EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP-2021-081
10 May 2021

Experimental evidence for an attractive p–ϕ interaction

ALICE Collaboration*

Abstract

This Letter presents the first experimental evidence of the attractive strong interaction between a proton and a ϕ meson. The result is obtained from two-particle correlations of combined p–ϕ $\oplus$ $\overline{\mathrm{p}}$–ϕ pairs measured in high-multiplicity pp collisions at $\sqrt{s}$ = 13 TeV by the ALICE collaboration. The spin-averaged scattering length and effective range of the p–ϕ interaction are extracted from the fully corrected correlation function employing the Lednický–Lyuboshits approach. In particular, the imaginary part of the scattering length vanishes within uncertainties, indicating that inelastic processes do not play a prominent role for the p–ϕ interaction. These data demonstrate that the interaction is dominated by elastic p–ϕ scattering. Furthermore, an analysis employing phenomenological Gaussian- and Yukawa-type potentials is conducted. Under the assumption of the latter, the N–ϕ coupling constant is found to be $g_{\mathrm{N}-\phi} = 0.14 \pm 0.03\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{syst.})$. This work provides valuable experimental input to accomplish a self-consistent description of the N–ϕ interaction, which is particularly relevant for the more fundamental studies on partial restoration of chiral symmetry in nuclear medium.

*See Appendix A for the list of collaboration members

Quantum Chromodynamics (QCD) is the theory of the strong interaction, where the degrees of freedom are represented by colored quarks and gluons. The observable degrees of freedom at low energies, however, are composite hadrons, and their mass is dynamically generated by the interplay between spontaneous and explicit chiral symmetry breaking. The spontaneous breaking arises from the non-zero vacuum expectation value $\langle 0|\overline{\mathrm{q}}\mathrm{q}|0\rangle$ of the ground state of the QCD Lagrangian, the quark condensate $\overline{\mathrm{q}}\mathrm{q}$. The consideration of the quark mass term leads to the explicit breaking of chiral symmetry. A link between the hadron properties and $\langle 0|\overline{\mathrm{q}}\mathrm{q}|0\rangle$ is provided by the QCD sum rule method [1–4], with the hadrons being interpreted as excitations of the $\overline{\mathrm{q}}\mathrm{q}$ ground state. Chiral symmetry is expected to be partially restored in a dense and/or hot strongly interacting medium [5]. Consequently, the modification of the $\overline{\mathrm{q}}\mathrm{q}$ condensate in the medium is reflected in the spectral shape of its hadronic excitations. This results in a potentially measurable mass shift and/or width broadening of the hadrons. From the experimental point of view, the light vector mesons ρ, ω and ϕ represent the most suitable hadronic probes due to the short lifetime [6, 7]. The detection through the dileptonic decay channels ($\mathrm{e}^+\mathrm{e}^-$and $\mu^+\mu^-$) allows to infer on the meson properties at the time of their decay [8–12].

In this context, the ϕ meson represents an experimentally challenging probe due to the narrow decay width in vacuum, which renders its spectral shape distinguishable from that of the ρ and ω mesons. The KEK-PS E325 collaboration measured the ϕ spectral function in p–C and p–Cu reactions and reported a slight mass shift and moderate increase of the width, which was in a model-dependent manner interpreted as an in-medium modification [13]. The collected data were, however, limited due to the small branching ratio (BR $\approx 3\times10^{-4}$ [14]) of the $\phi \to \mathrm{e}^+\mathrm{e}^-$ decay. Larger data samples were collected by the Spring8-LEPS collaboration in order to determine the ϕ production and absorption cross section in photon-induced reactions by exploiting the decay to $\mathrm{K}^+\mathrm{K}^-$ (BR $\approx$ 50% [14]) [15]. The N–ϕ cross section in nuclear matter was found to be much larger than the vacuum cross section, corresponding to an in-medium ϕ width of about 110 MeV$/c^2$. A similar conclusion was reached by other experiments from transparency ratio measurements in photon- [16] and proton-induced reactions [17].

The interpretation of these results is far from trivial due to the lack of model-independent information on the N–ϕ interaction and its complex dynamics. Because of the hidden strangeness content ($\mathrm{s}\overline{\mathrm{s}}$) of the ϕ, the direct coupling to u and d quarks in the nucleon is expected to be suppressed due to the OZI rule [18–20]. Indications for a possible OZI-rule violation were reported by the HADES collaboration [10]. In addition, several scenarios allow for a direct interaction of the ϕ meson with the nucleon, including a coupling to its strangeness content [21]. An alternative is the QCD Van der Waals interaction [22], mediated by multi-gluon exchange, which has been identified as relevant for the ($\mathrm{c}\overline{\mathrm{c}}$)–N system [23]. Using a phenomenological Yukawa-type potential with adjusted parameters, the QCD Van der Waals force is able to form a N–ϕ bound state [24]. However, the direct N–ϕ coupling is typically not considered in theoretical descriptions of the interaction in vacuum and in medium. OZI-allowed N–ϕ processes can also proceed via the coupling to particle pairs with same quantum numbers, such as K–Λ, K–Σ, K^*–Λ, K^*–Σ [25–27]. More importantly, the properties of the ϕ are defined by the $\phi-\mathrm{K}\overline{\mathrm{K}}$ coupling [18–20]. Accordingly, $\mathrm{K}\overline{\mathrm{K}}$ loops and tadpole diagrams contribute to the self-energy of the ϕ [26–28], linking the ϕ properties to the complex dynamics of the K–N and $\overline{\mathrm{K}}$–N systems [29]. This was explored by HADES in π–nucleus reactions at beam energies of 1.65 GeV, demonstrating a constant ϕ/K^- ratio in different collision systems [30]. Since a strong K^- absorption was observed also a strong ϕ absorption is expected. The overall N–ϕ interaction is defined by the interplay of all aforementioned processes. However, the present theoretical and experimental situation is far from being resolved [31]. Indeed, a consistent description of the available photon- and proton-induced data [15–17] is still out of reach [25]. This demonstrates the need for a direct measurement of the two-body N–ϕ interaction in vacuum, in order to constrain theoretical models and correctly interpret the data from nuclear collisions.

Recently, detailed measurements of the final-state interaction were conducted employing two-particle correlations in ultra-relativistic proton–proton (pp) collisions [32–39]. In this Letter, these studies are extended to protons and ϕ mesons.

The observable is the two-particle correlation function $C(k^*)$, defined as $C(k^*) = \mathcal{N} \times \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$ [40] where N_{same} and N_{mixed} are the distributions of the relative momentum, $k^* = \frac{1}{2} \times |\mathbf{p}_1^* - \mathbf{p}_2^*|$ between both particles in the pair rest frame and a normalization constant $\mathcal{N}$, evaluated from same and mixed events, respectively. The Koonin-Pratt equation $C(k^*) = \int \mathrm{d}^3r^*\; S(r^*)\; |\; \Psi(\vec{r^*},\vec{k^*})\; |^2$ [40] relates the observable to the source function $S(r^*)$ and the two-particle wave function $\Psi(\vec{r^*},\vec{k^*})$ incorporating the final-state interaction, where r^* is the relative distance between the two particles.

The results reported in this Letter are based on the analysis of a data sample of pp collisions at $\sqrt{s} = 13$ TeV recorded by ALICE [41, 42] during the LHC Run 2 (2015–2018). A high-multiplicity trigger relying on the measured signal amplitudes in the V0 detectors [43] is employed to select collisions with on average 30 produced charged particles in the pseudorapidity interval $|\eta| < 0.5$ [38]. The resulting data sample constitutes the upper 0.17% of all inelastic collisions with at least one charged particle in the range $|\eta| < 1$ (referred to as INEL > 0) [37]. The event selection follows [32, 37]. The reconstructed primary vertex is required to be located within ± 10 cm of the nominal interaction point along the beam direction to assure a uniform detector coverage. Meson-baryon correlation measurements in pp collisions are contaminated by a so-called minijet background, induced by jet-like structures associated with hard parton-parton scatterings [35, 44], which influence the event shape [45, 46]. Therefore, a selection on the transverse sphericity S_{T} [35, 45, 46], defined as in Ref. [45], is utilized to reduce the minijet contribution. A total of 5×10^8 events with $0.7 < S_{\mathrm{T}} < 1.0$ [35] are analyzed.

The subsystems employed in the analysis are the Inner Tracking System (ITS) [41], the Time Projection Chamber (TPC) [47] and the Time-Of-Flight (TOF) detector [48], covering the full azimuthal angle and the pseudorapidity interval $|\eta| < 0.9$. The detectors are immersed in a uniform magnetic field of 0.5 T along the beam direction.

The proton candidates are selected following the methods used in Ref. [32]. The particle identification (PID) is conducted employing the TPC and TOF detectors by determining the deviation n_σ between the signal hypothesis for a proton and the measurement, normalized by the detector resolution σ. Contributions from secondary particles stemming from weak decays or the interaction of primary particles with the detector material are extracted using Monte Carlo (MC) template fits to the measured distribution of the Distance of Closest Approach (DCA) of the track to the primary vertex [32]. This results in a proton purity of 99%, with a primary fraction of 82% [33].

