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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 - $\phi \oplus \bar{p}$ - 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 $g_{N-\phi} = 0.14 \pm 0.03$ (stat.) ± 0.02 (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.

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*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 $\langle 0|\bar{q}q|0\rangle$ of the ground state of the QCD Lagrangian, the quark condensate $\bar{q}q$. The consideration of the quark mass term leads to the explicit breaking of chiral symmetry. A link between the hadron properties and $\langle 0|\bar{q}q|0\rangle$ is provided by the QCD sum rule method [1–4], with the hadrons being interpreted as excitations of the $\bar{q}q$ 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 $\bar{q}q$ 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 (e^+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 ($BR \approx 3 \times 10^{-4}$ [14]) of the $\phi \rightarrow e^+e^-$ 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 K^+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 $110 \text{ MeV}/c^2$. 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 ($s\bar{s}$) 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 $(c\bar{c})$ - 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 $\phi - K\bar{K}$ coupling [18–20]. Accordingly, $K\bar{K}$ 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 \bar{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 $C(k^*) = \mathcal{N} \times \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$ [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 $C(k^*) = \int d^3r^* S(r^*) |\Psi(\vec{r}^*, \vec{k}^*)|^2$ [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 $0.7 < S_T < 1.0$ [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 $\phi \rightarrow K^+K^-$ as in Refs. [49–51]. Charged kaons are identified with a transverse momentum of $p_T > 0.15$ 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 ($|DCA_z| < 0.8$ cm) and transverse plane ($|DCA_{xy}| < 0.4$ cm) is employed to increase the fraction of kaons from ϕ decays. The purity of the kaon sample is > 90% for $p_T < 1.25$ GeV/c. The K^+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/c² 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 \bar{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- $\phi \oplus \bar{p}$ - ϕ . 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

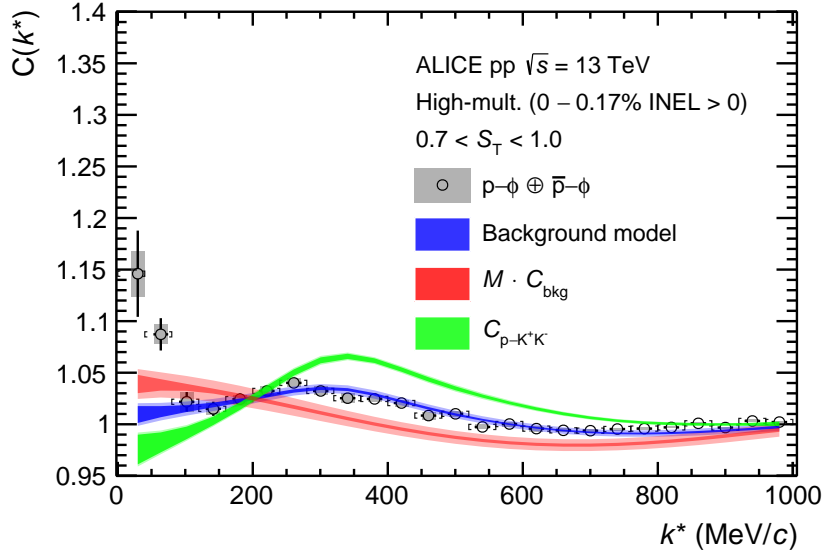


Figure 1: The experimental p - ϕ correlation function and various contributions as described in Eq. 1. Statistical (bars) and systematic uncertainties (boxes) are shown separately. The width of the dark (light) shaded bands depicts the statistical (total) uncertainty.

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 $C_{\text{exp}} = \sum_i \lambda_i C_i$, 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 $C_{\text{exp}}(k^*)$ is decomposed as

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

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

As seen in Table 1, the combinatorial K^+K^- background, referred to as p - (K^+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 $0.995 - 1.011 \text{ GeV}/c^2$ and $1.028 - 1.044 \text{ GeV}/c^2$ 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 $C_{p-(K^+K^-)}(k^*)$ which is absorbed by a renormalization of the λ parameters. Since the p - (K^+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 $C_{\text{bkg}}(k^*) = C_{\text{baseline}}(k^*) + C_{\text{minijet}}(k^*)$ is dominated by residual minijet contributions $C_{\text{minijet}}(k^*)$ 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 $\langle m_T \rangle = 1.66$ 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 σ 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

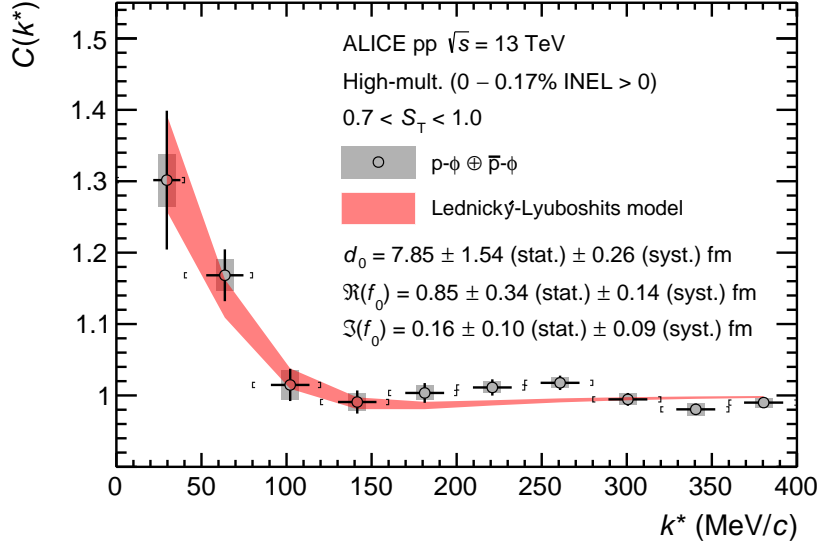


Figure 2: The genuine p- ϕ correlation function with statistical (bars) and systematic uncertainties (boxes). The red band depicts the results from the fit employing the Lednický–Lyuboshits approach [56]. The width corresponds to one standard deviation of the uncertainty of the fit.

