estadual Paulista <sup>a</sup>, Universidade Federal do ABC <sup>b</sup>, São Paulo, Brazil

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

### 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

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

**Beihang University, Beijing, China**W. Fang<sup>2</sup>, X. Gao<sup>2</sup>, L. Yuan**Department of Physics, Tsinghua University, Beijing, China**

M. Ahmad, Z. Hu, Y. Wang

**Institute of High Energy Physics, Beijing, China**G.M. Chen<sup>8</sup>, H.S. Chen<sup>8</sup>, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang<sup>8</sup>, J. Zhao**State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China**

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

**Zhejiang University, Hangzhou, China**

M. Xiao

**Universidad de Los Andes, Bogota, Colombia**

C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, 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. Giljanović, 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, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov<sup>9</sup>, T. Susa**University of Cyprus, Nicosia, Cyprus**

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, 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<sup>10</sup>, M. Finger Jr.<sup>10</sup>, 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**M.A. Mahmoud<sup>11,12</sup>, Y. Mohammed<sup>11</sup>**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

**Department of Physics, University of Helsinki, Helsinki, Finland**

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

**Helsinki Institute of Physics, Helsinki, Finland**

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

**Lappeenranta University of Technology, Lappeenranta, Finland**

P. Luukka, T. Tuuva

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

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro<sup>13</sup>, M. Titov, G.B. Yu

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

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

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

J.-L. Agram<sup>14</sup>, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte<sup>14</sup>, J.-C. Fontaine<sup>14</sup>, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, N. Tonon, P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

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

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

**Georgian Technical University, Tbilisi, Georgia**

T. Toriashvili<sup>15</sup>

**Tbilisi State University, Tbilisi, Georgia**

Z. Tsamalaidze<sup>10</sup>

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

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

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

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

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

G. Flügge, W. Haj Ahmad<sup>16</sup>, O. Hlushchenko, T. Kress, T. Müller, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl<sup>17</sup>

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borrás<sup>18</sup>, V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo<sup>19</sup>, A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem<sup>18</sup>, M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann<sup>20</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, R.E. Sosa Ricardo, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

**University of Hamburg, Hamburg, Germany**

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

**Karlsruher Institut fuer Technologie, Karlsruhe, Germany**

M. Akbiyik, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann<sup>17</sup>, C. Heidecker, U. Husemann, M.A. Iqbal, S. Kudella, S. Maier, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, D. Savoie, D. Schäfer, M. Schnepf, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf, S. Wozniewski

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

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

**National and Kapodistrian University of Athens, Athens, Greece**

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

**National Technical University of Athens, Athens, Greece**

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

**University of Ioánnina, Ioánnina, Greece**

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

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

M. Bartók<sup>21</sup>, R. Chudasama, M. Csanad, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

**Wigner Research Centre for Physics, Budapest, Hungary**

G. Bencze, C. Hajdu, D. Horvath<sup>22</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>†</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni, S. Czellar, J. Karancsi<sup>21</sup>, J. Molnar, Z. Szillasi

**Institute of Physics, University of Debrecen, Debrecen, Hungary**

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

**Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary**

T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

**Indian Institute of Science (IISc), Bangalore, India**

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

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

S. Bahinipati<sup>24</sup>, C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak<sup>25</sup>, D.K. Sahoo<sup>24</sup>, S.K. Swain

**Panjab University, Chandigarh, India**

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra<sup>26</sup>, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi

**University of Delhi, Delhi, India**

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

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**

R. Bhardwaj<sup>27</sup>, M. Bharti<sup>27</sup>, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep<sup>27</sup>, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber<sup>28</sup>, M. Maity<sup>29</sup>, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh<sup>27</sup>, S. Thakur<sup>27</sup>

**Indian Institute of Technology Madras, Madras, India**

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

**Bhabha Atomic Research Centre, Mumbai, India**

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

**Tata Institute of Fundamental Research-A, Mumbai, India**

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, Ravindra Kumar Verma

**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, N. Sahoo, S. Sawant

**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

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

S. Chenarani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, R. Aly<sup>a,b,30</sup>, C. Calabria<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, A. Di Florio<sup>a,b</sup>, W. Elmetenawee<sup>a,b</sup>, L. Fiore<sup>a</sup>, A. Gelmi<sup>a,b</sup>, G. Iaselli<sup>a,c</sup>, M. Ince<sup>a,b</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, J.A. Merlin<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>,

S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, F.M. Simone<sup>a,b</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>