The ϕ is reconstructed in its hadronic decay to charged kaons $\phi \rightarrow \mathrm{K}^+\mathrm{K}^-$ as in Refs. [49–51]. Charged kaons are identified with a transverse momentum of $p_{\mathrm{T}} > 0.15$ GeV/c and $|\eta| < 0.8$. For momenta $p < 0.4$ GeV/c the PID selection provided by the TPC is used, while for larger momenta the information of TPC and TOF is combined. A selection on the DCA of the track to the primary vertex in both the beam direction ($|\mathrm{DCA}_z| < 0.8$ cm) and transverse plane ($|\mathrm{DCA}_{xy}| < 0.4$ cm) is employed to increase the fraction of kaons from ϕ decays. The purity of the kaon sample is $> 90\%$ for $p_{\mathrm{T}} < 1.25$ GeV/c. The $\mathrm{K}^+\mathrm{K}^-$ invariant mass is calculated combining two oppositely charged kaons assuming their nominal masses [14]. The ϕ candidates are selected within a window of ± 8 MeV/c^2 around the nominal ϕ mass, resulting in a total number of 5.8×10^6 with a purity of 66%.

A total of 4.17×10^4 p–ϕ and 3.61×10^4 $\overline{\mathrm{p}}$–ϕ pairs with $k^* < 200$ MeV/c contribute to N_{same} of the respective correlation function. Both are compatible within uncertainties and combined. In the following, p–ϕ refers to p–$\phi \oplus \overline{\mathrm{p}}$–$\phi$. The correlation function is normalized within $k^* \in [800, 1000]$ MeV/c. The data are unfolded for the finite momentum resolution of the detector [52], which modifies the correlation function by 0.7% at low k^*. The measured p–ϕ correlation function is shown in Fig. 1. The k^* value of the data points is chosen according to $\langle k^* \rangle$ of N_{same} in the corresponding interval. For $150 < k^* < 600$ MeV/c a rise in the correlation function attributed to residual minijet background is visible. Therefore, any conclusion on the genuine p–ϕ interaction demands a treatment of all contributions. They can arise

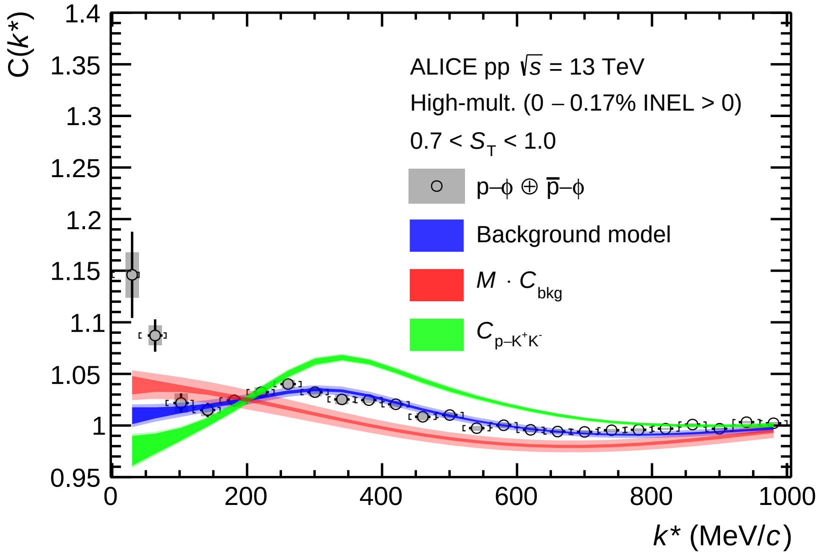

Figure 1: The experimental p–ϕ correlation function and various contributions as described in Eq. 1. Statistical (bars) and systematic uncertainties (boxes) are shown separately. The width of the dark (light) shaded bands depicts the statistical (total) uncertainty.

because of residual correlations from weak decays feeding to the particles of interest (feed-down) and misidentifications [32]. The total correlation function is decomposed as $C_{\mathrm{exp}} = \sum_i \lambda_i C_i$, where the index i runs over all contributions. The parameters λ_i, summarized in Table 1, are obtained in a data-driven way from single-particle properties [32]. As the purity of the ϕ candidates depends on p_{T}, it is evaluated for those entering the correlation function, and found to be 57%.

The experimental p–ϕ correlation function $C_{\mathrm{exp}}(k^*)$ is decomposed as

$$C_{\mathrm{exp}}(k^*) = M \times C_{\mathrm{bkg}}(k^*) \times \left[\lambda_{\mathrm{p}-\phi} \times C_{\mathrm{p}-\phi}(k^*) + \lambda_{\mathrm{flat}} \times C_{\mathrm{flat}}(k^*)\right] + \lambda_{\mathrm{p}-(\mathrm{K}^+\mathrm{K}^-)} \times C_{\mathrm{p}-(\mathrm{K}^+\mathrm{K}^-)}(k^*), \quad (1)$$

where M is a normalization constant, $C_{\mathrm{p}-\phi}(k^*)$ the genuine p–ϕ correlation function, $C_{\mathrm{p}-(\mathrm{K}^+\mathrm{K}^-)}(k^*)$ arises from combinatorial $\mathrm{K}^+\mathrm{K}^-$ background, and $C_{\mathrm{bkg}}(k^*) = C_{\mathrm{baseline}}(k^*) + C_{\mathrm{minijet}}(k^*)$ is the background including a baseline and the minijet contribution. All other contributions are assumed to be $C_{\mathrm{flat}}(k^*) \approx 1$.

As seen in Table 1, the combinatorial $\mathrm{K}^+\mathrm{K}^-$ background, referred to as p–($\mathrm{K}^+\mathrm{K}^-$), significantly contributes to the measured correlation function. Its shape is extracted from the sidebands of the invariant mass selection and mainly driven by p–K^+ and p–K^- interactions. The sideband intervals are chosen as $0.995 - 1.011$ GeV$/c^2$ and $1.028 - 1.044$ GeV$/c^2$ to avoid threshold effects and have comparable kinematic properties as the ϕ candidates. The resulting correlation function is parametrized with a double Gaussian and a quadratic polynomial. Finally, a residual ϕ amount of 8.6% in the sidebands is considered, which arises from the tail of the ϕ resonance extending into the sideband intervals. This results in a 7% contribution to the experimental $C_{\mathrm{p}-(\mathrm{K}^+\mathrm{K}^-)}(k^*)$ which is absorbed by a renormalization of the λ parameters. Since the p–($\mathrm{K}^+\mathrm{K}^-$) contribution is obtained from data, the corresponding residual minijet background and energy-momentum conservation effects are accounted for. The resulting correlation function is depicted by the yellow band in Fig. 1.

The remaining background $C_{\mathrm{bkg}}(k^*) = C_{\mathrm{baseline}}(k^*) + C_{\mathrm{minijet}}(k^*)$ is dominated by residual minijet contributions $C_{\mathrm{minijet}}(k^*)$ of p–ϕ. It is obtained from PYTHIA 8 [53] generated events, which yield a consistent description of the background associated with minijets [54, 55]. Additionally, energy-momentum conservation effects lead to a modification of the correlation function at larger k^* described by a quadratic

Table 1: Weight parameters of the individual components of the p–ϕ correlation function.

Pair	Weight λ (%)
p–ϕ	46.3
p–(K^+K^-)	43.3
Flat	10.4

baseline $C_{\text{baseline}}(k^*)$. The resulting $C_{\text{bkg}}(k^*)$ is shown by the red band in Fig. 1.

The genuine p–ϕ correlation function is extracted by fitting the data with the background model (Eq. 1 with $C_{\text{p}-\phi} = 1$) within $k^* \in [200, 800]$ MeV/c. The λ parameters, minijet and p–(K^+K^-) background are fixed from data. Only the normalization and baseline are free parameters. The resulting mean value of the normalization constant is $M = 0.96$. The blue band in Fig. 1 represents the total background, which accurately reproduces the enhancement within 200 MeV/c to 1000 MeV/c. The rise at low k^* is therefore fully attributed to the genuine p–ϕ interaction.

The systematic uncertainties of the data and the background description are assessed by varying simultaneously the selection criteria of protons and kaons by $\approx 15\%$ and the lower limit of the sphericity. Only variations with a maximal modification of $\pm 20\%$ of N_{same} within $k^* < 200$ MeV/c are accepted to retain the statistical significance. Systematic uncertainties associated with the background description are evaluated by varying the fit ranges, including a linear baseline. Uncertainties related to the unfolding are accounted for according to Ref. [38]. This results in a relative systematic uncertainty at low k^* of 2.8%.

In general, the p–ϕ interaction features one isospin and two spin configurations. Since the latter cannot be disentangled, spin-averaged results are presented. The strong p–ϕ interaction is modeled employing the Lednický–Lyuboshits approach [56]. Coupled channel effects are incorporated via an imaginary contribution to the scattering length. For large values of d_0, the term $\propto d_0/r_0$ that corrects the asymptotic wave function for small sources has an impact on the modeled correlation function [34]. Additionally, in line with studies of charmonium states [23, 57], phenomenological potentials are employed to model the p–ϕ interaction [24], including Yukawa-type, $V_{\text{Yukawa}}(r) = -A \times r^{-1} \times e^{-\alpha \times r}$, and Gaussian-type $V_{\text{Gaussian}}(r) = -V_{\text{eff}} \times e^{-\mu \times r^2}$ potentials. The correlation functions based on these potentials are obtained with *The Correlation Analysis Tool using the Schrödinger Equation* (CATS) [58].

The particle-emitting source is fixed from studies of p–p and p–Λ pairs [33], which demonstrated that by accounting for the effect of strong resonances feeding to the particle pair of interest, a common source for both pairs is found. The primordial source depends on the transverse mass m_{T} of the particle pair and is obtained by evaluating the core radius at the $\langle m_{\text{T}} \rangle = 1.66$ GeV/c^2 of the p–ϕ pairs. The strong decays feeding to protons are explicitly considered, while for the ϕ a 100% primordial fraction is assumed [14]. The resulting source function is parametrized by a Gaussian profile with $r_{\text{eff}} = (1.08 \pm 0.05)$ fm.

The interaction parameters are extracted by fitting the genuine p–ϕ correlation function with the respective model within $k^* < 200$ MeV/c. The systematic uncertainties of the procedure are assessed by varying the upper limit of the fit range by ± 30 MeV/c and the source radius within its uncertainties.

The genuine p–ϕ correlation function is shown in Fig. 2. For $k^* > 200$ MeV/c, it is flat and consistent with unity within uncertainties. At low k^* a pronounced enhancement with a significance of $4.7 - 6.6\ \sigma$ becomes apparent, which evidences the attractive nature of the p–ϕ interaction.

In correlation measurements, the detected pairs are emitted in the final state of the scattering processes. The correlation function of the sample is then sensitive to elastic and inelastic channels produced in the collision [59]. Inelastic channels opening below threshold act as an effective increase of the correlation function. The relevant channels for the p–ϕ system, Λ–K and Σ–K are located substantially below threshold. A quantitative discussion of their contribution to the measurement follows below. Channels

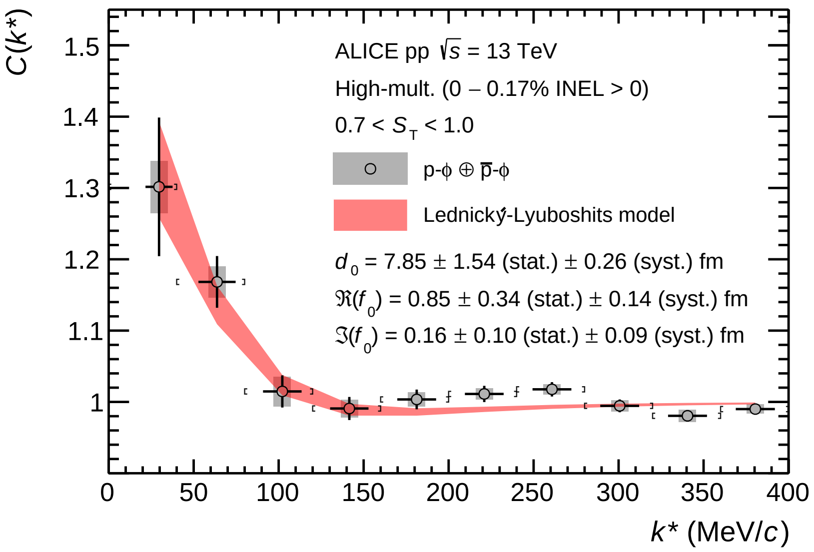

Figure 2: The genuine p–ϕ correlation function with statistical (bars) and systematic uncertainties (boxes). The red band depicts the results from the fit employing the Lednický–Lyuboshits approach [56]. The width corresponds to one standard deviation of the uncertainty of the fit.

appearing above threshold lead to a cusp structure in $C(k^*)$ in the vicinity of the threshold. Because of the large uncertainties and the broad bin width, no such structures are observed at the opening of the Λ–K* ($k^* = 221.6$ MeV$/c$) and Σ–K* ($k^* = 357.4$ MeV$/c$) thresholds. Results from the upcoming LHC Run 3 will constrain the respective coupling strengths [60].

More quantitative conclusions on the interaction and the coupled channels can be obtained employing the Lednický–Lyuboshits approach. The fit determines a scattering length with a real and imaginary contribution of $\Re(f_0) = 0.85 \pm 0.34\,(\mathrm{stat.}) \pm 0.14\,(\mathrm{syst.})$ fm and $\Im(f_0) = 0.16 \pm 0.10\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.})$ fm, and an effective range of $d_0 = 7.85 \pm 1.54\,(\mathrm{stat.}) \pm 0.26\,(\mathrm{syst.})$ fm.

The resulting $\Re(f_0)$ deviates by 2.3σ from zero, indicating the attractiveness of the p–ϕ interaction in vacuum. Notably, $\Im(f_0)$ vanishes within uncertainties, indicating that inelastic processes do not play a prominent role in the interaction. Instead, the elastic p–ϕ interaction appears to be dominant in vacuum. The scattering length is larger than values found in literature: a recent analysis of data recorded with the CLAS experiment reports $|f_0| = (0.063 \pm 0.010)$ fm [61]; a value of around $f_0 = 0.15$ fm is consistent with LEPS measurements of the ϕ cross section [62, 63]; studies of an effective Lagrangian combining chiral SU(3) dynamics with vector meson dominance obtain $f_0 = (-0.01 + i0.08)$ fm [64]; and a QCD sum rule analysis finds $f_0 = (-0.15 \pm 0.02)$ fm [65]. This underlines the importance of direct measurements of the two-body N–ϕ interaction in vacuum to provide constraints for theoretical models.

Finally, the data are employed to constrain the parameters of phenomenological Gaussian- and Yukawa-type potentials. As the imaginary contribution of the scattering length is consistent with zero, only real values are used for the parameters. The fits yield a comparable degree of consistency as the fit with the Lednický–Lyuboshits approach. The resulting values for the Gaussian-type potential are $V_{\mathrm{eff}} = 2.5 \pm 0.9\,(\mathrm{stat.}) \pm 1.4\,(\mathrm{syst.})$ MeV and $\mu = 0.14 \pm 0.06\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.})$ fm^{-2}, indicating a much shallower strong interaction potential than lattice QCD results for the N–J$/\psi$ strong interaction [66]. For the Yukawa-type potential the fit yields $A = 0.021 \pm 0.009\,(\mathrm{stat.}) \pm 0.006\,(\mathrm{syst.})$ and $\alpha = 65.9 \pm 38.0\,(\mathrm{stat.}) \pm 17.5\,(\mathrm{syst.})$ MeV. Studies of N–ϕ bound states with the same kind of potential but $\alpha = 600$ MeV and $A = 1.25$ [24] are therefore incompatible with this measurement. The N–ϕ coupling constant under the assumption of a Yukawa-type potential, directly extracted as $g_{\mathrm{N}-\phi} = \sqrt{A}$, is

$g_{\mathrm{N}-\phi} = 0.14 \pm 0.03\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{syst.})$.

In conclusion, this Letter presents the first correlation-based measurement of the p–ϕ interaction. The correlation function reflects the pattern of an attractive interaction. The scattering parameters, extracted with the Lednický–Lyuboshits approach, are $\Re(f_0) = 0.85 \pm 0.34\,(\mathrm{stat.}) \pm 0.14\,(\mathrm{syst.})$ fm, $\Im(f_0) = 0.16 \pm 0.10\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.})$ fm, and $d_0 = 7.85 \pm 1.54\,(\mathrm{stat.}) \pm 0.26\,(\mathrm{syst.})$ fm. Remarkably, the imaginary contribution to the scattering length vanishes, indicating that inelastic processes do not play a prominent role. Instead, the interaction is dominated by the elastic p–ϕ dynamics. Under the assumption of a Yukawa-type potential for the N–ϕ interaction, the value of the coupling constant is extracted as $g_{\mathrm{N}-\phi} = 0.14 \pm 0.03\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{syst.})$.
This measurement demonstrates for the first time that the p–ϕ interaction in vacuum is attractive and dominated by elastic scattering. It provides valuable experimental input on the N–ϕ interaction, which is fundamental to reach a self-consistent description of the interaction as required for the correct interpretation of data from nuclear collisions.

Acknowledgements

The ALICE Collaboration is grateful to P. Gubler and N. Kaiser for valuable discussions.

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centres and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Ministry of Education of China (MOEC) , Ministry of Science & Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research | Natural Sciences, the VILLUM FONDEN and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l'Energie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; Indonesian Institute of Science, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology , Nagasaki Institute of Applied Science (IIST), Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Academico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Education and Science, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics and Ministry of Research and Innovation and Institute of Atomic Physics, Romania; Joint Institute for Nuclear Research (JINR), Ministry of Education and Science of the Russian Federation, National Research Centre Kurchatov Institute, Russian Science Foundation and Russian Foundation for Basic Research, Russia; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSDTA) and Office of the Higher Education Commission under NRU project of Thailand, Thailand; Turkish Energy, Nuclear and Mineral Research Agency (TENMAK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America.

References

[1] T. Hatsuda and S. H. Lee, "QCD sum rules for vector mesons in the nuclear medium", *Phys. Rev.* **C46** (1992) 34.

[2] S. Leupold, V. Metag, and U. Mosel, "Hadrons in strongly interacting matter", *Int. J. Mod. Phys.* **E19** (2010) 147.

[3] S. Zschocke, O. P. Pavlenko, and B. Kampfer, "Evaluation of QCD sum rules for light vector mesons at finite density and temperature", *Eur. Phys. J.* **A15** (2002) 529.

[4] G. E. Brown and M. Rho, "Scaling effective Lagrangians in a dense medium", *Phys. Rev. Lett.* **66** (1991) 2720.

[5] R. Brockmann and W. Weise, "The chiral condensate in nuclear matter", *Phys. Lett.* **B367** (1996) 40.

[6] R. Rapp and J. Wambach, "Chiral symmetry restoration and dileptons in relativistic heavy ion collisions", *Adv. Nucl. Phys.* **25** (2000) 1.

[7] V. Metag, M. Nanova, and K.-T. Brinkmann, "In-medium properties of mesons", *EPJ Web Conf.* **134** (2017) 03003.

[8] **CERES** Collaboration, G. Agakichiev *et al.*, "Enhanced production of low mass electron pairs in 200-GeV/u S - Au collisions at the CERN SPS", *Phys. Rev. Lett.* **75** (1995) 1272.

[9] **NA60** Collaboration, R. Arnaldi *et al.*, "First measurement of the rho spectral function in high-energy nuclear collisions", *Phys. Rev. Lett.* **96** (2006) 162302.

[10] **HADES** Collaboration, G. Agakishiev *et al.*, "Dielectron production in Ar+KCl collisions at 1.76A GeV", *Phys. Rev.* **C84** (2011) 014902.

[11] **PHENIX** Collaboration, A. Adare *et al.*, "Dielectron production in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev.* **C93** (2016) 014904.

[12] **STAR** Collaboration, L. Adamczyk *et al.*, "Dielectron mass spectra from Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. Lett.* **113** (2014) 022301.

[13] **KEK-PS-E325** Collaboration, R. Muto *et al.*, "Evidence for in-medium modification of the phi meson at normal nuclear density", *Phys. Rev. Lett.* **98** (2007) 042501.

[14] **Particle Data Group** Collaboration, M. Tanabashi *et al.*, "Review of Particle Physics", *Prog. Theor. Exp. Phys.* **2020** (2020) 083C01.

[15] T. Ishikawa *et al.*, "ϕ photo-production from Li, C, Al, and Cu nuclei at E(γ) = 1.5 GeV to 2.4 GeV", *Phys. Lett.* **B608** (2005) 215.

[16] **CLAS** Collaboration, M. Wood *et al.*, "Absorption of the ω and ϕ Mesons in Nuclei", *Phys. Rev. Lett.* **105** (2010) 112301.

[17] A. Polyanskiy *et al.*, "Measurement of the in-medium phi-meson width in proton-nucleus collisions", *Phys. Lett.* **B695** (2011) 74.

[18] S. Okubo, "Phi meson and unitary symmetry model", *Phys. Lett.* **5** (1963) 165.

[19] G. Zweig, "An SU_3 model for strong interaction symmetry and its breaking; Version 2." CERN-TH-412, 1964.

[20] J. Iizuka, "Systematics and phenomenology of meson family", *Prog. Theor. Phys. Suppl.* **37** (1966) 21.

[21] J. R. Ellis, E. Gabathuler, and M. Karliner, "The OZI Rule Does Not Apply to Baryons", *Phys. Lett.* **B217** (1989) 173.

[22] T. Appelquist and W. Fischler, "Some remarks on van der Waals forces in QCD", *Phys. Lett.* **B77** (1978) 405.

[23] S. J. Brodsky, I. Schmidt, and G. F. de Téramond, "Nuclear-bound quarkonium", *Phys. Rev. Lett.* **64** (1990) 1011.

[24] H. Gao, T. Lee, and V. Marinov, "ϕ - N bound state", *Phys. Rev.* **C63** (2001) 022201.

[25] D. Cabrera, A. Hiller Blin, M. Vicente Vacas, and P. Fernández De Córdoba, "ϕ meson transparency in nuclei from ϕN resonant interactions", *Phys. Rev.* **C96** (2017) 034618.

[26] D. Cabrera, A. N. Hiller Blin, and M. J. Vicente Vacas, "ϕ meson self-energy in nuclear matter from ϕ*n* resonant interactions", *Phys. Rev.* **C95** (2017) 015201.

[27] F. Klingl, T. Waas, and W. Weise, "Modification of the phi meson spectrum in nuclear matter", *Phys. Lett.* **B431** (1998) 254.

[28] P. Gubler and W. Weise, "Phi meson spectral moments and QCD condensates in nuclear matter", *Nucl. Phys.* **A954** (2016) 125.

[29] Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, and W. Weise, "K^-p Correlation Function from High-Energy Nuclear Collisions and Chiral SU(3) Dynamics", *Phys. Rev. Lett.* **124** (2020) 132501.

[30] **HADES** Collaboration, J. Adamczewski-Musch *et al.*, "Strong absorption of hadrons with hidden and open strangeness in nuclear matter", *Phys. Rev. Lett.* **123** (2019) 022002.

[31] L. Tolos and L. Fabbietti, "Strangeness in Nuclei and Neutron Stars", *Prog. Part. Nucl. Phys.* **112** (2020) 103770.

[32] **ALICE** Collaboration, S. Acharya *et al.*, "p-p, p–Λ and Λ–Λ correlations studied via femtoscopy in pp reactions at $\sqrt{s}$ = 7 TeV", *Phys. Rev.* **C99** (2019) 024001.

[33] **ALICE** Collaboration, S. Acharya *et al.*, "Search for a common baryon source in high-multiplicity pp collisions at the LHC", *Phys. Lett.* **B811** (2020) 135849.

[34] **ALICE** Collaboration, S. Acharya *et al.*, "Study of the Λ–Λ interaction with femtoscopy correlations in pp and p–Pb collisions at the LHC", *Phys. Lett.* **B797** (2019) 134822.

[35] **ALICE** Collaboration, S. Acharya *et al.*, "Scattering studies with low-energy kaon-proton femtoscopy in proton-proton collisions at the LHC", *Phys. Rev. Lett.* **124** (2020) 092301.

[36] **ALICE** Collaboration, S. Acharya *et al.*, "First observation of an attractive interaction between a proton and a multi-strange baryon", *Phys. Rev. Lett.* **123** (2019) 112002.

[37] **ALICE** Collaboration, S. Acharya *et al.*, "Investigation of the p-Σ^0 interaction via femtoscopy in pp collisions", *Phys. Lett.* **B805** (2020) 135419.

[38] **ALICE** Collaboration, S. Acharya *et al.*, "Unveiling the strong interaction among hadrons at the LHC", *Nature* **588** (2020) 232.

[39] L. Fabbietti, V. Mantovani Sarti, and O. Vázquez Doce, "Hadron-hadron interactions measured by ALICE at the LHC", `arXiv:2012.09806 [nucl-ex]`.

[40] M. A. Lisa, S. Pratt, R. Soltz, and U. Wiedemann, "Femtoscopy in relativistic heavy ion collisions", *Ann. Rev. Nucl. Part. Sci.* **55** (2005) 357.

[41] **ALICE** Collaboration, K. Aamodt *et al.*, "The ALICE experiment at the CERN LHC", *J. Instrum.* **3** (2008) S08002.

[42] **ALICE** Collaboration, B. Abelev *et al.*, "Performance of the ALICE experiment at the CERN LHC", *Int. J. Mod. Phys.* **A29** (2014) 1430044.

[43] **ALICE** Collaboration, E. Abbas *et al.*, "Performance of the ALICE VZERO system", *J. Instrum.* **8** (2013) P10016.

[44] **ALICE** Collaboration, B. Abelev *et al.*, "Multiplicity dependence of jet-like two-particle correlation structures in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Lett.* **B741** (2015) 38.

[45] **ALICE** Collaboration, S. Acharya *et al.*, "Event-shape and multiplicity dependence of freeze-out radii in pp collisions at $\sqrt{s} = 7$ TeV", *JHEP* **09** (2019) 108.

[46] **ALICE** Collaboration, B. Abelev *et al.*, "Transverse sphericity of primary charged particles in minimum bias proton-proton collisions at $\sqrt{s} = 0.9$, 2.76 and 7 TeV", *Eur. Phys. J.* **C72** (2012) 2124.

[47] J. Alme *et al.*, "The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events", *Nucl. Instrum. Methods* **A622** (2010) 316.

[48] A. Akindinov *et al.*, "Performance of the ALICE Time-of-Flight detector at the LHC", *Eur. Phys. J. Plus* **128** (2013) 44.

[49] **ALICE** Collaboration, B. Abelev *et al.*, "Production of $K^*(892)^0$ and $\phi(1020)$ in pp collisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J.* **C72** (2012) 2183.

[50] **ALICE** Collaboration, S. Acharya *et al.*, "$K^*(892)^0$ and $\phi(1020)$ production at midrapidity in pp collisions at $\sqrt{s} = 8$ TeV", *Phys. Rev.* **C102** (2020) 024912.

[51] **ALICE** Collaboration, S. Acharya *et al.*, "Multiplicity dependence of $K^*(892)^0$ and $\phi(1020)$ production in pp collisions at $\sqrt{s}$ =13 TeV", *Phys. Lett.* **B807** (2020) 135501.

[52] T. Adye, "Unfolding algorithms and tests using RooUnfold", in *PHYSTAT 2011*, p. 313. CERN, Geneva, 2011.

[53] T. Sjöstrand *et al.*, "An Introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159.

[54] **ALICE** Collaboration, K. Aamodt *et al.*, "Femtoscopy of pp collisions at $\sqrt{s} = 0.9$ and 7 TeV at the LHC with two-pion Bose-Einstein correlations", *Phys. Rev.* **D84** (2011) 112004.

[55] **ALICE** Collaboration, J. Adam *et al.*, "Two-pion femtoscopy in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV", *Phys. Rev.* **C91** (2015) 034906.

[56] R. Lednický and V. L. Lyuboshits, "Final State Interaction Effect on Pairing Correlations Between Particles with Small Relative Momenta", *Sov. J. Nucl. Phys.* **35** (1982) 770.

[57] A. Yokota, E. Hiyama, and M. Oka, "Possible existence of charmonium–nucleus bound states", *Prog. Theor. Exp. Phys.* **2013** (2013) 113D01.

[58] D. L. Mihaylov, V. Mantovani Sarti, O. W. Arnold, L. Fabbietti, B. Hohlweger, and A. M. Mathis, "A femtoscopic Correlation Analysis Tool using the Schrödinger equation (CATS)", *Eur. Phys. J.* **C78** (2018) 394.

[59] J. Haidenbauer, "Coupled-channel effects in hadron–hadron correlation functions", *Nucl. Phys.* **A981** (2019) 1.

[60] **ALICE** Collaboration, S. Acharya *et al.*, "Future high-energy pp programme with ALICE", Tech. Rep. ALICE-PUBLIC-2020-005, 2020. `https://cds.cern.ch/record/2724925`.

[61] I. I. Strakovsky, L. Pentchev, and A. Titov, "Comparative analysis of ωp, ϕp, and $J/\psi p$ scattering lengths from A2, CLAS, and GlueX threshold measurements", *Phys. Rev.* **C101** (2020) 045201.

[62] A. I. Titov, T. Nakano, S. Daté, and Y. Ohashi, "Differential cross section of ϕ-meson photoproduction at threshold", *Phys. Rev.* **C76** (2007) 048202.

[63] W. C. Chang *et al.*, "Forward coherent phi-meson photoproduction from deuterons near threshold", *Phys. Lett.* **B658** (2008) 209.

[64] F. Klingl, N. Kaiser, and W. Weise, "Current correlation functions, QCD sum rules and vector mesons in baryonic matter", *Nucl. Phys.* **A624** (1997) 527.

[65] Y. Koike and A. Hayashigaki, "QCD Sum Rules for ρ, ω, ϕ Meson-Nucleon Scattering Lengths and the Mass Shifts in Nuclear Medium", *Progr. Theo. Phys.* **98** (1997) 631.

[66] T. Sugiura, Y. Ikeda, and N. Ishii, "Charmonium-nucleon interactions from $2+1$ flavor lattice QCD", *PoS* **LATTICE2018** (2019) 093.