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 $\Re(f_0) = 0.85 \pm 0.34$ (stat.) ± 0.14 (syst.) fm and $\Im(f_0) = 0.16 \pm 0.10$ (stat.) ± 0.09 (syst.) fm, and an effective range of $d_0 = 7.85 \pm 1.54$ (stat.) ± 0.26 (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 $V_{\text{eff}} = 2.5 \pm 0.9$ (stat.) ± 1.4 (syst.) MeV and $\mu = 0.14 \pm 0.06$ (stat.) ± 0.09 (syst.) fm $^{-2}$, indicating a much shallower strong interaction potential than lattice QCD results for the N- J/ψ strong interaction [66]. For the Yukawa-type potential the fit yields $A = 0.021 \pm 0.009$ (stat.) ± 0.006 (syst.) and $\alpha = 65.9 \pm 38.0$ (stat.) ± 17.5 (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 $g_{\text{N-}\phi} = \sqrt{A}$, is

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

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 $\Re(f_0) = 0.85 \pm 0.34 \text{ (stat.)} \pm 0.14 \text{ (syst.) fm}$, $\Im(f_0) = 0.16 \pm 0.10 \text{ (stat.)} \pm 0.09 \text{ (syst.) fm}$, and $d_0 = 7.85 \pm 1.54 \text{ (stat.)} \pm 0.26 \text{ (syst.) fm}$. 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 $g_{N-\phi} = 0.14 \pm 0.03 \text{ (stat.)} \pm 0.02 \text{ (syst.)}$.

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.