**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borgonovi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, C. Ciocca<sup>a</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, E. Fontanesi<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, F. Iemmi<sup>a,b</sup>, S. Lo Meo<sup>a,31</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a,b</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>

**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, Italy**

S. Albergo<sup>a,b,32</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,32</sup>, C. Tuve<sup>a,b</sup>

**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup>, A. Cassese<sup>a</sup>, R. Ceccarelli<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, F. Fiori<sup>a</sup>, E. Focardi<sup>a,b</sup>, G. Latino<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, L. Viliani<sup>a</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, D. Piccolo

**INFN Sezione di Genova <sup>a</sup>, Università di Genova <sup>b</sup>, Genova, Italy**

M. Bozzo<sup>a,b</sup>, F. Ferro<sup>a</sup>, R. Mulargia<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

**INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, Italy**

A. Benaglia<sup>a</sup>, A. Beschi<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, V. Ciriolo<sup>a,b,17</sup>, M.E. Dinardo<sup>a,b</sup>, P. Dini<sup>a</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, L. Guzzi<sup>a,b</sup>, M. Malberti<sup>a</sup>, S. Malvezzi<sup>a</sup>, D. Menasce<sup>a</sup>, F. Monti<sup>a,b</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>, D. Valsecchi<sup>a,b,17</sup>, D. Zuolo<sup>a,b</sup>

**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli 'Federico II' <sup>b</sup>, Napoli, Italy, Università della Basilicata <sup>c</sup>, Potenza, Italy, Università G. Marconi <sup>d</sup>, Roma, Italy**

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, A. De Iorio<sup>a,b</sup>, A. Di Crescenzo<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a</sup>, G. Galati<sup>a</sup>, A.O.M. Iorio<sup>a,b</sup>, L. Layer<sup>a,b</sup>, L. Lista<sup>a,b</sup>, S. Meola<sup>a,d,17</sup>, P. Paolucci<sup>a,17</sup>, B. Rossi<sup>a</sup>, C. Sciacca<sup>a,b</sup>, E. Voevodina<sup>a,b</sup>

**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy**

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, A. Bragagnolo<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S.Y. Hoh<sup>a,b</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, J. Pazzini<sup>a,b</sup>, M. Presilla<sup>b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, A. Tiko<sup>a</sup>, M. Tosi<sup>a,b</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy**

A. Braghieri<sup>a</sup>, D. Fiorina<sup>a,b</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a</sup>, P. Vitulo<sup>a,b</sup>

**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, Italy**

M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, R. Leonardi<sup>a,b</sup>, E. Manoni<sup>a</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>

**INFN Sezione di Pisa <sup>a</sup>, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa <sup>c</sup>, Pisa, Italy**

K. Androsov<sup>a</sup>, P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, V. Bertacchi<sup>a,c</sup>, L. Bianchini<sup>a</sup>, T. Boccali<sup>a</sup>, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, S. Donato<sup>a</sup>, L. Giannini<sup>a,c</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a</sup>, F. Ligabue<sup>a,c</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, G. Rolandi<sup>a,c</sup>

S. Roy Chowdhury<sup>a,c</sup>, A. Scribano<sup>a</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, N. Turini<sup>a</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma <sup>a</sup>, Sapienza Università di Roma <sup>b</sup>, Rome, Italy**

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

**INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Torino, Italy, Università del Piemonte Orientale <sup>c</sup>, Novara, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, A. Bellora<sup>a,b</sup>, C. Biino<sup>a</sup>, A. Cappati<sup>a,b</sup>, N. Cartiglia<sup>a</sup>, S. Cometti<sup>a</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, N. Demaria<sup>a</sup>, J.R. González Fernández<sup>a</sup>, B. Kiani<sup>a,b</sup>, F. Legger<sup>a</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, G. Ortona<sup>a</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Salvatico<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, D. Soldi<sup>a,b</sup>, A. Staiano<sup>a</sup>, D. Trocino<sup>a,b</sup>

**INFN Sezione di Trieste <sup>a</sup>, Università di Trieste <sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, V. Candelise<sup>a,b</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, A. Da Rold<sup>a,b</sup>, G. Della Ricca<sup>a,b</sup>, F. Vazzoler<sup>a,b</sup>, A. Zanetti<sup>a</sup>

