EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2020-219
2021/02/26

CMS-HIN-19-005

# Evidence for X(3872) in PbPb collisions and studies of its prompt production at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

The CMS Collaboration*



## Abstract

The first evidence for X(3872) production in relativistic heavy ion collisions is reported. The X(3872) production is studied in lead-lead (PbPb) collisions at a center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ per nucleon pair, using the decay chain $\mathrm{X}(3872) \to \mathrm{J}/\psi\,\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$. The data were recorded with the CMS detector in 2018 and correspond to an integrated luminosity of $1.7\,\mathrm{nb}^{-1}$. The measurement is performed in the rapidity and transverse momentum ranges $|y| < 1.6$ and $15 < p_{\mathrm{T}} < 50\,\mathrm{GeV}/c$. The significance of the inclusive X(3872) signal is 4.2 standard deviations. The prompt X(3872) to $\psi(2\mathrm{S})$ yield ratio is found to be $\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})$, to be compared with typical values of 0.1 for pp collisions. This result provides a unique experimental input to theoretical models of the X(3872) production mechanism, and of the nature of this exotic state.

*Submitted to Physical Review Letters*



*See Appendix A for the list of collaboration members

The X(3872), also known as $\chi_{c1}(3872)$, is an exotic particle that was first observed by the Belle Collaboration [1], and then confirmed and studied by other experiments at electron-positron [2, 3] and hadron colliders [4–8]. The quantum numbers of the X(3872) have been determined to be $J^{PC} = 1^{++}$ by the CDF [9] and LHCb [10] Collaborations. However, the nature of this particle is still not fully understood and interpretations in terms of conventional charmonium (a bound state of charm-anticharm quarks), $\mathrm{D}^*(2010)^0\,\overline{\mathrm{D}}^0$ molecules [11], tetraquark states [12], and their admixture [13] have been proposed. The production and survival of the X(3872) in a quark-gluon plasma (QGP), a deconfined state of quarks and gluons [14, 15], is expected to depend upon the X(3872)'s internal structure [16, 17]. Thus, the recent large data set of lead-lead (PbPb) collisions at a center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ per nucleon pair, delivered by the Large Hadron Collider (LHC) at CERN at the end of 2018, opened new opportunities to probe the nature of this exotic state [18–20].

It is expected that in relativistic heavy ion collisions, the formation of the QGP could enhance or suppress the production of the X(3872) particle. Coalescence mechanisms could enhance the X(3872) production yield [16, 19]. These mechanisms can be modeled via the overlap of the density matrix of the constituents in an emission source with the Wigner function of the produced particle [21]. Therefore, the enhancement of the X(3872) production in the QGP would depend on the spatial configuration of the exotic state. Moreover, a longer distance between the quarks and antiquarks that constitute the state could also lead to a higher X(3872) dissociation rate, similar to that from the mechanism of quarkonium suppression in heavy ion collisions [22]. Therefore, the study of the X(3872) state in the QGP may be used as a tool to distinguish a compact tetraquark configuration with a radius $\sim$0.3 fm from a molecular state with a radius greater than 1.5 fm [23]. Such a measurement would be complementary to the recent evidence for the radiative decay $\mathrm{X}(3872) \to \psi(2\mathrm{S})\gamma$ in proton-proton (pp) collisions reported by LHCb Collaboration [24], which does not support a pure $\mathrm{D}^*(2010)^0\,\overline{\mathrm{D}}$ molecular interpretation. In addition, measurements of prompt X(3872) production could provide an interesting test of the statistical hadronization model, which assumes that the produced matter is in thermodynamic equilibrium [25].

In this Letter, the first evidence for X(3872) production in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ is reported. The PbPb sample corresponds to an integrated luminosity of $1.7\,\mathrm{nb}^{-1}$. The X(3872) candidates are reconstructed through the decay chain $\mathrm{X}(3872) \to \mathrm{J}/\psi\,\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$. At the LHC energies, the inclusive X(3872) yields in pp and PbPb collisions contain a significant nonprompt contribution coming from b hadron decays [8]. The nonprompt X(3872) component is related to the medium-modified beauty hadron production in heavy ion collisions, which is out of the scope of this paper. Here, we focus on the prompt component, from charm quark fragmentation, for which the ratio $\rho^i$ ($i$ is pp or PbPb) between the corrected yields of X(3872) and $\psi(2\mathrm{S})$ mesons (where the $\psi(2\mathrm{S})$ is reconstructed with the same final-state particles in order to reduce systematic uncertainties) is presented:

$$\rho^i = \frac{N_i^{\mathrm{X}(3872)\to \mathrm{J}/\psi\,\pi\pi}}{N_i^{\psi(2\mathrm{S})\to \mathrm{J}/\psi\,\pi\pi}}. \tag{1}$$

The ratios in pp and PbPb collisions are connected to the nuclear modification factors $R_{\mathrm{AA}}^{\mathrm{X}(3872)}$ and $R_{\mathrm{AA}}^{\psi(2\mathrm{S})}$ (the meson yield ratio in nucleus-nucleus and pp interactions normalized by the number of inelastic nucleon-nucleon collisions) via the following relation:

$$\rho^{\mathrm{PbPb}} = \rho^{\mathrm{pp}}\,\frac{R_{\mathrm{AA}}^{\mathrm{X}(3872)}}{R_{\mathrm{AA}}^{\psi(2\mathrm{S})}}. \tag{2}$$

The central feature of the CMS detector is a superconducting solenoid, which provides a magnetic field of 3.8 T. Within the solenoid volume there are a silicon pixel and strip tracker that measures the trajectories of the charged particles in the pseudorapidity range $|\eta| < 2.5$, a lead-tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. For charged particles of transverse momentum $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}/c$ and $|\eta| < 1.4$, the typical track resolutions are 1.5% in $p_{\mathrm{T}}$ and 25–90 (45–150) $\mu$m in the transverse (longitudinal) impact parameter [26]. Muons are measured in the range $|\eta| < 2.4$ with a muon spectrometer which is located outside the solenoid and uses three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. The muon reconstruction algorithm starts by finding tracks in the muon spectrometer, which are then matched with tracks reconstructed in the silicon tracker to form muon candidates. Matching muons to tracks measured in the tracker results in a relative $p_{\mathrm{T}}$ resolution for muons with $20 < p_{\mathrm{T}} < 100\,\mathrm{GeV}/c$ of 1.3–2.0% in the barrel ($|\eta| < 1.2$) and better than 6% in the endcaps ($1.6 < |\eta| < 2.4$) [27]. The hadron forward (HF) calorimeter uses steel as an absorber and quartz fibers as sensitive material. The two halves of the HF calorimeters are located 11.2 m away from the interaction point, one on each end, together providing coverage in the range $3.0 < |\eta| < 5.2$. In this analysis, the HF information is used for performing an offline event selection and determining centrality (the degree of overlap between the two colliding nuclei). The results refer to the collisions with 0–90% centrality, i.e., the top 90% events based on the total transverse energy deposition in both HF detectors [28], which corresponds to the 90% of collisions having the largest overlap of the two nuclei. A detailed description of the CMS experiment and coordinate system can be found in Ref. [29].

Events of interest were selected in real-time using the CMS two-tiered trigger system: the first level (L1), composed of custom hardware processors [30], and the high-level trigger (HLT), consisting of a farm of processors running a version of the full event reconstruction software optimized for fast processing [31]. The selection required the presence of two muon candidates, with at least one muon reconstructed in the outer muon spectrometer, and one muon reconstructed using information from both the outer muon spectrometer and the inner tracker. The dimuon candidate invariant mass is required to be $1 < m_{\mu\mu} < 5\,\mathrm{GeV}/c^2$. For the offline analysis, events have to pass a set of selection criteria designed to reject events from background processes (beam-gas collisions, beam scraping events and electromagnetic interactions) as described in Ref. [32]. Events are required to have at least one reconstructed primary interaction vertex formed by two or more tracks, with a distance from the center of the nominal interaction point of less than 15 cm along the beam axis. The shapes of the clusters in the pixel detector have to be compatible with those expected from particles produced by a PbPb collision [33]. In order to select hadronic collisions, the PbPb events are also required to have at least two towers (i.e., a geometrically defined group of calorimeter cells) in each of the HF detectors with total energy deposits of more than 4 GeV per tower. This analysis is restricted to events within centrality 0–90%, for which the hadronic event selection is fully efficient.

Dedicated PbPb $\mathrm{X}(3872)$ and $\psi(2\mathrm{S})$ Monte Carlo (MC) simulated samples were generated in order to estimate the acceptance and selection efficiencies, to study the background components, and to evaluate systematic uncertainties. The PYTHIA 8 v212 [34] Tune CP5 [35] was used to generate the $\mathrm{X}(3872)$ and $\psi(2\mathrm{S})$ signals at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$. Since the $\mathrm{X}(3872)$ cannot be generated by PYTHIA, the $\chi_{\mathrm{c1}}(1\mathrm{P})$ particle is used, with a modified mass of $3.8716\,\mathrm{GeV}/c^2$ [36]. The $\chi_{\mathrm{c1}}(1\mathrm{P})$ has the quantum numbers $J^{PC} = 1^{++}$, identical to those of the $\mathrm{X}(3872)$. The EVTGEN 1.3.0 package [37] was used to force the $\mathrm{X}(3872)$ and $\psi(2\mathrm{S})$ to decay into $\mathrm{J}/\psi\,\pi^+\pi^-$ (assuming the $\rho$ resonance dominates the pion pair spectrum [7, 8]), followed by the $\mathrm{J}/\psi$ meson decaying into two muons. Final-state radiation was generated using PHOTOS 2.0 [38]. The $\chi_{\mathrm{c1}}(1\mathrm{P}) \to \mathrm{J}/\psi\,\pi^+\pi^-$ decay is generated with EVTGEN. The samples with prompt (fragment-

ing in charm quarks) and nonprompt (originating from b hadron decays) $\psi(2S)/X(3872)$ production are generated separately. Each PYTHIA event is embedded in a PbPb collision event generated with HYDJET 1.8 [39], which is tuned to reproduce global event properties such as the charged-hadron $p_T$ spectrum and particle multiplicity.

The $X(3872)$ signal is extracted in the following steps. Each muon candidate must be matched to a triggered muon and have $p_T^\mu > 3.5\,\text{GeV}/c$ in the interval $|\eta^\mu| < 1.2$, $p_T^\mu > (5.47 - -1.89\,|\eta^\mu|)\,\text{GeV}/c$ in the interval $1.2 < |\eta^\mu| < 2.1$, or $p_T^\mu > 1.5\,\text{GeV}/c$ in the forward region $2.1 < |\eta^\mu| < 2.4$. Two muons of opposite sign, with an invariant mass within $\pm 150\,\text{MeV}/c^2$ of the world-average $J/\psi$ meson mass [36] are selected to reconstruct a $J/\psi$ candidate. The opposite-sign muon pairs are fitted with a common vertex constraint and are kept if the $\chi^2$ probability of the fit is greater than 1%, thus reducing the background from charm and beauty hadron semileptonic decays. The $X(3872)$ and $\psi(2S)$ candidates are built by combining the $J/\psi$ candidates with two additional tracks, which have $p_T > 0.9\,\text{GeV}/c$, $|\eta| < 2.4$ and pass a high purity selection, assumed to be produced by two pions. Then, a kinematic fit to the $J/\psi\,\pi^+\pi^-$ system is performed, requiring that the four tracks originate from a common vertex and forcing the mass of the dimuon pair to be equal to the nominal $J/\psi$ mass [36]. The selection is further optimized, using a boosted decision tree (BDT) algorithm [40], in order to maximize the statistical significance of $X(3872)$. The $X(3872)$ decay vertex probability, the radial distance between the pion and the $J/\psi$ candidate momentum vectors ($\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where $\phi$ is the azimuthal angle), and the $p_T$ of each pion are used in the BDT algorithm to distinguish signal and combinatorial background formed by random combinations of tracks. The $X(3872)$ signal samples are taken from simulation, while the background samples for the multivariate training are taken from data sidebands of the $X(3872)$ meson invariant mass. The BDT selection determined in this way is applied to entries in the whole invariant mass range from 3.62 to $4\,\text{GeV}/c^2$ in data.

The raw inclusive yields of $X(3872)$ and $\psi(2S)$ are extracted by an extended unbinned maximum-likelihood fit. A double-Gaussian function with a common mean but independent widths is used to model the signal component for each of the $X(3872)$ and $\psi(2S)$ peaks. This was preferred to a single-Gaussian or a Breit–Wigner function since it described better (i.e., superior $\chi^2$ of the fit) the signal shape in MC simulations. For describing the combinatorial background, mostly produced by the random combination of a $J/\psi$ candidate with tracks that are not coming from $X(3872)$ or $\psi(2S)$ decay, a 4th-order polynomial is used, which gives the best fit in terms of $\chi^2$ per degrees of freedom and stability during all studies. For the signal, only the magnitude of the two peaks is left free in the fit, the rest (the mean and widths of the two Gaussian functions, as well as their relative contribution to the signal yield in either $X(3872)$ or $\psi(2S)$ peaks) are set to the values derived from simulation. The five parameters of the combinatorial background are all allowed to float. The invariant mass range considered for the fit is 3.62 to $4\,\text{GeV}/c^2$. The invariant mass fits for both the inclusive and nonprompt samples, with BDT selection optimized for $X(3872)$, are shown in Fig. 1. The significance of the inclusive $X(3872)$ signal against background-only hypothesis is 4.2 standard deviations. This significance is calculated as the square root of the logarithm of the profile likelihood ratio where the signal is zero. It considers all the systematic uncertainties related to modeling the signal component of the $X(3872)$ peak, as detailed below.

The contribution from b hadron decays is subtracted from the inclusive result using the "pseudo-proper" decay length $l_{xy}$, defined as the distance in the transverse plane, $L_{xy}$, between the vertex formed by the 4-tracks and the closest reconstructed primary vertex in the $z$ direction (along the beam axis), corrected by the transverse Lorentz boost of the candidate: $l_{xy} = L_{xy}\, m_{J/\psi\pi\pi} c/|\vec{p}_T|$. The prompt-component fraction ($f_{\text{prompt}}$) is estimated using a cutoff-

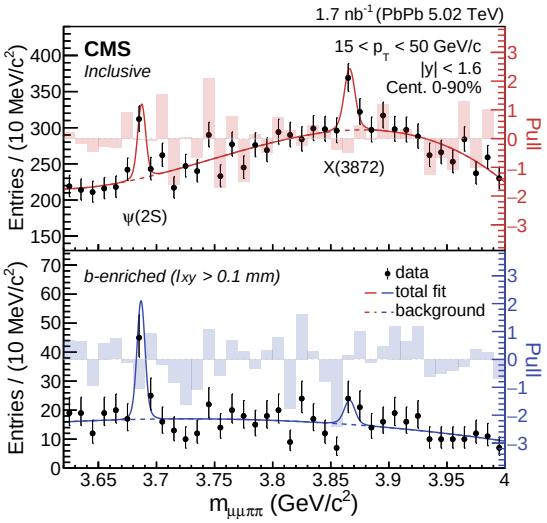


Figure 1: Invariant mass distribution of $m_{\mu\mu\pi\pi}$ in PbPb collisions, for the inclusive (upper) and b-enriched (bottom) samples. The vertical lines represent statistical uncertainties in the data. The results of the unbinned maximum-likelihood fits for the signal+background and background alone are also shown by the solid and dashed lines, respectively. The pull distribution is represented by the shaded bars.

based method in the following way. Since the $l_{xy}$ of the prompt component was found in MC studies to be smaller than 0.1 mm, the prompt fraction, $f_{\text{prompt}}$, can be derived from: i) the raw inclusive yield, $N_{\text{incl}}$, obtained from the fit to the invariant mass distributions of all candidates, shown in Fig. 1, and ii) $N_{\text{b-enr}}$, the "b-enriched" yield, obtained from a fit to the invariant mass distribution only containing candidates that passed the selection $l_{xy} > 0.1\,\text{mm}$, also shown in Fig. 1. In addition, $N_{\text{b-enr}}$ has to be corrected to account for nonprompt candidates, with $l_{xy} < 0.1\,\text{mm}$, that have been missed: $f^{\text{b-enr}}_{\text{nonprompt}} = N_{\text{nonprompt}}(l_{xy} > 0.1\,\text{mm})/N_{\text{nonprompt}}$. The correction was obtained from simulation. The raw prompt fraction is then calculated as:

$$f_{\text{prompt}} = 1 - \frac{N_{\text{b-enr}}/f^{\text{b-enr}}_{\text{nonprompt}}}{N_{\text{incl}}}, \tag{3}$$

separately for $\mathrm{X}(3872)$ and $\psi(2\mathrm{S})$ states. The corrected yield of the prompt component can then be derived as:

$$N^{i\to \mathrm{J}/\psi\pi\pi} = N^{i}_{\text{raw}}\, f^{i}_{\text{prompt}}/(\alpha\,\epsilon_{\text{reco}}\,\epsilon_{\text{sel}})^{i}, \tag{4}$$

where $i$ is $\mathrm{X}(3872)$ or $\psi(2\mathrm{S})$, $\alpha$ is the acceptance, $\epsilon_{\text{reco}}$ is the candidate reconstruction efficiency and $\epsilon_{\text{sel}}$ is the candidate selection efficiency. Since the two states are reconstructed in the same decay channel and are relatively close in mass, their corresponding $\alpha\,\epsilon_{\text{reco}}$ values are similar. The choice of the BDT optimization criteria results in $\epsilon_{\text{sel}}$ being higher for the $\mathrm{X}(3872)$ than for the $\psi(2\mathrm{S})$.

The measurement of $\rho^{\text{PbPb}}$ is affected by several sources of systematic uncertainty, arising from the candidate selection, invariant mass fit, and efficiency corrections. To estimate the systematic uncertainty associated with the BDT selection, the BDT cutoff values are varied within the range that allows a robust invariant mass fit procedure, and the maximum difference of the final $R$ value from the nominal result (40%) is quoted as the systematic uncertainty. The relatively large $R$ uncertainty associated with BDT cutoff value is the convolution of two causes: the BDT variables distribution differences in data and MC samples for the $\mathrm{X}(3872)$ meson, and the statistical limitation of the signal in data.

The uncertainty in the invariant mass fit (8.0%) is calculated by adding in quadrature the maximum deviations from the nominal result to that found using two alternative fitting functions for both signal and background. For the signal, one variation consists of using a triple-Gaussian function, while for the other the signal width of the nominal fit is allowed to float to account for the resolution difference between data and MC. Other choices for the signal shape (e.g., one-Gaussian function) were not considered because of their poor-quality fits. For the background, the fit function is changed once to a third-order polynomial (as an exponential function or lower-order polynomials could not describe the data), and the fit range is also changed from 3.62–4 GeV/$c^2$ to 3.62–3.9 GeV/$c^2$ to exclude the right-hand shoulder.

The efficiency corrections obtained from simulation are sensitive to how well the $p_{\mathrm{T}}$ spectrum of the X(3872) and $\psi$(2S) candidates is modeled. The uncertainty related to the simulated $p_{\mathrm{T}}$ shape is evaluated by comparing the reconstruction and selection efficiencies calculated using the default PYTHIA MC sample, with another MC sample in which the $p_{\mathrm{T}}$ distributions of X(3872) and $\psi$(2S) are tuned to reproduce the extracted X(3872) and $\psi$(2S) $p_{\mathrm{T}}$ and $y$ spectra obtained in data, by performing mass fits in bins of X(3872) and $\psi$(2S) $p_{\mathrm{T}}$ and $y$. The $p_{\mathrm{T}}$ and $y$ spectra of the alternative MC samples are allowed to vary within the statistical uncertainties in data. The mean of the differences between efficiencies from the alternative MC samples and the default PYTHIA MC due to the variation of $p_{\mathrm{T}}$ and $y$ spectra, which is 13%, is quoted as the systematic uncertainty.

The uncertainties in the trigger efficiency, in the muon reconstruction and identification are evaluated using single muons from J/$\psi$ meson decays in both simulated and collision data, with the tag-and-probe method [27, 41]. This combined uncertainty is found to be negligible, below 1%. Scale factors, calculated as the ratio of data to simulated efficiencies as a function of $p_{\mathrm{T}}^{\mu}$ and $\eta^{\mu}$, are applied to each dimuon pair on a muon-by-muon basis. The uncertainties of the scaling factors from tag-and-probe studies are quoted as systematic uncertainties.

To estimate the uncertainty in the prompt fraction arising from potential differences between the resolution in data and simulation, a template fit of the $l_{xy}$ distribution in data is performed using prompt and nonprompt $l_{xy}$ templates from simulation. Data are binned in $l_{xy}$, and an invariant mass fit is performed to extract the inclusive yield in each $l_{xy}$ bin. This background-subtracted $l_{xy}$ distribution is then fitted using a two component fit, which includes the prompt and nonprompt $l_{xy}$ templates from simulation. The widths of the simulated DCA distributions are varied by a floating scale factor, and the best simulated smearing scale factor to match data is determined by minimizing the $\chi^2$ of the two-component fit. The difference between the ratio of the prompt fractions of X(3872) to $\psi$(2S) using the template fit method and the nominal result (8.1%) is quoted as a systematic uncertainty.

When calculating the uncertainties in the ratio of the acceptance-corrected yields of prompt X(3872) production over prompt $\psi$(2S) production, the uncertainties of X(3872) and $\psi$(2S) yields are assumed to be independent except for the systematic uncertainties from muon reconstruction, efficiencies, and prompt fractions.

The ratio $\rho^{\mathrm{PbPb}}$ is shown in Fig. 2, together with $\rho^{\mathrm{pp}}$ measured as a function of $p_{\mathrm{T}}$. The pp data were measured at $\sqrt{s} = 7$ and 8 TeV, in the $|y| < 1.2$ and $|y| < 0.75$ intervals, respectively [7, 8, 10]. The 7 TeV result was derived using the CMS Collaboration published ratio of the inclusive yields [7] and prompt fractions [7, 42]. From Fig. 2 it is clear that the prompt $\rho^{\mathrm{pp}}$ does not depend significantly on collision energy or rapidity. In pp collisions at $\sqrt{s} = 8$ TeV, in the kinematic range of $16 < p_{\mathrm{T}} < 22$ GeV/$c$, the $\rho^{\mathrm{pp}}$ measured by the ATLAS Collaboration is $0.106 \pm 0.008\,(\mathrm{stat}) \pm 0.004\,(\mathrm{syst})$ [8]. This is to be compared to the $\rho^{\mathrm{PbPb}}$ measured in this Letter, $\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})$.

In the interval $15 < p_T < 20\,\text{GeV}/c$, the yield of the prompt $\psi(2S)$ in PbPb collisions was reported to be significantly suppressed with respect to pp collisions, $R_{AA}^{\psi(2S)} = 0.142 \pm 0.061\,(\text{stat}) \pm 0.020\,(\text{syst})$ [43]. This leads, using Eq. (2), to an $R_{AA}^{X(3872)}$ central value larger than 1 (i.e., enhancement of the prompt $X(3872)$ yield in PbPb compared to pp collisions). However, the uncertainties are such that $R_{AA}^{X(3872)}$ is compatible with 1 within $\sim$1 standard deviation, and with $R_{AA}^{\psi(2S)}$ within $\sim$2 standard deviations. Thus, it is possible that in PbPb collisions, the prompt $X(3872)$ yield has either no suppression with respect to pp collisions, or as much suppression as the $\psi(2S)$ state. The much larger data sample expected in Run 3 at the LHC will answer whether $R_{AA}^{X(3872)}$ is different from $R_{AA}^{\psi(2S)}$ and significantly above unity. It may answer whether the $\psi(2S)$ meson production (a bound state of a c and $\bar{c}$ quarks, with $r \sim 0.9\,\text{fm}$), is affected differently by the medium produced in PbPb collisions than the $X(3872)$ state (that could be made of c, $\bar{c}$, u, and $\bar{u}$ quarks, with a radius of $r \sim 0.3\,\text{fm}$ or $r > 1.5\,\text{fm}$), the difference in both size and quark content playing a role into their production mechanisms. It will also answer whether the $X(3872)$ prompt state production is different in PbPb collisions compared to pp collisions. The question whether $X(3872)$ is a tetraquark or a molecule cannot yet be answered, because of the statistical limitation of the data, and the disagreement among models. For example, while the AMPT transport model [16] predicts $R_{AA}^{\text{molecule}} >> R_{AA}^{\text{tetraquark}}$ with $R_{AA}^{\text{molecule}} > 1$, the TAMU transport model [17] predicts $R_{AA}^{\text{molecule}} \sim R_{AA}^{\text{tetraquark}}/2$ (albeit, considering only the $X(3872)$ from regeneration processes).

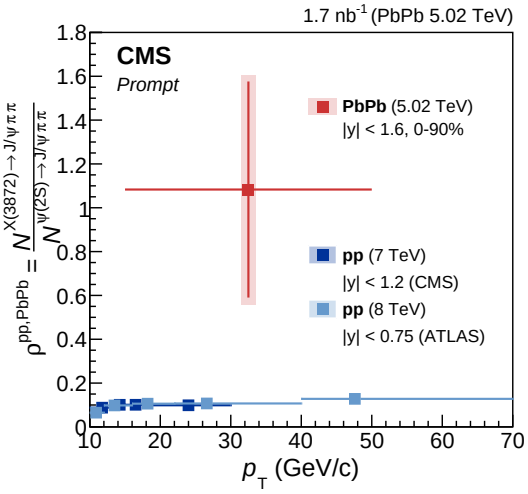


Figure 2: The yield ratio $\rho^{PbPb}$ of prompt $X(3872)$ over $\psi(2S)$ production in PbPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The yield ratios $\rho^{pp}$ of prompt $X(3872)$ over $\psi(2S)$ production in pp collisions at $\sqrt{s} = 8\,\text{TeV}$, measured by ATLAS [8], and at $\sqrt{s} = 7\,\text{TeV}$, measured by CMS [7] are also shown.

In summary, the first evidence for $X(3872)$ production in heavy ion collisions is presented using lead-lead collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ per nucleon pair, recorded with the CMS detector. The $X(3872)$ state is reconstructed using the decay chain $X(3872) \to J/\psi\,\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$. The measurement is performed for transverse momentum values of the $X(3872)$ of $15 < p_T < 50\,\text{GeV}/c$ and rapidity $|y| < 1.6$. The significance of the inclusive $X(3872)$ signal is 4.2 standard deviations. The ratio $\rho^{PbPb}$ between the prompt $X(3872)$ and $\psi(2S)$ yields times their branching fractions into $J/\psi\,\pi^+\pi^-$ is found to be $1.08 \pm 0.49\,(\text{stat}) \pm 0.52\,(\text{syst})$, to be compared with typical values of 0.1 for pp collisions. This result provides a unique experimental input to theoretical models of the $X(3872)$ production mechanism, and of

the nature of this exotic state.

## Acknowledgments

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

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, and 765710 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the Ministry of Science and Higher Education and the National Science Center, contracts Opus 2014/15/B/ST2/03998 and 2015/19/B/ST2/02861 (Poland); the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, project no. 0723-2020-0041 (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 Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

## References


[1] Belle Collaboration, "Observation of a narrow charmonium-like state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}\mathrm{J}/\psi$ decays", *Phys. Rev. Lett.* **91** (2003) 262001, doi:10.1103/PhysRevLett.91.262001, arXiv:hep-ex/0309032.

[2] BaBar Collaboration, "Study of the $B \to \mathrm{J}/\psi K^{-}\pi^{+}\pi^{-}$ decay and measurement of the $B \to X(3872)K^{-}$ branching fraction", *Phys. Rev. D* **71** (2005) 071103, doi:10.1103/PhysRevD.71.071103, arXiv:hep-ex/0406022.

[3] BESIII Collaboration, "Observation of $e^{+}e^{-} \to X(3872)$ at BESIII", *Phys. Rev. Lett.* **112** (2014) 092001, doi:10.1103/PhysRevLett.112.092001, arXiv:1310.4101.

[4] CDF Collaboration, "Observation of the narrow state $X(3872) \to \mathrm{J}/\psi\pi^{+}\pi^{-}$ in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV", *Phys. Rev. Lett.* **93** (2004) 072001, doi:10.1103/PhysRevLett.93.072001, arXiv:hep-ex/0312021.

[5] D0 Collaboration, "Observation and properties of the X(3872) decaying to $\mathrm{J}/\psi\pi^{+}\pi^{-}$ in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV", *Phys. Rev. Lett.* **93** (2004) 162002, doi:10.1103/PhysRevLett.93.162002, arXiv:hep-ex/0405004.

[6] LHCb Collaboration, "Observation of X(3872) production in pp collisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J. C* **72** (2012) 1972, doi:10.1140/epjc/s10052-012-1972-7, arXiv:1112.5310.

[7] CMS Collaboration, "Measurement of the X(3872) production cross section via decays to $\mathrm{J}/\psi\pi^{+}\pi^{-}$ in pp collisions at $\sqrt{s} = 7$ TeV", *JHEP* **04** (2013) 154, doi:10.1007/JHEP04(2013)154, arXiv:1302.3968.

[8] ATLAS Collaboration, "Measurements of $\psi(2\mathrm{S})$ and $X(3872) \to \mathrm{J}/\psi\pi^{+}\pi^{-}$ production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector", *JHEP* **01** (2017) 117, doi:10.1007/JHEP01(2017)117, arXiv:1610.09303.

[9] CDF Collaboration, "Analysis of the quantum numbers $J^{PC}$ of the X(3872)", *Phys. Rev. Lett.* **98** (2007) 132002, doi:10.1103/PhysRevLett.98.132002, arXiv:hep-ex/0612053.

[10] LHCb Collaboration, "Determination of the X(3872) meson quantum numbers", *Phys. Rev. Lett.* **110** (2013) 222001, doi:10.1103/PhysRevLett.110.222001, arXiv:1302.6269.

[11] N. A. Tornqvist, "Isospin breaking of the narrow charmonium state of Belle at 3872 MeV as a deuson", *Phys. Lett. B* **590** (2004) 209, doi:10.1016/j.physletb.2004.03.077, arXiv:hep-ph/0402237.

[12] L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, "Diquark-antidiquarks with hidden or open charm and the nature of X(3872)", *Phys. Rev. D* **71** (2005) 014028, doi:10.1103/PhysRevD.71.014028, arXiv:hep-ph/0412098.

[13] C. Hanhart, Yu. S. Kalashnikova, and A. V. Nefediev, "Interplay of quark and meson degrees of freedom in a near-threshold resonance: multi-channel case", *Eur. Phys. J. A* **47** (2011) 101, doi:10.1140/epja/i2011-11101-9, arXiv:1106.1185.

[14] J. C. Collins and M. J. Perry, "Superdense matter: neutrons or asymptotically free quarks?", *Phys. Rev. Lett.* **34** (1975) 1353, doi:10.1103/PhysRevLett.34.1353.

[15] E. V. Shuryak, "Quark-gluon plasma and hadronic production of leptons, photons and pions", *Phys. Lett. B* **78** (1978) 150, doi:10.1016/0370-2693(78)90370-2. [*Yad. Fiz.* **28** (1978) 796].

[16] H. Zhang et al., "Deciphering the nature of X(3872) in heavy ion collisions", (3, 2020). arXiv:2004.00024.

[17] B. Wu, X. Du, M. Sibila, and R. Rapp, "X(3872) transport in heavy-ion collisions", (6, 2020). arXiv:2006.09945.

[18] ExHIC Collaboration, "Multi-quark hadrons from heavy ion collisions", *Phys. Rev. Lett.* **106** (2011) 212001, doi:10.1103/PhysRevLett.106.212001, arXiv:1011.0852.

[19] ExHIC Collaboration, "Studying exotic hadrons in heavy ion collisions", *Phys. Rev. C* **84** (2011) 064910, doi:10.1103/PhysRevC.84.064910, arXiv:1107.1302.

[20] A. Martinez Torres et al., "On X(3872) production in high energy heavy ion collisions", *Phys. Rev. D* **90** (2014) 114023, doi:10.1103/PhysRevD.90.114023, arXiv:1405.7583. [Erratum: doi:10.1103/PhysRevD.93.059902].

[21] H. Sato and K. Yazaki, "On the coalescence model for high energy nuclear reactions", *Physics Letters B* **98** (1981) 153, doi:10.1016/0370-2693(81)90976-X.

[22] T. Matsui and H. Satz, "J/$\psi$ suppression by quark-gluon plasma formation", *Phys. Lett. B* **178** (1986) 416, doi:10.1016/0370-2693(86)91404-8.

[23] L. M. Abreu et al., "X(3872) production and absorption in a hot hadron gas", *Phys. Lett. B* **761** (2016) 303, doi:10.1016/j.physletb.2016.08.050, arXiv:1604.07716.

[24] LHCb Collaboration, "Evidence for the decay $X(3872) \to \psi(2S)\gamma$", *Nucl. Phys. B* **886** (2014) 665, doi:10.1016/j.nuclphysb.2014.06.011, arXiv:1404.0275.

[25] A. Andronic, P. Braun-Munzinger, and J. Stachel, "Hadron production in central nucleus-nucleus collisions at chemical freeze-out", *Nucl. Phys. A* **772** (2006) 167, doi:10.1016/j.nuclphysa.2006.03.012, arXiv:nucl-th/0511071.

[26] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[27] CMS Collaboration, "Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV", *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[28] CMS Collaboration, "Observation and studies of jet quenching in PbPb collisions at nucleon-nucleon center-of-mass energy = 2.76 TeV", *Phys. Rev. C* **84** (2011) 024906, doi:10.1103/PhysRevC.84.024906, arXiv:1102.1957.

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

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

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

[32] CMS Collaboration, "Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *JHEP* **04** (2017) 039, doi:10.1007/JHEP04(2017)039, arXiv:1611.01664.

[33] CMS Collaboration, "Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV", *JHEP* **02** (2010) 041, doi:10.1007/JHEP02(2010)041, arXiv:1002.0621.

[34] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

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

[36] Particle Data Group, P. A. Zyla et al., "Review of particle physics", *Prog. Theor. Exp. Phys.* **2020** (2020) 083C01, doi:10.1093/ptep/ptaa104.

[37] D. J. Lange, "The EvtGen particle decay simulation package", *Nucl. Instrum. Meth. A* **462** (2001) 152, doi:10.1016/S0168-9002(01)00089-4.

[38] E. Barberio, B. van Eijk, and Z. Was, "Photos — a universal Monte Carlo for QED radiative corrections in decays", *Comput. Phys. Commun.* **66** (1991) 115, doi:10.1016/0010-4655(91)90012-A.

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

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

[41] CMS Collaboration, "Measurements of inclusive W and Z cross sections in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$", *JHEP* **01** (2011) 080, doi:10.1007/JHEP01(2011)080, arXiv:1012.2466.

[42] CMS Collaboration, "J/$\psi$ and $\psi(2\mathrm{S})$ production in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$", *JHEP* **02** (2012) 011, doi:10.1007/JHEP02(2012)011, arXiv:1111.1557.

[43] CMS Collaboration, "Measurement of prompt and nonprompt charmonium suppression in PbPb collisions at 5.02 TeV", *Eur. Phys. J. C* **78** (2018) 509, doi:10.1140/epjc/s10052-018-5950-6, arXiv:1712.08959.

# A The CMS Collaboration

**Yerevan Physics Institute, Yerevan, Armenia**
A.M. Sirunyan[†], 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[1], M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck[1], R. Schöfbeck, M. Spanring, W. Waltenberger, C.-E. Wulz[1], 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[2], A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

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

**Université Libre de Bruxelles, Bruxelles, Belgium**
D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, 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[3], 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[4], E. Coelho, E.M. Da Costa, G.G. Da Silveira[5], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, J. Martins[6], D. Matos Figueiredo, M. Medina Jaime[7], 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[4], F. Torres Da Silva De Araujo, A. Vilela Pereira

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

**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[2], X. Gao[2], 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[8], H.S. Chen[8], M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang[8], 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[9], 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[10], M. Finger Jr.[10], A. Kveton, J. Tomsa

**Escuela Politecnica Nacional, Quito, Ecuador**
E. Ayala

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

**Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**
M.A. Mahmoud[11,12], Y. Mohammed[11]

**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[13], M. Titov, G.B. Yu

**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, 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[14], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte[14], J.-C. Fontaine[14], 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

**Institut de Physique des 2 Infinis de Lyon (IP2I ), 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[15]

**Tbilisi State University, Tbilisi, Georgia**
Z. Tsamalaidze[10]

**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[16], O. Hlushchenko, T. Kress, T. Müller, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[17]

**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. Borras[18], 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, L.I. Estevez Banos, E. Gallo[19], A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem[18], M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann[20], 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. Multhaup, 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[17], 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. Savoiu, 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. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas, F.A. Triantis, D. Tsitsonis

**MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary**
M. Bartók[21], 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[22], F. Sikler, V. Veszpremi, G. Vesztergombi†

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**
N. Beni, S. Czellar, J. Karancsi[21], 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[24], C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak[25], D.K. Sahoo[24], S.K. Swain

**Panjab University, Chandigarh, India**
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra[26], R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi, G. Walia

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

**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 [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy**
M. Abbrescia[a,b], R. Aly[a,b,30], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], W. Elmetenawee[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], J.A. Merlin[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], 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,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,31], 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], N. Tosi[a]

**INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy**
S. Albergo[a,b,32], S. Costa[a,b,32], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,32], C. Tuve[a,b]

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

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**
L. Benussi, S. Bianco, D. Piccolo

**INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy**
M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a,b], E. Robutti[a], S. Tosi[a,b]

**INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy**
A. Benaglia[a], A. Beschi[a,b], F. Brivio[a,b], V. Ciriolo[a,b,17], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M. Malberti[a], S. Malvezzi[a], D. Menasce[a], F. Monti[a,b], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Valsecchi[a,b,17], D. Zuolo[a,b]

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

**INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy**
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S.Y. Hoh[a,b], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], M. Presilla[b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko[a], M. Tosi[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**
A. Braghieri[a], D. Fiorina[a,b], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

**INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy**
M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

**INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa Italy, Università di Siena [d], Siena, Italy**
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], S. Donato[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[a,c],

S. Roy Chowdhury[a,c], A. Scribano[a], 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], Rome, Italy**
F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a,b], R. Tramontano[a,b]

**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], A. Cappati[a,b], N. Cartiglia[a], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], J.R. González Fernández[a], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Salvatico[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], D. Trocino[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], F. Vazzoler[a,b], A. Zanetti[a]

**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**
H. Kim, D.H. Moon

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

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

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

**Sejong University, Seoul, Korea**
H.S. 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[33]

**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[34], 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[35], 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[3], 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. Szleper, P. Zalewski

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**
K. Bunkowski, A. Byszuk[36], 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, Y. Ershov, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[37,38], V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, B.S. Yuldashev[39], A. Zarubin, V. Zhiltsov

**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**
L. Chtchipounov, V. Golovtcov, Y. Ivanov, V. Kim[40], E. Kuznetsova[41], 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[42], V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

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

**National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia**
O. Bychkova, R. Chistov[43], M. Danilov[43], S. Polikarpov[43], 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. Demiyanov, A. Ershov, A. Gribushin, O. Kodolova, V. Korotkikh, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

**Novosibirsk State University (NSU), Novosibirsk, Russia**
A. Barnyakov[44], V. Blinov[44], T. Dimova[44], L. Kardapoltsev[44], Y. Skovpen[44]

**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[45], P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

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

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

**Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain**
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, S. Sanchez Cruz

**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Russo[46], L. Scodellaro, I. Vila, J.M. Vizan Garcia

**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**
T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita[47], D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, T. James, P. Janot, O. Karacheban[20], J. Kaspar, J. Kieseler, M. Krammer[1], N. Kratochwil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo[17], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[48], J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**
L. Caminada[49], 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. Lustermann, 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[50], 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[29], 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[51], S. Damarseckin[52], Z.S. Demiroglu, F. Dolek, C. Dozen[53], I. Dumanoglu[54], G. Gokbulut, Emine Gurpinar Guler[55], Y. Guler, I. Hos[56], C. Isik, E.E. Kangal[57], O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[58], A.E. Simsek, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

**Middle East Technical University, Physics Department, Ankara, Turkey**
B. Isildak[59], G. Karapinar[60], M. Yalvac[61]

**Bogazici University, Istanbul, Turkey**
I.O. Atakisi, E. Gülmez, M. Kaya[62], O. Kaya[63], Ö. Özçelik, S. Tekten[64], E.A. Yetkin[65]

**Istanbul Technical University, Istanbul, Turkey**
A. Cakir, K. Cankocak[54], Y. Komurcu, S. Sen[66]

**Istanbul University, Istanbul, Turkey**
S. Cerci[67], B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci[67]

**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[68], 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[69], 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[70], 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[71], 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[17], 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[18], D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan[72], K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir[73], R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

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

**University of California, Los Angeles, USA**
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

**University of California, Riverside, Riverside, USA**
K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, 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. Gecse, 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[74], 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

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

**Florida International University, Miami, USA**
Y.R. Joshi

**Florida State University, Tallahassee, USA**
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[55], K. Dilsiz[75], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[76], A. Moeller, J. Nachtman, H. Ogul[77], Y. Onel, F. Ozok[78], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi[79]

**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

**The University of Kansas, Lawrence, USA**
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

**University of Maryland, College Park, USA**
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†, 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†, 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[37], 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[80], M. Dalchenko, M. De Mattia, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[81], 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 [a], Università di Bari [b], Politecnico di Bari [c], 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 Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
41: Also at University of Florida, Gainesville, USA
42: Also at Imperial College, London, United Kingdom
43: Also at P.N. Lebedev Physical Institute, Moscow, Russia
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, Siena, Italy
47: Also at INFN Sezione di Pavia [a], Università di Pavia [b], 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

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 Rektörlügü, Yozgat, Turkey, 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