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Experimental Evidence for an Attractive p - ϕ Interaction

S. Acharya *et al.**
(ALICE Collaboration)

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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 $g_{N-\phi} = 0.14 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$. 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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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 nonzero 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 us 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 ($B \approx 3 \times 10^{-4}$ [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^- ($B \approx 50\%$ [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-induced [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 Okubo-Zweig-Iizuka (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

*Full author list given at the end of the article.

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meson with the nucleon, including a coupling to its strangeness content [21]. An alternative is the QCD van der Waals interaction [22], mediated by multigluon exchange, which has been identified as relevant for the $N-(c\bar{c})$ system [23]. Using a phenomenological Yukawa-type potential with adjusted parameters, the QCD van der Waals force is able to form a $N-\phi$ bound state [24]. However, the direct $N-\phi$ coupling is typically not considered in theoretical descriptions of the interaction in vacuum and in medium. OZI-allowed $N-\phi$ processes can also proceed via the coupling to particle pairs with same quantum numbers, such as $K-\Lambda, K-\Sigma, K^*-\Lambda, K^*-\Sigma$ [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 $N-\phi$ 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 $N-\phi$ 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 ultrarelativistic 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 $C(k^*) = \mathcal{N} \times (N_{\text{same}}(k^*)/N_{\text{mixed}}(k^*))$ [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 (denoted by the $*$) 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 Collaboration [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 represents the upper 0.17% of the charged-particle distribution 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 jetlike 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 [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 meson is reconstructed from 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 ($|\text{DCA}_z| < 0.8$ cm) and transverse plane ($|\text{DCA}_{xy}| < 0.4$ 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/ 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 $p-\phi$ and 3.61×10^4 $\bar{p}-\phi$ pairs with $k^* < 200$ MeV/ c contribute to the N_{same} distribution of the respective correlation function. As they are compatible within uncertainties, both correlation functions are combined. In the following, $p-\phi$ refers to $p-\phi \oplus \bar{p}-\phi$. The correlation function is normalized within $k^* \in [800, 1000]$ MeV/ c , where all the contributions to the correlation function are expected to be flat. The data are unfolded for the finite momentum resolution of the detector

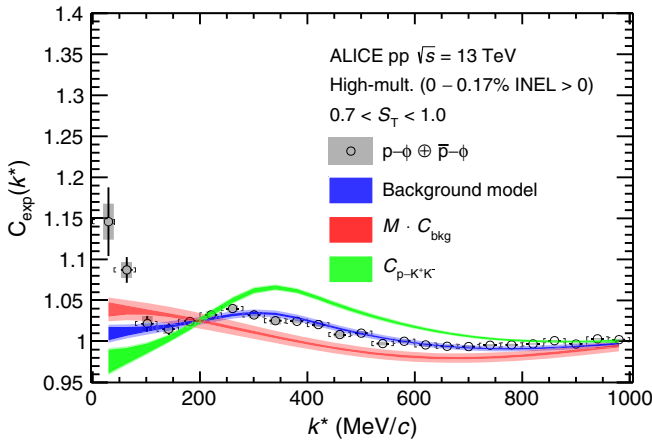


FIG. 1. The experimental p - ϕ correlation function $C_{\text{exp}}(k^*)$ and various contributions as described in Eq. (1). Statistical (bars) and systematic uncertainties (boxes) are shown separately. The width of the dark (light) shaded bands depicts the statistical (total) uncertainty.

[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 determined by the average $\langle k^* \rangle$ of the N_{same} distribution in the corresponding interval. In the region $150 < k^* < 600$ 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 the contributions due to residual correlations from the underlying event topology (minijets and energy-momentum conservation), weak decays feeding to the particles of interest (feed-down) and misidentifications [32].

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, $C_{\text{bkg}}(k^*)$ is the nonfemtoscopic background, $C_{p-\phi}(k^*)$ the genuine p - ϕ correlation function, $C_{\text{flat}}(k^*) \approx 1$ considers the effect from weak decays and single particle misidentification and $C_{p-(K^+K^-)}(k^*)$ is the contribution from combinatorial K^+K^- background. Correlations are summed for independent pairs and multiplied when considering different effects acting on the same pair. The parameters λ_i , summarized in Table I, 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 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 K^+K^- invariant mass selection and mainly driven by

TABLE I. 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

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 $C_{p-(K^+K^-)}(k^*)$, 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 $C_{p-(K^+K^-)}(k^*)$ is depicted by the green band in Fig. 1.

The nonfemtoscopic background $C_{\text{bkg}}(k^*)$ in Eq. (1) is multiplied to the genuine p - ϕ and flat contributions. $C_{\text{bkg}}(k^*) = C_{\text{baseline}}(k^*) + C_{\text{minijet}}(k^*)$ is dominated by residual minijet contributions $C_{\text{minijet}}(k^*)$ obtained from PYTHIA8 [53] generated events, which yield a consistent description of such background [54,55]. However, further correlations at large k^* due to energy-momentum conservation effects are not properly reproduced by PYTHIA8 [56]. Therefore, an additional $C_{\text{baseline}}(k^*)$ function, described by a second order polynomial, is considered.

The data are then fitted with a background model [Eq. (1) with $C_{p-\phi}(k^*) = 1$] within $k^* \in [200, 800]$ MeV/ c , which accounts for all contributions besides the genuine p - ϕ interaction. The λ parameters and the shape of the minijet and p - (K^+K^-) background are fixed in the fit. Only the normalization constant and baseline parameters are free. The resulting $C_{\text{bkg}}(k^*)$ is shown by the red band in Fig. 1 and the mean value of the normalization constant is $M = 0.96$. Accordingly, the total background is obtained as the blue band in Fig. 1, which accurately reproduces the enhancement between 200 and 1000 MeV/ c .

The genuine p - ϕ contribution $C_{p-\phi}(k^*)$, is extracted from Eq. (1) by subtracting the obtained background contributions from the experimental correlation and 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 $4.7 - 6.6\sigma$ with respect to the unity becomes apparent, which evidences the attractive nature of the p - ϕ interaction. The systematic uncertainties of the data and the background description are assessed by varying simultaneously the

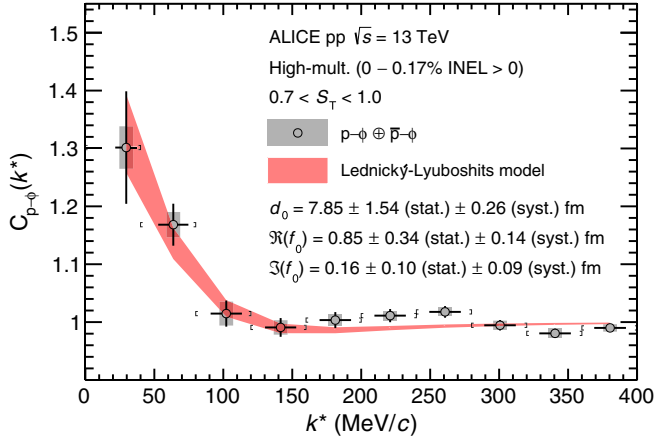


FIG. 2. The genuine p - ϕ correlation function $C_{p-\phi}(k^*)$ with statistical (bars) and systematic uncertainties (boxes). The red band depicts the results from the fit employing the Lednický-Lyuboshits approach [57]. The width corresponds to one standard deviation of the uncertainty of the fit.

selection criteria of protons and kaons as well as the lower limit of the sphericity. These variations are chosen such that any combination leads to a maximum change of $\pm 20\%$ of N_{same} within $k^* < 200$ MeV/ c in order to retain the statistical significance. Systematic uncertainties associated with the background description are evaluated by varying the fit ranges and the order of the polynomial assumed for $C_{\text{baseline}}(k^*)$. 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 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 [58]. 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. Channels 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.

In order to interpret the measured genuine p - ϕ correlation one has to consider that 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 [57]. 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 [23,59], 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) [60].

The particle-emitting source is extracted 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 [33], 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 $C_{p-\phi}(k^*)$ 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 real and imaginary parts of the scattering length obtained from the Lednický-Lyuboshits fit are $\Re(f_0) = 0.85 \pm 0.34(\text{stat}) \pm 0.14(\text{syst})$ fm and $\Im(f_0) = 0.16 \pm 0.10(\text{stat}) \pm 0.09(\text{syst})$ fm. The resulting effective range is $d_0 = 7.85 \pm 1.54(\text{stat}) \pm 0.26(\text{syst})$ fm. $\Re(f_0)$ deviates by 2.3σ from zero, indicating the attractiveness of the p - ϕ interaction in the approximate vacuum of pp collisions. 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]. The obtained scattering lengths are rather model dependent since the data refer to the properties of the ϕ meson inside a nucleus and not to a two-body system as in this work. This underlines the importance of direct measurements of the two-body N - ϕ interaction 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 $V_{\text{eff}} = 2.5 \pm 0.9(\text{stat}) \pm 1.4(\text{syst})$ MeV and $\mu = 0.14 \pm 0.06(\text{stat}) \pm 0.09(\text{syst})$ 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 $A = 0.021 \pm 0.009(\text{stat}) \pm 0.006(\text{syst})$ and $\alpha = 65.9 \pm 38.0(\text{stat}) \pm 17.5(\text{syst})$ MeV. Predictions of possible N - ϕ bound states employing the same kind of potential with modified parameters ($\alpha = 600$ 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 ($g_{N-\phi} = \sqrt{A}$) 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 $g_{N-\phi} = 0.14 \pm 0.03(\text{stat}) \pm 0.02(\text{syst})$.

These results seem to contradict the interpretation of the ϕ production off nuclear targets in terms of large absorption cross-sections but more data are needed to extract the precise value of the imaginary part of the scattering length and the here reported results should serve as an input for more advanced modelings in medium. The upcoming Run 3 and Run 4 data taking at the LHC will allow to significantly improve the precision of the extracted interaction parameters. 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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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
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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. König,⁷⁰ S. A. Königstorfer,¹⁰⁸ P. J. Konopka,^{2,35}
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,^{66,113} 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,^{27a,27b} 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,^{24a,24b,59,142}
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,^{28a,28b} 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,^{77,d} 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,^{24a,24b} 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. Maserà,^{25a,25b} A. Masoni,⁵⁶ L. Massacrier,⁸⁰ A. Mastroserio,^{54,141} A. M. Mathis,¹⁰⁸ O. Matonoha,⁸³
P. F. T. Matuoka,¹²³ A. Matyja,¹²⁰ C. Mayer,¹²⁰ A. L. Mazuecos,³⁵ F. Mazzaschi,^{25a,25b} M. Mazzilli,³⁵ M. A. Mazzoni,⁶⁰
J. E. Mdhului,¹³⁴ A. F. Mechler,⁷⁰ F. Meddi,^{22a,22b} Y. Melikyan,⁶⁵ A. Menchaca-Rocha,⁷³ E. Meninno,^{30a,30b,116}
A. S. Menon,¹²⁷ M. Meres,¹³ S. Mhlanga,^{74,126} Y. Miake,¹³⁶ L. Micheletti,^{25a,25b,61} L. C. Migliorin,¹³⁸ D. L. Mihaylov,¹⁰⁸
K. Mikhaylov,^{77,95} A. N. Mishra,¹⁴⁷ D. Miśkowiec,¹¹⁰ A. Modak,^{4a,4b} 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,^{23a,23b} 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,^{50,134}
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,^{59,142} 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,^{35,104} B. Paul,^{23a,23b} J. Pazzini,^{59,142} 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,^{72,117}
S. Piano,⁶² M. Pikna,¹³ P. Pillot,¹¹⁷ O. Pinazza,^{35,55} L. Pinsky,¹²⁷ C. Pinto,^{27a,27b} 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,^{4a,4b} R. Preghenella,⁵⁵ F. Prino,⁶¹ C. A. Pruneau,¹⁴⁵ I. Pshenichnov,⁶⁵ M. Puccio,³⁵

S. Qiu,⁹³ L. Quaglia,^{25a,25b} 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,^{34a,34b} 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,^{88,e} 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,^{27a,27b} 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,^{26a,26b} O. V. Rueda,⁸³ R. Rui,^{24a,24b} B. Romyantsev,⁷⁷ P. G. Russek,² A. Rustamov,⁹⁰ E. Ryabinkin,⁹¹ Y. Ryabov,¹⁰¹ A. Rybicki,¹²⁰ H. Ryttonen,¹²⁸ W. Rzeska,¹⁴⁴ O. A. M. Saarimaki,⁴⁵ R. Sadek,¹¹⁷ S. Sadovskiy,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,^{96,101,a} 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,^{70,99} A. R. Schmier,¹³³ R. Schotter,¹³⁹ J. Schukraft,³⁵ Y. Schutz,¹³⁹ K. Schwarz,¹¹⁰ K. Schweda,¹¹⁰ G. Scioli,^{26a,26b} E. Scomparin,⁶¹ J. E. Seger,¹⁵ Y. Sekiguchi,¹³⁵ D. Sekihata,¹³⁵ I. Selyuzhenkov,^{96,110} 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,^{28a,28b} 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,^{7,137} Z. Tang,¹³¹ M. Tarhini,¹¹⁷ M. G. Tarzila,⁴⁹ A. Tauro,³⁵ G. Tejada Muñoz,⁴⁶ A. Telesca,³⁵ L. Terlizzi,^{25a,25b} 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. Cruz-Torres,⁸² S. R. Torres,³⁸ A. Trifiró,^{33,57} S. Tripathy,^{55,71} T. Tripathy,⁵⁰ S. Trogolo,^{28a,28b,35} G. Trombetta,^{34a,34b} 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,^{23a,23b} M. Vala,³⁹ N. Valle,^{29,59} S. Vallerio,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,^{25a,25b} 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,^{30a,30b} V. Vislavicius,⁹² A. Vodopyanov,⁷⁷ B. Volkel,³⁵ M. A. Völkl,¹⁰⁷ K. Voloshin,⁹⁵ S. A. Voloshin,¹⁴⁵ G. Volpe,^{34a,34b} 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,^{24a,24b} A. Zaman,¹⁴ C. Zampolli,³⁵ H. J. C. Zanolli,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. Zhrebchevskii,¹¹⁵ Y. Zhi,¹¹ D. Zhou,⁷ Y. Zhou,⁹² J. Zhu,^{7,110} Y. Zhu,⁷ A. Zichichi,^{26a,26b} G. Zinovjev,³ and N. Zurlo^{59,142}

(ALICE Collaboration)

¹A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation

²AGH University of Science and Technology

³Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine

^{4a}Bose Institute, Department of Physics

^{4b}Centre for Astroparticle Physics and Space Science (CAPSS)

⁵Budker Institute for Nuclear Physics

- ⁶California Polytechnic State University
⁷Central China Normal University
⁸Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN)
⁹Centro de Investigación y de Estudios Avanzados (CINVESTAV)
¹⁰Chicago State University
¹¹China Institute of Atomic Energy
¹²Chungbuk National University
¹³Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics
¹⁴COMSATS University Islamabad
¹⁵Creighton University
¹⁶Department of Physics, Aligarh Muslim University
¹⁷Department of Physics, Pusan National University
¹⁸Department of Physics, Sejong University
¹⁹Department of Physics, University of California
²⁰Department of Physics, University of Oslo
²¹Department of Physics and Technology, University of Bergen
^{22a}Dipartimento di Fisica dell'Università 'La Sapienza'
^{22b}Sezione INFN
^{23a}Dipartimento di Fisica dell'Università
^{23b}Sezione INFN
^{24a}Dipartimento di Fisica dell'Università
^{24b}Sezione INFN
^{25a}Dipartimento di Fisica dell'Università
^{25b}Sezione INFN
^{26a}Dipartimento di Fisica e Astronomia dell'Università
^{26b}Sezione INFN
^{27a}Dipartimento di Fisica e Astronomia dell'Università
^{27b}Sezione INFN
^{28a}Dipartimento di Fisica e Astronomia dell'Università
^{28b}Sezione INFN
²⁹Dipartimento di Fisica e Nucleare e Teorica, Università di Pavia
^{30a}Dipartimento di Fisica 'E.R. Caianiello' dell'Università
^{30b}Gruppo Collegato INFN
³¹Dipartimento DISAT del Politecnico and Sezione INFN
³²Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino
³³Dipartimento di Scienze MIFT, Università di Messina
^{34a}Dipartimento Interateneo di Fisica 'M. Merlin'
^{34b}Sezione INFN
³⁵European Organization for Nuclear Research (CERN)
³⁶Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split
³⁷Faculty of Engineering and Science, Western Norway University of Applied Sciences
³⁸Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague
³⁹Faculty of Science, P.J. Šafárik University
⁴⁰Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt
⁴¹Fudan University
⁴²Gangneung-Wonju National University
⁴³Gauhati University, Department of Physics
⁴⁴Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn
⁴⁵Helsinki Institute of Physics (HIP)
⁴⁶High Energy Physics Group, Universidad Autónoma de Puebla
⁴⁷Hiroshima University
⁴⁸Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT)
⁴⁹Horia Hulubei National Institute of Physics and Nuclear Engineering
⁵⁰Indian Institute of Technology Bombay (IIT)
⁵¹Indian Institute of Technology Indore
⁵²Indonesian Institute of Sciences
⁵³INFN, Laboratori Nazionali di Frascati
⁵⁴INFN, Sezione di Bari
⁵⁵INFN, Sezione di Bologna
⁵⁶INFN, Sezione di Cagliari

- ⁵⁷*INFN, Sezione di Catania*
⁵⁸*INFN, Sezione di Padova*
⁵⁹*INFN, Sezione di Pavia*
⁶⁰*INFN, Sezione di Roma*
⁶¹*INFN, Sezione di Torino*
⁶²*INFN, Sezione di Trieste*
⁶³*Inha University*
⁶⁴*Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef*
⁶⁵*Institute for Nuclear Research, Academy of Sciences*
⁶⁶*Institute of Experimental Physics, Slovak Academy of Sciences*
⁶⁷*Institute of Physics, Homi Bhabha National Institute*
⁶⁸*Institute of Physics of the Czech Academy of Sciences*
⁶⁹*Institute of Space Science (ISS)*
⁷⁰*Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt*
⁷¹*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México*
⁷²*Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS)*
⁷³*Instituto de Física, Universidad Nacional Autónoma de México*
⁷⁴*iThemba LABS, National Research Foundation*
⁷⁵*Jeonbuk National University*
⁷⁶*Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik*
⁷⁷*Joint Institute for Nuclear Research (JINR)*
⁷⁸*Korea Institute of Science and Technology Information*
⁷⁹*KTO Karatay University*
⁸⁰*Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie*
⁸¹*Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3*
⁸²*Lawrence Berkeley National Laboratory*
⁸³*Lund University Department of Physics, Division of Particle Physics*
⁸⁴*Moscow Institute for Physics and Technology*
⁸⁵*Nagasaki Institute of Applied Science*
⁸⁶*Nara Women's University (NWU)*
⁸⁷*National and Kapodistrian University of Athens, School of Science, Department of Physics*
⁸⁸*National Centre for Nuclear Research*
⁸⁹*National Institute of Science Education and Research, Homi Bhabha National Institute*
⁹⁰*National Nuclear Research Center*
⁹¹*National Research Centre Kurchatov Institute*
⁹²*Niels Bohr Institute, University of Copenhagen*
⁹³*Nikhef, National institute for subatomic physics*
⁹⁴*NRC Kurchatov Institute IHEP*
⁹⁵*NRC «Kurchatov» Institute—ITEP*
⁹⁶*NRNU Moscow Engineering Physics Institute*
⁹⁷*Nuclear Physics Group, STFC Daresbury Laboratory*
⁹⁸*Nuclear Physics Institute of the Czech Academy of Sciences*
⁹⁹*Oak Ridge National Laboratory*
¹⁰⁰*Ohio State University*
¹⁰¹*Petersburg Nuclear Physics Institute*
¹⁰²*Physics department, Faculty of science, University of Zagreb*
¹⁰³*Physics Department, Panjab University*
¹⁰⁴*Physics Department, University of Jammu*
¹⁰⁵*Physics Department, University of Rajasthan*
¹⁰⁶*Physikalisches Institut, Eberhard-Karls-Universität Tübingen*
¹⁰⁷*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg*
¹⁰⁸*Physik Department, Technische Universität München*
¹⁰⁹*Politecnico di Bari*
¹¹⁰*Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH*
¹¹¹*Russian Federal Nuclear Center (VNIIEF)*
¹¹²*Saha Institute of Nuclear Physics, Homi Bhabha National Institute*
¹¹³*School of Physics and Astronomy, University of Birmingham*
¹¹⁴*Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú*
¹¹⁵*St. Petersburg State University*
¹¹⁶*Stefan Meyer Institut für Subatomare Physik (SMI)*

- ¹¹⁷*SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3*
- ¹¹⁸*Suranaree University of Technology*
- ¹¹⁹*Technical University of Košice*
- ¹²⁰*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences*
- ¹²¹*The University of Texas at Austin*
- ¹²²*Universidad Autónoma de Sinaloa*
- ¹²³*Universidade de São Paulo (USP)*
- ¹²⁴*Universidade Estadual de Campinas (UNICAMP)*
- ¹²⁵*Universidade Federal do ABC*
- ¹²⁶*University of Cape Town*
- ¹²⁷*University of Houston*
- ¹²⁸*University of Jyväskylä*
- ¹²⁹*University of Kansas*
- ¹³⁰*University of Liverpool*
- ¹³¹*University of Science and Technology of China*
- ¹³²*University of South-Eastern Norway*
- ¹³³*University of Tennessee*
- ¹³⁴*University of the Witwatersrand*
- ¹³⁵*University of Tokyo*
- ¹³⁶*University of Tsukuba*
- ¹³⁷*Université Clermont Auvergne, CNRS/IN2P3, LPC*
- ¹³⁸*Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon*
- ¹³⁹*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
- ¹⁴⁰*Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Département de Physique Nucléaire (DPHN)*
- ¹⁴¹*Università degli Studi di Foggia*
- ¹⁴²*Università di Brescia*
- ¹⁴³*Variable Energy Cyclotron Centre, Homi Bhabha National Institute*
- ¹⁴⁴*Warsaw University of Technology*
- ¹⁴⁵*Wayne State University*
- ¹⁴⁶*Westfälische Wilhelms-Universität Münster, Institut für Kernphysik*
- ¹⁴⁷*Wigner Research Centre for Physics*
- ¹⁴⁸*Yale University*
- ¹⁴⁹*Yonsei University*

^aDeceased.

^bAlso at Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy.

^cAlso at Dipartimento DET del Politecnico di Torino, Turin, Italy.

^dAlso at M.V. Lomonosov Moscow State University, D.V. Skobel'syn Institute of Nuclear, Physics, Moscow, Russia.

^eAlso at Institute of Theoretical Physics, University of Wrocław, Poland.