Experimental Evidence for an Attractive p-phi Interaction

Acharya, S.; Adamova, D.; Adler, A.; Adolfsson, J; Rinella, G.A.; Agnello, Maria; Agrawal, N.; Ahammed, Z.; Ahmad, S.; Ahn, S.U.; Bearden, Ian; rtc312, rtc312; bsm989, bsm989; Gaardhøje, Jens Jørgen; Moravcova, Zuzana; Nielsen, Børge Svane; Thoresen, Freja; Vislavicius, Vytautas; Zhou, You; Alice Collaboration

Published in:
Physical Review Letters

DOI:
10.1103/PhysRevLett.127.172301

Publication date:
2021

Document version
Publisher's PDF, also known as Version of record

Document license:
CC BY

Citation for published version (APA):
Experimental Evidence for an Attractive $p$-$\phi$ Interaction

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

(Received 16 June 2021; revised 8 September 2021; accepted 14 September 2021; published 20 October 2021)

This Letter presents the first experimental evidence of the attractive strong interaction between a proton and a $\phi$ meson. The result is obtained from two-particle correlations of combined $p$-$\phi$ $\bar{p}$-$\phi$ 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 $p$-$\phi$ 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 $p$-$\phi$ interaction. These data demonstrate that the interaction is dominated by elastic $p$-$\phi$ scattering. Furthermore, an analysis employing phenomenological Gaussian- and Yukawa-type potentials is conducted. Under the assumption of the latter, the $N$-$\phi$ 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 $N$-$\phi$ interaction, which is particularly relevant for the more fundamental studies on partial restoration of chiral symmetry in nuclear medium.

DOI: 10.1103/PhysRevLett.127.172301

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 $\rho$, $\omega$, and $\phi$ 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 $\phi$ meson represents an experimentally challenging probe due to the narrow decay width in vacuum, which renders its spectral shape distinguishable from that of the $\rho$ and $\omega$ mesons. The KEK-PS E325 Collaboration measured the $\phi$ 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 $\phi \to e^+e^-$ decay. Larger data samples were collected by the Spring8-LEPS Collaboration in order to determine the $\phi$ production and absorption cross section in photon-induced reactions by exploiting the decay to $K^+K^-$ ($B \approx 50\%$) [15]. The $N$-$\phi$ cross section in nuclear matter was found to be much larger than the vacuum cross section, corresponding to an in-medium $\phi$ 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 $N$-$\phi$ interaction and its complex dynamics. Because of the hidden strangeness content ($s\bar{s}$) of the $\phi$, 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 $\phi$...
charged particles in the pseudorapidity interval employed to select collisions with on average 30 produced energies of 1.65 GeV, demonstrating a constant explored by HADES in π dynamics of the K the ultrarelativistic proton-proton (pp) collisions are out of reach [25]. This demonstrates the need for a direct interplay of all aforementioned processes. However, the frame (denoted by the \( k_t \)) is the Koonin-Pratt equation \( C(k') = N \times (N_{\text{same}}(k')/N_{\text{mixed}}(k')) \) [40] where \( N_{\text{same}} \) and \( N_{\text{mixed}} \) are the distributions of the relative momentum \( k' = 1/2 \times (p_1 - p_2) \) between both particles in the pair rest frame (denoted by the \( * \)) and a normalization constant \( N \), evaluated from same and mixed events, respectively. The Koonin-Pratt equation \( C(k') = \int d^3r S(r') |\Psi(r', k')|^2 \) [40] relates the observable to the source function \( S(r') \) and the two-particle wave function \( |\Psi(r', k')| \) 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 from 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 \( \times \) 10^6 events with \( 0.7 < S_T < 1.0 \) [35] are analyzed. The sub-systems 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 \( n_r \) between the signal hypothesis for a proton and the measurement, normalized by the detector resolution \( \sigma \). 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 \( \phi \) 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 (\( \Delta C A_x < 0.8 \) cm) and transverse plane (\( |\Delta C A_y| < 0.4 \) cm) is employed to increase the fraction of kaons from \( \phi \) 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 \( \phi \) candidates are selected within a window of \( \pm 8 \) MeV/c^2 around the nominal \( \phi \) mass, resulting in a total number of \( 5.8 \times 10^8 \) with a purity of 66%.

A total of 4.17 \( \times \) 10^4 \( p - \phi \) and 3.61 \( \times \) 10^4 \( \bar{p} - \phi \) pairs with \( k^* < 200 \) MeV/c contribute to the \( N_{\text{same}} \) 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.

PHYSICAL REVIEW LETTERS 127, 172301 (2021)
which modifies the correlation function by 0.7% at low \( k^* \). The measured \( p-\phi \) correlation function is shown in Fig. 1. The \( k^* \) value of the data points is determined by the average \( \langle k^* \rangle \) of the \( N_{\text{same}} \) distribution in the corresponding interval. In the region \( 150 < k^* < 600 \) \( \text{MeV}/c \) a rise in the correlation function attributed to residual minijet background is visible. Therefore, any conclusion on the genuine \( p-\phi \) 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 \( p-\phi \) correlation function \( C_{\exp}(k^*) \) is decomposed as

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

where \( M \) is a normalization constant, \( C_{\text{bkg}}(k^*) \) is the nonfemtoscopic background, \( C_{p-\phi}(k^*) \) the genuine \( p-\phi \) 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 \( \lambda_i \), summarized in Table I, are obtained in a data-driven way from single-particle properties [32]. As the purity of the \( \phi \) 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 \( p-K^+ \) 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 \( \phi \) candidates. The resulting correlation function is parametrized with a double Gaussian and a quadratic polynomial. Finally, a residual \( \phi \) amount of 8.6% in the sidebands is considered, which arises from the tail of the \( \phi \) 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 \( \lambda \) 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 \( p-\phi \) 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 PYTHIA [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 PYTHIA [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 \( k^* \in [200, 800] \) \( \text{MeV}/c \), which accounts for all contributions besides the genuine \( p-\phi \) interaction. The \( \lambda \) 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 \( \text{MeV}/c \).

The genuine \( p-\phi \) 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 \( k^* > 200 \) \( \text{MeV}/c \), 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 \( p-\phi \) interaction. The systematic uncertainties of the data and the background description are assessed by varying simultaneously the
model the $p$-$\phi$ interaction [24], including Yukawa-type, $V_{\text{Yukawa}}(r) = -A \times r^{-1} \times e^{-\alpha r}$, and Gaussian-type $V_{\text{Gaussian}}(r) = -V_{\text{eff}} \times e^{-\mu r^2}$ 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 $p$-$\Lambda$ 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 $(m_T) = 1.66$ GeV/$c^2$ of the $p$-$\phi$ pairs. The strong decays feeding to protons are explicitly considered [33], while for the $\phi$ 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 $p$-$\phi$ 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 $\Re(f_0) = 0.85 \pm 0.34$(stat) $\pm 0.14$(syst) fm and $\Im(f_0) = 0.16 \pm 0.10$(stat) $\pm 0.09$(syst) fm. The resulting effective range is $d_0 = 7.85 \pm 1.54$(stat) $\pm 0.26$(syst) fm. $\Re(f_0)$ deviates by 2.3σ from zero, indicating the attractiveness of the $p$-$\phi$ 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 $p$-$\phi$ 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 $\phi$ cross section [62,63]; studies of an effective Lagrangian combining chiral SU(3) dynamics with vector meson dominance obtain $f_0 = (-0.01 \pm 0.08)$ 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 $\phi$ 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 $N$-$\phi$ 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 \( V_{\text{eff}} = 2.5 \pm 0.9 \text{(stat)} \pm 1.4 \text{(syst)} \text{ MeV} \) and 
\( \mu = 0.14 \pm 0.06 \text{(stat)} \pm 0.09 \text{(syst)} \text{ fm}^{-2} \), indicating a much shallower strong interaction potential than lattice QCD results for the \( N-J/\gamma \) 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 \( \alpha = 65.9 \pm 38.0 \text{(stat)} \pm 17.5 \text{(syst)} \text{ MeV} \). Predictions of possible \( N-\phi \) bound states employing the same kind of potential with modified parameters \((\alpha = 600 \text{ MeV} \text{ and } A = 1.25) [24] \) are therefore incompatible with this measurement. The \( N-\phi \) 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 \( p-\phi \) interaction. The correlation function reflects the pattern of an attractive interaction. The scattering parameters, extracted with the Lednicky-Lyuboshits approach, are \( R(f_0) = 0.85 \pm 0.34 \text{(stat)} \pm 0.14 \text{(syst)} \text{ fm}, \lambda(f_0) = 0.16 \pm 0.10 \text{(stat)} \pm 0.09 \text{(syst)} \text{ fm}, \) and \( d_0 = 7.85 \pm 1.54 \text{(stat)} \pm 0.26 \text{(syst)} \text{ fm}. \) 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 \( p-\phi \) dynamics. Under the assumption of a Yukawa-type potential for the \( N-\phi \) 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 \( \phi \) 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 \( p-\phi \) interaction in vacuum is attractive and dominated by elastic scattering. It provides valuable experimental input on the \( N-\phi \) interaction, which is fundamental to reach a self-consistent description of the interaction as required for the correct interpretation of data from nuclear collisions.

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

[47] S. Acharya et al. (ALICE Collaboration), $K^*(892)^0$ and $\phi(1020)$ production at midrapidity in $pp$ collisions at $\sqrt{s} = 8$ TeV, Phys. Rev. C 102, 024912 (2020).
[51] K. Aamodt et al. (ALICE Collaboration), Femtoscopy of $pp$ collisions at $\sqrt{s} = 0.9$ and 7 TeV at the LHC with two-pion Bose-Einstein correlations, Phys. Rev. D 84, 112004 (2011).
[58] I. I. Strakovsky, L. Pentchev, and A. I. Titov, Comparative analysis of $\omega\rho$, $\phi\phi$, and $J/\psi\rho$ scattering lengths from A2, CLAS, and GlueX threshold measurements, Phys. Rev. C 101, 045201 (2020).
INFN, Sezione di Catania
INFN, Sezione di Padova
INFN, Sezione di Pavia
INFN, Sezione di Roma
INFN, Sezione di Torino
INFN, Sezione di Trieste
Inha University
Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef
Institute for Nuclear Research, Academy of Sciences
Institute of Experimental Physics, Slovak Academy of Sciences
Institute of Physics, Homi Bhabha National Institute
Institute of Physics of the Czech Academy of Sciences
Institute of Space Science (ISS)
Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México
Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS)
Instituto de Física, Universidad Nacional Autónoma de México
Institute of Physics, Homi Bhabha National Institute
Institute of Physics of the Czech Academy of Sciences
Institute of Space Science (ISS)
Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt
Joint Institute for Nuclear Research (JINR)
Korea Institute of Science and Technology Information
KTO Karatay University
Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3
Lawrence Berkeley National Laboratory
Lund University Department of Physics, Division of Particle Physics
Moscow Institute for Physics and Technology
Nagasaki Institute of Applied Science
Nara Women’s University (NWU)
National and Kapodistrian University of Athens, School of Science, Department of Physics
National Centre for Nuclear Research
National Institute of Science Education and Research, Homi Bhabha National Institute
National Nuclear Research Center
National Research Centre Kurchatov Institute
Niels Bohr Institute, University of Copenhagen
NRC Kurchatov Institute IHEP
NRC «Kurchatov» Institute—ITEP
NRNU Moscow Engineering Physics Institute
National Centre for Nuclear Research
National Institute of the Czech Academy of Sciences
Oak Ridge National Laboratory
Ohio State University
Petersburg Nuclear Physics Institute
Physics department, Faculty of science, University of Zagreb
Physics Department, Panjab University
Physics Department, University of Jammu
Physics Department, University of Rajasthan
Physikalisches Institut, Eberhard-Karls-Universität Tübingen
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg
Physik Department, Technische Universität München
Politecnico di Bari
Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH
Russian Federal Nuclear Center (VNIIEF)
Saha Institute of Nuclear Physics, Homi Bhabha National Institute
School of Physics and Astronomy, University of Birmingham
Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú
St. Petersburg State University
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

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