**Kyungpook National University, Daegu, Korea**

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**

G. Bak, H. Kim, H. Lee, 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

**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, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon

**University of Seoul, Seoul, Korea**

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

**Sungkyunkwan University, Suwon, Korea**

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

**Riga Technical University, Riga, Latvia**

V. Veckalns<sup>33</sup>

**Vilnius University, Vilnius, Lithuania**

V. Dudenas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, J. Vaitkus

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

F. Mohamad Idris<sup>34</sup>, 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<sup>35</sup>, R. Lopez-Fernandez, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, C. Oropeza 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<sup>3</sup>, N. Raicevic

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

S. Bheesette, P.H. Butler, P. Lujan

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

A. Ahmad, M. Ahmad, 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. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szeleper, P. Zalewski

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

K. Bunkowski, A. Byszuk<sup>36</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, 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, G. Strong, O. Toldaiev, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev<sup>37,38</sup>, P. Moiseenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

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

L. Chtchipunov, V. Golovtsov, Y. Ivanov, V. Kim<sup>39</sup>, E. Kuznetsova<sup>40</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev



**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, 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. Nikitenko<sup>41</sup>, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, 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. Chistov<sup>42</sup>, M. Danilov<sup>42</sup>, S. Polikarpov<sup>42</sup>, E. Tarkovskii

**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. Ershov, A. Gribushin, A. Kaminskiy<sup>43</sup>, O. Kodolova, V. Korotkikh, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

**Novosibirsk State University (NSU), Novosibirsk, Russia**

A. Barnyakov<sup>44</sup>, V. Blinov<sup>44</sup>, T. Dimova<sup>44</sup>, L. Kardapol'tsev<sup>44</sup>, Y. Skovpen<sup>44</sup>

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, 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. Adzic<sup>45</sup>, 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**

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**University of Colombo, Colombo, Sri Lanka**

D.U.J. Sonnadara

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

W.G.D. Dharmaratna, N. Wickramage

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

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**Paul Scherrer Institut, Villigen, Switzerland**

L. Caminada<sup>49</sup>, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, 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. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Luster, R.A. Manzoni, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>50</sup>, C. Botta, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, K. Schweiger, Y. Takahashi, S. Wertz

**National Central University, Chung-Li, Taiwan**

C.M. Kuo, W. Lin, A. Roy, T. Sarkar<sup>29</sup>, S.S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**

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, N. Suwonjandee

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

A. Bat, F. Boran, A. Celik<sup>51</sup>, S. Damarseckin<sup>52</sup>, Z.S. Demiroglu, F. Dolek, C. Dozen<sup>53</sup>, I. Dumanoglu<sup>54</sup>, G. Gokbulut, Emine Gurpinar Guler<sup>55</sup>, Y. Guler, I. Hos<sup>56</sup>, C. Isik, E.E. Kangal<sup>57</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir<sup>58</sup>, A.E. Simsek, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

**Middle East Technical University, Physics Department, Ankara, Turkey**

B. Isildak<sup>59</sup>, G. Karapinar<sup>60</sup>, M. Yalvac<sup>61</sup>

**Bogazici University, Istanbul, Turkey**

I.O. Atakisi, E. Gülmez, M. Kaya<sup>62</sup>, O. Kaya<sup>63</sup>, Ö. Özçelik, S. Tekten<sup>64</sup>, E.A. Yetkin<sup>65</sup>

**Istanbul Technical University, Istanbul, Turkey**

A. Cakir, K. Cankocak<sup>54</sup>, Y. Komurcu, S. Sen<sup>66</sup>

**Istanbul University, Istanbul, Turkey**

S. Cerci<sup>67</sup>, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci<sup>67</sup>

**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. Burns<sup>68</sup>, 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. Belyaev<sup>69</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, 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, Gurpreet Singh CHAHAL<sup>70</sup>, D. Colling, P. Dauncey, G. Davies, M. Della Negra, P. Everaerts, G. Hall, G. Iles, M. Komm, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, A. Morton, J. Nash<sup>71</sup>, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, A. Tapper, K. Uchida, T. Virdee<sup>17</sup>, 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, 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, L. Sulak, D. Zou

**Brown University, Providence, USA**

G. Benelli, B. Burkle, X. Coubez<sup>18</sup>, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan<sup>72</sup>, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir<sup>73</sup>, 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<sup>†</sup>, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

**University of California, Los Angeles, USA**

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**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, B.R. Yates, 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, G. Zevi Della Porta

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

N. Amin, R. Bhandari, C. Campagnari, M. Citron, 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

**Cornell University, Ithaca, USA**

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

**Fermi National Accelerator Laboratory, Batavia, USA**

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee,

L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gece, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena<sup>74</sup>, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, M. Wang, H.A. Weber, A. Woodard