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A The ALICE Collaboration

S. Acharya¹⁴³, D. Adamová⁹⁸, A. Adler⁷⁶, J. Adolfsson⁸³, G. Aglieri Rinella³⁵, M. Agnello³¹, N. Agrawal⁵⁵, Z. Ahammed¹⁴³, S. Ahmad¹⁶, S.U. Ahn⁷⁸, I. Ahuja³⁹, Z. Akbar⁵², A. Akindinov⁹⁵, M. Al-Turany¹¹⁰, S.N. Alam⁴¹, D. Aleksandrov⁹¹, B. Alessandro⁶¹, H.M. Alfanda⁷, R. Alfaro Molina⁷³, B. Ali¹⁶, Y. Ali¹⁴, A. Alici²⁶, N. Alizadehvandchali¹²⁷, A. Alkin³⁵, J. Alme²¹, T. Alt⁷⁰, L. Altenkamper²¹, I. Altsybeev¹¹⁵, M.N. Anaam⁷, C. Andrei⁴⁹, D. Andreou⁹³, A. Andronic¹⁴⁶, M. Angeletti³⁵, V. Anguelov¹⁰⁷, F. Antinori⁵⁸, P. Antonioli⁵⁵, C. Anuj¹⁶, N. Apadula⁸², L. Aphecetche¹¹⁷, H. Appelshäuser⁷⁰, S. Arcelli²⁶, R. Arnaldi⁶¹, I.C. Arsene²⁰, M. Arslanodok^{148,107}, A. Augustinus³⁵, R. Averbeck¹¹⁰, S. Aziz⁸⁰, M.D. Azmi¹⁶, A. Badalà⁵⁷, Y.W. Baek⁴², X. Bai^{131,110}, R. Bailhache⁷⁰, Y. Bailung⁵¹, R. Bala¹⁰⁴, A. Balbino³¹, A. Baldisseri¹⁴⁰, B. Balis², M. Ball⁴⁴, D. Banerjee⁴, R. Barbera²⁷, L. Barioglio^{108,25}, M. Barlou⁸⁷, G.G. Barnaföldi¹⁴⁷, L.S. Barnby⁹⁷, V. Barret¹³⁷, C. Bartels¹³⁰, K. Barth³⁵, E. Bartsch⁷⁰, F. Baruffaldi²⁸, N. Bastid¹³⁷, S. Basu⁸³, G. Batigne¹¹⁷, B. Batyunya⁷⁷, D. Bauri⁵⁰, J.L. Bazo Alba¹¹⁴, I.G. Bearden⁹², C. Beattie¹⁴⁸, I. Belikov¹³⁹, A.D.C. Bell Hechavarria¹⁴⁶, F. Bellini^{26,35}, R. Bellwied¹²⁷, S. Belokurova¹¹⁵, V. Belyaev⁹⁶, G. Bencedi⁷¹, S. Beole²⁵, A. Bercuci⁴⁹, Y. Berdnikov¹⁰¹, A. Berdnikova¹⁰⁷, D. Berenyi¹⁴⁷, L. Bergmann¹⁰⁷, M.G. Besoiu⁶⁹, L. Betev³⁵, P.P. Bhaduri¹⁴³, A. Bhasin¹⁰⁴, I.R. Bhat¹⁰⁴, M.A. Bhat⁴, B. Bhattacharjee⁴³, P. Bhattacharya²³, L. Bianchi²⁵, N. Bianchi⁵³, J. Bielčik³⁸, J. Bielčiková⁹⁸, J. Biernat¹²⁰, A. Bilandzic¹⁰⁸, G. Biro¹⁴⁷, S. Biswas⁴, J.T. Blair¹²¹, D. Blau⁹¹, M.B. Blidaru¹¹⁰, C. Blume⁷⁰, G. Boca^{29,59}, F. Bock⁹⁹, A. Bogdanov⁹⁶, S. Boi²³, J. Bok⁶³, L. Boldizsár¹⁴⁷, A. Bolozdynya⁹⁶, M. Bombara³⁹, P.M. Bond³⁵, G. Bonomi^{142,59}, H. Borel¹⁴⁰, A. Borissov⁸⁴, H. Bossi¹⁴⁸, E. Botta²⁵, L. Bratrud⁷⁰, P. Braun-Munzinger¹¹⁰, M. Bregant¹²³, M. Broz³⁸, G.E. Bruno^{109,34}, M.D. Buckland¹³⁰, D. Budnikov¹¹¹, H. Buesching⁷⁰, S. Bufalino³¹, O. Bugnon¹¹⁷, P. Buhler¹¹⁶, Z. Buthelezi^{74,134}, J.B. Butt¹⁴, S.A. Bysiak¹²⁰, D. Caffarri⁹³, M. Cai^{28,7}, H. Caines¹⁴⁸, A. Caliva¹¹⁰, E. Calvo Villar¹¹⁴, J.M.M. Camacho¹²², R.S. Camacho⁴⁶, P. Camerini²⁴, F.D.M. Canedo¹²³, F. Carnesecchi^{35,26}, R. Caron¹⁴⁰, J. Castillo Castellanos¹⁴⁰, E.A.R. Casula²³, F. Catalano³¹, C. Ceballos Sanchez⁷⁷, P. Chakraborty⁵⁰, S. Chandra¹⁴³, S. Chapeland³⁵, M. Chartier¹³⁰, S. Chattopadhyay¹⁴³, S. Chattopadhyay¹¹², A. Chauvin²³, T.G. Chavez⁴⁶, C. Cheshkov¹³⁸, B. Cheynis¹³⁸, V. Chibante Barroso³⁵, D.D. Chinellato¹²⁴, E.S. Chizzali¹⁰⁸, S. Cho⁶³, P. Chochula³⁵, P. Christakoglou⁹³, C.H. Christensen⁹², P. Christiansen⁸³, T. Chujo¹³⁶, C. Cicalo⁵⁶, L. Cifarelli²⁶, F. Cindolo⁵⁵, M.R. Ciupek¹¹⁰, G. Clai^{II,55}, J. Cleymans^{I,126}, F. Colamaria⁵⁴, J.S. Colburn¹¹³, D. Colella^{109,54,34,147}, A. Collu⁸², M. Colocci^{35,26}, M. Concas^{III,61}, G. Conesa Balbastre⁸¹, Z. Conesa del Valle⁸⁰, G. Contin²⁴, J.G. Contreras³⁸, M.L. Coquet¹⁴⁰, T.M. Cormier⁹⁹, P. Cortese³², M.R. Cosentino¹²⁵, F. Costa³⁵, S. Costanza^{29,59}, P. Crochet¹³⁷, E. Cuautle⁷¹, P. Cui⁷, L. Cunqueiro⁹⁹, A. Dainese⁵⁸, F.P.A. Damas^{117,140}, M.C. Danisch¹⁰⁷, A. Danu⁶⁹, I. Das¹¹², P. Das⁸⁹, P. Das⁴, S. Das⁴, S. Dash⁵⁰, S. De⁸⁹, A. De Caro³⁰, G. de Cataldo⁵⁴, L. De Cilladi²⁵, J. de Cuveland⁴⁰, A. De Falco²³, D. De Gruttola³⁰, N. De Marco⁶¹, C. De Martin²⁴, S. De Pasquale³⁰, S. Deb⁵¹, H.F. Degenhardt¹²³, K.R. Deja¹⁴⁴, L. Dello Stritto³⁰, S. Delsanto²⁵, W. Deng⁷, P. Dhankher¹⁹, D. Di Bari³⁴, A. Di Mauro³⁵, R.A. Diaz⁸, T. Dietel¹²⁶, Y. Ding^{138,7}, R. Divià³⁵, D.U. Dixit¹⁹, Ø. Djuvsland²¹, U. Dmitrieva⁶⁵, J. Do⁶³, A. Dobrin⁶⁹, B. Dönigus⁷⁰, O. Dordic²⁰, A.K. Dubey¹⁴³, A. Dubla^{110,93}, S. Dudi¹⁰³, M. Dukhishyam⁸⁹, P. Dupieux¹³⁷, N. Dzalaiova¹³, T.M. Eder¹⁴⁶, R.J. Ehlers⁹⁹, V.N. Eikeland²¹, F. Eisenhut⁷⁰, D. Elia⁵⁴, B. Erazmus¹¹⁷, F. Ercolessi²⁶, F. Erhardt¹⁰², A. Erokhin¹¹⁵, M.R. Ersdal²¹, B. Espagnon⁸⁰, G. Eulisse³⁵, D. Evans¹¹³, S. Evdokimov⁹⁴, L. Fabbietti¹⁰⁸, M. Faggin²⁸, J. Faivre⁸¹, F. Fan⁷, A. Fantoni⁵³, M. Fasel⁹⁹, P. Fecchio³¹, A. Feliciello⁶¹, G. Feofilov¹¹⁵, A. Fernández Téllez⁴⁶, A. Ferrero¹⁴⁰, A. Ferretti²⁵, V.J.G. Feuillard¹⁰⁷, J. Figiel¹²⁰, S. Filchagin¹¹¹, D. Finogeev⁶⁵, F.M. Fionda^{56,21}, G. Fiorenza^{35,109}, F. Flor¹²⁷, A.N. Flores¹²¹, S. Foertsch⁷⁴, P. Foka¹¹⁰, S. Fokin⁹¹, E. Fragiaco⁶², E. Frajna¹⁴⁷, U. Fuchs³⁵, N. Funicello³⁰, C. Furget⁸¹, A. Furs⁶⁵, J.J. Gaardhøje⁹², M. Gagliardi²⁵, A.M. Gago¹¹⁴, A. Gal¹³⁹, C.D. Galvan¹²², P. Ganoti⁸⁷, C. Garabatos¹¹⁰, J.R.A. Garcia⁴⁶, E. Garcia-Solis¹⁰, K. Garg¹¹⁷, C. Gargiulo³⁵, A. Garibli⁹⁰, K. Garner¹⁴⁶, P. Gasik¹¹⁰, E.F. Gauger¹²¹, A. Gautam¹²⁹, M.B. Gay Ducati⁷², M. Germain¹¹⁷, J. Ghosh¹¹², P. Ghosh¹⁴³,

S.K. Ghosh⁴, M. Giacalone²⁶, P. Gianotti⁵³, P. Giubellino^{110,61}, P. Giubilato²⁸, A.M.C. Glaenger¹⁴⁰, P. Glässel¹⁰⁷, D.J.Q. Goh⁸⁵, V. Gonzalez¹⁴⁵, L.H. González-Trueba⁷³, S. Gorbunov⁴⁰, M. Gorgon², L. Görlich¹²⁰, S. Gotovac³⁶, V. Grabski⁷³, L.K. Graczykowski¹⁴⁴, R.D. Grande¹⁰⁸, L. Greiner⁸², A. Grelli⁶⁴, C. Grigoras³⁵, V. Grigoriev⁹⁶, A. Grigoryan^{1,1}, S. Grigoryan^{77,1}, O.S. Groettvik²¹, F. Grosa^{35,61}, J.F. Grosse-Oetringhaus³⁵, R. Grosso¹¹⁰, G.G. Guardiano¹²⁴, R. Guernane⁸¹, M. Guilbaud¹¹⁷, K. Gulbrandsen⁹², T. Gunji¹³⁵, A. Gupta¹⁰⁴, R. Gupta¹⁰⁴, I.B. Guzman⁴⁶, S.P. Guzman⁴⁶, L. Gyulai¹⁴⁷, M.K. Habib¹¹⁰, C. Hadjidakis⁸⁰, G. Halimoglu⁷⁰, H. Hamagaki⁸⁵, G. Hamar¹⁴⁷, M. Hamid⁷, R. Hannigan¹²¹, M.R. Haque^{144,89}, A. Harlenderova¹¹⁰, J.W. Harris¹⁴⁸, A. Harton¹⁰, J.A. Hasenbichler³⁵, H. Hassan⁹⁹, D. Hatzifotiadou⁵⁵, P. Hauer⁴⁴, L.B. Havener¹⁴⁸, S. Hayashi¹³⁵, S.T. Heckel¹⁰⁸, E. Hellbär⁷⁰, H. Helstrup³⁷, T. Herman³⁸, E.G. Hernandez⁴⁶, G. Herrera Corral⁹, F. Herrmann¹⁴⁶, K.F. Hetland³⁷, H. Hillemanns³⁵, C. Hills¹³⁰, B. Hippolyte¹³⁹, B. Hofman⁶⁴, B. Hohlweger^{93,108}, J. Honermann¹⁴⁶, G.H. Hong¹⁴⁹, D. Horak³⁸, S. Hornung¹¹⁰, A. Horzyk², R. Hosokawa¹⁵, P. Hristov³⁵, C. Huang⁸⁰, C. Hughes¹³³, P. Huhn⁷⁰, T.J. Humanic¹⁰⁰, H. Hushnud¹¹², L.A. Husova¹⁴⁶, A. Hutson¹²⁷, D. Hutter⁴⁰, J.P. Iddon^{35,130}, R. Ilkaev¹¹¹, H. Ilyas¹⁴, M. Inaba¹³⁶, G.M. Innocenti³⁵, M. Ippolitov⁹¹, A. Isakov^{38,98}, M.S. Islam¹¹², M. Ivanov¹¹⁰, V. Ivanov¹⁰¹, V. Izucheev⁹⁴, M. Jablonski², B. Jacak⁸², N. Jacazio³⁵, P.M. Jacobs⁸², S. Jadlovská¹¹⁹, J. Jadlovsky¹¹⁹, S. Jaelani⁶⁴, C. Jahnke^{124,123}, M.J. Jakubowska¹⁴⁴, M.A. Janik¹⁴⁴, T. Janson⁷⁶, M. Jercic¹⁰², O. Jevons¹¹³, F. Jonas^{99,146}, P.G. Jones¹¹³, J.M. Jowett^{35,110}, J. Jung⁷⁰, M. Jung⁷⁰, A. Junique³⁵, A. Jusko¹¹³, J. Kaewjai¹¹⁸, P. Kalinak⁶⁶, A. Kalweit³⁵, V. Kaplin⁹⁶, S. Kar⁷, A. Karasu Uysal⁷⁹, D. Karatovic¹⁰², O. Karavichev⁶⁵, T. Karavicheva⁶⁵, P. Karczmarczyk¹⁴⁴, E. Karpechev⁶⁵, A. Kazantsev⁹¹, U. Kebschull⁷⁶, R. Keidel⁴⁸, D.L.D. Keijdener⁶⁴, M. Keil³⁵, B. Ketzer⁴⁴, Z. Khabanova⁹³, A.M. Khan⁷, S. Khan¹⁶, A. Khanzadeev¹⁰¹, Y. Kharlov⁹⁴, A. Khatun¹⁶, A. Khuntia¹²⁰, B. Kileng³⁷, B. Kim^{17,63}, D. Kim¹⁴⁹, D.J. Kim¹²⁸, E.J. Kim⁷⁵, J. Kim¹⁴⁹, J.S. Kim⁴², J. Kim¹⁰⁷, J. Kim¹⁴⁹, J. Kim⁷⁵, M. Kim¹⁰⁷, S. Kim¹⁸, T. Kim¹⁴⁹, S. Kirsch⁷⁰, I. Kisel⁴⁰, S. Kiselev⁹⁵, A. Kisiel¹⁴⁴, J.P. Kitowski², J.L. Klay⁶, J. Klein³⁵, S. Klein⁸², C. Klein-Bösing¹⁴⁶, M. Kleiner⁷⁰, T. Klemenz¹⁰⁸, A. Kluge³⁵, A.G. Knospe¹²⁷, C. Kobdaj¹¹⁸, M.K. Köhler¹⁰⁷, T. Kollegger¹¹⁰, A. Kondratyev⁷⁷, N. Kondratyeva⁹⁶, E. Kondratyuk⁹⁴, J. König⁷⁰, S.A. Königstorfer¹⁰⁸, P.J. Konopka^{35,2}, G. Kornakov¹⁴⁴, S.D. Koryciak², L. Koska¹¹⁹, A. Kotliarov⁹⁸, O. Kovalenko⁸⁸, V. Kovalenko¹¹⁵, M. Kowalski¹²⁰, I. Králik⁶⁶, A. Kravčáková³⁹, L. Kreis¹¹⁰, M. Krivda^{113,66}, F. Krizek⁹⁸, K. Krizkova Gajdosova³⁸, M. Kroesen¹⁰⁷, M. Krüger⁷⁰, E. Kryshen¹⁰¹, M. Krzewicki⁴⁰, V. Kučera³⁵, C. Kuhn¹³⁹, P.G. Kuijjer⁹³, T. Kumaoka¹³⁶, D. Kumar¹⁴³, L. Kumar¹⁰³, N. Kumar¹⁰³, S. Kundu^{35,89}, P. Kurashvili⁸⁸, A. Kurepin⁶⁵, A.B. Kurepin⁶⁵, A. Kuryakin¹¹¹, S. Kushpil⁹⁸, J. Kvapil¹¹³, M.J. Kwon⁶³, J.Y. Kwon⁶³, Y. Kwon¹⁴⁹, S.L. La Pointe⁴⁰, P. La Rocca²⁷, Y.S. Lai⁸², A. Lakrathok¹¹⁸, M. Lamanna³⁵, R. Langoy¹³², K. Lapidus³⁵, P. Larionov⁵³, E. Laudi³⁵, L. Lautner^{35,108}, R. Lavicka³⁸, T. Lazareva¹¹⁵, R. Lea^{142,24,59}, J. Lee¹³⁶, J. Leibrach⁴⁰, R.C. Lemmon⁹⁷, I. León Monzón¹²², E.D. Lesser¹⁹, M. Lettrich^{35,108}, P. Lévai¹⁴⁷, X. Li¹¹, X.L. Li⁷, J. Lien¹³², R. Lietava¹¹³, B. Lim¹⁷, S.H. Lim¹⁷, V. Lindenstruth⁴⁰, A. Lindner⁴⁹, C. Lippmann¹¹⁰, A. Liu¹⁹, J. Liu¹³⁰, I.M. Lofnes²¹, V. Loginov⁹⁶, C. Loizides⁹⁹, P. Loncar³⁶, J.A. Lopez¹⁰⁷, X. Lopez¹³⁷, E. López Torres⁸, J.R. Luhder¹⁴⁶, M. Lunardon²⁸, G. Luparello⁶², Y.G. Ma⁴¹, A. Maevskaya⁶⁵, M. Mager³⁵, T. Mahmoud⁴⁴, A. Maire¹³⁹, M. Malaev¹⁰¹, Q.W. Malik²⁰, L. Malinina^{14,77}, D. Mal'Kevich⁹⁵, N. Mallick⁵¹, P. Malzacher¹¹⁰, G. Mandaglio^{33,57}, V. Manko⁹¹, F. Manso¹³⁷, V. Manzari⁵⁴, Y. Mao⁷, J. Mareš⁶⁸, G.V. Margagliotti²⁴, A. Margotti⁵⁵, A. Marín¹¹⁰, C. Markert¹²¹, M. Marquard⁷⁰, N.A. Martin¹⁰⁷, P. Martinengo³⁵, J.L. Martinez¹²⁷, M.I. Martínez⁴⁶, G. Martínez García¹¹⁷, S. Masciocchi¹¹⁰, M. Masera²⁵, A. Masoni⁵⁶, L. Massacrier⁸⁰, A. Mastroserio^{141,54}, A.M. Mathis¹⁰⁸, O. Matonoha⁸³, P.F.T. Matuoka¹²³, A. Matyja¹²⁰, C. Mayer¹²⁰, A.L. Mazuecos³⁵, F. Mazzaschi²⁵, M. Mazzilli³⁵, M.A. Mazzoni⁶⁰, J.E. Mdhluli¹³⁴, A.F. Mechler⁷⁰, F. Meddi²², Y. Melikyan⁶⁵, A. Menchaca-Rocha⁷³, E. Meninno^{116,30}, A.S. Menon¹²⁷, M. Meres¹³, S. Mhlanga^{126,74}, Y. Miake¹³⁶, L. Micheletti^{61,25}, L.C. Migliorin¹³⁸, D.L. Mihaylov¹⁰⁸, K. Mikhaylov^{77,95}, A.N. Mishra¹⁴⁷, D. Miśkowiec¹¹⁰, A. Modak⁴, A.P. Mohanty⁶⁴, B. Mohanty⁸⁹, M. Mohisin Khan¹⁶, Z. Moravcova⁹², C. Mordasini¹⁰⁸, D.A. Moreira De Godoy¹⁴⁶, L.A.P. Moreno⁴⁶, I. Morozov⁶⁵, A. Morsch³⁵, T. Mrnjavac³⁵, V. Muccifora⁵³, E. Mudnic³⁶,

D. Mühlheim¹⁴⁶, S. Muhuri¹⁴³, J.D. Mulligan⁸², A. Mulliri²³, M.G. Munhoz¹²³, R.H. Munzer⁷⁰, H. Murakami¹³⁵, S. Murray¹²⁶, L. Musa³⁵, J. Musinsky⁶⁶, C.J. Myers¹²⁷, J.W. Myrcha¹⁴⁴, B. Naik^{134,50}, R. Nair⁸⁸, B.K. Nandi⁵⁰, R. Nania⁵⁵, E. Nappi⁵⁴, M.U. Naru¹⁴, A.F. Nassirpour⁸³, A. Nath¹⁰⁷, C. Nattrass¹³³, A. Neagu²⁰, L. Nellen⁷¹, S.V. Nesbo³⁷, G. Neskovic⁴⁰, D. Nesterov¹¹⁵, B.S. Nielsen⁹², S. Nikolaev⁹¹, S. Nikulin⁹¹, V. Nikulin¹⁰¹, F. Noferini⁵⁵, S. Noh¹², P. Nomokonov⁷⁷, J. Norman¹³⁰, N. Novitzky¹³⁶, P. Nowakowski¹⁴⁴, A. Nyanin⁹¹, J. Nystrand²¹, M. Ogino⁸⁵, A. Ohlson⁸³, V.A. Okorokov⁹⁶, J. Oleniacz¹⁴⁴, A.C. Oliveira Da Silva¹³³, M.H. Oliver¹⁴⁸, A. Onnerstad¹²⁸, C. Oppedisano⁶¹, A. Ortiz Velasquez⁷¹, T. Osako⁴⁷, A. Oskarsson⁸³, J. Otwinowski¹²⁰, K. Oyama⁸⁵, Y. Pachmayer¹⁰⁷, S. Padhan⁵⁰, D. Pagano^{142,59}, G. Paic⁷¹, A. Palasciano⁵⁴, J. Pan¹⁴⁵, S. Panebianco¹⁴⁰, P. Pareek¹⁴³, J. Park⁶³, J.E. Parkkila¹²⁸, S.P. Pathak¹²⁷, R.N. Patra^{104,35}, B. Paul²³, J. Pazzini^{142,59}, H. Pei⁷, T. Peitzmann⁶⁴, X. Peng⁷, L.G. Pereira⁷², H. Pereira Da Costa¹⁴⁰, D. Peresunko⁹¹, G.M. Perez⁸, S. Perrin¹⁴⁰, Y. Pestov⁵, V. Petráček³⁸, M. Petrovici⁴⁹, R.P. Pezzi^{117,72}, S. Piano⁶², M. Pikna¹³, P. Pillot¹¹⁷, O. Pinazza^{55,35}, L. Pinsky¹²⁷, C. Pinto²⁷, S. Pisano⁵³, M. Płoskoń⁸², M. Planinic¹⁰², F. Pliquett⁷⁰, M.G. Poghosyan⁹⁹, B. Polichtchouk⁹⁴, S. Politano³¹, N. Poljak¹⁰², A. Pop⁴⁹, S. Porteboeuf-Houssais¹³⁷, J. Porter⁸², V. Pozdniakov⁷⁷, S.K. Prasad⁴, R. Preghenella⁵⁵, F. Prino⁶¹, C.A. Pruneau¹⁴⁵, I. Pshenichnov⁶⁵, M. Puccio³⁵, S. Qiu⁹³, L. Quaglia²⁵, R.E. Quishpe¹²⁷, S. Ragoni¹¹³, A. Rakotozafindrabe¹⁴⁰, L. Ramello³², F. Rami¹³⁹, S.A.R. Ramirez⁴⁶, A.G.T. Ramos³⁴, T.A. Rancien⁸¹, R. Raniwala¹⁰⁵, S. Raniwala¹⁰⁵, S.S. Räsänen⁴⁵, R. Rath⁵¹, I. Ravasenga⁹³, K.F. Read^{99,133}, A.R. Redelbach⁴⁰, K. Redlich⁸⁸, A. Rehman²¹, P. Reichelt⁷⁰, F. Reidt³⁵, H.A. Reme-ness³⁷, R. Renfordt⁷⁰, Z. Rescakova³⁹, K. Reygers¹⁰⁷, A. Riabov¹⁰¹, V. Riabov¹⁰¹, T. Richert^{83,92}, M. Richter²⁰, W. Riegler³⁵, F. Riggi²⁷, C. Ristea⁶⁹, S.P. Rode⁵¹, M. Rodríguez Cahuantzi⁴⁶, K. Røed²⁰, R. Rogalev⁹⁴, E. Rogochaya⁷⁷, T.S. Rogoschinski⁷⁰, D. Rohr³⁵, D. Röhrich²¹, P.F. Rojas⁴⁶, P.S. Rokita¹⁴⁴, F. Ronchetti⁵³, A. Rosano^{33,57}, E.D. Rosas⁷¹, A. Rossi⁵⁸, A. Rotondi^{29,59}, A. Roy⁵¹, P. Roy¹¹², S. Roy⁵⁰, N. Rubini²⁶, O.V. Rueda⁸³, R. Rui²⁴, B. Rumyantsev⁷⁷, P.G. Russek², A. Rustamov⁹⁰, E. Ryabinkin⁹¹, Y. Ryabov¹⁰¹, A. Rybicki¹²⁰, H. Rytkonen¹²⁸, W. Rzesza¹⁴⁴, O.A.M. Saarimäki⁴⁵, R. Sadek¹¹⁷, S. Sadovsky⁹⁴, J. Saetre²¹, K. Šafařík³⁸, S.K. Saha¹⁴³, S. Saha⁸⁹, B. Sahoo⁵⁰, P. Sahoo⁵⁰, R. Sahoo⁵¹, S. Sahoo⁶⁷, D. Sahu⁵¹, P.K. Sahu⁶⁷, J. Saini¹⁴³, S. Sakai¹³⁶, S. Sambyal¹⁰⁴, V. Samsonov^{1,101,96}, D. Sarkar¹⁴⁵, N. Sarkar¹⁴³, P. Sarma⁴³, V.M. Sarti¹⁰⁸, M.H.P. Sas¹⁴⁸, J. Schambach^{99,121}, H.S. Scheid⁷⁰, C. Schiaua⁴⁹, R. Schicker¹⁰⁷, A. Schmah¹⁰⁷, C. Schmidt¹¹⁰, H.R. Schmidt¹⁰⁶, M.O. Schmidt¹⁰⁷, M. Schmidt¹⁰⁶, N.V. Schmidt^{99,70}, A.R. Schmier¹³³, R. Schotter¹³⁹, J. Schukraft³⁵, Y. Schutz¹³⁹, K. Schwarz¹¹⁰, K. Schweda¹¹⁰, G. Scioli²⁶, E. Scapparini⁶¹, J.E. Seger¹⁵, Y. Sekiguchi¹³⁵, D. Sekihata¹³⁵, I. Selyuzhenkov^{110,96}, S. Senyukov¹³⁹, J.J. Seo⁶³, D. Serebryakov⁶⁵, L. Šerkšnytė¹⁰⁸, A. Sevcenco⁶⁹, T.J. Shaba⁷⁴, A. Shabanov⁶⁵, A. Shabetai¹¹⁷, R. Shahoyan³⁵, W. Shaikh¹¹², A. Shangaraev⁹⁴, A. Sharma¹⁰³, H. Sharma¹²⁰, M. Sharma¹⁰⁴, N. Sharma¹⁰³, S. Sharma¹⁰⁴, O. Sheibani¹²⁷, K. Shigaki⁴⁷, M. Shimomura⁸⁶, S. Shirinkin⁹⁵, Q. Shou⁴¹, Y. Sibiriak⁹¹, S. Siddhanta⁵⁶, T. Siemiarczuk⁸⁸, T.F. Silva¹²³, D. Silvermyr⁸³, G. Simonetti³⁵, B. Singh¹⁰⁸, R. Singh⁸⁹, R. Singh¹⁰⁴, R. Singh⁵¹, V.K. Singh¹⁴³, V. Singhal¹⁴³, T. Sinha¹¹², B. Sitar¹³, M. Sitta³², T.B. Skaali²⁰, G. Skorodumovs¹⁰⁷, M. Slupecki⁴⁵, N. Smirnov¹⁴⁸, R.J.M. Snellings⁶⁴, C. Soncco¹¹⁴, J. Song¹²⁷, A. Songmoolnak¹¹⁸, F. Soramel²⁸, S. Sorensen¹³³, I. Sputowska¹²⁰, J. Stachel¹⁰⁷, I. Stan⁶⁹, P.J. Steffanic¹³³, S.F. Stiefelmaier¹⁰⁷, D. Stocco¹¹⁷, I. Storehaug²⁰, M.M. Storetvedt³⁷, C.P. Stylianidis⁹³, A.A.P. Suaide¹²³, T. Sugitate⁴⁷, C. Suire⁸⁰, M. Suljic³⁵, R. Sultanov⁹⁵, M. Šumbera⁹⁸, V. Sumberia¹⁰⁴, S. Sumowidagdo⁵², S. Swain⁶⁷, A. Szabo¹³, I. Szarka¹³, U. Tabassam¹⁴, S.F. Taghavi¹⁰⁸, G. Taillepied¹³⁷, J. Takahashi¹²⁴, G.J. Tambave²¹, S. Tang^{137,7}, Z. Tang¹³¹, M. Tarhini¹¹⁷, M.G. Tarzila⁴⁹, A. Tauro³⁵, G. Tejeda Muñoz⁴⁶, A. Telesca³⁵, L. Terlizzi²⁵, C. Terrevoli¹²⁷, G. Tersimonov³, S. Thakur¹⁴³, D. Thomas¹²¹, R. Tieulent¹³⁸, A. Tikhonov⁶⁵, A.R. Timmins¹²⁷, M. Tkacik¹¹⁹, A. Toia⁷⁰, N. Topilskaya⁶⁵, M. Toppi⁵³, F. Torres-Acosta¹⁹, T. Tork⁸⁰, R.C. Torres⁸², S.R. Torres³⁸, A. Trifiro^{33,57}, S. Tripathy^{55,71}, T. Tripathy⁵⁰, S. Trogolo^{35,28}, G. Trombetta³⁴, V. Trubnikov³, W.H. Trzaska¹²⁸, T.P. Trzcinski¹⁴⁴, B.A. Trzeciak³⁸, A. Tumkin¹¹¹, R. Turrisi⁵⁸, T.S. Tveter²⁰, K. Ullaland²¹, A. Uras¹³⁸, M. Urioni^{59,142}, G.L. Usai²³, M. Vala³⁹, N. Valle^{59,29}, S. Vallero⁶¹, N. van der Kolk⁶⁴, L.V.R. van Doremalen⁶⁴, M. van

Leeuwen⁹³, P. Vande Vyvre³⁵, D. Varga¹⁴⁷, Z. Varga¹⁴⁷, M. Varga-Kofarago¹⁴⁷, A. Vargas⁴⁶, M. Vasileiou⁸⁷, A. Vasiliev⁹¹, O. Vázquez Doce¹⁰⁸, V. Vechernin¹¹⁵, E. Vercellin²⁵, S. Vergara Limón⁴⁶, L. Vermunt⁶⁴, R. Vértesi¹⁴⁷, M. Verweij⁶⁴, L. Vickovic³⁶, Z. Vilakazi¹³⁴, O. Villalobos Baillie¹¹³, G. Vino⁵⁴, A. Vinogradov⁹¹, T. Virgili³⁰, V. Vislavicius⁹², A. Vodopyanov⁷⁷, B. Volkel³⁵, M.A. Völkl¹⁰⁷, K. Voloshin⁹⁵, S.A. Voloshin¹⁴⁵, G. Volpe³⁴, B. von Haller³⁵, I. Vorobyev¹⁰⁸, D. Voscek¹¹⁹, J. Vrláková³⁹, B. Wagner²¹, C. Wang⁴¹, D. Wang⁴¹, M. Weber¹¹⁶, R.J.G.V. Weelden⁹³, A. Wegrzynek³⁵, S.C. Wenzel³⁵, J.P. Wessels¹⁴⁶, J. Wiechula⁷⁰, J. Wikne²⁰, G. Wilk⁸⁸, J. Wilkinson¹¹⁰, G.A. Willems¹⁴⁶, E. Willsher¹¹³, B. Windelband¹⁰⁷, M. Winn¹⁴⁰, W.E. Witt¹³³, J.R. Wright¹²¹, W. Wu⁴¹, Y. Wu¹³¹, R. Xu⁷, S. Yalcin⁷⁹, Y. Yamaguchi⁴⁷, K. Yamakawa⁴⁷, S. Yang²¹, S. Yano^{47,140}, Z. Yin⁷, H. Yokoyama⁶⁴, I.-K. Yoo¹⁷, J.H. Yoon⁶³, S. Yuan²¹, A. Yuncu¹⁰⁷, V. Zaccolo²⁴, A. Zaman¹⁴, C. Zampolli³⁵, H.J.C. Zanoli⁶⁴, N. Zardoshti³⁵, A. Zarochentsev¹¹⁵, P. Závada⁶⁸, N. Zaviyalov¹¹¹, H. Zbroszczyk¹⁴⁴, M. Zhalov¹⁰¹, S. Zhang⁴¹, X. Zhang⁷, Y. Zhang¹³¹, V. Zhrebchevskii¹¹⁵, Y. Zhi¹¹, D. Zhou⁷, Y. Zhou⁹², J. Zhu^{7,110}, Y. Zhu⁷, A. Zichichi²⁶, G. Zinovjev³, 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 Wrocław, 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, Département 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