A The ALICE Collaboration

S. Acharya[143], D. Adamová[98], A. Adler[76], J. Adolfsson[83], G. Aglieri Rinella[35], M. Agnello[31], N. Agrawal[55], Z. Ahammed[143], S. Ahmad[16], S.U. Ahn[78], I. Ahuja[39], Z. Akbar[52], A. Akindinov[95], M. Al-Turany[110], S.N. Alam[41], D. Aleksandrov[91], B. Alessandro[61], H.M. Alfanda[7], R. Alfaro Molina[73], B. Ali[16], Y. Ali[14], A. Alici[26], N. Alizadehvandchali[127], A. Alkin[35], J. Alme[21], T. Alt[70], L. Altenkamper[21], I. Altsybeev[115], M.N. Anaam[7], C. Andrei[49], D. Andreou[93], A. Andronic[146], M. Angeletti[35], V. Anguelov[107], F. Antinori[58], P. Antonioli[55], C. Anuj[16], N. Apadula[82], L. Aphecetche[117], H. Appelshäuser[70], S. Arcelli[26], R. Arnaldi[61], I.C. Arsene[20], M. Arslandok[148,107], A. Augustinus[35], R. Averbeck[110], S. Aziz[80], M.D. Azmi[16], A. Badalà[57], Y.W. Baek[42], X. Bai[131,110], R. Bailhache[70], Y. Bailung[51], R. Bala[104], A. Balbino[31], A. Baldisseri[140], B. Balis[2], M. Ball[44], D. Banerjee[4], R. Barbera[27], L. Barioglio[108,25], M. Barlou[87], G.G. Barnaföldi[147], L.S. Barnby[97], V. Barret[137], C. Bartels[130], K. Barth[35], E. Bartsch[70], F. Baruffaldi[28], N. Bastid[137], S. Basu[83], G. Batigne[117], B. Batyunya[77], D. Bauri[50], J.L. Bazo Alba[114], I.G. Bearden[92], C. Beattie[148], I. Belikov[139], A.D.C. Bell Hechavarria[146], F. Bellini[26,35], R. Bellwied[127], S. Belokurova[115], V. Belyaev[96], G. Bencedi[71], S. Beole[25], A. Bercuci[49], Y. Berdnikov[101], A. Berdnikova[107], D. Berenyi[147], L. Bergmann[107], M.G. Besoiu[69], L. Betev[35], P.P. Bhaduri[143], A. Bhasin[104], I.R. Bhat[104], M.A. Bhat[4], B. Bhattacharjee[43], P. Bhattacharya[23], L. Bianchi[25], N. Bianchi[53], J. Bielčík[38], J. Bielčíková[98], J. Biernat[120], A. Bilandzic[108], G. Biro[147], S. Biswas[4], J.T. Blair[121], D. Blau[91], M.B. Blidaru[110], C. Blume[70], G. Boca[29,59], F. Bock[99], A. Bogdanov[96], S. Boi[23], J. Bok[63], L. Boldizsár[147], A. Bolozdynya[96], M. Bombara[39], P.M. Bond[35], G. Bonomi[142,59], H. Borel[140], A. Borissov[84], H. Bossi[148], E. Botta[25], L. Bratrud[70], P. Braun-Munzinger[110], M. Bregant[123], M. Broz[38], G.E. Bruno[109,34], M.D. Buckland[130], D. Budnikov[111], H. Buesching[70], S. Bufalino[31], O. Bugnon[117], P. Buhler[116], Z. Buthelezi[74,134], J.B. Butt[14], S.A. Bysiak[120], D. Caffarri[93], M. Cai[28,7], H. Caines[148], A. Caliva[110], E. Calvo Villar[114], J.M.M. Camacho[122], R.S. Camacho[46], P. Camerini[24], F.D.M. Canedo[123], F. Carnesecchi[35,26], R. Caron[140], J. Castillo Castellanos[140], E.A.R. Casula[23], F. Catalano[31], C. Ceballos Sanchez[77], P. Chakraborty[50], S. Chandra[143], S. Chapeland[35], M. Chartier[130], S. Chattopadhyay[143], S. Chattopadhyay[112], A. Chauvin[23], T.G. Chavez[46], C. Cheshkov[138], B. Cheynis[138], V. Chibante Barroso[35], D.D. Chinellato[124], E.S. Chizzali[108], S. Cho[63], P. Chochula[35], P. Christakoglou[93], C.H. Christensen[92], P. Christiansen[83], T. Chujo[136], C. Cicalo[56], L. Cifarelli[26], F. Cindolo[55], M.R. Ciupek[110], G. Clai[II,55], J. Cleymans[I,126], F. Colamaria[54], J.S. Colburn[113], D. Colella[109,54,34,147], A. Collu[82], M. Colocci[35,26], M. Concas[III,61], G. Conesa Balbastre[81], Z. Conesa del Valle[80], G. Contin[24], J.G. Contreras[38], M.L. Coquet[140], T.M. Cormier[99], P. Cortese[32], M.R. Cosentino[125], F. Costa[35], S. Costanza[29,59], P. Crochet[137], E. Cuautle[71], P. Cui[7], L. Cunqueiro[99], A. Dainese[58], F.P.A. Damas[117,140], M.C. Danisch[107], A. Danu[69], I. Das[112], P. Das[89], P. Das[4], S. Das[4], S. Dash[50], S. De[89], A. De Caro[30], G. de Cataldo[54], L. De Cilladi[25], J. de Cuveland[40], A. De Falco[23], D. De Gruttola[30], N. De Marco[61], C. De Martin[24], S. De Pasquale[30], S. Deb[51], H.F. Degenhardt[123], K.R. Deja[144], L. Dello Stritto[30], S. Delsanto[25], W. Deng[7], P. Dhankher[19], D. Di Bari[34], A. Di Mauro[35], R.A. Diaz[8], T. Dietel[126], Y. Ding[138,7], R. Divià[35], D.U. Dixit[19], Ø. Djuvsland[21], U. Dmitrieva[65], J. Do[63], A. Dobrin[69], B. Dönigus[70], O. Dordic[20], A.K. Dubey[143], A. Dubla[110,93], S. Dudi[103], M. Dukhishyam[89], P. Dupieux[137], N. Dzalaiova[13], T.M. Eder[146], R.J. Ehlers[99], V.N. Eikeland[21], F. Eisenhut[70], D. Elia[54], B. Erazmus[117], F. Ercolessi[26], F. Erhardt[102], A. Erokhin[115], M.R. Ersdal[21], B. Espagnon[80], G. Eulisse[35], D. Evans[113], S. Evdokimov[94], L. Fabbietti[108], M. Faggin[28], J. Faivre[81], F. Fan[7], A. Fantoni[53], M. Fasel[99], P. Fecchio[31], A. Feliciello[61], G. Feofilov[115], A. Fernández Téllez[46], A. Ferrero[140], A. Ferretti[25], V.J.G. Feuillard[107], J. Figiel[120], S. Filchagin[111], D. Finogeev[65], F.M. Fionda[56,21], G. Fiorenza[35,109], F. Flor[127], A.N. Flores[121], S. Foertsch[74], P. Foka[110], S. Fokin[91], E. Fragiacomo[62], E. Frajna[147], U. Fuchs[35], N. Funicello[30], C. Furget[81], A. Furs[65], J.J. Gaardhøje[92], M. Gagliardi[25], A.M. Gago[114], A. Gal[139], C.D. Galvan[122], P. Ganoti[87], C. Garabatos[110], J.R.A. Garcia[46], E. Garcia-Solis[10], K. Garg[117], C. Gargiulo[35], A. Garibli[90], K. Garner[146], P. Gasik[110], E.F. Gauger[121], A. Gautam[129], M.B. Gay Ducati[72], M. Germain[117], J. Ghosh[112], P. Ghosh[143], S.K. Ghosh[4], M. Giacalone[26], P. Gianotti[53], P. Giubellino[110,61], P. Giubilato[28], A.M.C. Glaenzer[140], P. Glässel[107], D.J.Q. Goh[85], V. Gonzalez[145], L.H. González-Trueba[73], S. Gorbunov[40], M. Gorgon[2], L. Görlich[120], S. Gotovac[36], V. Grabski[73], L.K. Graczykowski[144], R.D. Grande[108], L. Greiner[82], A. Grelli[64], C. Grigoras[35], V. Grigoriev[96], A. Grigoryan[I,1], S. Grigoryan[77,1], O.S. Groettvik[21], F. Grosa[35,61], J.F. Grosse-Oetringhaus[35], R. Grosso[110], G.G. Guardiano[124], R. Guernane[81], M. Guilbaud[117], K. Gulbrandsen[92], T. Gunji[135], A. Gupta[104], R. Gupta[104], I.B. Guzman[46], S.P. Guzman[46], L. Gyulai[147], M.K. Habib[110], C. Hadjidakis[80], G. Halimoglu[70], H. Hamagaki[85], G. Hamar[147], M. Hamid[7], R. Hannigan[121], M.R. Haque[144,89], A. Harlenderova[110], J.W. Harris[148], A. Harton[10], J.A. Hasenbichler[35], H. Hassan[99], D. Hatzifotiadou[55], P. Hauer[44], L.B. Havener[148], S. Hayashi[135], S.T. Heckel[108], E. Hellbär[70], H. Helstrup[37], T. Herman[38], E.G. Hernandez[46], G. Herrera Corral[9], F. Herrmann[146], K.F. Hetland[37], H. Hillemanns[35], C. Hills[130], B. Hippolyte[139], B. Hofman[64], B. Hohlweger[93,108], J. Honermann[146], G.H. Hong[149], D. Horak[38], S. Hornung[110], A. Horzyk[2], R. Hosokawa[15], P. Hristov[35], C. Huang[80], C. Hughes[133], P. Huhn[70], T.J. Humanic[100], H. Hushnud[112], L.A. Husova[146], A. Hutson[127], D. Hutter[40], J.P. Iddon[35,130], R. Ilkaev[111], H. Ilyas[14], M. Inaba[136], G.M. Innocenti[35], M. Ippolitov[91], A. Isakov[38,98], M.S. Islam[112], M. Ivanov[110], V. Ivanov[101], V. Izucheev[94], M. Jablonski[2], B. Jacak[82], N. Jacazio[35], P.M. Jacobs[82], S. Jadlovska[119], J. Jadlovsky[119], S. Jaelani[64], C. Jahnke[124,123], M.J. Jakubowska[144], M.A. Janik[144], T. Janson[76], M. Jercic[102], O. Jevons[113], F. Jonas[99,146], P.G. Jones[113], J.M. Jowett [35,110], J. Jung[70], M. Jung[70], A. Junique[35], A. Jusko[113], J. Kaewjai[118], P. Kalinak[66], A. Kalweit[35], V. Kaplin[96], S. Kar[7], A. Karasu Uysal[79], D. Karatovic[102], O. Karavichev[65], T. Karavicheva[65], P. Karczmarczyk[144], E. Karpechev[65], A. Kazantsev[91], U. Kebschull[76], R. Keidel[48], D.L.D. Keijdener[64], M. Keil[35], B. Ketzer[44], Z. Khabanova[93], A.M. Khan[7], S. Khan[16], A. Khanzadeev[101], Y. Kharlov[94], A. Khatun[16], A. Khuntia[120], B. Kileng[37], B. Kim[17,63], D. Kim[149], D.J. Kim[128], E.J. Kim[75], J. Kim[149], J.S. Kim[42], J. Kim[107], J. Kim[149], J. Kim[75], M. Kim[107], S. Kim[18], T. Kim[149], S. Kirsch[70], I. Kisel[40], S. Kiselev[95], A. Kisiel[144], J.P. Kitowski[2], J.L. Klay[6], J. Klein[35], S. Klein[82], C. Klein-Bösing[146], M. Kleiner[70], T. Klemenz[108], A. Kluge[35], A.G. Knospe[127], C. Kobdaj[118], M.K. Köhler[107], T. Kollegger[110], A. Kondratyev[77], N. Kondratyeva[96], E. Kondratyuk[94], J. Konig[70], S.A. Konigstorfer[108], P.J. Konopka[35,2], G. Kornakov[144], S.D. Koryciak[2], L. Koska[119], A. Kotliarov[98], O. Kovalenko[88], V. Kovalenko[115], M. Kowalski[120], I. Králik[66], A. Kravčáková[39], L. Kreis[110], M. Krivda[113,66], F. Krizek[98], K. Krizkova Gajdosova[38], M. Kroesen[107], M. Krüger[70], E. Kryshen[101], M. Krzewicki[40], V. Kučera[35], C. Kuhn[139], P.G. Kuijer[93], T. Kumaoka[136], D. Kumar[143], L. Kumar[103], N. Kumar[103], S. Kundu[35,89], P. Kurashvili[88], A. Kurepin[65], A.B. Kurepin[65], A. Kuryakin[111], S. Kushpil[98], J. Kvapil[113], M.J. Kweon[63], J.Y. Kwon[63], Y. Kwon[149], S.L. La Pointe[40], P. La Rocca[27], Y.S. Lai[82], A. Lakrathok[118], M. Lamanna[35], R. Langoy[132], K. Lapidus[35], P. Larionov[53], E. Laudi[35], L. Lautner[35,108], R. Lavicka[38], T. Lazareva[115], R. Lea[142,24,59], J. Lee[136], J. Lehrbach[40], R.C. Lemmon[97], I. León Monzón[122], E.D. Lesser[19], M. Lettrich[35,108], P. Lévai[147], X. Li[11], X.L. Li[7], J. Lien[132], R. Lietava[113], B. Lim[17], S.H. Lim[17], V. Lindenstruth[40], A. Lindner[49], C. Lippmann[110], A. Liu[19], J. Liu[130], I.M. Lofnes[21], V. Loginov[96], C. Loizides[99], P. Loncar[36], J.A. Lopez[107], X. Lopez[137], E. López Torres[8], J.R. Luhder[146], M. Lunardon[28], G. Luparello[62], Y.G. Ma[41], A. Maevskaya[65], M. Mager[35], T. Mahmoud[44], A. Maire[139], M. Malaev[101], Q.W. Malik[20], L. Malinina[IV,77], D. Mal'Kevich[95], N. Mallick[51], P. Malzacher[110], G. Mandaglio[33,57], V. Manko[91], F. Manso[137], V. Manzari[54], Y. Mao[7], J. Mareš[68], G.V. Margagliotti[24], A. Margotti[55], A. Marín[110], C. Markert[121], M. Marquard[70], N.A. Martin[107], P. Martinengo[35], J.L. Martinez[127], M.I. Martínez[46], G. Martínez García[117], S. Masciocchi[110], M. Masera[25], A. Masoni[56], L. Massacrier[80], A. Mastroserio[141,54], A.M. Mathis[108], O. Matonoha[83], P.F.T. Matuoka[123], A. Matyja[120], C. Mayer[120], A.L. Mazuecos[35], F. Mazzaschi[25], M. Mazzilli[35], M.A. Mazzoni[60], J.E. Mdhluli[134], A.F. Mechler[70], F. Meddi[22], Y. Melikyan[65], A. Menchaca-Rocha[73], E. Meninno[116,30], A.S. Menon[127], M. Meres[13], S. Mhlanga[126,74], Y. Miake[136], L. Micheletti[61,25], L.C. Migliorin[138], D.L. Mihaylov[108], K. Mikhaylov[77,95], A.N. Mishra[147], D. Miśkowiec[110], A. Modak[4], A.P. Mohanty[64], B. Mohanty[89], M. Mohisin Khan[16], Z. Moravcova[92], C. Mordasini[108], D.A. Moreira De Godoy[146], L.A.P. Moreno[46], I. Morozov[65], A. Morsch[35], T. Mrnjavac[35], V. Muccifora[53], E. Mudnic[36],

D. Mühlheim[146], S. Muhuri[143], J.D. Mulligan[82], A. Mulliri[23], M.G. Munhoz[123], R.H. Munzer[70], H. Murakami[135], S. Murray[126], L. Musa[35], J. Musinsky[66], C.J. Myers[127], J.W. Myrcha[144], B. Naik[134,50], R. Nair[88], B.K. Nandi[50], R. Nania[55], E. Nappi[54], M.U. Naru[14], A.F. Nassirpour[83], A. Nath[107], C. Nattrass[133], A. Neagu[20], L. Nellen[71], S.V. Nesbo[37], G. Neskovic[40], D. Nesterov[115], B.S. Nielsen[92], S. Nikolaev[91], S. Nikulin[91], V. Nikulin[101], F. Noferini[55], S. Noh[12], P. Nomokonov[77], J. Norman[130], N. Novitzky[136], P. Nowakowski[144], A. Nyanin[91], J. Nystrand[21], M. Ogino[85], A. Ohlson[83], V.A. Okorokov[96], J. Oleniacz[144], A.C. Oliveira Da Silva[133], M.H. Oliver[148], A. Onnerstad[128], C. Oppedisano[61], A. Ortiz Velasquez[71], T. Osako[47], A. Oskarsson[83], J. Otwinowski[120], K. Oyama[85], Y. Pachmayer[107], S. Padhan[50], D. Pagano[142,59], G. Paić[71], A. Palasciano[54], J. Pan[145], S. Panebianco[140], P. Pareek[143], J. Park[63], J.E. Parkkila[128], S.P. Pathak[127], R.N. Patra[104,35], B. Paul[23], J. Pazzini[142,59], H. Pei[7], T. Peitzmann[64], X. Peng[7], L.G. Pereira[72], H. Pereira Da Costa[140], D. Peresunko[91], G.M. Perez[8], S. Perrin[140], Y. Pestov[5], V. Petráček[38], M. Petrovici[49], R.P. Pezzi[117,72], S. Piano[62], M. Pikna[13], P. Pillot[117], O. Pinazza[55,35], L. Pinsky[127], C. Pinto[27], S. Pisano[53], M. Płoskoń[82], M. Planinic[102], F. Pliquett[70], M.G. Poghosyan[99], B. Polichtchouk[94], S. Politano[31], N. Poljak[102], A. Pop[49], S. Porteboeuf-Houssais[137], J. Porter[82], V. Pozdniakov[77], S.K. Prasad[4], R. Preghenella[55], F. Prino[61], C.A. Pruneau[145], I. Pshenichnov[65], M. Puccio[35], S. Qiu[93], L. Quaglia[25], R.E. Quishpe[127], S. Ragoni[113], A. Rakotozafindrabe[140], L. Ramello[32], F. Rami[139], S.A.R. Ramirez[46], A.G.T. Ramos[34], T.A. Rancien[81], R. Raniwala[105], S. Raniwala[105], S.S. Räsänen[45], R. Rath[51], I. Ravasenga[93], K.F. Read[99,133], A.R. Redelbach[40], K. Redlich[V,88], A. Rehman[21], P. Reichelt[70], F. Reidt[35], H.A. Reme-ness[37], R. Renfordt[70], Z. Rescakova[39], K. Reygers[107], A. Riabov[101], V. Riabov[101], T. Richert[83,92], M. Richter[20], W. Riegler[35], F. Riggi[27], C. Ristea[69], S.P. Rode[51], M. Rodríguez Cahuantzi[46], K. Røed[20], R. Rogalev[94], E. Rogochaya[77], T.S. Rogoschinski[70], D. Rohr[35], D. Röhrich[21], P.F. Rojas[46], P.S. Rokita[144], F. Ronchetti[53], A. Rosano[33,57], E.D. Rosas[71], A. Rossi[58], A. Rotondi[29,59], A. Roy[51], P. Roy[112], S. Roy[50], N. Rubini[26], O.V. Rueda[83], R. Rui[24], B. Rumyantsev[77], P.G. Russek[2], A. Rustamov[90], E. Ryabinkin[91], Y. Ryabov[101], A. Rybicki[120], H. Rytkonen[128], W. Rzesa[144], O.A.M. Saarimaki[45], R. Sadek[117], S. Sadovsky[94], J. Saetre[21], K. Šafařík[38], S.K. Saha[143], S. Saha[89], B. Sahoo[50], P. Sahoo[50], R. Sahoo[51], S. Sahoo[67], D. Sahu[51], P.K. Sahu[67], J. Saini[143], S. Sakai[136], S. Sambyal[104], V. Samsonov[I,101,96], D. Sarkar[145], N. Sarkar[143], P. Sarma[43], V.M. Sarti[108], M.H.P. Sas[148], J. Schambach[99,121], H.S. Scheid[70], C. Schiaua[49], R. Schicker[107], A. Schmah[107], C. Schmidt[110], H.R. Schmidt[106], M.O. Schmidt[107], M. Schmidt[106], N.V. Schmidt[99,70], A.R. Schmier[133], R. Schotter[139], J. Schukraft[35], Y. Schutz[139], K. Schwarz[110], K. Schweda[110], G. Scioli[26], E. Scomparin[61], J.E. Seger[15], Y. Sekiguchi[135], D. Sekihata[135], I. Selyuzhenkov[110,96], S. Senyukov[139], J.J. Seo[63], D. Serebryakov[65], L. Šerkšnytė[108], A. Sevcenco[69], T.J. Shaba[74], A. Shabanov[65], A. Shabetai[117], R. Shahoyan[35], W. Shaikh[112], A. Shangaraev[94], A. Sharma[103], H. Sharma[120], M. Sharma[104], N. Sharma[103], S. Sharma[104], O. Sheibani[127], K. Shigaki[47], M. Shimomura[86], S. Shirinkin[95], Q. Shou[41], Y. Sibiriak[91], S. Siddhanta[56], T. Siemiarczuk[88], T.F. Silva[123], D. Silvermyr[83], G. Simonetti[35], B. Singh[108], R. Singh[89], R. Singh[104], R. Singh[51], V.K. Singh[143], V. Singhal[143], T. Sinha[112], B. Sitar[13], M. Sitta[32], T.B. Skaali[20], G. Skorodumovs[107], M. Slupecki[45], N. Smirnov[148], R.J.M. Snellings[64], C. Soncco[114], J. Song[127], A. Songmoolnak[118], F. Soramel[28], S. Sorensen[133], I. Sputowska[120], J. Stachel[107], I. Stan[69], P.J. Steffanic[133], S.F. Stiefelmaier[107], D. Stocco[117], I. Storehaug[20], M.M. Storetvedt[37], C.P. Stylianidis[93], A.A.P. Suaide[123], T. Sugitate[47], C. Suire[80], M. Suljic[35], R. Sultanov[95], M. Šumbera[98], V. Sumberia[104], S. Sumowidagdo[52], S. Swain[67], A. Szabo[13], I. Szarka[13], U. Tabassam[14], S.F. Taghavi[108], G. Taillepied[137], J. Takahashi[124], G.J. Tambave[21], S. Tang[137,7], Z. Tang[131], M. Tarhini[117], M.G. Tarzila[49], A. Tauro[35], G. Tejeda Muñoz[46], A. Telesca[35], L. Terlizzi[25], C. Terrevoli[127], G. Tersimonov[3], S. Thakur[143], D. Thomas[121], R. Tieulent[138], A. Tikhonov[65], A.R. Timmins[127], M. Tkacik[119], A. Toia[70], N. Topilskaya[65], M. Toppi[53], F. Torales-Acosta[19], T. Tork[80], R.C. Torres[82], S.R. Torres[38], A. Trifiró[33,57], S. Tripathy[55,71], T. Tripathy[50], S. Trogolo[35,28], G. Trombetta[34], V. Trubnikov[3], W.H. Trzaska[128], T.P. Trzcinski[144], B.A. Trzeciak[38], A. Tumkin[111], R. Turrisi[58], T.S. Tveter[20], K. Ullaland[21], A. Uras[138], M. Urioni[59,142], G.L. Usai[23], M. Vala[39], N. Valle[59,29], S. Vallero[61], N. van der Kolk[64], L.V.R. van Doremalen[64], M. van

Leeuwen[93], P. Vande Vyvre[35], D. Varga[147], Z. Varga[147], M. Varga-Kofarago[147], A. Vargas[46], M. Vasileiou[87], A. Vasiliev[91], O. Vázquez Doce[108], V. Vechernin[115], E. Vercellin[25], S. Vergara Limón[46], L. Vermunt[64], R. Vértesi[147], M. Verweij[64], L. Vickovic[36], Z. Vilakazi[134], O. Villalobos Baillie[113], G. Vino[54], A. Vinogradov[91], T. Virgili[30], V. Vislavicius[92], A. Vodopyanov[77], B. Volkel[35], M.A. Völkl[107], K. Voloshin[95], S.A. Voloshin[145], G. Volpe[34], B. von Haller[35], I. Vorobyev[108], D. Voscek[119], J. Vrláková[39], B. Wagner[21], C. Wang[41], D. Wang[41], M. Weber[116], R.J.G.V. Weelden[93], A. Wegrzynek[35], S.C. Wenzel[35], J.P. Wessels[146], J. Wiechula[70], J. Wikne[20], G. Wilk[88], J. Wilkinson[110], G.A. Willems[146], E. Willsher[113], B. Windelband[107], M. Winn[140], W.E. Witt[133], J.R. Wright[121], W. Wu[41], Y. Wu[131], R. Xu[7], S. Yalcin[79], Y. Yamaguchi[47], K. Yamakawa[47], S. Yang[21], S. Yano[47,140], Z. Yin[7], H. Yokoyama[64], I.-K. Yoo[17], J.H. Yoon[63], S. Yuan[21], A. Yuncu[107], V. Zaccolo[24], A. Zaman[14], C. Zampolli[35], H.J.C. Zanoli[64], N. Zardoshti[35], A. Zarochentsev[115], P. Závada[68], N. Zaviyalov[111], H. Zbroszczyk[144], M. Zhalov[101], S. Zhang[41], X. Zhang[7], Y. Zhang[131], V. Zherebchevskii[115], Y. Zhi[11], D. Zhou[7], Y. Zhou[92], J. Zhu[7,110], Y. Zhu[7], A. Zichichi[26], G. Zinovjev[3], N. Zurlo[142,59]

Affiliation Notes

[I] Deceased
[II] Also at: Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy
[III] Also at: Dipartimento DET del Politecnico di Torino, Turin, Italy
[IV] Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia
[V] Also at: Institute of Theoretical Physics, University of Wroclaw, Poland

Collaboration Institutes

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[2] AGH University of Science and Technology, Cracow, Poland
[3] Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[4] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
[5] Budker Institute for Nuclear Physics, Novosibirsk, Russia
[6] California Polytechnic State University, San Luis Obispo, California, United States
[7] Central China Normal University, Wuhan, China
[8] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
[9] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
[10] Chicago State University, Chicago, Illinois, United States
[11] China Institute of Atomic Energy, Beijing, China
[12] Chungbuk National University, Cheongju, Republic of Korea
[13] Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia
[14] COMSATS University Islamabad, Islamabad, Pakistan
[15] Creighton University, Omaha, Nebraska, United States
[16] Department of Physics, Aligarh Muslim University, Aligarh, India
[17] Department of Physics, Pusan National University, Pusan, Republic of Korea
[18] Department of Physics, Sejong University, Seoul, Republic of Korea

[19] Department of Physics, University of California, Berkeley, California, United States
[20] Department of Physics, University of Oslo, Oslo, Norway
[21] Department of Physics and Technology, University of Bergen, Bergen, Norway
[22] Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy
[23] Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[24] Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[25] Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[26] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
[27] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
[28] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[29] Dipartimento di Fisica e Nucleare e Teorica, Università di Pavia, Pavia, Italy
[30] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[31] Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
[32] Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy
[33] Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
[34] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[35] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[36] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
[37] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
[38] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[39] Faculty of Science, P.J. Šafárik University, Košice, Slovakia
[40] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[41] Fudan University, Shanghai, China
[42] Gangneung-Wonju National University, Gangneung, Republic of Korea
[43] Gauhati University, Department of Physics, Guwahati, India
[44] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[45] Helsinki Institute of Physics (HIP), Helsinki, Finland
[46] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
[47] Hiroshima University, Hiroshima, Japan
[48] Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms, Germany
[49] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[50] Indian Institute of Technology Bombay (IIT), Mumbai, India
[51] Indian Institute of Technology Indore, Indore, India
[52] Indonesian Institute of Sciences, Jakarta, Indonesia
[53] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[54] INFN, Sezione di Bari, Bari, Italy
[55] INFN, Sezione di Bologna, Bologna, Italy
[56] INFN, Sezione di Cagliari, Cagliari, Italy
[57] INFN, Sezione di Catania, Catania, Italy
[58] INFN, Sezione di Padova, Padova, Italy
[59] INFN, Sezione di Pavia, Pavia, Italy
[60] INFN, Sezione di Roma, Rome, Italy
[61] INFN, Sezione di Torino, Turin, Italy

[62] INFN, Sezione di Trieste, Trieste, Italy
[63] Inha University, Incheon, Republic of Korea
[64] Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands
[65] Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
[66] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
[67] Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
[68] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[69] Institute of Space Science (ISS), Bucharest, Romania
[70] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[71] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[72] Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
[73] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[74] iThemba LABS, National Research Foundation, Somerset West, South Africa
[75] Jeonbuk National University, Jeonju, Republic of Korea
[76] Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
[77] Joint Institute for Nuclear Research (JINR), Dubna, Russia
[78] Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
[79] KTO Karatay University, Konya, Turkey
[80] Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France
[81] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
[82] Lawrence Berkeley National Laboratory, Berkeley, California, United States
[83] Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
[84] Moscow Institute for Physics and Technology, Moscow, Russia
[85] Nagasaki Institute of Applied Science, Nagasaki, Japan
[86] Nara Women's University (NWU), Nara, Japan
[87] National and Kapodistrian University of Athens, School of Science, Department of Physics , Athens, Greece
[88] National Centre for Nuclear Research, Warsaw, Poland
[89] National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
[90] National Nuclear Research Center, Baku, Azerbaijan
[91] National Research Centre Kurchatov Institute, Moscow, Russia
[92] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[93] Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
[94] NRC Kurchatov Institute IHEP, Protvino, Russia
[95] NRC «Kurchatov»Institute - ITEP, Moscow, Russia
[96] NRNU Moscow Engineering Physics Institute, Moscow, Russia
[97] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[98] Nuclear Physics Institute of the Czech Academy of Sciences, Řež u Prahy, Czech Republic
[99] Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
[100] Ohio State University, Columbus, Ohio, United States
[101] Petersburg Nuclear Physics Institute, Gatchina, Russia
[102] Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
[103] Physics Department, Panjab University, Chandigarh, India
[104] Physics Department, University of Jammu, Jammu, India
[105] Physics Department, University of Rajasthan, Jaipur, India
[106] Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
[107] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

[108] Physik Department, Technische Universität München, Munich, Germany
[109] Politecnico di Bari and Sezione INFN, Bari, Italy
[110] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[111] Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
[112] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[113] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[114] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[115] St. Petersburg State University, St. Petersburg, Russia
[116] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[117] SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France
[118] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[119] Technical University of Košice, Košice, Slovakia
[120] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[121] The University of Texas at Austin, Austin, Texas, United States
[122] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[123] Universidade de São Paulo (USP), São Paulo, Brazil
[124] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[125] Universidade Federal do ABC, Santo Andre, Brazil
[126] University of Cape Town, Cape Town, South Africa
[127] University of Houston, Houston, Texas, United States
[128] University of Jyväskylä, Jyväskylä, Finland
[129] University of Kansas, Lawrence, Kansas, United States
[130] University of Liverpool, Liverpool, United Kingdom
[131] University of Science and Technology of China, Hefei, China
[132] University of South-Eastern Norway, Tonsberg, Norway
[133] University of Tennessee, Knoxville, Tennessee, United States
[134] University of the Witwatersrand, Johannesburg, South Africa
[135] University of Tokyo, Tokyo, Japan
[136] University of Tsukuba, Tsukuba, Japan
[137] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[138] Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon , Lyon, France
[139] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
[140] Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Départment de Physique Nucléaire (DPhN), Saclay, France
[141] Università degli Studi di Foggia, Foggia, Italy
[142] Università di Brescia, Brescia, Italy
[143] Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
[144] Warsaw University of Technology, Warsaw, Poland
[145] Wayne State University, Detroit, Michigan, United States
[146] Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany
[147] Wigner Research Centre for Physics, Budapest, Hungary
[148] Yale University, New Haven, Connecticut, United States
[149] Yonsei University, Seoul, Republic of Korea