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

#### **Florida International University, Miami, USA**

Y.R. Joshi

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

#### **Florida Institute of Technology, Melbourne, USA**

M.M. Baarmand, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

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

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

#### **The University of Iowa, Iowa City, USA**

M. Alhusseini, B. Bilki<sup>55</sup>, K. Dilsiz<sup>75</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili<sup>76</sup>, A. Moeller, J. Nachtman, H. Ogul<sup>77</sup>, Y. Onel, F. Ozok<sup>78</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi<sup>79</sup>

#### **Johns Hopkins University, Baltimore, USA**

B. Blumenfeld, A. Cocoros, N. Eminizer, A.V. Gritsan, W.T. Hung, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vámi

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

#### **Kansas State University, Manhattan, USA**

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

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A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, 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, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

**University of Minnesota, Minneapolis, USA**

R.M. Chatterjee, A. Evans, S. Guts<sup>†</sup>, P. Hansen, J. Hiltbrand, Sh. Jain, 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, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow<sup>†</sup>, 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, G. Fedi, 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, Y. Musienko<sup>37</sup>, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf

**The Ohio State University, Columbus, USA**

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

**Princeton University, Princeton, USA**

G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, 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**

A. Barker, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, D.H. Miller, 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, U. Behrens, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun 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, 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<sup>80</sup>, M. Dalchenko, M. De Mattia, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>81</sup>, 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, F. De Guio, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

**Vanderbilt University, Nashville, USA**

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**

M.W. Arenton, P. Barria, 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**

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

**University of Wisconsin - Madison, Madison, WI, USA**

K. Black, T. Bose, J. Buchanan, C. Caillol, D. Carlsmith, 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. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert

†: 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 Fayoum University, El-Fayoum, Egypt
- 12: Now at British University in Egypt, Cairo, Egypt
- 13: Also at Purdue University, West Lafayette, USA
- 14: Also at Université de Haute Alsace, Mulhouse, France
- 15: Also at Tbilisi State University, Tbilisi, Georgia
- 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 Brandenburg University of Technology, Cottbus, Germany
- 21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
- 22: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 23: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
- 24: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
- 25: Also at Institute of Physics, Bhubaneswar, India
- 26: Also at G.H.G. Khalsa College, Punjab, India
- 27: Also at Shoolini University, Solan, India
- 28: Also at University of Hyderabad, Hyderabad, India
- 29: Also at University of Visva-Bharati, Santiniketan, India
- 30: Now at INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy
- 31: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 32: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 33: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
- 34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 37: Also at Institute for Nuclear Research, Moscow, Russia
- 38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Also at University of Florida, Gainesville, USA
- 41: Also at Imperial College, London, United Kingdom
- 42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 43: Also at INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy, Padova, Italy
- 44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 46: Also at Università degli Studi di Siena, Siena, Italy
- 47: Also at INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy, Pavia, Italy
- 48: Also at National and Kapodistrian University of Athens, Athens, Greece
- 49: Also at Universität Zürich, Zurich, Switzerland
- 50: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
- 51: Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey
- 52: Also at Şırnak University, Sirnak, Turkey
- 53: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China



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- 54: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
- 55: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
- 56: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
- 57: Also at Mersin University, Mersin, Turkey
- 58: Also at Piri Reis University, Istanbul, Turkey
- 59: Also at Ozyegin University, Istanbul, Turkey
- 60: Also at Izmir Institute of Technology, Izmir, Turkey
- 61: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- 62: Also at Marmara University, Istanbul, Turkey
- 63: Also at Milli Savunma University, Istanbul, Turkey
- 64: Also at Kafkas University, Kars, Turkey
- 65: Also at Istanbul Bilgi University, Istanbul, Turkey
- 66: Also at Hacettepe University, Ankara, Turkey
- 67: Also at Adiyaman University, Adiyaman, Turkey
- 68: Also at Vrije Universiteit Brussel, Brussel, Belgium
- 69: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 70: Also at IPPP Durham University, Durham, United Kingdom
- 71: Also at Monash University, Faculty of Science, Clayton, Australia
- 72: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
- 73: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 74: Also at California Institute of Technology, Pasadena, USA
- 75: Also at Bingol University, Bingol, Turkey
- 76: Also at Georgian Technical University, Tbilisi, Georgia
- 77: Also at Sinop University, Sinop, Turkey
- 78: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 79: Also at Nanjing Normal University Department of Physics, Nanjing, China
- 80: Also at Texas A&M University at Qatar, Doha, Qatar
- 81: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea